THE ATMOSPHERE AND THE SEA IN MOTION

THE ROSSBY MEMORIAL VOLUME

THE ATMOSPHERE AND THE SEA IN MOTION

CARL-GUSTAF ROSSBY

1898—1957

THE ATMOSPHERE AND THE SEA IN MOTION

SCIENTIFIC CONTRIBUTIONS TO THE ROSSBY MEMORIAL VOLUME

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Preface

In July 1957 invitations were extended to colleagues and former students of Professor Rossby, to submit scientific contributions for a special volume to commemorate Professor Rossby's sixtieth birthday anniversary, 28 December 1958. A month later, on 19 August 1957, Professor Rossby died suddenly after a heart attack, in his office at the Institute of Meteorology in Stockholm. His death, at the age of 58, deprived the world of science and his many friends of a man who, by force and charm of personality, power of intellect, and indomitable spirit and energy was a central figure in the explosive development of meteorology that has taken place during the past three decades.

Fate thus has altered the title of this volume, but not its purpose, which is to provide a permanent testimony of the remarkable impact of a man who has been an enormous source of inspiration as a teacher and an international leader in science and scientific cooperation.

The five persons whose names are listed below are responsible for the organization of the Rossby Memorial Volume, and for any defects which may be found in the final publication. Apart from the editorial work, which has been carried out entirely by Dr. Bolin, the most difficult aspect of our responsibilities has been the selection of contributors. The aim which guided us in this selection was to seek contributions that could be grouped around the general theme "The atmosphere and the sea in motion" — the subtitle of the Volume, which epitomizes the scientific work of Professor Rossby. However, the number of close colleagues or former students who could make suitable contributions was so great that we were forced to exclude many prominent names in order to satisfy the rather stringent requirements of economy.

During the months preceding his death, Professor Rossby completed an article entitled *Aktuella Meteorologiska Problem,* which was published in the 1956 yearbook of the National Science Research Council of Sweden. This essay which has been translated into English by Staff Members of the International Meteorological Institute in Stockholm, is presented here in its entirety, under the title "Current problems in meteorology." Written for the non-specialist, it is a penetrating appraisal of many of the dominant problems of meteorology and exemplifies the characteristically broad sweep of Professor Rossby's vision.

We wish to express our appreciation to all those whose contributions made this Volume possible. We are particularly grateful to two of Professor Rossby's life-long associates, Professor Tor Bergeron of the University of Uppsala and Professor Horace R. Byers of the University of Chicago, for their biographical sketches.

March 1959

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WEATHER FORECASTING

Current Problems in Meteorology[1]

C.-G. Rossby

Introduction

The following survey of current problems in meteorological research deals primarily with the classical problem of meteorology, the quantitative analysis of the state and motion of the atmosphere based upon the laws of physics. In addition we shall discuss some recent problems concerning the role played by the atmosphere as a carrier of insoluble minerals, soluble condensation nuclei and industrial pollutants, problems of importance for understanding the rọle of the atmosphere in certain geological processes, and as a milieu for the biological processes at the surface of the earth. Investigations on such problems in the past have been considered to be of peripheral interest to meteorology, partly because the feed-back of these windborne substances on the general circulation of the atmosphere is usually insignificant. It has, however, become apparent lately that one of the important tasks for applied meteorology will be to forecast the effects of large-scale diffusion processes in the atmosphere. In addition, a systematic study of the distribution of air-borne particles can give us valuable information concerning the tracks of individual air particles, and thereby also the dynamics of the atmosphere. Such information cannot always be obtained through the analysis of the daily meteorological observations at our disposal. For these reasons more attention lately has been devoted to trajectory and diffusion problems in the atmosphere.

One essential criterion which will show that the classical task of meteorology has been solved will be our ability to compute objectively the future state and motion of the atmosphere on the basis of theoretical principles; in other words to issue numerical forecasts of the weather. By and large this means trying to find an answer to the question: "What will the wind direction, wind speed, pressure etc. be at a given place at a given instant in the future?" The diffusion problem, on the other hand, which more and more engages the attention of meteorologists, can be formulated in a prognostic question of the type: "Where will a given air particle be at a given instant in the future?" To the extent that it is possible to solve these two problems with the aid of the basic equations of hydrodynamics, the diffusion problem means one additional time integration and therefore puts far greater demands on the accuracy of both theory and meteorological observations.

It is hardly necessary to stress that the following survey is both incomplete and subjective in the choice of problems discussed. The incompleteness is a result not only of the lack of space but also depends upon the fact that it is hardly possible any longer for one meteorologist to acquire detailed knowledge of the whole front along which meteorological research is carried out today. This research includes a large number of special problems and problems of a local character which are of great theoretical and practical importance. Such questions have been disregarded here for the problems of a more global character.

In the first part of the review certain problems concerning the atmosphere as a whole and its interaction with the ocean are briefly considered. A discussion of the general circulation of the atmosphere follows, and in this connection an analysis of the present status of numerical forecasting is given. In connection with problems of forecasting, certain aspects of trajectories in the atmosphere are presented, followed by a discussion of some circulation and diffusion problems in the field of atmospheric chemistry. The review is concluded with some brief comments concerning the possibility of controlling some atmospheric processes artificially. The mutual dependence of various branches of geophysics as well as the similarity of the problems in these different fields is everywhere stressed as being

[1] This article is a translation of "Aktuella meteorologiska problem», published in *Svensk Naturvetenskap 1956* by the Swedish Natural Science Research Council.

particularly true for meteorology, oceanography, hydrology and geochemistry. Sooner or later these intimate connections must be considered by those who have the responsibility for the future training of geophysicists and for the planning of purposeful and responsible geophysical research.

In the preparation of the following review the writer has received many valuable suggestions and critical comments from his associates at the International Meteorological Institute in Stockholm, in particular from Dr. BERT BOLIN, who has been in charge of the work in numerical forecasting at the Institute for a number of years, and has also played a role in other research activities at the Institute.

Planetary problems of balance and circulation

A. *Radiation balance and heat storage*

During the decades which have passed since meteorology first took shape shortly after the beginning of this century, the network of meteorological stations which is at our disposal for the study of the daily changes in state and movements of the atmosphere, has been extended in an impressive way. It is now possible to give a rather satisfying picture of the air movements of the troposphere and the lower stratosphere twice a day over the major part of the northern hemisphere. At the same time our knowledge of the dynamics and physics of the atmosphere has to some degree become more profound. In spite of, or perhaps because of this better knowledge, one finds that certain fundamental postulates, which earlier were regarded as so self-evident that they were not even dealt with in the meteorological textbooks, now must be looked upon as rather uncertain. The heat balance of the atmosphere serves as a good example.

The solar radiation falling perpendicularly upon a surface of one square centimeter at the outer edge of the atmosphere, amounts to about 1.95 cal min^{-1}. This value, the "solar-constant", is of course uncertain, as it is determined by extrapolation to the outer border of the atmosphere from measurements within the atmosphere. However, for the particular estimates which are given here, this uncertainty can be regarded as unimportant. Because the surface of the earth is four times greater than its cross-section, it follows that about 0.49 cal cm^{-2} min^{-1} is available to maintain the circulations of the atmosphere and the sea. It is generally supposed that between 30 and 40 per cent of this amount of energy is reflected back to space as short-wave radiation by the upper surfaces of the clouds, snow covered areas, to some degree by the sea surface, and finally by the atmosphere itself (Rayleigh scattering). The exact amount of the total reflection is still uncertain. The remaining amount of energy, of the order of 0.3 cal cm^{-2} min^{-1}, thus represents the effective solar radiation which keeps the air (and the sea) in motion. It is assumed, usually without discussion, that our planet as a whole is in radiation balance with its surroundings, so that the same amount of energy, 0.3 cal cm^{-2} min^{-1}, thus will be sent back to space as long wave (infrared) radiation from the earth's surface, from the upper surfaces of the clouds and, even of more importance, by the water vapour in the atmosphere. How precisely the equilibrium condition must be maintained is, however, uncertain and should, as the following calculations indicate, depend strongly upon the time interval taken into consideration.

In three extremely interesting papers at the end of the 1920's G. C. SIMPSON investigated the radiation balance of the atmosphere and calculated the geographical and yearly variation of the outgoing long-wave radiation. Simpson found that this outgoing radiation was very evenly distributed both in space and in time, and that within the accuracy of the computations the total outgoing radiation from our planet as a whole, during each of the months of the year, was balanced by the total effective incoming solar radiation. Simpson does not deal with the total amount of heat stored in the sea and the solid surface of the earth, and these questions are generally ignored by the meteorologists studying the radiation balance. Thus the good agreement between the calculated incoming and outgoing radiation indicates that it is possible to neglect variations of the stored heat even for as short a period as one year or even a few months, as long as one limits oneself to the entire planet. This result is really rather astonishing, if one takes into account the great uniformity in space and time of the outgoing radiation found by Simpson. Such uniformity indicates that the atmosphere is rather incapable of adjusting locally the outgoing radiation to the very great variation in space and time of the incoming effective solar radiation.

Qualitatively Simpson's result may be explained in the following way. The intensity of long-wave radiation in the atmosphere is determined primarily by the vertical distribution of water vapour and temperature. The minor deviations, which are due to carbon dioxide absorption and emission may be neglected in a first approximation. If one disregards a gap between 8,5 μ and 11 μ in the absorption spectrum of water vapour where Simpson considers a cloudless atmosphere to be completely transparent, the water vapour atmosphere is rather opaque, and therefore the major part of the radiation which goes out into space must be emitted from the middle or upper parts of the troposphere and from the upper surfaces of clouds. Because of the permanent convective mixing in the atmosphere and the upper limit of the water vapour concentration, which for each temperature is determined by the saturation vapour pressure, the vertical distribution of water vapour will be very closely tied to the vertical temperature distribution; as a matter of fact Simpson starts his calculations from an empirical formula, by which the relative humidity is uniquely determined by the temperature. The temperature at the top of the clouds is supposed to be the same everywhere. Since the outgoing radiation, because of the atmosphere's absorption, in this way almost entirely emanates from the upper parts of the water vapour atmosphere where the temperature is given, it does not matter at what height above the surface this layer is situated, or in other words, what temperature there is at the earth's surface. Thus, outgoing radiation flow is almost uniquely determined.

Since Simpson's time much work has been done on a detailed study of the selective absorption spectrum of water vapour and in developing graphical methods for reliable calculations of the atmospheric long-wave radiation flow from the observed vertical temperature and humidity distribution. The leading name in this branch of research was for many years W. Elsasser.

A fundamental advantage of these graphical methods is that they eliminate the analytic connection between the water vapour and temperature distribution, which served as a starting point for the calculations of Simpson. It has been shown above that this forms a constraint which hinders the local adjustment of outgoing radiation to the incoming solar radiation. On the other hand one must remember that the connection between temperature and water vapour content is an empirical, statistical fact, which therefore ought to show up even in graphical estimates based upon observations of the vertical stratification. Thus it is rather doubtful whether these more refined methods now available can lead to large fundamental differences from the uniformity and the lack of adaptation of the outgoing radiation as found by Simpson. A few years ago H. G. Houghton published a new computation of the annual heat (radiation) balance, based upon recent data concerning cloud distribution and light reflection, and applying Elsasser's graphical method to the upper-air data now available from a rather great number of radiosonde stations. According to Houghton both the incoming and the outgoing radiation are considerably higher than the results of Simpson indicate, but the question concerning the ability of the atmosphere to adapt to the outgoing long-wave radiation to the effective incoming radiation remains unanswered.

In the study of post-glacial climatic fluctuations, it has been assumed to be of great importance to know how the radiation exchange between our planet and space adapts to possible variations of the solar constant. Simpson's answer is that as the outgoing radiation can hardly be modified to any great extent, the adaptation must take place in form of variations in total cloudiness in such a way that increasing incoming radiation causes increasing cloudiness by increasing evaporation from the sea surface, thus causing greater reflection of incoming radiation. This conclusion seems at first to be rather surprising when considering the relatively small changes of the planetary cloud cover from winter to summer. On the other hand, as a support of his hypothesis, Simpson develops an extremely interesting comparison between the radiation balances of the planets Venus, the Earth and Mars. If the cloudiness is expressed in terms of tenths of the total cloudiness, one finds that this figure varies from 10/10 on Venus, to about 5/10 on the Earth and 0/10 on Mars. The resulting differences in the ability of these planets to reflect the incoming radiation of the sun (albedo) is to a large degree enough to compensate for the differences in the incoming radiation depending on the mean distance of the planets from the sun.

Our knowledge of the variations in the total solar radiation which reaches the outer border of the atmosphere, is for obvious reasons very rudimentary, but it is likely that variations of one or a few per cent of the total energy occur. The greatest part of this variation is probably to be found in the ultra-violet part of the incoming radiation, which is absorbed almost totally in the upper parts of the atmosphere and therefore is not directly able to influence the lower atmosphere and its circulation. Variations in the absorbed solar radiation must, because of the extremely low density of the atmosphere at these high altitudes, lead to strong local temperature fluctuations. Many attempts have been made to construct mechanisms by which such fluctuations in their turn could influence the circulation of the troposphere. These efforts have not yet led to the goal, but considering the strong vertical stability which characterizes the lower layers of the stratosphere (15—35 km) it is very unlikely that variations of the temperature and structure of the higher atmosphere should have any noticeable influence on the circulation of the troposphere. But it ought to be pointed out that this personal opinion of the writer is not shared by all meteorologists.

It has already been observed that Simpson's work does not touch on the possibility of secular changes in the stored heat. The yearly cycle of the heat which is stored in the solid earth's crust and the sea, was dealt with for the first time extensively in 1934 and 1935, by F. Bauer and H. Phillips, who considered the heat balance of the atmosphere in a renewed treatment along the same lines as Simpson, but starting from much more accurate values of the parameters. Bauer and Phillips assume, however, that the local storage has an annual cycle prescribed in such a way that the net accumulation for one year vanishes everywhere. Because of the very low heat conductivity of the earth's crust, variations in its heat storage must be rather unimportant, which is shown for instance by the fact that the temperature climate of isolated desert regions follows the sun very closely. The ability of the atmosphere to store heat is also rather limited. As an illustration it can be mentioned that if during one year 1 % of the total effective solar radiation, i.e. 0.003 cal cm^{-2} min^{-1}, should be stored instead of being sent back to space, this would lead to an increase of the mean temperature of the atmosphere of about 6.3° C, but as the capacity of the atmosphere to absorb water vapour from the sea would increase at the same time, the resulting temperature increase would probably amount to only half this value.

The magnitude and character of the variations of the total heat, both realized and latent, stored in the atmosphere is not known. In spite of the well organized international meteorological network there is at present no international organization responsible and equipped for the enormous statistical work which current computations of this kind would demand.

In the surface layer of the sea the perpetually shifting winds cause mixing and a vertical homogeneous layer of water, the medium depth of which is of the order of magnitude of 50—100 m. If the heat capacity of this layer is taken into account, it is found that a storage of 1 per cent of the effective incoming solar radiation would lead to a mean temperature increase in the entire storage layer (the atmosphere plus the homogeneous surface layer) of only a few tenths of a degree.

It is not difficult to demonstrate that the storage of heat in the turbulent surface layer ought to be taken into account in local radiation balance computations. For this purpose one can choose the surroundings of Bermuda, where the advection of warm and cold water masses is of very secondary importance. It is easily found that the excess of the incoming, effective solar radiation in the warm season is more than sufficient to explain the increase with time of the heat stored in the surface layer, which reaches its maximum about three months after the summer solstice. At the same time Simpson's tables, as well as Bauer's and Phillips' calculations, show that the outgoing radiation in that part of the world is practically independent of the season.

The heat stored in the surface layer of the ocean in the southern hemisphere is decreased at the same time as the heat storage in the northern hemisphere is increased, and the surface layer is perhaps of minor importance of the total heat balance of the earth, which would very well agree with the results of Simpson. Considering, however, the difference between the hemispheres in regard to the distribution of land and sea, it is not self-evident that such an equalization occurs.

The role of the sea as a secular heat reservoir assumes quite a different character at the moment that one takes up the question of secular changes of the total heat balance, taking into account the circulation of the deeper layers. An elementary calculation gives the result that even as much as 1 % of the total incoming heat radiation could be stored in a layer of 1,000 m thickness in the interior of the sea, without producing a temperature increase greater than 0.015° C per year; for thicker layers the temperature increase would become proportionally smaller. — *These deeper layers are insulated from the atmosphere by stably stratified warmer watermasses near to the sea* *surface and are not able directly to restore the radiation balance by means of an increased evaporation and cloud formation.* The figure mentioned above should be increased by 50 per cent in order to correct for that part of the earth's surface which is covered by continents and continental shelves, but the correction is of course unimportant for these rough estimates.

The deep water is produced along the borders of the Antarctic, especially along the Atlantic sector and during the colder season possibly even in some limited regions of the northern Atlantic near Greenland. Furthermore it is certainly necessary to take into account that water in the northern parts of the North Atlantic is forced into the deep ocean by the prevailing wind system in the whole North Atlantic Ocean, which ordinarily forces the surface water to the north. The deep water masses formed in this way gradually spread to the other oceans by the Antarctic circumpolar currents, and finally end up in the Pacific Ocean, where the "oldest" water masses are found. The cycle is probably closed by the very slow mechanical mixing of the superimposed warmer layers with the stagnated deep layers, which in this way are able to rise to the sea surface again. As the intensity of the mechanical mixing must necessarily decrease with increased temperature contrast between the surface water and the deep water, i.e. with increased vertical stability, it is not unlikely that the intensity of the whole thermohaline cycle mentioned above must undergo strong and probably rather irregular, slow fluctuations. The total volume of the water masses normally taking part in this cycle is not known, but its order of magnitude lies probably between 10 and 100 million m^3 per second, corresponding to a circulation period for the whole sea of 4,000 years in the former and 400 years in the latter case. A period of about 400 years fits fairly well into the values which have been deduced e.g. from instantaneous "age measurements" of the deep sea with the aid of C^{14}-analyses and from estimates of the oxygen consumption in the deeper layers of the sea.

On the basis of these (admittedly loose) estimates, one is probably justified in expressing the following two suggestions:

a) The assumption that our planet as a whole stands in firm radiation balance with outer space cannot be accepted without reservations, even if periods of several decades are taken into account.

b) Anomalies in heat probably can be stored and temporarily isolated in the sea and after periods of the order of a few decades to a few centuries again influence the heat and water-vapour exchange with the atmosphere.

If this latter assumption is correct, it does not seem unlikely that the problem of post-glacial climate fluctuations lasting a few hundred years can take on new aspects. But it must be pointed out that if these anomalies in heat which are stored in the interior of the sea are gradually distributed in greater water masses, they must, when they finally reach the sea surface again, be characterized by very small temperature amplitudes. How such exceedingly small variations in temperature could possibly have a significant influence on the atmosphere is still an unanswered question. It is perhaps more likely that the changes by no means take place at a constant rate but fluctuate so that the contrast in temperature between the surface water and the deep water shows strong variations with time.

Considering what has been said above, it is obvious that measurements or reliable estimates of the heat exchange between our planet and outer space must be looked upon as a major question for meteorologists and oceanographers interested in the global circulation systems of the sea and atmosphere and their fluctuations. Our knowledge of long-wave radiation streams which penetrate the atmosphere is yet too uncertain to permit more reliable numerical estimates of their intensity. For easily understandable reasons oceanography has not yet become a synoptic science, and large parts of the interior of the sea are yet too little explored to permit any computations of secular variations of stored heat. An attempt to examine the possible existence of such variations is, however, being made during the International Geophysical Year by measurements in some parts of the Atlantic Ocean, which were investigated by the Meteor Expedition in the 1920's.

It is obviously of great importance for both meteorology and oceanography that some preparatory instrumental work has been started in order to measure the total heat exchange of the earth with space by means of satellites, which will be sent up during the International Geophysical Year. In order to determine the heat exchange it is necessary to measure simultaneously not only the incoming radiation (the solar constant) and the earth's albedo (reflection power), as was originally planned, but also the total outgoing longwave radiation. As we are mainly interested in what are probably very small differences between the amounts of incoming and outgoing radiation, the technical difficulties are enormous, but as the problem is now accepted as being of fundamental importance, certainly intensive work will be conducted in order to solve the problems connected with such measurements.[1]

B. *Carbon dioxide and its cycle*

The circulation of water between the surface and the deep layers of the sea, and especially its period of circulation, is of fundamental importance when studying another global meteorological problem of great interest to climatology, i.e. the increase of the carbon-dioxide content of the atmosphere. This increase seems to be a result of the steadily increasing consumption of fossil fuel in the last 50 to 100 years. How large this increase really is must to a great degree depend upon whether the sea, particularly the deep layers, is able to absorb slowly or quickly the excess of carbon dioxide constantly supplied to the atmosphere.

It has been pointed out frequently that mankind now is performing a unique experiment of impressive planetary dimensions by now consuming during a few hundred years all the fossil fuel deposited during millions of years. The meteorological consequences of this experiment are as yet by no means clarified, but there is no doubt that an increase of carbon-dioxide content in the atmosphere would lead to an increased absorption of the outgoing infrared radiation from the earth's surface thus causing an increase of the mean temperature of the atmosphere. As we know, SVANTE ARRHENIUS was first to point out that variations in the carbon-dioxide content of the air, resulting from the volcanic activity of the earth, could explain the variations in climate, which characterize the geological history of our plante. Quite recently G. N. PLASS calculated that, assuming all other factors to be constant, a doubling of the carbon dioxide in the atmosphere would lead to a mean air temperature increase of about 3.6° C, while a reduction of the carbon dioxide to half its value would lower the temperature by 3.8° C. It is almost certain that these figures will be subjected to many strong revisions, depending mainly on the fact that those complicated processes, which finally determine the mean temperature of the atmosphere, cannot be dealt with as independent, additive phenomena. For instance, a higher mean temperature caused by carbon dioxide must lead to

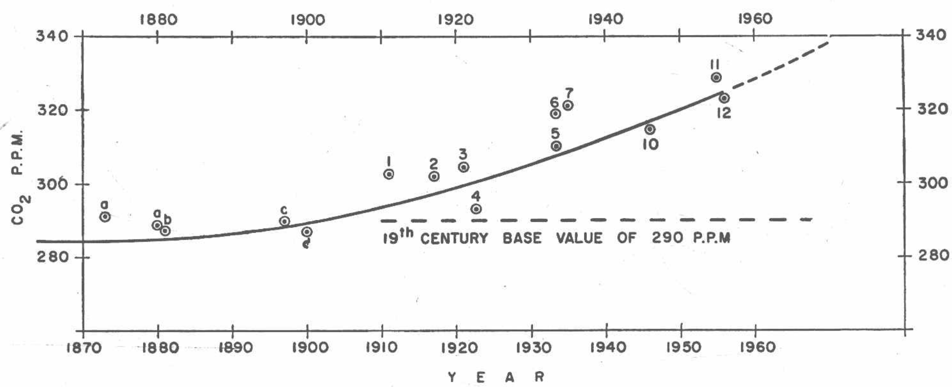

Fig. 1. In this diagram by G. S. CALLENDAR an attempt is made to illustrate the increase, in recent years, of the content of carbon dioxide in the atmosphere by means of observational series which were critically selected. The continuous ascending line represents the theoretically estimated content of carbon dioxide under the assumption that none of the carbon dioxide liberated through combustion is stored in the sea or in increased vegetation.

[1] In this connection it ought to be mentioned that Simpson's as well as Houghton's calculations of the outgoing long-wave radiation from different latitudes have been corrected by multiplication with a factor common for all latitudes and chosen in such a way that complete balance is obtained between the total incoming and outgoing radiation. Considering the imperfection of the methods of calculation this procedure is, of course, completely justified, as the deviations resulting from the computations have no physical significance, whatsoever. On the other hand, it must be emphasized that in fact real deviations of this order of magnitude (1—3 per cent) could be of outstanding importance from the paleo-climatological point of view.

an increase of atmospheric water vapour content and therefore of the infrared absorption by the water vapour but probably also to an increased cloudiness.

Has there really been a considerable increase in the content of carbon dioxide in the air during the very much expanded industrial activity of the last decades? In 1940 G. S. CALLENDAR thought it possible to show that the carbon-dioxide content of the atmosphere had increased by approximately 10 per cent since the beginning of the century. The observational material at this disposal was very extensive but of very uneven quality with a highly unsatisfactory geographical distribution of the observation sites (most of them were situated at places in central Europe, which were highly polluted by industrial activity). Callendar selected the series of observations that he thought were most reliable and representative, but an inspection of the material used with its enormous spread gives a strong impression of the uncertainty which necessarily characterizes his estimates. In a paper published recently, however, and based on a critical review of older as well as more recent data Callendar maintains his opinion about the rapid increase of the atmospheric carbon dioxide.

An increase by 10 per cent of the total carbon-dioxide content of the air would, according to Callendar, approximately correspond to the amount of carbon dioxide liberated through the consumption of fossil fuel during the three or four first decades of this century. In order to explain this high value of the increase of carbon-dioxide content, one must assume that only a very small fraction of the amounts released to the atmosphere has been absorbed in the sea in spite of the fact that the capacity of the marine reservoir is about sixty times greater than that of the atmosphere. Thus one is immediately faced with a great number of difficult problems. How should measurements of the total carbon-dioxide content of the atmosphere be conducted in the best way? How should measurements or estimates be made in order to gain increased knowledge of the carbon-dioxide exchange at the sea surface. Finally, how rapid is the exchange between the surface layer and the deep sea?

For almost two years a small group of Scandinavian scientists has maintained a network consisting of 15 stations on the Scandinavian peninsula, Denmark and Finland from which air samples for carbon dioxide analysis have been taken three times every month. The sampling stations and times are chosen to suppress the local sources of error as much as possible. Nevertheless it is found that the carbon-dioxide content varies so much with the origin of the prevailing air masses that it possibly could be used as a diagnostic, synoptic element. It is not unusual to find variations of 10 per cent across a well-developed front. Therefore it seems almost hopeless to arrive at reliable estimates of the atmospheric carbon-dioxide reservoir and its secular changes by such measurements in limited areas.

In order to overcome this difficulty to some extent it has been suggested that regular carbon-dioxide analyses of the air near the surface should be performed in some synoptically inactive parts of the world far from industrial regions, the sea, and densely vegetated regions where also the assimilation could influence locally the values obtained. Carbon-dioxide determinations in the free atmosphere and in desert regions, mainly in the not yet too heavily industrialized southern hemisphere ought therefore to be of special interest, but they must, of course, be made concurrently and during a great number of years in order to establish secular changes in the total carbon-dioxide content of the atmosphere.

As a contribution to the study of these important problems, a rather extensive observational program will be conducted during the International Geophysical Year. In addition to the rather modest Scandinavian network meteorologists and oceanographers have planned an extended network of synoptic carbon-dioxide stations in North and South America, the Artic and the Antarctic. Carbon-dioxide determinations will furthermore be made on a great number of islands in the Pacific and the Atlantic, and on mountain stations in North and South America. Furthermore, there will be regular flights along certain meridians in order to determine the carbon-dioxide content in the free atmosphere.

In spite of the rich material which will thus be collected, it is very likely that great difficulties will be encountered in every attempt to compute the content of carbon dioxide in the atmosphere and its secular changes from such scattered observations. For this reason it is of special interest that a new, perhaps more promising method, is being developed based upon comparative determinations of the content of the atmosphere and the biosphere of radioactive carbon (C^{14}). The first attempt to determine the secular change of the carbon-dioxide content of the atmosphere by this method were made by

H. Suess in 1953, and the problem has later been taken up by others.

In principle, this method is based upon the fact that the carbon dioxide, which is brought to the atmosphere by the combustion of fossil fuel, must be free from radioactive carbon, the half-life of which is 5,568 years. By comparison of the C^{14} content of annual tree rings from the middle of the last century with the youngest annual rings in trees recently felled one can thus determine whether the assimilated carbon dioxide originates from the earlier "natural" carbon dioxide reservoir of the atmosphere, in which the C^{14} content represents an equilibrium between the production and decay of radioactive carbon, or from the extra supply of "dead" carbon dioxide which originates from the fossil fuel consumed.

The method has the great advantage that it is very likely to eliminate local synoptic variations in the atmospheric carbon-dioxide content. However, the industrial consumption of industrial fuel shows very great geographical variations with a minimum in the southern hemisphere. Therefore it is obvious that definitive conclusions concerning secular variations can be drawn only when samples from widely separated parts of the world have been analysed.

It should perhaps be stressed that investigations concerning such problems as the total variation of the heat stored in the sea, or of the total content of carbon dioxide in the atmosphere, biosphere or the sea, mean a completely new class of questions in theoretical meteorology and oceanography. In these investigations one is hardly interested in geographical distributions. As a first approximation the problem consequently may be reduced to systems of simultaneous ordinary and usually nonlinear differential equations, which express the interplay between the different reservoirs. Under special conditions thermomechanical systems of this type are able to maintain nonlinear oscillations of finite amplitude, as if their self-regulating properties were defective in some way. E. Eriksson and P. Welander have recently suggested that the combined carbon dioxide system should be characterized by such oscillations. Their result depends to a great extent on some much debated assumptions about the interior properties of the system, but it is obvious that the possible existence of such oscillations in the total heat balance system, including the heat storage in the sea, would be of great climatological interest.

C. *Tritium and the hydrologic cycle*

Water vapour, which evaporates from the sea surface, is transported over the continents by maritime winds to condense and finally precipitate as rain or snow. A part of this precipitation is perhaps temporarily stored in lakes or in the ground water and another part is restored to the atmosphere by the transpiration of vegetative cover or by evaporation from the ground, but on the average as much water must flow into the sea by streams and rivers as the net amount which is brought inland by the maritime wind systems. A careful analysis of this complicated hydrologic cycle with its many epicycles is an important prerequisite for a rational treatment of climatology. In some highly industrialized regions in the world, where in recent years the industrial per capita consumption of water has increased very rapidly, the knowledge of the hydrologic cycle has become of increasing practical importance, e.g. in connection with the many experiments now performed in order to increase the water supply by artificially initiated precipitation or by suppression of the evaporation from lakes and reservoirs.

The evaporation from the sea is supposed to be of the order of 2—3 mm water per day. A systematic estimate of average supply of water vapour in the atmosphere has not been made, but should lead to a value of one or a few g cm^{-2}. Thus the residence time of water vapour in the atmosphere as a whole must be of the order of a few days or at most one week. It is, however, obvious that the small fraction of the water vapour evaporated from the sea which is brought over the continents and is stored in the ground water, must have a circulation time of quite another order of magnitude. W. F. Libby and his students have recently shown that radioactive tritium (H^3), which is normally formed in the atmosphere by cosmic ray activity and which is furthermore produced in much greater amounts by hydrogen-bomb explosions, could be used for determinations of the average storage time of water as ground water.

Tritium has a half-time of 12½ years and is very well suited for studying such cycles, the circulation times of which are of the same order of magnitude. Libby and his collaborators determined the tritium content of the precipitation in Chicago and of Mississippi-river water in the years 1953—56. Shortly after the hydrogen-bomb explosion "Castle" in spring 1954 the tritium