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MODERN METEOROLOGY.

MODERN METEOROLOGY:

AN OUTLINE OF THE GROWTH AND PRESENT CONDITION OF SOME OF ITS PHASES.

BY

FRANK WALDO, Ph.D.,

MEMBER OF THE GERMAN AND AUSTRIAN METEOROLOGICAL SOCIETIES, ETC.

Late Junior Professor, Signal Service, U.S.A.

WITH 112 ILLUSTRATIONS.

LONDON:

WALTER SCOTT, LTD.,

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PREFACE.

THE material which I have here brought together will be of interest mainly to those persons who take a special delight in meteorology but who have little access to original sources of information ; among this class are the great majority of the small army of Meteorological Observers and many teachers of physical geography and general physics. The general reader may find it partly supplementary to such works as Scott's *Meteorology*, Abercromby's *Weather*, or the articles in the *Encyclopædia Britannica.*

Living at a distance of several hundred miles from any considerable meteorological library, it was impossible for me to consult many original authorities and to give a complete historical treatment of the various subjects; and it must be remarked that, as I have been mainly a student of what may be termed the German school of Meteorology, I probably have not brought into sufficient notice the names and work of French, English, and Italian meteorologists; recognising this, I have tried not to bring prominently forward names in those connections where justice to others would probably require mention of their names also. It may be added that the various lines of meteorology have been so rapidly developed within the past decade or two, that a com-

prehensive treatment of any one of the half a dozen divisions of the subject which are brought into notice here would have required a volume longer than the present: so that variety of topics is obtained only at the expense of the completeness of detail which is necessary to render the treatment of a subject generally interesting.

The main object of this little book is to bring the reader into closer contact with the work which has been and is actually engaging the attention of working meteorologists rather than to present finished results.

Chapter I. is mainly devoted to the mention of some of the principal sources of information concerning the recent progress in meteorological science.

Chapter II. contains a history and description of some important meteorological instruments and the methods of using them. In the preparation of this chapter the freest use has been made of Professor Abbe's treatise on Meteorological Apparatus and Methods (printed by the U.S. Signal Service). In the section on thermometers I would have made a more extended use of Guillaume's *Thermomètrie* if it had been available at the time of writing. As there is no work published in English which gives an adequate description of meteorological instruments, I have given more prominence to this topic than would otherwise be warrantable; the subjects of thermometers, barometers, and wind-measuring instruments receiving the most attention. In fact, the relatively large amount of space devoted to these has compelled me to make but a brief mention or omit altogether other less common instruments. The illustrations of observatories will

serve to show that while meteorology may not have reached the dignified position occupied by astronomy, yet these evidences of its stability indicate the firm foothold it has obtained among state-subsidised sciences. Special attention is called to the details of equipment and routine of the Pawlowsk (Russia) Observatory, which are available through the courtesy of Director Wild and Dr. Leyst. I know of no similar published account of the work of an observatory.

Chapter III. is mainly made up of an abstract of the important memoirs on Thermodynamics of the Atmosphere, recently communicated to the Berlin Academy of Sciences by Professor von Bezold. I consider his ideas of the greatest importance in the development of atmospheric mechanics and the study of atmospheric conditions. It is improbable that von Bezold's ideas will creep into elementary English text-books for a number of years to come, and so the necessity for their presentation here seemed the more pressing, although it may require more time than the average reader will give in order to understand portions of the reasoning. I have endeavoured to follow closely von Bezold's own presentation of the subject.

Chapter IV. contains a partial outline of the history of the development of theories of the general atmospheric circulation, with a brief statement of Professor Ferrel's completed theory and an account of some recent contributions to the subject by Möller, Oberbeck, von Siemens, and von Helmholtz. In these also I have followed closely the text of the authors named, so far as I have presented their ideas.

Chapter V. is devoted to a historical sketch and

partial explanation of the secondary atmospheric circulation to which the local character of winds can usually be referred—at least in the middle latitudes. Special attention is called to the attempt of von Bezold to unite the older and newer theories, as explained in his communication to the Berlin Academy of Science; and the results of his study occupy a considerable portion of the present chapter.

Chapter VI. contains some of the principal results obtained by Dr. Brückner in his recent discussion of the results of meteorological observations from the time of their commencement to the present time. The points mainly dwelt on are the long-period oscillations of climatic factors. The second part of the chapter, which treats of the application of meteorology to agriculture, I have been permitted by the Assistant Secretary of Agriculture to abstract from an unpublished essay prepared by me for the Department of Agriculture, U.S.A.

I wish to express my thanks to the various authors and publishers who have permitted the use of their illustrations; due credit is given in the proper place. I am indebted to Professor Wild for the photograph of the Pawlowsk Observatory, and to Professor Whipple for the photographs of the Kew Observatory and apparatus.

In closing I must not omit to make mention of the substantial assistance rendered by my wife in the preparation of this book.

FRANK WALDO.

PRINCETON, NEW JERSEY, U.S.A.

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MODERN METEOROLOGY.

CHAPTER I.

SOURCES OF MODERN METEOROLOGY.

§ 1.—*Development.*

IN giving an idea of the present status of the science of meteorology it would be best to trace its general growth from the condition in which we find it about the year 1860. At this period many of the new departures which have aided in the wonderful progress of the past two or three decades originated, although most of the important work has been accomplished within the last twenty years. Ferrel's pioneer papers (1856–58–59) on the theory of atmospheric motions had been written, and the important law of Buys Ballot[1] concerning the wind's direction discovered, just before 1860; and Schoch had worked out the application of spherical functions to the representation of the mean temperature over the surface of the earth (1856). Le Verrier had begun to issue the reports of simultaneous meteor-

[1] Erman had arrived at a conclusion similar to this some years earlier (*Poggendorf's Annalen*, lxxxviii.).

ological observations in the *Bulletin International de l'Observatoire* (1856). Welsh had mounted a normal barometer at the Kew Observatory (1856), which was the first instrument of other than ordinary construction, set up to serve as a standard of reference for other barometers intended for use in observatories. Regnault's normal barometer, constructed ten years earlier, had been mainly for laboratory use.

These and many more innovations had been made before the publication of Schmid's great work on meteorology, but their importance was not yet felt, and so they remained unmentioned by him. This special mention is made of Schmid's *Meteorologie* (Leipzig, 1860), because in this one volume the author brought together the main facts of meteorological science as they were accepted by most of the scientists of that period. The volume occupied seven years in the making, and is a veritable treasury of facts and references. While it is not so original as Kaemtz's *Meteorologie*, published twenty-five years earlier, yet it is far more valuable as a work of reference. In fact, the publication of Schmid's book makes the year 1860 a very definite epoch in meteorological history. Buchan's *Handy Book of Meteorology*, published a few years later (1867), presents very strongly the new tendency of meteorological investigation, and perhaps it may be regarded as the first of the modern treatises which have since appeared at short intervals.

Government meteorological organisations established.—The modern rapid development of meteorology has been due to the usefulness of meteorological data in practical life rather than to a desire on the part of its supporters to encourage a study of it as a science.

Without government support of meteorological work as a separate department, the rapid growth of the past twenty years would have been impossible. Shortly after the period (1860) which has just been mentioned, the different governments began to establish meteorological organisations which had no direct dependence on other institutions, and which could thus be dealt with in a manner not possible so long as they were merely appendages to some other organisations. There were then few specialists in meteorology, for there had been scarcely any positions in which the incumbents were permitted to devote their whole time to this one department of science; but the aid derived from the State has allowed the enlistment of investigators of the best abilities in the cause of meteorological science.

Introduction of dynamical methods.—Not only was new life infused into meteorological work by the increased support which it received, but new methods were introduced. The older method of investigation has been termed the statistical, and the new departure the dynamical method. The latter has not displaced the former, but it is made accessory to it. By the old method, data were accumulated and discussed singly, and certain facts were deduced; by the new they are examined in the aggregate, and the relation of these facts worked out both as to cause and progressive development. Notwithstanding the fact that there are certain general characteristics of weather and climate which are brought to light by the discussion of observations extending over long periods of time, yet the great variability and rapid succession of changes of weather conditions show that if we will investigate their cause, it must be looked

for in immediate connection with the event. By the older methods this was attempted by considering the time-relation merely, but the new meteorology shows that we must also take into account the space-distribution, both geographically and, to a relatively small amount, also in altitude.

Sub-departments of meteorological organisation.—While the meteorological services of different countries do not present the same characteristics in the details of organisation, yet there is a normal plan of organisation which, to a certain extent, fits them all. The service controlled by the general government consists of a central office and outlying observing stations managed by a scientific director, who has several assistants having immediate charge of the various departments into which the work is, for convenience, sub-divided. These assistants are, or soon become, specialists in their line of work, and perform their duties or have their headquarters at the central office. These sub-departments may be named nearly as follows: Supervision of Observing Stations; Climatology; Weather Predictions, Storm Warnings, and Summaries of Current Weather; Management of the Central Observatory; Care of the Standard Instruments, and verification of Instruments to be used at the various observing stations; and, in some cases, Maritime Meteorology.

Establishment of stations of different classes.—In the larger organisations these assistants have a force of computers or observers to assist them in their work. The central meteorological observatory is of the first class; that is, observations of the chief elements are made every hour, or self-registering instruments are in operation. A detailed account of the work of this

central office is given in another chapter. The outlying observing stations may be classified as follows:

Additional, but less completely equipped and manned, stations of the first class.

Second-class stations, at which the barometric pressure, temperature, rainfall, humidity, wind (direction and force), and cloudiness are observed twice or thrice daily, and miscellaneous observations are also made, such as thunder-storms, frosts, hail, &c.; these stations are distributed over the country as uniformly as may be convenient, and are in charge of skilled observers, who, if they are not already employed by the government, usually receive pay for their services.

Third-class stations are those at which temperature, precipitation, and some miscellaneous observations are made. The observers are usually persons who, for different reasons, are sufficiently interested in meteorology to be willing to make and record two or three observations at stated times daily, but who are at liberty to discontinue the work at any time, as it is entirely voluntary.

Special stations for the observation of rainfall and thunder-storms have also become numerous in most countries, and they are likewise conducted by a volunteer corps of observers.

All of these observers send copies of their records to the central office, usually at intervals of a month, where the observations are made use of by the proper departments. In cases, however, where the observations are required for use in making weather predictions, they are telegraphed to the central office with little delay.

§ 2.—*Meteorological Publications.*

Professional papers.—While the smaller meteorological services have usually had to be content with publishing merely the bi- or tri-daily instrumental readings or the averages of the observations made under their control, nearly all of the larger or national services have given us additional publications. The most important of these are the volumes of memoirs, in which the meteorologists of the service, usually of the staff at the central office, work up the observations which have been made by the service and which in many cases can be used only by persons having access to the archives in which are stored the records of individual observations. Some of the services are provided with the means of still further usefulness, which permit these professional papers to include discussions of methods and results in general; these often involve long-continued experiments, or the gathering together of material obtained from various parts of the globe. Such memoirs were of necessity formerly infrequent, because the investigators were obliged to publish their work mostly in scattered transactions, where only a limited amount of space could be assigned for the use of any one science, and where, as in the case of journal publications, numerical tables and expensive illustrations and charts are not inserted unless of great value.

The Indian *Meteorological Memoirs*, the French *Annales du Bureau Central Météorologique de France*, the Italian *Annali dell' Officio Centrale di Meteor. Italiana*, the German *Aus dem Archiv der Deutschen Seewarte*, the *Abhandlungen d. Kon. Preussischen*

Meteor. Instituts, the *Professional Papers* (formerly issued) and *Annual Reports of the United States Weather Bureau*, the Argentine *Annales de la Oficina Meteorologica Argentina*, and the Russian *Repertorium für Meteorologie* (sometimes called *Wild's Repertorium*), are the chief examples of this class of publications. The Russian *Repertorium für Meteorologie* outranks the others, especially as regards the number of papers and the variety of topics treated.

Monthly Weather Reports.—The monthly division of time has been the plan usually followed in the presentation of meteorological data, but it was not until after the establishment of Weather Services that the need was felt for the frequent publication of these data.

The immediate use of observations for weather predicting, the increasing demand of the public for information in regard to current weather conditions for practical applications, the study of the courses of storms which could be followed for only a few days at the utmost, the greatly increased number of observing stations, which made the mass of data too bulky to manipulate properly if left to accumulate until the end of the year, the more general appreciation of the fact that short periods of time had distinctive characteristics in the seasonal changes of the year, and the impatience of the users of meteorological data, who ordinarily had to wait a couple of years or more after they were recorded before they could receive them in tabulated form, all combined to necessitate the publication of this data at frequent intervals.

The month was chosen as a proper subdivision on account of its convenience. It was no simple matter to decide on just the form this new mode of publica-

tion should take, as it was to be merely accessory to the usual annual *résumé* of observations. The *Monthly Weather Review* of the United States Signal Service at Washington (established 1872) was the first[1] of these publications as now issued, covering a great extent of territory; and its original form was, I believe, due to Professor Cleveland Abbe, although its more recent extension has been carried out under the guidance of Lieutenant Dunwoody. While this publication has served in a great measure as a pattern for similar ones in Europe, yet it gives far more information than any of them, containing, as it does (for instance, August, 1891), the results obtained from a discussion of reports for the month from 2,575 regular and voluntary observers, and covering not only the United States, but Canada and a portion of the Atlantic Ocean. The monthly averages of temperature and precipitation are given for about 2,000 observing stations in the United States; and averages for all of the usual meteorological elements for about 160 stations. A special feature of this *Weather Review* is the report concerning the passage of areas of high and low atmospheric pressure across the United States and a portion of the Atlantic Ocean. The charts showing the course taken by storms, and the distribution of atmospheric pressure, temperature, rainfall, and winds for the month, are of great scientific and practical value.

The monthly report of the *Deutsche Seewarte*, at Hamburg, is the most important European publication of this class. It was at first prepared by Dr. Köppen, but afterwards by Dr. van Bebber, who still has it

[1] Monthly reports had been previously published for single stations and limited areas.

in charge. At first this report stood alone, on the Continent, but the gradual introduction of the system of a monthly publication of local weather characteristics into many of the other weather services, has caused Director Neumayer of the *Seewarte* to give the Review more of an international character. So that now it is not published for several months after the observations are made, and it contains a record of the storm-tracks and weather for the North Atlantic Ocean, as well as Europe. These two monthly Weather Reviews cover the whole region from the west coast of North America to the eastern boundary of Europe.[1] It is not necessary to enter into an explanation of the purely tabular publications.

General Treatises.—Those students of meteorology who were obliged to acquire their knowledge at first-hand, that is, from the original sources, must be somewhat envious of the facilities now offered for a rapid survey of what has been accomplished in various directions. For a time all the compilations which were published after 1860 were of the school-book type, and this continued until Blanford's *Indian Meteorologist's Vade-Mecum* appeared in 1876–77. This is the first of the treatises which introduce us to some of the ideas of the modern school of dynamical meteorology. Its publication in India, together with its considerable cost, deprived the book of a wide circulation, and it has not, outside of India, accomplished the good which it was capable of doing; it was, for many years, undoubtedly the best treatise on modern meteorology in any language.

[1] Each publication may be obtained at an annual subscription of six shillings.

Blanford's book was but the forerunner of the important compilations which began to appear some years later. Foremost of these came Hann's *Climatologie* in 1883. This most excellent work gives an account of the climatic factors in general, and then gives the special features of the climate of all parts of the globe, and the causes which produce them. Few tables of data are given, as it has been the author's object to trace out the philosophy of the climatic conditions in a way which will attract the general reader. This book was the natural outcome of the frequent contribution of tables of climatic data given in the *Oster. Zeitschrift für Meteorologie* during a period of nearly twenty years. Next there appeared in Germany Sprung's *Lehrbuch der Meteorologie*, in 1885, in which the author has confined himself mainly to the discussion of actual atmospheric occurrences, and has sought to explain these by means of physical-mechanical laws. He has, indeed, added an appendix on the subject of the registration of meteorological phenomena; but this is suggestive, rather than an account of apparatus in common use. Sprung has first of all explained the principal mechanical and physical laws, which are then used as a basis for subsequent development of the theories concerning the statics and dynamics of the atmosphere. His is the only attempt which has been made to fit together the various theories of the atmospheric motions, the history of which subject is traced in another chapter. This is the main feature of the book, although the latest views on other topics, such as the influence of solar radiation, the daily period and the variability of the meteorological elements, are also given. The book is well adapted for university instruction and for study

by professional meteorologists; but most of it cannot be comprehended by the casual reader.

In 1884, van Bebber, of the *Deutsche Seewarte*, published Part I. of his book on *Witterungskunde*. This, together with Part II., published a year or two later, forms a compendium of what has been done from the earliest times in the matter of investigating the cause of weather changes. The various questions, varying in degree from the proverbs of folk-lore to the modern systems of weather-maps and forecasting of weather, based on the telegraphic transmission of observations made thousands of miles distant, are all discussed in a historic as well as scientific manner. While the work is of the greatest value to students of meteorology, who will for a long time to come go to it as a storehouse of knowledge on this special subject, yet the author has, by the fulness of his text, made it of popular interest as well.

Ferrel's book on *Recent Advances in Meteorology* (1885) next appeared, and it differs in one respect from the other works here mentioned, in the fact that it was published entirely under Government auspices. It has, therefore, not been obtainable by purchase; and its circulation has not depended on its importance, but upon the will of the chief of the United States Signal Service at Washington. Naturally, few persons except those on the "exchange list" of this department have been able to obtain a copy. This work was prepared for professional use, and while portions of it could be understood by the general reader, the difficulty in reading it as a whole is such, that its inaccessibility to the public is not so much to be deplored as would have been the case had it been written more popularly. Its chief value is that we

find given in a single volume of moderate compass, and in a connected manner, the most important results of the author's thirty years' labour in the field of meteorology.

The fact that most of our meteorological publications are weak in the department of apparatus, and also that many, perhaps most, of the descriptions of original inventions and improvements have been published in scattered journals, proceedings, and reports, made it desirable that a comprehensive account of them should be given in a single volume. This was in a large measure accomplished by Abbe's *Treatise on Meteorological Apparatus and Methods* (Washington, 1888), which was prepared and published at the expense of the United States Government, and gives us not only a historical sketch of the development of the subject, but also shows its condition at the present time. He has given special attention to the theory of the principal instruments, and we find reproduced about everything of importance that has been done in this line of investigation. The numerous illustrations form an especially valuable feature of the work, which has been rendered as complete as possible. Having access to the great collections of books which have been gathered together at Washington, and having as a source of guidance the manuscript catalogue of meteorological literature which has been accumulated at the Washington Meteorological Office, mainly by the international co-operation of some individual meteorologists with the hope of its speedy publication, the author enjoyed facilities not elsewhere obtainable for rendering his work exhaustively complete. While the diagrams and descriptions of instruments which

are given will interest all who are students of meteorology to only a limited degree, yet the main importance of the work is to the professional meteorologist, who will find the need of a mathematical training in order to read it.

Woeikoff's work on Climatology (*Die Klimate der Erde*, 1887) must also be mentioned in this list, for in it he has given us an excellent picture of climatic conditions and their effects as viewed by a physical geographer. Portions of the book are, indeed, somewhat similar to Hann's work, mentioned above; but its main value is the general climatic relations which it gives, rather than the climate of any special places, so that it is largely supplementary to Hann's *Climatologie*.

Recognising the difficulty not only in reading, but also in obtaining his above-mentioned work, Professor Ferrel has written out in a popular manner his theories of atmospheric motions and their attendant phenomena, and has also given a careful comparison of these theories with the observed facts. While this book, which bears the title, *A Popular Treatise on the Winds* (New York, 1889), is by no means light reading, yet mathematical analysis has been so far omitted that only an elementary knowledge of algebra and trigonometry are requisite for comprehending it, and it is certainly the most complete statement of the subject that has yet been made.

Blanford has presented some of the results of his many years' labour in India in his book on the *Climates and Weather of India* (London, 1889); and while it is, as a work on local climatology, at present of more value to the English people than any other, yet the majority of meteorologists, who have no

opportunity of seeing the original Indian Meteorological Memoirs, have welcomed this inexpensive summary of the important contributions made by English meteorologists in a region which presents the most diverse field of topographic and climatic characteristics of any limited region on the earth's surface.

I must also mention the German memoirs recently published in Penck's Geographical Series at Vienna: *Luftdruck in Europa*, by Hann; *Klimaschwankungen*, by Bruckner; and *Schneedecke*, by Woeikoff.

The following partial list of recent popular works on meteorology is given: Marie Davy's *Météorologie Générale* (Paris, 1877); Mohn's *Grundzuge der Meteorologie* (Berlin, 1883); Scott's *Elementary Meteorology* (London, 1890); van Bebber's *Lehrbuch der Meteorologie* (Stuttgart, 1890); and the works on *Weather*, and *Seas and Skies of Many Lands* (London, 1888), by Abercromby; and *American Weather*, by Greely (New York, 1888). On the subject of Weather Predicting, van Bebber's little book, *Wettervorhersage* (Stuttgart, 1891), and Scott's older book, *Weather Charts and Storm Warnings* (London, 1887), give quite full information. Mention must also be made of Hann's *Atlas der Meteorologie*, which forms part of the last edition of Berghaus' *Physikal. Atlas.* This work is composed of numerous charts, which are invaluable to the student of meteorology.

There is still one general topic which remains to be written on, and this is the reduction and use of meteorological observations. There are many finished memoirs which may serve as patterns for the manipulation of special observations, such, for

instance, as Wild's great works on the temperature and rainfall of the Russian Empire, but if an observer wishes to know just what is the best thing to do with any particular series of observations, he is many times at a loss to find reliable guidance. There are throughout the world many thousand observers who are willing to take the pains to make regular observations, which they usually reduce to monthly averages before handing them over to some central observatory where the averages may be published, but where the individual observations are consigned to the archives of the institution, there to lie buried and unused. There are perhaps a few score of men who have given in detail the best possible methods of investigating observations, and it is the combined knowledge of these men that should be put into a volume accessible to all observers, so that each one can work up his own observations in the most systematic way. Such a compendium would undoubtedly be the cause of the rapid completion of a detailed meteorological survey of all civilized lands, for it would multiply a hundred-fold the present working force of climatologists.

Periodical Literature. — We usually make the periodical literature of a subject the measure of its condition and progress, and so this literature relating to meteorology requires more than a passing mention. Our modern methods of work and research require a convenient channel for the timely interchange of ideas between specialists not only of the same country, but of different parts of the globe. But a subject cannot be specialized to the extent of supporting technical journals until it has reached a certain stage of cutting loose from the apron-string

of some mother-subject under whose wing it has been sheltered until able to stand alone. Thus meteorology was fostered by both astronomy and general physics, and the earlier writings on meteorology are to be found mainly in the journals nominally devoted to these two topics. There had been a number of attempts made to establish technical meteorological journals before the period of which I am now writing; but the lack of support had rendered them of short life, a single exception being the *Annuaire de la Société Météorologique de France*, which really dates from 1849. The functions of this journal have been to report the discussions which have taken place at the local meetings of the society, and to promote the interests of, and report on the meteorology of France. This journal is, then, chiefly of interest to those who wish to know what French meteorologists are doing. I think that this localising tendency has prevented this monthly publication from exercising as great an influence as it ought on the general progress of meteorology.

In 1866 the *Osterreichischen Zeitschrift für Meteorologie* was established, and as the society which publishes it holds only annual meetings, it can be easily imagined that it bears little resemblance to the just-mentioned French journal. The Austrian journal had a separate existence for twenty years, when it was combined (1886) with the newly (1884) established German *Meteorologische Zeitschrift*, and is now published under the joint control of the Austrian and German societies. Dr. Hann and Dr. Hellmann, of Berlin (succeeding Dr. Köppen, of Hamburg), Austrian and German meteorologists of world-wide

reputations, are the editors of this, the most important and influential meteorological publication in existence. It has always been under an exceptionally able editorship, which has prevented worthless matter from appearing in its columns, although of course many contributions, especially of the earlier volumes, are seemingly unimportant as we look at them from the present position of meteorology. Dr. Hann was early associated with Dr. Jalinek in the publication of the first volumes, when the character of the journal was being formed, and when the former assumed the entire control, which he exercised during the years of the most rapid elevation of the level of meteorological work, we find, if any change can be noted, an improvement on what was so well done before. Published at first bi-monthly, and later as a monthly, this journal furnishes a ready means for publishing, without the delay usually associated with official government or institutional publications, original papers, some of considerable length, contributed by meteorologists from all parts of the world. While these contributors are mainly those who use the German language, yet national sectionalism is nowhere to be remarked, for apart from editorial work more of the contributed matter comes from Germany than from Austria, the nominal home of the journal. In addition to the valuable original leading articles, there are given reviews and notices of important meteorological publications and undertakings, and also many topics of interest are treated in the so-called *Referat*, which in this case is usually a kind of editorial review, in which the notice of some important paper is made the excuse for bringing together the most valuable ideas which have

been previously advanced on the subject, the reviewer himself adding something to our knowledge of it. This class of reviews requires an immense amount of time in preparation, and it is remarkable that Dr. Hann has been able to do so much in this line in addition to his other duties. Still another feature is the mass of climatological data which has been gradually accumulated, mainly through the personal labour of Dr. Hann; for it will be found that almost every number of the journal contains tabulated average data for the principal elements for one or more out-of-the-way places, or the results obtained by many years observations at some so-called normal station. These tables have proved to be of great service in many original researches undertaken by meteorologists, and a searcher for information concerning the climate of any portion of the globe will not be likely to turn away unrewarded from a file of this journal. We find in its pages an almost complete account of the progress of meteorology during the past twenty-five years, and it is safe to affirm that no one unacquainted with its contents can claim to be thoroughly informed of the progress of meteorology during the period when it passed from a sub-science to the dignity of a separate science, demanding the entire attention of any one who will master its details. Of all the meteorological publications this is the most international and widely read, and it is on this account that its columns are used by writers of so many nationalities, and from all parts of the world, who may wish to secure for their ideas the widest circulation. There is, however, one department, that of instruments and apparatus, in which

there are not given sufficient details to enable one to obtain a good idea of the subject from this publication alone.

Since 1884 Germany has also given us a more popular meteorological monthly magazine, known as *Das Wetter.*

Great Britain furnishes three journals: *The Quarterly Journal of the Royal Meteorological Society*, *The Quarterly Journal of the Scottish Meteorological Society*, and *Symons' Meteorological Magazine.* The two former contain papers by the members of the societies, and they are usually quite elaborate, being similar to the leading articles in the Austro-German journal. Symons' magazine is more popular in nature, and the articles are somewhat like those in the German *Wetter.*

The American Meteorological Journal, published monthly, was established in 1884, and has contributed largely to the recent advancement of meteorological science in the United States. This journal is a private enterprise, and was instituted by Professor M. W. Harrington, of Ann Arbor, Michigan.

The Italian meteorologists also publish a journal, bearing the title *Bolletino Mensuale Moncalieri;* this was established in 1880.

§ 3.—*International Meteorology.*

The rapid spread of an active interest in meteorology in various lands, and the resulting marked increase in the amount of meteorological data published, had caused frequent utterance of the idea that a greater uniformity in the methods of

procedure adopted in different countries was not only desirable but indispensable to the proper use of this material. No definite step was taken however until, in the spring of 1872, a circular, signed by Bruhns of Leipsic, Wild of St. Petersburg, and Hann of Vienna, was issued to those practically interested in meteorology, stating that a conference would be held at Leipsic in August, 1872, for the purpose of studying the needs of international meteorology. In order that something definite might be accomplished at this meeting a list was proposed of twenty-six questions, which were to be discussed at this meeting. Fifty-two persons responded to this invitation, and the conference met on August 14, 1872, at Leipsic. The report of the proceedings of this meeting is extremely interesting, and shows the wide divergence of opinion which then prevailed concerning the collection of meteorological data, both as regards methods of observation and the manner in which they ought to be treated.

Only two of the points brought out at this meeting will be mentioned, viz., that it was desirable for each country to publish in full the tri-daily observations for a number of its selected stations and in a uniform manner, the form then in use in Russia being considered most desirable; and that a more systematic and more extensive use should be made of telegraphic weather reports.

The Leipsic meeting, however, was merely preliminary to, and to open the way for, the International Meteorological Congress which it was decided to hold in Vienna in 1873. This congress was convened on September 2, 1873, and all the principal European Countries (except France), the

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United States of America and China were represented by delegates whose official positions and scientific attainments signified the importance of the meeting, and indicated that it would be a veritable turning-point in the development of meteorology. Among the important results accomplished at this meeting may be mentioned the following: Appointment of a Permanent Meteorological Committee with self-perpetuating power; and the proposal by the delegate from the United States of America for the establishment of single daily simultaneous observations as nearly as possible over the whole northern hemisphere. Many questions of great importance were left to be decided on by the Permanent Committee, and the reports of sub-committees and discussions concerning apparatus and methods form the most valuable *résumé* we possess of the worth of instruments and methods in use at that time.

Meetings of this Permanent Committee were held in 1874, London 1876, Utrecht 1878; and in 1874 a Conference on Maritime Meteorology was held in London by the sub-committee appointed by the Permanent Committee of the Vienna Congress of 1873. At these meetings many questions concerning the present status and suggested improvements in meteorological methods were discussed, and enough matter demanding formal action was accumulated to warrant the calling of a second International Meteorological Congress at Rome in 1879. At this meeting the work accomplished by the Permanent Committee since 1873 was fully considered; the value of the changes which had been directly and indirectly the results of the Vienna meeting of 1873 was carefully

discussed, as well as further questions of importance. A special feature of this meeting was the numerous reports which were presented on various topics by those who were recognised authorities; these reports having been requested by the Committee. A more permanent organisation of the Permanent Committee was effected by which nine members were appointed to it, with only one from any one country. This Committee from this time has been known as the International Meteorological Committee. It first met at Rome, April 22, 1879; again at Berne, August, 1880; Copenhagen, August, 1882; Paris, September, 1885; Zurich, September, 1888.

As it was found that another early International Meteorological Congress was not desirable, the Permanent Committee agreed upon a dissolution at the Zurich meeting; the President, Wild, of St. Petersburg, and the Secretary, Scott, of London, being charged with taking steps for convening, at a suitable time, an international meeting of the representatives of the various Meteorological Services.

Such a meeting was held in Munich from August 26 to September 2, 1891. In response to a circular issued by Messrs. Wild and Scott, there were present at this meeting the heads of the various European meteorological services, and other prominent meteorologists from these and distant lands. The following countries were represented: France, Great Britain, Germany, Russia, Finland, Norway, Sweden, Denmark, Hungary, Roumania, Netherlands, Switzerland, Spain, Bulgaria, Queensland, United States, and Brazil. The subjects discussed were, briefly stated: the best methods of making observations; the adoption of absolute standards of reference; methods of

calculation or reduction of observations; the forms for publication of observations, and the methods for discussing them; the improvements to be made in telegraphing weather conditions and making weather forecasts, and especially in obtaining a knowledge of the weather conditions to the westward of Europe; methods of making and reducing observations of the earth's magnetism and atmospheric electricity; co-operation in observing cloud movements; the means for best securing international co-operation in meteorological work; the question of the organisation and work of a proposed International Meteorological Bureau; and finally, the formation of a new International Committee composed of seventeen members. This last was carried out and the members chosen. An informal meeting is expected to be held at Chicago, U.S., in 1893, but it was decided that a formal meeting should take place at Paris within five years.

Reports (in English) of these various meetings can be obtained from the Meteorological Office, London, for one or two shillings each.

In October, 1879, through the action of the Permanent Committee, an International Polar Conference was held at Hamburg, for the purpose of planning the work of the proposed temporary Circumpolar Meteorological-Magnetic Stations. In April, 1880, mainly by the action of the executives of the Permanent Committee, there was held at Vienna an International Conference for Agriculture and Forest Meteorology.

Only a very limited general statement can be given of the international benefits derived from these meetings; but they may be stated as follows:

The classification of meteorological observing stations into orders according to the number and variety of observations made, and the establishment of a form for the printing of their results.

The general adoption of either the meter-centigrade or the inch-Fahrenheit scales, and recognised standards of reference.

A European system of weather telegraphy with uniform code of exchange.

The daily simultaneous international observations made at 0h. 43m., Greenwich mean time. (Published by the United States Government, but now discontinued.)

The establishment of the International Circumpolar Stations during 1882–83.

The publication of International Reduction Tables for meteorological observations.

The systematic reduction and publication of Ocean Meteorological data.

CHAPTER II.

APPARATUS AND METHODS.

§ 1.—*Thermometers.*

HISTORICAL.—The history of the early development of the thermometer is not known with certainty, but in the latter part of the sixteenth century Galileo used at Padua a kind of thermoscope which consisted of a glass bulb (*a*) with a narrow bore tube (*b*), a couple of spans in length, attached. A general idea of the construction is given in Fig. 1. After the air in the bulb had been rarified by heating, the open end of the tube was inserted into water in an open vessel (*c*), and the tube was held upright. The water would rise to some extent in the tube, as the air in the bulb cooled; and the level of the water in the tube would oscillate somewhat with any change of temperature to which the air bulb would be subjected. In this first instrument the fluctuations of the atmospheric pressure would of course introduce some errors, but the principle of the modern thermometer had been discovered, and its further completion did not need the genius of Galileo to develop it. It is not certain who suggested the next step in the gradual improvement of the instrument. Abbe ascribes it to Galileo, and Hellmann thinks that the search now

being made by Javaro concerning Galileo's career may bring to light some further information. At present, however, we must say (according to Hellmann) that a French physician, Jean Rey, about the year 1631, conceived the idea of inverting the Galileo thermometer and filling it with a liquid and observing the expansion of this. Sometime before 1641, the Grand Duke Ferdinand II had adopted the plan of using alcohol as the fluid, and closing the open end of the tube so as to exclude the air.

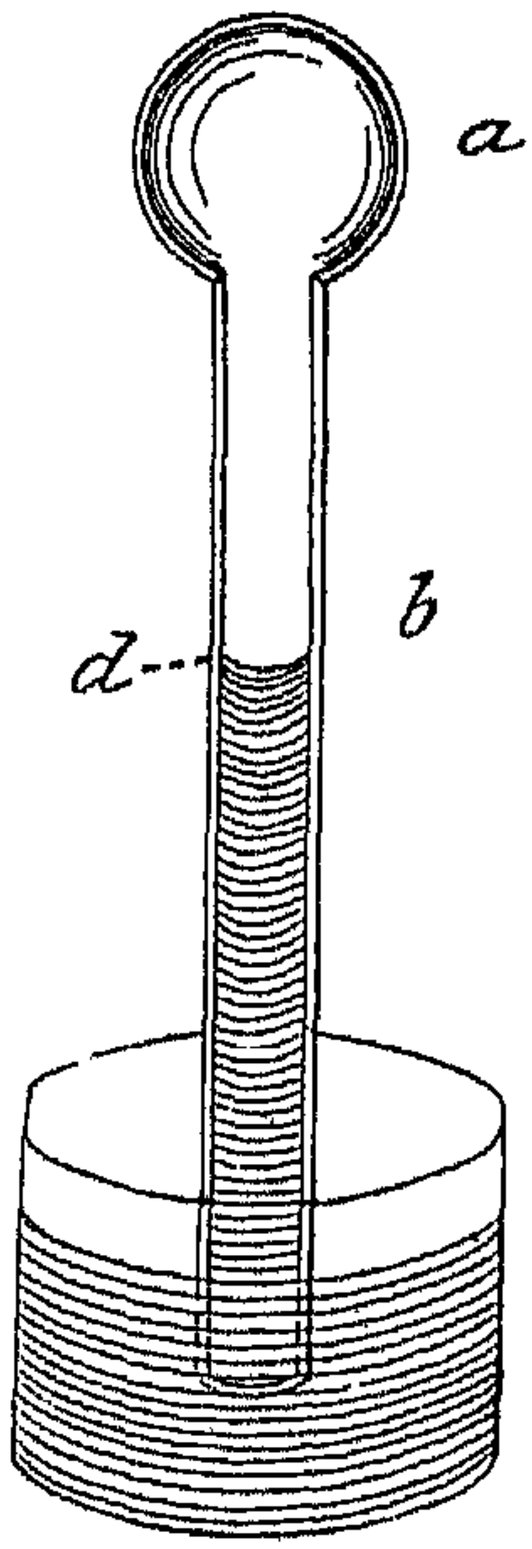


FIG. 1.

The members of the Accademia del Cimento, most of whom were pupils of Galileo, devised several forms of thermometer, the most important of which was known as the "Little Florentine Thermometer." This instrument, as illustrated in Fig. 2, had a fixed scale with the zero at about the point shown by the freezing mixture of salt and water, and the 13·5 division mark at the freezing point of water. The graduations which were arbitrary were small glass particles about the size of a pin head attached to the glass tube.

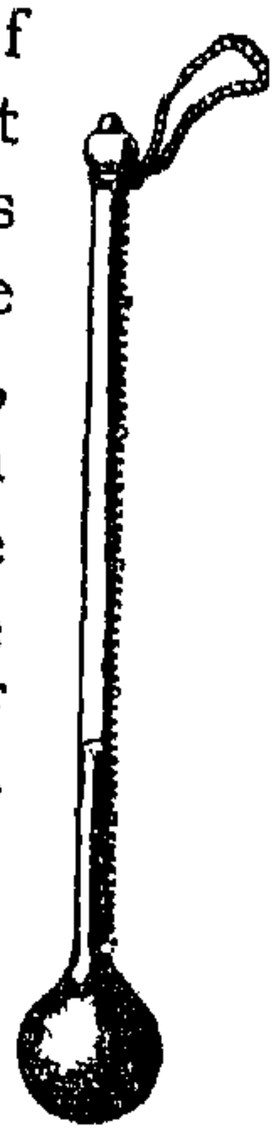


FIG. 2.

It is worthy of note that Galileo's thermometer was introduced into medical practice by Sanctorius at some time previous to 1624.

The history of the development of the modern

mercurial thermometer must be passed over, with the remark that Fahrenheit was the first who fully accepted the necessity of having two fiducial points, the freezing and the boiling of water, and he settled down to the use of mercury in the construction of the thermometer. It has been suggested that the term "degrees" as applied to the thermometer readings was derived from an early form of thermometer in which the tube was bent into a circular form (or arc), and the degrees of the circle were used to show the position of the substance in the tube. It is hardly necessary to enter into an account of the Fahrenheit, Reaumur, and Centigrade (Celsius) thermometer scales, as it is given in every text-book of general physics, and in encyclopædias; but it may be remarked that the Centigrade scale is in use among meteorologists in nearly all but the English-speaking countries, and in these the Fahrenheit scale is still so firmly established that the international assemblages of meteorologists have been obliged to sanction the publication of temperatures in either scale. Usage has therefore prevented the general adoption of the Centigrade scale, although it is in every way preferable to its rival.

In giving an idea of the present state of thermometric science as applied to meteorology, only a brief mention can be made of the question of the various errors of construction of thermometers and their final reference to normal instruments; for while, in the laboratory, errors of hundredths or even thousandths of a degree are being taken into account, yet in the practical use of thermometers for determining air temperature there are still discrepancies in various systems of instrument exposure which may amount to one or more degrees,

Standard Thermometers.—It has been shown by physicists that the changes in volume or pressure of an ideal gas will give an absolute scale for measuring temperatures. But as we have no ideal gas, Sir William Thomson proposed for use an absolute scale which should have a temperature of 273°·7 at the freezing point of water, and 373°·7 at the boiling point of water, thus fitting it to the divisions of the Centigrade scale. This scale agrees with the readings of the actual gas thermometer at the two points mentioned, but at intermediate points, and above and below these limits, a correction has to be applied to the observed temperatures in order to reduce them to the absolute scale.

The following table shows the corrections necessary to reduce some gas thermometers to the absolute scale. All but Thomson's first series are under constant volume.

Absolute Scale.	Centigrade.	Thomson Air Thermometer.		Weinstein Air Thermometer.	Carbonic Acid Gas.
		Constant pressure	Constant volume.		
		°C.	°C.	°C.	°C.
273°·7 + 0°	0°	·000	·000	·000	·000
+ 20°	20°	— 040	—·030	—·013	—·034
+ 40°	40°	— 048	·040	—·018	—·051
+ 60°	60°	—·047	—·037	—·018	—·050
+ 80°	80°	—·028	—·022	—·012	—·032
+ 100°	100°	·000	·000	·000	·000

But for most practical purposes it is necessary to use mercurial thermometers, and we must know how their readings stand with regard to gas thermometers.

Recent comparisons, at the International Bureau

at Sèvres, of standard mercurial thermometers with gas thermometers, show that the following corrections must be applied to the readings of the former instruments in order to reduce them to the latter standards:

Corrections.—To reduce hard-glass thermometers by Tonnelot (Paris) to thermometers of—

Hydrogen Gas		Nitrogen Gas.		Carbonic Acid Gas.	
At Temp ° C	Correction	At Temp. ° C.	Correction.	At Temp. ° C.	Correction.
—25° C.	+·233° C.	—25° C.	+·216° C.		
—20	+·172	—20	+·159	—19° C.	+·094° C.
—15	+·119	—15	+·109	—15	+·069
—10	+·073	—10	+·067	—10	+·041
— 5	+·034	— 5	+·030	— 5	+·019
0	·000	00	·000	0	·000
20	—·085	20	—·075	20	—·042
40	—·107	40	—·097	40	—·048
60	—·090	60	—·085	60	—·037
80	—·050	80	—·052	80	—·019
100	·000	100	·000	100	·000

Wild, in 1888, referred to the scale of the Hydrogen thermometer as the International Temperature Scale.

Comparison of Standard Thermometers.—Although ultimately the absolute scale will be the standard to which all thermometric work will be referred, the actual working standard will probably be the gas thermometer adopted by the International Bureau of Weights and Measures at Sèvres. The gradual distribution of the best standard mercurial thermometers, after a thorough investigation, from Sèvres to various countries, will no doubt introduce practical uniformity in all laboratory thermometric work the world over. A collection of such standard thermometers is represented in Fig. 3. At present a number of standard thermometers are in use. Abbe gives a little summary for a few instruments which have come

to his notice at Washington. The Signal Service (Washington) air thermometer was found to be 0°·01 C. lower than Rowland's air thermometer at Baltimore. Above 0° C. the Signal Service air thermometer agreed with the mercurial standard, after the latter has had applied to it the ordinary corrections to reduce its readings to those of an air thermometer. Also from + 32° F. to − 38° F. the Kew and Signal Service mercurial thermometer agree, but at − 38° F. the Signal Service alcohol thermometers are 0°.6 F. below the Kew alcohol thermometers. Also the Signal Service air thermometer agrees with the Sèvres hydrogen thermometer (in 1885) to within ± ·01° C.

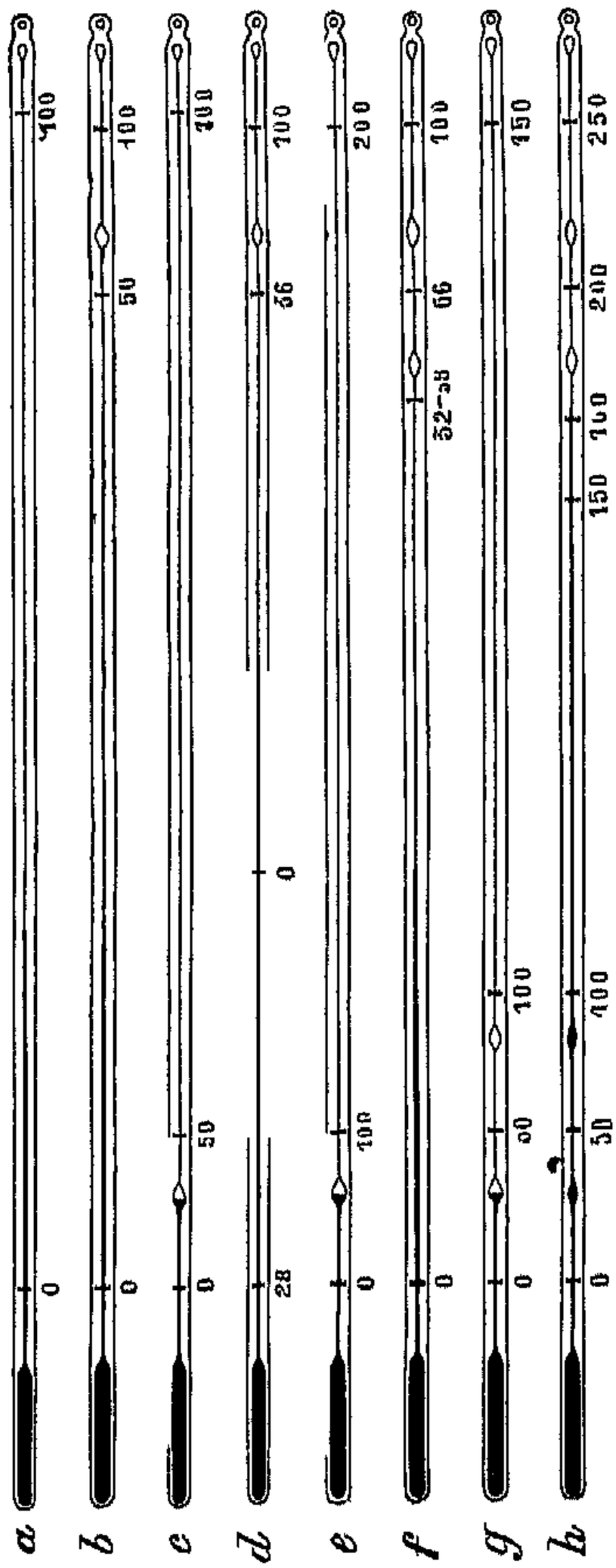


FIG. 3.

Wild, at the Central Physical Observatory, has three thermometers (made of Thuringian glass) which he has been using as a standard. In 1888 these were compared from 0° C. to 40° C. with a Tonnelot mercurial standard

(of hard glass), which had been compared with the hydrogen gas thermometer at Sèvres. The following table shows the result of this comparison :

CORRECTIONS OF ST. PETERSBURG STANDARD THERMOMETERS.

	Geissler No. 2.		Geissler No. 10.		Pupss No. 1.	
Temp	Tonnelot	Hydrogen Sèvres	Tonnelot.	Hydrogen Sèvres.	Tonnelot.	Hydrogen Sèvres
0° C.	·00° C.	0° C.	·00° C.	·00° C.	·00° C.	·00° C.
10	—·0	—·06	—·03	—·08	—·01	—·07
20	—·03	—·11	—·05	—·13	—·02	—·11
30	—·05	—·15	—·05	—·16	—·03	—·13
40	—·07	·18	—·05	—·16	—·04	—·15

In 1875 the corrections of Geissler No. 10, as referred to the mercurial scale were :

Temperature ...	0° C.	10° C.	20° C.	30° C.	40° C.
Correction ..	·00	—·03	—·04	—·07	—·07.

These show that for at least fifteen years this observatory has had practically standard thermometer readings.

Fig. 4 shows the usual method of comparing the readings of mercurial thermometers, when the instruments are immersed in a water bath, which may be made to vary in temperature by means of a lamp beneath.

Mercurial Thermometers. — The mercurial stem thermometer of the best construction consists of a slender glass tube with capillary bore terminating at one end in a thin glass bulb filled with pure mercury, and having at the other end, and connected with the capillary bore, a small empty reservoir called

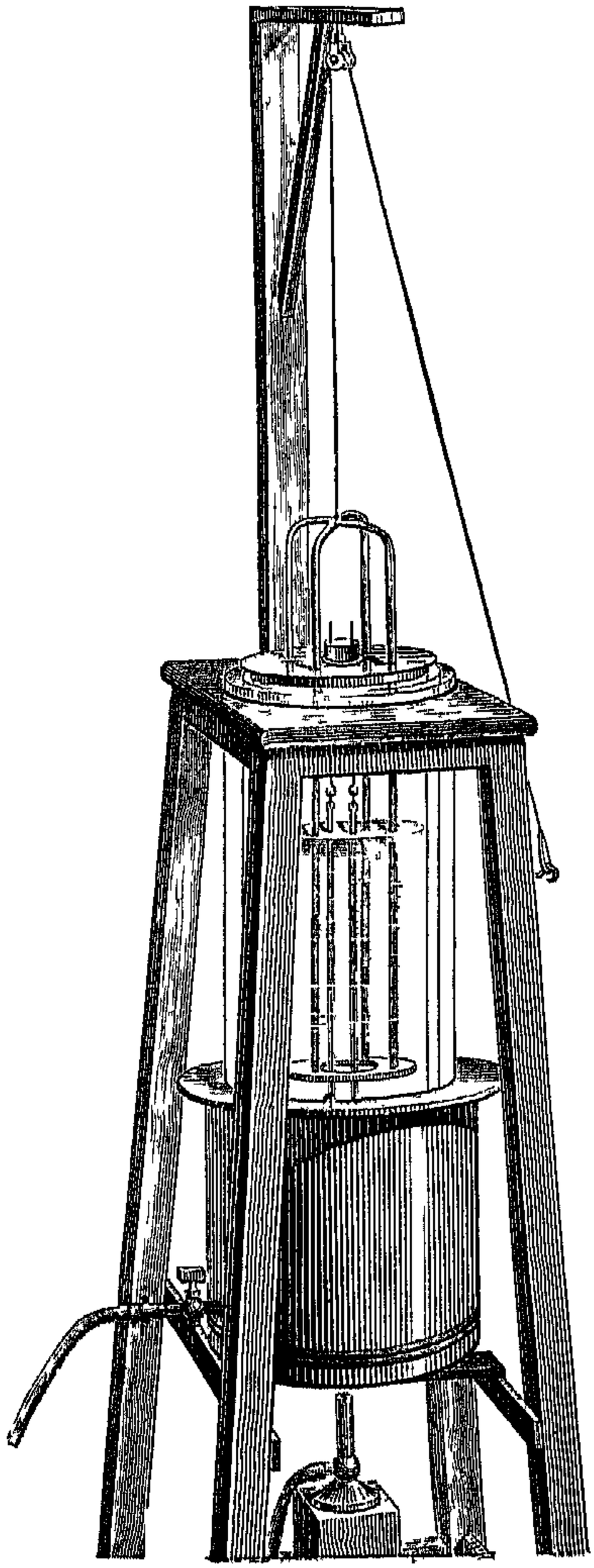


FIG. 4.

the calibrating chamber (Fig. 5). The stem has marked on it, first, the boiling point, and second, the freezing point, after which, in the case of the Centigrade thermometer (which we shall alone consider), the distance between these two parts is divided into one hundred equal spaces called degree divisions. These subdivisions are either ruled directly on the stem, as in the case of the Tonnelot (Paris) thermometers, or they are marked off on a piece of white enamel glass, which is placed behind the thermometer stem with the zero and hundred degree points directly opposite the corresponding points on the stem, as in the case of the Fuess (Berlin) patent barometer. These graduations are extended slightly above, and considerably below, these two fiducial points for ordinary use. In the thermometers shown in Fig. 3 it will be noticed that enlargements of the capillary bore occur. These are mainly for the purpose of allowing a much larger scale of degrees to be used than would be possible otherwise, but it necessitates the use of several thermometers in order to get the complete scale. Temperatures can be measured until the enlarged portion of the bore is reached, but this must be filled and the mercury pass up into the narrow bore above, before additional readings can be made. The enlargement is so made as to require an increase of a certain number of degrees of heat in order to fill it, and if temperatures within this limit are to be read, another thermometer with the enlargement in a different part of the scale must be used. By this means the fiducial points may be determined on each

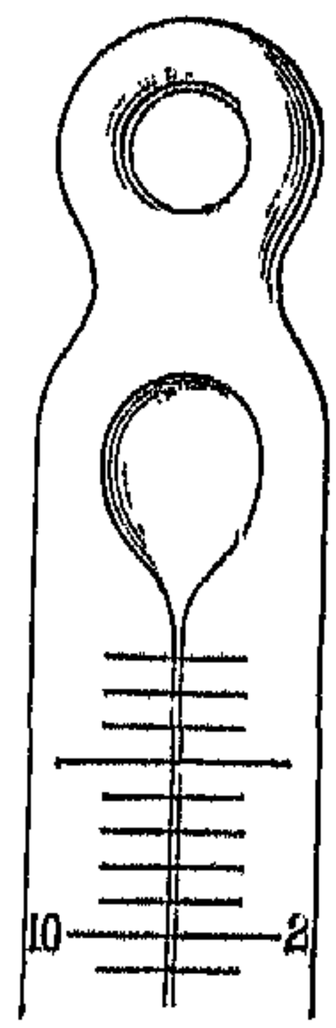


FIG. 5.

thermometer, no matter what range of temperature the graduations may include. We will consider briefly the various errors which may be met with in such a thermometer of the best construction and the methods of determining the corrections necessary to allow for them. These are as follows:

1. *Correction for Parallax and Refraction.* — In either form of construction of the scale the divisions are not exactly adjacent to the mercury thread in the tube, and consequently the reading will vary somewhat with the direction of the line of sight. In case the thermometer can be carefully adjusted so that the reading can take place at the angle of normal incidence, it should be done, thus avoiding this error, but it will frequently be the case that this is impracticable, in which case the correction must be computed; in which computation the index of refraction of the glass (from the bore to the exterior surface of the stem) must be included in the ordinary formula for parallax. In cases where it can be done, it is better to eliminate the refraction by taking the mean of the readings when the scale is on the side nearest the observer, and again when placed opposite.

2. *Scale and calibration corrections.*—In thermometers of this highest class the scale divisions should be accurate, far within the limits of any readings that are to be made; but in case they are not, this error of graduation is combined with that of calibration about to be described. It is impossible to get a tube or stem that is exactly cylindrical, and in which the size of the bore is absolutely uniform. It is customary therefore, in originally selecting the tube for the thermometer, to put a short thread of mercury in it, and to observe the length of this thread in different

portions of the tube. If the bore is quite uniform the thread of mercury will be of about the same length throughout. This work is of course done by the maker. After the thermometer has been constructed and the scale attached, a similar but more refined process is gone through, in order to give quantitative values to the corrections to be made for the combined errors of graduation and inequality of bore. By an artificial heating or cooling of the thermometer bulb the mercury in the stem can be

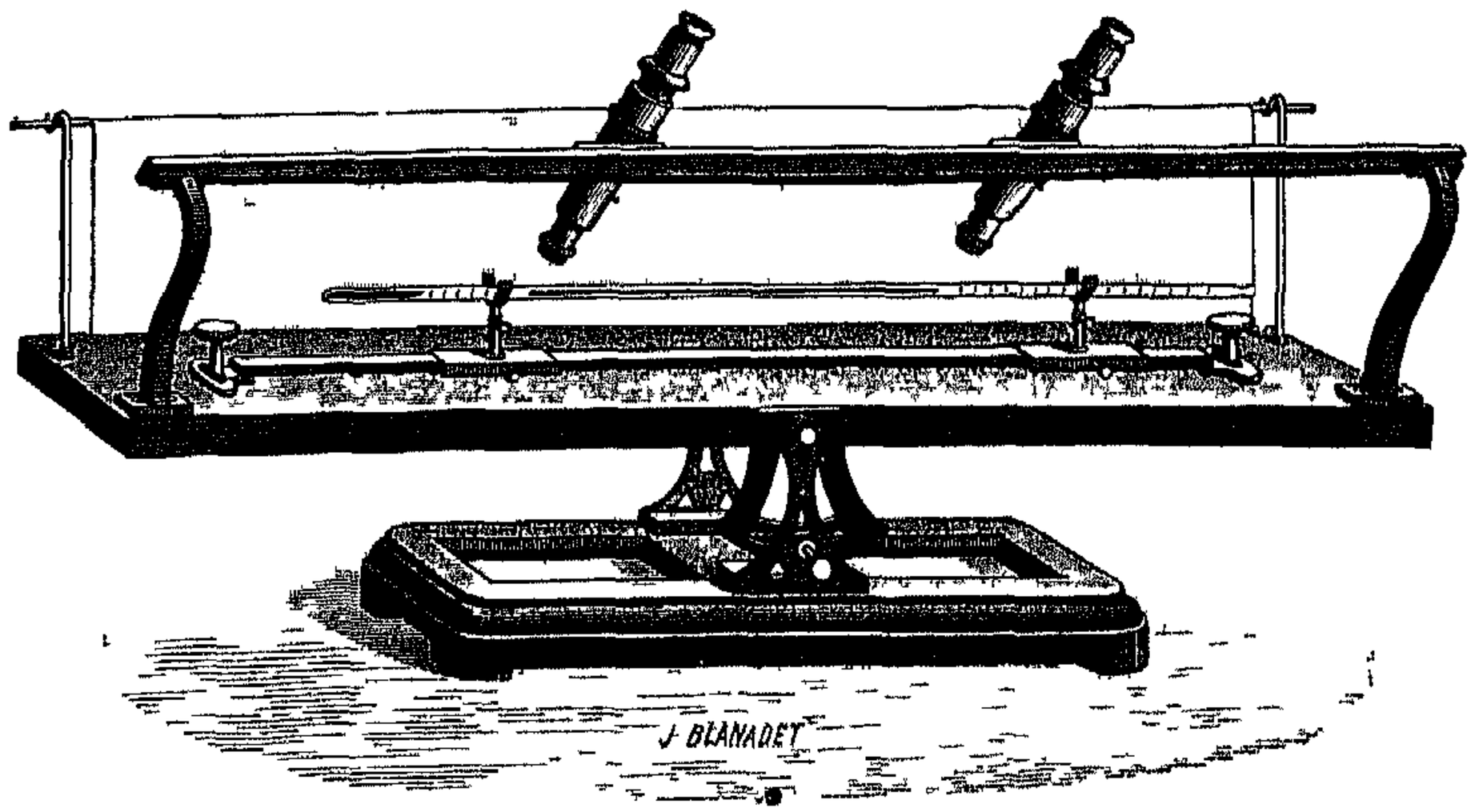


FIG. 6.

brought to any desired length, so that upon a slight jarring of the instrument a thread of mercury of any required length will be separated from the main mass of mercury. This thread is at first chosen, say 5° in length. The thermometer being kept at constant temperature, the length of the thread (of constant volume) is observed in terms of the scale divisions at various portions of the stem from one end to the other. The process is repeated with threads of 10°, 15°, . . . 95° length, in order to insure

a greater accuracy, and to prevent the accumulation of errors due to the use of a short thread alone. In order to secure ease of manipulation and accuracy of work, the thermometer is placed in a holder, as shown in Fig. 6, and the graduations read by means of microscopes. By the insertion of these observed lengths in a system of symmetrical equations, which must be excluded here, the calibration and scale corrections for various portions of the tube are computed. The following little table shows these corrections for two of Tonnelot's normal thermometers :—

Scale Reading.	Calibration Correction. No I.	No II.
°C.	°C.	°C.
0	0 0000	0'000
20	— 0'0569	—0'250
40	+ 0 0709	—0'464
60	+ 0'1968	— 0 372
80	+ 0 1667	— 0 471
100	0 0000	— 0'000

3. *Determination of the fiducial points.* *a.* The *boiling point.* The thermometer must be hung inside of a double casing, with the bulb suspended at a little distance above the boiling water. The whole thermometer must be enveloped in the steam, and a hole in the outer casing allows the free escape of this vapour. All air in the inner casing must be replaced by steam. A manometer must show the difference in pressure between the steam inside the apparatus and the air outside. A model apparatus for determining the boiling point is shown in Fig. 7, in which T is the thermometer, L the reading telescope, A the vapour chamber, and C the water reservoir. Whenever a reading is made of the thermometer a corresponding reading must also be made of the manometer, and also of a barometer.

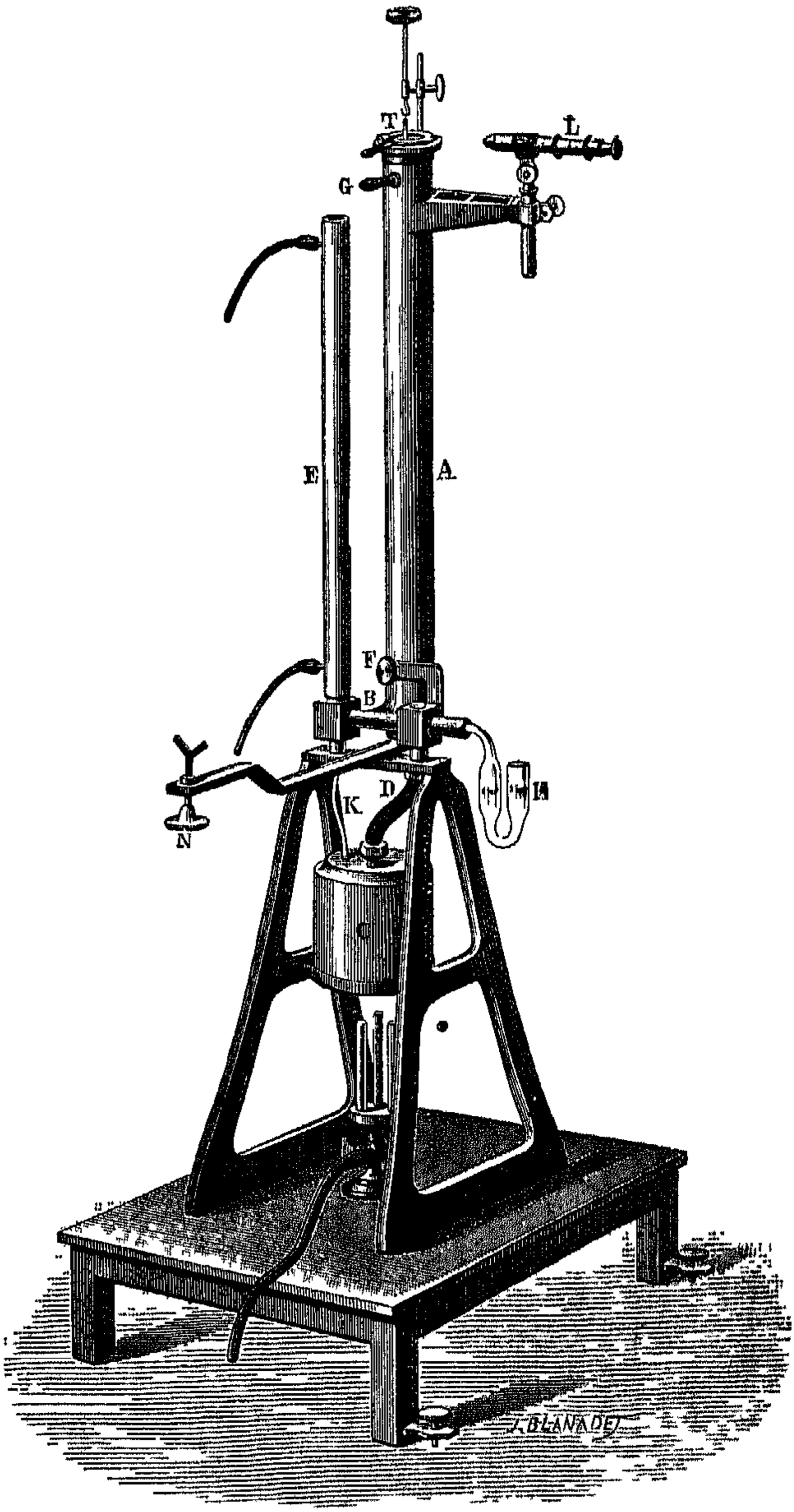


FIG. 7.

If the mercury in the thermometer is carefully observed as it rises up to the boiling point, it will be found to reach a height which it does not permanently retain, and if the boiling is continued for a sufficiently long time, the mercury will be found to have slightly receded from its highest reading. This lower reading is the desired boiling point, and this slight lowering is due to a gradual change in the capacity of the thermometer bulb. It has been found that the true boiling point can best be determined by taking the thermometer from the apparatus, and making a determination of the freezing point, after which a new determination of the boiling point must be again made. If these two successive determinations agree, we may consider that the true boiling point has been obtained. It is necessary that the experiment be performed with the thermometer horizontal as well as vertical. Various standards of atmospheric pressure and geographical position have been adopted by thermometer makers of different countries, but that at present in international use is the boiling point which corresponds to an atmospheric pressure of 760 mm. of mercury at zero degrees C. at the latitude of 45°, and sea-level. In determining this pressure the manometer reading must be applied to the observed barometer reading in order to get the true pressure inside of the apparatus.

b. The freezing point. This is determined by subjecting the thermometer to the temperature of melting ice. The water which has been frozen must be pure, and if ice is used the water must have previously been distilled; but freshly fallen snow furnishes a very good substitute. Not only the bulb but the stem of the thermometer should be immersed

in the ice, the freshly melted water flowing over the bulb. An illustration of this process conducted with

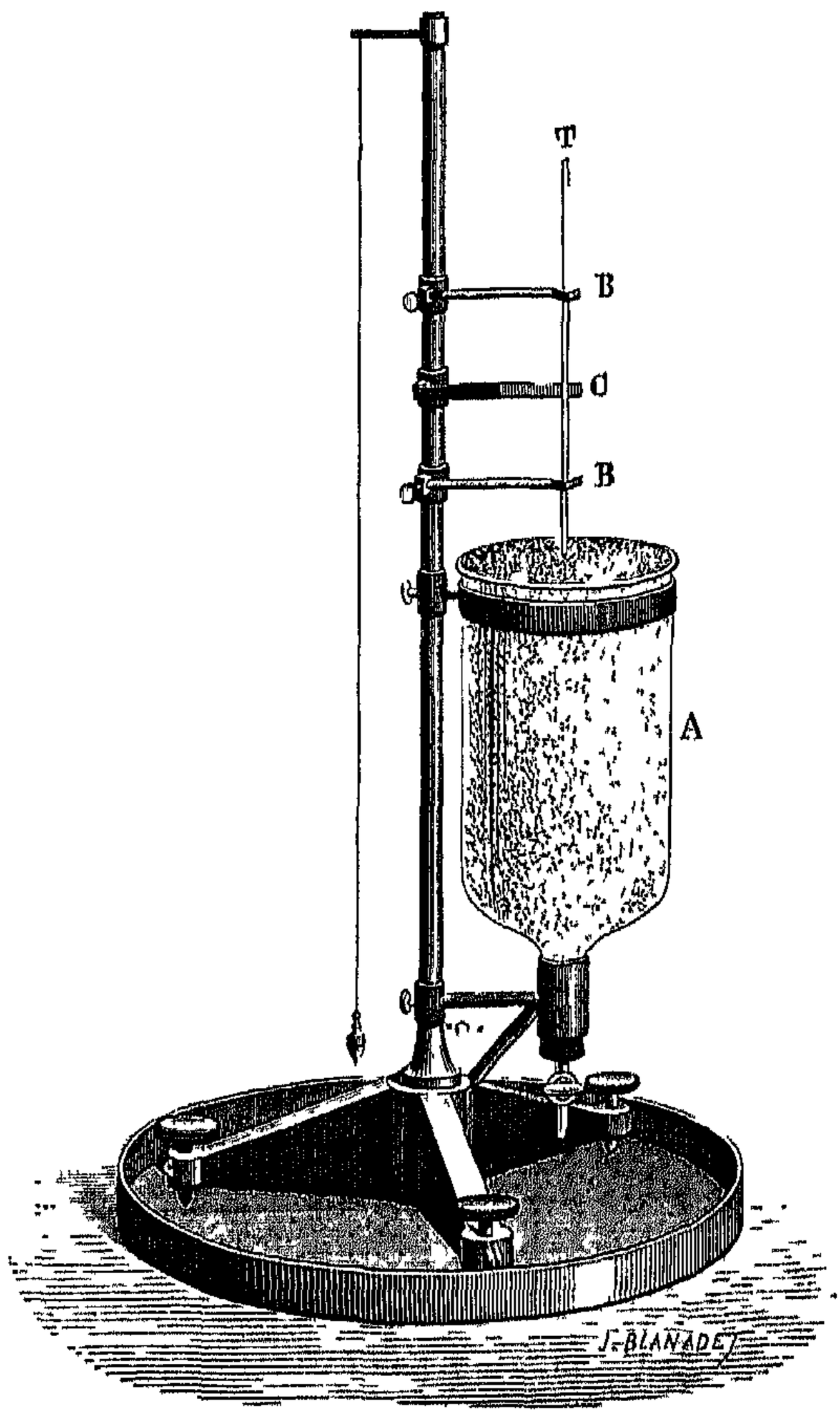


FIG. 8.

proper apparatus is shown in Fig. 8, in which T is the thermometer. When the thermometer is first inserted

in the finely chipped ice, the mercury will rise, since the glass bulb contracts the more quickly, but a little later the mercury falls rapidly, and soon comes to a stand-still at the *depressed freezing point.* This point depends on the condition of the bulb just before it was put into the melting ice. If the thermometer is kept at this temperature the mercury slowly rises, and in the course of twenty-four to ninety-six hours it will reach a point called the *raised zero*, which can be attained more rapidly by warming up and cooling the thermometer slowly; but if the latter is subjected to the ordinary air temperature immediately after the depressed zero point has been noted, and is kept at this temperature for a year or so, then at the end of this time it will show a slightly higher reading than it would have if it was kept at the freezing temperature. If now it is again put into the melting ice, then what is called the *zero of long repose* is at once attained, and will be found to differ very slightly from the just mentioned *raised zero.* These changes are slower and of less extent, the more nearly the thermometer is kept at the boiling point of water. The higher the temperature which the thermometer had before it was put into the melting ice, the lower will be the observed zero. The observed zero of a thermometer depends not only upon the highest temperature to which it has recently been subjected, but also upon the time which has elapsed since it was at that temperature; so that for very accurate work in thermometry the depressed zero point must be determined immediately after any measurements of temperature. In order to facilitate the determination of the freezing point, where it must be found frequently, a rapidly stirred mixture of one part water and five parts of slowly

melting ice will be found preferable to the ordinary melting snow or chipped ice.

When making an observation of the depressed zero point it is usual to note the thermometer reading several times near the point; as the mercury approaches it, reaches it, and recedes from it. Pernet found that this depressed zero corresponding to any temperature varies as the square of the temperature above 0° C. It is the custom at the International Bureau of Weights and Measures to determine the freezing point of a thermometer in a room having a temperature of from 6° to 12° C.; for an error of 0°·01 C. may be expected if the room is at ordinary temperature. Change of pressure has also a very slight effect on the temperature of melting ice, an increase of pressure lowering the freezing point.

It is also necessary to place the thermometer in a horizontal as well as in a vertical position in determining the freezing point.

The distance between the depressed boiling point and the depressed freezing point, when the latter is determined within, say, an hour after the former, can be determined within 0°·01 C., or 0°·02 C. from a single trial, when the precautions already mentioned have been taken, and Guillaume has shown that the constancy of this distance for *hard* glass thermometers is within the limits of the errors of observation.

Whenever any very accurate measurement of temperature is to be made the fiducial points must be determined at the time, and used as reference points for the observed temperature. Pernet has worked out a plan for this which is very much more accurate than the older methods by which discrepancies amounting to 0°·2 C. might arise. Pernet's method is represented by

such a simple formula that its introduction here will doubtless be excused. It is as follows:

$$t = (X - Z_t)\frac{100}{S_{100} - Z_{100}}$$

Here t is the required temperature; X is the observed thermometer reading for t; Z_t the depressed freezing point which is determined immediately *after* observing X; S_{100} is the depressed boiling point determined immediately after Z_t; Z_{100}, the depressed freezing point determined just after finding S_{100} And, also, $\frac{100}{S_{100} - Z_{100}}$ is the value of one of the degrees on the thermometer in terms of true Centigrade degrees.

4. *Corrections for different temperature of scale or stem.*—In the case of thermometers with brass scales in which the bulb, scale, and stem have different temperatures, errors of several hundredths of a degree C. may be made by not allowing for the expansion of the brass; errors of one or two-hundredths of a degree by not allowing for the expansion of the glass stem; and errors amounting up to a quarter or half a degree by not allowing for the expansion of the mercury thread in the capillary bore, and in case alcohol or ether is used in place of mercury this last error would be increased seven and ten-fold respectively.

What is known as Poggendorf's correction (so named from the physicist who first applied it in 1826), takes account of the variation in the capacity of the capillary bore due to changes of temperature. The standard adopted is for the thermometer stem at 100° C., while the bulb is at the temperature to be determined. The amount of this correction is 0·00° C. at 100° C. and at 0° C.; the maximum may be from 0°·05 to 0°·08 C. at 50° C., and has a negative sign;

at —40° C. the correction may be from 0°·11 to 0°·17 C. with a positive sign; the limits given are for different coefficients of expansion of glass.

There is still an error due to the irregularities in the relative expansions of the bulb and the mercury in it, but usually the correction for this is included with that for the Poggendorf correction. The combined correction is 0°·00 C. at 0° C. and 100° C., and has a maximum of —0°·207 C. at 50° C. But no set of theoretical corrections can be assigned to convert the scale for mercury into that of the gas thermometer. That the observed differences are mainly due to different qualities of the glass used is shown by similar corrections being obtained for the same kinds of glass. Wiebe and Guillaume maintain that mercurial thermometers can be constructed which will agree with the gas thermometer, and in which the readings are proportional to the temperatures.

5. *Correction for pressure on the bulb.*—There is an external and internal pressure on the thin glass of the bulb. As a standard for reduction, a pressure of one atmosphere inside and outside may be adopted, according to Guillaume.

If the external pressure in the case of a cylindrical bulb Tonnelot thermometer is increased 1 atmosphere it increases the reading 0°·09 C.; for 0·6 of an atmosphere the increase is 0°·055 C. It would have been more for a spherical bulb on account of thinner glass. At high elevations above the sea-level this quantity must be taken into account in ordinary work, unless the fiducial points were determined at a pressure like that at the altitude of observation.

The part of the internal pressure of the bulb which consists of the hydrostatic pressure of the column (or

thread) of mercury, will vary with the temperature and with the inclination of the stem to the vertical, and will have a maximum in the vertical position.

Different kinds of glass possess different elastic properties, and the effect of pressures on the bulbs consequently is not the same for all thermometers; but it is practically constant for the same kinds of glass, and knowing the correction for one kind of glass, that for another kind of known composition can be computed. Guillaume has given a formula expressing the relation between hard glass and crystal glass.

There is a strong capillary action in thermometer tubes. It will cause a downward pressure of about one-sixth of an atmosphere for a bore of 0·10 mm.; and this is to be added to the weight of the column of mercury in stating the inside pressure. In an extreme case the sum of the two amounted to 0°·15 C. In order to be free from this capillary error *all* of the readings must be made with a rising of the mercury. Where, however, the differential capillary error does enter, in the case of a stationary temperature, it may be found by taking half the difference between the temperature for a rising and falling column of mercury. When the thermometer changes from a rising to a falling temperature, it fails to indicate the change of double the amount of this correction, and this "dead space" may amount to 0°·07 C. for a bore of 0·03 mm., according to Pernet. Guillaume found that a difference of 0°·04 C. existed in the determination of the boiling point when it was made with a rising and rounded meniscus, and again with a falling and flat meniscus.

6. *Sluggishness.*—It requires an exposure of some

duration for a thermometer to attain its true reading, and cylindrical bulbs are more sensitive than spherical bulbs; but the time also depends on the kind of exposure. When a circulation exists in the surrounding medium, as, for instance, a current of air, the true reading is obtained with the minimum rapidity. For a quiet medium the correction for sluggishness can be determined by experiment for each thermometer at rising and falling temperatures.

7. *Thermal reaction and change of zero.*—Bellini, in 1832, and later, Faraday, Regnault, and others, investigated the slow permanent changes in the position of the zero of thermometers. The amount of this change varies for different kinds of glass, and may even reach 0°·8 C. for apparently excellent thermometers when made of some ordinary kinds of glass. The greater part of this change takes place, however, within two or three years after the thermometer has been made.

The fact that the readings of thermometers depend somewhat on the temperatures to which they have recently been exposed makes the spring readings of an out-of-doors thermometer a little too high after the winter's cold; and the fall temperatures a little too low after the summer's heat. This seasonal variation may reach even 0°·10 C.

In order to overcome this elastic or thermal reaction, many experiments have been made to obtain a glass in which the change is a minimum. The best composition yet found is that obtained at the Jena Laboratory, by Abbé. The composition of this glass is as follows: Quartz 67·5, soda 14·0, oxide of zinc 7·0, lime 7, clay 2·5, borax 2·0 per cent. With this glass the depression of the freezing point amounts to only

0°·05 C.; and the change of the zero point will not exceed 0°·01 C. in a long time.

Thermographs.—The self-registering thermometers in use are by no means as satisfactory as is desirable. There are many different kinds, such as the photographic, the metal spiral, the electric, the automatic position, and the air thermographs. Of all these the photographic, as used principally at Kew and other English observatories, is undoubtedly the most accurate, but it has the disadvantage, under which all photographic registrations must come, that its manipulation is difficult, and requires the expenditure of much time and skill. In this form the mercurial thermometer is made with such a long stem that the bulb can be exposed in the thermometer shelter or screen, while the upper part of the mercury column is inside of the photographic box or the dark room. A small air bubble is introduced into the capillary tube of the thermometer, and separates the thread of mercury by an air space. A light is thrown through this space, by means of reflectors and condensors, on to a revolving drum bearing the photographic paper. The amount of rise and fall of the successive records, thus made, is carefully measured, and when compared at stated intervals with the direct readings of an adjacent thermometer, they can be readily reduced to the ordinary thermometric scale.

The metal spiral thermometer, as used in the Hipp, Hottinger, Wild-Hassler, and other thermographs consists of a compensated spiral, the expansion or contraction of which with higher or lower temperatures is communicated to a pointer whose varying position is registered on a recording sheet.

In the electric contact thermometer, as used in the

Secchi, Theorell, and Hough thermographs, the upper end of the thermometer tube is open, and a fine wire is made to descend into it until contact with the mercury, when a circuit is closed since it has the other pole connected with the mercury in the thermometer's bulb. The distance the wire is obliged to descend from a fixed position to the mercury is automatically measured and recorded.

In the air thermograph a vessel of metal is filled with dry air, which is allowed to raise or lower the

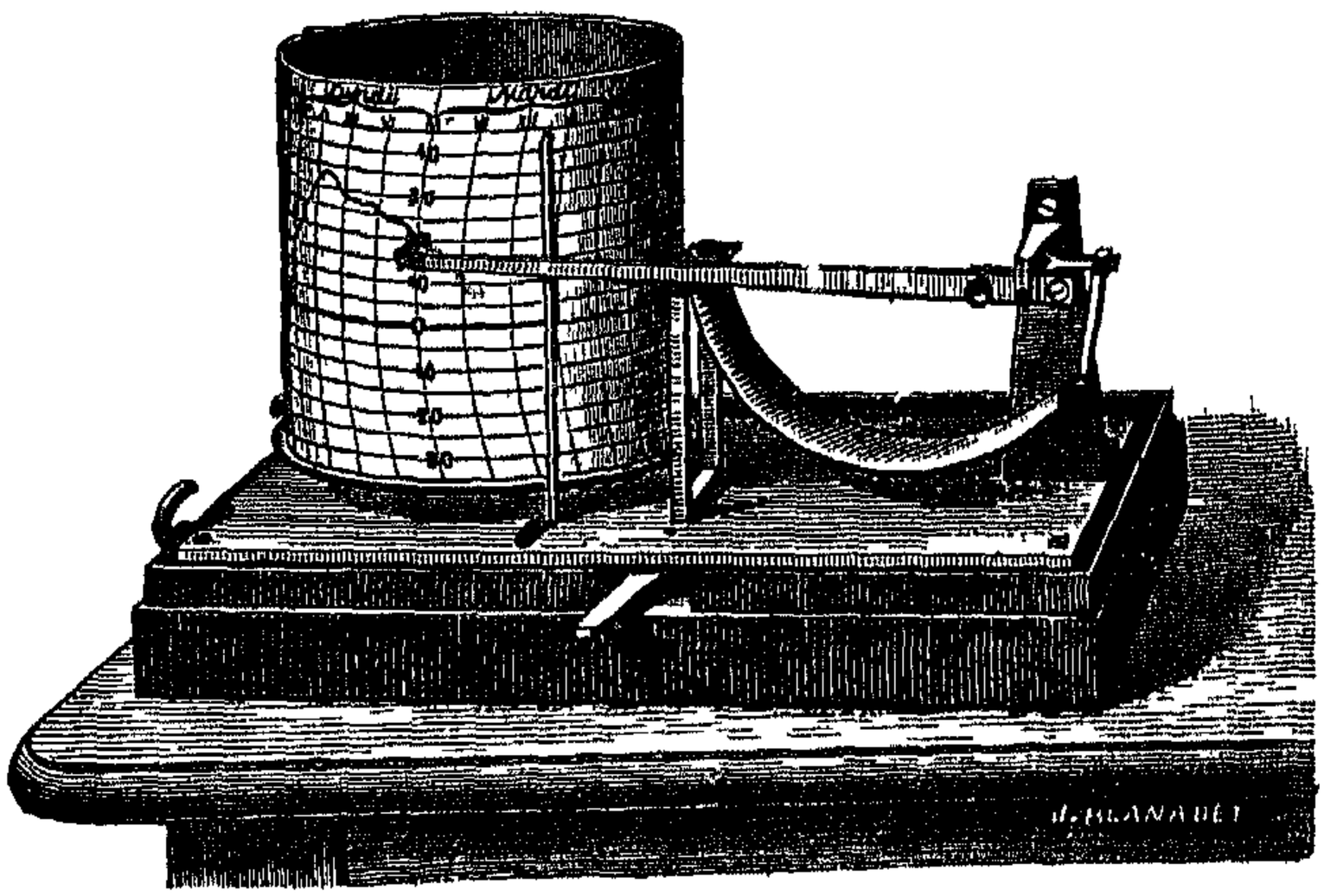


FIG 9.

pressure in some form of manometer, by being connected with it by means of a metal tube of very small bore. The variations of pressure, as shown by the manometer, are recorded by various devices, such as are to be found in the instruments of Schreiber, Sprung, &c.

In the Richard thermograph, as shown in Fig. 9, a curved tube on the Bourdon plan is hermetically

sealed after being filled with alcohol. One end of the tube is fixed (at the left end, as shown in the figure) and the other end curves up or straightens out with the contraction or expansion of the alcohol. This motion of the free end is communicated to the long arm carrying the pencil, which records the motion on the cylindrical register.

The automatic position thermograph, or "upset" thermometer, is so constructed that when the thermometer is inverted at any designated time by the automatic action of clockwork, a portion of the mercurial thread is broken off at a narrow point of the tube, and the mercury runs to the top (inverted) of the thermometer, where the length of the broken thread is measured by means of a scale. If twelve of these thermometers are so arranged that successive ones shall be inverted at successive hours, and if the apparatus is set in operation twice daily, an hourly record of the temperature can be obtained.

As in the case of other records made by means of delicate apparatus, the accuracy attainable by means of these various forms of thermograph depends very much on the care in manipulation and reduction of the observations.

For instruments like the Sprung or Wild-Hassler thermographs the readings are usually accurate to within 0·2° or 0°·3 Fahrenheit, and for the photographic or Kew form the error is only about half of this amount.

In all of these forms where a thermogram gives the variations in temperature, a bi- or tri-daily reading of an adjacent mercurial thermometer must be made in order to reduce the record to true degrees.

Exposure of Thermometers.—In the construction,

investigation, and reading of thermometers the utmost refinement may be practised, and hundredths of a degree considered; but this care is all lost unless proper precautions are taken to so expose the thermometers that their readings give the true air temperatures. In order to find a proper exposure for the thermometer, the various sources of error must first be considered. The thermometer receives heat by conduction from the surrounding air (and in this convection plays a most prominent part), and by radiation from surrounding objects; it, in turn, gives off heat by radiation and conduction. The question to be considered is the means by which the proper balance between these can be so regulated that the thermometer shall read neither too high nor too low. It must be also taken into account, that in meteorology we do not wish to obtain the temperature of a small quantity of air, which may

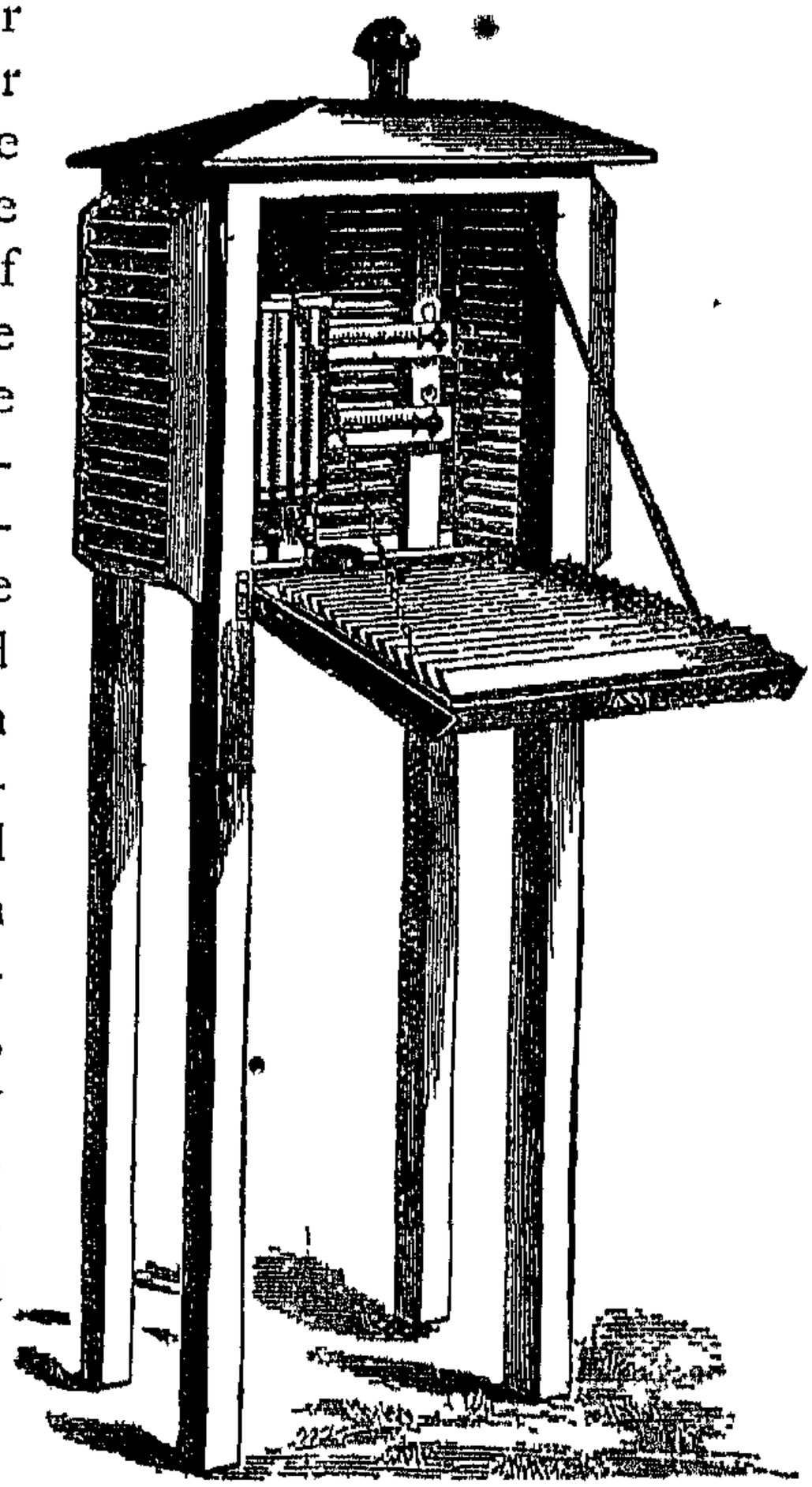


FIG. 10.

itself be subject to local influences, but we desire the temperature of the main body of air.

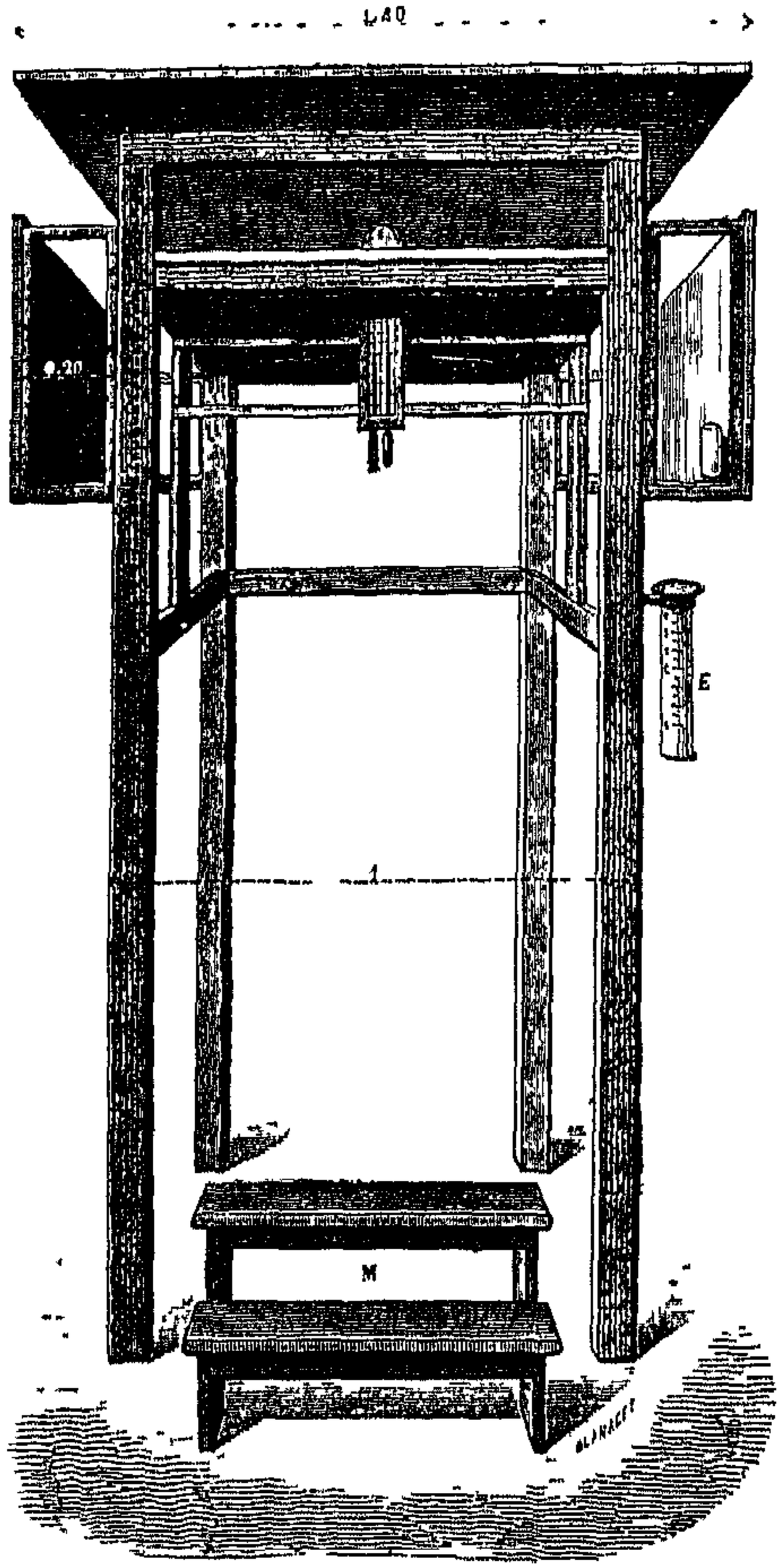


FIG. 11.

Many forms of fixed thermometer shelters or screens have been devised which, as was considered by the originators, had solved the problem of the true thermometer exposure. The most widely known and used of these are the Glaisher, Stevenson, Stow, Renou, Wild, and Signal Service shelters. The main plan on which most of these have been constructed is a box-like structure of wood, with the sloping top of solid wood, while the sides and floor are of various designs according to the ideas of the proposers. There is no doubt that different climates require some differ-

ences of details of construction for these screens, and so no one form can be recommended for all regions. In England the Stevenson screen (see Fig. 10) is

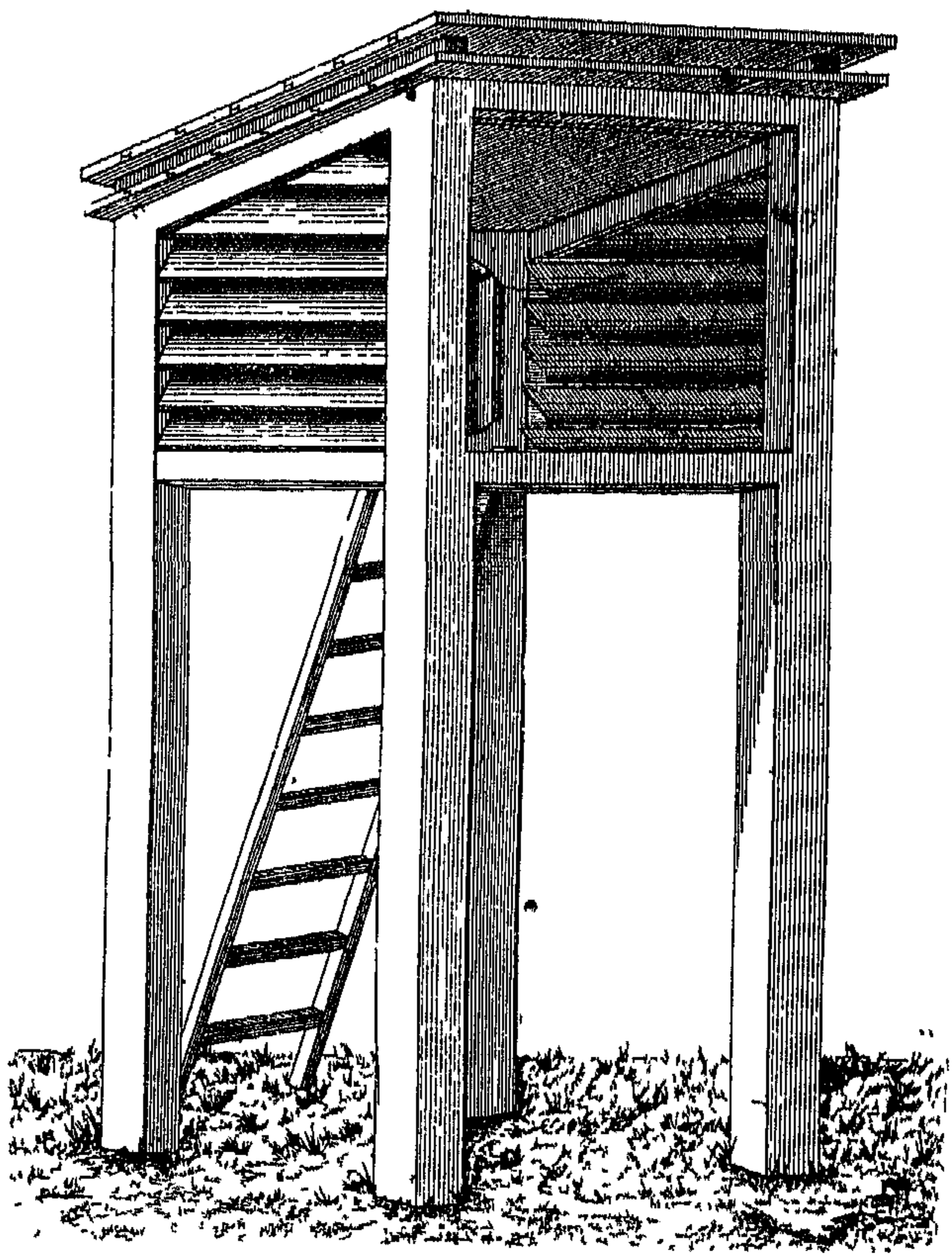


FIG. 12.

much used, and it has double louvred sides and floor, thus permitting the free entrance of the air, but excluding rain and preventing the vitiating action of

radiation. The thermometer is placed about four feet above the sod.

In France the Renou screen, as shown in Fig. 11, is used. It consists essentially of a double roof of wood or sheet zinc, inclined about 30° to the horizon, with an air space between the outer and the inner cover. The thermometers are placed near the inner cover, and are about seven feet from the ground, which must be covered with a sod. On each side is a board or similar shield to prevent the sun's rays from striking the thermometers in the morning or afternoon hours. One shield is sufficient if it is shifted from the west side to the east side at evening, and back again at noon.

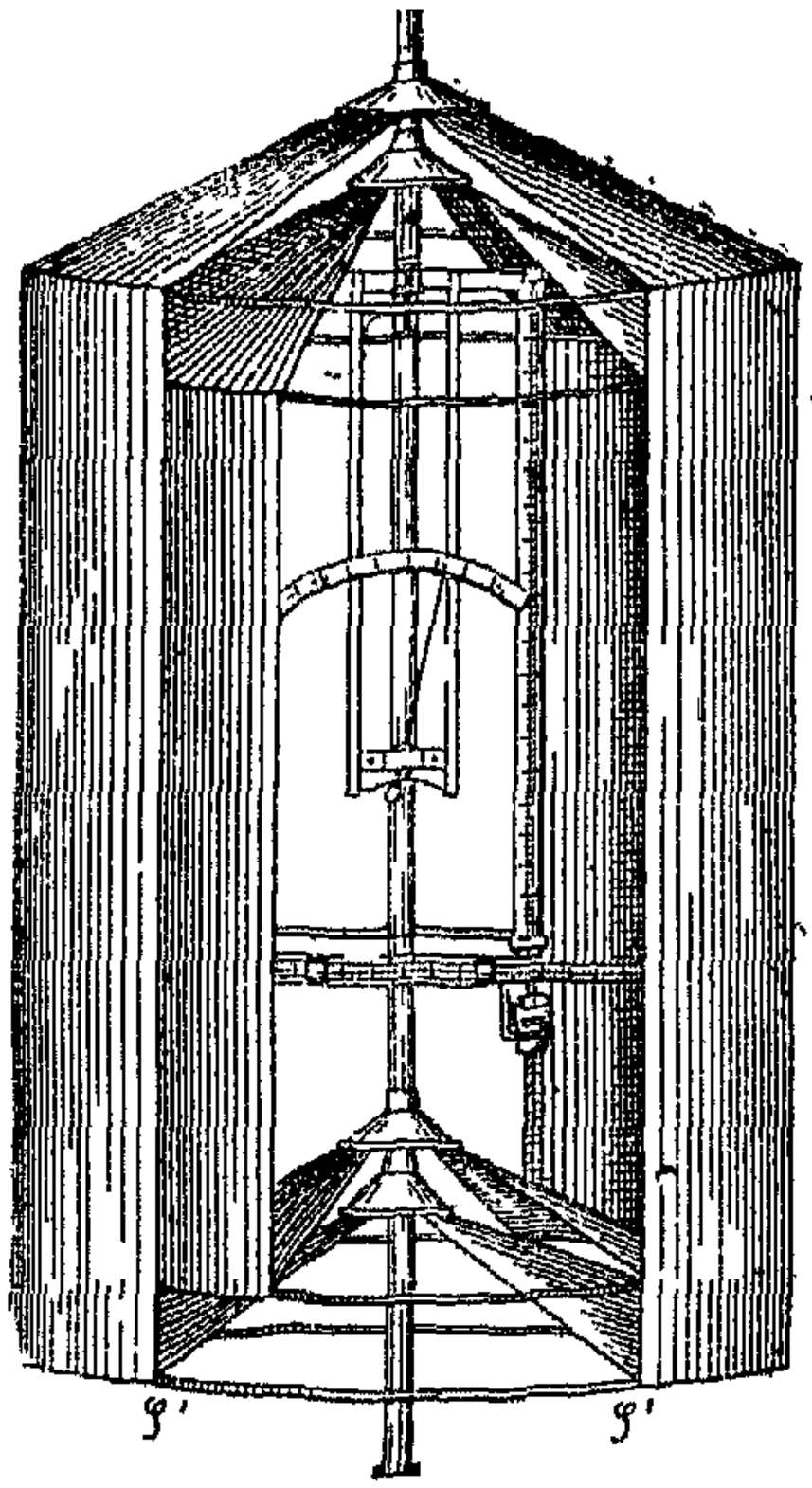


FIG. 13.

In Russia the Wild shelter is used; this is shown in Fig. 12. It is of wood, and has a double board roof and south side, with open space between the outer and inner covering. The sides are double louvred to admit the air freely, and the floor and north side are open. Within this wooden shelter is placed a zinc broken cylindrical case, which contains the thermometers, this case being so arranged as to freely admit the air, as is seen in Fig. 13, where the cylinder is opened to permit a reading of the instruments. At

the lower end of this inner metal shelter, and replacing the conical bottom shown in the diagram, is a fan-like arrangement, by means of which the air is forced through it (and over the thermometers) for two minutes before each observation. For the ordinary dry bulb thermometer Wild finds that the ventilated shelter and the unventilated shelter give the same results to within about 0°·1 C. The thermometer is placed about ten feet above sodded ground.

The Hazen thermometer shelter, as used by the United States Weather Bureau, is a cube three and a half feet long, three feet high, and three feet deep. The top and the bottom are of solid boards; the roof being sloping and double, with an air space of six inches between the outer and inner boards. The sides are to be single louvred with wide slats. In order to thoroughly mix the air inside of the shelter the wet and dry bulb thermometers are whirled rapidly in a circle eight inches in diameter, just before reading. When mounted on a roof the shelter must be nine feet above the platform, and when at the ground, sixteen feet above the sod, and supported in all cases by four posts.

In Fig. 14 the method of exposing the bulbs of the self-registering dry and wet bulb thermometers is shown as used at Kew, where the shelter is attached to a wall. The stems pass through the wall to the photographic apartment within the building.

Numerous comparisons of various forms of thermometer shelters have been made, not only to see how they differ among themselves, but also to determine their absolute accuracy. The Royal Society's experiments made by Griffith at Strathfield Sturges, Hampshire, which extend over the period from Novem-

ber, 1868, to April, 1870, and in which about eighteen different methods of thermometer exposure were compared, is the most elaborate investigation of the subject yet undertaken, and it might be thought that other experiments were unnecessary; but since then several government institutions and societies, and a

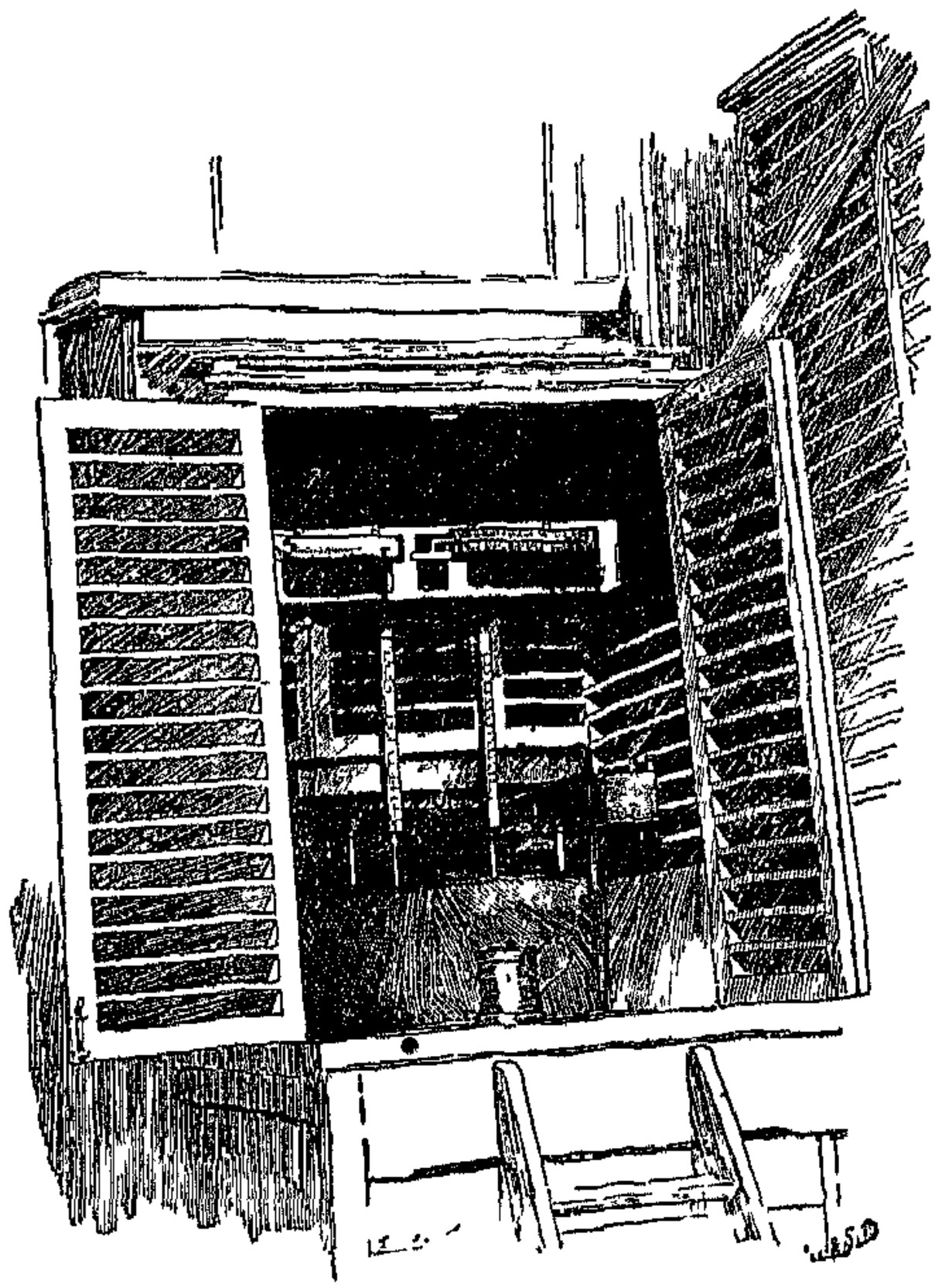


FIG. 14.

large number of individuals have investigated the question anew. The paper by Köppen, of the *Deutsche Seewarte* at Hamburg, bearing the title *Investigations on the Determination of Air Temperature* (*Studien über die Bestimmung der Luft-temperatur und des Luftdrucks. Erster Abhandlung. Untersuchungen über die Bestimmung der Luft-temperatur*),

and published in 1888, gives the latest summary we have of what has been done by the various experimenters.

Even the bare results of these researches cannot be given here, but it may be said that each of the recent forms of shelter probably has some advantage over others; but it has not been possible to obtain an agreement among meteorologists to adopt any one form to the exclusion of others, and the question of a standard form for universal use is still an open one, and not likely to be settled in the near future. Koppen proposed a simple form of thermometer shelter, in which the thermometer bulbs are placed between two horizontally-placed boards, as shown in the accompanying figure, No. 15.

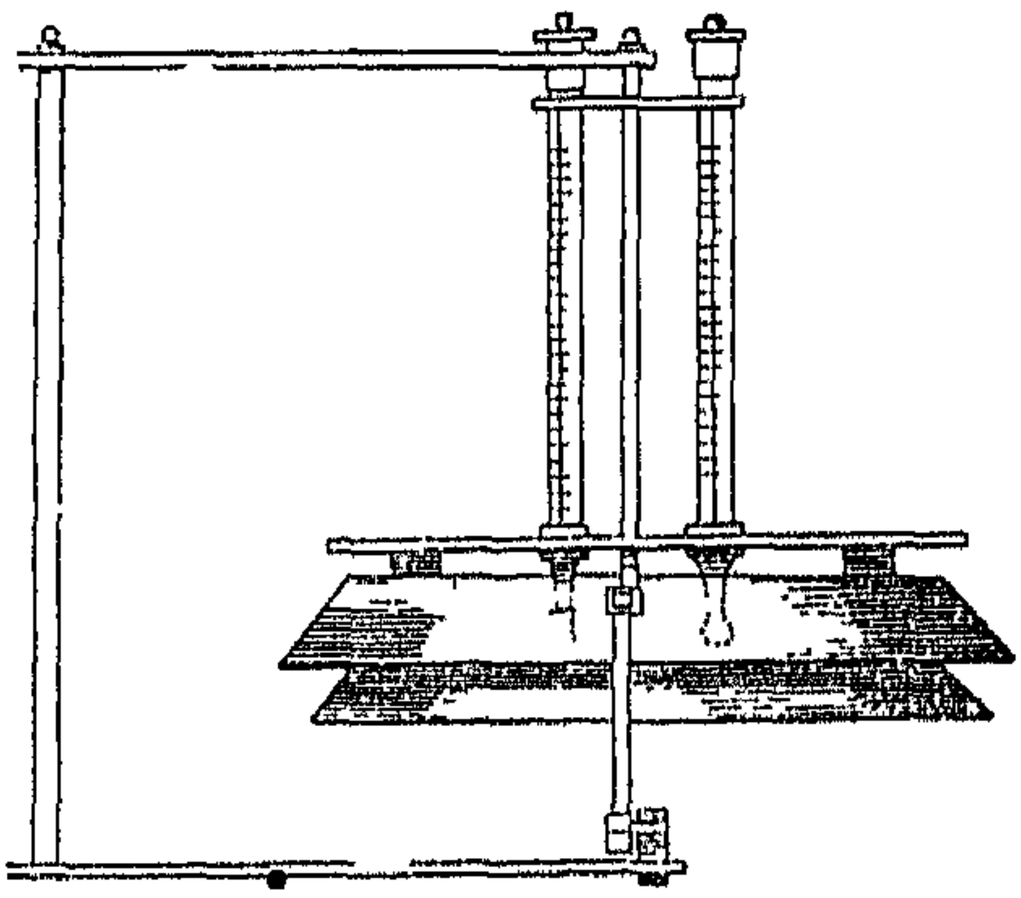


FIG. 15.

Normal Temperature.—It will be obviously impossible to arrive at any definite decision as to what is the best mode of exposing a thermometer in order to obtain the true temperature, until some absolute standard for comparison has been adopted; and yet this is what meteorologists have been trying to accomplish. It has been assumed, and is still so considered by many meteorologists, that if a thermometer is whirled quite rapidly in a shady place, so as not to be exposed to the direct rays of the sun, and so as not to radiate heat itself to the sky, then its

readings after whirling will indicate the true air temperature. Usually in performing this operation the thermometer has a string attached to the upper end, and is whirled after the fashion of using a sling. The whirled wet bulb thermometer was first used by Saussure; but the application of the method to ordinary thermometers was first made by Bravais in 1836, and later by Arago.

As a means of producing an artificial current of air which will flow past the thermometer bulbs three methods are in use by meteorologists: the slinging, or whirling by hand at the end of a string, as just mentioned; the ventilating, in which the current is caused by aspiration or some form of fanning; the rotating, in which the thermometers are whirled by a machine of some kind, or, as in the case of the Renou method, the shelter is rapidly rotated.

Observations by Joule and Thomson have shown that if a wind blows against an obstacle the temperature of the air is higher on the windward than on the leeward side; this is due to the dynamic heating by increase of pressure, and in exposing a thermometer care must be taken not to subject it to this source of error. Even for a thermometer exposed to a free current the reading is increased by 0°·1 C. for a velocity of wind of ten meters per second, and by about 0°·5 C. for a velocity of about thirty-five meters per second.

In 1817 Fourier proposed using two thermometers having bulbs of different degrees of radiation and absorption: *viz.*, the plain glass bulb, and one covered with lamp-black; and then from their readings he would compute the correction to be made for radiation.

In 1851 Liais proposed using three thermometers having bulbs of different absorptive powers. In

1865 Abbe (of Washington), then at Pulkowa, also proposed and applied the use of two thermometers. Fourier gave a simple formula for the reduction, depending on the absorption of glass and lamp-black; and quite recently Ferrel gave a more complete formula taking into account the velocity of the convective current of air to which the thermometers are exposed. Hazen made an independent proposal of the method of Liais, and his bringing the subject to public notice has resulted in some recent experiments in whirling of two thermometers, one with a gilded bulb, and the other with a bulb covered with lamp-black; but Abbe had recommended in 1883, and on earlier occasions, the use of the black and silvered or gilded bulb thermometers for determining the temperature even in open sunshine.

In 1857 Neumayer conducted experiments with white, red, and black bulb thermometers at the Flagstaff Observatory at Melbourne, for the purpose of determining the effects of radiation, but just what use he made of them has not been made public by publication; and Aitken independently proposed the use of thermometers having bulbs with different powers of radiation. It is seen, then, that so many different persons have independently suggested this general method that its discovery cannot be assigned to any one of the later proposers.

In the summers of 1885 and 1886 (as well as at other times), Wild made some very careful and complete experiments at Pawlowsk, Russia, with various kinds of thermometers, in order to arrive at some practical method for obtaining the absolute true air temperature. He used thermometers with

plain-glass, gilded, and blacked bulbs, and compared them, both at rest and with strong current of wind produced by a rotary motion, with the thermometers in his form of shelter (Fig. 12).

These experiments show, in the first place, that in the present condition of our knowledge of the theory of heat it is impossible to obtain, under all circumstances, in bright sunshine and in the shade, even with rapidly moving air, the temperature of the air by means of two thermometers having bulbs of different coefficients of radiation, as, for instance, the blackened-bulb and gilded-bulb thermometers; however, if these thermometers are in the shade, and enveloped in moving air, the true temperature is probably very nearly obtained by subtracting from the observed temperature of the gilded thermometer 15 per cent. of the difference between the two thermometers. Some of the observations made with a free sun exposure gave as much as 1° C. too high a temperature at about 20° C. by this same formula. The plain thermometer whirled in the midday sunlight gave results about 0°·4 C. too high, and in the shade 0°·5 C. too low, and in the evening after sundown this depression below the air temperature increased to 0°·8 C. In the most unfavourable cases on clear, calm summer days, the Wild-shelter sometimes gave a temperature 0°·5 C. too high for the ordinary thermometers without an air current, but when, by means of the ventilator beneath the inner metal shelter, a current of two meters per second was forced through it, the reading of the thermometer was only 0°·1 too high; so that if this shelter is used in the lower latitudes where such days frequently occur, the ventilating attachment must be used. On these calm days with strong

radiation, the air temperature can vary 0°·5 C. or more, at distances from one to four meters above the ground, according to the method of sheltering the thermometer, whether it be in the shade of a house, of a small-shelter, or of a large sail canvas.

Sprung has also recently published the results of some experiments made at Berlin, and his work shows, with that of others, the necessity of internationally conducted experiments.

§ 2.—*Barometers.*

Early History of Barometers.—The barometer was discovered by Torricelli in the year 1643, a year after the death of Galileo, who had shown that the air has an appreciable weight. The simplest form of this instrument is obtained by filling a glass tube, sealed at one end, with pure mercury, and placing a finger over the open end invert the tube and plunge this end, finger and all, into a cup containing mercury; then remove the finger, and, if the tube is somewhat over thirty inches in length, the mercury will flow out until the surface of that in the tube is about thirty inches above that in the cup, if the experimenter is near the sea-level. This experiment was first actually performed by the mathematician Viviani at the suggestion of Torricelli, and his instrument only differed from the above description by there having been a glass bulb blown at the closed end of the tube, so that when the mercury ran out, this bulb, as well as a portion of the tube, was left empty.

If this tube is clamped in a vertical position to a rigid support, and a scale of inches is placed beside it, also vertical, with the lower end, marking the zero of scale, resting on the surface of the mercury in the cup,

it will be observed that from day to day, or sometimes from hour to hour, the scale reading of the height of the mercury in the glass tube will vary considerably. This variation may amount to as much as a couple of inches in the course of a few days.

The instrument is, however, seldom used in this simple form, because it could furnish only very rough measures of the changes in the atmospheric pressure. Experience and experiment have caused many different forms of barometers to be constructed, in order to combine accuracy and convenience, and it is the gradual improvement of these instruments that we wish to follow out.

In Fig. 16 is shown an early form of the barometer as used by members of the Accademia del Cimento; in this a nearly closed cistern was used; the air being admitted by an orifice in a neck, and the gradations, which were arbitrary, were small protuberances on the glass tube.

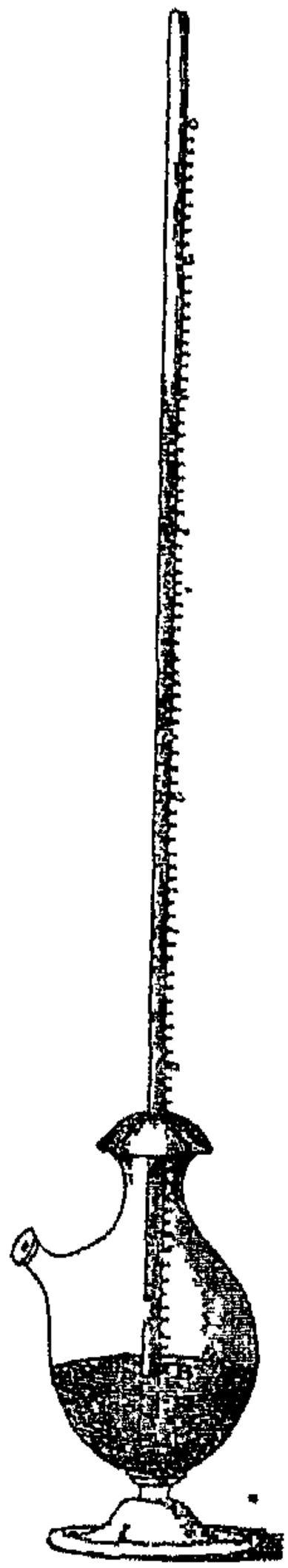


Fig. 16.

In order that the glass tube, in the case of the simple cistern barometer already described, may not be easily injured, it is usually surrounded by one of metal, and as this tube is in all parallel to the glass one, it can be graduated and serve as a scale for reading the height of the mercury column. Then, too, that the instrument may be easily carried about, the mercury cup at the bottom is so arranged that it can be screwed on to the lower end of the metal baro-

meter tube. The instrument in this simple form is a cistern barometer with immovable bottom, and is much used at sea.

If, instead of having the cup or cistern of mercury at the bottom of the tube, the lower end of the tube is bent into a U-shaped form, we have the so called syphon barometer, which was a very popular form until within recent years. In this case the difference in the height of the surface of mercury in the two legs of the tube gives the atmospheric pressure. (See Fig. 17, where the upper and lower scale readings are to be added together.)

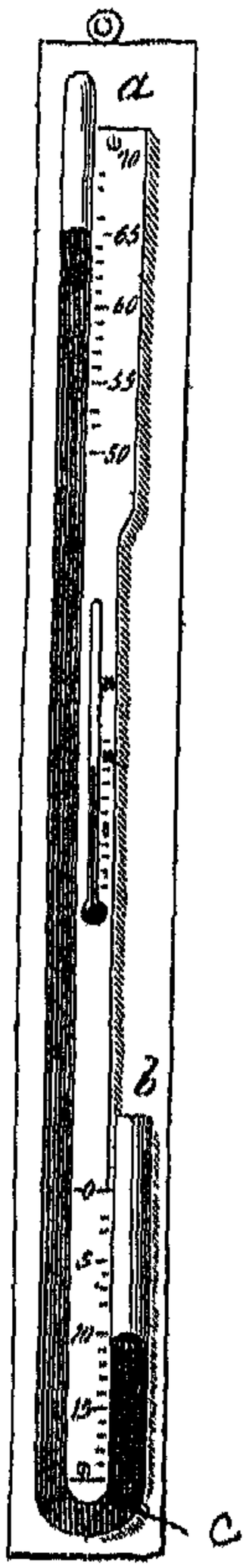


FIG. 17.

Various Forms of Barometers.—With this general idea of the construction of the barometer in mind, it will not be difficult to understand the details concerning some of the improvements which have been made in the last few years, and which are described below. The most popular form of instrument is the Fortin barometer. This is a cistern barometer, in which the lower end of the reading scale terminates in a fixed ivory pencil (within the glass cistern), the lower point of which is at the zero of the scale. The lower part of the mercury cistern usually has a soft leather lining which is pressed upon by a screw from below. The large milled head of this screw is turned by the observer until the surface of the mercury in the cistern is raised so high as to just come in contact with the ivory point marking the zero of the scale;

then the scale reading of the height of the mercury in the tube gives the "barometer height." There are numerous makers of this form of barometer, but they differ only slightly in details of construction, and the general form is to be found illustrated in most books on physics or meteorology. A cheap construction by Baudin, of Paris, is, however, of sufficient novelty to deserve notice. This instrument is shown in Fig. 18. The scale divisions are ruled directly on the glass tube, and the cistern is entirely of glass, but it has a metal rim which screws into another metal rim encircling the lower end of the barometer tube. The zero of the scale is at the end of a pencil of glass which is attached to the barometer tube, and is brought in contact with the mercury in the glass cistern when a reading is to be made.

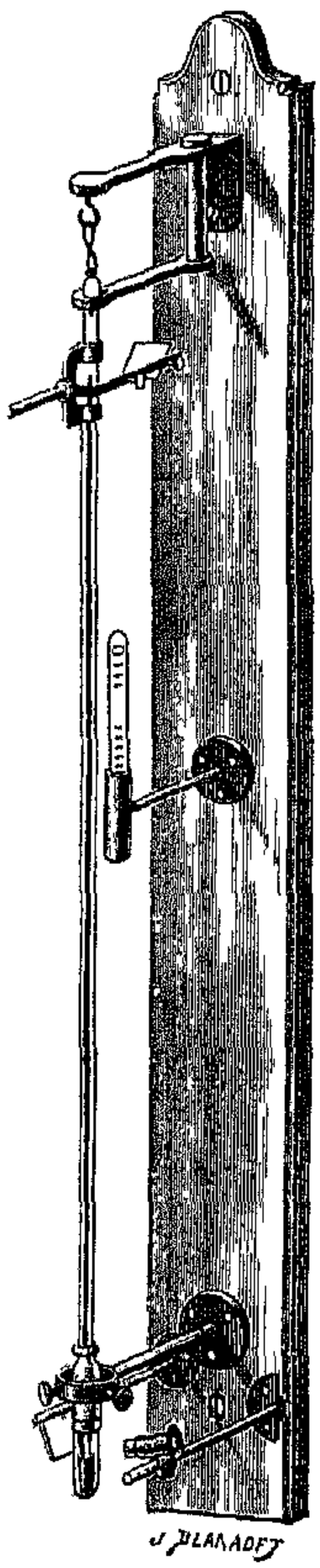


FIG. 18.

About 1830 Kupfer invented the syphon-cistern barometer, various forms of which are now used extensively in Continental Europe, under the names of Turrettini, Köppen-Fuess, Wild-Fuess, &c. Many improvements have been made in the original design, and probably the best at present in use are those of the Wild pattern, manufactured by Fuess of Berlin. As the name suggests, this form of instrument is a combination of the cistern-syphon barometers in which the attempt is made to bring into one instru-

ment the good points of both forms. The arrangement of the barometer tube is best realised if we imagine a syphon barometer tube with the shorter leg cut through at the beginning of the bend (at the point *c* shown in Fig. 17), and the bent portion straightened out; both of the cut ends are then inserted in a closed cistern filled with mercury, beneath which is an adjusting screw, as in the case of a Fortin barometer. In making a reading, the mercury is forced up into both legs of the barometer until the mercury surface in the short leg is brought up to a fixed index at the zero of the scale, when the reading of the latter, showing the height of the mercury in the longer leg, gives directly the barometer reading.

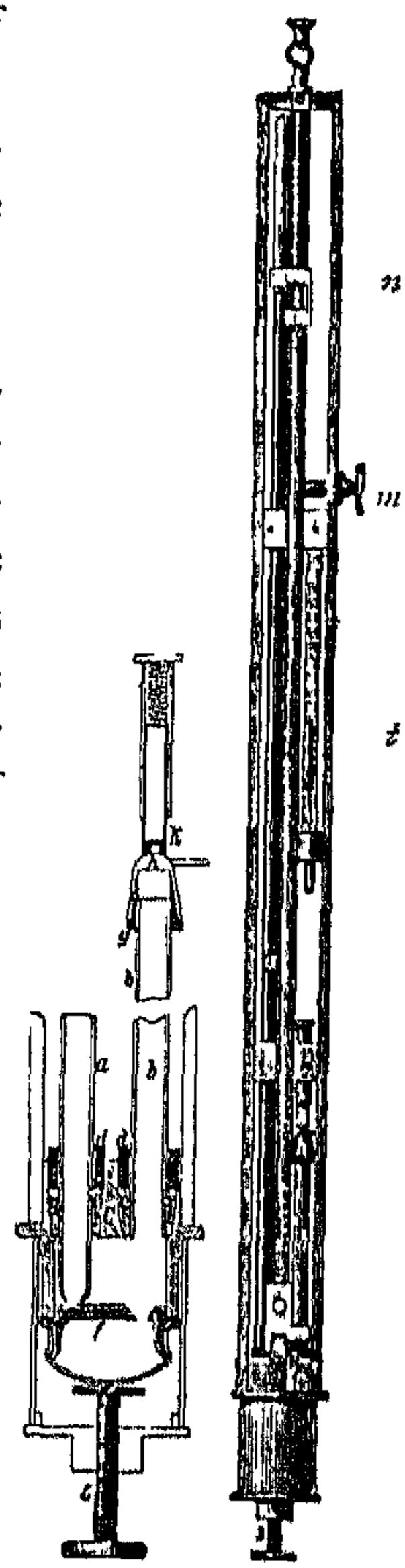


Fig. 19.

Fig. 19 shows the Koppen-Fuess form, in which the principle of construction can best be seen, as both tubes are straight, and two brass bars take the place of the usual encircling brass tube, thus permitting the glass tubes to be seen. In making an observation with this instrument the screw head *s* at the bottom is turned towards the right until the mercury in the short tube on the right is brought up to a fixed zero index at *c*: the upper reading sight at *n* is then adjusted to the top of the mercury column in the long tube on the left by means of the screw at *m*. The ther-

mometer at *t*, it will be noticed, is unprotected in this case, to make the exposure uniform with that of the glass tube of the barometer. This form of barometer is little used outside of Germany.

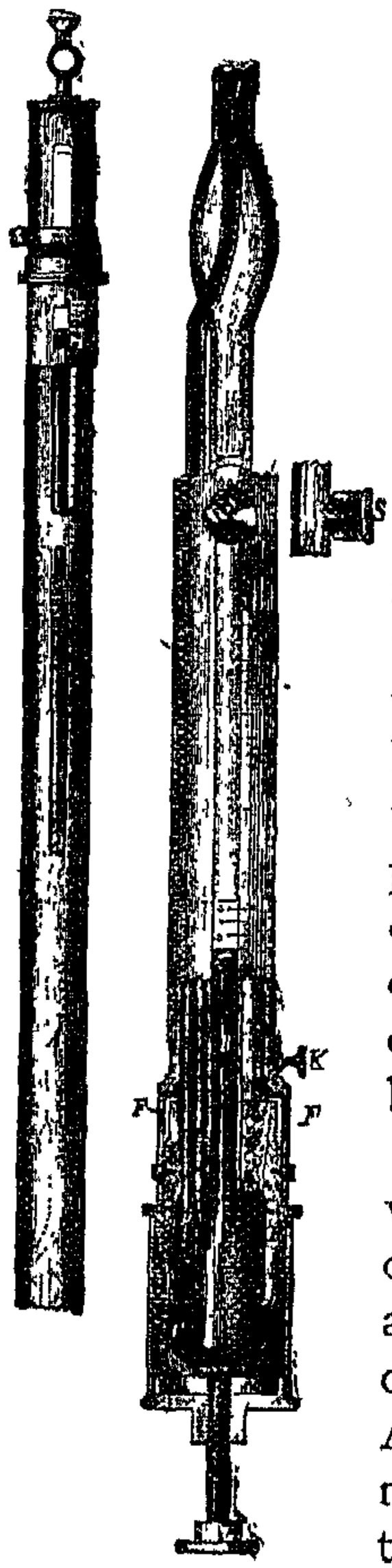


FIG. 20.

Fig. 20 shows the Wild-Fuess barometer, which is much more complex than the one just described, owing chiefly to the fact that in this form there is a bend in the longer leg, which permits the short leg to be located directly under the upper part of the longer leg, so that the two surfaces of mercury which are to be observed will be in the same vertical. In the diagram the upper part of the barometer is shown at the left, and the lower part at the right; a portion of the outer brass tubular covering being omitted in this last case in order that the construction of the glass tubes can be seen to better advantage.

As this barometer has come into very extensive use on the Continent of Europe as a refined form of portable instrument, a more lengthy description is desirable. The tubes A and B connect with the closed mercury cistern C. A is the longer tube and passes up, being considerably constricted, to a bulb blown in the continuation of the tube B; here a turn to the right is made, and A passes through this bulb O

until it is directly over the short tube B. When A leaves the bulb O it expands into the full diameter which it has at the point of reading above. The short tube B is of the same diameter throughout up to the air hole S, and it is continued up to the place of meeting the tube A merely for the additional rigidity it gives the instrument. In making an observation with the instrument the bottom screw G is turned until the mercury surface in B comes in contact with the zero sight (which is adjustable to the zero of the scale by means of the screw K) which is shown just above it in the diagram.

The height of the surface of the mercury in the longer tube is read off by means of the sight at N, which is carefully adjusted by means of a screw motion. The framework of this sight, on which is also placed the vernier divisions, encircles the brass tube covering the glass tubes.

The outside air enters the short tube through the small opening in the arm covered by the screw cap S; this screw cap being left open during the observation, but kept closed at other times.

For this barometer the attached thermometer is within the encircling brass tube, but the scale is exposed to view through a slit; the thermometer bulb being well covered.

When the barometer is not in use, the mercury is screwed up into B until about all the air is expelled through the hole at S, when the cap at S is screwed on and any outflow of mercury is prevented. In this condition the barometer may safely be inverted for transportation, as the tube A becomes filled with mercury long before the mercury in B reaches S; but in inverting the barometer the screw cap S must be

turned towards the manipulator, and the cistern end of the barometer moved upwards to the right (*i.e.*, with the right hand with which it is grasped below); and in restoring it again to its normal position, S must still be towards the person and the exact reverse directions be traversed by the right hand. In this process of inversion the short tube is kept uppermost, and there is thus no chance for the bubble of air to enter the long tube A as it passes from S along the short tube B to the highest point of the cistern.

A great theoretical advantage of this form of instrument is that it admits of a determination of the amount of air in the imperfect vacuum above the long column of mercury in the tube A. This can be done by a double measuring of the difference in the height of the mercury in the two tubes; first when the vacuum space in A is four or five inches long, and then again after it has been reduced to a fraction of an inch by forcing the mercury from the cistern up into both of the tubes A and B by means of the lower adjusting screw G. If any air is present in the vacuum space, it will be more compressed in the second case than in the first, and the second barometer height will consequently be less than the first. The relation of this difference to the space occupied by the air, in the two readings, allows the amount of air in the vacuum chamber to be computed. This is an application of what is known as the Arago method to a portable barometer. In carrying out this process, the screw cap S must be entirely removed from the barometer, when the reading micrometer N, vernier and all, can be slipped down the brass tubular covering, and be used for making the scale reading of the

mercury surfaces in the glass tube B as well as that in A.

I have now given some idea of the forms of portable barometer in common use and also of their manipulation, but in all of them they have been used as received from the maker, already filled with mercury. It has long been considered desirable to have a form of barometer which could be easily filled with mercury, so that it could be transported from place to place with the tubes emptied of the mercury, the weight of which makes it such a risky matter to move a barometer. A number of methods have been proposed by which this can be accomplished, but none of them have been subject to such tests as the barometer constructed by Professor Sundell of Helsingfors, which has been brought into very prominent notice by having been used in the splendid series of international barometer comparisons, carried out by the inventor, which will be spoken of a little later. This barometer is shown in Fig. 21 and Fig. 22. The former shows the system of tubes stripped of the mounting and the encircling brass tube which serves as a scale as well as for protection.

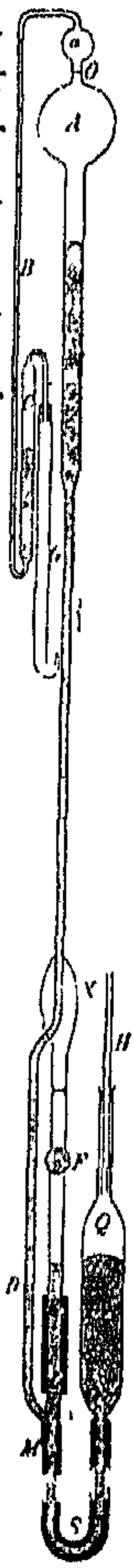


FIG. 21.

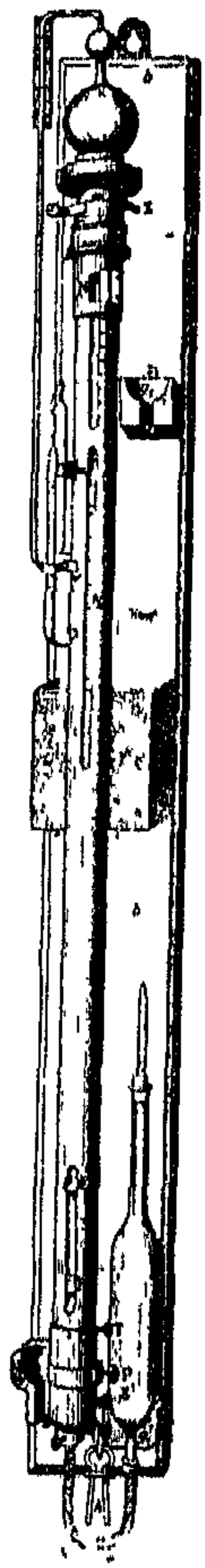


FIG. 22.

A duplicate glass tube of a Wild-Fuess barometer is used as a foundation for this barometer, the inner diameter of the tubes at the points of observation being 11·1 mm. At the upper end of the tube there is attached by melting a spherical bulb A with a content of about 110 c. cm.; between this bulb and the capillary tube B (having a length of 43 cm. and surface aperature of 1·63 sq. mm.), there is inserted a small spherical bulb *a*, having a content of 5 c. cm. The reservoir C, having a length of 10 cm. and an inner diameter of 11 mm., which is joined to the tube B, is connected with the drying tube G by means of a narrow tube which prevents any foreign substance from passing from G into C. The tube G is stopped up at the top with wool, and is fastened into C by means of a cork, the joint being made air-tight by means of resin and bees' wax. As a means of drying, phosphoric anhydric acid is used. At the lower end of the contracted tube D, a T tube is melted on, and so bent that the axis of the tube LM coincides with the axis of the open leg of the barometer tube which terminates at K; the two tube ends K and L, which are about 5 cm. apart, are then connected by means of a rubber tube, which latter can be somewhat compressed by means of the screw P (see Fig. 22). The end of the tube M is connected by means of the wrapped tube S (length 120 cm., inside diameter 5 mm.) with the glass reservoir Q which holds 200 c. mm. At the top of Q is a drying tube containing chloride of calcium. In Fig. 22, N is the upper sight having a micrometer motion, R is the lower fixed sight, and Y is the attached thermometer inside of the brass tube, but with scale visible through the slit. The method of manipulation is as follows:

We will start with the barometer emptied. The pure mercury is put into the reservoir Q (Fig. 21), after which the cork which is used to stop up the lower end of G is pierced with a needle, and the screw F, which controls admission of the air to the lower open leg of the barometer, is tightened to prevent the entrance of air into this lower leg. By slowly raising the reservoir Q, which can be easily done as the tube S is of rubber, and is many times larger than represented in the diagram, being in fact 120 cm. long, the mercury will gradually rise in the barometer tube until it has forced the air out of the spherical bulb A and the reservoir C. By slowly lowering Q the mercury flows back again, and the air flowing into the tubes again through G is dried in its passage. A repetition of this filling and emptying process, two or three times, letting the air fill the barometer tube each time, will suffice to dry the tube thoroughly. The barometer tube is now finally filled with mercury and the reservoir Q is allowed to rest in the upper holder g_3 (Fig. 22), which is so placed, and the amount of mercury in Q is so chosen, that when Q rests in g_3, the tube C is just filled with mercury. The small opening in the end of the drying tube G is now closed by means of a heated knitting needle, which is used to melt the wax which had previously been pierced to admit the air. Q is then again lowered and C is only so far emptied of mercury that the air still remaining in it holds in equilibrium, by its tension, a mercury column of the height of the capillary tube B. Then the mercury will break above at the beginning of the capillary tube and draw itself back to the vertical part of the tube; on the other side it sinks lower and lower in

the bulb A, leaving above it a Torricellian vacuum. Q should now be lowered as far as possible in order to set free any little air bubbles that may have found lodgment between the mercury and the sides of the tube D. By an additional raising of Q the remaining small quantity of air is driven over into C. Q is then returned to the holder g. The instrument is now ready for making an observation, and the distribution of the mercury is as shown by the shaded lines in Fig. 21. There is always, however, a measurable quantity of gas consisting mostly of water vapour remaining in the vacuum chamber; and the amount of this gas must always be determined by the method of varying pressures (Arago's method). Sundell has found the gas tension to be somewhat variable, being as high as 0·37 mm. and as low as ·07 mm. A full and very interesting account of the manipulation of this barometer is to be found in Sundell's rather inaccessible original paper in the *Acta soc. Fennicae*, tome xvi.

In regard to the accuracy of the readings (which must not be confused with the absolute accuracy of the instruments as referred to a common standard) of the various forms of portable barometers, it is difficult to give positive values, and the following are somewhat, although not entirely, personal estimates. If two ordinary Fortin barometers are compared with each other, the readings differ by 0·25 mm. from one comparison to another. In other words, if we know the error of the barometer as compared with an accurate standard instrument, we can be pretty sure of obtaining the true atmospheric pressure to within 0·25 mm. by a single reading at any time. A Fortin barometer of the highest class will give single read-

ings, with an accuracy of perhaps 0·12 mm. A Wild-Fuess (syphon-cistern) barometer of the best construction will give single readings with an accuracy of perhaps 0·06 mm. For the latter instruments, if a series of ten readings is made simultaneously on two barometers, and each difference is subtracted from the mean of the ten, the average deviation of the single readings from the mean should not be more than 0·03 mm. There have been constructed a very few Fortin instruments which could perhaps be read as closely as the Wild-Fuess barometers, but the personal equation between two observers is undoubtedly less for the latter form of instrument.

Standard or Normal Barometers.—All ordinary barometers must first be compared with a standard barometer before the results obtained by them can be used, as they are never perfect in construction and differ among themselves. In practice the following plan has been usually carried out. A barometer of unusually good construction, in the filling of the tube of which great care has been taken, is selected to be used as a standard, and mounted permanently at some observatory of repute. This is adopted as a standard for the observations officially made by the country or state, and the barometers used in making observations in this region are compared with it. This comparison is made either by bringing the barometer, to be compared, to the observatory, and making the comparison with the standard direct; or else by comparing a barometer with the standard and then carrying this second barometer to the observing station, and comparing it with the observing barometer in the location and condition in which it is to be used for actual observations. This last method is

considered the best, although a slight error enters into the comparison due to the use of the intervening portable barometer.

With the gradual increase of accuracy in making barometric observations, and especially in the more frequent combination of the observations made in different lands, it became evident that these so-called standard barometers should be replaced by still more accurate instruments which should have an absolute accuracy, and which should agree with each other the world over, *after* certain theoretical corrections had been applied to their readings. This great reform, which we owe more to Professor Wild (of St. Petersburg), than to any other single individual, has only partially taken place, and is still in progress; and it is this progress which I propose to outline. It would require a special treatise on barometers to contain a complete description of all the normal instruments now in use, and so only a brief mention can be made here of the different constructions; and, as these differences occur mainly in the method of reading the height of the mercury column, they are pointed out in the text treating of the errors of this operation. I have, however, given diagrams of many normal barometers, descriptions of which have been published; believing that such a complete series has not been heretofore collected in any single publication.

Regnault's normal barometer at the Collége de France, Paris, was the first instrument constructed that could lay claim to this title. This barometer, which was constructed for his own use in carrying out the investigations described in his famous memoir published in 1847, had its origin in his desire to do accurate work rather than in any idea of establishing

a standard barometer, with which other and less accurate instruments might be compared. Regnault's normal barometer (Fig. 23) was a combined manometer and barometer. The tube A in the illustration is the barometer tube, and the tube B (towards which the reading telescope of the cathetometer points) is the manometer tube.

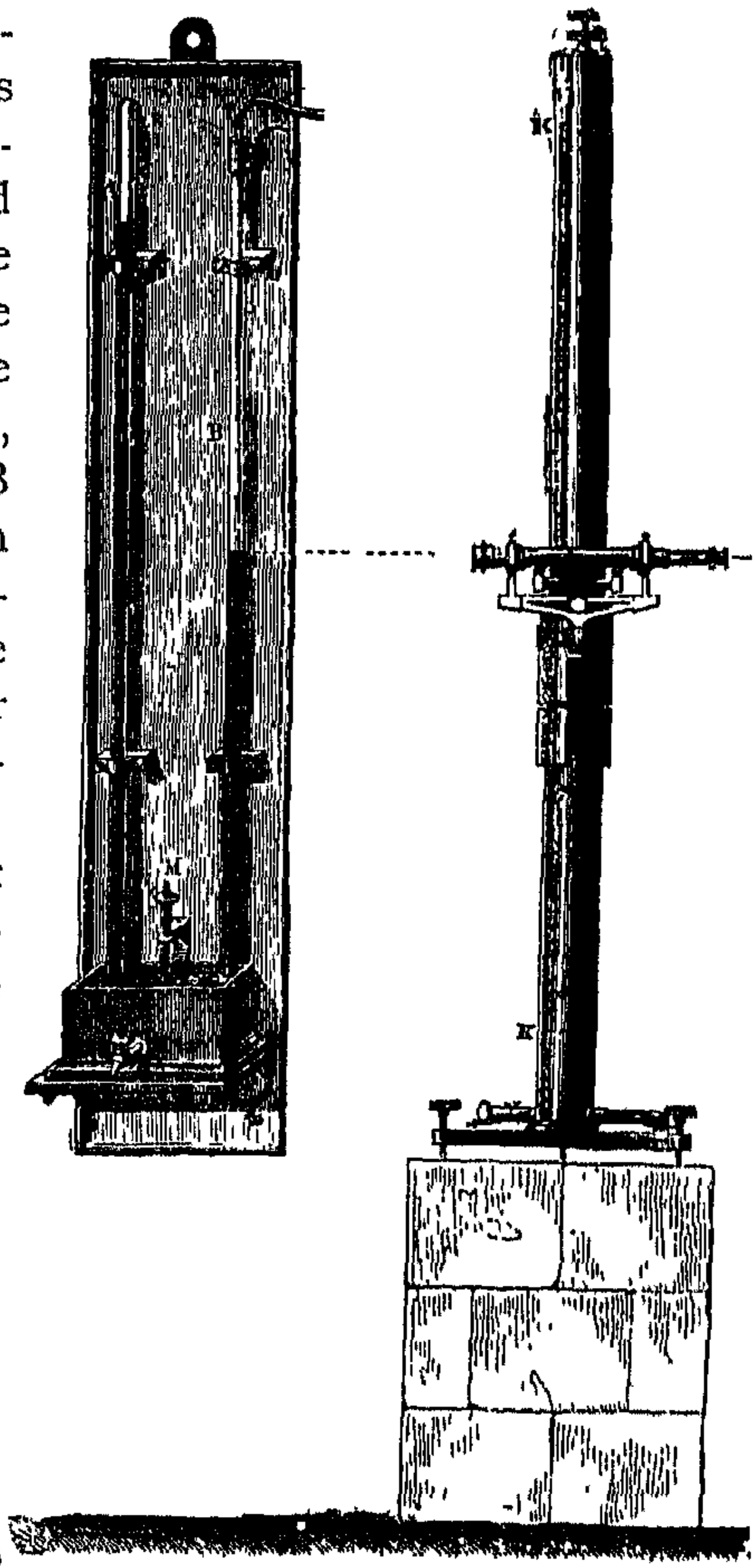


FIG. 23.

Experiments at the Kew Observatory during the years 1853–4 resulted in the final establishment in 1855 of the Kew normal barometer (Fig. 24), the cathetometer belonging to which was somewhat similar to that shown in Fig. 23. This was really the first normal barometer set up as a standard for meteorological purposes. The Regnault and Kew normals are not very different in construction.

About ten years later, in 1866 or 1867, Wild established at Berne a normal barometer which embodied the main ideas of the instrument established by him a little later at the Central Physical Observatory at St. Petersburg, and which is shown in Fig. 25. For outline plan see Fig. 31.

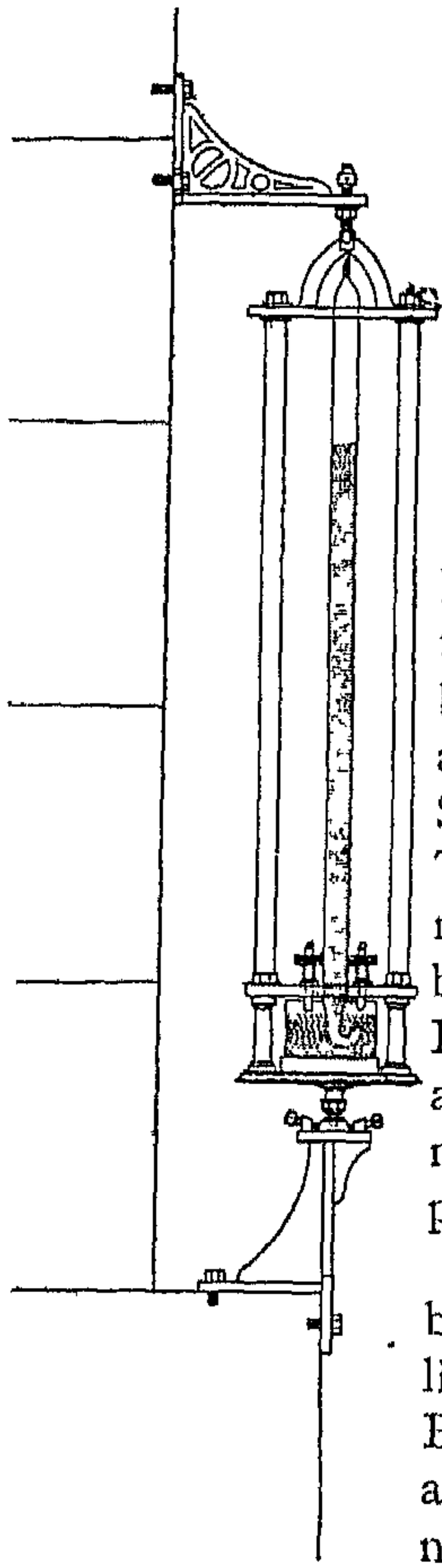


FIG. 24.

Another pause of ten years followed, during which Wild, Neumayer, Hellmann, and others, strongly urged the establishment of other normals; and then, in 1881, the Fuess normal barometer (Fig. 26) was mounted at the laboratory of the Normal Standards Commission in Berlin. This and another barometer mounted about the same time by Pernet, at the International Bureau of Weights and Measures at Sèvres, followed out in the main the method of construction proposed by Wild.

About 1882, Marek's normal barometer (Fig 27) was established at the International Bureau of Weights and Measures at Sèvres; and in 1883 a Fuess normal was obtained by Neumayer, for the Deutsche Seewarte at Hamburg (Fig. 28). A new normal barometer of novel construction was mounted, probably in 1886 (perhaps in 1885), by Sundell, at Helsingfors

(Fig. 29), according to a plan proposed by him somewhat earlier.

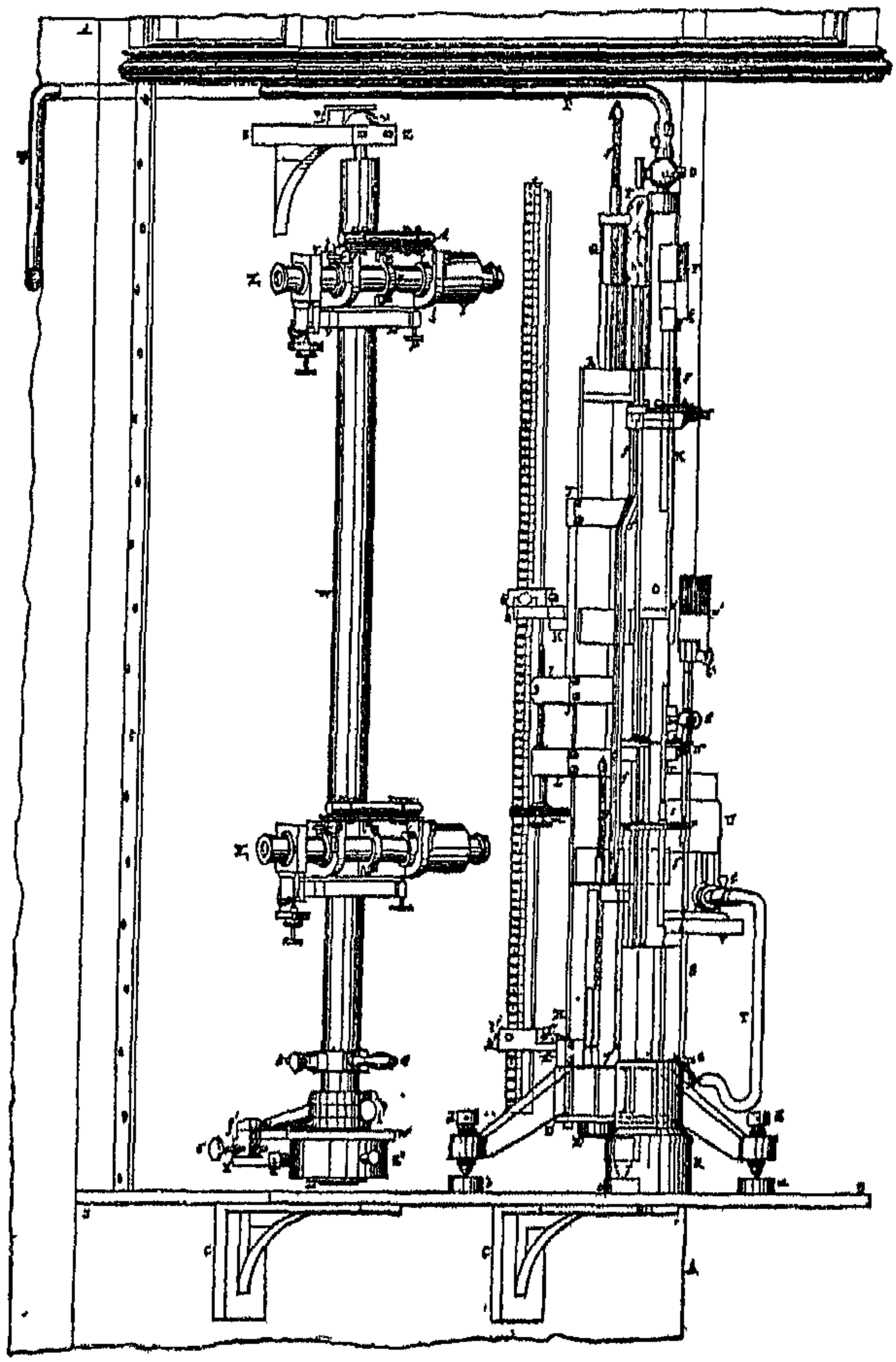


FIG. 25.

The latest addition to this list of normal barometers is the one mounted by Wild at the observatory at

Pawlowsk, Russia, in 1887; but the details of its construction have not yet been published.

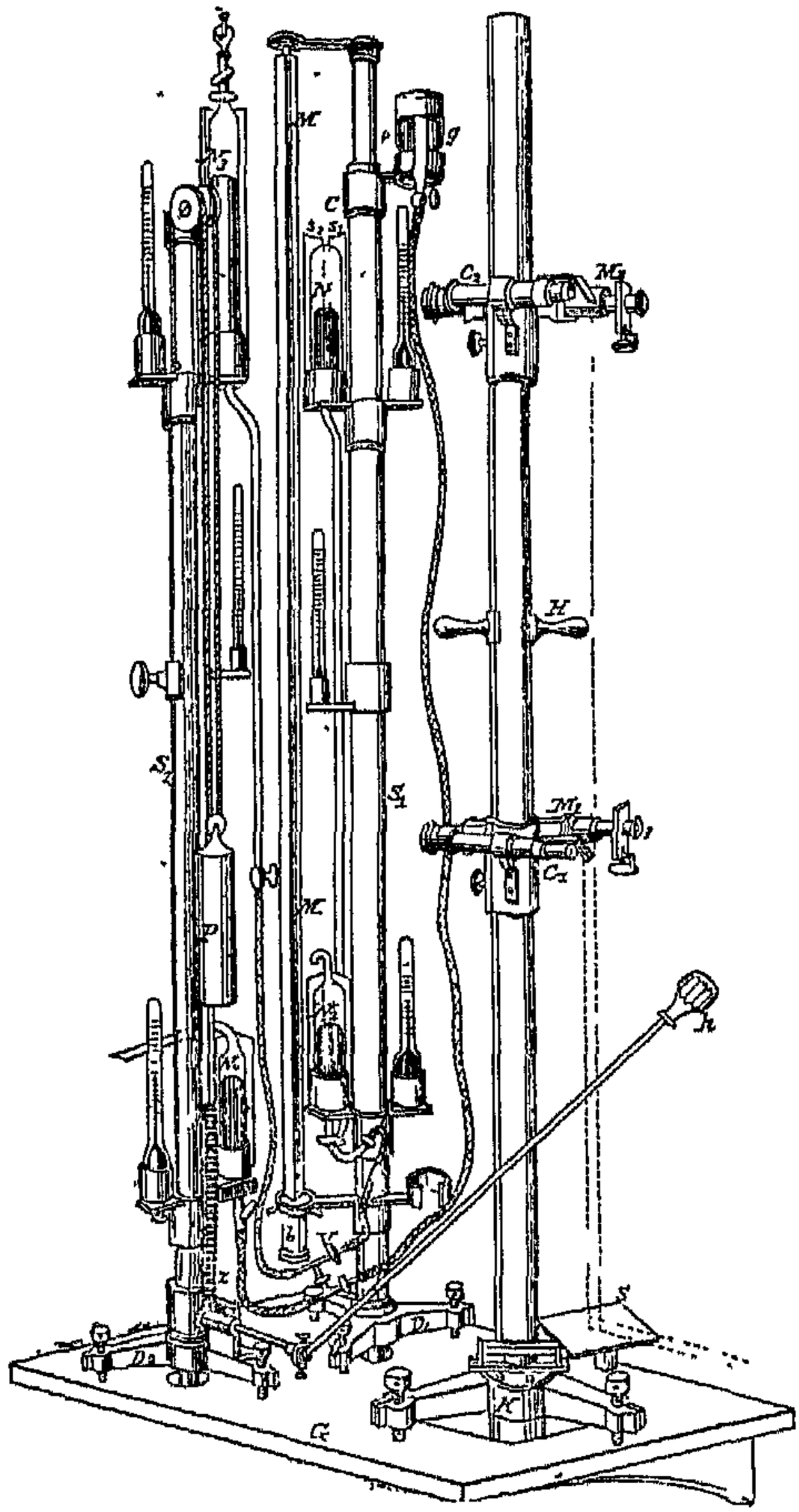


FIG. 26.

These various normal barometers may be divided into two classes. The Regnault and Kew normals form the first class, in which the practically straight

barometer tube projects into a cistern of mercury, and the methods of reading the upper and lower

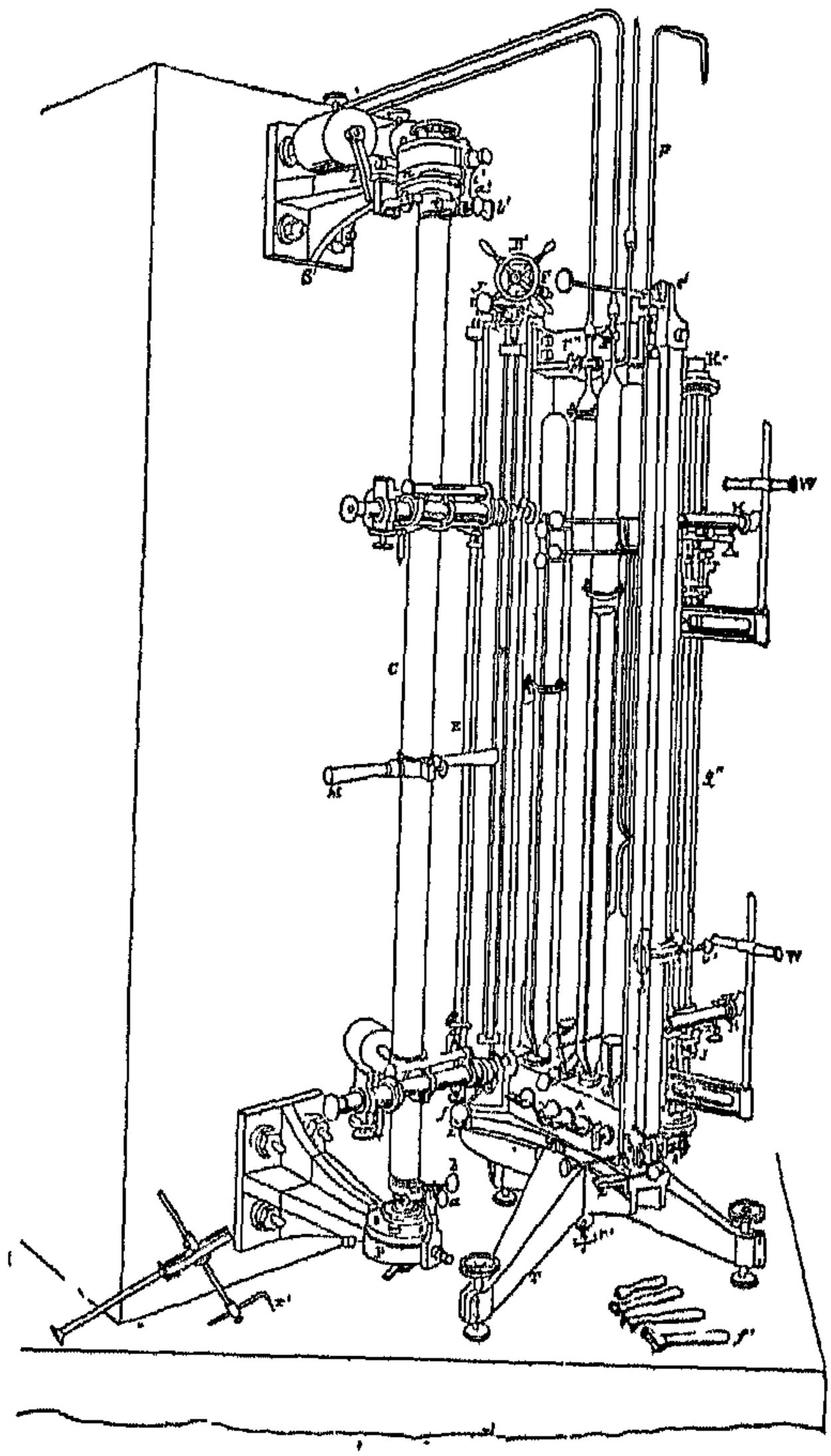


FIG. 27.

mercury surface are quite unlike. The remaining normals belong to the second class, inaugurated by Wild, in which the tube is of syphon form, thus

permitting the same system of reading the mercury surfaces to be used above and below; and an accessory cistern of mercury to be used in adjusting the surfaces is connected with the barometer tube at the lower bend: this form of barometer is most distinctly shown in Fig. 28, as the usually accompanying manometer is not attached in this case: this is the normal barometer at the Deutsche Seewarte, Hamburg. The special differences in these barometers will be pointed out in appropriate places in the mention of the various errors pertaining to these instruments.

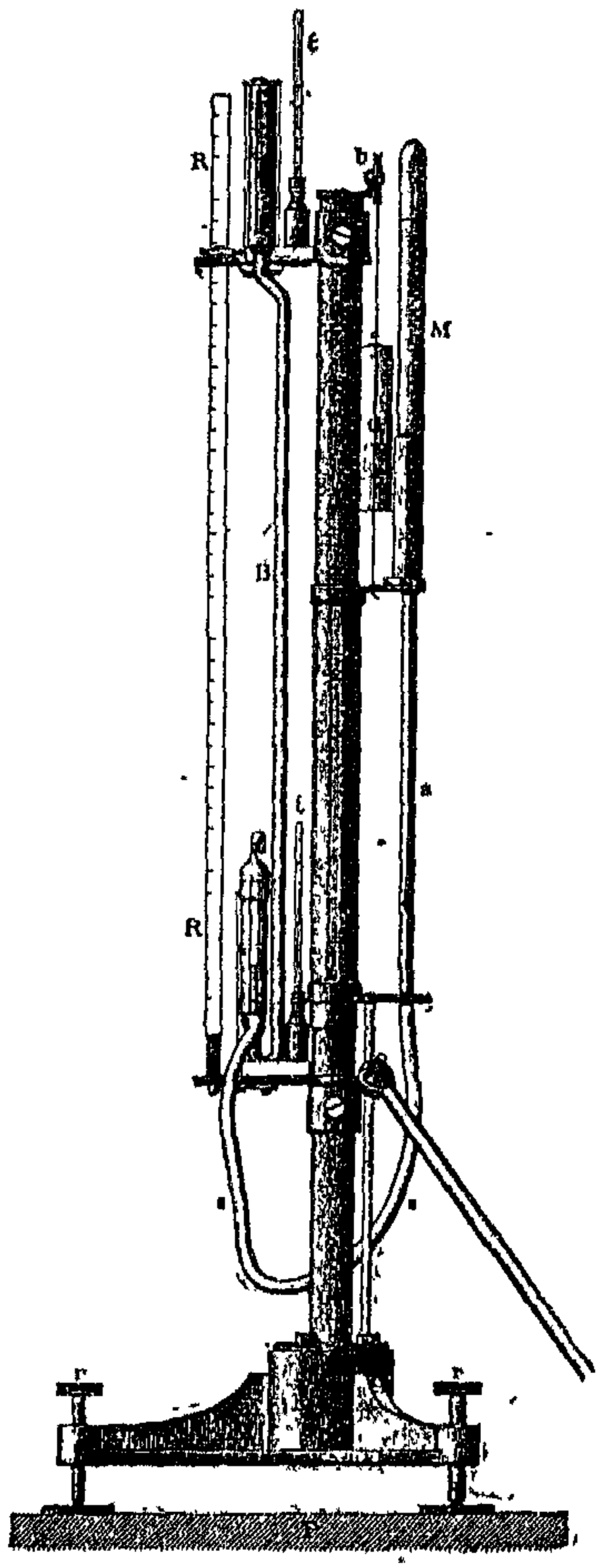


FIG. 28.

Sources of Errors in Barometers.—There are many sources of error in determining the true atmospheric pressure. Regnault claimed for his normal barometer, that the inaccuracy was not greater than 0·10 mm. Wild, however, set the admissible outside limit of any error at 0·01 mm.; and he adopted this as a criterion in the investigation

of the St. Petersburg normal (Fig 25), which he claimed, and I think justly, to be the first normal barometer ever fully investigated for its errors with this precision.

I will now make a brief mention of these special sources of error, and give the precautions necessary to keep the errors within 0·01 mm.

1. Effect of the changes of temperature of the mercury.

For an ordinary temperature, of say 20° C., the mean temperature of the mercury column, for its entire length, must be determined with an accuracy of ±0°·07 C. This can only be done by mounting two, and perhaps three, thermometers at different points close to the barometer tube, and they must have their bulbs immersed in glass tubes containing mercury, and with diameters the same as for the barometer tube.

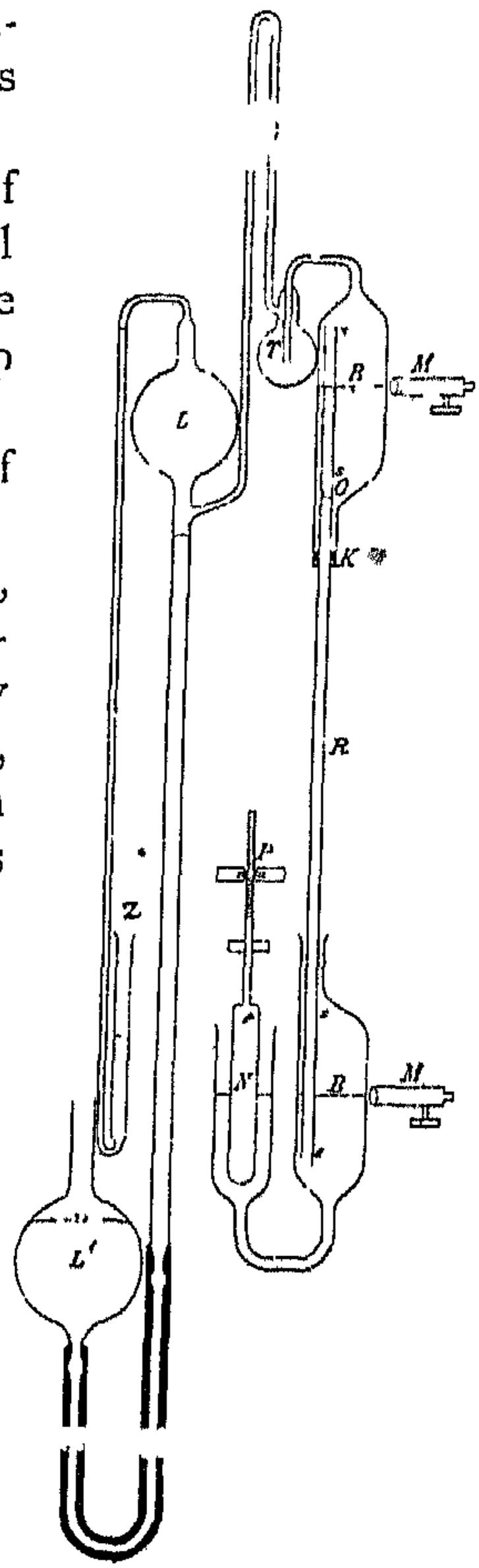


FIG. 29.

2. Influence of temperatures on the brass scale.

At about 20° C., the reading of the scale temperature must have an accuracy of ±0°·7 C.

3. The correction to standard gravity.

The latitude of 45°, and sea level has been adopted

as the place to which the observations are to be reduced as a mean point; and whenever the place of observation is more than 8′ (two geographical miles), from the latitude 45°, or is more than 42 meters above the sea-level, the gravity correction must be applied.

4. The impurity of the mercury.

It is much easier to obtain pure mercury than to use that which is not pure, and then have to determine the specific gravity of it; which it would be necessary to do in order to prevent an error of more than two units in the fourth decimal place of this constant.

Mercury of sufficient purity can be obtained by first washing commercial mercury in dilute acid; shake the bottle containing the combination frequently during several days, and then pour off the acid, and wash the mercury in pure water. Now pour it into a clean glass vessel containing some chloride of iron, which being removed, and the mercury being filtered, it is ready for distillation; and this can be done by means of a Weinhold distilling apparatus, or Wright's modification of the Weinhold form.

5. Inclination of the reading scale.

In mounting the graduated scale, great care must be taken to get it vertical, and it must be so firmly fixed that it cannot be easily moved by any jarring. A plumb line suspended from a steady support will do to show the verticality with sufficient accuracy.

6. Error of scale graduation.

The only way to find out this error is to compare the scale graduations with a normal scale of known accuracy. The comparisons must be made, not only for the extreme length of the scale, but also for perhaps a dozen points throughout the length.

Much of the accuracy of the scale reading depends upon the carefulness with which the graduation has been carried out.

7. Elasticity of the scale.

The scale having been compared with the normal in a horizontal position, and then hung vertically suspended from its upper end, the length will be found to have increased 0·01 mm. when the whole weight supported by the scale amounts to 0·8 kilograms for each square mm. of cross section.

8. Influence of gas in the vacuum chamber.

In the filling of a barometer tube with mercury, it is impossible to obtain an absolute vacuum, and the difficulty increases when the attempt is made to fill the complicated system of tubes of a modern normal barometer. It has been customary in the best investigated normal barometers to fill the tubes as carefully as possible, and then determine the amount of gas in the vacuum by means of the Arago method already referred to. That is, to measure the height of the mercury column when the mercury is low in the main tube and the length of the vacuum space is several inches, and then make a reading when the mercury has been raised in the tube until the vacuum space has been reduced to very small dimensions. The difference of the two readings compared with the dimensions of the vacuum space in the two instances, permits a determination to be made of the pressure of the gas which is to be applied to the actual readings of the instrument in order to reduce them to the case of an actual vacuum. For one of the normal barometers at the International Bureau of Weights and Measures at Sèvres, the reading of the normal barometer must be corrected by +0·13 mm.

to allow for the pressure of gas in the vacuum tube. The St. Petersburg normal requires a correction of about 0·06 mm. for the same purposes. The amount of gas in the vacuum tube depends principally on care in filling.

The best method for accomplishing this last is the one used by Wild at St. Petersburg, and also adopted at Sèvres. In the purification of mercury by the Weinhold process, it is distilled directly into the barometer tube, after the tube (and the system of tubes) has been exhausted of air as far as can be done by use of a mercurial air pump.[1]

Wild mentions the fact that in 1874 he used a Weinhold's distilling apparatus for filling barometer tubes. In 1883 I found this was still in use, and giving excellent results, with almost no danger to the barometer tube. The drawing given here (Fig. 30) is from a rough sketch I made of the apparatus, and is merely intended to give an idea of its shape and general appearance. It is drawn only approximately to scale, and shows the system of tubes emptied of air. All of that part to the left of the point P pertains to the mercurial air pump. A is the reservoir of mercury to supply the air pump, and the mercury flows into the tube C by way of the small hole E, which flow can be regulated by the handle B which moves the cover of the hole E. The mercury falls through the tube H into L and passes out through M into N, from which it is forced back into A again. For expediting matters, the tube G is used (G is shorter than thirty inches), and I and K are filled with mercury, which is drawn up through G and passes over into L by way of H.

[1] See Wild's monograph on barometers in the Russian *Repertorium fur Meteorologie*, Band III. p. 145.

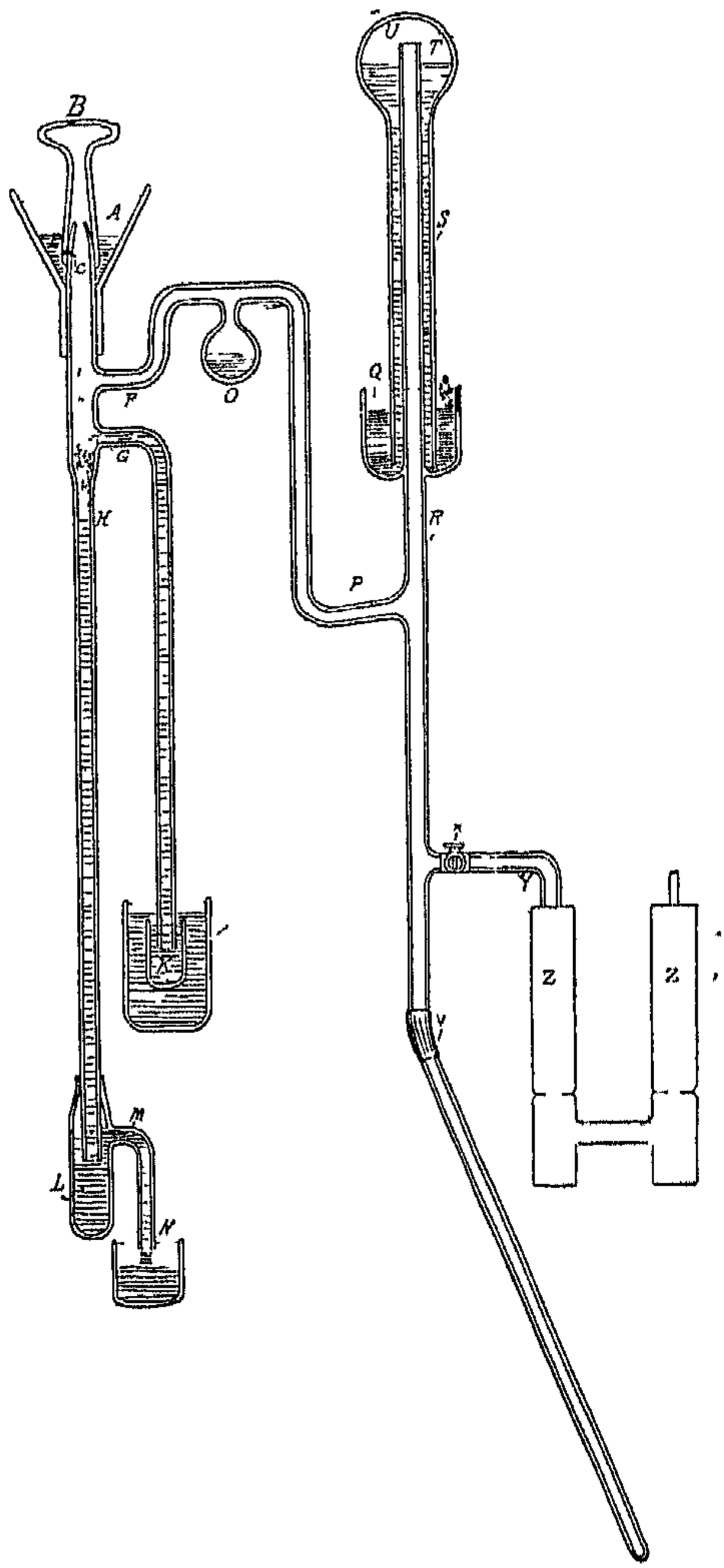


FIG. 30.

The mercury to be distilled and put into the barometer tube is poured into Q (having been first washed in acids, &c.). W is the barometer tube to be filled, and V is a short piece of unvulcanized rubber connecting W with the long glass tube R, the joints being sealed with sealing-wax. ZZ is an arrangement for drying the air, *x* is a stop-cock, R is a long tube running from *x* up through Q and inside of the tube S into T where it has an opening. NS is a tube passing into the mercury in Q, and has a large bulb (perhaps five or six inches in diameter) T at the top. The gas burner for heating the mercury is just below T, and encircles S. In operation, pour some mercury into A, K, and I, and the mercury to be distilled into Q. Open *x*, and by turning or raising B form a connection between A and C by E: the mercury now flows through C into L and carries air with it, causing more air to enter the system of tubes ZZ, where it is dried. After this has been continued until the original air has been expelled from the tubes, the cock *x* is closed (alternately opening and closing this during the operation just described is best). When *x* is closed the air of the system becomes rarified by the action of the air pump, and the mercury in Q rises into S (around R) up into T, but not up to *u*. The mercury also flows from K up into G and over into H. When the air has been thoroughly exhausted from the system of tubes, then the burner under T is lighted, and the mercury in T will distill from T over into *u*, and fall through the cooling chamber R down into the barometer tube, where any vapour that may pass into P will condense into O. When W is filled with the pure mercury then the flame is extinguished and *x* is

turned, and air let into the system. The barometer tube is then taken off by melting the wax, and is then ready for use. Paraffin is a good material for covering joints, and does not soil the mercury During the operation of filling, the bubbles must be forced out of the tube by means of a Bunsen burner, that can be passed along the barometer tube and directed on to the place where any bubble is seen.

In filling a barometer of the Wild-Fuess control pattern having a tube of eleven millimetres diameter, about 375 grammes $\pm$25 grammes of mercury is used; and it must not be forgotten to wash the mercury carefully in acid or chloride of iron before using. It is better to distil a little mercury into another tube first, so that any oxide of mercury that may be present can pass off, and then change to the one to be filled. This is unnecessary when the apparatus is in constant use for distilling. It takes from fifteen to thirty minutes to get the air out of the tube, and the accomplishment of this can be recognised by the noisy action of the mercury in the air pump.

In the Helsingfors normal barometer, Sundell has for filling the tubes the arrangement shown in Fig. 29. The upper chamber B is connected with a drying vessel T, which contains phosphoric anhydric acid, and which in turn connects with the mercurial air pump LL′. The spherical bulbs LL′ have a capacity of 193 cubic centimeters. Pure mercury is poured into the lower chamber B, and the mercury air pump is put into operation by filling the lower bulb L′ with mercury and then raising it up until the mercury rises up into L, fills it (which necessitates the addition of more mercury to L′), and overflows into the tube shown on the left. Now

lower L′ until the mercury in the tube connecting L and L′ is a little below the tube connecting it with the barometer tube. Pour mercury into Z and it will pass from the narrow tube into L and downwards. The circulation of the mercury is kept up by adding mercury to Z, and, I suppose, by lowering L′, as there is no conveniently arranged overflow tube joined to L′. The air is gradually exhausted from the barometer tube by being carried out through L′, and as gradually the mercury rises from lower B up through R and flows out through O into upper B until the vacuum is as complete as possible; L′ is then lowered and the mercury assumes the position shown in the Fig. 29. Sundell claims that the gas pressure in the vacuum can be reduced to 0·005 mm. by this process.

9. Errors of Capillarity. Very little reliance can be placed on capillary corrections for small tubes, and in order to reduce this capillary correction to less than ·01 mm., the barometer tube must be at least 24 mm. (about 1 inch) in diameter, and just before each observation the mercury must be made to rise in the two legs of the tube. In the normals at Helsingfors (Fig. 29) and at Pawlowsk the inner diameter of the mercury chambers at the place of reading is about 40 millimeters.

The mercury is made to rise in most of the barometers of the Wild form by raising the accessory connected reservoir M (Fig 28), but Sundell has a plunger N (Fig. 29) which is lowered into the reservoir by means of a screw motion.

10. Errors of the methods of reading the height of the mercury column. In order to keep the error of reading down to the limit fixed upon (·01 mm.), the

utmost precautions must be taken in the whole detail of making the readings. Up to about 1873, there had never been a barometer that had been read with this desired accuracy. The various errors in reading may be arranged systematically as follows :—

a. The readings must take place in the same way for both mercury surfaces, that is, both surfaces must be as nearly alike as possible, both as regards form and method of reading; and with any arrangement, such as the Fortin, where the top and bottom readings are made differently, the desired accuracy could not be attained. This form is shown in Regnault's barometer (Fig. 23) where the mercury surface at A is observed, and then by means of the cathetometer telescope the top of the adjustable screw M (of known length) is also observed.

The modern method of bending the tube of a syphon barometer, so that the lower mercury surface is directly beneath the upper one, gives two surfaces as nearly alike as can be obtained. This is best seen in Figs. 28 and 29, and also 31.

b. The mercury must be raised in both tubes just before the reading is made, and this is done by having another tube (of rubber) leading from the bend in the syphon to a small mercury reservoir (Fig. 31), that can be raised or lowered at will, thus changing the height of the mercury in the two legs of the syphon. This is also necessary for getting rid of capillary errors as already described.

c. With the ordinary form of cathetometer for reading the height of the mercury, only the most skilful observing and careful adjustment could give the desired accuracy, because the reading microscope must be at a little distance from the barometer tube

on account of changes due to heat from the body. So, in all modern barometers the cathetometer scale is suspended close to the barometer tube, and two reading microscopes are mounted on a vertical stand at a distance of several feet from the scale and barometer. When a reading is to be made, the cross hairs of the telescopes are set on the upper and lower mercury surfaces, and then the microscope stand is turned slightly around the vertical axis, and the telescopes pointed to the scale and the divisions read off, the fractions of the divisions being read by means of micrometers on the microscopes. In Fig. 27 the brass scale RR is shown at the right, the old or less accurate form being well shown in Fig. 23.

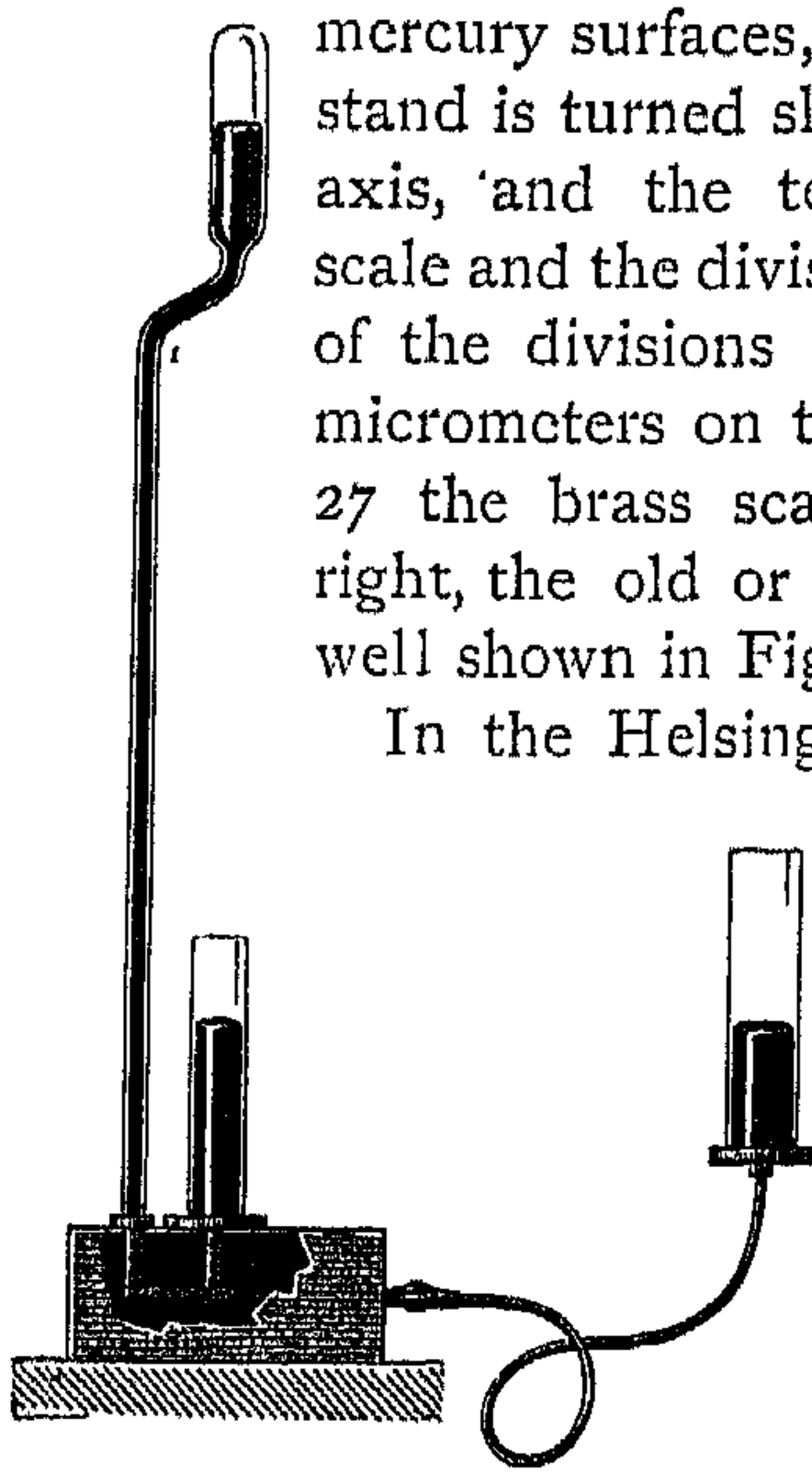


FIG. 31.

In the Helsingfors barometer (Fig. 29) the scale divisions are ruled directly on the glass tube SSSS., and are read by means of the microscope MM. A similar method, proposed by Thiesen, is (I believe) adopted for the new Pawlowsk normal barometer. This is mainly, however, to aid in reducing the error next to be mentioned.

d. It is important to be sure that the reading of the true mercury surface is obtained. In order to accomplish this, various forms of illumination have been proposed, and a steady improvement has been made. At first a piece of white paper, or other

light reflector, was put behind the barometer tube, and the dark mercury surface projected against this background was observed with considerable accuracy. In the Wild normal barometer (see *g* and *g'* at the right in Fig. 25) there is a plate, which is half black and half white, behind the mercury column. For a telescope reading the upper half is black and the lower half white, and the dividing line is brought just above the mercury surface, so that the top of it is projected against the white surface, and the black surface is just above, for contrast. For a microscope reading the white and black surfaces are reversed in position. In the Fuess normal barometer of *1881* (see Fig. 26) at the Normal Standards Office, Berlin, we find a different method of illumination by means of reflectors. Here the barometer is in a dark underground chamber, and gas illumination alone is used. The rays of light, which are rendered parallel by interposing a lens, strike the mirror S, and are reflected upwards to mirrors on the collimators C_1 C_2, and are by them directed through the collimator to those points to be read by the microscopes. Behind the mercury surface to be observed are double reflectors (see S_1 S_2 at N) with a space between. The left side of the front opening of the collimator is partially closed by a cover with sharp horizontal edge, and which has a fine vertical motion by means of a screw. The light from the right half of the collimator falls on the scale to be read, but that from the left half falls first on the reflector S_1, is reflected to S_2, and finally over the top of the mercury surface at N back to the microscope. The image of the sharp horizontal edge of the partial cover on the collimator is seen in the centre of the mercury surface after the double reflec-

tion, and is sharply defined in the reading microscope. This is essentially the same as the black and white background of the Wild barometer (Fig. 25), but is more convenient and probably more accurate. Perhaps the best method, however, is that proposed by Marek and used in reading one of the normal barometers at the International Bureau of Weights and Measures at Sèvres (Fig. 27). At least as early as 1873 Wild used a method of making an accurate reading of the mercury height in the open tube, by causing a needle to descend the middle of it, until the point almost touched the mercury. (I have recently seen a reference to this as Pernet's method.) In this way a sharp image of this needle point will be seen in the mercury, and if a setting is made of the microscope cross wires on this reflected image, and then on the point of the needle itself, the mean of the two readings will give the height of the mercury surface with great accuracy. (Any one can perform this experiment by taking a thin glass bottle an inch in diameter and pouring a little clean mercury into it; then insert a needle from the top, and place the eye on a level with the mercury surface. Both the needle point and its reflected image can be seen with great distinctness.) This is not so easily done in the closed tube, but Marek has found and applied a method. By means of a collimator, as shown at HH on the right in Fig. 27, the image of the cross wires is formed in the middle of the barometer tube just above the mercury surface. This image and the reflection as seen in the mercury are both observed, and the mean of the two is taken as the surface of the mercury. This is done for both the upper and lower mercury surfaces. The error of a reading is about

·0015 mm., as found by Marek; this is far within the necessary limits, and the method is so simple that it will probably be used very extensively in the future. Thiesen has proposed another modification of this principle. He uses a wide barometer tube, so that the observing mercury surface will be about 40 mm. in diameter, and a pencil point or other sharply defined object is placed outside the tube, but near it, where this object observed directly and also its image reflected in the mercury can be used as points of observation; and the graduations can be on the barometer tube, thus greatly simplifying the manipulation of the normal barometer. This method has been applied by Sundell, and can be seen in Fig. 29, where the scale divisions are shown between SS and SS opposite the reading microscope MM. (It must be remembered that Fig. 29 is merely a sketch of the plan of the actual instrument.) Wild also mentions the application of Thiesen's method to the new normal barometer at Pawlowsk. For an illuminating power the electric light is undoubtedly the best.

In the case of the Kew normal barometer (Fig. 24) there are two steel pointers about two inches long, and one has the edge curved like the meniscus in the barometer tube. The lower end is in one case a knife-edge rounded like the upper meniscus, and in the other a point; both are brought in contact with their reflections. The mercury is agitated in the tube by rotating the barometer and so producing a slight vertical movement by centrifugal action in the cistern, and the result of this is assumed to be the equivalent of the Fortin cistern action.

e. Considerable attention has also been given to

another error which may enter into a barometer reading and which is due to the influence of the wind. If a barometer is placed to the leeward or windward side of an obstacle, its reading will be slightly decreased in the former case and increased in the latter. Theory gives unsatisfactory values of the amounts of this error. Abbe supplies the following theoretical table of increase of pressure on the windward side:—

Wind. Miles per hour	20	40	60	80	120
Increase of barometric pressure in inches...	0·015	0·061	0·138	0·383	0·548

In order to determine the amount of this error within a room, experiments were made on Mount Washington by the United States Signal Service in 1886, and the following table shows the results; but it must be remarked that a barometer could not be read with the greatest accuracy in such a high wind on account of the unavoidable jarring of the building, and consequently of the instrument:—

Date.	WIND.			EFFECT ON BAROMETER OF OPENING THE—				
	Direction.	Average velocity (miles per hour).	Gusts (miles per hour).	Chimney flue.	Leeward window.		Windward window.	
				Effect.	Aspect of Window.	Effect.	Aspect of Window.	Effect.
1886.				Inch.		Inch.		Inch.
Sept. 29	W.N.W.	65	85	−0·005	E.N.E.	−0·014	W.S.W.	+0·029
Sept. 29	W.N.W.	65	85	+0·003	E.N.E.	−0·008	W.S.W.	+0·045
Oct. 15	W.S.W.	70	85	+0·006	E.N.E.	−0·011	W.S.W.	+0·045
Oct. 21	W.S.W.	65	80	+0·003	E.N.E.	−0·018	W.S.W.	+0·062
Oct. 22	N.N.W.	70	90	−0·006	E.N.E.	−0·025	W.S.W.	+0·032

Comparison of Standard or Normal Barometers,—

Since the establishment of truly normal barometers, it has become very important that they should be compared with each other, and that the older standard barometers of various countries should be compared with them. Since the report of Professor Neumayer (of Hamburg), there have been not only numerous comparisons between isolated standards, made during the travels of individual meteorologists, but there have also been several series of comparisons of international standards made by persons who have carried portable barometers from place to place with the aim of determining as nearly as possible the differences existing between these standards and so-called normal barometers. The results obtained in this work are far from satisfactory, and show very clearly that Wild was right when he urged that each meteorological service must have its own thoroughly investigated normal barometer which will furnish normal readings at any time; and that it will not do, as is commonly supposed, to use an ordinary barometer as a standard, on the strength of its having been compared either directly or indirectly with a true normal barometer located at some distant place.

Hellmann, of Berlin, has at various times compared many of the European standard barometers, but as his results have not all been collected and reduced to any one system, they have not been included in the table given here. In 1881 Chistoni, of Rome, carried a portable barometer of good construction to various cities of Europe, and made comparisons with standard barometers there, but we do not understand that the journey was made especially for the purpose of comparing these instruments. In 1883 F. Waldo, then of Washington, U.S., also made a comparison of various

standards, not only in Europe but later also in America, in which from one to four portable barometers of the Fuess-Wild (Fig. 20) pattern were used. In 1886 Sundell, of Helsingfors, by means of a single barometer (see Fig. 21), which was carried from station to station with the tube emptied of mercury, made the most extensive series of comparisons yet undertaken. I cannot refrain from expressing regret that he did not also carry a barometer of the usual construction, the tube of which should remain filled during the journey. In 1887 Brounow, of St. Petersburg, also made, by means of a single barometer, a long series of comparisons of various European barometric standards. The results of these four separate series of comparisons, which may be said to give the present state of our knowledge, are to be found in the table on page 95. The figure 1 after the name of the barometer mentioned, shows that the comparison was not made directly with this normal barometer, but by means of a second instrument adjacent to it, the relation of which to the normal was known.

The bracketed numbers after the results given for Waldo's observations denote the number of the portable barometers used in the comparison; in this series the observations at Berlin, and a portion of those at St. Petersburg, were not made by Waldo, but entirely by meteorologists at those places. In the last column are given the corrections to some of the various barometers, as applied at the institutions where they are located, in order to reduce their barometer readings to some adopted standard. These are as given by Sundell for the date of 1886 or 1887, except in the case of Toronto, Canada, which was obtained by Waldo in 1883; and in the results given

TABLE OF RESULTS OF INTERNATIONAL BAROMETER COMPARISONS.

Ref. No.	Place of Comparison	Institution where the Comparison was made.	Designation of the Barometer	Correction to Reduce to the Normal Barometer at St. Petersburg according to				Corrections applied to actual readings of the local standard to obtain the adopted standard
				Chistoni. 1881.	Waldo. 1883	Sundell. 1886.	Brounow. 1887.	
				mm	*mm.*	*mm.*	*mm.*	*mm.*
1.	Paris.	Central Meteorological Bureau.	Regnault 1.	—0, 04	0, 05 [2]	0, 16	0, 11	
2	,,	Astronomical Observatory.	Fortin		0, 10 [2]		—	
3.	,,	International Bureau of Weights and Measures (Sèvres).	Wild-Pernet 1.	—	0, 24 [2]	—		
			Marek 1.	—	0, 20 [2]	0, 21	0, 10	
		,,	Chappuis 1.	—		0, 32	—	
4.	Berlin.	Meteorological Institute.	Fuess, No. 76	—	—0, 04 [1]	0, 02	—0, 02	
5.	,,	Normal Standards Commission	Greiner, No. 320.	1, 16	—			
		,,	Normal Barometer 1.	—	0, 25 [3]	0, 05		
6	Vienna.	Central Meteorological Institute.	Pistor, No. 279.	0, 17	0, 08 [3]	0·13	0, 11	
7.	Hamburg.	Deutsche Seewarte.	Normal Barometer 1.	0, 11	0, 04 [4]	0, 14	0, 07	
8	Kew.	Observatory.	Standard Barometer.	—0, 01	0, 10 [2]	0, 05		
9.	Rome.	Observatory.	Deluil, No 6.	—0, 02			—	
10	Stockholm.	Academy of Sciences.	Pistor and Martins, No. 579.	0, 00		0, 06	—	
		,,						
11.	Christiania.	Meteorological Institute.	Wild-Fuess, No. 214.		—	0, 05	—	+·12
12.	Copenhagen.	Meteorological Institute.	Junger and Co	—0, 11	—		—	
		,,	Wild-Fuess, No. 87.			0, 28		·15
13	Brussels	Astronomical Observatory.	Fortin-Tonnelot.		—	0, 17	0, 18	
14.	Utrecht.	Meteorological Institute.	Becker.		—	0, 44	0, 32	
15.	Zurich.	Swiss Central Office.	Wild Fuess, No. 168.			0, 01	0, 16	+·10
		,,	Fuess, Syphon bar.			0 05		·08
16.	Munich.	Meteorological Institute.	Wild-Fuess, No. 43.	—	—	0, 08	—	
		,,	Wild-Fuess, No. 4.		—	0, 00	—	
17.	Chemnitz.	Meteorological Institute.	Wild Fuess, No. 163.			0, 13	—	+12
18.	Helsingfors.	Laboratory of Professor Sundell, Meteorological Institute.	Normal Barometer.	—	—	0, 01	—	
			Wild Fuess, No. 129	—		0, 18		—·18
		,,	Casella, No. 1155.		—	—0, 08		·05
		,,	Girgensohn.			0·18	—	·60
19.	Washington.	Signal Service.	Standard.	—	0·18 [4]			
20.	Toronto.	Canada Meteor. Observatory.	Newman 33.		0·09 [1]			—·18

in the present table these corrections have been applied. This table is as compiled by Schönrock, of St. Petersburg, with some slight additions and a single correction. The negative sign indicates that the amount of the correction is to be subtracted. Where no sign is given a positive sign is to be understood.

It is seen from this table of recent intercomparisons of standard barometers that the results obtained are quite contradictory. In 1889 Schonrock attempted to find out the causes of these discrepancies, but was able to offer only very general possible explanations. In 1890 Koppen made a more critical study of this same material, with somewhat better success; but even he was unable to find any definite reasons for the great differences existing for the individual barometers. He finds, however, that if a correction of −0·09 mm. is applied to Waldo's observations as referred to the St. Petersburg normal, and a correction of +0·10 mm. to Sundell's, and −0·06 mm. to Brounow's observations, then a much better agreement is found to exist between the comparisons. It may be added that Wild finds that the new normal at Pawlowsk practically agrees with the St. Petersburg normal; and as late as 1889 Schonrock says that at that date these two normals and Sundell's normal at Helsingfors were the only ones whose errors had been thoroughly investigated. Speaking generally, the following causes may be assigned as accounting for some of the discrepancies of the results given in the previous table:

Sudden changes may occur in the barometer readings, due to displacements of some portions of the apparatus.

Gradual changes undoubtedly occur in all barometers with greater or less degree of slowness.

Where an intermediate sub-standard is used in the comparison, its readings may change before it is compared with the normal.

Insufficient number of days of comparison, and variation in the height of the barometer.

Differences in illumination undoubtedly exist for the various comparisons, due not only to the diurnal variations of light, but also to the fact that the portable barometers have not been mounted in exactly the same place and position in each comparison at any one observatory. A uniform artificial illumination is certainly to be recommended in all future comparisons of this kind.

Insufficient investigation of the normal barometers prevents an invariable normal reading being obtained at the different times.

Fluctuations due to capillary changes in all barometers with tubes having small bores would undoubtedly account for differences as large as those found in most of the comparisons that were made, and the careful experiments of Schönrock about to be mentioned will show the folly of placing any reliance on the usually applied tables of capillary corrections for tubes of various bores.

Capillary Action in Barometer Tubes.—In the case of barometer tubes in which there exists a capillary depression, there are changes occurring in the form and height of the meniscus, which materially change the readings of the instrument. Wiebe, Thiesen, and others have made some investigations on the absolute amount of these changes, but the question needs much more notice than has yet

been given to it. While this change is due mainly to the tube becoming fouled, yet other items also must be taken into consideration. Schönrock has made some very interesting comparative experiments on tubes having different bores, using the 25·2 mm. diameter barometer tube of the St. Petersburg normal as a standard. He finds that:

1. For the tube 12·8 mm. in diameter under different circumstances of pure and impure (oxidized) mercury the depression varied from 0·23 mm. to 0·41 mm. For comparatively dry air over the meniscus the variation was considerable, and the greatest readings were obtained; but when the air was about saturated with moisture regular readings of about ·33 mm. were obtained. With this same bore of tube, and for clear mercury and dry air above, a depression of 0·39 mm. gave a meniscus of 1·71 mm. height when the pure mercury was slowly raised in the tube, and of 1·44 when it was raised rapidly.

2. For the tube of 11·2 mm. bore, for pure mercury and dry air above, the depression varied between 0·45 and 0·52 mm., with an average depression of 0·49 mm.; for moist air above the mercury the variation was between 0·43 and 0·47 mm., average 0·45 mm. The depression varied between 0·34 and 0·52 mm. in all the experiments. The height of the meniscus was 1·36 mm. for a rapid rise, and 1·45 mm. for a slow rise for pure mercury.

3. For a tube 8·4 mm. bore, the depression varied between 0·69 and 0·83 mm., with average depression, 0·78 mm. for dry air above the mercury, and 0·71 mm. for moist air; the greatest extremes were 0·56 and 0·85 mm. The height of the meniscus was 1·25 mm. for a slow rise, and 1·05 mm. for a rapid rise of the mercury.

4. For a tube 6·4 mm. bore, the variation of depression for dry air above, was between 1·13 and 1·25 mm., with the average depression 1·18 mm.; for moist air, between 0·91 and 1·09 mm., with the average 1·00 mm. The greatest extremes of depression found were 0·91 and 1·34 mm. The height of the meniscus was 1·11 mm. for a slow rise, and 0·80 mm. for a rapid rise.

Such differences as these show that no reliance whatever can be made on the usually published corrections for the capillarity of small tubes, if one wishes to obtain accurate results.

The Aneroid Barometer.—Concerning this instrument I will only briefly remark that it is chiefly useful as a house barometer, and should never be relied on for scientific purposes where great accuracy is required. It is a very delicate instrument, and, being subject to sudden changes, can only be used with confidence when it can frequently be compared with a mercurial barometer. Before an aneroid can be used at all, it must be carefully compared with a standard mercurial barometer at all of the various temperatures and pressures to which it may be subjected in its use. The effects of the changes of temperature vary for different instruments. Wild gives the following changes with time, in the corrections of an aneroid by Goldschmid: April, 1869, correction = −15·13 mm.; December, 1873, correction = −27·16 mm. Another instrument by the same maker changed its correction only 2·5 mm. in three years.

A thoroughly investigated aneroid of the best construction can be relied on to within 0·2 mm., only when frequently compared, and when kept in one position. In travelling, the readings of an aneroid may be considerably altered, and it is impossible to fix a limit

to its inaccuracy. The instrument must always be gently tapped with the finger before a reading is made, and it is also necessary to observe the temperature and apply a corresponding correction just as for a mercurial barometer, but the same table of corrections does not apply to all aneroids of the same construction, as is the case for mercurial barometers.

The Thermo-Barometer.—If a thermometer is carried to an elevation above the sea-level it will be found that water will boil at a lower temperature than at sea-level; this is due to the decrease in atmospheric pressure. The law of this change in the temperature of free steam with the change of pressure is known, and if this temperature can be accurately observed the atmospheric pressure can be computed. In order to determine the pressure within $\pm 0{\cdot}1$ mm. the error of the temperature determination must not exceed $\pm {\cdot}004^\circ$ C., and any such accuracy is simply impossible However, thermometers are now constructed of Jena glass, by means of which the pressure can be determined within, say, 0·3 of a millimeter with portable apparatus in the laboratory, but it seems doubtful if this accuracy can be attained during a journey. This boiling-point apparatus is, however, far preferable to an aneroid barometer when no mercurial barometer is available for comparison. The general precautions and methods used for determining the boiling point on a standard mercurial thermometer are applicable to the manipulation of this instrument.

Barographs.—It has long been considered desirable to record the readings of a barometer automatically, and in accomplishing this many different forms of mechanical construction have come into use. These

can be divided into the following classes: 1. The purely mechanical arrangement, which has a float in the open leg of the barometer, and the motions of this float are recorded. 2. The electrical method, in which a platinum wire is made to descend the open leg of the tube, and when this wire, which is a pole of a battery, reaches the mercury surface, a circuit is closed by having the other pole already touching the mercury. The varying distance the wire moves from a certain point in order to reach the mercury surface is measured, and the successive measurements locate the barometric curve. 3. The photographic method, by which the height of the mercury in the closed leg of the barometer is photographed continuously. 4. The balance barograph, in which the variation of weight of the mercury in the tube is measured when the latter projects into a cistern containing mercury, but is not in rigid contact with the vessel containing the mercury. The barometer tube is suspended from one end of the balance arm, and is counterpoised by a weight on the other end.

There are, perhaps, twenty different constructions of barographs, but they nearly all belong to these four classes, although there have been other forms proposed but not much used. These instruments are of various degrees of accuracy; perhaps the best one being the Sprung balance barograph with sliding weight, constructed by Fuess, of Berlin. The mean deviation of a registration of this instrument from the direct observations on a good ordinary barometer is only $\pm$·04 mm.; and this is about equal in accuracy to the direct comparison of two portable barometers of the highest degree of excellence.

Several other barographs are scarcely inferior in

accuracy to the Sprung form, especially the Wild-Hasler, as used at St. Petersburg, and the Photographic at Kew. Eylert has also succeeded in getting good results from the Fuess barographs of the *Deutsche Seewarte* model. Much depends on the method of reduction of the barogram, however, and the very common method of interpolating the direct recorded readings when compared with those from a mercurial barometer is not sufficient. The barogram is the record traced by the instrument on a sheet of paper.

The Sprung balance barograph is shown in Fig. 32, and with the photographic barograph has the advantage over some other forms that it gives a continuous record of the atmospheric pressure, while most others record it only at stated intervals, as, for instance, every ten minutes.

In the accompanying diagram of Sprung's balance barograph, the barometer tube B is suspended from the one arm (on the right) of the balance, and is counterpoised by the weight *g* and various minor accessories attached to the other arm. The barometer tube remains practically stationary, and when the changing pressure of the air varies the force acting downward on the barometer tube, the effect is at once counterbalanced by a slight shifting of the wheel R, which rides on the opposite arm of the balance, and whose motion is controlled by the carriage V below it; this latter has attached to it the pencil S which marks on the tablet T its backwards and forwards motion. The tablet T has a uniform vertical slow motion imparted by the clockwork, and the fixed pencil S′ marks on the tablet a straight line which is used as a base line of reference from which to measure distance of the points on the irregular line drawn

by S, and which follows the fluctuations in the barometric pressure.

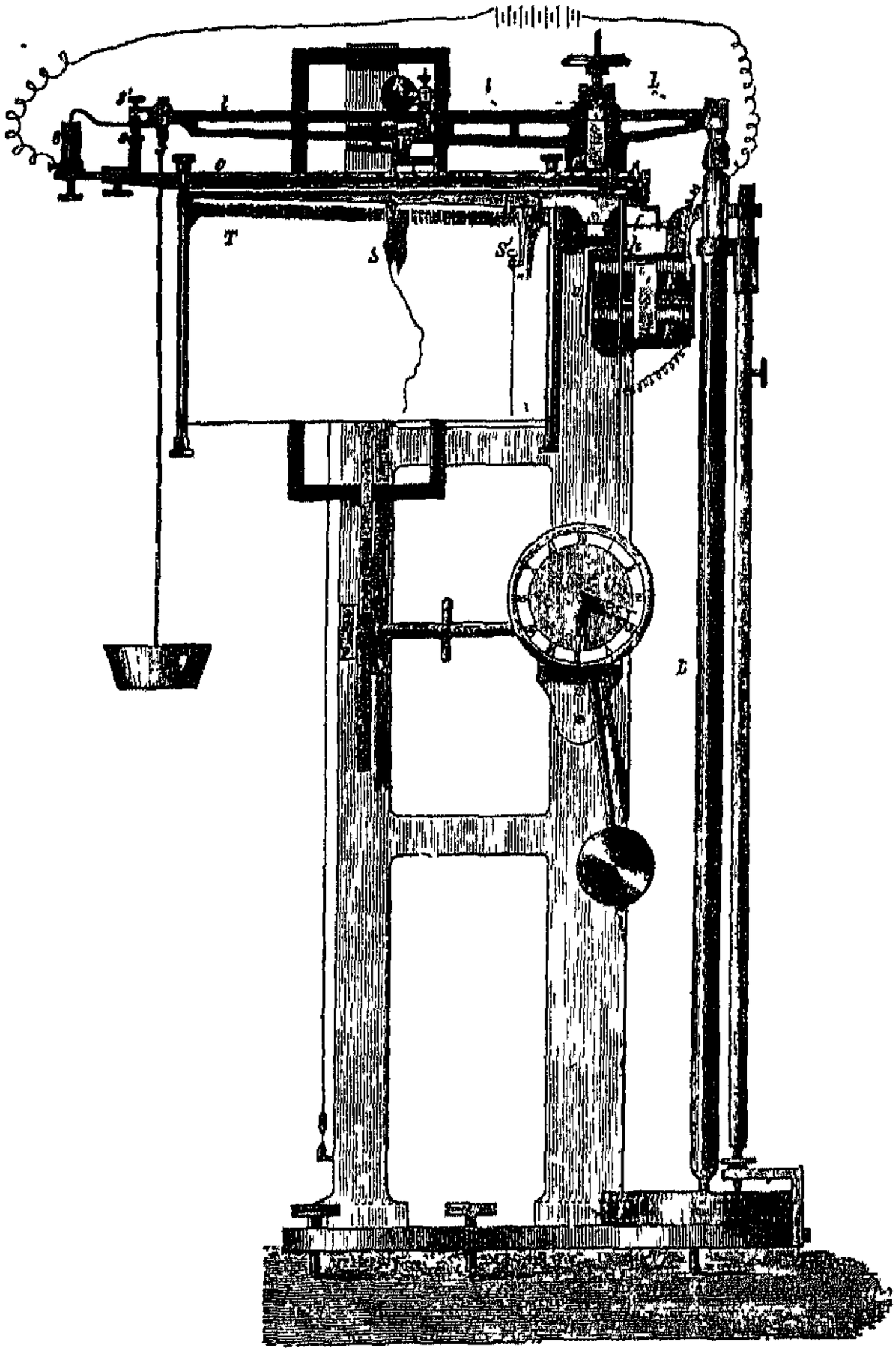


FIG 32.

As Sprung has applied this same principle to making registrations of several of the meteorological

elements, and as the instruments are fast growing in favour, a more detailed statement of the method of operation seems to be necessary here.

The lower end of the barometer B dips into the large mercury cistern F, but it is in contact with no rigid body below the point of suspension on the balance arm. M is merely a parallel reading scale to be used when required, by means of which the height of the mercury in the tube of the barograph may be read as for an ordinary barometer. The vertical rod *t* has a constant rotary motion imparted to it at its lower end by the clockwork, and at the upper end it has a horizontal bevelled wheel, which has a slight horizontal freedom, permitting it to press against either of two vertical levelled wheels which are rigidly attached to the screw CC′ (on the right). When a current is passed through the coils EE, the rod *t* is drawn towards the left by means of the armature *a* and the connection *h*, and the rotary motión of *t* is imparted to the screw CC′ by means of the bevelled wheel on the left; when the current is cut off from the coils EE the spring F draws *t* towards the right, and the contrary motion is imparted to the screw CC′ by means of the bevelled wheel on the right. Let it be assumed that the atmospheric pressure is decreasing, then the left end of the balance which has a slight play between S′ and S descends until a contact is made with the mercury at *e*, when the circuit is closed and the armature *a* draws *t* towards the left, and the screw CC′ is then revolved in a right-hand direction; this causes a motion of the carriage V, which propels the running weight R along the balance beam until the connection at *e* is broken, when the spring *f* is allowed to draw *t* towards the right, which causes the

motion of CC′, and consequently V, R, and S, to be reversed until the current is closed again. By means of this constant, but alternating motion, the equilibrium of the two arms of the balance is maintained within the limit of play at SS′, and yet the carriage V and pencil S are permitted to move laterally in proportion to the amount of change in the barometric pressure. In the Sprung barograph in use at Magdeburg the pencil S moves over a space five times as

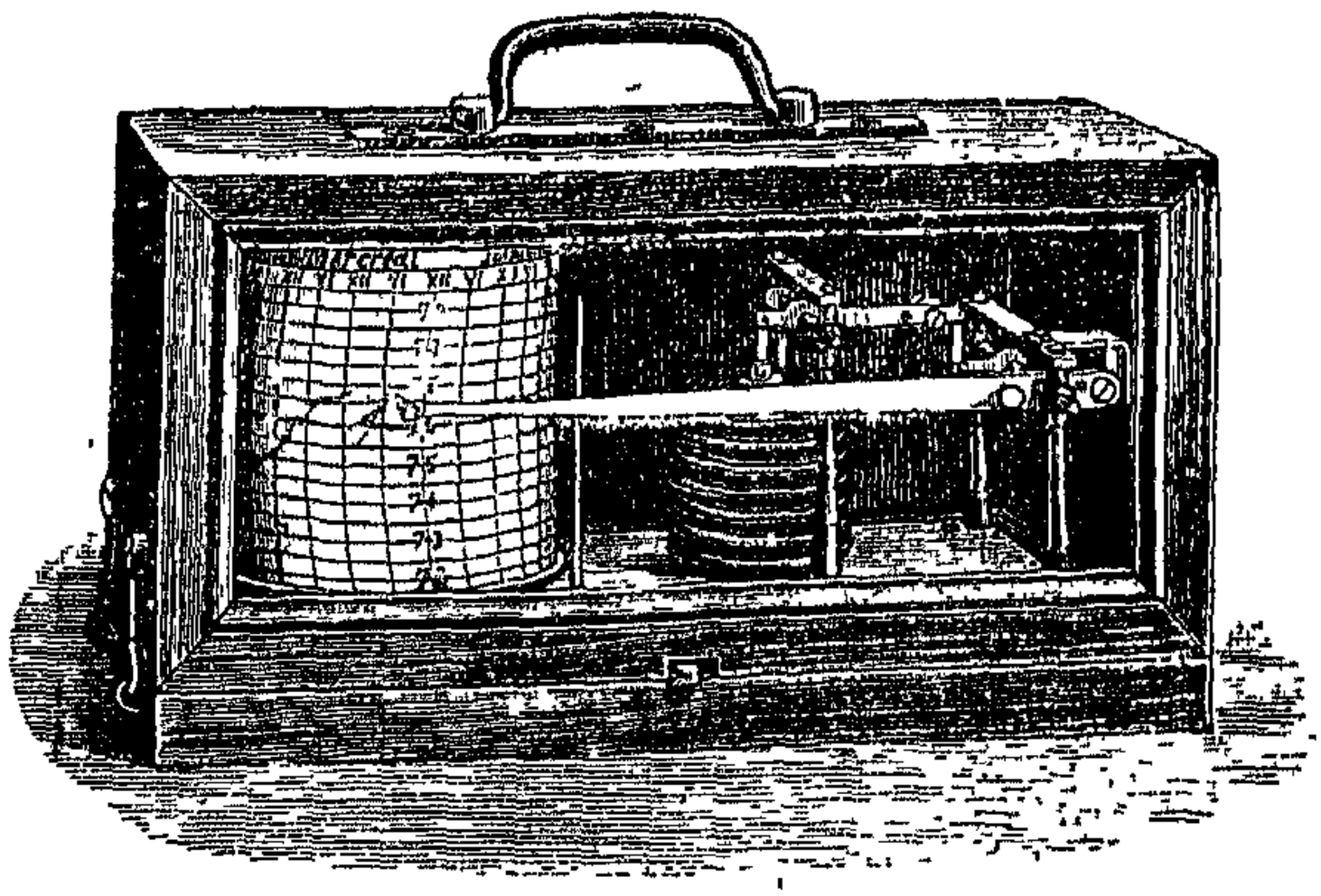


FIG. 33.

great as the change in the height of the mercury column.

The Aneroid Barograph.—The Hipp aneroid barograph is the most widely used at the older European meteorological stations, and the Hottinger form is also used, but at present the newly constructed Richard barograph (Fig. 33) is attracting the most attention from meteorologists. Any of these forms just mentioned will give results within, perhaps, 0·2 mm. when the instruments are compared tri-daily with the

mercurial barometer, and the records of the barogram are submitted to an exhaustive treatment; but at most of the larger observatories where these instruments are in operation, their record is used merely for the interpolation of omissions from the record of the mercurial barograph.

§ 3.—*Apparatus for Measuring the Wind.*

History of Apparatus for Measuring Wind Direction.—The characteristics of the winds from the four points of the compass were made the subject of remark probably as early as 1000 B.C.; and 500 years later the Grecians had added four additional intermediate directions, which were gradually increased to twenty-four directions in still very early times. Twelve points were in more common use, however, and under different names, until the time of Charlemagne, when the intermediate directions were compounded from the four cardinal points, somewhat as in our present nomenclature.

The oldest arrangement, of which we have a knowledge, for accurately locating the directions of the wind is the octagonal Tower of the Winds at Athens (Fig. 34), which was constructed about 100 B.C. At the centre of the roof was placed a wind vane in the form of a triton, whose sceptre always pointed to the wind octant, but was inclined downwards towards the walls, where there were to be found not only the Grecian names of the winds, but also allegorical figures in relief, characterising the wind which came from each direction. M. Terentius Varro also relates that he mounted a wind vane.

The first weather-cock on a church spire is accre-

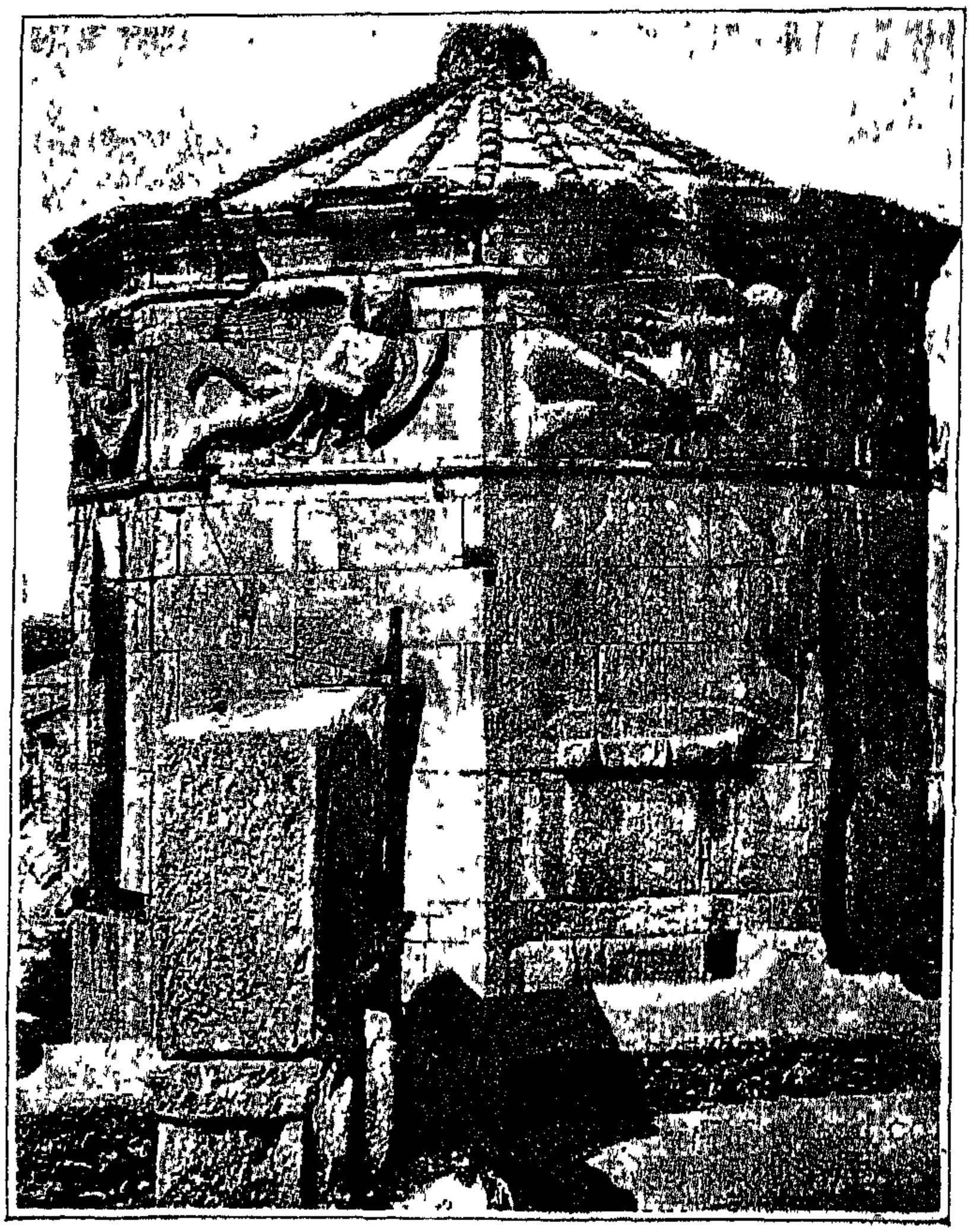


FIG. 34.

dited to a church in Tyrol in the year 820, when Bishop Rampertus von Brixen had it set up. But the first wind vanes of the modern form were those used by the Italian, Egnatio Danti, at Bologna and Florence, in the middle of the sixteenth century, and were of the construction shown in Fig. 35. The regular observation of wind vanes for meteorological purposes was not commenced in Italy until about 1650, however, and in England a few years later. Hellmann has furnished a very interesting account of these early attempts at measuring the wind.

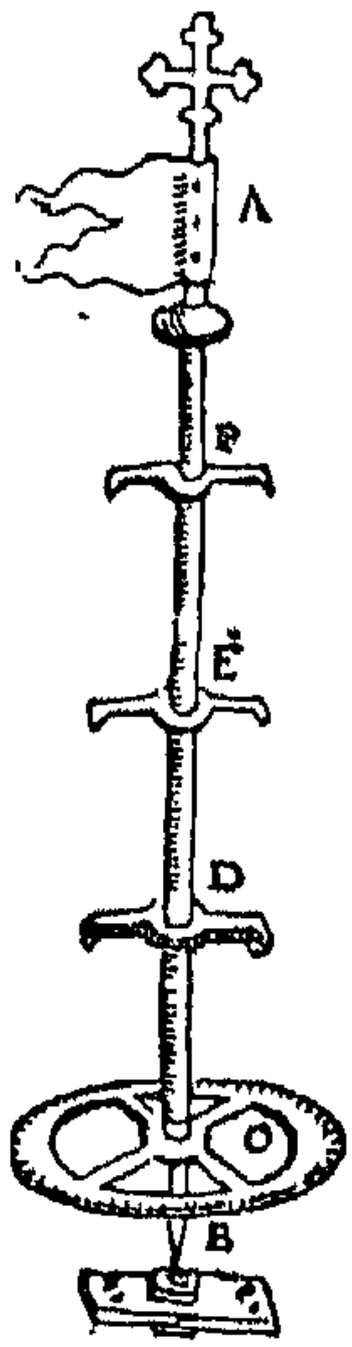


Fig. 35.

It would seem that for so simple an instrument as the arrow vane, now almost universally used, there could be very little said concerning its errors and the theory of its action ; and this is true to a certain extent, but there are some points which require to be considered.

Instead of the vane revolving around the axis on which it is placed, as evenly balanced as possible, it is the custom to attach the vane rigidly to the axis, and let the latter be supported between friction wheels, so that it can turn with as little resistance as possible. The lighter the vane the truer will be its indications ; as, if the vane is too heavy it is not sensitive enough to rapid changes of direction in a light wind, and when once in motion its momentum causes too great a change in a gusty wind. It is desirable also to have attached to the lower end of the axis to which the vane is fixed some sort of damper, which shall prevent the vane from following the quick unsteady changes of the wind

which have only local significance, and yet will allow it to follow the more permanent changes. This can be accomplished by attaching some light paddles to the lower end of the vane rod and immersing them in oil or glycerine, in which they will revolve with the rod.

It has also become the custom to construct the arrow vane with a double or spread tail, after the fashion set by Parrot in 1797. (A small vane with this arrangement is shown in Fig. 37.) By this means the tendency to continual oscillations, with slight sudden shifts of the winds, is much reduced. The best angle of divergence of these tails has not been a subject of agreement among meteorologists. Parrot made the angle of spread 45°, but in the English vanes the angle was made but $22\frac{1}{2}°$ (adopted about 1840); and this last has been quite universally adopted. Curtis has investigated theoretically the action of the single tail and spread tail vanes in steady winds, and finds that for the latter the proper angle of divergence is less than 30° in all cases, but that the best angle will depend on the amount of the shift of wind, and is consequently not assignable until the average amount of shift (in degrees) is known. Comparing, theoretically, the single and spread vanes, Curtis deduces the following relations for steady winds: "The oscillations of both vanes are smaller as the vanes are longer and larger; the spread vane is always more stable than the straight vane, and this advantage in stability is greater for long vanes than for short vanes, and is independent of the wind velocity."

The arrow vane, as already described, shows the horizontal direction of air currents. It is also very desirable to know the vertical inclination of such

currents, but no apparatus for this purpose has come into regular use among meteorologists. Benzenberg, Montigny, Hennessey, Descheverens, and others, have proposed various methods by which this has been attempted; and Cassella makes a very ingenious self-registering double vane, one with a vertical and the other with a horizontal motion, but the difficulty in properly exposing any such instrument, so as to obtain trustworthy results, has not yet been overcome.

Apparatus for Measuring Wind Force or Velocity.—Instruments for measuring the velocity of the wind are usually called anemometers. These may be divided into three general classes: those measuring pressure, rotation, and suction.

The pressure anemometer is usually made according to one of two forms: either a metal plate of small dimensions, and pendulously suspended from its upper edge, is allowed to swing with the wind, and its departure from the vertical is noted; or a plate of, say, a foot square is exposed, fronting the wind, and its pressure is received on springs, the movement of which permits the force to be noted. Many other forms have also been proposed, the earliest and simplest being that in which the air blows into the mouth of a tube which has some manometric attachment to show the variations in pressure.

In the rotation anemometer, a wheel is rotated by the force of the wind; the wheel having some sort of a fan-shaped bladed surface, or consisting of merely four spokes terminating in cups presenting sides of different resistances.

The suction anemometer, which is as yet not much more than a toy, but which has great possibilities for

future usefulness, consists of a tube placed vertically, so that the wind blows across the open mouth, by which action part of the air is drawn out of the tube: the amount of diminution of air pressure in the tube is measured by some delicate contrivances placed within the tube.

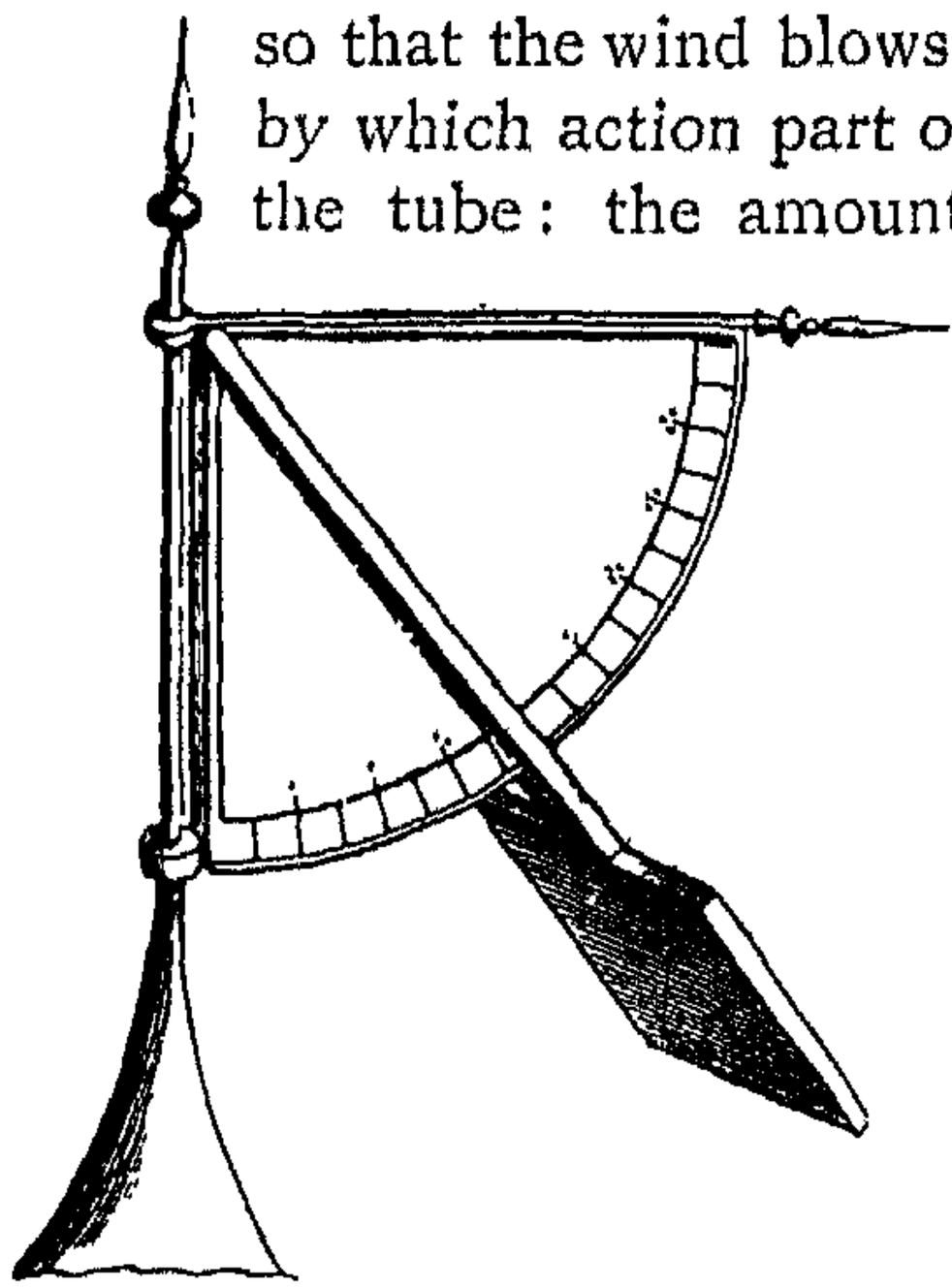


FIG. 36

The pendulum anemometer, on account of its great simplicity and cheapness of construction, is at present used in the Russian Empire, and in some other, principally European, countries. This instrument consists essentially of a freely hanging metal plate suspended on a horizontal axis from above. The wind blowing against this plate causes it to swing out of the normal vertical position, the angle of displacement from the vertical varying with the force of the wind. This instrument was probably first proposed by Hooke, but on account of the uncertainty as to who was the inventor, Abbe recommends that it be

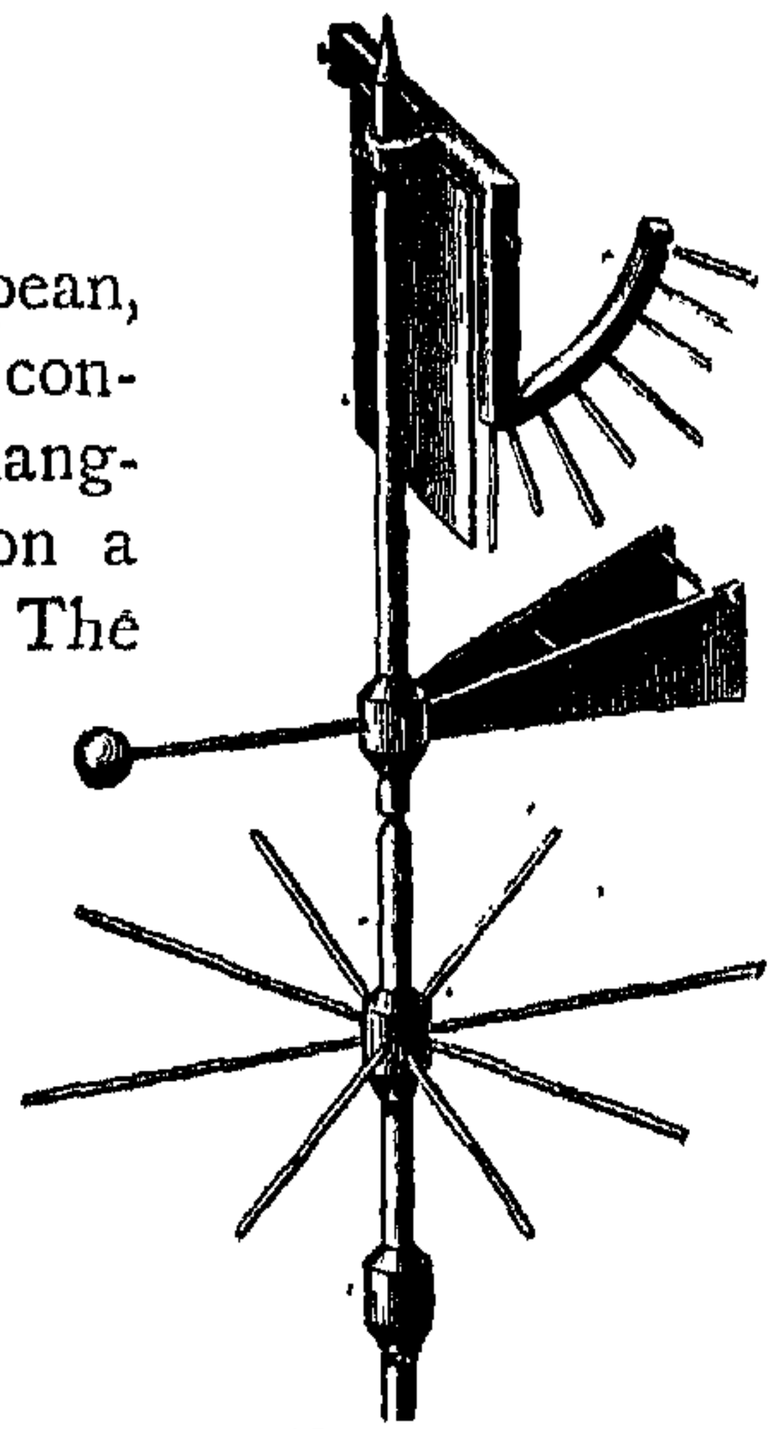


FIG. 37.

called the anemometer of the first meteorological committee of the Royal Society. The first description was published by Hooke in 1667, and its construction is shown in Fig. 36. In its most widely used modern form, as shown in Fig. 37, it is known as the Wild wind force tablet, and is mounted on the same vertical rod as the wind vane, which latter always keeps the plate facing the direction of approach of the wind.

Thiesen has given a theoretical treatment of the action of this instrument, and has introduced into his formula numerical values determined by Dohrandt and himself, by experiments with a wind force tablet mounted on the St. Petersburg Combes' whirling machine.

He deduces the following relation for the Wild tablets of the size 15 × 30 centimeters and a weight of 195 grammes; when the barometer reads 758 mm. and the thermometer 15° C.

Wind Velocity. Meters per Second.	1.	2.	3.	4.	5.	6.	7.
Angle of Displacement from the Vertical, in Degrees.	1°·1	4°·1	9°·2	15°·7	23°·0	31°·0	38°·7
Wind Velocity. Meters per Second.	8.	9.	10.	11.	12.	13.	20.
Angle of Displacement from the Vertical, in Degrees.	45°·7	52°·1	58°·0	62°·5	66°·4	74°·0	80°·5

A change of weight of 1 gramme, in the tablet, will give a change of one-fourth of 1 per cent. in the velocities for the same angle.

At ordinary wind velocities Wild considers that this instrument will furnish results within 10 per cent. of

the truth; but it is not suitable for observing winds of over 20 meters per second velocity, on account of the slight increase in the angle (from the vertical) with a large increase of wind.

The invention of the cup-anemometer is attributed to Edgeworth, who suggested it to Robinson; but in the Royal Ethnographical Museum at Berlin there is an apparatus very similar to it, only it is made of wood and the cups are oval and not complete hemispheres; this came from Thibet, and probably illustrates a form of wind-mill, the small copy being used as a wind-mill god; and in connection with this, Dr. Grünwedel (of the Museum) remarks that in Pallas's *Mongolische Volker*, 1770, there is a diagram of a similar apparatus. The accompanying diagram (Fig. 38) is re-drawn from an illustrated article in the *Century Magazine*, January, 1891, giving an account of Rockhill's journey in Mongolia and Thibet. It is seen that this device, which is undoubtedly very old, is almost the exact model of the modern cup anemometer. We find here also the

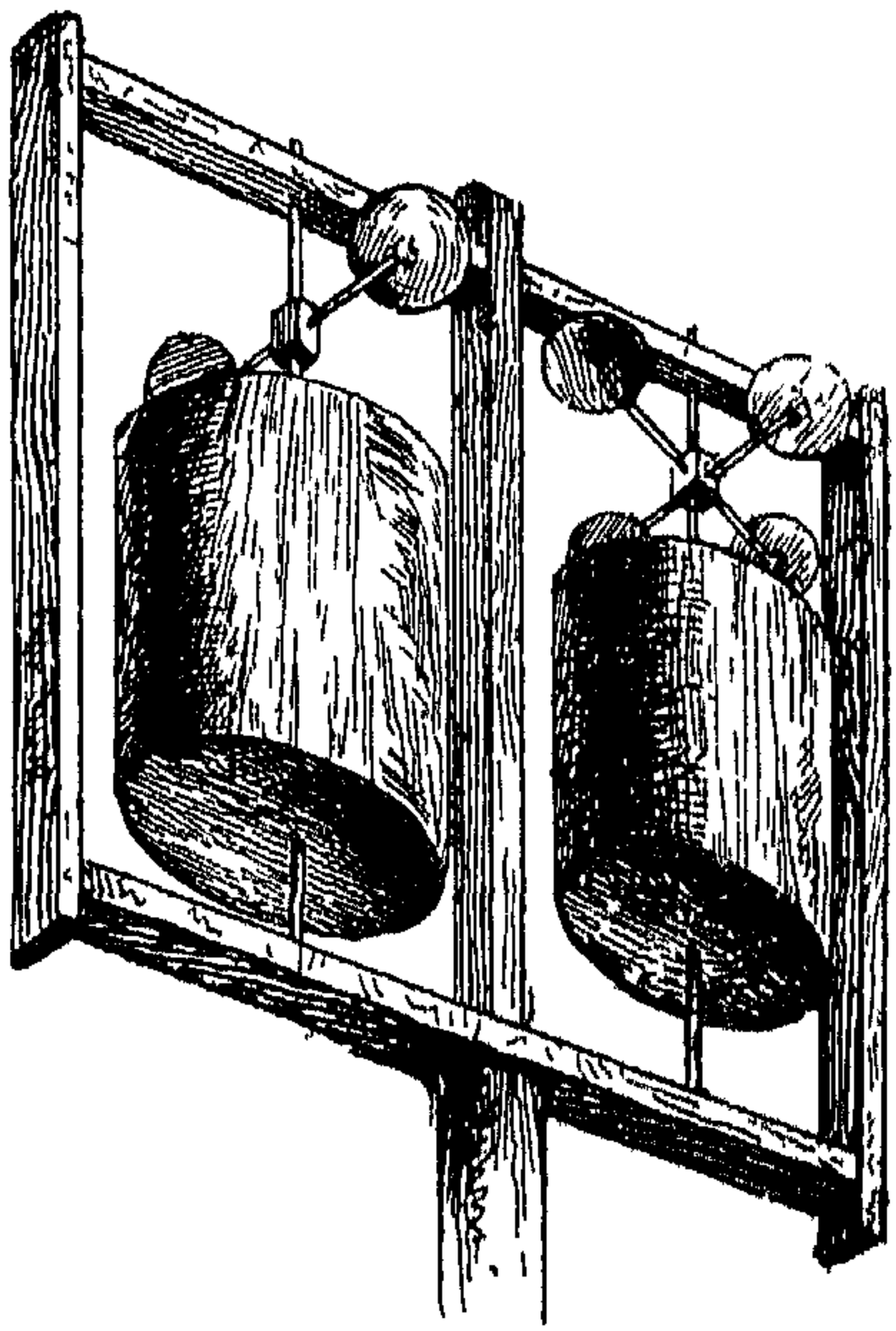


FIG. 38.

suggestion of the double-cup anemometer. So that, although Edgeworth may have used it first as a scientific instrument, and probably re-invented it, the idea of construction is by no means new.

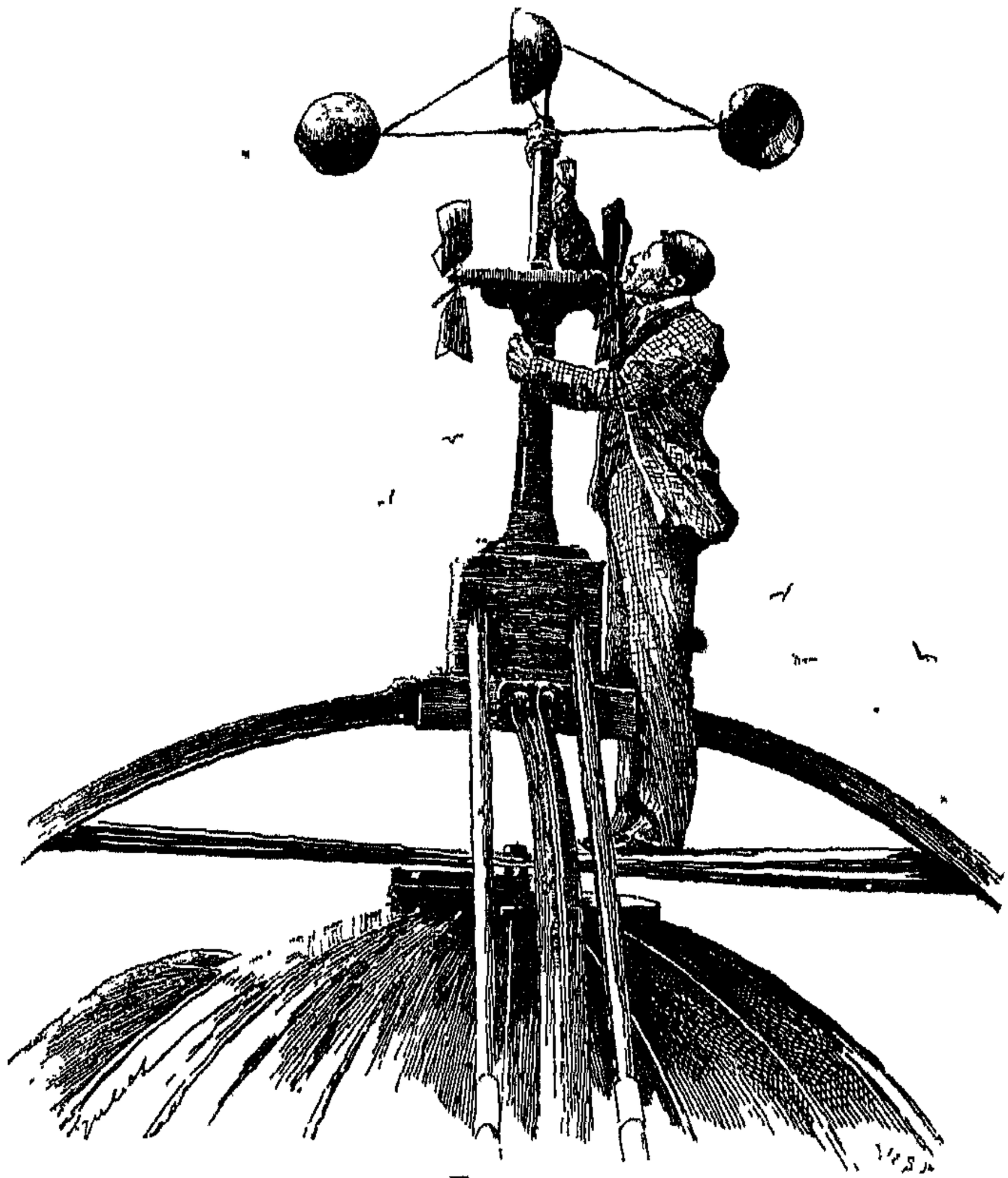


FIG. 39.

The Robinson cup anemometer (Fig. 39) [1] consists of four hemispherical cups of thin metal, attached to

[1] In this illustration the anemometer is shown as mounted on the highest point of the top of a building, as it is usually exposed to the

the extremities of two light metal rods crossing each other at right angles, so that all of the four arms (or spokes) formed by the rods are of the same length. The cups are attached to the arms (as the rods are usually called) in such a manner that they all face the same way—that is, either to the right or to the left. The arms are placed in a horizontal position, and are rigidly attached to a vertical spindle at their intersection. This spindle passes downwards through a hollow stand encircling it, and which supports it, but does not prevent its turning as freely as possible, except that the unavoidable friction will offer a slight resistance. The lower end of the spindle rests in a bearing (where also the friction has been reduced to a minimum), and carries, just above the end, an endless screw encircling it. This endless screw has a small toothed wheel geared into it, so that the wheel is turned by revolving the endless screw. This wheel is geared into a series of wheels, each of which may have an indicator and a dial to show the number of revolutions.

If, now, the instrument is exposed to an air current, the unequal pressure of the air against the windward convex and concave surfaces of the cups will cause the cups, and consequently the spindle, to rotate around the vertical spindle as an axis. This rotation is communicated to the train of wheels, and the number of revolutions of the anemometer cups around the vertical axis can be read off from the dials of the wheels, which are so arranged that a certain number of revolutions of the spindle causes one revolution of the

wind. The particular model shown here is the "Kew" anemometer, and beneath the cups are to be seen the bladed wheels of the Beckley wind vane.

first wheel, and a certain number of revolutions of this wheel causes one revolution of the second wheel, and so on. By means of this apparatus the number of revolutions of the anemometer cups is obtained; and the distance passed over by the middle point of one of the hemispherical cups is, of course, 2 × 3·1416 × R, where R is the radius of the circle described by this middle point. This is not the true velocity of the wind, but Robinson found by experiment, however, that if the velocity of the cups is multiplied by 3, it will give approximately the velocity of the wind. And this factor 3 is used by all nations in the reduction of the anemometer observations. In order to save the labour of making this reduction each time, the wheels and dials of anemometers are so made that the miles and fractions, or kilometers and fractions, can be read off directly, the factor 3 being taken into account in the construction.

Robinson constructed a cup anemometer in 1846, and shortly afterwards gave a mathematical analysis of its action; but his theory of the instrument, published in 1850, was not very satisfactory, although the results were approximately correct. The constants to be used in his formulæ he determined by experiments with a large anemometer on a whirling machine; he found that the velocity of the centre of the cups must be multiplied by 3·00 (as just mentioned) in order to get the wind velocity. Robinson found that a small anemometer tested also on a whirling machine (Combes' apparatus) gave nearly the same results, and meteorologists, generally, accepted this value.

Other experiments of Cavallero in Turin, and Stowe in England (1870–72), showed, however, that this result was only approximate; the latter's obser-

vations making it clear that the constant of multiplication (adopted as 3) is not the same for anemometers of different dimensions, but varies with the relation between the length of the arms and the radius of the cups themselves. Dohrandt at St. Petersburg was the first to show that the constant of multiplication could be computed if the dimensions of the radial arms and cups are known. These and other experiments have shown that anemometers of the size commonly used record wind velocities about 20 per cent. too great, and although this has been known for nearly twenty years, yet no change has been made in the erroneous value introduced by Robinson, and the wind observations published by the various meteorological institutions at the present time have only a relative but not absolute value.

For common sizes of anemometers, it is fairly accurate to deduct 20 per cent. of the anemometer record (given in meters per second) and then add 0·8 meter per second to the result, in order to obtain true wind velocities. Recent experiments by Dines show that for the large cup-anemometers of the Kew pattern the true constant multiple is from 2·0 to 2·2 instead of 3·0 for moderate velocities. It is very probable that many experiments on the relation of wind velocities to wind pressures have been made, in which this anemometer correction has not been properly applied.

Although the theory of the instrument has been given by several physicists, notably by Robinson and Thiesen, in the general terms of hydrodynamical analysis, yet they consider that the subject is one that can be best treated by experiment. And while the theory may serve to outline the general action of the instru-

ment, still in actual practice it is better to investigate each separate instrument, as must be done in case of thermometers.

Standard Anemometry.—Numerous methods of testing not only the comparative but also the absolute accuracy of anemometers have been proposed; but the method which has been usually adopted in practical meteorological work is that in which the instruments are mounted side by side and their readings noted for similar wind velocities; and yet this can furnish only comparative results. During the last twenty years, however, experiments with the Combes' whirling apparatus have become so frequent, that its use for testing anemometers will probably become general, since it can be used at any time and for any velocity up to its limits of operation. This apparatus (Deutsche Seewarte model, Fig. 40) which, according to Thiesen, was used by Smeaton and Zeiher before Combes, consists of a horizontal arm, ZQt, of at least ten feet in length; this arm has a horizontal motion around a vertical axis, Z, at one end of it. The free end, t, carries another vertical arm, to which is attached the vertical spindle of an anemometer D, the cups being horizontal. The long horizontal arm is now made to rotate about the vertical axis at Z by causing this last to revolve; which can be done by means of a small engine of one- or two-horse power (man power has sometimes been used). The anemometer will consequently sweep horizontally through a circle, of which the revolving axis, Z, is the centre, and the long horizontal arm, Z t, the radius. The motion of the anemometer causes a resistance from the air, which acts on the anemometer in nearly the same way as if the anemometer were at

and a reading of the anemometer dial is made at the beginning and end of this time, we can find out how many feet of motion of the anemometer cups around the spindle correspond to the number of feet passed over in a second by the whole anemometer at the end of the revolving arm. Knowing the actual velocity of the counter-wind caused by the rotation of the arm, the readings of the dial of the anemometer cups can be reduced to actual measure. The lineal velocity is deduced from that recorded by the anemometer by causing the latter to be whirled in the direction with the hands of a clock, then counter clock wise, and taking the mean between the two results.

The Deutsche Seewarte apparatus is located in the middle of an inner court, which is closed at the top by glass roofing, and is surrounded by corridors opening into the court, and the following additional details are given to show more clearly the method of its manipulation.

The long horizontal arm is not more than three feet from the smooth polished floor, but the anemometer D is perhaps eight feet above the floor, and three times that distance from the ceiling. The vertical axis Z of the revolving arm passes downward to a trap A just beneath the floor, where the rotary motion is communicated by a horizontal axis by means of a conical gearing; and this long horizontal axis is rotated by means of a gas motor in the basement. At one side of the court there is a frame R, supporting at the end of the horizontal rod a small anemometer, which can be placed just above the path of the centre of the anemometer to be tested. (In the Physical Observatory at St. Peters-

burg the small anemometer is placed just outside and in the same plane of the circle in which the large anemometer is whirled.) This small anemometer is for measuring the velocity of the weak current of air produced by the motion of the anemometer, and which has a motion *with* the anemometer (*Mit-wind*). The velocity of the current is about 5 per cent. of the velocity shown by the large anemometer, and this must be allowed for in determining the true reading of the latter.

In one corner of the court, at the left, there is a little balcony K, where the observer may place himself when the apparatus is in motion. Here there is a crank handle *r*, that has communication with two conical cylinders in the basement, near the engine, around which the driving belting passes. By means of the crank this belting is caused to slide along the cones, so that the velocity of the driving arm, and consequently of the whirling apparatus and the anemometer, can be varied by the operator in the balcony.

In the balcony is also mounted a chronograph, *p*, on which is automatically registered, electrically, the seconds, the number of revolutions of the long rotation arm, and the number of revolutions of the anemometer cups. This complex record allows of a more complete discussion of the observations than could be otherwise made.

Apparatus of this nature have been constructed by Robinson in Ireland; Stowe, Whipple, and others in England; Hagen, Rechnagle, and Neumayer in Germany; Wild in Russia; Marvin in America, &c.; but the most complete one is that of the Deutsche Seewarte, at Hamburg, constructed by Neumayer, and shown in Fig. 40.

When all of the meteorological services shall have adopted a whirling machine of some uniform size and exposure, on which to test anemometers used by them, then the observations of wind velocities in different countries can be made comparable; but even then the results will be purely relative. Experiments have still to be made which will show conclusively the relation of the velocities obtained by the whirling apparatus to true absolute wind velocities as actually observed in the open air.

Estimates of Wind Force.—It will be found that instruments for measuring wind velocities have been used by the majority of meteorological observers in but few countries, and at sea not at all. Where this is the case, the personal estimates of wind force are made by the observers according to some arbitrary scale. While it would probably be just as accurate to use the more readily understood expressions—calm, gentle, fresh, strong, gale, hurricane, to indicate the various grades of wind, yet in dealing with masses of such observations it is more convenient to replace these expressions by numbers. As early as 1780 what is known as the Mannheim Scale was introduced, and for many years widely used. This scale extends from 0 (calm) to 4 (strong gale). Since then several scales have been used, at various times and in different countries, in which the number of graduations, so to speak, have been from 0 (calm) to 6, 7, 8, 9, 10, and 12; these last numbers indicating the most violent winds that might occur. Of these, the most interesting and important is the scale 0–12, which was introduced by Admiral Beaufort in 1805 for use on board ship; and this is at present almost universally used at sea. This scale was based on the

amount of sail a ship could carry in the different winds, but the system also came into use at land stations, especially those on the coast; although in applying it to land stations in general only half the number of divisions are used (0–6). In the past twenty years a 0–10 scale has also been widely used in the international work of the United States Weather Bureau, and Abbe ("Meteorological Apparatus and Methods") has given its graduations in terms of the other scales, which are brought together here in a little table.

U.S. Weather Bureau Scale 0—10.	Beaufort's Scale 0—12.	Jahnel's Austrian Scale 0—10.	Wild's Russian Scale 0—10.	Old Russian Scale.	French Meteor. Ass'n. Scale 1—7.	Paris Met. Bureau Scale 0—6.	English Land Scale 0 6.	Mannheim Scale 0—4.
0	0	0	0	0	0	0	0	0
1	0.5 and 1	—	1	0	1	1	0	—
2	1.5 and 2	1	2	1	2	—	1	1
3	2.5 and 3	—	3	1	3	2	—	1 to 2
4	3.5 and 4	2	4	2	4	3	2	2
5	4.5 and 5	3	5	2	—	—	—	—
6	5.5 and 6	4	6	3	5	4	3	3
7	7	5	7	3	—	—	4	—
8	7.5—9	6.7	8	4	6	5	5	4
9	10	8.9	9	4½	—	—	6	—
10	11.12	10	10	—	7	6	—	—

Abbe has also given the velocities and pressures of the winds for these different graduations of the 0–10 scale, but as they differ widely from some recent results in this same line of work, and as little information is given as to their derivation, they are omitted.

Very little has been done towards determining the value of these scales of estimation in terms of actual wind velocities, but Mohn has brought together

(*Meteor. Zeits.*, Feb., 1890) the results of a number of comparisons which have been made within the past twenty years, between the estimations on Beaufort's Scale and anemometer observations. As a result of such comparisons, made chiefly at lighthouses on the English, German, and Norwegian coasts, the following values, given in round numbers, were obtained:

Beaufort's Scale.	1	2	3	4	5	6	7	8	9	10
True velocities. Meters per Second.	2·	3·5	5·5	7·0	9·0	11·0	13·0	15·0	17·	19.

A few observations made on the open ocean give about the same values up to 5 of the Beaufort's scale, but somewhat larger velocities corresponding to the scale estimations of stronger winds.

Estimations of winds above 10 of this scale are scarcely to be relied on. In order to reduce these true wind velocities to those given by an ordinary anemometer, whose readings are obtained by means of the multiple 3, it is necessary to subtract from each velocity 1 meter per second, and then increase the remainder by one-fourth of its amount.

Self-Registering Anemometric Apparatus.—The recording apparatus for the ordinary pressure anemometer is so arranged, that the force of momentary gusts of wind is clearly brought out, but total wind movements for any definite time, as an hour or a day, are obtained with great inconvenience.

The registrations of the cup anemometer with electric contacts do not show the force of sudden gusts of wind, unless they continue for some time; but the record is well adapted for showing the hourly or daily amounts of wind. The former is more im-

portant for engineering purposes, and the latter for meteorological purposes. The registering instrument which will accomplish both purposes, as well as each of these does its part, has yet to be constructed.

According to Westphal's researches, the attempts at constructing apparatus for measuring and recording wind-force and wind-direction extend back to the year 1667, and the names of Hooke, Pickering, Christian Wolf, Lentmann and Leupold are given as having been early experimenters.

Count d'Ons-en-Bray, in the year 1734, constructed a registering apparatus for wind direction very similar to the form devised later by Beckley; the wind velocity being recorded by a hammer raised by means of a small wind wheel, and allowed to fall against a recording paper, having a uniform motion, at every 400 revolutions of the wheel.

The Robinson anemometer register, in use in many of the principal European observatories, is the Beckley form; in which a long vertical rod is geared to the anemometer spindle by means of an endless screw. At the lower end of this rod is a gearing by which a small horizontal cylinder is made to revolve (once for every 100 kilometers of wind in the Fuess instrument). A spiral knife-blade-shaped strip of metal encircles the cylinder once in its whole length, and the edge of this metal blade touches a chronograph cylinder beneath it at one point only at a time; but during a complete revolution of the small cylinder, each point of the edge of the spiral blade comes in contact with the chronograph at successive points from left to right. The chronograph sheet being of metallic register paper, the contacts of the metal blade are recorded.

A similar arrangement records the wind direction, the small cylinder and its spiral metal strip making a complete revolution for each revolution of the wind vane, and a particular point of the strip always coming in contact with the chronograph sheet for the same position of the wind vane.

Perhaps the best form of anemometer-register in common use is the electrical, in which a platinum contact is inserted in the wheel work showing the number of revolutions, in such a manner that for every kilometer or mile of wind a circuit will be closed and cause a registration to be made on a chronograph. There is less friction with this method than with others. The wind direction is registered by means of an electro-magnet and pencil for each direction—for instance, eight magnets and pencils for eight points of compass, the circuit being closed automatically by the vane entering that sector of the circle of revolution of which the direction is the middle point.

The anemometer record can be made on the same register as that used for showing the direction of the wind vane, and the apparatus so constructed that the miles or kilometers will appear opposite the wind direction at the time of registration; thus enabling one to easily obtain by mere inspection of the anemogram the velocities for the various directions.

But a form of integrating anemometer, which has been independently proposed and its success proven by years of use in several countries, but first in Russia and France, in which the anemometer is included in the circuit of the conducting wires of the direction register, causes the miles or kilometers to be recorded by the pencils showing the direction at that time;

thus recording the velocities under the headings of their proper directions. This is not only a great convenience to the person who takes the data from the anemogram, but it affords a ready material for the rapid

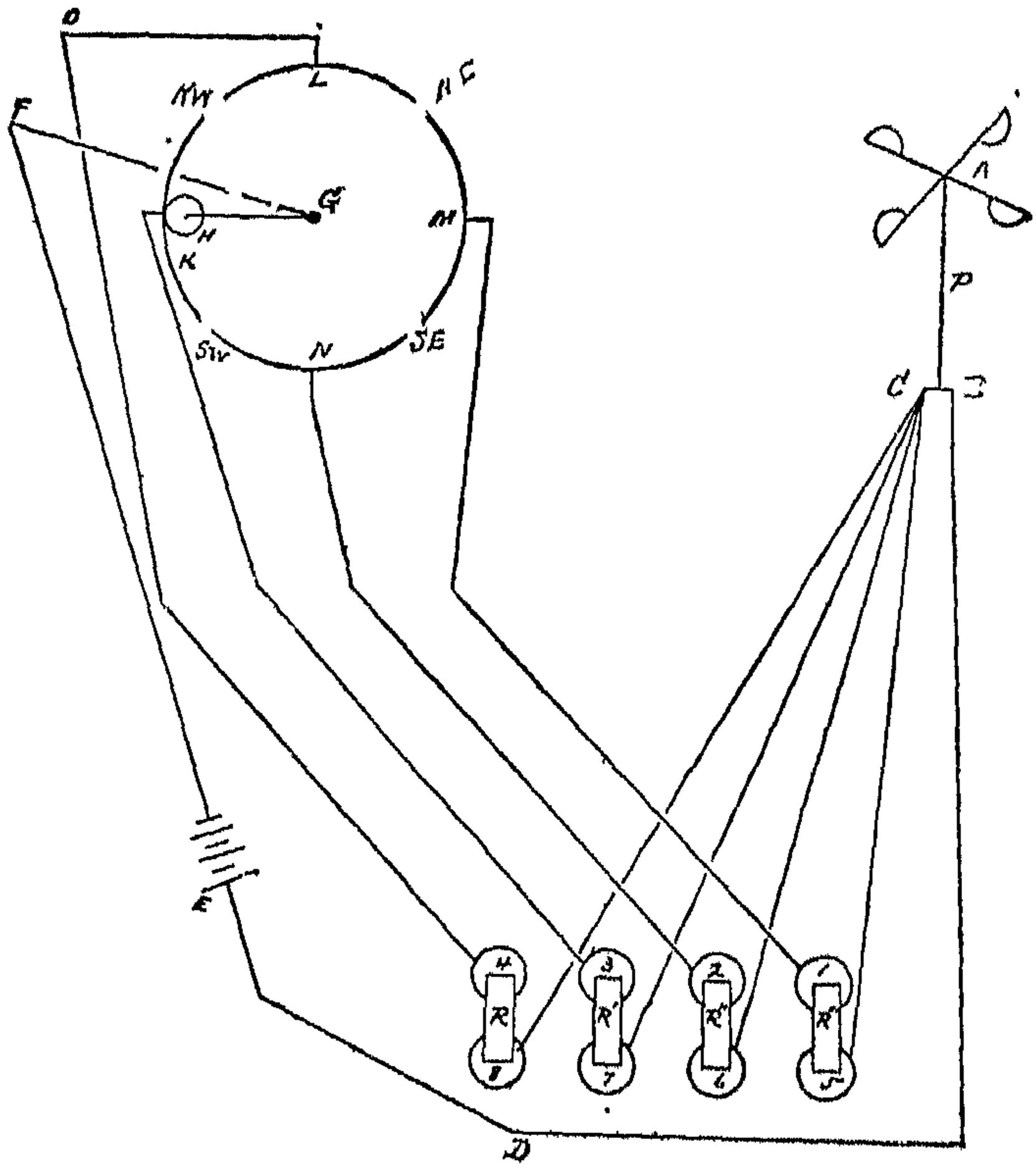


FIG. 41.

comparison of the directions and velocities of wind on successive days, as the record sheets for each day can be laid side by side.

The general principle upon which this device works is shown more plainly by the accompanying Fig. 41.

In this A represents the Robinson anemometer; P, the supporting frame; and C and B, the posts to which the conducting wires are attached as in the ordinary form of electrical self-registering anemometer, in which C and B have metallic connection through P at the completion of each mile or kilometer of wind as shown by the anemometer dial; at other times the circuit connection between C and B is broken. By means of a wire, B is connected with one pole of the battery E. Wires also pass from C to binding-screws on 5, 6, 7, 8, electro-magnets of the recording apparatus. The left-hand part of the diagram is shown in a horizontal plan. G is the lower end of a rod passing from the roof to the room beneath. This rod, being in rigid connection with the wind vane, will revolve with the latter. Near the lower end of the rod at G an arm is placed at right angles to the rod, and terminates in the small friction wheel H. This wheel H runs along a metallic rim encircling G; the rim not being continuous, but having small breaks at the points touched by the wheel H when the vane points N.E., S.E., S.W., N.W. These breaks are so short that when H, in its revolution around G, leaves one segment of the rim, it almost instantly rests against the next. The segment L is connected with the binding-screw of 4, by the wire passing through O. Similarly K is connected with 3, N is connected with 2, and M is connected with 1. The continual wire GF is in metallic connection with GH, and is also connected with the free pole of the battery E.

We will now suppose that the anemometer and vane are exposed to the wind, which is from the west. We shall then have the arrangement shown in the diagram. The circuit connection C 7 3 KHGFEDB will be

complete (except at BC), and whenever the anemometer closes the circuit BC, the armature R′ will be attracted by the double coil magnet 3 7. Thus, for any winds between S.W. and N.W., the action of the armature R′ will indicate each mile or kilometer of wind. Similarly the armatures R, R″, R‴ will indicate northerly, southerly, or easterly winds.

By attaching recording pencils to the armatures R, R′, R″, R‴, and allowing a chronograph sheet to pass beneath them, we can register in separate columns the amount of wind from the four points. By doubling the number of segments, electro-magnets, and recording pencils, the velocities can be recorded for eight points of compass; and by recording a combination of two directions at a time twice as many points of compass may be registered as there are recording pencils.

There are many more common methods of recording the wind direction. The simplest of these is to prolong the spindle, rotating with the wind vane, to a room below, and let this spindle terminate in a conical bearing, so that the friction will be small. Near the lower end of the spindle mount a cylinder encircling it and rotating with it. On this cylinder will be placed the recording sheet. Against this sheet there presses a recording pencil which has a slow motion in a vertical direction only, and which is regulated by clock-work. The cylinder rotating with the wind vane, and the pencil pressing against it continually, will cause the wind direction to be recorded for every instant of the time during which the pencil is moving in the vertical, which may be one day or several days for a single recording sheet, as has been allowed for in the construction. The motion of the

pencil can be imparted by the driving weight of an ordinary clock of good construction.

Measurement of Air Movements at High Altitudes.—Since the instruments in common use for denoting the direction or measuring the velocity of the wind must be placed in the currents to be observed, they can only be used near the earth's surface unless they are mounted on some mountain peak; but even this gives observations for relatively low altitudes; and besides, under the most favourable conditions of environment, the air which is to be measured cannot be kept free from local vitiating influences. While it has been proposed to observe the motion of toy balloons, the smoke of exploded shells fired vertically upward, the direction of smoke from chimneys of factories and boats, and to mount anemometers on captive balloons or kites, yet very little of this kind of work has ever been done.

The movements of the clouds offer the readiest means of observing the upper currents, and these have been included in the routine of observation in most meteorological services so far as *direction* of motion is concerned, but the measuring of the velocities has been neglected by all but a few observers.

(1) Direction of motion. The direction of approach of clouds is usually merely estimated by the observer, but this method, according to which most observations are made, gives only very approximate results unless the clouds are at the zenith. In some few observatories a cloud mirror is used, in which a ruled reflecting surface allows the motions of the image of the cloud to be co-ordinated, and some such apparatus as that of Fornioni's mentioned just below, adds greatly to the value of the observations, and relieves them of

large personal errors which exist for the ordinary method.

Fornioni's nephoscope, shown in Fig. 42, consists of a circular compass box about fifteen centimeters in diameter, with a free moving magnetic needle mounted at the centre. Above this needle, which cannot be seen in the illustration, there is a fixed horizontal glass mirror or reflector BB. On this mirror are traced the lines showing the principal points of the compass. In the sector extending from north to north-west the amalgam is removed from a portion of the mirror, so that the needle can be seen, and degree divisions are also so fixed that the position of the needle can be read. A pointer T can be moved around the whole circumference of the instrument. In use, the instrument is placed horizontally and oriented with regard to the *true* meridian. T is now brought into such a position that the eye forms a third point in a visual line passing through the aperture of the pointer, the centre of the mirror, and the reflection of some chosen point of the cloud.

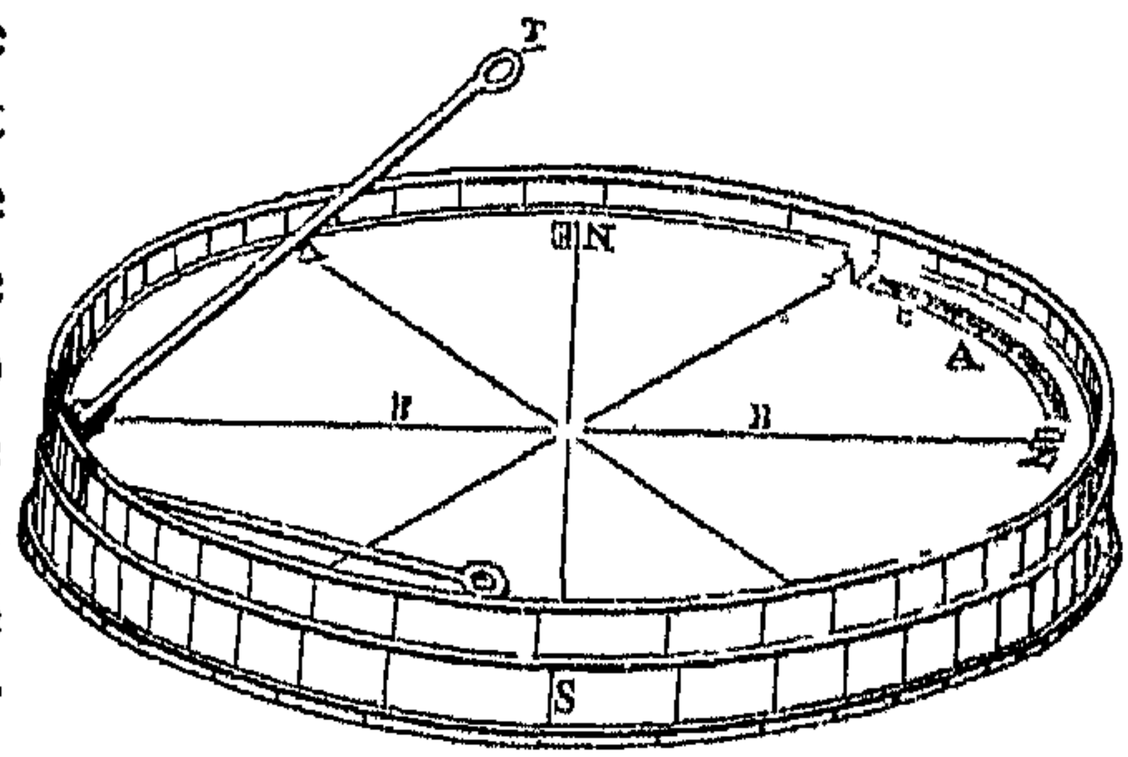


FIG. 42.

"The direction of the displacement that the reflected image will have undergone after a time, proportional to the velocity of the cloud, or inversely as its distance, will constitute the exact direction of the movement of the cloud."

In estimating the directions of clouds not in the zenith the following principle, as worded by Abbe, is found to be of great assistance: "All planes containing the observer's eye and the horizontal paths of the clouds moving parallel to each other, will intersect the horizon in a common vanishing point, whose bearing is the azimuthal direction of motion of the clouds."

(2) Velocity of motion. If the position of a cloud can be determined* at the beginning and end of an interval of time, its velocity is determined. The following are some of the methods which have been proposed for accomplishing this.

The trigonometric method, proposed by Riccioli about 1650, is the one which has in its various forms promised the best success. At the two extremities of a carefully measured base line two observers are placed, who measure simultaneously the altitude and azimuth of the cloud. Simple computation will then fix the position of the cloud. Two successive measures of this kind will give not only the velocity but also the direction of the wind at the elevation of the cloud.

If the observer is so located on an elevation that he can have a view of the surrounding country, he can observe the time of passage of the shadow of a cloud between two points of known distance apart, and by means of a map of the neighbourhood the directions as well as the velocities can be determined; and if the angular velocity of the cloud is also observed, the elevation can be computed.

The nephoscopic apparatus, which was first devised by Aimé in 1845, and later other forms by Braun, Marie Davie, Linns, Cecchi, Fornioni, Finemann, and

probably others, is very convenient for determining the apparent and relative motions of the clouds, which is a very desirable substitute, for the absolute motions if these cannot be observed. The principle on which this is planned is as follows :—

A cloud moves from K_1 to K_2 (in Fig. 43), and its reflection is found to move from m_1 to m_2 on a horizontal mirror, as seen by the observer's eye at o ; then "the distance m_1 m_2 is parallel to K_1 K_2, and is shorter than it, in the ratio of the vertical altitude O B to K_1 K_1^1, or in the ratio of the distances O m_1 to m_1 K_1,

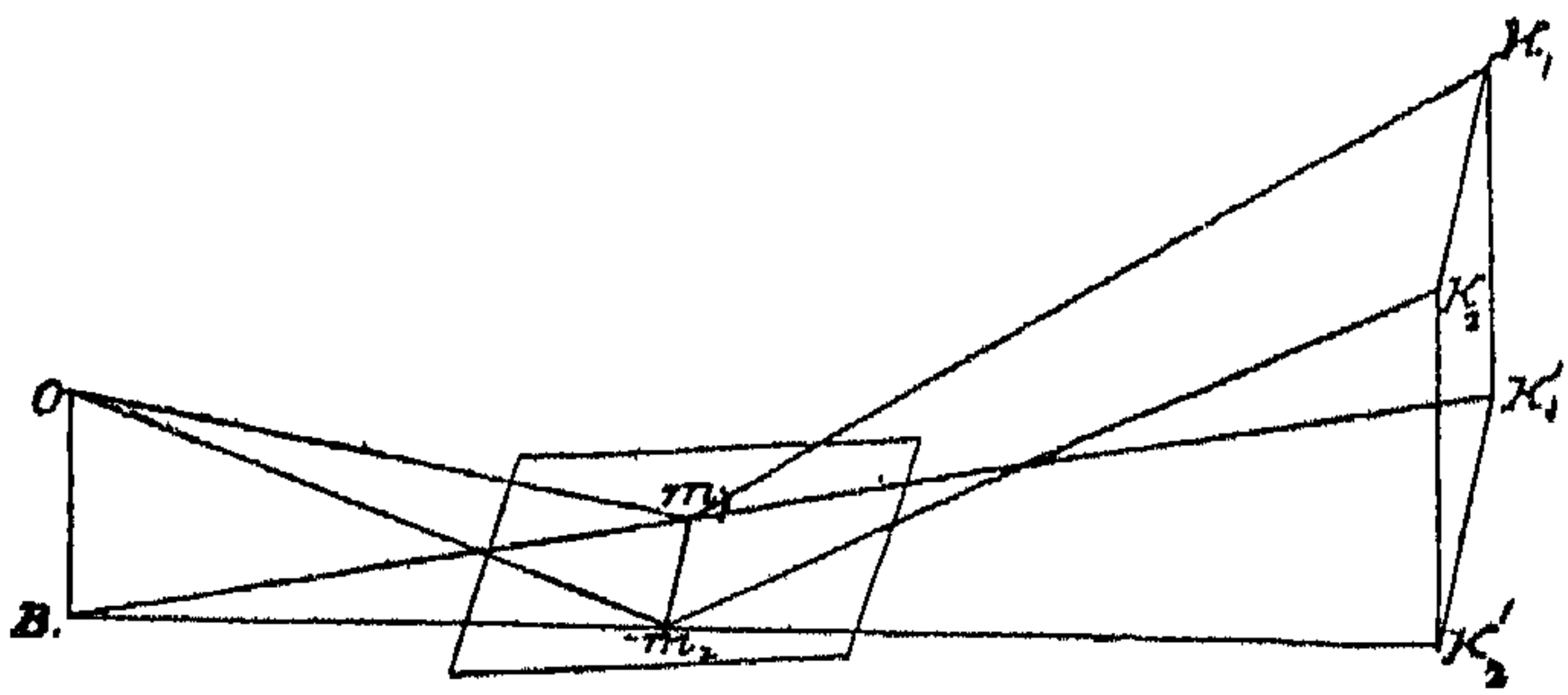


FIG. 43.

or in the ratio of the horizontal projection B m_1 to m_1 K_1^1." (Abbe).

Of the various forms of this class of nephoscopes which have been constructed, mention can be made of only one, that of Finemann, which is shown in Fig. 44. This instrument, like that of Fornioni, has a compass for orienting it when an observation is to be made, and also a horizontal mirror with lines drawn to the points of compass. This circular mirror has a circle of a certain radius drawn on it and concentric with it. A scale is placed at one side of the mirror and perpendicular to it; this scale has a slow

motion screw which moves it up or down, and the whole scale is so attached to a revolving band that it can be moved entirely around the edge of the mirror. In using it, the scale is so adjusted that the eye brings into the same range at the centre of the mirror the reflection of some chosen point of the cloud, and also that of the pointer. The selected point of the cloud will now move from the centre of the mirror along some one of the radial lines, and this gives the direction of the cloud motion; and the time t is noted, which it takes to move from the centre of the mirror to the circumference of the concentric circle.

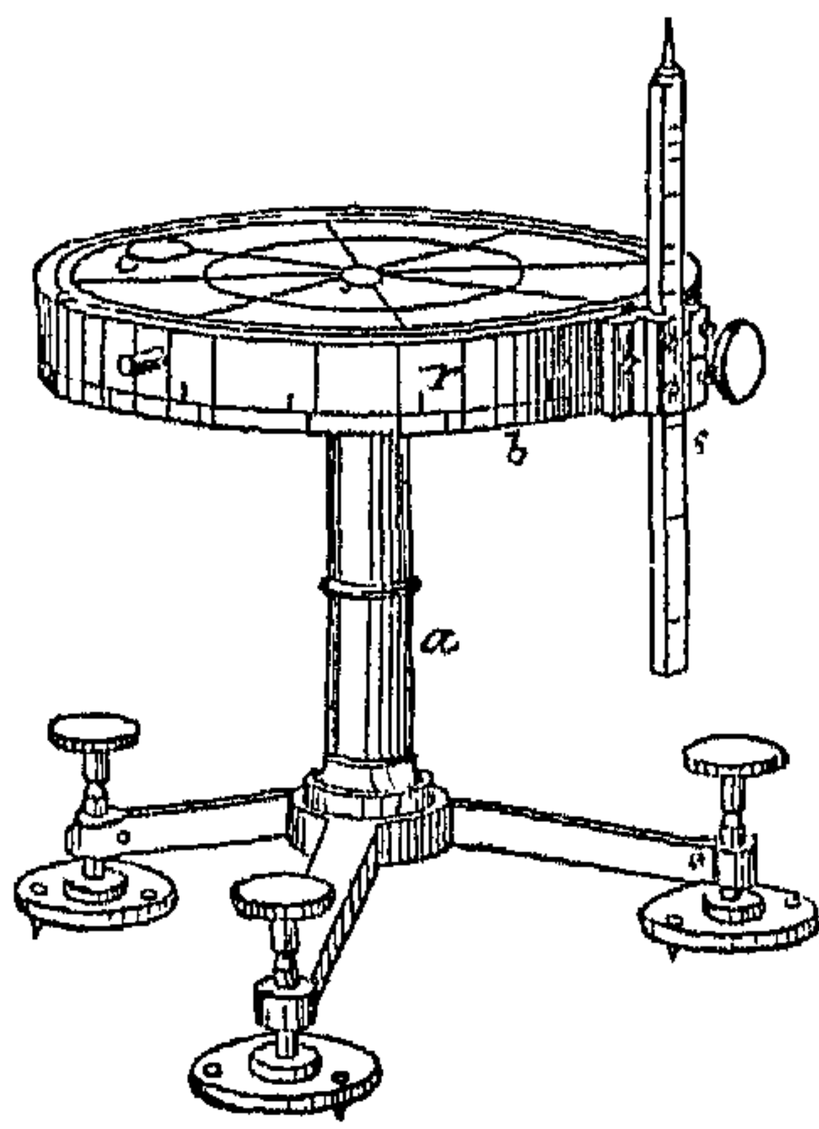


FIG. 44.

Now, as these measures are purely relative, it is convenient to use as a unit of reference the time T which it would take for the cloud to pass through a distance of 15° from the zenith, so that the observed time t must be reduced to this scale. This, trigonometry easily gives. If the radius of the circle on the mirror is chosen 26·8 millimeters, and the height b of the scale is also read in millimeters, then T is given by the simple formula, T=0·01 bt (Abbe). These values of T can be compared, and furnish very useful relative values of the velocities of the upper air currents.

§ 4.—*Instruments for Measuring Atmospheric Moisture and Precipitation*

In dealing with the continually repeated interchange which goes on between the air and surface of the earth, as regards the water which is found first in the one and then in the other, and which the Germans so conveniently call the *Kreislauf* (circuit) of the water, meteorologists have found it desirable to measure, 1st, the amount of moisture in the atmosphere, 2nd, the rate at which it descends to the earth as precipitation, 3rd, the amount of this precipitation, and 4th, the rate at which it is taken up again into the air: the first is accomplished by means of hygrometers, the second and third by rain gauges, and the fourth by evaporimeters.

Moisture of the Atmosphere.—Moisture may exist in the atmosphere both as an invisible vapour (aqueous vapour), and as visible particles of water, which may or may not be frozen. In applying the methods of gases to its measurement, it frequently becomes necessary to first reduce it to a uniform gaseous condition, which may be done by changing the temperature or pressure of a limited portion of the air to be investigated; after which the relations which laboratory experiments have shown to hold between the temperature, density, elastic pressure and volume may be applied. These relations for saturated vapour were thoroughly studied by Regnault, whose results were generally adopted; but the rediscussion of Regnault's observations by Broch, of the International Bureau of Weights and Measures at Sèvres, has furnished the best tables showing these relations.

Early Hygrometers.—According to Hellmann, the earliest instrument of which we have record for mea-

suring atmospheric moisture is the balance hygrometer described by Cardinal Nicolaus de Cusa in a posthumous work published in 1472. He said that if a considerable quantity of dry wool is placed on one side of a balance, and stones are placed on the other side until the balance is brought into equilibrium, experience shows that the weight of the wool increases or decreases according as the air becomes moister or drier. Reference is also made to the fact that the instrument is useful for conjecturing changes of temperature. The exact date of the invention cannot be determined; but since the Cardinal died in 1464, when Leonardo da Vinci was but twelve years old, the usually received priority of the latter as the suggestor of the hydroscope can no longer be accepted.

In 1554 Mizauld published the first notice of the influence of humidity on the strings of musical instruments; and a few years later Baptista Porta called attention to the hygrometric qualities of the "beard" of wild oats, which substance was widely used, as we find that Torricelli applied it nearly a century later.

The first condensing hygrometer was constructed by the Grand Duke Ferdinand II. of Tuscany. This instrument, as shown in Fig. 45, consisted of a reservoir, having the shape of the frustrum of a cone, and made of cork, painted on the inside, and covered with sheet metal within. The point of the cone was a conical glass funnel without outlet, beneath which was placed a glass measuring-cup Upon filling the reservoir with snow or powdered ice, the moisture in the air was condensed on the cooled outer surface of the funnel, and the drops fell into the measuring-cup,

and the time was noted which was necessary to collect a certain amount of this moisture. In 1665 Ferdinand tried to establish regular observations with this form of apparatus, and sent a number of them to his friends. But the first regular continued hygrometric observations of which we have a record are those commenced by Boyle on June 30, 1666, at Oxford, the *Geranium Moschatum* being used as a hygrometric substance.

Modern Methods of Determining the Amount of Moisture in the Air.—The most important of the various modern methods of determining the amount of moisture in the atmosphere are the following: the weight of moisture for given volumes of air, or volumetric method; temperature of saturation; temperature of evaporation, or psychrometric method; spectroscopic method; the proportional saturation of certain animal and vegetable substances; and, in a general way, the optical method.

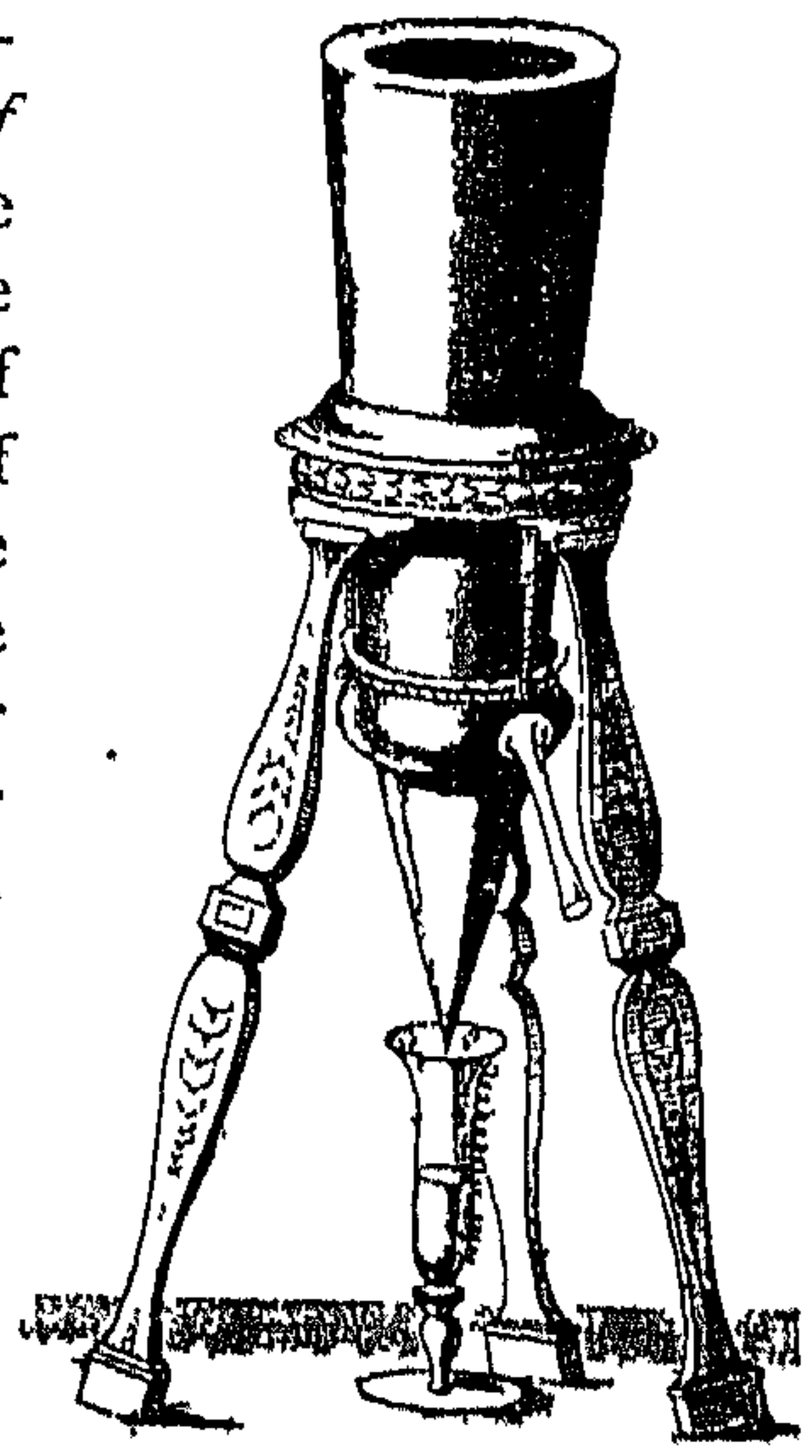


FIG. 45.

Of all these only two are in general use among meteorological observers; viz., that in which the psychrometer, or wet and dry bulb thermometer, and the hair hygrometer are used. It is true that considerable use is made of the optical method in which the colours of the sky or clouds are noted, as an aid to weather forecasts, and the spectroscopic method is

used at some few observatories; but neither of these have been sufficiently studied to allow quantitative values to be assigned to the observations.

The most refined methods of obtaining the amount of moisture in any given amount of air, properly belong to the laboratory for chemical physics. If air is allowed to pass through a glass drying tube, in which is placed a large surface of glass-wool, covered with strong sulphuric acid, or containing phosphorous pentoxide and glass-wool, and the feeding current passes through a small-bore tube at the rate of about two litres per hour, then a litre of the air thus dried does not contain over 0·0025 of a milligram of water. This accuracy is of course far greater than any meteorological requirements necessitate.

The tension or pressure of the vapour in the atmosphere may be determined directly by the method of Renou (1858) and Mantern (1880), by adding as much moisture to a definite amount of enclosed air as will entirely saturate the latter. The observed pressure of the air in the two conditions, as measured by a manometer, allows the vapour tension to be computed, as we know the pressure exerted by fully saturated air.

Edelmann (1879) invented an apparatus for measuring the pressure of a definite volume of air before and after its moisture had been absorbed by sulphuric acid; but the apparatus which has been most successfully used by a number of meteorologists (as, for instance, by Sworykin, Pernter, and Marvin) is that devised by Schwackhöfer (1878), and which is shown in Fig. 46. While this apparatus is somewhat cumbersome, yet it is sufficiently portable to allow of its use on scientific expeditions, being all contained in

a case easily carried by hand. In this apparatus the air from outside is drawn into the receiver B through

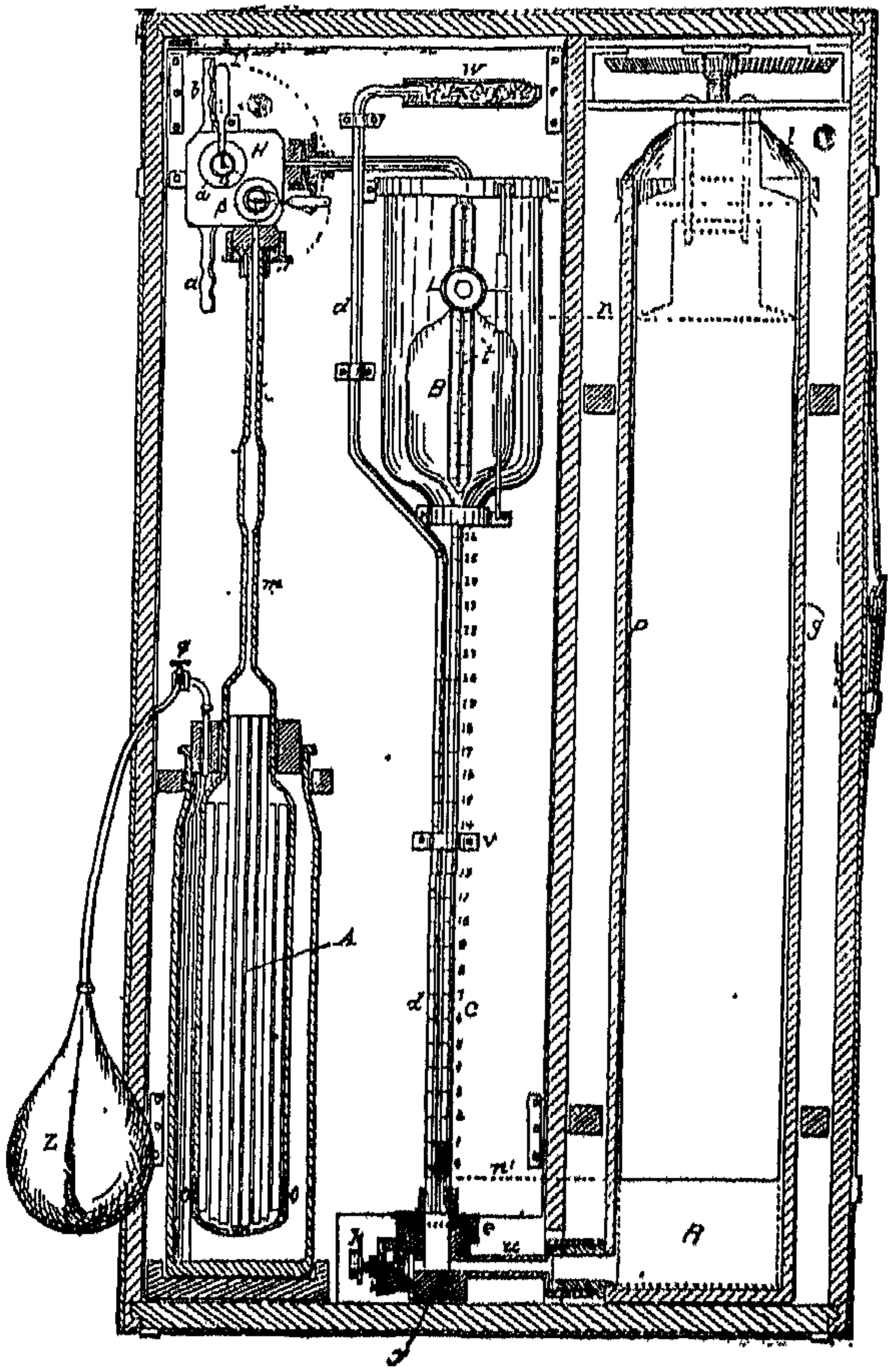


FIG. 46.

either of the glass tubes *a* or *b* (in the upper left-hand corner). When communication is cut off by means of the three-way cock, the confined air fills the

upper tube connecting with the reservoir B and the graduated tube beneath to about the zero, where it is limited by the surface of the mercury which fills the lower part of this tube, the tube u and the lower part of the glass cylinder P. By means of a hand crank and screw motion at the top, on the right, the loose-fitting wooden piston F can be forced into the mercury in the lower part of P and cause it to rise in P and also to fill B to any desired height; the suction power for filling the system B with air is obtained by starting with B full of mercury and raising the piston F. The reservoir B is surrounded by a second glass cistern containing glycerine for preserving a steady temperature, which is determined by means of the thermometer t. By means of the cocks α and β the confined air in B is placed in tubular communication with the drying chamber A, which contains glass rods and sulphuric acid. A communicates with the surrounding chamber by means of the small openings oo near the bottom. By squeezing the rubber bag Z, the air passes from it into the chamber containing the acid and forces this up to m; and the cock g being closed, the acid remains at this level.

The air which is in B and its connecting tubes is now forced into A by pushing the mercury into B by operating the plunger F; and the sulphuric acid is in turn forced from A into its enveloping receiver, and the cock q being opened again, the bag Z is once more filled with the air which it originally contained. As soon as the air in A has been deprived of its moisture by the action of the sulphuric acid, the bag Z is again squeezed simultaneously with the raising of the plunger F, and the acid flows again into A, and the dried air again fills B and its secondary tubes. It

will be found, however, that the mercury in the graduated tube c does not stop at the same point which it did before, but reaches a little higher in the tube, as the pressure of the dried air has been lessened by the abstraction of the water vapour.

Free access of outside atmospheric pressure is maintained by means of the tube *d*, which has the mouth at w protected by cotton, and the lower open end inserted in the same mercury with c. In order, now, to find the volumetric change in the dried air, the mercury surfaces in the tubes c and d are raised by lowering F, until these two surfaces coincide and indicate that the pressure of the air above each is the same. A reading of the volumetric graduations on c now shows the change of volume in the air caused by abstracting its moisture. The whole operation requires perhaps ten minutes for its accomplishment, and many thousand observations can be made after once filling with sulphuric acid.

Of the hygrometric instruments in practical use, and the results regularly published, the psychrometer or wet and dry bulb thermometers, and the hair hygrometer, are the chief ones. The last of these was invented by Saussure, and as there has been very little improvement since his time, except in slight mechanical details of construction, it may be dismissed with a few words. In the best instruments human hair is used which has been freed from oil, and which has a breaking stretch of 100 grammes, and an elastic stretch of 33 per cent. The expansion in length of such a hair ten inches in length is about 0·03 mm. for 1 per cent. increase in humidity. The one end is fixed, and the extension or contraction of the hair is communicated by the motion of the other end to an

index which magnifies this motion. The reading scale being properly divided from 0 to 100 as representing dryness and saturation, the index is set to 100 by inclosing the apparatus in a box in which wet cloths have been placed. It is frequently claimed that this apparatus furnishes results within 1 or 2 per cent. of the truth, and so it may in the laboratory, or for an immense number of observations, but Bergmann has shown (Wild's *Repertorium*) that for several years' observations the averages of the months of lowest humidity are higher by about 2 per cent., and of the highest humidity lower by about the same amounts, than when the psychrometer is used; and for single monthly averages differences of ± 8 per cent. occurred. Experience also shows that slight repairs and adjustments are necessary about once a year, and a new instrument must be substituted, or else the old one repaired by an instrument maker, about once in five years.

The Psychrometer. — The employment of a wet bulb mercurial thermometer for denoting the relative amount of moisture in the air by the amount it is cooled by evaporation was early carried out by Baume, Saussure, Hutton, and Leslie; but the modern psychrometer, composed of two thermometers, one with a dry bulb, and the other having its bulb covered with wet muslin, was the idea of Ivory (1822), and August (1825), who worked out about the same theory, independently of each other. August, however, pursued his investigations to a much greater extent, and brought the apparatus into practical use, and it is now known by his name. These early theoretical developments, although improved by Apjohn, Regnault, and others,

have now been displaced by the more thorough work of Stefan and Maxwell, the latter having given a beautiful treatment of the subject in his article on "Diffusion" in the *Encyclopædia Britannica.*

Additional necessary experimental work has been done by Sworykin in Russia, and by Marvin on Pikes Peak. Ferrel has combined the results of these with Stefan's theory, and has published, under the auspices of the United States Signal Service, what may be considered the most recent advance in the application of the theory of the apparatus to its practical use.

Method of using the Psychrometer.—In using the psychrometer the same precautions are necessary as for an ordinary thermometer, and, in addition, the wet bulb must in some way be subjected to the action of a current of air. As long ago as 1786 Saussure secured a good ventilation of the wet bulb thermometer by whirling it in a uniform but rather rapid manner, and this same or an analogous method has been independently proposed by a number of scientists, as, for instance, Belli (1830), Arago (1830), Bravais (1836), Espy (1840), &c. While it has long been recognised that psychrometer observations, and especially when the temperature is below freezing, may be very erroneous unless this ventilation does take place, yet the Italian meteorologists were the only ones who made a general practice of it until quite recently, when so much light has been thrown on the subject by Sworykin's investigations (Wild's *Repertorium*), that its general adoption is only a question of time. Within a few years it has been put into operation in the great network of stations controlled by the United States Weather Bureau.

Where this ventilation does not take place the hair hygrometer is the more accurate at temperatures below freezing.

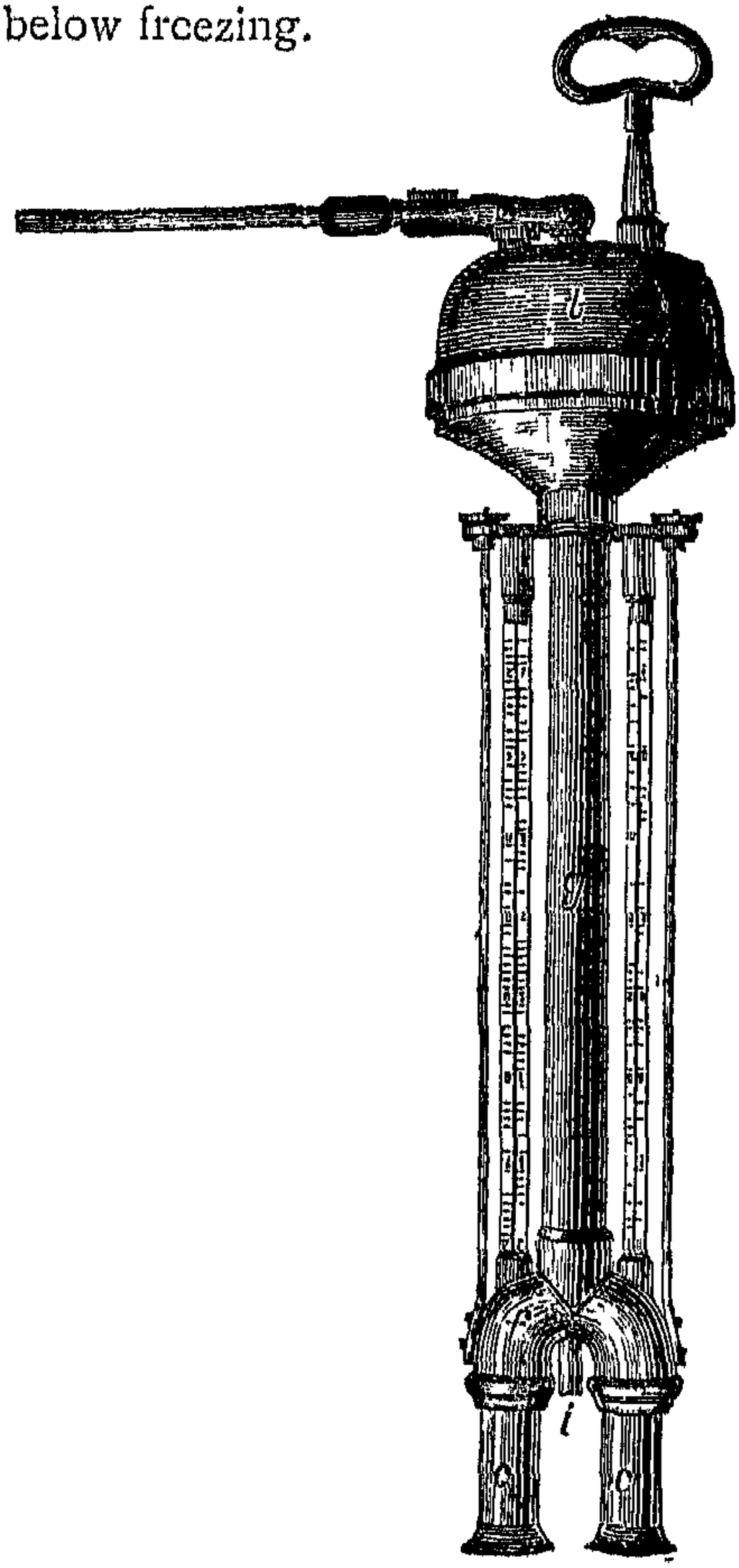


FIG. 47

It is necessary that the wet bulb be exposed to a current of two or three meters per second for about two minutes before an observation is made, and increasing the velocity above this amount does not make the accuracy appreciably greater.

Assmann has invented a portable apparatus (Fig. 47), in which the thermometer bulbs are screened by metal tubes through which an artificial current of air is made to pass by the employment of a pumping process. It is claimed that this will give accurate results when used in full sunshine, and it is therefore very useful for travelling observers.

Self-Registering Hygrometers.—The hair hygrometer is easily adapted to a system of registration, but the most accurate method is that by photographing the readings of the dry and wet bulb thermometers, in which case the ventilation and wetting of the bulb must be continuous.

Measurement of Precipitation.—The measurement of precipitation, whether it be in the form of rain or snow, has been more widely carried on under the auspices of meteorologists than any other department of this science; for in most countries there are many volunteer observing stations where no other records are kept. Although a uniform idea prevails as to what is to be measured, viz., the amount of water, whether it be rain or snow, which falls upon any given horizontal area, and that this is best done by catching it in an open-mouthed receiver; yet so different have been the ways in which this receiver has been constructed and exposed, that the results obtained by meteorologists might differ for the same locality by half the amount of precipitation.

There are several distinct features which give rise to these discrepancies: the size and shape of the mouth of the catch basin, the means of preventing the escape of drops after they have once entered the mouth, and, most of all, the precautions which are taken in exposing the gauge so as to prevent the vitiating effects of other phenomena, and especially of the winds.

The question of shape and size of the rain-gauge is as much secondary to that of exposure, as the careful investigation of a thermometer is to its exposure.

So far as shape is concerned, it is now almost

universally the custom to use a cylindrical sheet-metal vessel with a circular mouth (of from eight to ten inches diameter is best for general use, but in tropical regions perhaps three inches is sufficient), and with a funnel-shaped false bottom, at some distance below the mouth, through which the water may pass into the lower part of the gauge, which does not necessarily retain the shape or dimensions of the catch basin of the gauge. The rim should have a clean-cut edge (not rounded), and the fall should not be straight down from the orifice, but, especially in regions of snow, there should be a double outward bevelling just below the edge which forms an encircling catch pocket to prevent the rain drops from spattering out and the snow from being blown out. Wild has also recommended the insertion of four metal strips at right angles to an axis concentric with the axis of the gauge, as a preventive against the snow being blown out after it has once entered the gauge.

There are various methods of measuring the amount of precipitation caught. It may be weighed by ordinary weighing scales, its depth may be measured by means of a graduated stick or rod, or it may be poured into a graduated glass volumetric vessel such as is used by chemists. In some of the best gauges there is a stop-cock at the bottom, through which the water may be drawn off without inverting the gauge. Snow should be melted before being measured.

In mounting a rain-gauge it must be so placed that the effect of the wind on the amount of "catch" will be least, and the loss of water, due to evaporation before the measurement is made, will be reduced to a minimum.

The effect of the wind can be in a great part annulled by protecting the mouth of the gauge by some arrangement like the encircling shield of wire-netting as proposed by Nipher in 1878 (see Fig. 48). The wind which would otherwise strike just below the mouth of the gauge is deflected downward by this netting, and the spatter of water into the gauge, which would result from the use of a solid shield, does not occur when the wire is used. It has long been noticed (perhaps first by Heberden, in 1766) that there is a decrease in the catch of the rain-gauge with a slight elevation of exposure above the ground, and it was thought that for some unknown reason the amount of rainfall was actually less above, but it is now known that this deficiency is due to the action of the wind. A Nipher-shielded gauge will catch about the same amount of rain on the roof as on the ground, while an ordinary gauge may not catch more than three-fourths as much in the higher and more exposed position. It is worthy of note, however, that Wild, in planning the Pawlowsk Observatory (see Fig. 60), has so modelled the top of the tower as to deflect the wind downward and thus secure a normal condition on the roof.

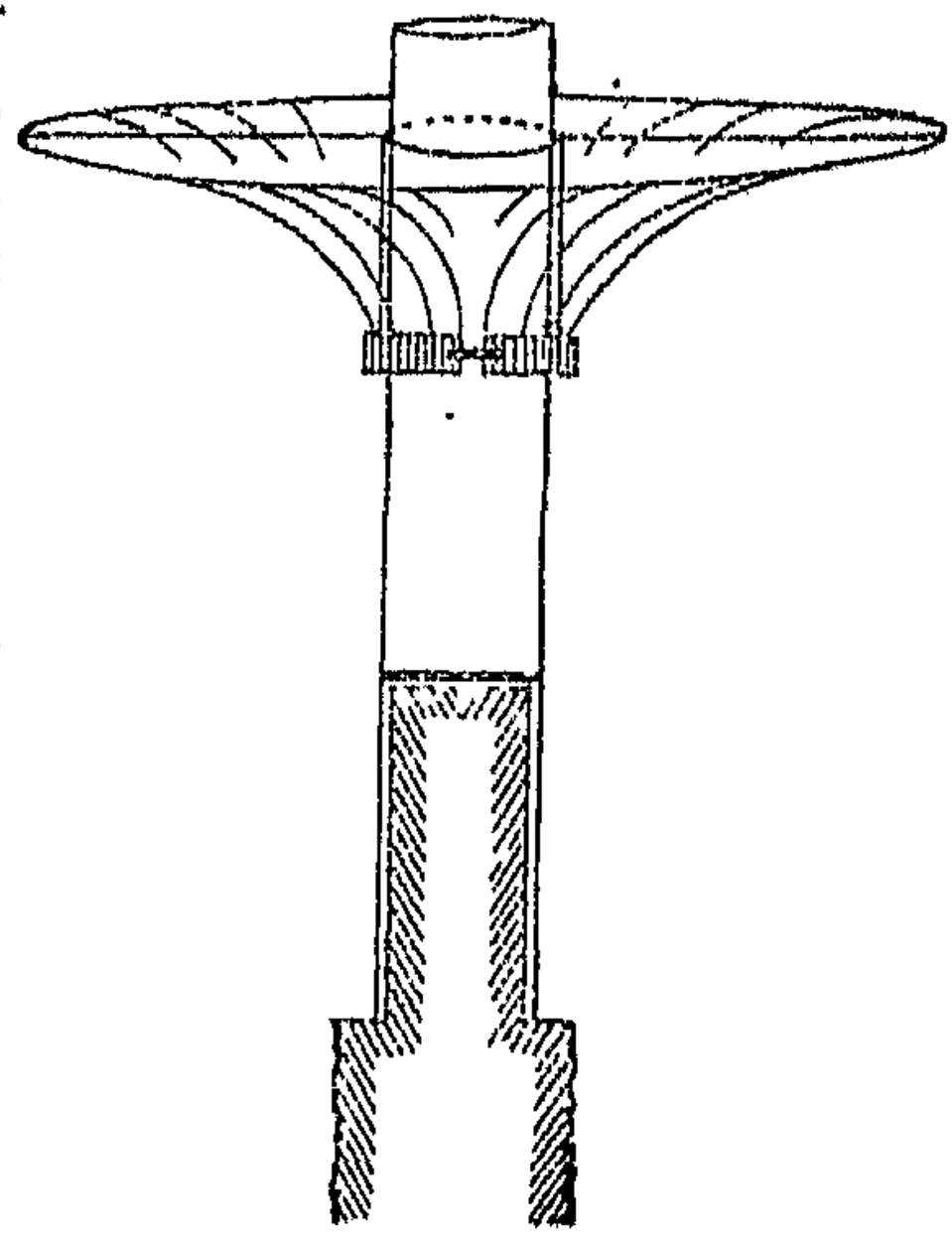


FIG. 48.

The effects of evaporation can be reduced to a minimum by so placing the final receiver of the rain-gauge that the sun cannot strike it, and by making the mouth through which the water enters as small as possible.

Many series of experiments have been made to determine the best form of rain-gauge; one of the latest being that of Hellmann (at Berlin), who wished to make the best selection for introduction among the stations of the recently reorganised Prussian Meteorological Bureau.

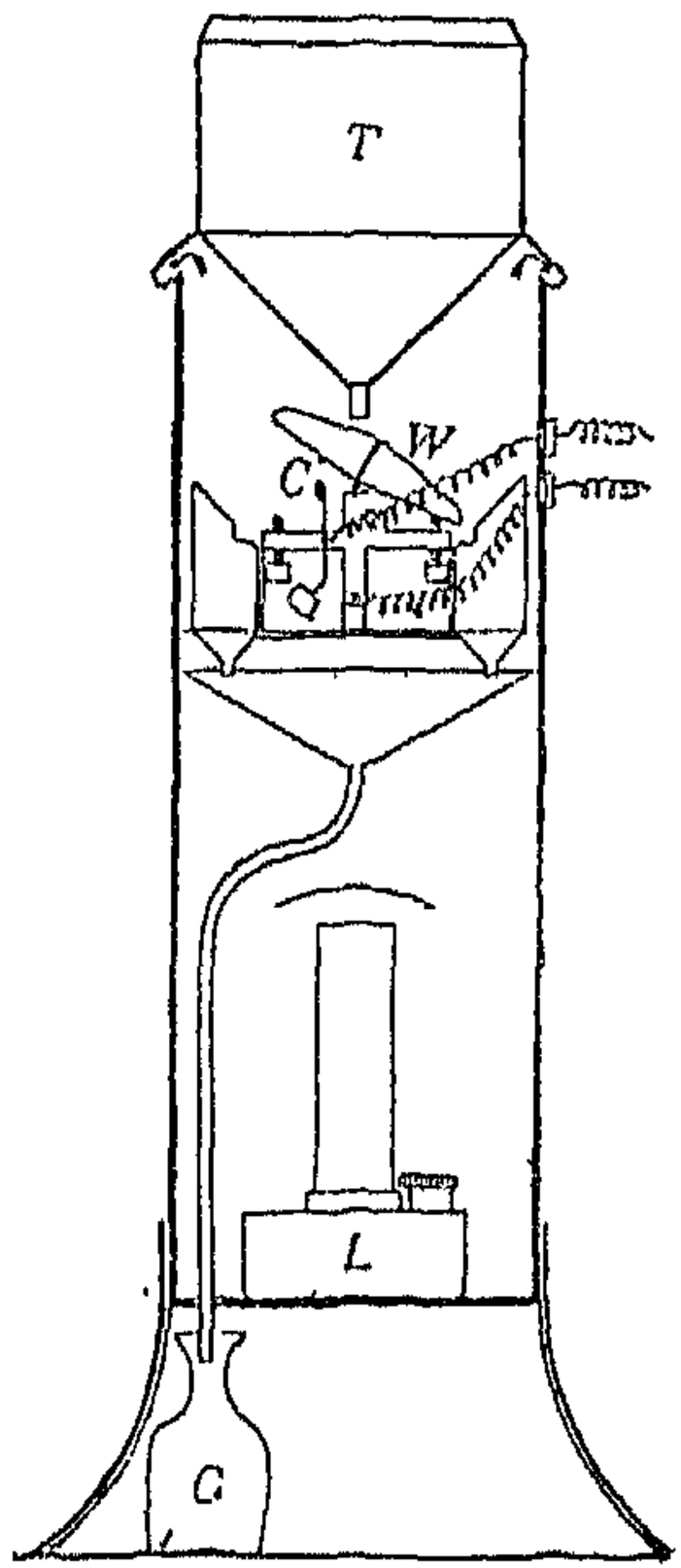


FIG. 49.

Self-Registering Rain-Gauges.—The self-registering instruments for recording the rainfall may be divided into three classes. There may be inserted in the gauge a float which will rise with the surface of the collected water, and the vertical motion of the float can be recorded by some one of the numerous methods of registration; another method, suggested by Horner, is that in which the water passes from the gauge directly into a sort of small balance scoop which automatically shifts its position from one side to the other, and empties itself whenever it contains a certain amount of water, and the number and times of shifting can be recorded either electrically or mechanically (see Fig. 49); the third method is to make a continuous or

automatically intermittent record of the relative weight of the water caught.

Evaporation.—While the observation of evaporation from a free water surface exposed in a well-ventilated thermometer shelter is to be accepted as the normal plan for investigating this phenomenon, yet as there are difficulties in carrying it out, the Piche evaporimeter (Fig. 50) has been proposed for ordinary meteorological stations, since it is not much more troublesome than a thermometer to manipulate. This instrument consists of a graduated glass tube filled with water and sealed at the upper end, but with a porous paper cover at the lower end. This porous paper constantly presents a wet surface to the air, and the moisture is evaporated; the renewal of moisture in the paper being made at the expense of the water in the tube. The variation in the height of the water in the tube shows the amount of water evaporated. It has been found that there exists a fairly constant relation between the water so evaporated, and that evaporated from a free water surface; so that when this relation has been accurately determined by experiment, the records of the former may be readily reduced to the standard terms of the latter. This relative evaporation is, however, so dependent on the wind velocity that this factor must also be carefully considered. Thomas Russell, of Washington, United States, found that with a wind of fifteen miles per hour five times as much water was evaporated as in a calm. The rate of evaporation

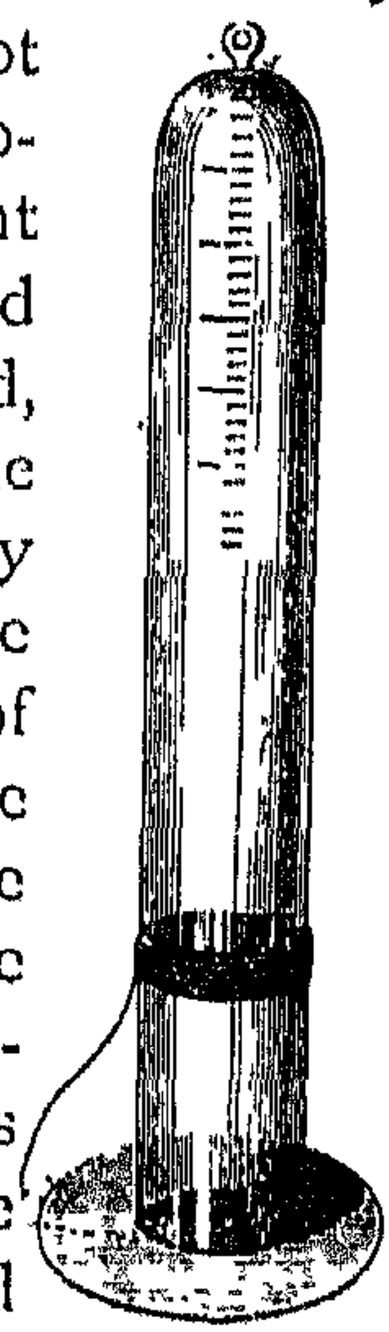


FIG. 50.

will also depend on the nature of the evaporating disc, so that no numerical values are offered giving the factor of reduction for the Piche instrument.

The self-registering evaporimeter may be operated by means of the first or last principles just described for the rain-gauge; the water surface being artificially prepared, as in the case of the ordinary normal evaporimeter, and in case the rainfall has access to it, the amount of precipitation, as shown by the records of the ombrograph, must be taken into account. The loss of water from a Piche evaporimeter may be registered by a system of automatic weighing.

Wild has had constructed, and has used quite successfully, a self-registering combination weighing apparatus (shown in Fig. 51), which not only measures the rainfall and evaporation, but also gives the direct weight of snowfall. On the left is seen the registering apparatus, which it is not necessary to describe further than to say that B is a metal vessel open at the top, and by means of the connecting tube A is attached at G to the right arm of the balance, and is counterpoised by the weights C and D. The lower end of the pointer Z, which is in rigid connection with the balance beam, is automatically pressed against the recording sheet every ten minutes, and any shifting in the balance beam due to an increase or decrease in the water in B (and A) is therefore recorded at ten-minute intervals. The middle diagram shows on a very much larger scale the *summer* (time of no frosts) arrangement of the exposed portion of the apparatus. A passes through a hole in the roof of the small building devoted to the instrument, so that B is above the roof. A small louvred shelter, M M,

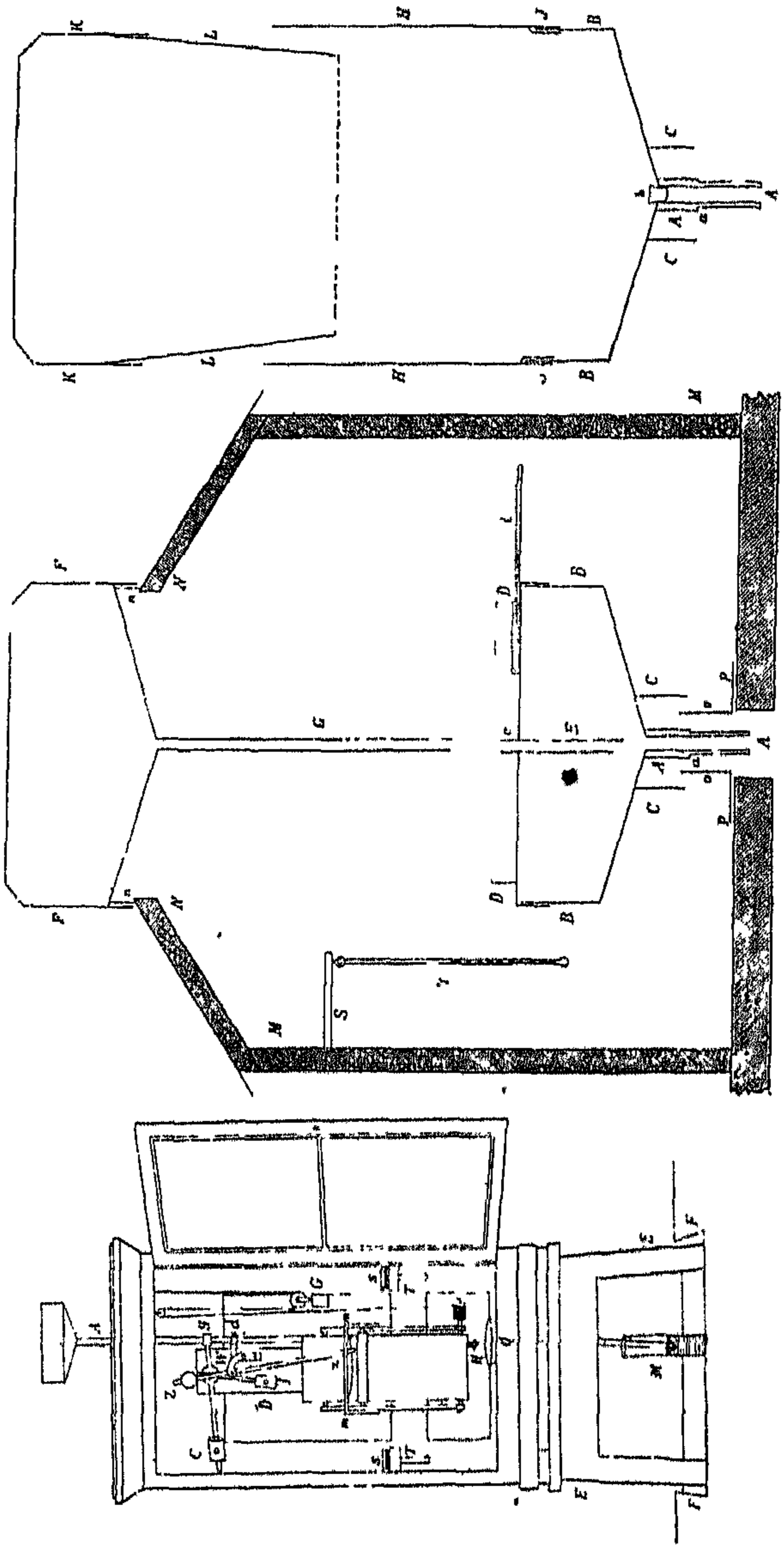


FIG. 51.

protects the vessel B. There is fitted to the top of B a shallow pan D, with a tube E passing through the bottom, and with the mouth e just below the edge of D, which is filled with water up to e. This water forms the evaporating surface. At the top of the shelter M is placed the rain collector F, from which the water flows through G into D, and from thence over into e, from which it is drawn off, through the cock H, at convenient intervals. The thermometer t shows the temperature of the water, and the thermometer T the temperature of the air in the shelter. When rain is falling, the water in D, B, and the secondary tubes e and A, increases the weight on the right arm of the balance, which causes a motion of the recording pointer. When no rain is falling and evaporation is taking place the weight is less, and a retrograde motion of the pointer takes place. These differential motions are easily read off from the recording sheet, and where the record is made only once in ten minutes, in case of showers of short duration, slight inaccuracies may enter, due to the compensatory evaporation during a portion of the interval of time, of the rain that has already fallen. Sprung's method of making a continuous record by the shifting-weight method would seem to be very applicable in the arrangement of this instrument. (See Barographs.)

In winter Wild replaces the metal pan D by the close-fitting cylinder H (as shown on the right-hand side of the illustration), and exchanges for the collector F the bottomless collector KKLL. The snow now falling into the open mouth of K passes downwards into B, and can become heaped up into H as it accumulates, but before it reaches up to

where it can touch L it must be removed from the gauge. Also in winter the mouth of the tube A is stopped up by means of a plug, so that it may not become filled with ice and become troublesome.

§ 5.—*Measurement of Clouds and Sunshine.*

Clouds.—The measurements of degree of cloudiness which are made by meteorological observers in general are exceedingly rough personal estimates of the relative portion of the sky which happens to be cloud-covered at the time of observation. It is now almost universally the custom to consider the whole dome of the sky from the zenith to the horizon as represented by 10, and to represent the degree of cloudiness by a scale from 0 (clear) to 10 (entire sky overcast). The matter of estimating the relative portion of the sky which is covered is left almost entirely to the judgment of the observer, who, unaided by any apparatus, glances at the clouds and makes an estimate that a certain amount of cloud is visible; and so he enters in his observation book, 1 for a small amount of cloud, 2 for a little larger amount, &c., up to 10.

In the accompanying diagram (Fig. 52), taken from a paper by Laurenty in Wild's *Repertorium*, vol. x., are shown the relative amounts for each tenth of the sky from the horizon to the zenith. For instance, a band extending around the whole horizon to a height of 5·7° would be 1 on the scale of 0–10, and would be just equal to the portion of the sky overhead extending to 25·8° from the zenith.

It may generally be said that the difficulty of an estimation increases with the increase of the zenith distance; and some meteorologists go so far as to take no account of the clouds below the altitude of

45°. And this last rule has the stronger claim, when it is considered that when a cloud is seen in the horizon we observe its vertical extent, while in the zenith only the base is to be seen.

Very few measures of thickness of clouds have been made, so that the great majority of observations merely denote in what proportions the various portions of the earth are screened by the clouds without regard to the density of this screen.

Perhaps the most efficient aid to judging of the

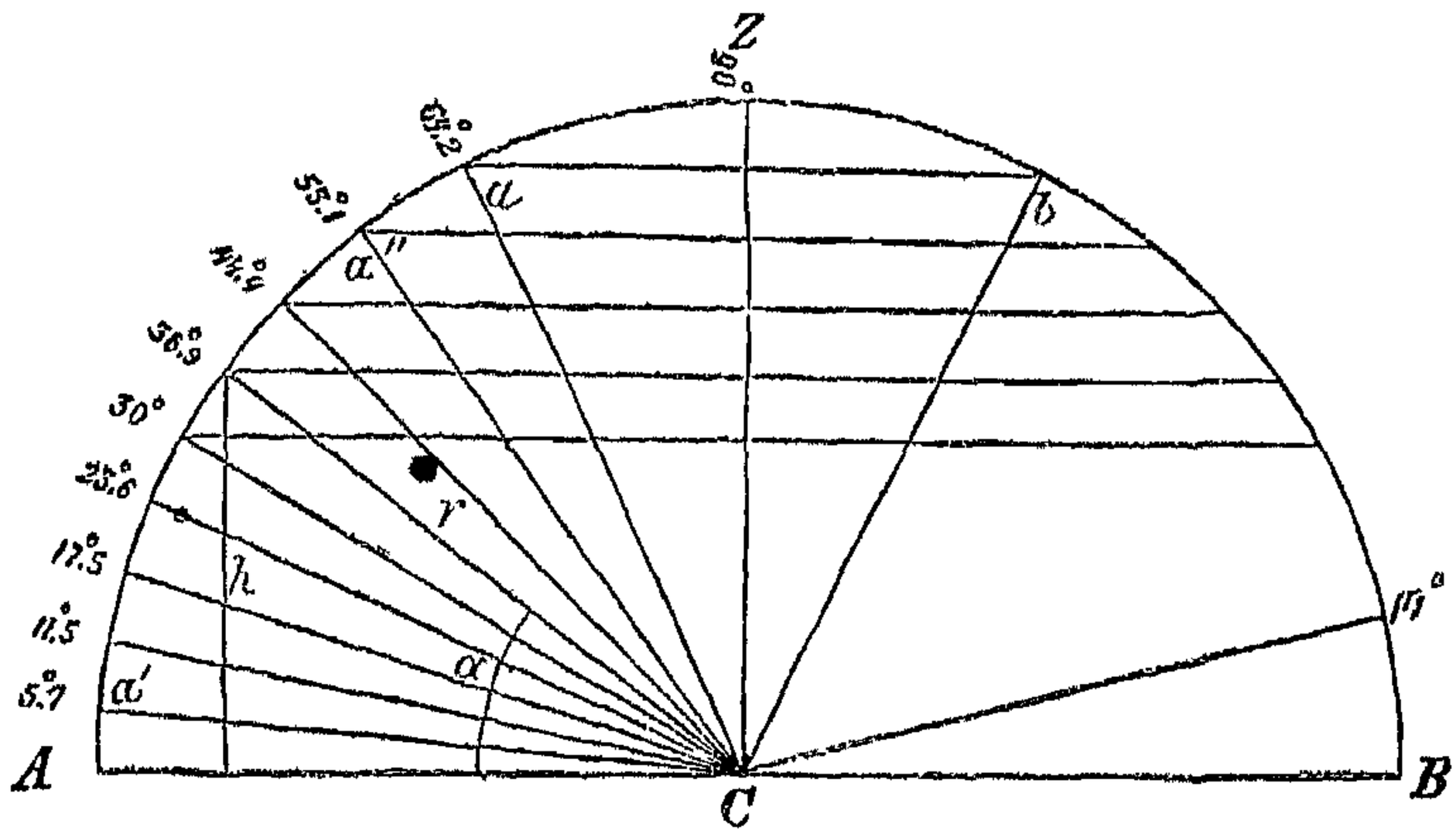


FIG. 52.

portion of sky covered by clouds is a cone-shaped framework of wire, such as is used at Pawlowsk. The eye of the observer being at the apex of the cone, the successive circles of wire as outlined against the sky divide it into zones, and the amount of cloud in each of these can be quite accurately estimated.

Altitude of Clouds.—It is a very important matter to obtain the elevation of clouds above the earth's surface, not only in order to measure the velocity of

the upper-air currents, but also to study the manner of cloud-formation ; for each of the recognised types has a distinctively physical cause, some of which are known with considerable certainty, but others are as

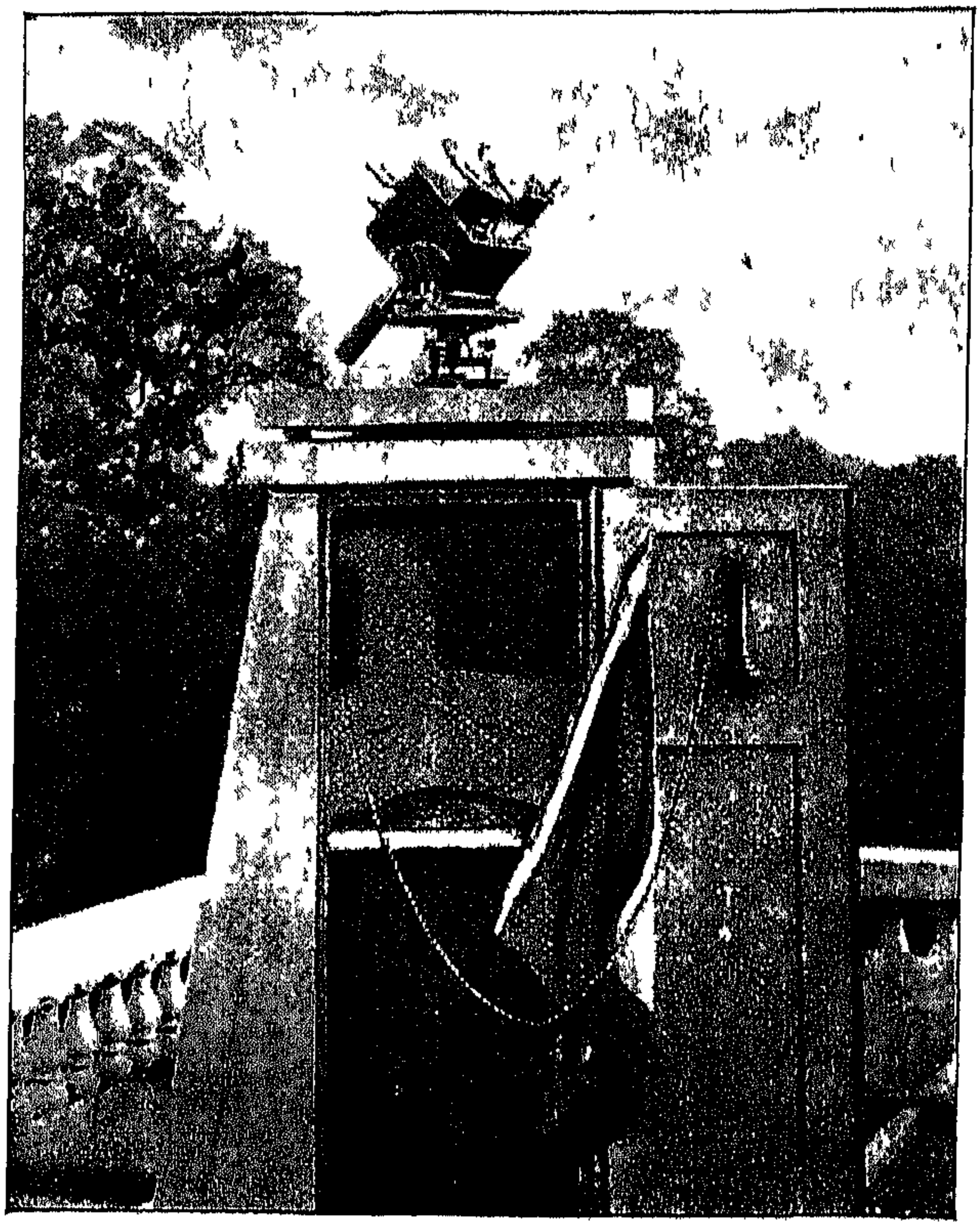


FIG. 53.

yet mere speculation. A number of methods have been proposed, the most successful of which promises to be that of simultaneously photographing the same cloud-region by means of two cameras mounted on alt-azimuth stands at the ends of a carefully measured

base line Knowing the altitudes and azimuths of any common points on the two photographs, and the length of the base line, a simple trigonometric computation (rapidly carried out by prepared tables or a

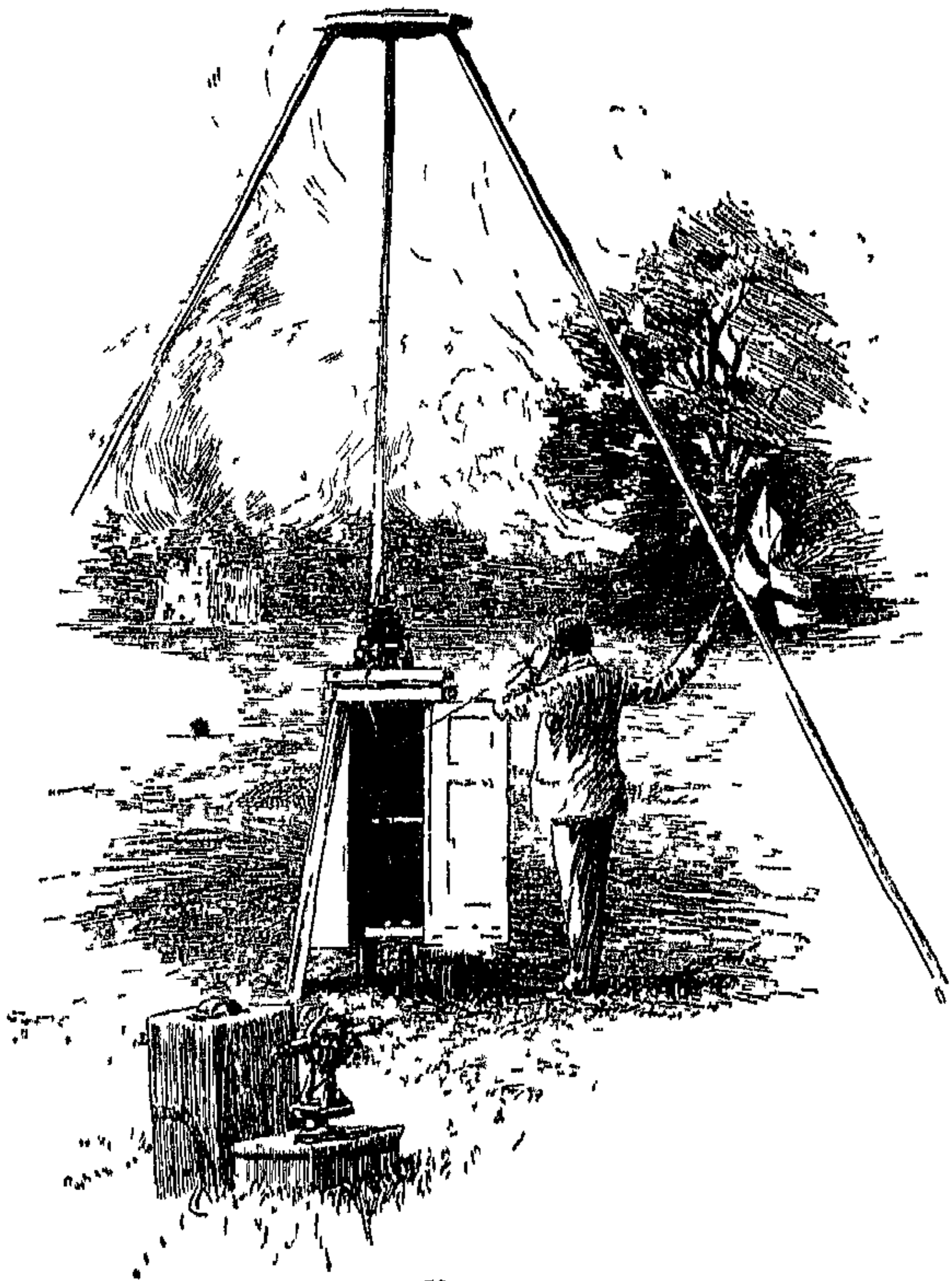


FIG. 54.

graphical process) gives the elevation, and the photograph shows exactly the kind of cloud which has been observed. Such an instrument is the photo-nephoscope (see Fig. 53), used at the Kew Observatory, and mounted by Abney about 1883.

The instrument in actual use is shown in Fig. 54, where one of the complete base stations is to be seen. The large tripod supports an overhead framework, which is necessary in adjusting the instrument. Communication is kept up between the observers at the two stations by means of signal flags and telephone connection. In fact, the telephone admits of such ready communication between the two stations that very useful observations can now be made directly by the observers without the application of photo-

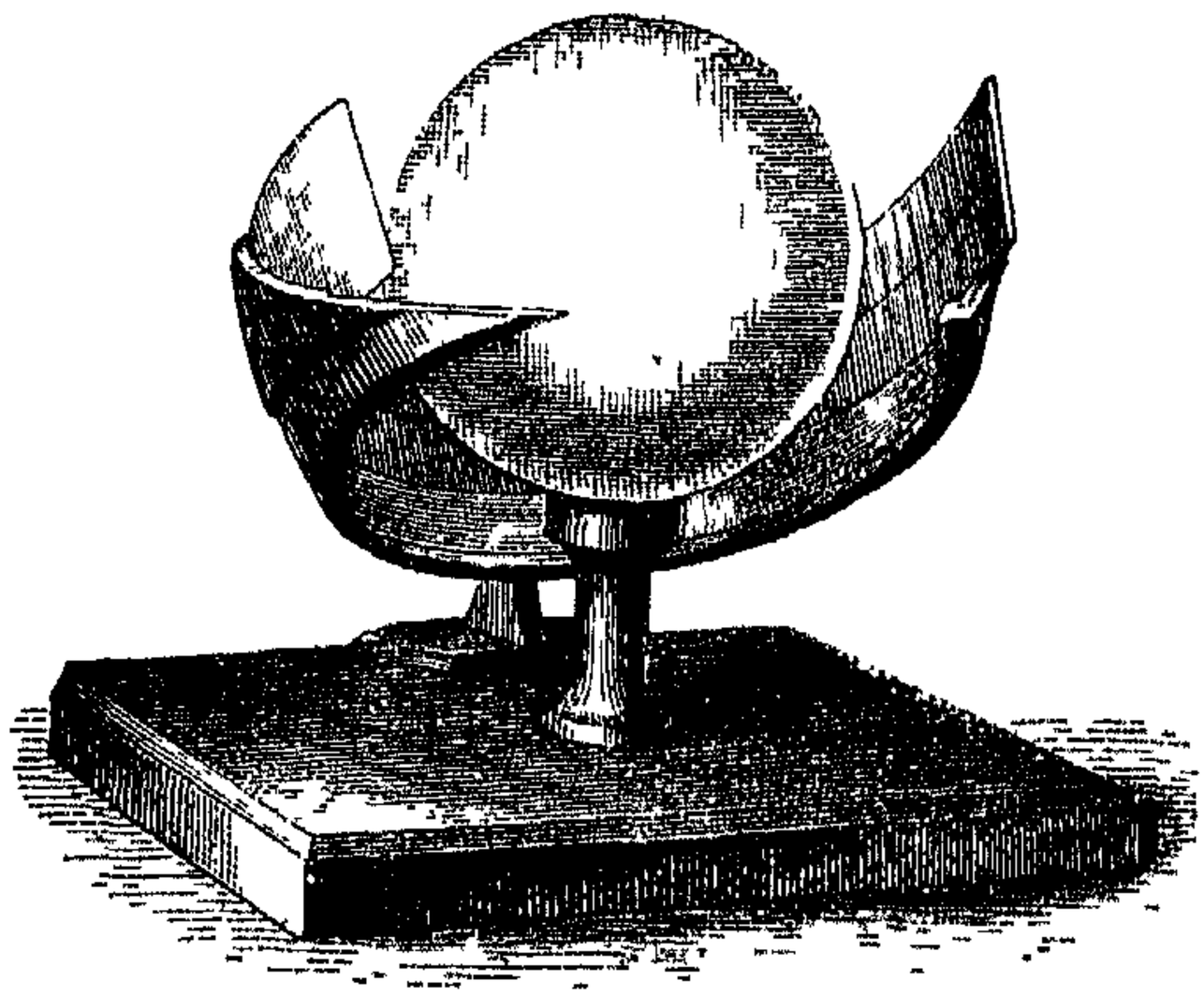


FIG. 55.

graphy, because the identification of some chosen point can be made with considerable certainty, which was an impossibility with slower methods of communication.

Sunshine.—The Campbell-Stokes sunshine recorder is the only instrument which has been used to any extent for the purpose of measuring the amount of sunshine; and beyond its introduction at some of the stations controlled by the English, its use is almost entirely limited to some few large observa-

tories. This instrument (see Fig. 55) consists of a spherical lens with the focus at a little distance from the surface. Partially encircling the lens is a strip of mill-board, so bent that its surface, held by means of a framework, coincides with the focal distance of the lens. The sun's rays passing through the lens burn a hole in the mill-board, and as the sun shifts its position the burning point on the board is likewise shifted, so that a narrow strip is burnt out. When clouds intervene this burnt strip becomes a broken line, so that its burnt part represents the time of sunshine and the unburnt part the time of cloud. By means of a graduation on the paper these times are converted into hours and minutes; but there is always a slight inaccuracy due to lack of definiteness in the edges of the burnt places, and the passage of clouds which obscure the sun for only three or four minutes is hardly noticeable.

A more accurate but much more troublesome method is the exposure of sensitised paper, which is affected by the action of sunlight.

Of the various other methods which have been proposed, and, as has been the case with many other devices for making meteorological observations, put into use by individual meteorologists, mention will only be made of Pickering's suggestion to apply in this case a variation of the idea which he has used so successfully with his meridian star photometer at Cambridge, U.S. The pole star has very little motion, and if a slowly-moving photographic plate is exposed toward it, a continuous record will be obtained on clear nights; but this will be broken by the passage of clouds which hide the star from view. Rotch has applied this method successfully at the Blue Hill

Observatory in Massachusetts. It will be seen that this method is supplementary to the Campbell-Stokes sunshine recorder, as the one can be used only by night and the other by day; but there would still remain the twilight hours unrecorded.

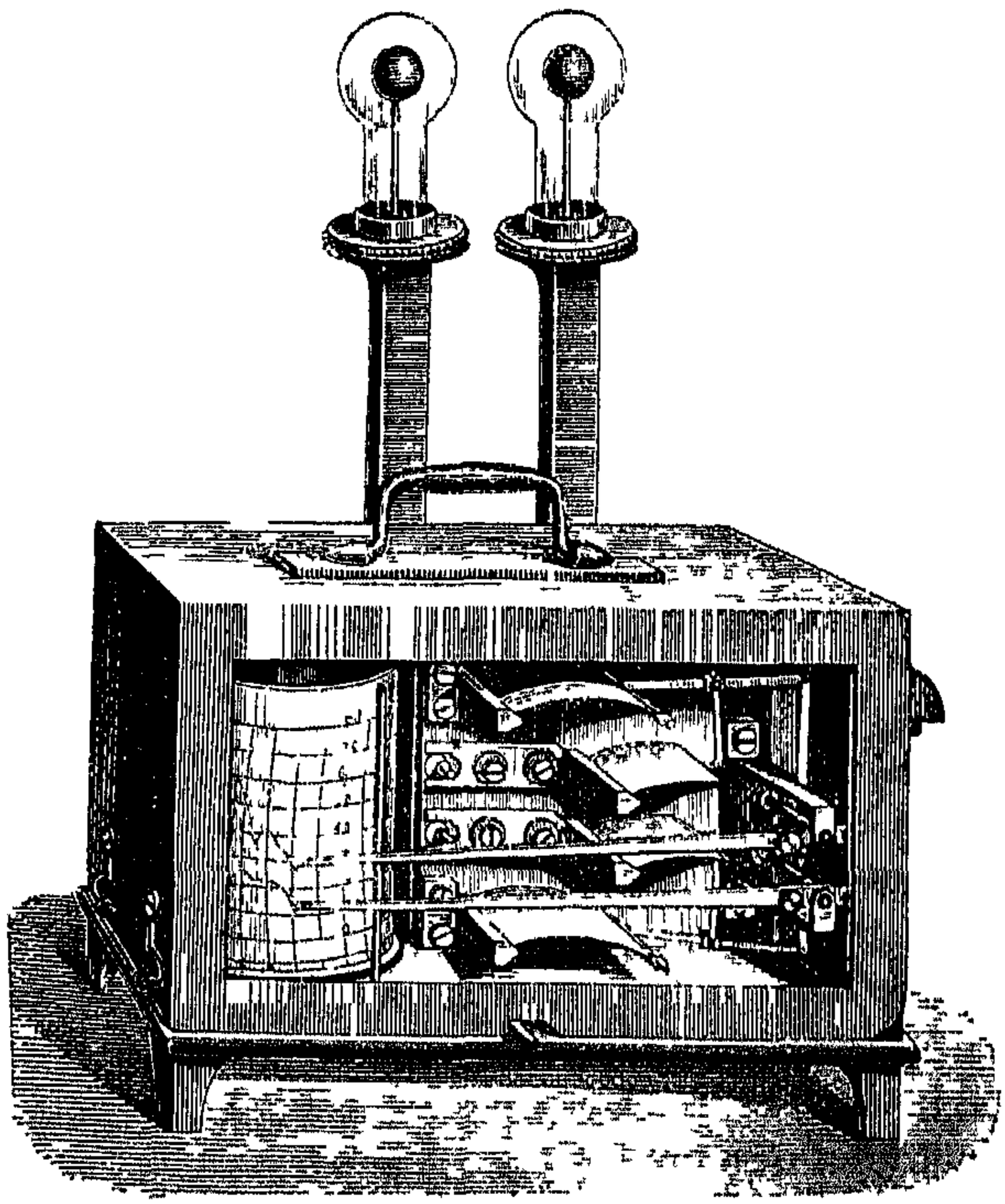


FIG. 56.

For obtaining a record of the times of cloud and sunshine the registering actimometer (Fig. 56) appears to be an especially valuable instrument. This consists essentially of two thermometers, one with a plain bulb and the other with blackened bulb, but

each placed in a vacuum chamber of glass. The form of registration shown in Fig. 56 is that made by Richard, of Paris. The record of the blackened bulb thermometer would show almost instantly the changes from cloud to sunshine; and in addition a computation would show the relative intensity of the sunshine on successive days. A good illustration of this is the use made of the actinometer by Upton on the Solar Eclipse Expedition to the Caroline Islands in 1883. By adopting Ferrel's formula for reducing actinometer observations he was able to show that on the day of the eclipse there must have been a slight haziness of the atmosphere, as the actinometer showed a less intensity of sunshine than was observed on other clear days, the amount being quite constant for some other days.

§ 6.—*Meteorological Observatories.*

History of their development.—For several centuries the word "observatory" conveyed only the idea of an astronomical observatory, and this meaning has become so deeply rooted that even now very few people would ask, "What kind of an observatory?" if reference is made to some institution under this name. In fact, in the earlier days of meteorology, the observations which were made and the apparatus used were of such a simple character that the place of observation was that which suited personal convenience and was freely changed at will, requiring no specially constructed building which distinctively marks the location of a telescope. The early observers were mainly physicians, teachers, cultivators of natural science, ecclesiastics, and others, who had no special

training in the use of instruments of precision. But astronomers also made observations and kept careful record of the meteorological elements; this they could easily do, as it required but a few minutes' time at stated intervals, and would not interfere with their regular work, of which it gradually became a part.

But as astronomy became a more exact science, astronomers increased also the accuracy of meteorological methods; and it was to them, more than to the early experimenters in physics, that we owe the gradual development of the modern systems of meteorological observing. In later years the introduction of observations of temperature and pressure of the atmosphere into astronomical computation rendered imperative the making of accurate observations of these elements at the various observatories. The permanency of location of the astronomical observatories has greatly increased the value of the meteorological observations made at them, and they furnish reference or normal conditions for the reduction of irregular observations at different places in their neighbourhoods. The observations made at the Paris and Greenwich Observatories furnish excellent examples of these long-continued records. For instance, the rainfall observations at Paris extend back over two hundred years.

In the astronomical observatories, too, the instruments were of the best construction, and these came to be used as standards for those of inferior construction and stability used elsewhere. This was particularly true for barometers.

A long continuance of this condition made meteorology seem to be a part of astronomical work; and

so, when national meteorological undertakings were commenced, the chief astronomical observatories were deemed the proper places for such centralisation as was necessary in carrying on this work: and when delicate self-registering apparatus came into use, the astronomers were about the only class of regular observers who had acquired the skill necessary for their manipulation. It was about the same with the making of observations of the earth's magnetism. Perhaps the most perfect development of this relation was that existing at the Paris Observatory up to within about fifteen years.

The interest which was aroused in observations of the phenomena of terrestrial physics by the work of Humboldt, about the beginning of the century, and which was continued a little later by Kupffer, Kaemtz, Sabine, and others, resulted in the gradual divorce of meteorology from astronomy; and it has become almost complete, so far as outside influence is concerned, although many astronomical observatories still continue to publish meteorological observations. While the independent organisation of many of the meteorological services was effected before this time, yet it was not until about the year 1850 that the great meteorological institutions, which have now become quite general, began to have an actual existence. The Central Physical Observatory of St. Petersburg and the Kew Observatory of the Royal Society are about the best examples we have of the newly-created institutions of that period.

Passing over the developing process which such meteorological institutions have undergone, but noting the fact that they early extended and still give to the department of magnetism the same nurture which

meteorology formerly received from astronomical observatories, their present general features will be outlined.

Central Observatories. — In each country which possesses a network of meteorological stations, there is a central institution, from which the work of the stations is directed and controlled, and to which their observations are sent for publication and discussion, or use collectively. These institutions have in general the same plan, but each one presents some special

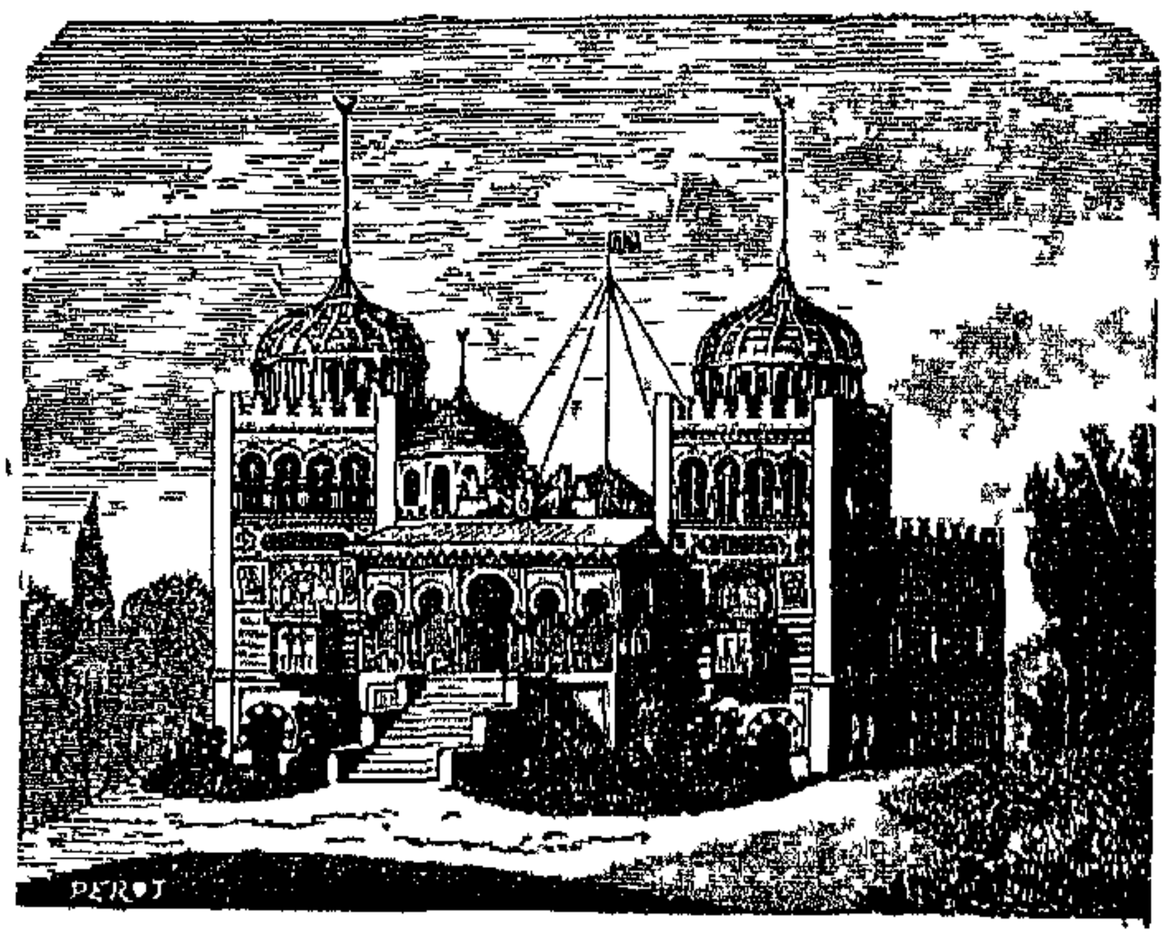


FIG. 57.

development of one or more features which gives it a distinct character of its own; and in noting the various fields of usefulness, special attention will be called to the institution showing them most markedly, although this last must be to a great extent a matter of personal judgment.

Before proceeding with the description of these central observatories, attention is directed towards the Paris Municipal Observatory of Montsouris (Fig. 57). The work of this observatory includes not only the study of the air from the meteorologist's stand-

point, but also from that of the chemist; and it is an institution which should be duplicated in every large city in the world. There are probably no more interesting reports of such work than the series of annual volumes devoted to "Meteorologie—Chemie—Micrographie. Applications à l'Hygiene," which is published (by Gauthier-Villars, Paris) under the title, *Annuaire de l'Observatoire Municipal de Montsouris.*

As these institutions were primarily needed as depositories for the collection and publication of observations from scattered observatories, they all perform this work, and in most cases it is done as well as could be wished. As the extent of country to be covered by each, and the corresponding number of tributary stations is very different for the different countries, this work is carried on by various systems, ranging from the method of the United States Weather Bureau, Washington, in which a large force of workers must necessarily perform their prescribed duties in a more or less mechanical manner, to that of the Austrian Bureau at Vienna, where similar work is done by, or at least comes directly under the eye of, scientists, any of whom could creditably direct the affairs of such an institution. In fact, this idea seems to be a governing one at the Vienna Central Meteorological Institution; for it is the most conservative of all the great central offices; its official work consisting of the making of local observations, the oversight of its secondary land stations, the preparation of the data thus collected for the international form of publication, and the issuing of weather forecasts from a city office totally removed from the main Observatory at Hohewarte; and probably nowhere else can

one find the unity and air of cosiness which is to be met with there, and which is due to the housing under one roof of about all that pertains immediately to the institution. At this observatory nearly all of the upper portion of the building is used as dwelling apartments for the chief scientists, thus allowing them to have easy access to the splendid library and to the work-rooms at all times. It must be remembered that this observatory has been a centre of international interest, and its influence widely felt through the agency of the meteorological journal which has been edited there for nearly twenty-five years, and although the official tabular publications contain little personal work of the director, Dr. Hann, yet his wonderful industry as a meteorological writer and critic, as shown in other channels, is unsurpassed.

While some of these Central Bureaus are so located as to combine the work of centralisation and that of a well-equipped and located observatory, such as is to be found at Höhewarte, Vienna, and at the Seewarte, Hamburg (Fig. 58), yet in most cases it has now come to be considered desirable to separate the two kinds of work by having a city office for administrative work, and an affiliate observatory at a sufficient distance in the country to ensure its best and most successful operation. Thus we find Kew Observatory to a great extent under the direction of the London Meteorological Office, Pawlowsk related to the Central Physical Observatory at St. Petersburg, and Parc St. Maur under the Central Meteorological Bureau at Paris. This is certainly the proper arrangement for securing the retirement and uninterrupted routine which are so necessary for the highest development of observatory work.

Special Work of some Observatories.—The work of verification of instruments to be used in making observations is a most important function of these central institutions, but such a department of work is much more fully developed in some than in others. No observatory has carried this on with a greater degree of success than that at Kew (Fig. 59), which is known all over the world by the certificates it has issued with instruments for use in nearly every land. While

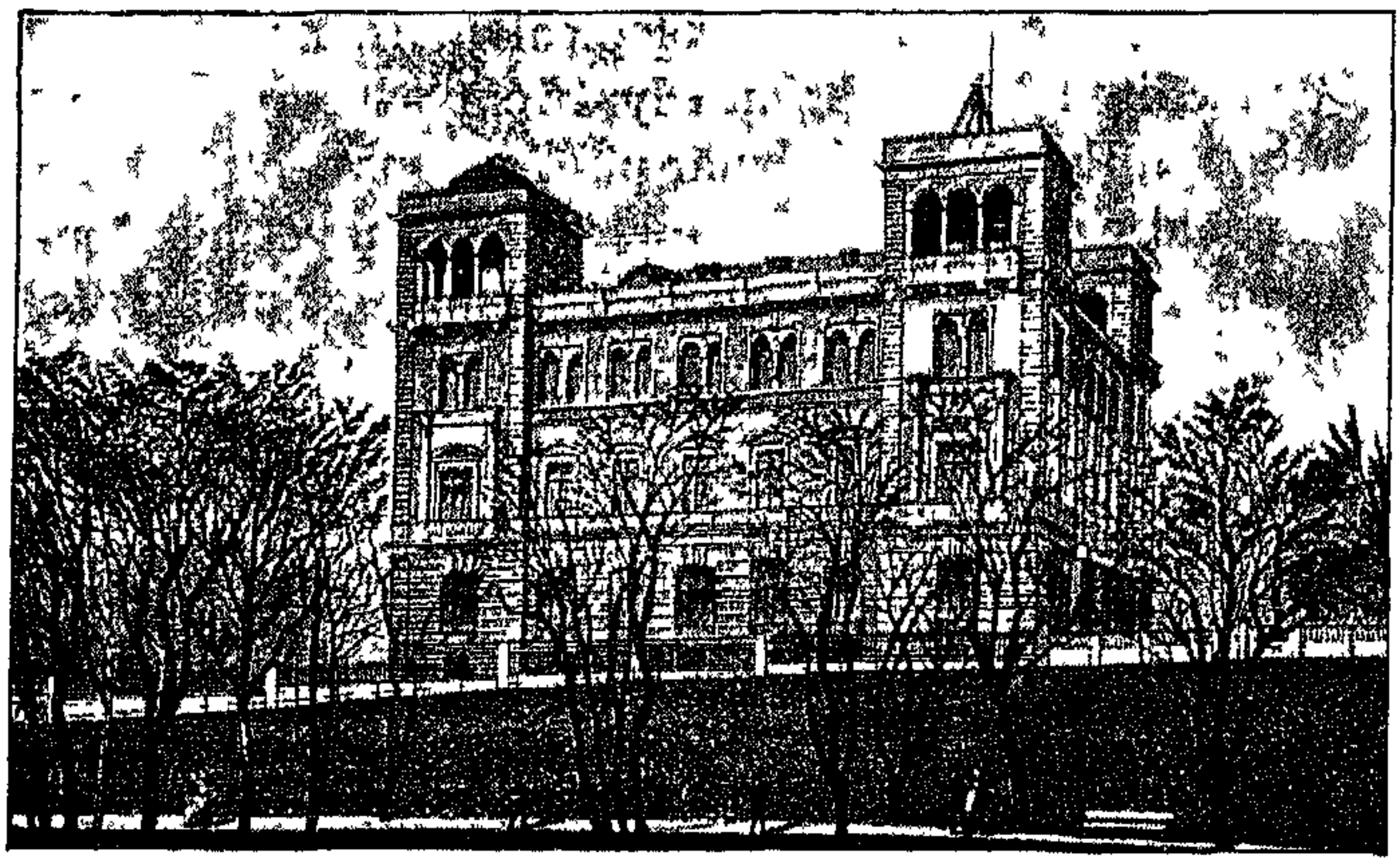


FIG. 58

this work at Kew is not of a higher order than that at some other institutions, as, for instance, the Central Physical Observatory at St. Petersburg, yet its influence has perhaps equalled that of all the others combined, especially in the extension of the matter to questions of practical life. About twenty years ago it was decided to take advantage of the reputation already acquired by the observatory, and establish a bureau for the testing of certain kinds of apparatus,

but principally those used in terrestrial physical measurements, and to make a regular charge there-

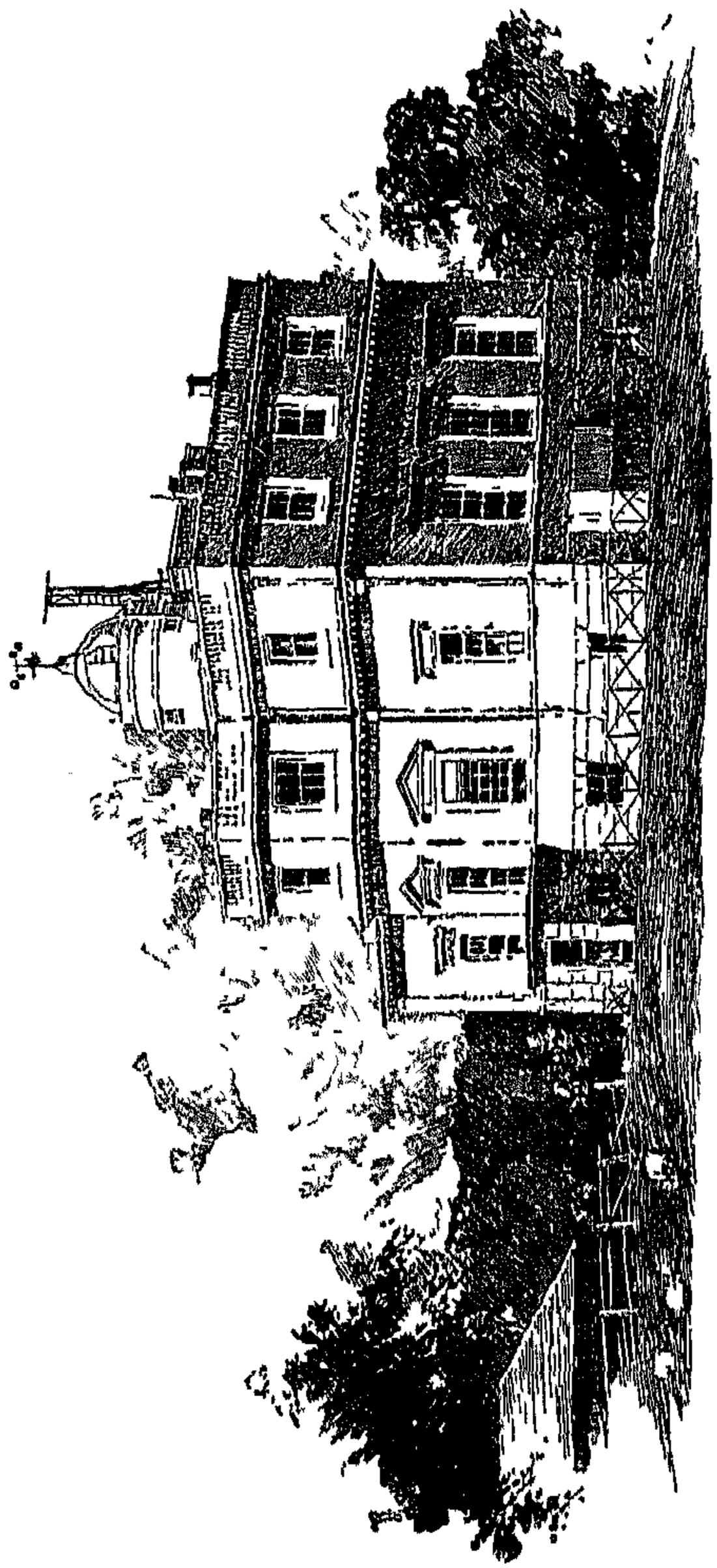


FIG. 59.

for. This work at Kew has grown to enormous dimensions, and the number of instruments verified

in 1890 was almost 20,000, of which about 12,500 were clinical thermometers. The revenue derived from this department defrays almost, if not quite, all the expenses of the whole observatory. The success at Kew has emboldened other observatories to follow its lead in this partially commercial enterprise.

The work of weather forecasts and storm warnings is carried on with the highest degree of promptitude and efficiency by the Washington Central Office of the United States Weather Bureau. This is due to the following causes: the work of predictions has been hitherto the chief work of the service, to which all else was secondary; the entire time of the observers, on whose telegraphic reports the forecasts are based, is controlled by the service; a large amount of money is available for telegraphic purposes, and the right of precedence in the use of wires is maintained; and as most of the storms come from the westward, they cannot approach the Central and Eastern United States so unexpectedly as those arriving on the European coasts. Of the European weather forecasts and storm warnings, those by the English office at London, and the German office at Hamburg, are the most important and the most efficiently conducted.

But it is as meteorological observatories that these central offices deserve most attention; as it is to be expected that one will find there the model organisations of the country not only as regards methods, but also apparatus, and that the highest ideal of what constitutes observational meteorology will be realised. In many cases it has been impossible for the present meteorologists to carry out their own ideas very fully, as they have been obliged to make use of apparatus

already provided, and an adequate sum of money to carry on the work, as it should be done, is not at their disposal.

The Observatory at Pawlowsk, Russia.—As a clearer idea of the work done at one of these observatories can be obtained by describing an actual case, the one which seems to me to be the nearest to the ideal observatory has been selected for this purpose.

The Pawlowsk Observatory came into existence under the most favourable circumstances. The director, H. Wild, whose ideas are embodied in it, had devoted a great amount of time during the fifteen years preceding its foundation to the study of an improvement in meteorological apparatus. His equipment of the astronomical observatory at Berne with meteorological apparatus (before and about 1865) marks an important epoch in the history of applied meteorology; and when, a few years later, he became director of the Central Physical Observatory at St. Petersburg, and consequently also of the Meteorological Service of Russia, he instituted equally important improvements in the methods of using meteorological apparatus, and especially in the manipulation of data furnished by self-registering instruments. But the facilities at his disposal were not just what were necessary to carry out fully his ideas: the opportunity for this came with the building of the Pawlowsk Observatory in 1876. Situated in a corner of the park of the Grand Duke Constantine, about twenty miles south-east of St. Petersburg, and one and a half miles from the village and summer resort, Pawlowsk, the observatory is located in a partially cleared grove of fir trees near the juncture of the wooded and open country. The land around is level or slightly rolling, and the

buildings are so situated that the exposition of various instruments is good, except in the case of the anemometer, which may not be at a sufficient distance above the level of the tree-tops to feel the full force of the wind.

In order to obtain proper drainage, advantage was taken of the natural slope of the land to draw into an excavation the surface water and thus form a pond, which could also serve for evaporation measurements on a large scale.

The method of detached buildings which has grown in favour with astronomers, was adopted as the plan of arrangement. The grounds lie between two highways, and on the side of the main entrance are placed the half dozen economic buildings, residences for the staff, &c, and at a distance of about 150 feet from the road is placed the main observatory building (rear view, Fig. 60). At some distance to the rear of this building are various minor buildings for the exposure or housing of single instruments, while still further back and near the centre of the grounds are the main magnetic buildings, one of which, above ground and of wood, is for absolute magnetic measures, and the other is an under-ground (or rather, earth-covered) chamber, and contains the self-registering magnetic apparatus. The buildings and equipment cost originally about £15,000.

The principal building, most of which, as is usual in such institutions, is mainly given up to the accessory work rather than direct observation, has the floor of the lower story slightly elevated above the ground, and in this story are the porter's dwelling room, a mechanic's work-room fitted up for metal and wood working, a physical laboratory room with the

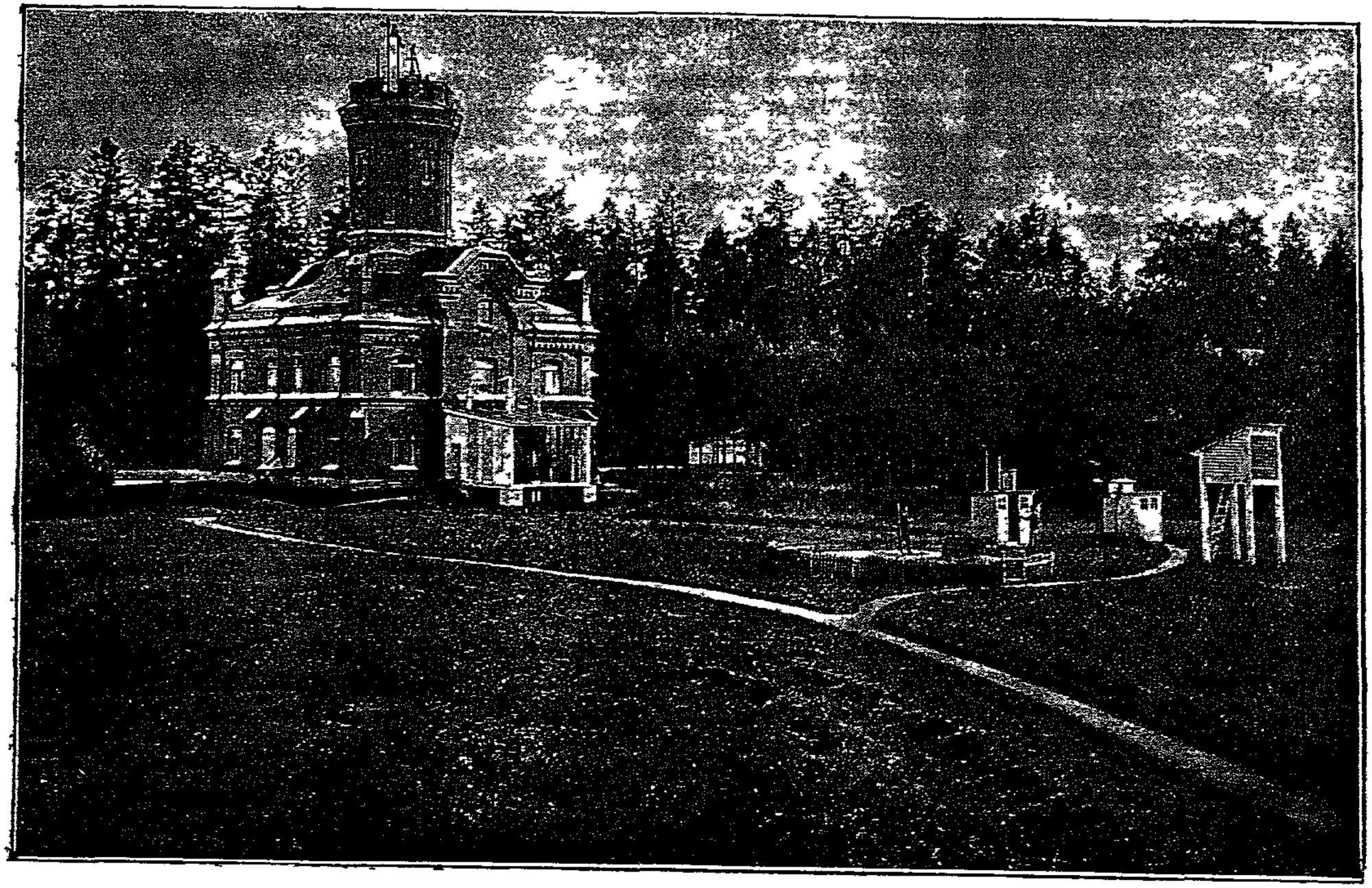


FIG. 60.

necessary comparator for measurements of length, scales, arrangements for magnetising steel magnets and investigating them, a chemical laboratory, a photographic laboratory and dark room, a battery room, and at the centre there is placed a central heating apparatus. Above this last, in the centre of the second story, is a small vaulted rotunda, in which are kept those instruments which require a constant temperature, viz., self-registering barometers, clocks, chronometers, &c.; and surrounding this central room is a room for the superintendent, one for the physicist or senior observer, two large ones for the younger observers and library, and one for the current observer; and this last room contains a number of meteorological instruments and self-registers, and is connected with the magnetic observatory by telephone. The roof of the tower is 23·5 metres above the ground, and serves as a place for observation of clouds, as well as for the exposition of a sunshine recorder, rain-gauge, registering wind-vane, and anemometers; these last being mounted from 3 to 5 metres above the platform. Special attention is called to the peculiar construction of the tower near its roof, that shape having been chosen which was considered as best adapted to prevent vitiating effects of winds deflected by such an obstacle as the tower.

Attached to the north side of the building, near the ground, is a large instrument-shelter open towards the north (see Fig. 60). This shelter is 5 metres high, and 5·3 metres long and wide, and the roof is double, and slightly inclined. The side nearest the building is made up of glass windows and doors, which allows space for a corridor between this and the wall of the building, and in case of extra refinement of observa

tions the instruments can be read through these windows by means of telescopes. The sides of the shelter are open to a height of 1·5 metres, but above this are closed by adjustable louvred blinds. The various instruments are approached by means of wooden grating walks; otherwise, the shelter is floorless to the sod beneath.

The instruments are mounted on separate piers or piles. In this large shelter are placed: the special thermometer shelter for direct observation of the temperature and humidity of the air by means of the psychrometer, hair hygrometer, maximum and minimum thermometer, self-registering thermograph and hydrograph; the inner shelter for the direct observations having a ventilating pipe reaching above the roof of the main shelter. A photographic psychrometer of the Adie (Kew) pattern, and a scale evaporimeter for direct observation complete the list of instruments exposed here. To the north of this main building is a large cleared space (partly shown in the foreground of Fig. 60), in which are located various isolated instrument shelters and other smaller buildings in which instruments are mounted.

I am indebted to Director Wild and the Superintendent, Dr. Leyst, for the following details concerning the Pawlowsk Observatory. They show the methods of a well-appointed meteorological observatory with a completeness not heretofore published.

Personnel of the Pawlowsk Observatory.—To conduct a completely equipped observatory the time of at least three persons is necessary, in order to carry on the meteorological observations and reduce them for publication; the addition of another person will permit the parallel work to be done for observation

of the earth's magnetism. At Pawlowsk the staff consists of a superintendent, a senior observer, three junior observers, a skilled mechanic, and one or two persons to perform the duties of messenger, &c.

The superintendent, in addition to his responsibilities as such, personally supervises the working up of the magnetic observations, while the senior observer does the same for the meteorological observations. These two positions are filled by men of decided scientific talents and attainments, who have had a careful preliminary training at the Central Physical Observatory; the secondary position having in fact served as a stepping-stone to higher positions of scientific trust for a number of men. The younger observers have been men of more moderate attainments, and their work is entirely a routine; and consists of the making of prescribed observations, and doing the laborious part of putting these in a form for use in the discussions made by their senior officers. There is also a large amount of observing, such as the determination of instrumental constants, investigations of new instruments and methods, which devolves upon the superintendent and senior observer. During the summer months, when the Director resides at Pawlowsk, a great amount of such work is carried out, or planned for future development.

METEOROLOGICAL INSTRUMENTS IN USE AT THE PAWLOWSK OBSERVATORY IN MAY, 1891.

I. Air Pressure.

For Direct Observation.

1. Mercurial barometer, Fuess No. 247, 1st class, for controlling observations and manipulation of the barograph.

2. Mercurial barometer, Turettini No. 58, 2nd class, for observations as at stations of second order.

Self-Registering.

3. Mercurial balance barograph, Wild-Hasler, with temperature compensation and arrangement for overcoming the adhesion of mercury to the glass; for hourly values of pressure to be published. Registers electrically every ten minutes.
4. Mercurial balance barograph, Sprung-Fuess, with sliding weight, tapping apparatus for overcoming the adhesion of the mercury to the glass, without temperature compensation. Registers continuously. For control.
5. Aneroid-barograph of Richard Bros. Registers continuously. For control.

Nos. 1 to 4 stand in the round central vault-like hall with almost constant temperature; No. 5 stands in the room for day service. All at the same altitude.

II. Air Temperature.

For Direct Observation.

Mercurial enclosed scale (Fuess) thermometers of Jena glass, spherical bulb, graduated to $\frac{1}{5}$° C.

1. In the sheet-zinc small shelter in the normal shelter (Wild's normal exposure), for stations of second order. Ventilation current 2·5m. per second.

2. In the sheet-copper shelter with lattice floor in Wild's new shelter. Ventilation 5m. per second. For control and comparison.
3. In the case of the thermograph B, Wild-Hasler, on the grass plot; for the manipulation of the thermograph registers.
4. In the shelter of the thermograph C, Wild-Hasler, near the house; for the manipulation of this thermograph.
5. In the sheet-copper shelter, near the house, ventilation 2½m. per second; for comparison with the exposure on the house.

Self-Registering.

6. Thermograph B of the form Wild-Hasler, bimetallic spiral (platinum-silver), electrical control register every 10 minutes, natural ventilation through walls made of louvred blinds and a 3m. high black painted chimney, in Wild's shelter, on the open grass plot; for the publication of hourly temperature values.
7. Thermograph C, Wild-Hasler, same as 6, but brass-steel spiral and shorter ventilation chimney, in the thermometer pavilion, with walls of louvred blinds, open towards the north, on the north side of the main building. For control.
8. Thermograph by Richard Bros., in Wild's normal shelter, with a Bourdon tube, registering continuously for 7 days on a single chronograph sheet.

Extreme Thermometers.

9. Maximum: Mercurial thermometer with long detached column of mercury. Minimum: Spirit thermometer with index — In the shelter with thermograph B, Wild-Hasler.

10. Maximum and minimum thermometer, same as 9, in the shelter of thermograph C, Wild-Hasler.

Nos. 1, 2, 3, 6, 8, 9, in shelters, distant 40–50 metres from trees and buildings; Nos. 4, 5, and 10 in the same as No. 7.

III. Earth Temperature.

1. Under pure sand surface of the fineness of quartz sand, and free from sod and snow.
   - 1 thermometer (common) on the surface.
   - 4 thermometers (common) in vertical glass tubes, the bulbs in brass hoods, at the depths of 0·05m., 0·10m., 0·20m., 0·40m.
   - 4 thermometers in ebony tubes at the depths 0·40m., 0·80m., 1·60m., 3·20m.
   - 4 thermometers in clay tubes at the depths 0·40m., 0·80m., 1·60m., 3·20m.
   - 1 maximum and 1 minimum thermometer (like II., 9) on the surface.
2. Under the natural surface (in summer under sod, in winter under snow). The ground of the fineness of quartz sand.
   - 5 thermometers in ebony tubes, which project one metre out of the ground and are painted white, at the depths of 0·00m., 0·20m., 0·40m., 0·80m., 1·60m.

3. On the natural surface (in summer on close-cut sod, and in winter on snow).
   1 common thermometer.
   1 maximum and 1 minimum thermometer, like II., 9.

IV. Radiation.

1 radiation thermometer by Hicks (black bulb in a vacuum).

V. Moisture.

For Direct Observation.

1. Psychrometer } in Wild's normal shelter
2. Hair hygrometer } (see II., 1).
3. Psychrometer in Wild's new shelter (see II., 2).
4. Psychrometer in sheet-copper shelter near the building (see II., 5).
5. Psychrometer } In the shelter of the thermo-
6. Hair hygrometer } hygrograph B (see II., 6).
7. Psychrometer } In the shelter of the thermo-
8. Hair hygrometer } hygrograph C (see II., 7).

Self-Registering.

9. Hygrograph B, Wild-Hasler, 1 hair, electrical contact register every 10 minutes (see II., 6); for hourly values of absolute and relative moisture.
10. Hygrograph C, Wild-Hasler, 1 hair (see II., 7); for control.
11. Hygrograph, Richard Bros., fitted with hair registering continuously for 7 days, in the Wild normal shelter. For control.

12. Hygrograph, Richard Bros., fitted with horn, registering continuously for 7 days. For comparisons.

VI. Precipitation and Evaporation.

For Direct Observation.

1. 1 pair Wild's rain-gauges for observations as at stations of second order.
2. 1 pair Wild's rain-gauges with Nipher's shield, for special observations (published in the *Annalen*) and control.
3. Wild's balance evaporimeter in a louvred shelter on the open lawn.

Self-Registering.

4. Ombro and atmograph, Wild-Hasler, with separate winter and summer collectors, a balance like that for Wild's balance-barograph, electrical contact registers every 10 minutes, in a shelter on the open lawn, evaporation basin in a louvred shelter on the roof. Used for the hourly record of the evaporation and precipitation. Is controlled by the rain-gauge, and balance evaporimeter.

All these instruments stand near each other on the open grass plot.

VII. Direction and Force of the Wind.

For Direct Observation.

Anemograph, Oettingen-Schultz. Direction in degrees of the vane on the tower. For control on the wind registration by electrical transmission of 8 recording pencils (16 direc-

tions) in the observing room below. Force, read on the apparatus in the tower, for control on the indicator (electrical transmission) in observing room below.

Self-Registering.

Anemograph, Munro, registers continuously on metallic paper the force and direction of the wind.

VIII. Cloudiness.

For direct observation, a cone formed of wires, and including 120°, in which the field of observation is divided into four parts by cross wires directed towards the cardinal points of the compass. For observations of the whole sky from the tower, as at stations of the second order, no instrumental means are employed.

An instrument for determining the angular velocity and direction of the clouds, by Fineman's method, and a cloud camera with an angular opening of 90°, for direct observation and photography (by Hesekiel, Berlin) are not in regular use.

IX. Sunshine.

1. Heliograph by Campbell (sunshine recorder); for the publication of hourly values.
2. Heliograph by Jordon, photographic, for control. Both instruments stand on the platform of the tower, with free exposure.

X. Electricity of the Air.

Electrometer, Mascart-Carpentier, Wild's water collector with constant water-pressure, and Mascart's form of foot receiver.

Wild-Edelmann scale telescope which is, at the same time, arranged for direct readings and for photographic registration. A transportable electrometer by Exner, Vienna, is not in regular use.

XI. Height of Snow.

6 metal strips divided into centimeters; one stands in a wooded exposure, the other 5 in an open exposure.

DAILY ROUTINE OF THE METEOROLOGICAL OBSERVERS AT THE PAWLOWSK OBSERVATORY (IN MAY, 1891).

The three younger observers have, alternately, 24 hours of observing service, another 24 hours of sub-service, and the third 24 hours free. The observer in sub-service is regularly on duty from 9 A.M. to 4 P.M., except from 12 to 1. The one in service is on duty from 6.20 A.M. to 9 A.M., after being awakened shortly before 6 A.M. by a night watchman observer, and is released at 9 A.M. by his successor, who remains on duty till 2.10 P.M., and then after dinner at 4 P.M. is again on duty till 10.10 P.M.; if there is a thunderstorm in the night he is awakened by the night watchman. From 2.10 to 4 P.M. his place is supplied by the observer in sub-service.

The daily order of making the regular observations is as follows:—

6.20–6.38 A.M. Revision of instruments; in winter the cleaning of frost from the thermometers; moistening the psychrometers; comparison of the pocket-watch of the observer with the standard clock of the observatory.

6.38 A.M. First reading of Oettingen's anemometer.

6.39 A.M. Reading of the electrometer at rest, and connecting it with the water collector.

6.43 A.M. Observation from the tower of the quantity, form, and direction of clouds for the whole heavens.

6.44 A.M. The wind direction read in degrees from Oettingen's anemograph.

6.47 A.M. Observation of atmospheric electricity.

6.48 A.M. Second reading of Oettingen's anemometer.

6.50 A.M. Reading the attached thermometer and control barometer (Fuess) of the 1st class.

6.52 A.M. Reading attached thermometer and station barometer (Turettini) of the 2nd class.

6.55 A.M. Reading the psychrometer before ventilation in the copper shelter on the north side of observatory.

6.56 A.M. Reading radiation thermometer, and thermometer on the sod.

6.57 A.M. Reading psychrometer after two minutes of ventilation.

6.58 A.M. Reading psychrometer and hair hygrometer before ventilation, in the zinc shelter within the isolated normal wooden shelter.

7.00 A.M. Reading same as preceding, after ventilation.

7.01 A.M. Reading psychrometer, before ventilation, in the sheet copper shelter with lattice floor, in the new shelter.

7.02 A.M. Clouds observed through a cone of 120°; amount, form and direction of motion.

7.03 A.M. Reading psychrometer, after ventilation, same as at 7.01.

7.04 A.M. Reading earth thermometers in a sand surface free from snow and sod, at the depths 0·00m., 0·05m., 0·20m., 0·40m., 0·80m.

7.06 A.M. Reading 4 ground thermometers under the natural surface (sod or snow) at the depths 0·00m., 0·20m., 0·40m., 0·80m.; measuring the height of the snow in winter.

7.10 A.M. Reading psychrometer and hair hygrometer in the shelter of the thermo-hygrograph B (Wild-Hasler) on the lawn.

These are used for the markings, at 7.10, on the thermo-hygraph and Ombro-atmograph.

7.12 A.M. Temperature, of the water in the evaporation vessel of the evaporimeter, in the evaporation vessel of the Ombro-Atmograph, and the air in the shelter with these.

7.13 A.M. Exchange of the rain-gauge, and measure of the precipitation; if snowy, after the melting of the snow.

7.19 A.M. Wind direction (to 16 directions), and the first reading of the indicator of the wheel-work on the anemometer Oettingen-Schultz.

7.20 A.M. Second reading on this wheel-work, and repetition of the wind direction. After this the reference marking is made on the balance barograph Wild-Hasler.

7.22–7.50 A.M. Reduction of the observations just made and entering them in the proper columns.

7.50–8.10 A.M. Magnetic service.

8.10–8.20 A.M. Arranging and telegraphing the meteorological telegrams to the Central Observatory at St. Petersburg, by means of a telegraphic apparatus, in the

service room, used by the observer in service.

8.20–9.00 A.M. Completing the reductions, and service in the photographic laboratory.

9.00 A.M. At 9 o'clock change of observers for 24 hours.

9.00–9.58 A.M. Control of all reductions and computations of the observations of the previous observer in the last 24 hours. Service in the photographic and chemical laboratory.

10.00 A.M. Reading the psychrometer and hair hygrometer in the shelter of the (second) thermo-hygrograph C, by Wild-Hasler, and marking the registration at 10 A.M.

10.02 A.M.–12.20 P.M. Continuation of the work of 9.0–9.58, and afterwards work on the records of the self-registering instruments.

12.20–1.03 P.M. The same as from 6.20–7.03, except that from 12.39–12.48 the anemograph Munro is to be attended to (paper changed, clock wound, &c.).

1.04 P.M. Reading of 13 ground thermometers under a sand surface at the depths 0·00m. to 3·20m.

1.06 P.M. Reading of 5 ground thermometers under the natural sur-

face at the depth 0·00m. to 1·60m.

1.10–1.12 P.M. Same as 7.10–7.12.

1.13 P.M. Reading of Wild balance evaporimeter.

1.19–2.10 P.M. Same as 7.19 8.10.

4.00 8.20 P.M. Working up the observations and registrations of the instruments.

8.20–9.12 P.M. Same as 6.20 7.12, except that the two heliographs of the form Campbell and Jordan are to be attended to between 8.39 8.43 P.M In summer, as long as the sun sets after 8.40, this is done after sunset.

9.04 P.M. Reading and setting the two extreme thermometers on the sand surface.

9.13 P.M. Reading and setting the extreme thermometers on the natural surface (sod or snow) and of 4 extreme thermometers for air temperature.

9.19 10.10 P.M. Same as 7.19 8.10 A.M., except that in the evening the daily averages for all the observations are to be computed.

The extreme care taken in the matter of observing is shown by the fact that the standard clock of the observatory is regulated by astronomical observations made at Pawlowsk, although the great observatory of Pulkowa is only a few miles distant. In order to

insure greater accuracy an electric time signal is automatically transmitted to a local gong, in some cases, so that the exact time of observation may be made known to the observer, who stands in readiness to accomplish his duty at the sounding of the gong.

On certain days of the week and month there is special work to be carried out. Every Monday at 11 A.M. four Richard self-registers are to be attended to, and on this day water has to be distilled in the chemical laboratory. On every first day of the month the paper for the preceding month is taken from the Wild-Hasler instruments and replaced. On the last day of every month the books and sheets for meteorological and magnetic work for the next month are prepared. The observer in sub-service, on 16 prescribed days of the month, reads for 2 or 3 hours the absolute magnetic variations apparatus. In the remaining time he works on observation and registration records.

Numerous series of experimental observations are carried on at the observatory, which require additional service on the part of all the observers.

Every day fifty-eight thermometers for the meteorological and magnetic service are regularly read by the observers. The working up of the meteorological results is carried on by two or three of the younger observers, and supervised by the senior observer. Before the close of the month, the results of the preceding month must be completely worked up. The first proof sheets of the publications are read by the one who has worked up the results; the second, by the one who has supervised them. All constants of the instruments, correction tables, reduction scales, &c., are obtained by an observer, and supervised by the senior

observer, or by the superintendent. The three younger observers work up under the supervision of the superintendent the magnetic observations and registrations.

§ 7.—*Mountain Observatories.*

Early History of Mountain Meteorology.—It became evident, very early in the history of instrumental meteorology, that if satisfactory explanations were to be given of the observed phenomena, something must be known of the conditions existing at some distance above the earth's surface at ordinary levels. Pascal recognised this when he caused the Torricellian tube to be carried to an elevated position, in order to note the change in atmospheric pressure.

But the originators or instigators of what is now termed high-level meteorology were Saussure; Gay-Lussac, and Humboldt; and each had a separate field of action. Saussure's remarkable work in the Alpine region, published in his *Voyages dans les Alpes* (Neuchatel, 1787–1796), was a revelation of what could be accomplished by such methods; and his results were at once applied to the forming of new theories. Gay-Lussac, about this same time and a little later, made his wonderful balloon ascents which for boldness and importance have never been surpassed, except, perhaps, by those of Glaisher; and his observations furnished the necessary data for extending the atmospheric theories to regions far above those which had been previously visited by man. Humboldt made an immense number of observations during his travels in the very elevated regions of the New World; and such was the care exercised by him, that even now his results have much more than historic interest, although the more complete work of

recent years gives them at present mainly a local value.

But it was not enough to gather together the results obtained during irregularly conducted excursions to high altitudes. It was necessary to establish permanent places of observation; and this could be done only by locating them high up on the mountains.

Of the mountain observatories, that on the Schneekoppe, Germany (lat. 50° 44′ N., long. 15° 44′ E.) has probably the earliest observations, since they date from 1786, but the records are fragmentary, and have attracted little attention. Most of these observatories have been established within recent years.

Use of Observations from Mountain Observatories.—In order to understand the conditions necessary for the correct classification of elevated observatories, it must be made clear what they are expected to accomplish.

Although much has been said on this subject in connection with the establishment of the older mountain observatories, yet the Vienna Meteorological Congress of 1873, in advocating a more universal adoption of this kind of work, considered it advisable to have a clear statement of the question, and Dr. Hann was appointed to make a report, which was submitted to the Meteorological Congress of 1879 at Rome. In general, these observations are expected to give the daily, seasonal, and annual march of the meteorological elements at that elevation above the sea; the decrease of temperature, variation of changes in pressure, increase of wind velocity, decrease of vapour capacity, increase of rainfall (to certain limits and then decrease), &c., with the elevation above the sea-level; and to show what relations exist at dif-

ferent elevations during the passage of areas of barometric maxima and minima, in order to be able to formulate a system of atmospheric mechanics which shall take account of the existing phenomena.

Some few of these questions can be investigated, at least partially, at elevated plateau stations, still more at mountain stations, where the land gradients have merely the necessary steepness to cause a rapid rise in elevation; but for investigating all of them it is necessary for the observatory to be located on a mountain peak above any neighbouring mountain tops, and with a companion observatory at the greatest possible distance below it (if possible near the sea level), but with the horizontal distance between the two as small as possible; and for the best opportunity to study the vertical relations in cyclones and anticyclones the chosen site for the observatory must lie in the path of their greatest frequency.

Partial List of Mountain Observatories.—The very great expense attending the construction and maintenance of such observatories, has limited their number, and they are for the most part confined to Central Europe, where the great Alpine range and its far-reaching spurs have offered favourable locations in a number of countries. In other regions we find that Scotland has furnished one, the United States three, and perhaps India some additional ones; but these last are probably to be classed among plateau stations. Mention must also be made of the occasional temporary observing stations which have been maintained by expeditions, especially in North and South America.

The following table shows the principal mountain observatories, the plateau stations not being given:—

Name.	Class, as Regards Equipment.	Altitude above Sea-level. Mètres.
Germany.		
Wendelstein ...	... II	1,728
Schneehoppe ...	... II	1,603
Schneeberg ...	... II	1,215
Brocken	... II	1,141
Hohe Peissenberg	... II	994
Inselsberg	... II	915
Austria.		
Sonnblick	... I	3,103
Hoch Obir ...	... I	2,043
Schmittenhohe ...	... II	1,935
Schafberg	... II	1,776
Gaisberg	... II	1,286
Switzerland.		
Santis	... I	2,467
Rigi-Kulm ...	... II	1,800
Gabris	.. II	1,250
Chaumont	... II	1,152
Italy.		
Etna	... I (?)	2,990
Mte. Cimone ...	... I (?)	2,168
Mte. Cavo	... II	966
France.		
Pic du Midi ...	... I	2,877
Mount Ventoux ...	... I (?)	1,912
Mount Aigougal ...	... I (?)	1,567
Puy de Dôme ...	... I	1,463
Eiffel Tower (Paris)	... I	300
Portugal.		
Serra da Estrella ...	... II	1,441
Great Britain.		
Ben Nevis... ...	... I	1,343
United States.		
Pike's Peak ...	... II	4,308
Mount Washington	... II	1,914
Mount Hamilton (Cal.)	... II (?)	

Probably the Cinchona Plantation in Jamaica, elevation 4,850 feet, and perhaps some of the high stations in India, should be included in this list.

Fig. 61 shows the observatory at the extreme top of the Eiffel Tower; while Fig. 62 gives an excellent idea of the Pic du Midi Observatory and its surroundings.

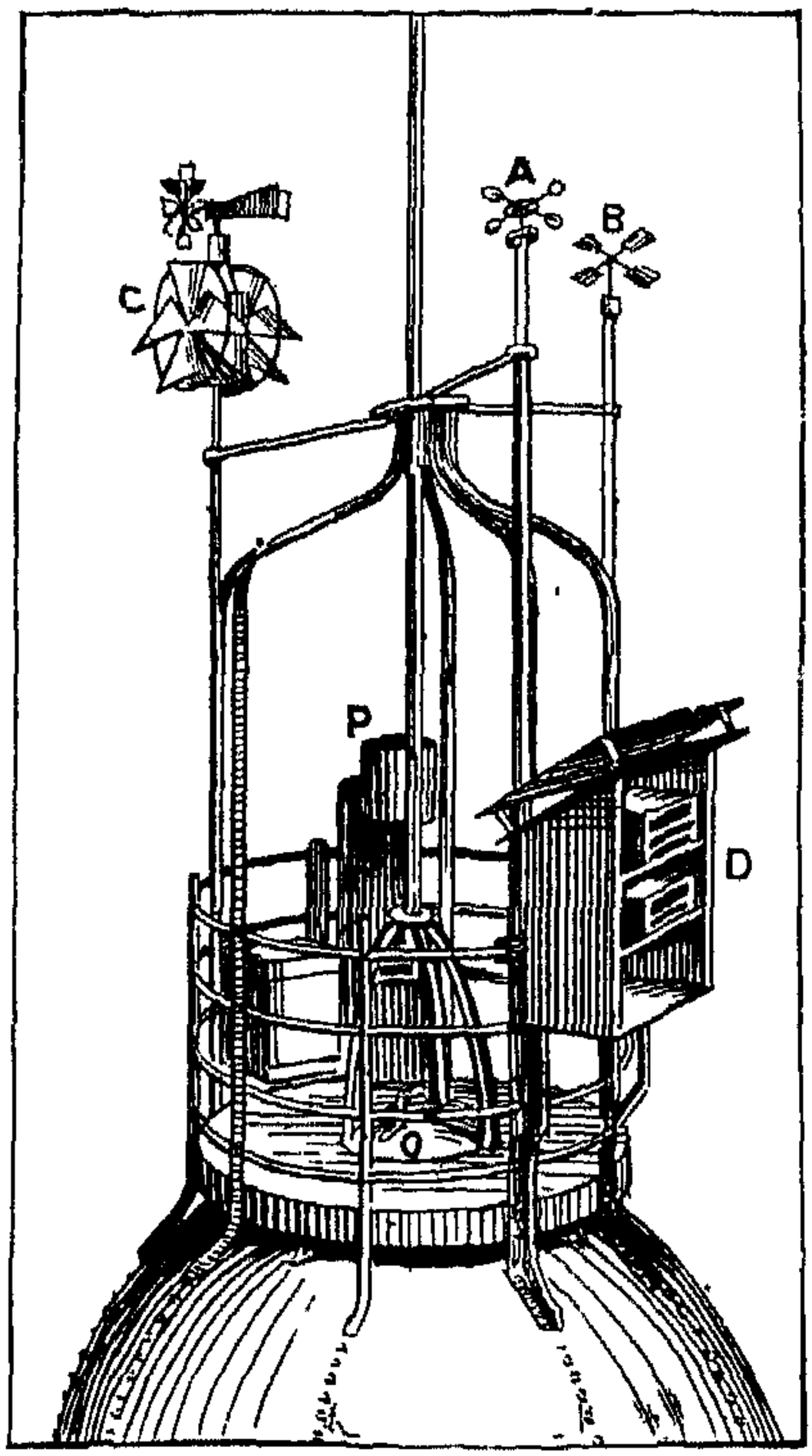


FIG. 61.

Difficulty in establishing Mountain Observatories.—These mountain observatories each have individual characteristics, due not only to difference in location, but also instrumental equipment and working force. Some of these can be pointed out, but for complete details it is necessary to go to the various publications in which descriptions are to be found. Rotch's papers on the Mountain Observatories of Europe, in the *American Meteorological Journal*, are the best summary we have of these, as he visited and made a careful study of almost all of these observatories.

The greater portion of the large sums of money expended in the establishment of mountain observatories was used in overcoming the natural disadvan-

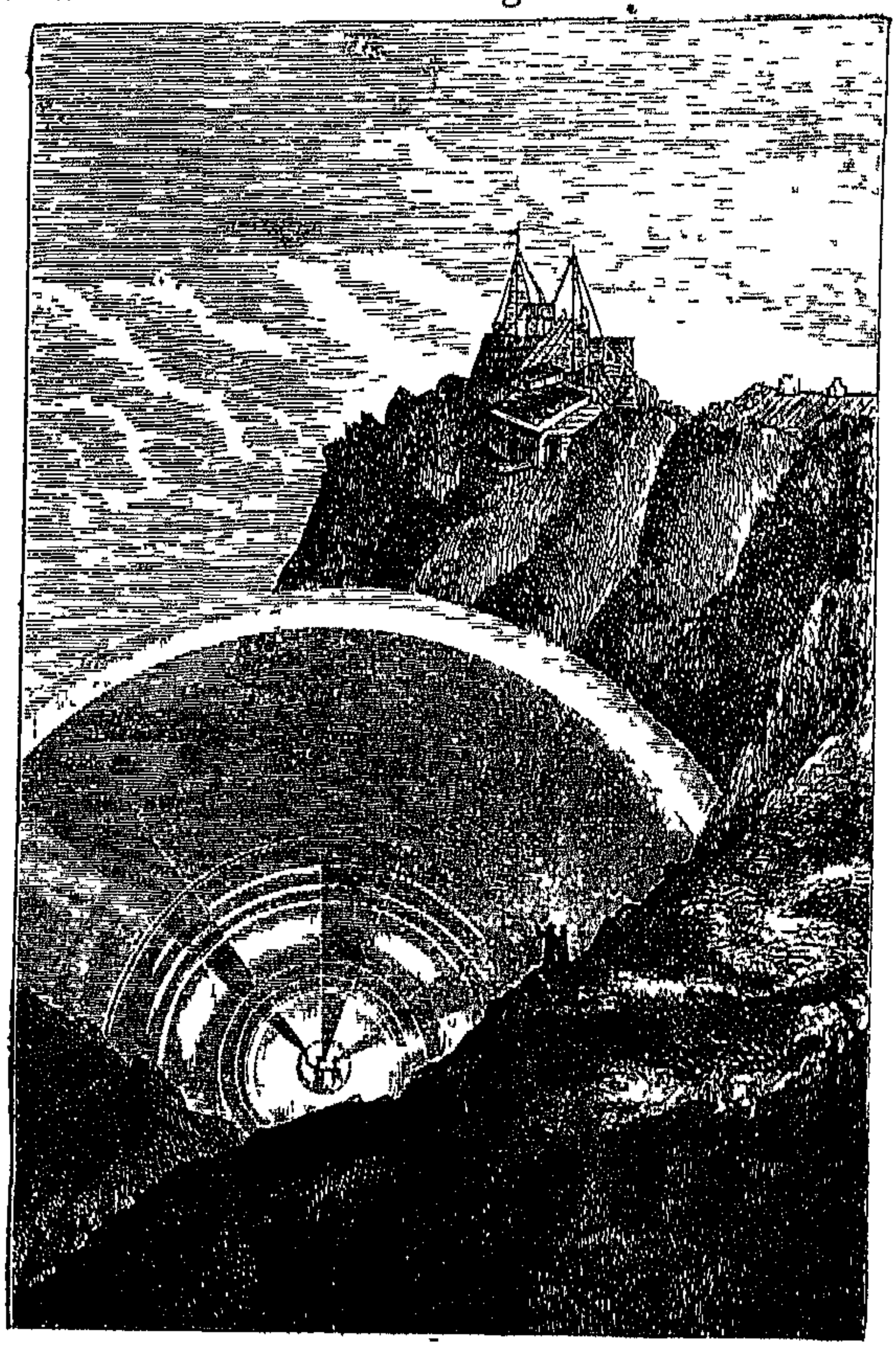


FIG. 62

tages which had to be dealt with. In some cases it was necessary to construct the very roadway over which to transport the necessary building material, fuel, and food to the mountain top; and on account

of the large distances and steep gradients, the transportation itself has been exceedingly costly; in many cases man power being all that was available, and a few pounds a load

In the establishment of these observatories a very different problem from that for low-level observatories had to be worked out.

In the first place, various economic matters needed to be planned. Suitable habitation must be provided for the observers who were to isolate themselves from their fellow men for months at a time, and in a climate where but little out-of-door life during the greater part of the year is possible on account of the continued severe cold and strong winds The living rooms must be directly connected with the observatory proper, as many times it is impossible for the observers to venture away from the building Storage must be provided for fuel and provisions sufficient to last through an entire winter, and telegraphic communication must be kept up between the observatory and some village, whence aid can perhaps be obtained in case of emergencies.

In the planning of the observatory itself, many matters connected with the placing of the various instruments have to be considered, in order to overcome difficulties which either do not occur for lower stations, or are greatly magnified by the exposed location of the elevated station. These difficulties are not the same, or rather not equally great, for all stations For instance, at stations where the air is very moist, frost-work forms on the cups of the Robinson anemometer so frequently and so rapidly that ordinary records are valueless during the seasons when this occurs. On the peak stations, where the

FIG. 63.

full force of the wind is felt, the difficulty in making any accurate measures of precipitation in winter is very great; the snow is blown away from the gauge or drifts over it, or the mouth of the gauge becomes so clogged with frost work that little precipitation enters it.

Some Special Mountain Observatories.—The highest meteorological observatory in Europe is that on the Sonnblick mountain, in Austria. The general surroundings can be well seen in Fig. 63, in which the observatory is placed at the highest point shown; and the character of the building and the immediate exposure is shown in Fig. 64. It is located at an elevation above sea-level of 3,103 metres, with the immediately accessible neighbouring inhabited valleys only half that elevation, and has adjacent base stations at Lienz (2,420m), Zell am See (2,340m), Kolm Saigurn (1,480m), Schmitten-hohe (1,150m), Obir (1,050m), the numbers in parenthesis signifying the vertical distance of the stations *below* the level of Sonnblick. The relation of the stations at Sonnblick Peak and at Kolm-Saigurn are particularly favourable for the determination of the decrease of temperature with elevation, since the vertical distance between the two amounts to 1,480 metres, and the horizontal distance to only about 2,500 metres; and the lower station has a remarkably free exposure, which prevents the stagnation of air which so frequently introduces anomalous data into such determinations. Hann remarks that no such favourable dual exposure can be duplicated in the Alps, and perhaps not elsewhere on the globe.

The Sonnblick observatory and the Pike's Peak observatory (Fig 65) in Colorado, U S, which is the

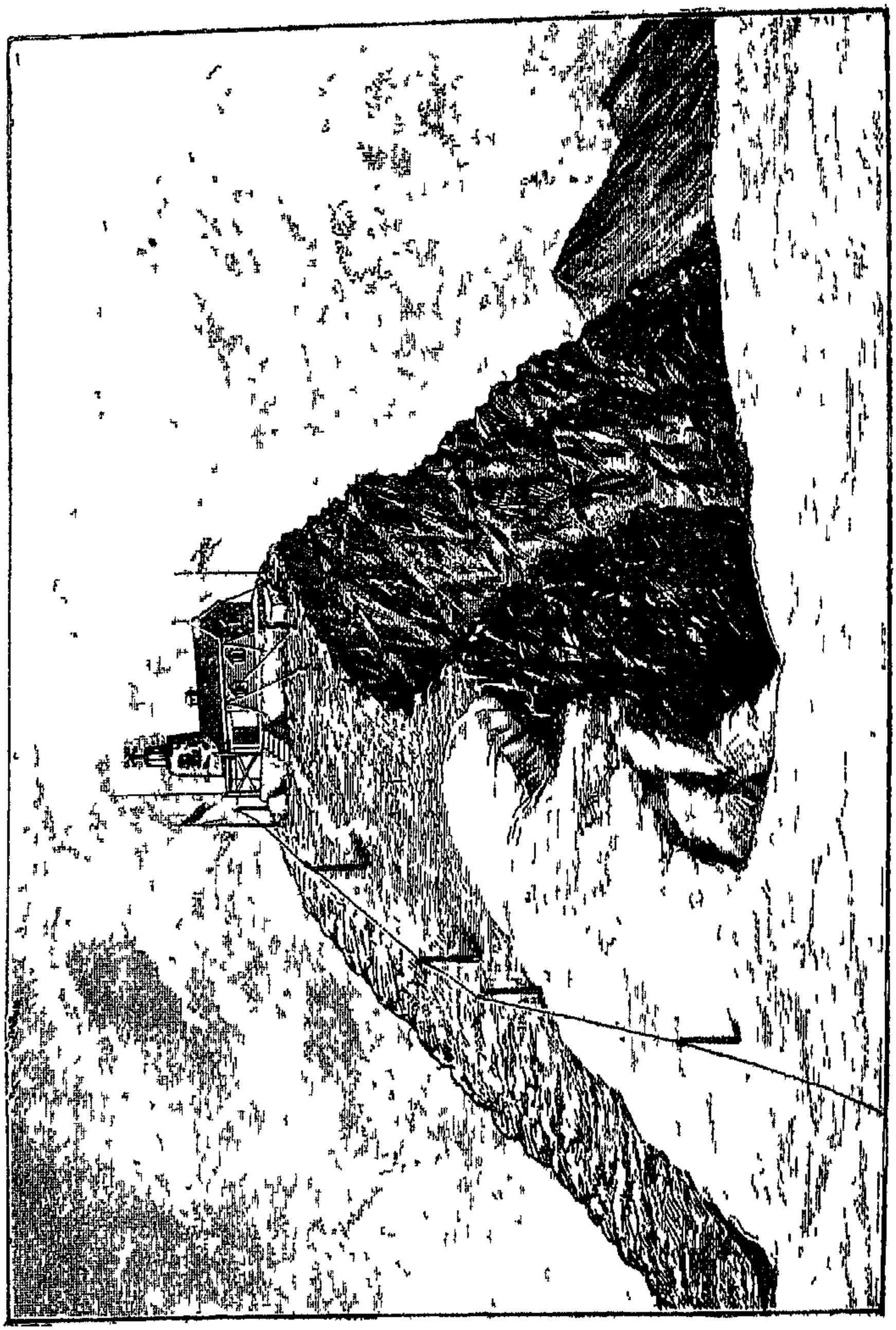


FIG 64

highest observatory in the world, are the best situated of the mountain stations having a purely continental location. But neither of these stations lies in the path of greatest frequency of cyclones and anti-cyclones. There are two, however, which could hardly be better placed for the study of cyclonic phenomena and the comparison of the general conditions of the atmosphere at about sea-level and at a moderate elevation of perhaps a mile, viz., the Mount Washington, New Hampshire, U.S., and the Ben Nevis, Scotland, observatories. The former, as also

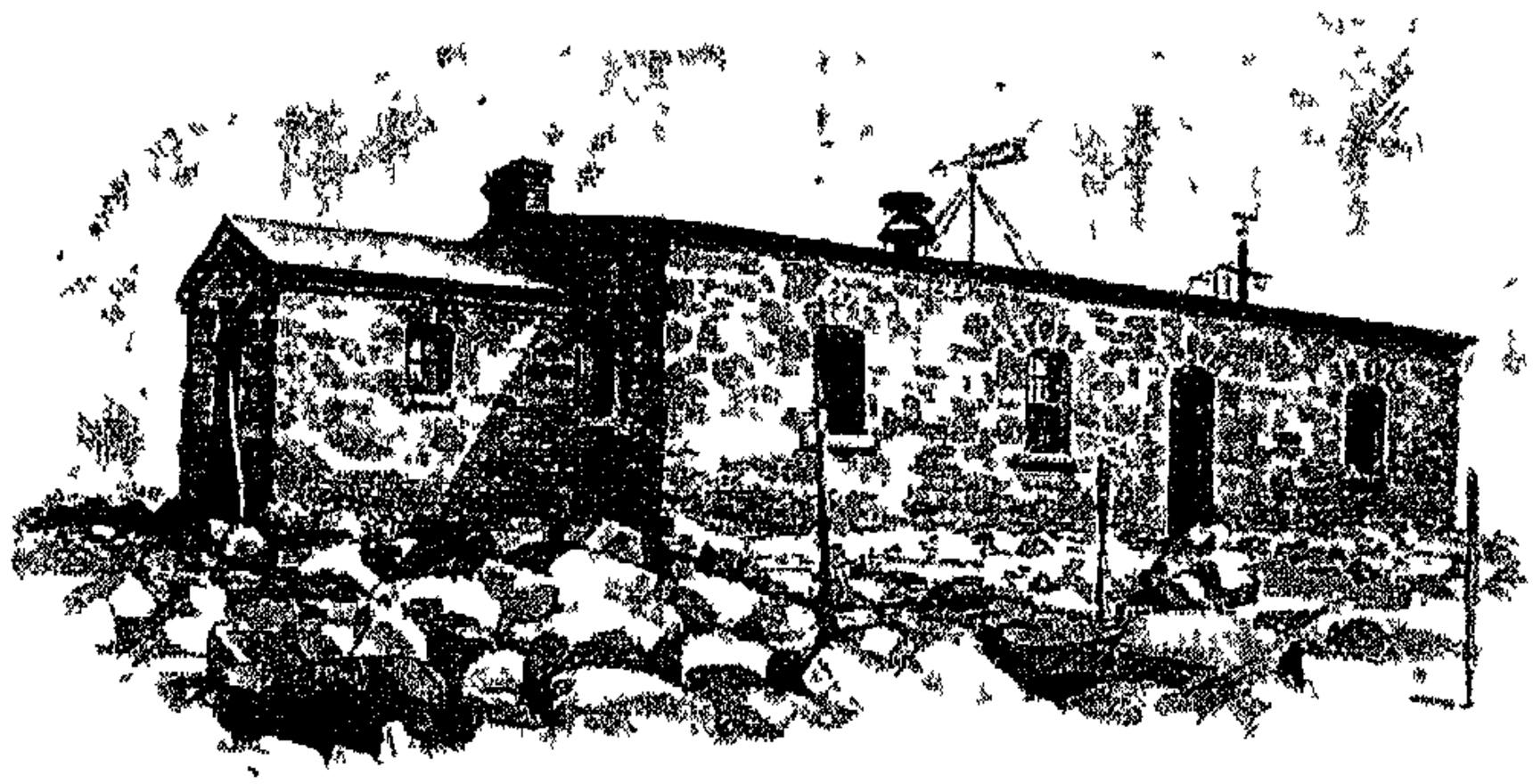


FIG. 65.

is the case with the Pike's Peak observatory, being a second-class station with scarcely any self-registering apparatus, and no very near permanent base stations, has had its possible usefulness greatly lessened by the lack of completeness in its organisation.

The Ben Nevis observatory (Fig. 66), with its companion base station at Fort William, only four miles distant, and located at sea-level, while one of the latest to be established, promises to offer a most fruitful field for investigation. Its oceanic exposure is on the side of approach of cyclonic disturbances,

which, by reason of the closeness of the mountain to the coast-line, reach it in their most perfect form; because in their previous course they have been subject to the symmetrical oceanic conditions. How-

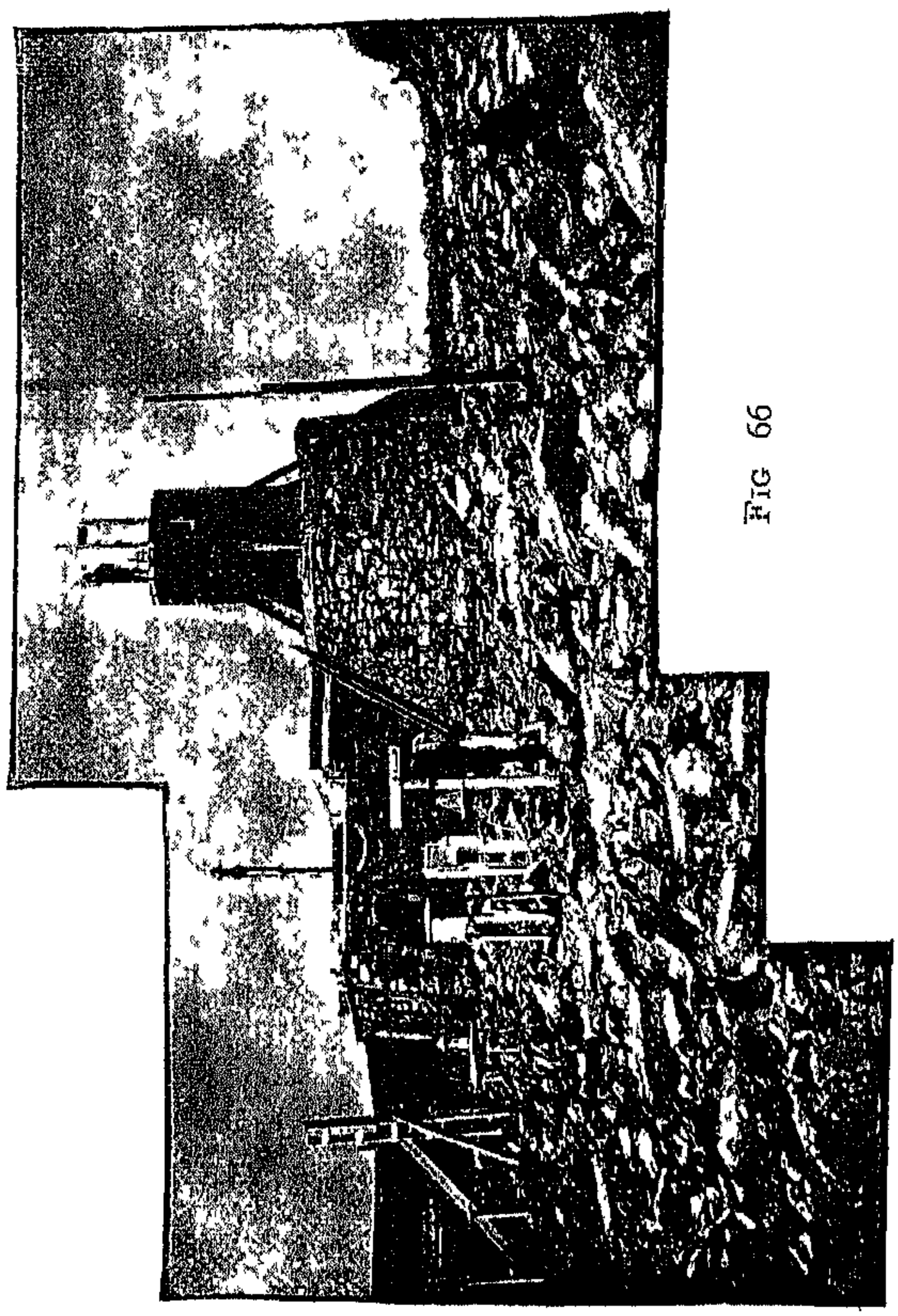


FIG 66

ever, the fact that the more or less distant land stations cannot entirely encircle Ben Nevis places it at somewhat of a disadvantage compared with the truly continental stations.

Management of Mountain Observatories. — The observers at these mountain stations are deserving of the deepest gratitude of those interested in meteorology. Isolated from all companionship during a great portion of the year, and kept indoors most of the time by the severe weather, their lives can only be compared with that of a lighthouse-keeper in an arctic climate; and where a single observer must winter alone, on account of lack of means for furnishing additional observers, it must require a great amount of fortitude on his part to undertake the task. Fig. 67 shows an interior of the Ben Nevis observatory; and its equipment and furnishings certainly indicate that utility and not comfort have been considered.

A few circumstances concerning the management of some individual observatories may be detailed. On the Brocken a hotel waiter makes the observations in winter, and the post-master in summer; on the Wendelstein the watchman is the observer; on the Hoch Obir there is a regular meteorological observer, who receives thirty florins a month, and part of the time an assistant at twenty florins per month, and the whole expense of the station is but nine hundred florins per year; on the Sentis there is one observer in summer, receiving two thousand francs per year, and in winter he has an assistant; on the Puy de Dôme there is a single observer with his family, who have three thousand francs per year income. On Ben Nevis there are three observers, and in this respect it is better fitted for undertaking necessary work than any other of the mountain observatories; and since in this case an observer can always be on duty, direct hourly observations can be made, and the results

properly tabulated and discussed by those who make them.

It must be impossible for one not having actually experienced mountain weather to know the disagree-

FIG. 67.

able features of the life of observers there. At most of the stations exposed instruments and everything else become frequently covered with frost-work which forms on the windward side when there is a

fog and the temperature is below freezing; and since this sometimes accumulates at the rate of an inch an hour, its removal from instruments must keep an observer very busy. On the Wendelstein there is

FIG. 68.

little of this frost-work, but on the Brocken and Ben Nevis it is very frequent. Fig. 68 shows the observatory at the latter place when the frost-work is present.

Exposure of Instruments at Mountain Observatories.—An additional mention must be made of the difficulties in properly exposing instruments, and the means of overcoming them.

On the Brocken, Assmann has successfully used a movable precipitation gauge, which he places on the lee side of the observatory. The exposed receiver of this gauge has a lamp, doubly encased, burning continually beneath it, and thus keeping it warm and melting the snow at once, so that it runs downward into a cold, covered, collector, where the heat of the lamp does not cause it to evaporate again. When the exposed gauge is kept warm, frost-work does not form on it. It has also been suggested to make the anemometer cups double, so that a heated current of air passing through between the outer and inner sheet metal would keep it warm and melt ice or prevent frost-work from forming. It would, however, seem simpler to use an aspiration anemometer, which could easily be kept heated. The thermometer shelters and other places of exposure for apparatus must be kept free from drifting snow and icy accumulations by the labours of the observer, and no substitute has been found for this work. The barometers must be attached to an isolated pier built up from the solid rock, otherwise they would be jarred by the high winds, and an accurate reading at such times would be impossible. The dynamic effect of high winds is also to be guarded against.

Taking into account these and other difficulties which could be mentioned, it must be admitted that mountain meteorology is still a very inexact branch of science.

CHAPTER III.

THERMODYNAMICS OF THE ATMOSPHERE.

§ 1.—*Preliminary Ideas.*

THE temperature of the air near the ground, as measured by the thermometer, has been pretty thoroughly studied for a large portion of the earth's surface; and in this study the laws of direct radiation, conduction, and convection of the heat derived from the sun have long been considered. While meteorologists had to be contented for a long time with this foundation work, as we may term it, of a knowledge of the actual temperature of the atmosphere, yet the few temperature observations made in balloon ascents and on mountain peaks, showed that unknown laws were yet to be discovered which might be applied to the data which could be collected at the bottom of the ocean of air, in order to obtain an idea of what condition prevailed in elevated regions. The demand for a knowledge of these unknown laws was made imperative when the mechanics of the atmosphere began to be studied with mathematical rigour. Fortunately the study of the behaviour of gases under varying circumstances of physical condition has received the continued attention of very eminent physicists, who have provided meteorologists with a means of developing many of the special laws which

are operative in the great gaseous ocean which we call our atmosphere.

While the static conditions of the air, which were at first studied on account of their simplicity, sufficiently explain certain classes of problems, yet the study of the atmospheric motions which are so ceaselessly transferring masses of air from one latitude and longitude to another, and from one altitude to another, has necessitated the inclusion of the more complex dynamic changes which must of necessity result from these ever-continued shiftings of bodies of air.

The laws of the dynamical theory of heat, as developed by Clausius and others, are directly applicable to the changes in the physical condition of these displaced air masses, and it is my intention to devote the present chapter of this work to following out some of the recent applications of these principles to atmospheric events.

While it is necessary to take for granted the reader's familiarity with the changes which occur in the condition of gases when they are subjected to various pressures, volumes, and temperatures, as developed in elementary text-books of physics, yet space has been taken to render clear the most important ideas which are introduced in these pages. As an elementary and easily-read introduction to this subject there is no better work than Maxwell's little book on Heat.

Evaporation of Moisture.—In investigating the physical conditions of the atmosphere we have generally to deal, not with dry air simply, but with a mixture of dry air and vapour of water. This vapour gets into the air by the process of evapora-

tion, and is distributed by subsequent diffusion and convective air currents. In any limited space the evaporation will go on until the vapour has acquired a certain density which is dependent on the temperature. The amount of vapour which can exist for any given temperature is the same whether it alone fills the space, or whether the space has been previously supplied with dry air; but in this latter case the time required for the vapour to permeate the whole space is greater than in the case of no air, for it must be diffused according to a kind of percolation. The density, pressure, and temperature are so connected that when we know any two the other can be ascertained, and for each temperature of the vapour there is a maximum pressure and maximum density which can exist without the vapour condensing and becoming water. When the vapour reaches this condition it is said to be saturated, and below this condition is called superheated vapour.

If dry air is first allowed to fill a confined space it will exert a certain pressure, and if vapour is introduced the pressure will be increased by the same amount that the vapour would have exerted if acting alone, and each gas exerts a pressure just as if the space occupied by the other gas were a vacuum. This very important principle was discovered by Dalton, who also found that the maximum density of vapour, when suspended above a water surface, is the same, whether the air is present or not; but the more air there is present the slower will be the process of evaporation.

It must be remembered that the volume of a gas when under constant pressure expands by a uniform fraction of itself when the temperature is raised;

and that air, when raised from the temperature of 0° C. to 100° C., will change its volume from 1·000 to 1·3665, if the pressure remains constant. Also, if the gases, air and vapour of water be taken in equal volumes at any given temperature and pressure, then for any other common temperature and pressure the volumes will also be equal.

Indicator Diagrams.—The atmosphere being a fluid, or rather a mixture of the two independent gaseous fluids, air and vapour of water, of variable volume, the study of its changes is so complex that the analytical method is ill adapted for an elementary explanation of these changes. A method of studying such changes for steam, in tracing the work done by a steam engine, was first invented by James Watt; but great improvements in the general method were made by subsequent investigators, among whom was Clapeyron, who applied the use of the indicator diagram, as it was called, to the study of fluids in general; and, later, Rankine made great use of the same method in his study of the steam engine. We must try now to obtain a clear idea of the principles on which this method is based, on account of its recent introduction into the science of meteorology by von Bezold of Berlin; for we shall neglect the older ways of procedure in studying what are known as the thermodynamic changes in the atmospheric air, in order to present more fully the new application of a method which has received the praise of such eminent physicists as Maxwell, Rankine, and others, and which consequently we may feel great confidence in using.

In using this method to determine the properties of gases when acted upon by heat, the accompanying

diagram (Fig. 69) which has the same framework as the ordinary rectangular co-ordinates in geometry, serves as base of representation. In the plane OPV lay off the rectangular axes OP and OV. The volumes are represented by the distances along OV, and the pressures by distances along OP. So that the co-ordinates of the point N will represent these conditions. The *condition of the gas for any point* N, is then represented by the volume which has a magnitude OM, and a pressure of the magnitude MN

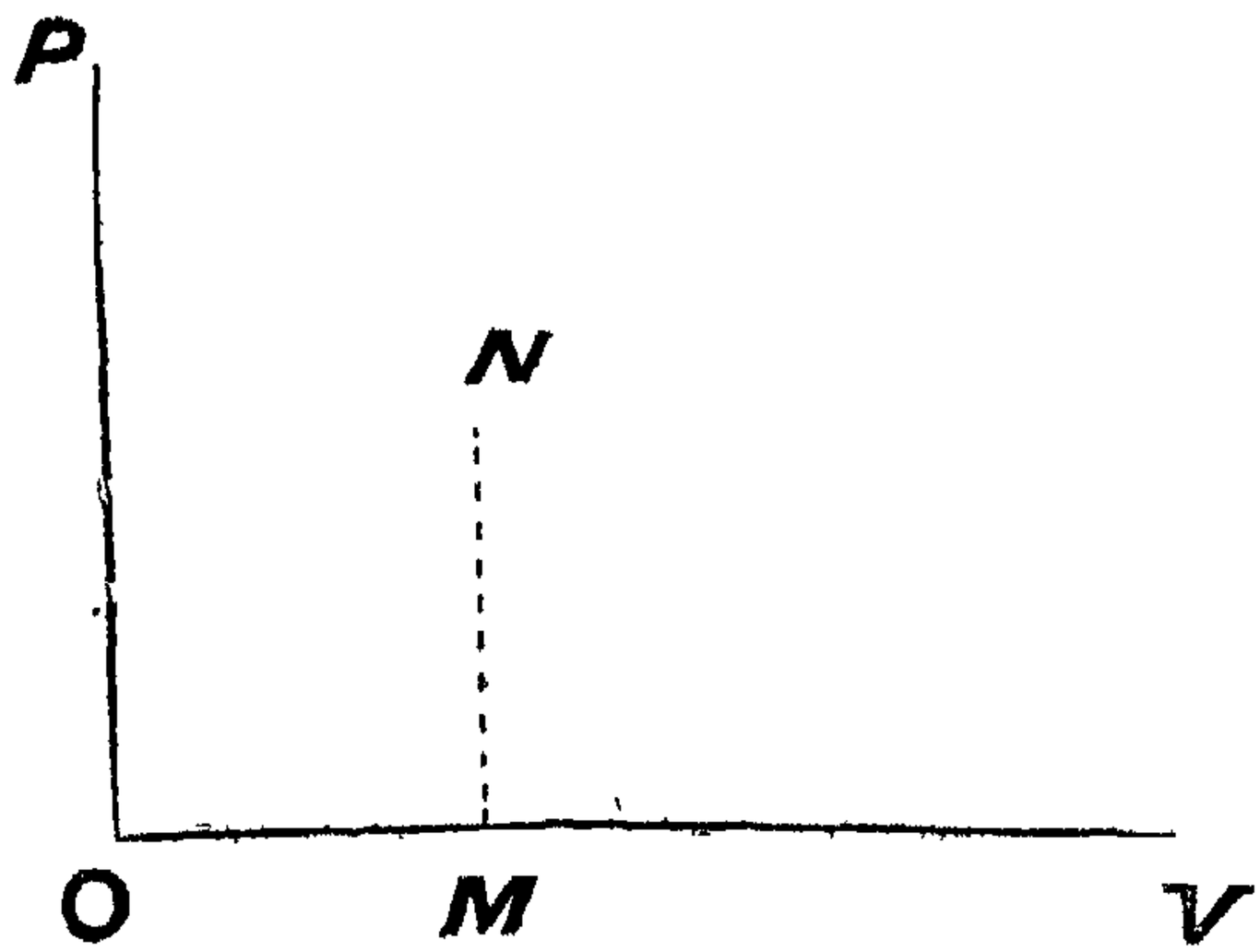


FIG. 69.

If now the temperature remains constant and the pressure is increased, then the point N will assume the position N′, which shows the consequent diminution of volume as seen in Fig. 70. If the pressure had been decreased, then N would have assumed the position N″, which would have shown an increase of volume.

If the volume diminishes as the pressure increases, as it will in the case of constant temperature, the line traced out by the point N is called an isothermal line.

If we take any gas, like air, for instance, a series of isothermals can be drawn for successive temperatures which will express the relations of pressure, volume, and temperature for that gas; and if the pressure and volume are given, the temperature is easily determined by interpolating on the graphical table.

Since by Boyle's law the product of the volume and pressure is constant, when the temperature remains constant, the temperature curves traced out by the point N must be hyperbolas, of which OP and OV

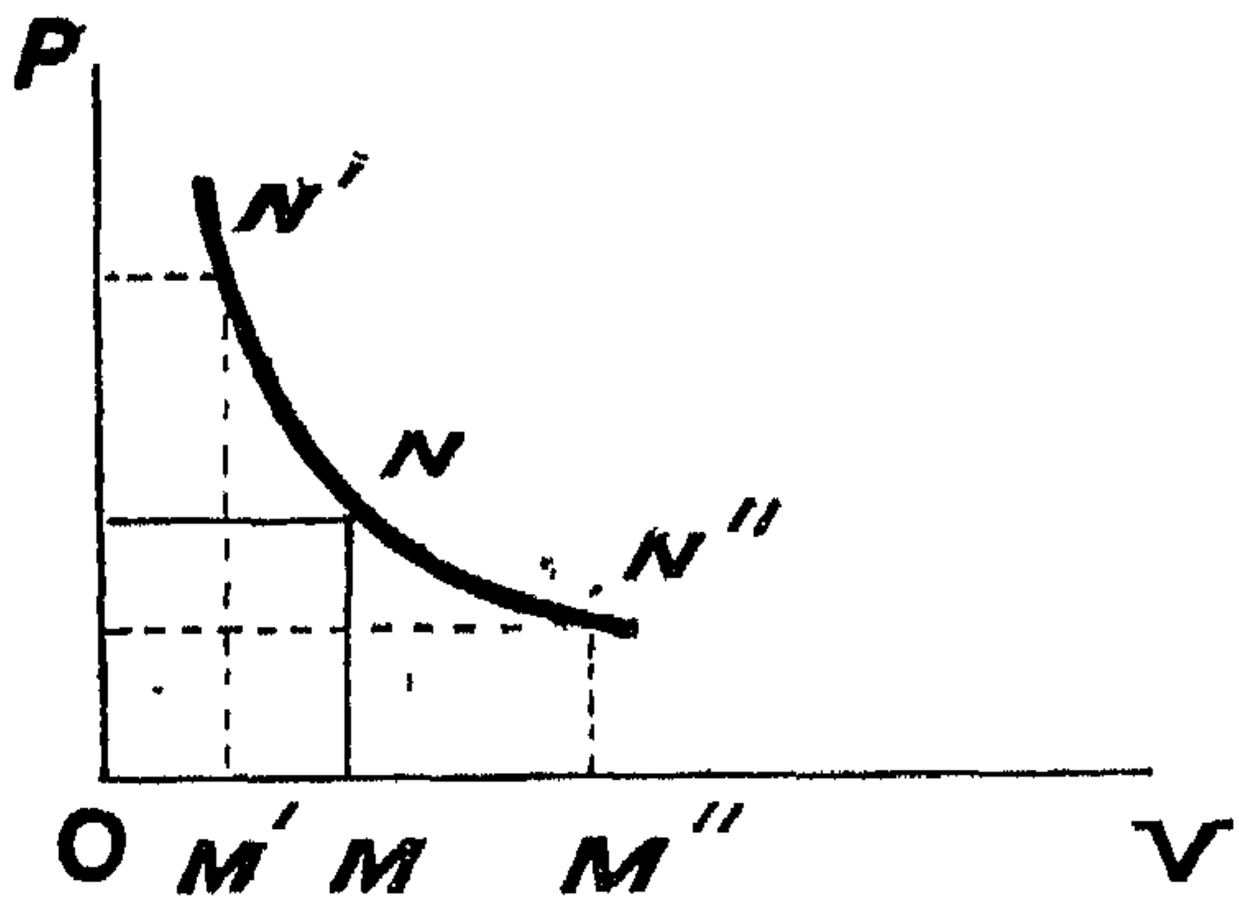


FIG. 70.

are the asymptotes. These temperature curves are called isothermal lines, or merely isothermals.

In the case of isothermal lines the temperature, as we have seen, is kept constant, and we will now consider the relations of pressure, volume, and temperature when no heat is communicated to or taken from the air. The curved line which would now be drawn on the diagram has been termed by Rankine the adiabatic line, and it is quite different from the isothermal line, although it has the same tendency and general direction of the curvature, on account of the

inverse changes of pressure and volume which govern the location of points along the lines in both cases.

The differences of isothermal and adiabatic changes are shown roughly in the accompanying diagrams, Fig. 71, and Fig. 72. The two lines, if drawn on the same scale on a single diagram, would intersect at a certain point, since a greater pressure is required to diminish the volume in what may be termed the constrained adiabatic changes, and therefore the inclination of the adiabatic line to the horizontal or

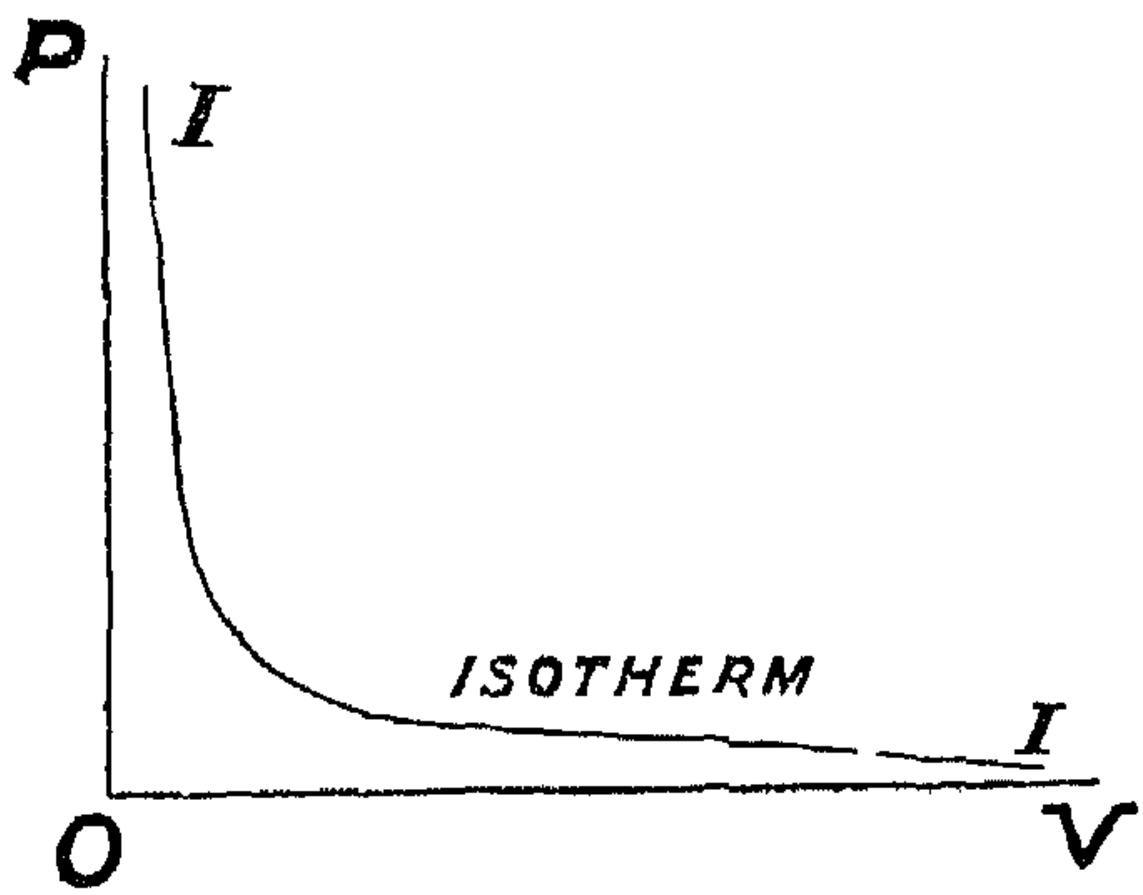


FIG. 71.

volume line is always greater than that of the isothermal line.

Vertical Circulation.—It has been customary in the application of the mechanical theory of heat to the theory of atmospheric motions and changes of condition, to consider the adiabatic changes merely; that is, those in which there was neither gain nor loss of heat during the expansion or contraction of the air mass.

It has been unfortunate that the limitation has been made, for it has probably retarded the progress which has been made in certain directions in explain-

ing observed phenomena. Take, for instance, the Fohn wind, which has been so thoroughly studied in the Alps, but which is also known under other names in other regions. The most acceptable explanation has been based on dynamical principles, as explained in another place, yet there is a very evident lack of completeness when no mention is made of any actual change in the amount of heat, although the far

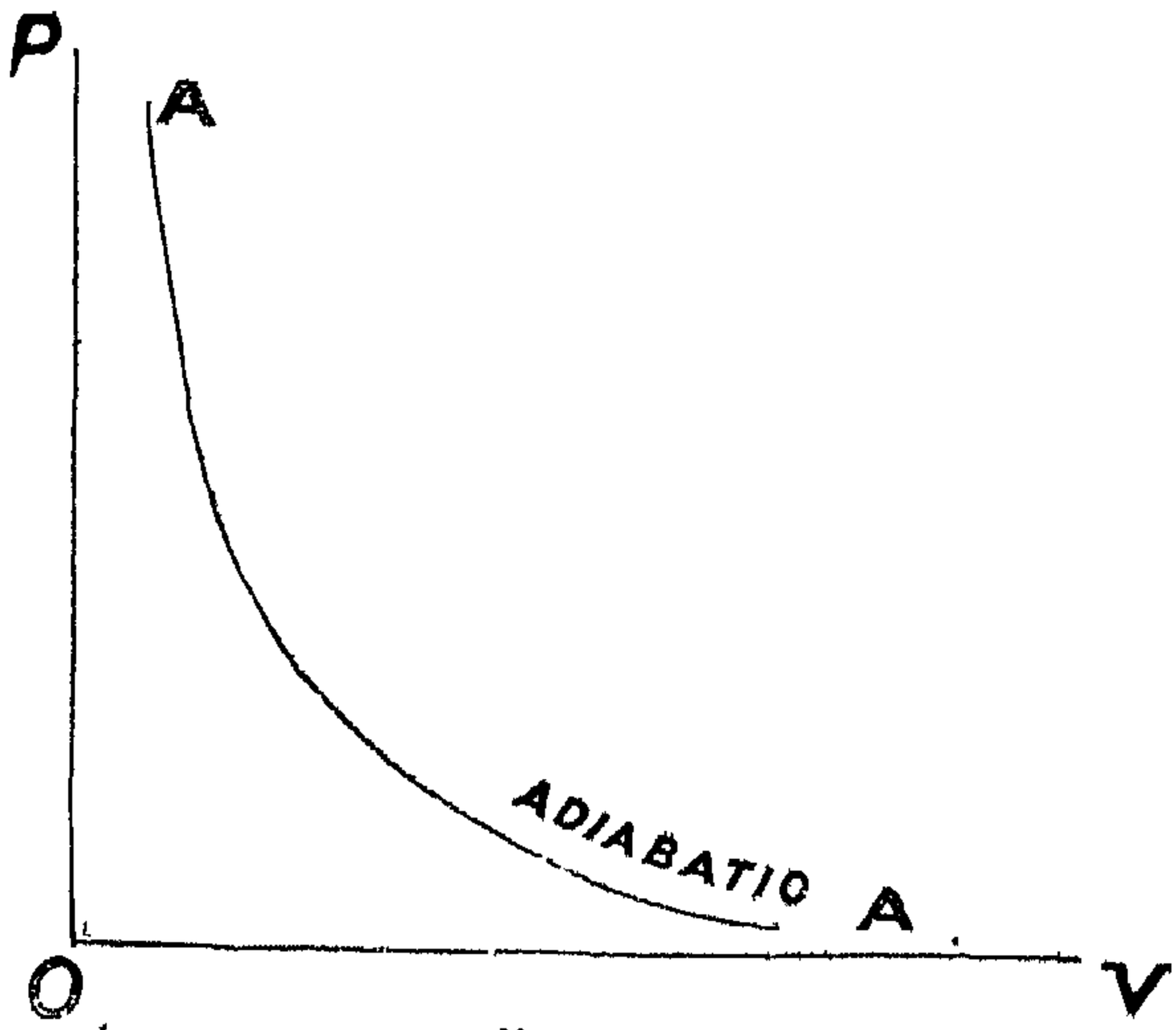


FIG. 72.

greater effects of expansion and compression so mask smaller thermal changes that the criticism of omission is not as forcible as in cases where the whole change is less. In the investigation of convective equilibrium, and especially in the interchanging motions in and between cyclones and anti-cyclones, the question of the addition and abstraction of heat can no longer be neglected, although the already very difficult hydrodynamical analysis will be ren-

dered still more complicated by its consideration. It is somewhat remarkable that the method of Carnot, so well known in thermodynamics, and applied more practically by Clapeyron,[1] should not have earlier attracted the attention of meteorologists. The work of von Bezold in this direction is the most important, as he was the first to fully show its advantages. As long ago as 1884 Hertz developed a graphical process (to be explained later) for showing the condition of moist air subject to adiabatic change, and Sprung incorporated this in his *Meteorologie* (1885); which shows that this last mentioned meteorologist manifested considerable keenness in recognising so quickly that the suggestions made by Hertz were of unusual importance; but several years elapsed before the real significance of the process was fully brought out and insisted on by von Bezold. Hertz used the graphical process, and dealt only with the limited problem of adiabatic changes of condition, and while the graphical method is well adapted to illustrate a process, and to obtain, easily, numerical results, it must be replaced by analytical forms in the consideration of the problem as a continuation of the hydrodynamical analysis which has of late years been applied to atmospheric motions. It is this difficult process which von Bezold has attempted to carry out on the lines pursued by Clapeyron, which latter require, however, considerable extension in the new investigation, and without the narrowing limitation of adiabatic condition as adopted by Hertz. I shall attempt to follow portions of von Bezold's work.

The experimental researches of Espy in the early

[1] *Poggendorf's Annalen*, Bd. 59.

part of this century, and the later theoretical deductions of Sir W. Thomson, Peslin, Reye, Hann, Ferrel, and others, showed to meteorologists the importance of the dynamic heating and cooling of vertically moving air masses as a consequence of the compression or expansion of the air. In the very important memoirs of Guldberg and Mohn, these authors have, in their treatment of this question, considered that the heat lost in the ascent of air currents is converted into the energy necessary for causing and maintaining vertical currents. This whole matter cannot be understood, however, without considering the main cause of the vertical circulation as being found in the differences of specific gravity in the air at different places, by which, in the place where the air is denser, a downward motion results, while where the air is lighter an upward motion ensues. Thus the energy necessary to raise the air in the one case is obtained by the fall of the air in the other case; and this motion once entered upon would continue indefinitely without the addition of externally derived force, were it not for the effect of friction. This compensatory flow, as it may be termed, is compared by Sprung (*Meteorologie*), von Bezold, and others, to the flow of water in a closed system of tubes, and Ferrel has illustrated it by the case of an open canal in which the two currents are separated by a neutral plane. In a water-heating apparatus we do not consider that the heat in the ascending water is lost in doing the work of raising the water, and that the cooling is the result of this work. Just so the changes in temperature of ascending or descending air masses cannot be connected with the work necessary for producing this motion, but it is entirely due to the expansion or

compression of the air, and the same changes of temperature would take place if the same changes of pressure and volume took place in a horizontal cylinder or a vertical cylinder. It cannot be too strongly insisted upon, nor made too plain, that the cooling of the ascending current is not brought about by loss of heat in the work of raising the air; nor is the heating up of the descending air due to the gain of energy by the fall. But the work of compression and expansion cannot be neglected, as has been done by some investigators.

As the atmosphere is never made up of pure dry air, but is a mixture of air and water, it devolves on the theoretical meteorologists to follow the course of this mixture in its changes, and not be content with the more easily treated hypothetical problem of dry air alone.

It has been customary, as shown by the work of Hertz and others, to adopt a unit of mass of the mixture which shall remain constant during the entire process, but this is not even very approximately correct, because, as a matter of fact, much of the moisture is lost by condensation and subsequent precipitation in the form of rain, hail, or snow. Now, while the moisture is a changeable quantity, we can consider the dry air as constant, and it is easier to treat the two quantities separately as having these characteristics than to treat the whole mixture as a variable one.

Four different mixtures are to be considered, and as these exist in the conditions which obtain in layers of the air taken progressively they are aptly termed stadia.

We have first the dry stadium, in which the air is

not saturated with moisture, and consequently in which there is no condensation and precipitation. The amount of the unsaturated or super-heated vapour in this stadium of the free air may be taken in general as constant; for there is no precipitation, and the further accumulation of any considerable amount of water vapour only happens at the earth's surface, and the intermixture of layers of different degrees of humidity are now unconsidered.

The rain stadium is reached by the air of the dry stadium being cooled, or subject to adiabatic expansion. In this case the mass of the mixture is less than in the dry stadium, except in the extreme limiting case, where they would be equal. The amount of fluid water present is small, unless there is an ascending current of great strength which supports the raindrops, and, in fact carries them along upward with the air. Such upward currents exist in the interior of tornadoes according to Ferrel's views. The vapour of water in the mixture is in the saturated state.

In the hail stadium the mass of the mixture is less than that in the rain stadium, but they approach equality in the limiting case. The mixture is made up of the unit of dry air, the saturated vapour, the drops of water which are present, and the drops of ice or hail. This condition can prevail only when raindrops are present to be converted into ice, and when the temperature has fallen to 0° C. to make this conversion possible.

The snow stadium is usually attained by the gradual cooling of the ascending air, which passes through the rain and hail stadium, but in which the rain and hail precipitation is so small that the latter

stadium at least, is practically jumped over, and so in this case there exists but the dry air, the saturated vapour and the snowflakes. The mass in this layer is still less than in the hail stadium.

Von Bezold points out that there may exist here an application of the mechanical theory of heat which has not yet been considered, viz., the reconversion of a portion of the condensed water, or drops, back into the vapour condition, by the process of warming up or compression; and if this is carried out to a sufficient degree, the mixture will again enter the dry stadium, but the amount of vapour will not be the same as the original amount.

§ 2. *Von Bezold's Graphical Analysis.*

The analytical discussion which von Bezold has made of these conditions cannot be reproduced here on account of the mathematical forms which are necessarily used by him, but the importance of the investigation demands that some notice should be taken of such portions as can be easily put into an elementary form. The number of variables which have to be considered is sufficient to cause great complexity in the equations of condition; so that a graphical, but, it must be distinctly understood, schematic, representation is all that can be produced.

The volume v, the pressure p, the temperature t, and the water vapour x, are the quantities with which we have principally to deal. The precipitation, whether occurring as rain or as hail or snow, is so small that its influence on the pressure and volume can be neglected.

In the diagram, Fig. 73, let the ordinate OP

represent p, the pressure, and the abscissa OV represent v, the volume. A third co-ordinate OX is imagined drawn from O towards the reader, that is, perpendicular to the plane OPV, and this ordinate, or one of its parallels, represents x, the water vapour. By this choice of co-ordination the representation of all conditions having the self-same values of x may be confined to one plane which does not deviate much from the plane OPV (shown in the diagram), when we take an atmospheric pressure as the unit of pressure and lines of equal

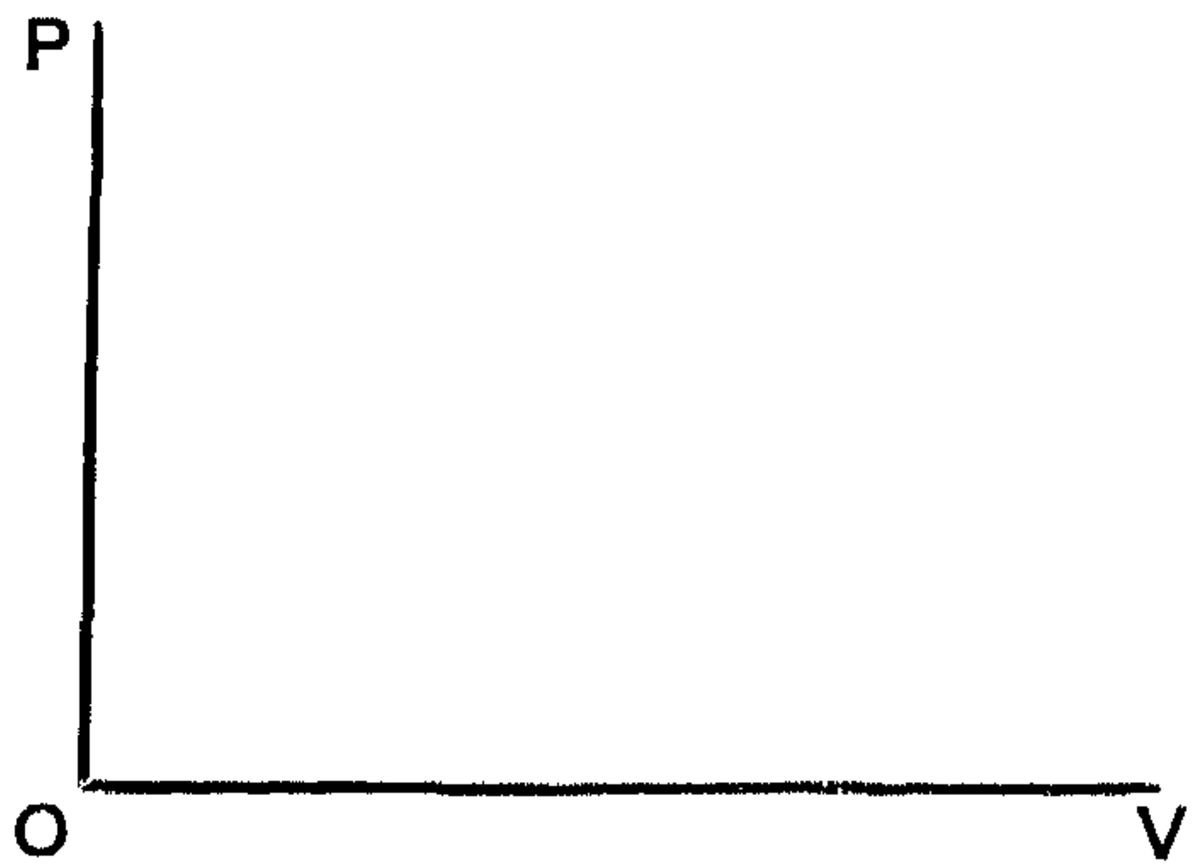


FIG. 73.

length along the axes OV and OX as unit of volume (1 cubic metre) and mass. If we imagine successive (transparent) planes, representing the progressive conditions step by step, in, say, thousandths of the chosen unit, or from gramme to gramme, superimposed like the leaves of a book, then we can follow out the changes of condition by means of the curve on the plane OPV, which is the projection on this plane of the actual curve connecting the points in the successive layers. This simplification renders possible the schematic conception of a problem which

must otherwise remain unknown to the reader unskilled in mathematical reasoning.

Dry Stadium—Mathematical considerations show that the line representing the isothermal for moist unsaturated air and also for dry air, is an equilateral hyperbola, or a portion of one.

The main condition for the existence of the dry stadium is that the existing pressure be less than the pressure necessary for the forming of condensed

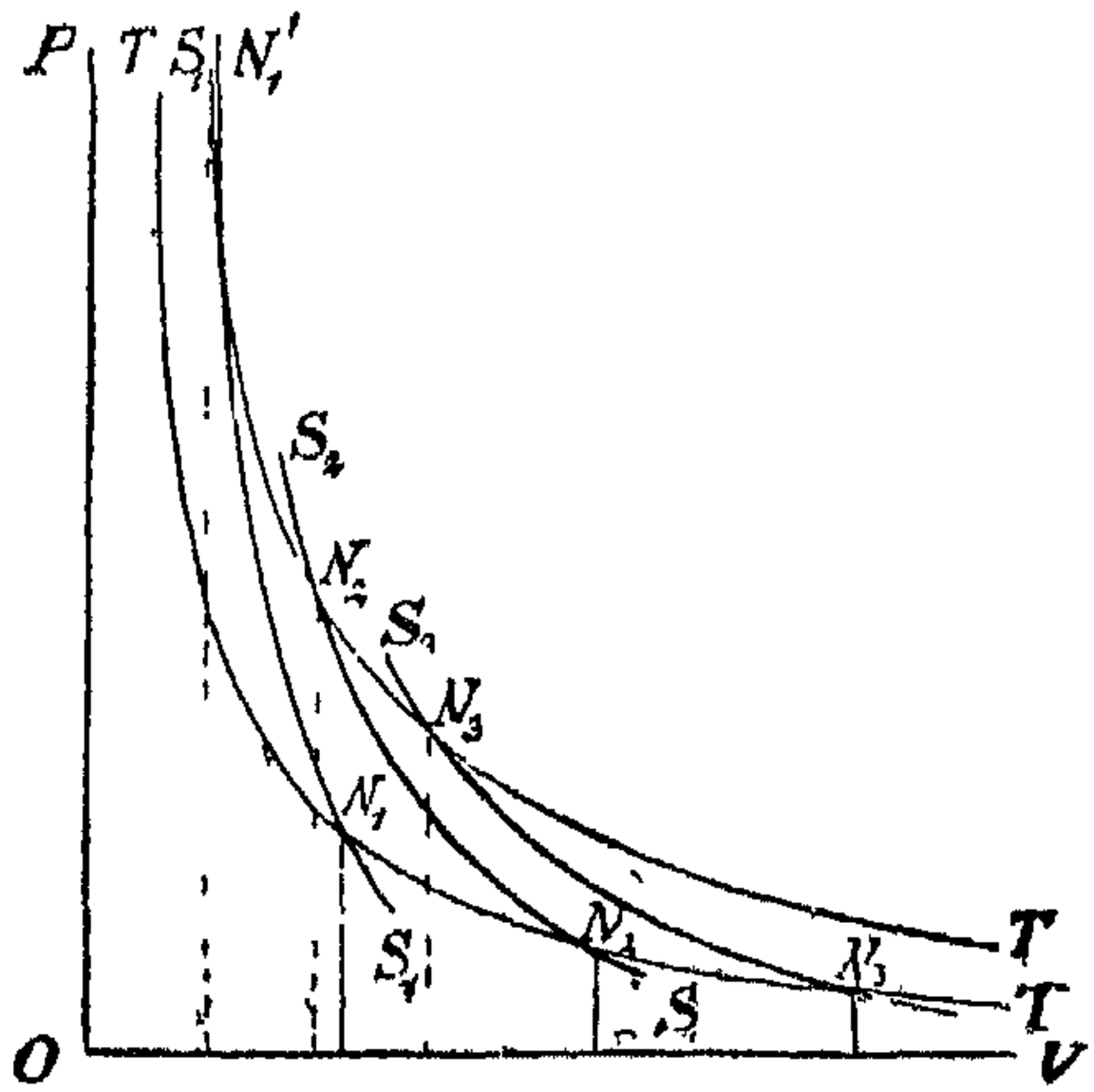


FIG. 74.

vapour at the same temperature; this last pressure is dependent on the temperature and increases with the latter, but more rapidly than it. The characteristic curves to be investigated are the isotherms, adiabatics and curves of constant amount of saturation.

In Fig. 74, the curve S_1S_1 represents the "dew-point curve" or "curve of saturation"; and this curve bounds the plane of dry stadium with any constant amount of vapour. Consequently when the curve of condition starting in the dry stadium

intersects the "curve of saturation," the dry stadium is departed from and the stadium of condensation, the rain, or snow stadium, entered. So that for the dry stadium, the isothermals (for any constant amount of vapour) must terminate in the "curve of saturation." Therefore the course of this latter curve is determined by the hyperbolic isotherms and the origin of the abscissas.

In the diagram Fig. 74 let N_1 be the point on the "*curve of saturation*," which is the *starting-point* of the isothermal line T, which is drawn for a definite temperature T and for a certain vapour quantity x. The "curve of saturation" S_1S_1 corresponds to this vapour quantity x; and for any other vapour quantities x_2 and x_3 we should have the corresponding "curves of saturation" S_2S_2 and S_3S_3; and for a constant T the starting-points of the abscissas of the isotherms corresponding to the same temperature, but different vapour quantities, are proportional to these vapour quantities. The dew-point curves S_2, S_3, as drawn in the Fig. 74, show about how these curves run for vapour quantities of two and three times the amount for which the curve S_1 was drawn.

The isotherms, corresponding to the different amounts of vapour which really exist, would run so close together that they can roughly be taken as lying within the single line T, which is shown in the diagram; only it must be remembered that each has a starting-point on the hyperbolic curve, and the position of this starting-point depends on the amount of vapour of water in the atmosphere. By further expansion of the air, the curves of saturation S_2 and S_3 will replace S_1.

In the dry stadium, which lies to the right of the

curve of saturation in the diagram, the characteristic curves will nearly obey the same laws as for a perfect gas. We should have consequently, adiabatically, the products of the volumes and pressures a constant quantity, for any probable quantities of water vapour which might be present. Applying the proper numerical constant we should have $(pv)^{1.41} = (p_1 v_1)^{1.41}$, as expressing this more exactly.

Von Bezold now uses the so-called line of constant entropy as synonymous with the adiabatic curve ; and he is thus able to show that by the decrease of entropy by isothermal expansion from one volume to another, if (see the diagram) we proceed along the isotherms which cut an adiabatic S_1 (line of constant entropy) a second adiabatic S_2 will be reached ; the relations of expansion remaining constant.

As soon as we know the course of an adiabatic, it is easy, by a process similar to that for dew-point curves, to construct such additional adiabatics that each shall have a constant difference of entropy with the next adjoining.

Rain Stadium.—In the *rain stadium* the changes which occur are seldom reversible, that is, capable of retaining the mixture to the original condition, on account of the abstraction of water by rainfall. The line which indicates the changes of condition will seldom stretch out into the concave side of the dew-point curve, and it is only possible to go back to the old condition in case the condition of super-saturation exists and the line is above the curve of saturation. This is more fully explained later.

In the rain stadium the isotherm is an equilateral hyperbola as in the dry stadium, since the vapour pressure remains at a constant value, and the one as-

symptote coincides with the axis of p (the pressures) as in the dry stadium, while the other is slightly inclined to the axis of v in the direction of p. There is, however, very little difference between the isothermal curves for any given temperature in the dry and wet stadia, and the one joins on to the other in passing from one stadium to the other with only a slight notching of the curve, with point of the notch turned towards the right and above. This is noticeable in the curves showing the changes of condition in the air in the vertical air currents mentioned later, and it is due to the fact that the isotherm for the rain stadium contains the starting-point of all the isotherms in the dry stadium which corresponds to a certain amount of moisture, which is, however, less than the original amount of moisture which we started with in the dry stadium.

In investigating the adiabatic curve we must know the amount of heat which is added during any change both to the dry air and the water with which the air is mixed. The former is easily computed, but the latter is a variable quantity depending on the amount of water which exists in the form of vapour, and the amount of water which is lost in the form of rain; and we find here two extreme limits, which have to serve as guides in the absence of any accurate knowledge as to the relative or absolute amounts of water lost out or retained. All of the waterdrops may fall out as rain, or all of them may be carried along by the motions of the air, so that no water is lost. While it is probable that in nature neither of these limiting cases occurs, or at least with any frequency, yet we must examine them to see the extreme conditions which are possible. Graphically represented, these

two conditions would mean that the same plane is passed along; that is, there is a constant quantity of water, or else the path is along the dew-point curve in which all the water immediately falls away and the condition of saturation is just maintained. Von Bezold thinks the latter condition is the nearest that which we find in nature, although the former is that which is usually assumed as a basis for investigation. Still, in the practical case of tornado action, where there is a strong upward current assumed, this case probably does occur. These two cases von Bezold also distinguishes as having in the one case a maximum super-saturation (*Übersättigung*), and in the other case a normal saturation. It will be seen that the amount of heat added (algebraically considered) would have to be zero, in order to have an adiabatic condition of change; and this could occur only in the case of the maximal excess of saturation, if the term adiabatic is strictly limited in meaning.

If the adiabatic condition is supposed to depend simply on the assumption that, in the change, heat is neither added nor taken away, then the two cases just cited are certainly adiabatic. However, if we define the adiabatic condition as one in which not only all external work is effected at the cost of energy, but also the whole of the lost energy is used in the external work; then the definition does not apply to the second limit mentioned, as well as to the intermediate changes in condition when any of the condensed water drops are present, but in which some have fallen out, and even when the condition of no gain or loss of heat is fulfilled. When the waterdrops fall out, we have a diminution of energy by the amount necessary for the external work, and

also by the amount corresponding to the definite temperature of the water which falls out.

Von Bezold carefully specialises those cases in which the water all falls out by calling the change *pseudo-adiabate* (pseudo-adiabatic); while the general cases in which the water entirely or partly falls out, he calls simply *pseudoadiabatische* (pseudo-adiabatical).

The analytical statements of the conditions controlling adiabatic and pseudo-adiabatic curves, and which are called the equations of these curves, can not be reproduced here, but they show that the pseudo-adiabatic curve sinks more rapidly than the adiabatic, or, in other words, the temperature falls more rapidly when all of the condensed water falls out at once than when some of the raindrops are retained and carried along. Comparing these two curves with the dew-point curve, or curve of saturation, it is found that they sink more rapidly than the latter, as is evident from the fact that heat must be added to make the expansion take place along the dew-point curve; and in the graphical representation adopted here, curves showing changes of condition when heat is added are always inclined less steeply towards the abscissa axis than when the change of condition is adiabatic. In the expansion, the adiabatics depart from the dew-point curve, towards the abscissa axis, and the quantity of moisture decreases.

The course of the adiabatic curve cannot as yet be explicitly determined so as to give directly the relation between the volume and temperature, or the temperature and pressure, or between the pressure and the volume; and so an indirect method must be pursued in which use is made of the decrease of entropy in the passage from the initial condition to

the final condition. It is possible to compute the values of the entropy for a number of selected values of volume and pressure, as these are independent of the individual constants of the whole system ; and by interpolation, the entropy for a sufficient number of the intermediate values of the volume and pressure may be obtained to allow the construction of the lines of equal entropy, which are the adiabatics. Von Bezold finds it possible, and very convenient, to select for computation those points which lie consecutively on isotherms, so that in passing from one point to another it will be along the same isotherm, and the entropy will be constant if this condition is maintained. A consideration of these relations shows that the isentropic curves cut the isotherms at a sharper angle in the rain stadium than in the dry stadium ; and any definite change of entropy is the result of a greater change of volume in the case of the dry stadium than would be necessary in the rain stadium.

Limiting our view to a small portion of the plane of co-ordinates, the isotherms will appear as parallel straight lines running almost the same course in the two stadia, the dry and the rain stadia ; and to represent any chosen change of entropy, it would be necessary to pass along the isotherms a longer distance in the dry stadium than in the rain stadium. The dew-point curve sinks in further towards the positive side of the abscissa axis than the isotherms, and the adiabatics show a bend at the dew-point curve, as shown in Fig. 75, where S S represents a portion of the dew-point curve ; TT, T′T′ are isotherms, and AA, A′A′ are adiabatics.

The " pseudo-adiabatic " curve is still more difficult

to investigate, and still less only approximately correct solutions can be obtained even for the cases within the limits of actual use, which are fortunately more determinate than the general solution. But even the derivations for special cases are too complex to be explained here. It may be mentioned, however, that a consideration of the equation shows that the pseudo-adiabatic curve sinks more rapidly than the adiabatic. That is, the successive volumes for corresponding temperatures must be less for the pseudo-adiabatic changes than if the adiabatic had been followed.

Hail Stadium.—When the temperature descends below 273°C. on the absolute scale, or the freezing point of water, the conditions which have been outlined for the rain stadium must be modified. When the temperature is just at the freezing point, water and hail may exist side by side, and the change would be by isothermal expansion as long as this condition is maintained; the adiabatic in this case coinciding with the isothermal line. Von Bezold holds that the adiabatic will in reality be a pseudo-adiabatic, since the hail falls out under *any* circumstances (although Ferrel's theory of the vertical circulation in a tornado shows that the upward current may be so strong as not only to support the hail stones, but to actually carry them upwards), and in this condition, any increase of vapour requires addition of heat, and the formation of more hail means a loss of heat.

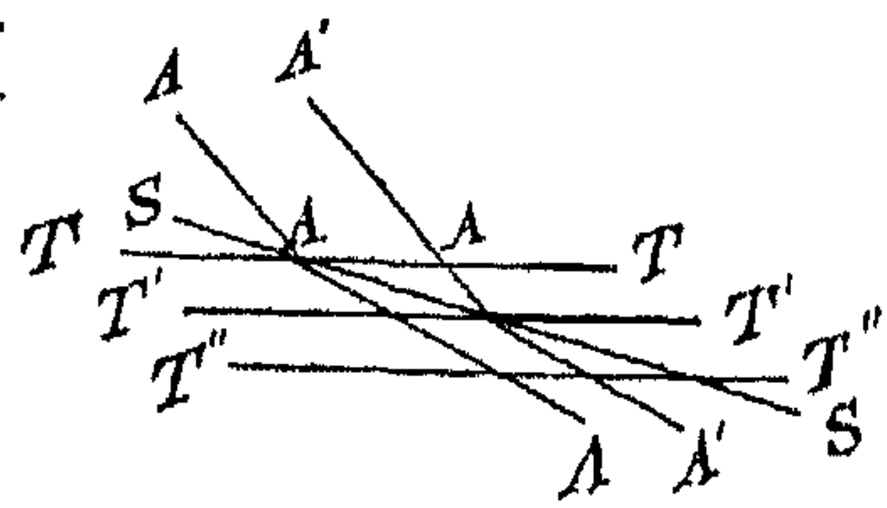


FIG. 75.

In the case of continued expansion, but without gain or loss of heat, through the hail stadium, there will be a continued increase in the amount of hail formed; but in this freezing process there is a simultaneous evaporation, so that at the upper limit of the hail stadium there is actually a greater amount of vapour present than at the entrance to this stadium.

The whole process and change in this stadium may be followed thus.—The determinite plane above the OPV plane, which corresponds to the amount of waterdrops *plus* the amount of saturated vapour, will be that one showing the condition of entrance into the hail stadium; and it is somewhere above the dew-point surface. The line which indicates the distance from the assumed plane OVP will cut the dew-point surface at the plane (above the OPV plane) which corresponds to the amount of vapour just necessary for complete saturation. If now the mixture expands isothermally, the just-mentioned point of intersection with the dew-point curve will gradually be raised, and the projection of its path on the OPV plane will be an equilateral hyperbola. It is plainly evident that while the point of intersection with the dew-point surface is thus slowly rising, the plane of the initial condition (depending on the waterdrops and saturated vapour) is being receded from as the frozen water drops out, and finally the two will come together at the plane where the hail stadium ceases.

The question naturally arises as to the relative or absolute amount of hail which is or may be formed. At the entrance of the hail stadium, the mixture contained water in the form of raindrops and saturated vapour, and all of this water is turned into hail: so

that the amount of hail will depend on the amount of water on entering the hail stadium, and the amount of change in the volume of the mixture by expansion. The hail stadium cannot be entered until there is at least an appreciable amount of water present in the form of drops; and the more of these there are, the greater will be the hail fall.

Snow Stadium.—When the air is saturated with water vapour and becomes cooled below freezing without the formation of raindrops, then the condition of the snow stadium exists. In this stadium the main conditions are somewhat similar to those of the rain stadium, but here the heat of melting takes the place of the heat of condensation. The amount of vapour which may be present depends on the temperature. The lower the temperature the less the vapour, and so, in this stadium, the less will be the amount of snow; and the lower the temperature becomes, the more nearly will the adiabatic curve in this stadium coincide with that of the dry stadium. We thus see why it is that in very cold weather the snow fall is comparatively light.

§ 3.—*Application to Fohn Winds and Cyclonic Circulation.*

In the widely-distributed and strongly-marked winds known as the Fohn, the moist air expands in passing upwards along the side of a mountain, and becomes compressed again in the descent on the opposite side, where it is much drier. It is interesting to follow von Bezold's application of the preceding ideas to this process. In Fig 76 let a represent the original condition and S*a* the corresponding dew-point curve, then the air expands according to the adiabatic of

the dry stadium until it cuts the curve S*a* at the point *b*; and the curve *ab* lies in one of the imagined planes parallel to the OPV plane at a distance of *x*a.

The temperature curve corresponds to the initial temperature shown by the line T*a*, and we see that in the change from *a* to *b* the temperature falls rapidly. As soon as the condition *b* is reached, the representative point glides down the dew-point surface; the adiabatic of the dry stadium goes over into the rain stadium *bc*, and forms with the curve

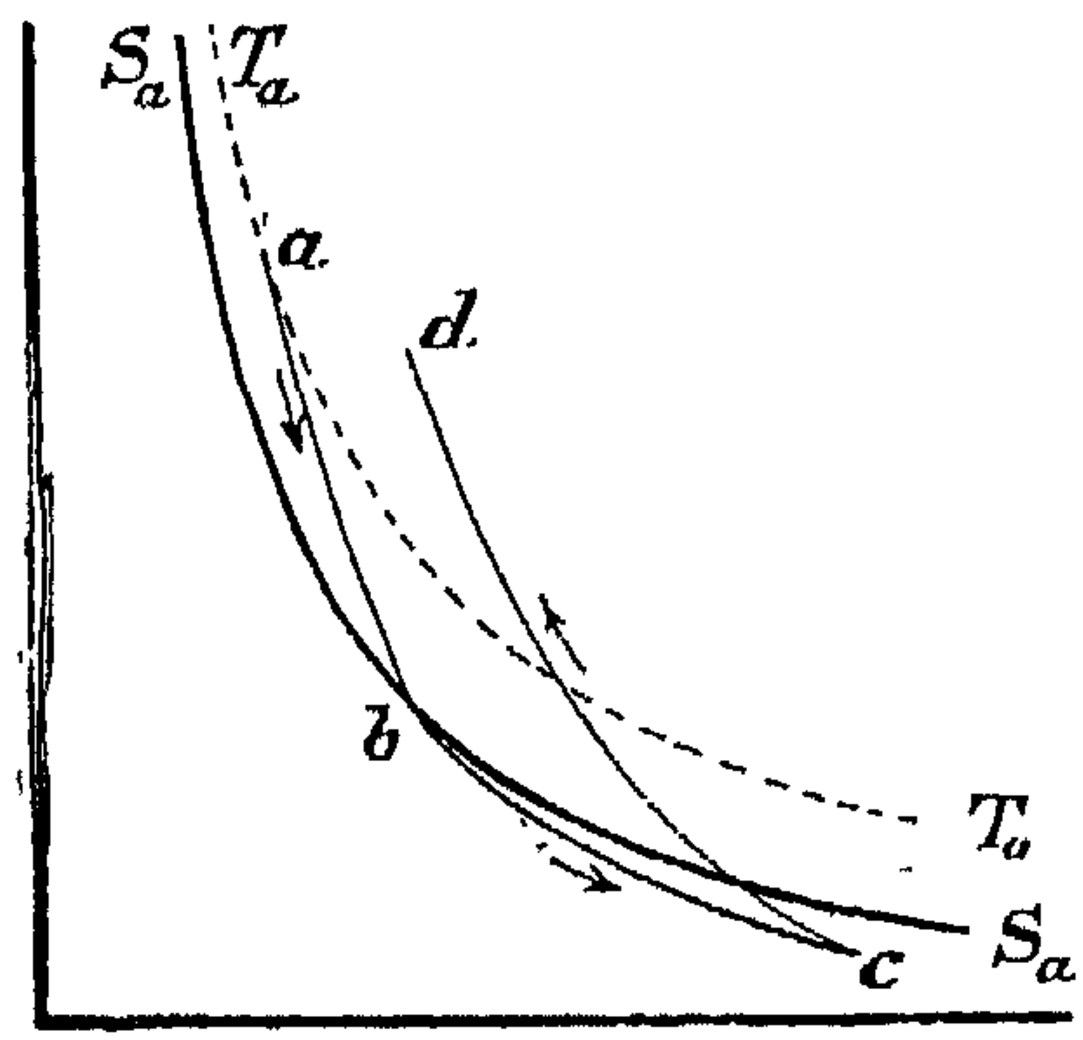


FIG. 76.

of saturation, a low angle. The temperature now sinks by a uniformly continued expansion much slower than before (as shown by the curve), and water is condensed as the line *bc* cuts the dew-point lines of lower amounts of vapour. The condensed water falls as rain, and if the process is continued far enough, later as snow; so that the line *bc* becomes, in fact, only pseudo-adiabatic, or rather it is the projection of a pseudo-adiabatic line. The hail

stadium is wholly passed over; or even in an extreme case would be scarcely perceptible.

We will suppose the expansion to cease at *c*, and that compression or a sinking takes place. In this reverse process, if no water has been abstracted by precipitation, the path will be a retracing of the same track which has been already followed, viz., from *c* to *b*, and then from *b* to *a*: and the greater the amount of water retained the more nearly will this path be followed. So that when the air does not leave the dry stadium there is no noticeable change in the air when it reaches its starting-point. If, however, water is lost by precipitation, then in the process of compression the fall will be that shown by the projected line *cd*. In this case, as is shown in the diagram by the intersection of *cd* with T*a*, the original temperature of the air is reached at a pressure lower than the original pressure, and in the farther descent which is necessary before the air reaches the original pressure the temperature is of course raised above the original temperature. So that now the amount of vapour is less, and the temperature greater than in the original condition, and we thus have the characteristics of the Föhn; which are, moist cool air on the preceding side of the mountain, and dry warm air on the following side. And, as may be seen from a consideration of the diagram, this peculiarity is the more strongly marked, the nearer the starting-point *a* lies to the curve of saturation, and the longer the path *bc* within the rain stadium

Cyclones—Thermodynamics.—A further more important application is to the great vertical currents of air in the cyclonic and anti-cyclonic areas,

According to the usually accepted theory we have in cyclones an ascending current and in anti-cyclones a descending current; the current from the anti-cyclone acting as a feeder to the cyclone. In this interchange of air-masses between the two, the air is subject to very much such changes as it experiences in rising on one side of the mountain and falling on the other side, as in the case of the Fohn Wind. In the cyclonic systems, however, the distances and the times are so great that an adiabatic condition (that is, without addition or abstraction of heat), cannot be assumed. Since the ascending current in the cyclone may be hundreds of miles from the descending current of the anti-cyclone, due allowance must be made for the changes in heat just mentioned, according to the conditions which are liable to exist. In the summer the addition of heat would be the preponderating condition, and in winter the abstraction of heat; the daytime and the night-time would also have this same relative connection.

The conditions of the interchanging circulation between the cyclones and anti-cyclones in summer is shown by the following diagram (Fig. 77). The air starts from the condition *a* (of the cyclone) and by expansion, but at the same time receiving heat, passes along *ab*, which is within the adiabatic curve as the decrease in temperature would be slower on account of the added heat. When the rain stadium is reached at the point of cloud condensation, the path would be *bc* close to the curve of saturation; but at greater elevation, where we find a much stronger addition of heat at the time of insolation at high elevations where the condensation is less and the density of the clouds decreases, the path will be as shown by *cd*, and the

condition will be within the dry stadium again, and will be approximately adiabatic when the water has been transformed into water vapour by the evaporation which must ensue, and has consequently lost the greater part of its capability for absorption. At *d* the mixture enters the second condensation stadium, that of the cirrus clouds. And in this stadium the curve must be truly adiabatic in most cases, as the ice needles do not fall in the form of precipitation, but remain in suspension. The curve of ascent *de* must

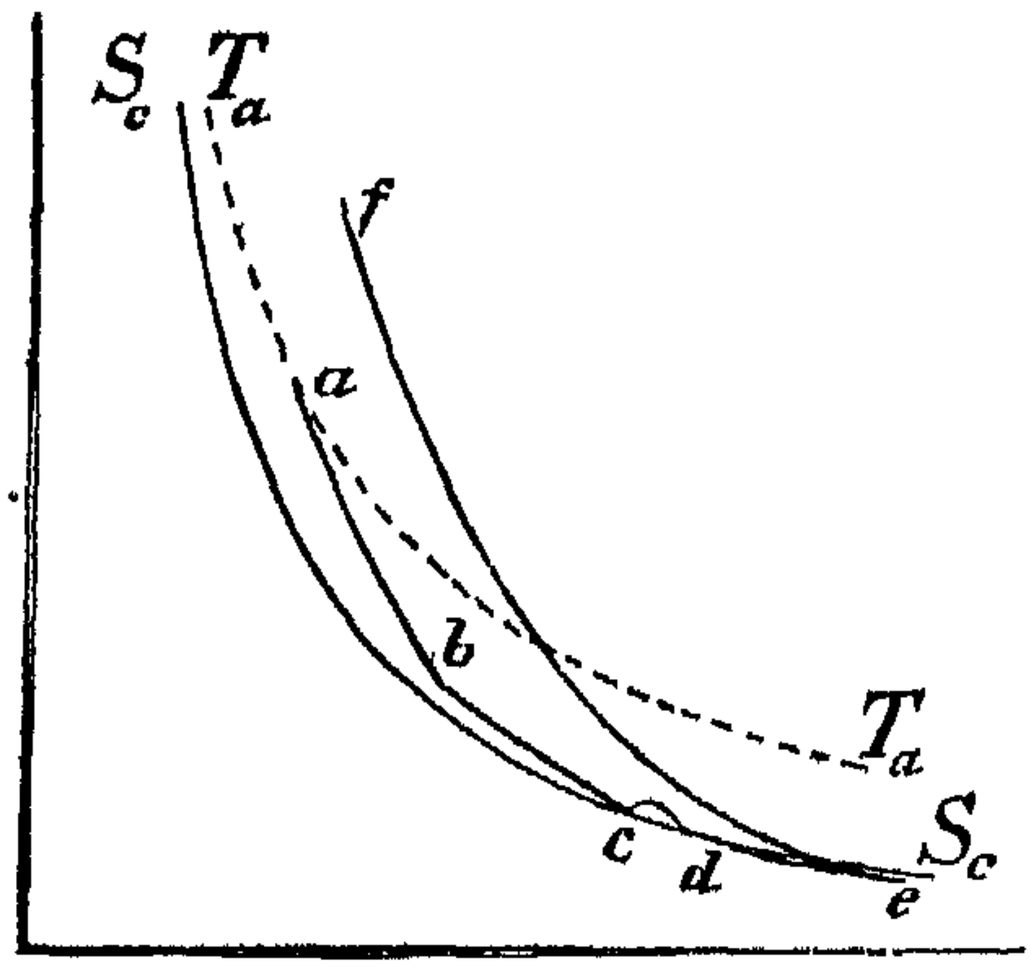


FIG. 77.

very closely approximate the curve of descent; but below this the latter, *ef*, departs more from the former as shown in the diagram.

The curve of descent *ef* is here represented by von Bezold as adiabatic, although this is not strictly true, especially in the lower layer of the atmosphere, in consequence of the warming up of these layers by reason of their nearness to the heated surface of the earth; but, as he points out, this departure from the adiabatic would imply the restoration of the condition of stable equilibrium.

The changes along *ef* take place in the downward current of the anti-cyclone, and the final pressure of the air mass on reaching the ground is greater than the pressure it originally had at the base of the cyclone, and consequently *f* lies farther above the abscissa axis than *a*. Thus we see that *f* may lie not only above, but to the right of *a*, so that the volume at *f* is greater than the volume at *a*, and consequently the air can be specifically lighter in the anti-cyclone than in the cyclone, notwithstanding the relatively higher pressure of the former. This is possible because of the compensating influence of the difference in temperature.

We thus see quite clearly that in the passage of air from the cyclone to the anti-cyclone, it is not entirely a question of the specific gravity of the air masses, but the dynamic relations play a very important part as has been insisted on by Hann[1] in his discussion of the observations made at the Alpine Sonnblick Observatory. Von Bezold considers that the region above the rain clouds, and especially that at their upper limit, should receive the most careful consideration at the hands of investigators, as the conditions existing there have not been properly taken into account.

The air, then, as it approaches the earth in the anti-cyclone is warm and dry until it reaches the lower layer, where it rapidly receives moisture from the evaporation from the earth's surface which is exposed to the unhindered radiation from the sun.

The air may now pass through the conditions *fa* and again become the feeding current of an atmospheric depression—under the same assumed conditions as

[1] *Meteorol. Zeits.*, vol. v. p. 15.

the first cyclone—having in its lower course (*fa*) added to its store of moisture.

In winter (and similarly the analogous night period) the changes of condition are different from that just outlined. Since the temperatures are not so high as those reached in summer, and therefore the isotherms lying at a considerable distance from the axis are not reached, at least the beginning and final changes of conditions occur closer to the co-ordinate axes (see Fig. 78). At the starting-point *a* in the cyclone, the condition is that of lower pressure and higher temperature, while in the final condition at *d* in the anti-cyclone, there is higher pressure and lower temperature; so that in the diagram, *d* must be above and to the left of *a*. Since we have assumed that the distance of the point representing the condition, from the axis of the plane of projection as shown in the diagram, depends on the amount of absolute moisture, then the curves which represent the changes of condition will not reach such a distance from the axes, since the amount of moisture remains less in the winter than in the summer.

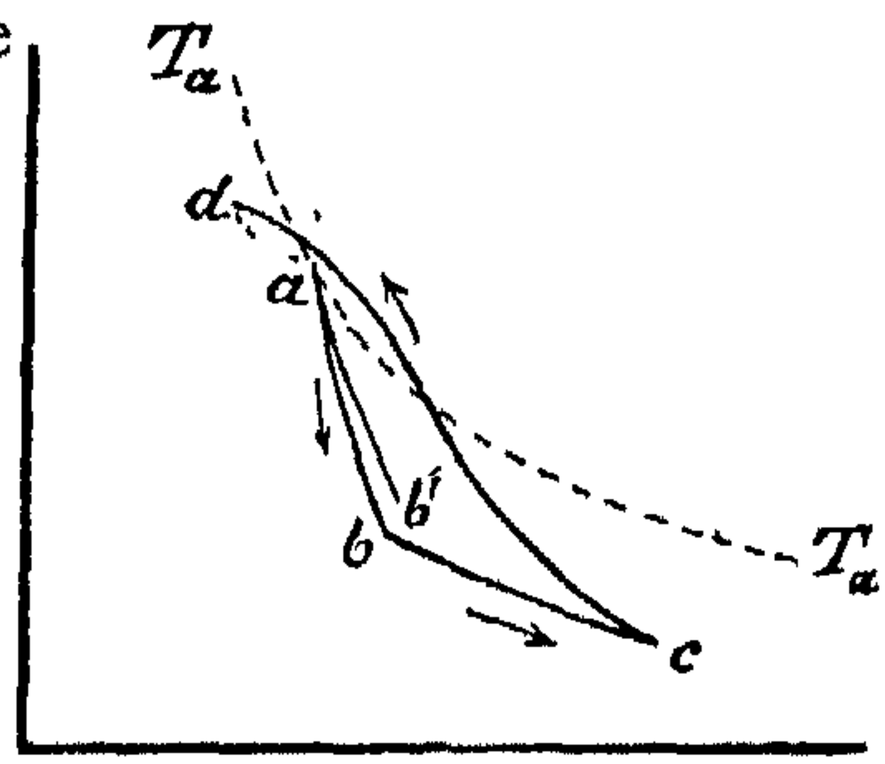


FIG. 78.

In the early part of the ascent in the cyclone the condition is nearly adiabatic, that is, *b* nearly coincides with *b'* (where *ab'* is the adiabatic course) for the path up to the upper limit of the cloud layers, as below this the radiation and irradiation is of secondary importance; but if there is a deviation from the

adiabatic, it must be in the opposite direction to that of the summer, and the lines will fall more than in the latter season. In the accompanying diagram (Fig. 78) this deviation is assumed, and it is supposed that the transformation takes place directly from the dry stadium to the snow stadium. From this point onward the curve of condition sinks more gradually, but with continually increasing inclination, on account of the greater cooling at great altitudes, up to the turning-point *c*, where expansion ceases and compression commences. The return path is marked by the line *cd*. So far as we are capable of judging, the curve of descent is adiabatic at high altitudes, and the adiabatic compression proceeds as for the dry stadium; but in the lower atmosphere, where the outward radiation is strong, the consequent cooling causes a departure from the adiabatic, inward towards the ordinate axis, as is shown by the lower part of the curve *cd*. We thus have the schematic graphical presentation of the inversion of temperature which occurs, especially in anti-cyclones, on clear winter days. In the last part of the descent, the path *cd* approaches and even intersects the dew-point curve near *d*, and in the latter case the condensation assumes the form of ground fog. But with the beginning of fog-formation the radiation increases, and so the temperature decrease becomes the more marked with the approach of the descending air-current to the ground. Whether the path *cd* can be throughout an adiabatic, requires further investigation. If it is so, then there must be a place at some elevation in the anti-cyclone where the same pressure and temperature exists as at a lower elevation over the cyclone; because in this case the projection of

the curve of condition, *i.e.*, the curve drawn in the plane of the diagram, must intersect itself.

§ 4.—*The Hertz Graphical Solution of the Adiabatic Process.*

Although the mass of the mixture of air and vapour decreases steadily with change from one stadium to the next, as has been shown by von Bezold, and although Hertz has not considered the pseudo-adiabatic changes, yet the graphical table of the latter writer can be used for approximate solutions in so many cases and with such ease, that it is given here for the benefit of any who may make use of it, but to whom the original is inaccessible. This will prove of assistance even in the solution of non-adiabatic changes, for any practical investigation of these will probably require the auxiliary use of the adiabatic changes. The original paper by Hertz bears the title, *Graphische Methode zur Bestimmung der adiabatischen Zustandänderungen feuchter Luft*, and was published in the *Meteorologische Zeitschrift*, Nov.–Dec., 1884. While reference has been made to it by various writers on meteorology, it is believed that the very important diagram accompanying that paper has not heretofore been reproduced elsewhere.

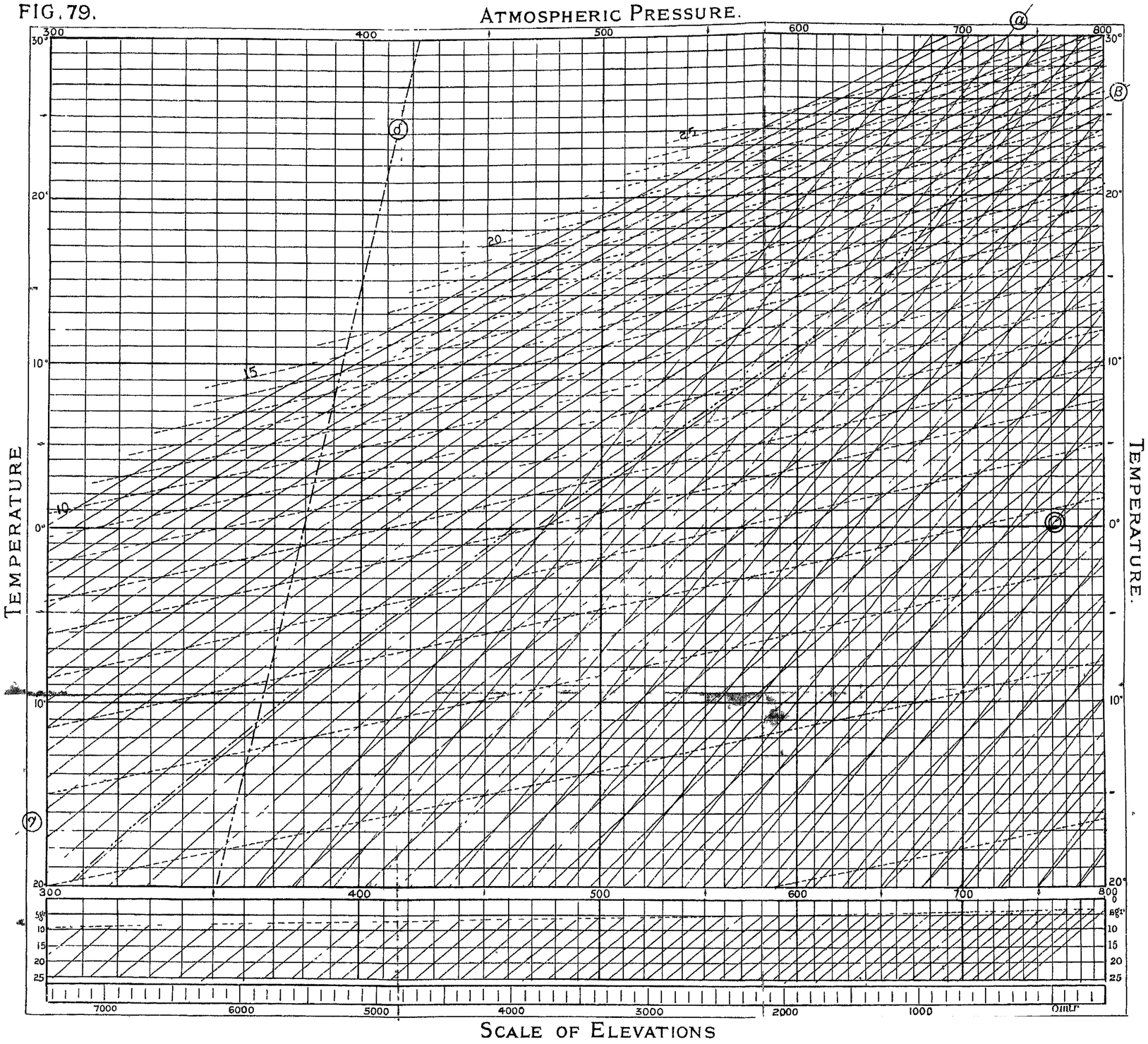
The cross-sectional groundwork of the diagram just mentioned, Fig. 79, is so arranged that the horizontal argument (abscissas) represents the atmospheric pressures (in millimetres) to which the air mixture may be subjected; and the vertical argument or ordinates represent temperatures between —20° C. and +20° C. But the relations are not so simple as may seem evident, for the construction is such that a chosen increase in the length of the co-ordinate

corresponds to the similar increase in the *logarithm* of the pressure or absolute temperature; the numbers themselves not being used; as, in case they were, curved lines, and not straight or approximately straight lines, would have to be used, which is inconvenient in any graphical work. The dotted lines passing from right to left across the page indicate the number of grammes of water present in each kilogramme of atmospheric air under the various conditions: each fifth line is made heavier than the others, and marked on the left with its appropriate number (of grammes) 5, 10, 15, 20, 25.

The courses of the adiabatics in the dry stadium are shown by the line marked α (see at the top on the right), and the lines parallel to it; the courses in the rain stadium are shown by the line marked β (at the right near the top), and the lines parallel to it, but it is to be noticed that they stop at the line of 0° C. temperature, or the freezing point; in the hail stadium the courses coincide with the isotherm of 0°; in the snow stadium the courses are shown by γ (on the left near the bottom), and the lines parallel to it, and it is seen that they nearly, but not quite, coincide with the lines β of the rain stadium, but they stop at the line of 0° C., for at a higher temperature than this the snow would be converted into rain.

The use of the graphical table is best illustrated by an example, and the one given by Hertz for this purpose is as follows:—At the sea-level a mass of air has barometric pressure of 750 mm, a temperature of 27° C., and a relative humidity of 50 per cent.; this mass of air is transported upwards under adiabatic conditions (*i.e.*, without addition or subtraction of

FIG. 79.


ATMOSPHERIC PRESSURE.
300
400
500
600
700
800
30°
20°
10°
0°
10°
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TEMPERATURE
TEMPERATURE.
25
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b
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d
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7000
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SCALE OF ELEVATIONS

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heat), and it is desired to know the changes which it undergoes, and where it enters the successive stadia which have been discussed.

The initial or starting condition of the air mass is shown on the graphical table near the upper right-hand corner at the point where the vertical isobar of 750 mm. intersects the horizontal isotherm 27° C. This point is almost exactly on the dotted line (these give the water content at saturation in grammes) 22, as read by the argument on the left hand of the table, so that, if the air mass were *thoroughly* saturated and consequently had a relative humidity of 100 per cent. at the starting-point, it would contain 22 grammes of water per kilogramme of air; but it has only 50 per cent. of saturation, and consequently contains only half of 22 grammes, or 11 grammes of water per kilogramme. Following the isobar 750 downwards to the bottom of the table, we find that it is about 100 metres above the zero of the scale of elevations given in metres, as this zero of sea-level has been assumed at 760 mm. air-pressure, so that the initial pressure is that at 100 metres elevation on the adopted scale, *and this amount must be subtracted from all altitudes obtained by using the table in solving the present problem.*

Now let the air mass be gradually elevated, and its condition will be represented by the broken line drawn parallel to the lines *a* from the point at 750 mm. and 27° C. on the diagram. If now we wish to find the condition of the air mass at an elevation of 700 metres above the starting-point, the altitude line at the bottom of the diagram is selected at 700 + 100 = 800 metres, and this is followed upwards to the intersection with the broken line which is found to

be at 687 mm. barometric pressure and 19°·3 C. (of course this broken line is drawn merely to represent the present problem, and a straight-edged ruler would in other cases be used in place of drawing a line). No condensation would take place until the broken line 11 of the water-content series is reached, and at this point, which has a barometric pressure of 640 mm. and a temperature of 13°·3, the condensation stadium would be entered upon. And now the direction of the broken line changes, and it will run parallel to the lines (β), which belong to the condensation stadium. But, before following this, it must be noticed that, if the line of 750 mm. pressure is followed downwards to the intersection with the line 11 of the water content, the temperature corresponding to this point will be 15°·8 C., and this, then, is the original dew-point temperature, but it is a somewhat higher temperature than the 13°·3 C. found as the actual dew point. This difference is due to the fact that the air has increased in volume as well as decreased in temperature in the ascent. The pressure 640 mm. is at an altitude of about 1270 metres, as found by means of the corresponding altitude scale at the bottom of the page, and at this altitude the cloud-forming commences. Following the broken line showing the changes in condition in the direction of the (β) lines in the condensation stadium, it is noticed that its inclination towards the axis of abscissas is less steep than in the former course, and consequently the temperature changes more slowly with the elevation, this being due to the freeing of the latent heat of the water vapour, and at an altitude of 1000 metres, *within* the condensation stadium, the temperature is still 8°·2 C., which is only

0°·51 C. decrease per 100 metres of elevation. At this elevation, too, the water-content line is 8·9, so that 2·1 grammes of water must have fallen out of each kilogramme of air, unless this water has been supported by an upward vertical current of air. Following the broken line to the intersection of the 0° C. line, or line of freezing, it is seen that this point lies at an altitude of 3750 metres, which corresponds to the pressure of 472 mm. For dry air, however, this temperature would have been reached at an altitude of 2600 metres, as is seen by continuing the broken line marking the path of change in the dry stadium down to the 0° C. line. At the 0° C. line, however, it is seen that about 4·9 grammes of water have become condensed. At the 0° C. line the water begins to freeze, and the temperature does not fall farther until all of the condensed water present is frozen, so that now for some distance the path is along the isotherm of 0° C. This distance is determined by aid of the small auxiliary table at the bottom of the diagram. We follow the isobar 472 mm. downwards to the dotted line drawn on the auxiliary table, and through this intersection draw a broken line parallel to the course in the condensation stadium. This line terminates opposite the 11 gramme point of the argument shown on the right of the page, and this termination is at the pressure of 463 mm. This last-found number indicates the pressure (along the 0° C. line of the main table) at which the water-freezing process ends, and in this case it extended through a layer of about 150 metres thickness. The decrease in temperature now continues from the elevation where the pressure is 463 mm. onward. The water now freezes as it is condensed, and as the amount of vapour

becomes less, the temperature falls more rapidly as the elevation increases.

The course of the broken line is now parallel to the lines (γ), and by it the condition may be obtained for any desired elevation. For instance, at an altitude of 7200 metres and a barometric pressure of 305 mm., the temperature would be —20° C., and the amount of moisture would be 2 grammes of water vapour per kilogramme of air, the other 9 grammes having been condensed. The relation of the density at any point to that at the place of starting may be determined by drawing lines through the points parallel to (α), and noting the place of intersection with the isotherm 0° C. This occurs at the pressures 330 mm. and 680 mm. in the present case, so that the densities are as 33 : 68. To reduce this to a normal standard of 760 mm. pressure and 0° C., the densities would be as 33 and 68 to 76.

The supposition has been made by Hertz that all of the condensed water remains in the air in the hail stadium, but this would not be a matter of fact in most actual cases. If one can, by judgment or a more accurate means, determine the amount lost from the original amount of moisture by condensation and falling out, then the graphical table of Hertz will be of use in the actual case as well as in the ideal case. Suppose, for instance, it has been determined that half of the *condensed* water has fallen out, then on reaching the 0° C. isotherm there would be only 8·5 grammes of water present in a kilogramme of air, so that the 8·5 gramme line must be used instead of the 11 gramme line, and this would be reached at a pressure of 466 mm. By changing the initial conditions, as, for instance, supposing, in the example

which has been used to explain Hertz's table, the relative humidity had been but 10 per cent., many interesting variations which must occur in nature can be traced out. In this case of only 10 per cent. relative humidity, but at 750 mm. barometric pressure and 27° C. temperature, the total amount of water would be but 2·2 grammes per kilogramme of air, and the so-called condensation would take place at a pressure of 455 mm. and a temperature of —13°·6 C., by which neither rain nor hail would have been formed, but there would be a sort of sublimation of the water particles from a vapour to a solid substance. This very interesting topic cannot be followed out any farther in the present connection, but enough has been said to show the usefulness and future possibilities of Hertz's method.

§ 5.—*Potential Temperature.*

In a very important recent memoir[1] von Helmholtz has introduced the term *Wärmegehalt*, which we may translate *heat-content*, and which is defined as the absolute temperature which a mass of air assumes when it is brought to the normal pressure under the adiabatic process. Since, however, it is a temperature and not a certain amount of heat which this term is intended to express, von Bezold proposes to replace the term *Wärmegehalt* by that of *potentielle Temperatur*, and which we may call the potential temperature. Von Bezold has applied this idea to some meteorological conditions, and has extended the limitation of this original definition to include what he calls pseudo-adiabatic changes. And this is a very im-

[1] *Ueber Atmosphärische Bewegungen, Sitz. ber. d. Berlin. Akad.*, 1888.

portant proviso in all questions of applying the principles of thermodynamics to atmospheric changes, for the truly adiabatic condition of change must be the exception. As before stated in an ascending current of air in which condensation has taken place, a truly adiabatic process would occur only when the rain does not fall, but is carried along with the current until changes in pressure cause re-evaporation to take place, and the moisture again exists as a vapour. In the case where the raindrops leave the mass of air

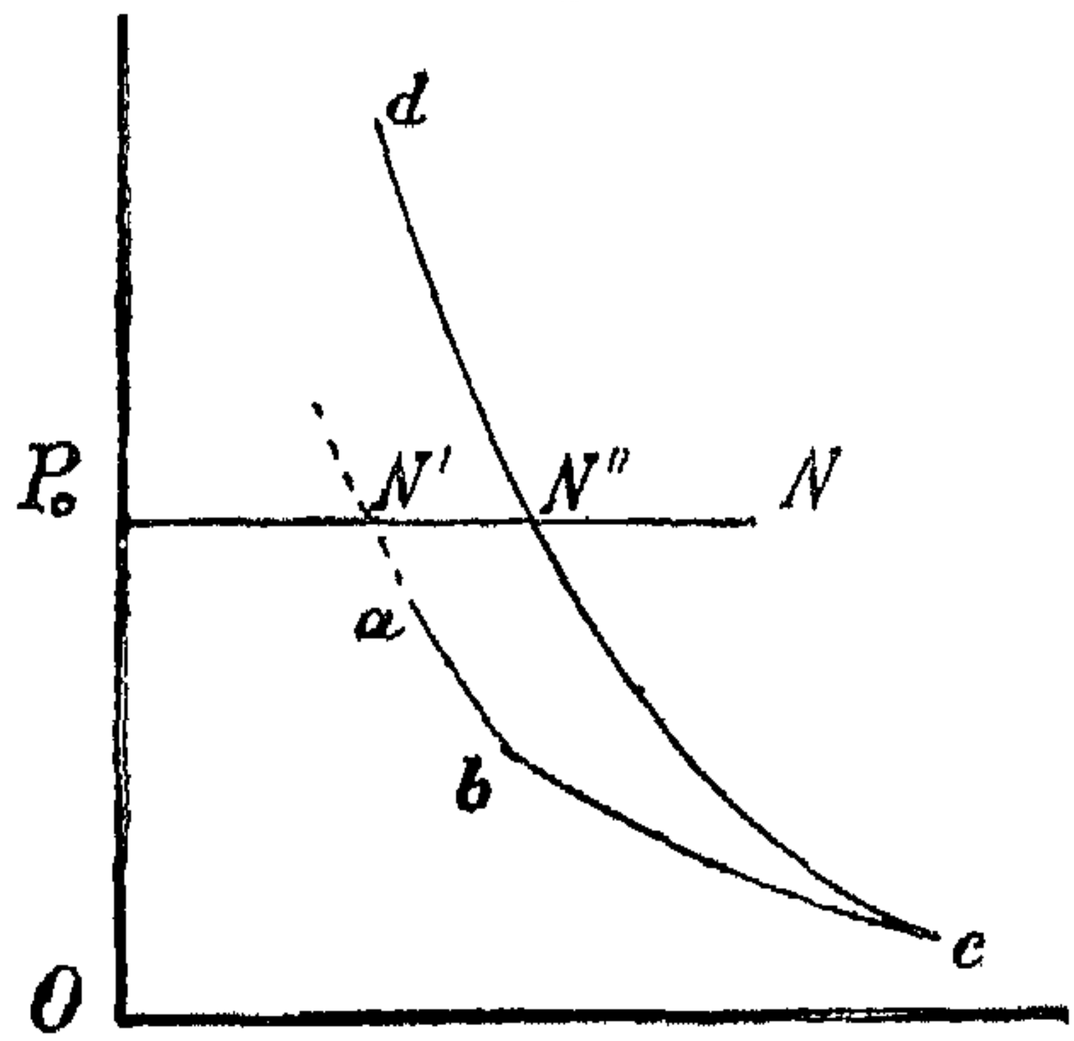

FIG. 80.

by descent, as is usually the case in nature, the process of change in the condition of the air would then be what von Bezold calls pseudo-adiabatic.

This potential temperature has also been illustrated by von Bezold's graphical method. For a constant pressure, the absolute temperature is proportional to the volume, or, in von Bezold's diagram, the abscissa OV.

Von Bezold gives the following rule :—

"For any given condition such as is represented by

a in the diagram (Fig. 80) one can find the corresponding potential temperature by drawing an adiabatic through *a* and finding its intersecting point N′ with the line P_0N drawn parallel to the abscissa at the distance P_0 from it. The distance of this point of intersection from the ordinate axis, that is, the abscissa of the point of intersection furnishes a measure for the potential temperature."

In the dry stadium the potential temperature corresponding to any definite point of departure has a constant value, but in the stadia with precipitation the potential temperature will increase with the amount of precipitation which leaves the air mass.

In the same diagram (Fig. 80) let the adiabatic of the dry stadium which passes through *a* intersect the dew-point curve (not shown) at *b*, and let further expansion of the air take place, then the path *bc* will be over the adiabatic (or pseudo-adiabatic) of the rain or snow stadium. If, now, it is the object to find the potential temperature for the point *c* (as conveniently placed on the diagram), which must be done by reduction to the normal pressure by adiabatic process, then the path of this adiabatic *cd* will not be back over the course *abc*, on account of the water which has fallen out and has thus been lost to this mass of air; and the normal pressure of the dry stadium which is reached over the new path of condition *cd* will be one with a less amount of water vapour than before. Let the point at which *cd* reaches the normal pressure be N″, and let the line *ab* be produced in the reverse direction until it intersects P_0 at N′; then P_0N' is less than P_0N'', or, in other words, the original potential temperature T′ is less than the final

temperature T″, which belongs to the air mass after the water has fallen from it. After pointing out this, von Bezold proposes the following theorem :—

"In adiabatic changes of condition of moist air, the potential temperature remains unchanged as long as the dry stadium is not departed from, but it increases when condensation occurs, and the degree of increase is the greater the more water the air loses." Briefly but more generally stated this theorem reads :—

"Adiabatic changes of condition in the free atmosphere—excluding, however, evaporation—leave the potential temperature either unchanged, or else increase it."

The author of this important theorem calls attention to Clausius' somewhat similar but not identical theorem concerning the increase of entropy. This comparison will be readily understood by a reference to p. 163 of Clerk Maxwell's *Theory of Heat* (6th edition, 1880), where, after explaining the meaning of the term entropy, he says that Clausius remarks that "the entropy of the system always tends towards a maximum value."

§ 6.—*Vertical Temperature Gradient.*

While the horizontal air currents are in general subject to only slight thermodynamic changes, the vertical currents are subject to powerful changes, on account of the very rapid expansion of the air which takes place in ascending currents, and the rapid compression in the descending currents. It is true that the inclination of the ordinary winds to the horizontal is very slight for a free flowing current of air, and in these the change in altitude is gradual; but there

are numerous causes which give rise to more nearly vertical currents in which the change in altitude is so rapid, or even almost sudden, that very great thermodynamic changes must take place within a few moments.

The changes in the amount of heat received or given off by radiation by the greater portion of the air, are so small as to be negligible, except in certain regions, such as that close to the earth's surface, where the superheating of the ground, and vapour dew, and frost-formation affect the changes in the air temperature; and also in the fog or clouds where the changes due to absorption or emission of heat and evaporation readily take place, and especially at the upper surface of the clouds. Commonly, then, the changes in the air moving in vertical currents may be considered as adiabatic, with the exception of such regions as have just been noted. And even in these regions, as von Bezold points out, the adiabatic condition is a sort of average between the conditions when the absorption or emission of heat is in excess. Still, for application, the times when there is a preponderance of emission of heat must be examined separately from those when the amount of heat absorbed is in excess. The former, as shown in Fig. 78, can be applied to the winter season, the night-time, or the cold zone; and the latter to the summer, the day-time, or the warm zone of the earth.

The average or normal condition for the ascending and descending air currents is given in Fig. 80. There, as before stated, *ac* represents the whole condition during the ascent, the portion *ab* is confined to the dry stadium, and *bc* is in the stadium of condensation; and *cd* represents the condition during