If the Earth went Dry.[1]

By Sir NAPIER SHAW, F.R.S.

THE various countries of the globe differ from one another in respect of dryness, though none are literally dry, year in and year out. Still some are very nearly dry; others are moist, and some, comparatively speaking, wet. Herein consists one of the main causes of the complication which students of the physics of the atmosphere have to face.

For a meteorologist, water in the form of vapour is the most important constituent of the atmosphere; it provides not only the material for clouds, rain, snow, and hail, but also the means of supplying the energy which makes those things possible. Recent investigations have made it clear that the important functions attributed somewhat loosely in meteorological literature to warm air really belong to the water vapour which the warm air carries. We may well therefore ask the question, "What on earth should we do without water?" What would meteorology be like if its warm air were never saturated and never could be saturated? The answer to the question is, "Very little would be left; but still something." It is that "something" to which I wish to direct attention. "What would be left of meteorology if the earth went dry?"

As a subject it is, of course, hypothetical. Water is an important constituent, not only of the atmosphere but also of all living material, so absolute prohibition in the sense in which I am using the term would put an end not only to that part of meteorology which I may call the joy of its life, but also to life itself in any form. So far as I know, it would be futile to put the question to a biologist. It is not so for the meteorologist. Although the most familiar conception of the meteorologist, the spontaneous ascent of warm air through its environment by what is called convection, would disappear, there would still remain quite unimpaired and even enhanced the spontaneous descent of air by cooling on a mountain slope and also a peculiar form of the ascent of warmed air by the building up of a layer of air in convective equilibrium—a new conception of considerable interest which gives a true representation of the convection of warm air as distinguished from saturated air.

A GENERAL VIEW OF ATMOSPHERIC STRUCTURE.

I start from a certain idea of atmospheric structure, which, though not novel, may require setting out. I will ask you to regard the meteorological atmosphere as being an envelope of some twenty kilometres' thickness, with a structure of the same type as the stratosphere which has been identified in our own upper atmosphere. By a stratosphere I mean a thermal structure expressed by approximately vertical isothermal surfaces which surround the polar axis like a series of collars projecting vertically outward from successive parallels of latitude. Such a structure would require a certain circulation of air, in order to balance the distribution of pressure which is inevitable when there are vertical columns of different temperature; but that being provided, the structure would be an extremely stable atmosphere, impenetrable by any convection. That is as it should be; because the structure is only possible if vertical convection is ruled out. Vertical convection of any sort would mix up the layers and transform the isothermal structure into some sort of approximation to the labile state of convective equilibrium. Any convection would be a step in that direction.

Taking the structure of the stratosphere as the original idea, we may say that the lower layers of our own atmosphere have been modified by convection, with the aid of water vapour, and have been converted into a state which approximates much more nearly to that of convective equilibrium than to the isothermal conditions of the stratosphere. The part of the atmosphere thus modified we call the troposphere. In this region temperature is arranged in layers which are nearly horizontal instead of in nearly vertical sheets or columns. Our present troposphere is not uniformly thick; it extends from the surface of the earth upward through about seventeen kilometres in the equatorial region, and about half that height at the poles. Its upper boundary, called the tropopause, may be said to mark the present limit of the operation of convection. If convection became more active, the troposphere would be enlarged at the expense of the stratosphere; if on the other hand convection became less active, the boundary would be lower, the stratosphere would come down nearer to the earth; and if there were no convection at all, the atmosphere would be all stratosphere.

We may therefore regard the troposphere as the result of persistent excavation by quarrying, carving, or nibbling of the under side of a stratospheric atmosphere by convection of one sort or other which originates in the warmth and moisture developed at the earth's surface or the loss of heat in the absence of the sun. In our present atmosphere convection is largely dependent upon water vapour, hence our first conclusion is that if there were no water vapour, the excavation would be greatly reduced and the stratosphere would be brought down much nearer to the surface and only interfered with by such convection as belongs to dry air.

It is possible that in the course of years this reduction of convection might affect the temperature of the stratosphere but its immediate results would be limited to the troposphere, and its effects upon the body of air comprised within the troposphere are dynamical as well as thermal. The troposphere may be said to form the flywheel of the atmospheric engine. It is in a state of perpetual motion, which we call the general circulation of the atmosphere, as the dynamical effect of heat received from the sun by radiation, communicated chiefly at the ground level and afterwards radiated into space from the earth's surface and the atmosphere. The working of the atmospheric engine would be much simplified if there were no water vapour, because then, without serious error, the atmosphere might be regarded as perfectly transparent both

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for the solar radiation by which the heat is gained and for the terrestrial radiation by which the heat is lost.[2] Loss or gain would take place only at the surface and the balance of loss or gain of heat would be the result of a comparatively simple account.

THE BALANCE OF GAIN AND LOSS OF HEAT.

As a prelude to the question of downward convection, which is applicable equally to dry air and moist air, let us examine the question of the balance of gain of heat from the sun and the loss of radiation from the ground.

Taking a station such as Davos, the diurnal and seasonal isopleths of the intensity of solar radiation, which is referred to a surface normal to the sun's rays, shows that the diminution of the intensity with the increasing obliquity of the sun's rays is due to absorption by the atmosphere, principally by water vapour. If there were no water in the atmosphere, the intensity of solar radiation would reach and remain at the amount indicated by the solar constant throughout the period of sunlight, changing instantaneously to zero with the disappearance of the sun at sunset and recovering its full activity at sunrise. That activity is about 1·93 gram calories per square centimetre per minute, equivalent to 135 kilowatts per square dekametre or 1·35 kilowatt (2 horse-power) per square metre.

I digress for a moment to direct attention to the vastness of the power of the sun. Some days ago, looking at the Montmorency Falls, a distinguished engineer suggested that the energy represented by the Falls might be 20,000 horse-power. The power of sunlight upon an area of 200 yards by 100 yards, about four acres, would exceed that amount—if the whole of the energy of sunlight could be converted into work, as practically the energy of a waterfall can be.

We have supposed the area to be at right angles to the sun's rays. To get the amount on a square dekametre of horizontal surface, we must multiply the figure for normal incidence by the sine of the angle between the sun's rays and the horizontal surface, the sine of the sun's altitude. As the sun recedes from its noon altitude the intensity of its radiation decreases gradually from its noon value to zero when at sunset the sun is at grazing incidence.

To set against this gain of energy by solar radiation we have the loss of heat by radiation into space, which, if the atmosphere be perfectly transparent (as we will assume dry air to be), depends upon the fourth power of the temperature, and nothing else, except the radiating power of the surface. Taking that radiating power as that of a perfectly black body, as we may fairly do if there is no ice or snow, the loss of heat by radiation according to Stefan's law is σt^4 where t is the absolute temperature and σ is a constant, namely, $5{\cdot}72 \times 10^{-12}$ watts per square centimetre.

Thus we get the following table for the sun's altitude when there is a balance of solar and terrestrial radiation for a horizontal surface:

Temperature.		Sun's Altitude for Balance.	Temperature.		Sun's Altitude for Balance.
Tercentesimal.[3]	Centigrade.		Tercentesimal.	Centigrade.	
200	−73	3½°	310	+37	20¾°
210	−63	4¼°	320	+47	23¾°
220	−53	5°	330	+57	27°
230	−43	6°	340	+67	31°
240	−33	7¼°	350	+77	35¼°
250	−23	8½°	360	+87	40°
260	−13	10°	370	+97	46°
270	−3	11¾°	380	+107	53¼°
280	+7	13¾°	390	+117	62¼°
290	+17	15¾°	400	+127	79¼°
300	+27	18°	402	+129	90°

THE UPWARD CONVECTION OF DRY AIR.

Since the air is dry it must necessarily cool on rising to the maximum extent of 1t per 100 metres. It can only penetrate the air above it if the lapse rate of the environment is of the same magnitude. That is the condition for what is called convective equilibrium (Bjerknes's barotropic condition). Consequently, upward convection by warmed air can only occur by building up a layer in convective equilibrium; and then, an infinitesimal increase of temperature at the surface would cause the passage of the warmed air to the top of the existing convective layer and its subsequent extension with only an infinitesimal difference of temperature beyond the existing top. When the penetrative convection caused by water vapour is non-existent, we are limited to this gradual piling up of a layer which differs only infinitesimally from convective equilibrium and increases in thickness with the continuance of the solarisation of the ground. Certain amplifications of this statement are necessary when the solarised surface is not horizontal, and locally when the angle of elevation varies from place to place; but, subject to that reservation, we may understand that if the earth were dry, upward convection would mean the compilation of a layer of air in convective equilibrium.

We may ask how far the layer would extend under given conditions of solarisation and the answer depends upon the condition of the atmosphere when the solarisation begins. From our knowledge of the maximum and minimum temperatures in a dry atmosphere, such as that of Egypt, we may conclude that the convective layer which is formed during the day is abolished during the night by the turbulence due to winds operating upon the surface layer cooled by terrestrial radiation from the ground.

For the present, let us suppose that the diurnal range at the ground is 20t (the normal range at Helwan), and that this range falls off uniformly with height until the undisturbed level is reached. Let h be the height of that level and let d be the mean density of the column. Then by equating the amount required to warm the atmosphere with the heat gained during a day under a sun which is vertical at noon, and

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[2] This statement may be admitted for the purpose of computation in this paper, although, according to observations of Anders Ångström, "the perfectly dry atmosphere has a radiating power as great as 50% of the radiation of a black body at the temperature of the place of observation" (Smithsonian Misc. Coll., vol. 65, No. 3, p. 88, 1915).

[3] Tercentesimal temperature is the temperature measured in centigrade degrees from a zero 273 degrees below the normal freezing point of water. It is approximately equal to the absolute or "Kelvin" temperature, but there is a technical difference between the two which cannot always be ignored. In this as in other papers a unit step on the tercentesimal scale is denoted by t.

allowing for a loss by outward radiation to the extent of that corresponding with the mean temperature for Helwan, we get an equation for h. This equation can be solved with the aid of the pressure equation and gives approximately 2 kilometres for the height of the daily convective layer at Helwan.

Similar equations can be got for other latitudes, and the average height of the convective layer works out for the year as follows:

Latitude . .	0	10	20	30	40	50	60	70	80	90
Solar radiation per day (gm. cal. per cm.^{2})	916	904	869	807	725	629	521	435	393	380
Height of the convective atmosphere (km.)	2	2	1·9	1·8	1·6	1·4	1·1	1·0	0·8	0·8

Mean values for the year have no real practical application for the polar regions, but let that pass.

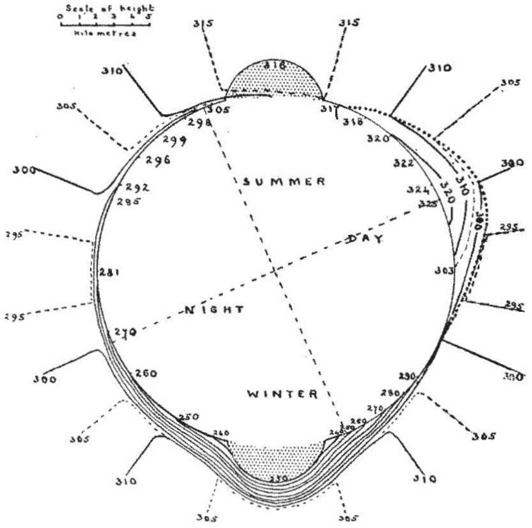

FIG. 1.—Distribution of temperature in a dry atmosphere at the northern solstice on a globe with hemispherical polar caps.

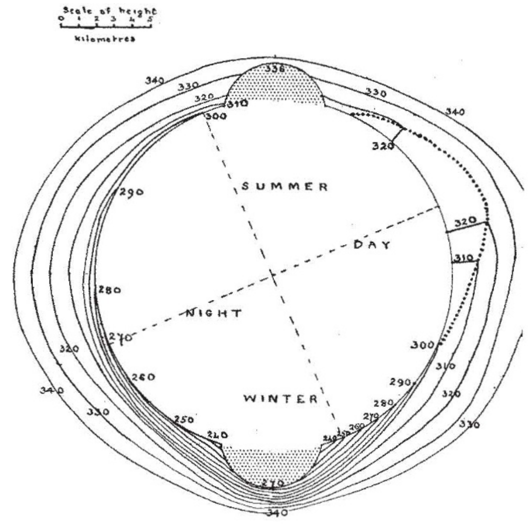

FIG. 3.—Distribution of potential temperature corresponding with Figure 1.

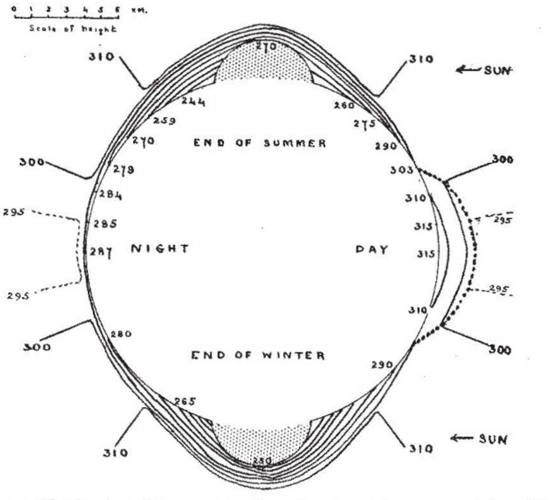

FIG. 2.—Distribution of temperature in a dry atmosphere on a globe with hemispherical polar caps at the autumnal equinox of the northern hemisphere.

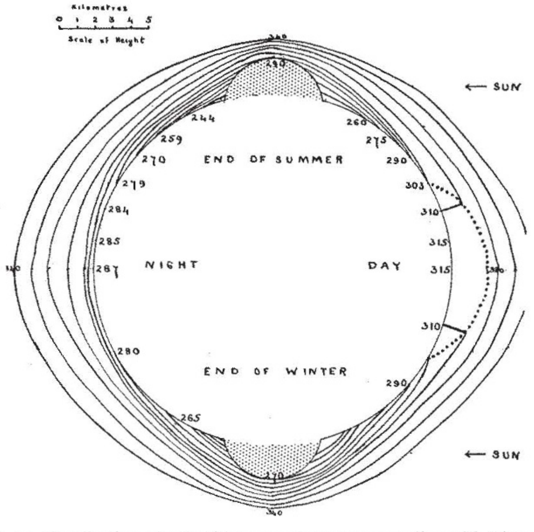

FIG. 4.—Distribution of potential temperature corresponding with Figure 2.

The boundary of the convective atmosphere is indicated in each diagram by a line of dots.

THE DOWNWARD CONVECTION OF DRY AIR: KATABATIC WINDS.

Downward convection along a surface which is losing heat by radiation will proceed with undiminished or even increased intensity when the earth is dry, and we may form a rough estimate of the result of the process by considering the case of a conical surface in the polar regions with its vertex 2 kilometres above sea level and a base of 500 kilometres radius.

We proceed from the knowledge that a slope is required in order to cause a downward flow at all, and that in the polar regions a pool of cold air is formed during the seasonal night with the coldest air at the bottom, in spite of the fact that descending air is automatically warmed to the extent of 1t for every 100 metres of descent. We assume further that during the winter the air at the base does not get persistently and continually colder from the first incidence of shadow to the end of night, but reaches a steady state in which the further cooling of the air at the foot of the slope is prevented by air coming down under the influence of the loss of heat from the slope. The descending air has its temperature raised by the increase of pressure; but it loses heat to the cooling ground over which it marches. Eddy convection will bring a certain thickness of the descending current into contact with the ground. The increased temperature of the descending air is used to wash away, so to speak, the loss of heat by radiation from the whole slope. When a steady state has thus been reached, if we suppose the temperature of the base to be maintained at 10t below that of the summit and the turbulence to be sufficient to mix up the surface air to a thickness of 50 metres, we find that it will be necessary to have a radial outflow of 300 km. per hour over the periphery of the circle of 500 km. radius in order to wash away the result of radiation and keep the thermal balance.

That is a tremendous wind and perhaps we have cause to be thankful that the polar regions are not entirely dry. There is, of course, ample opportunity for mistakes in the assumptions and even in the arithmetic; but no changes either in assumptions or in arithmetic can, so far as I can see, enable us to escape from the conclusion that katabatic winds on polar slopes are a very real and very potent phenomenon of the atmosphere, which would certainly not be diminished by its becoming dry.

Diagrams of Temperature and Potential Temperature.

With the physical principles thus enunciated I have endeavoured to construct diagrams representing the distribution of temperature and potential temperature over the earth at the solstice and equinox, making use of the information about diurnal range and seasonal variation given by extant observations in regions that are approximately dry. I use both temperature and potential temperature in consequence of the interesting reciprocity between them. We have only three types of condition: stratosphere, convective equilibrium, and downward convection. In the stratosphere, isotherms are vertical, lines of equal potential temperature horizontal; in the convective equilibrium, exactly the reverse is the case. Where downward convection is maintained there is horizontal stratification with inversion of temperature.

As illustrations of the material upon which the figures of the diagrams are based, I quote the following:

1. Seasonal variation of thermal structure of the polar atmosphere at Maudhavn, North Siberia, Lat. 77½° N. from H. U. Sverdrup, Maud-Ekspeditionens Videnskabelige Arbeide, 1918–19.

Temperatures at various Dates.
(Tercentesimal Scale.)

Height in Metres.	Feb. 26.	Mar. 22.	April 11.	June 17.	July 11.
0	229	241	253	274	280
200	239	240	251·5	272·5	279
1000	246	247	259	271·5	274

There is transition from continuous and very rapid *increase* of temperature with height, 17t for 1000 metres, in February (before sunrise) to the common *lapse-rate* of the world, 6t for 1000 metres, in July.

2. Data for diurnal range of temperature in July in dry tropical regions.

Diurnal Ranges.
(Tercentesimal Scale.)

	Mean.	Mean Max.	Mean Min.	Abs. Max.	Abs. Min.	Period.
Wadi Halfa .	304·4	313·8	296·2	322	290	1902–20
Helwan . .	300·3	308·4	294	315·9	289	1904–20
Salt Lake City	..	309	284	312	279	..

On the principles mentioned and with data of this kind culled from various sources, I have made out diagrams of the distribution of temperature in a dry atmosphere at the solstice (Fig. 1) and at the equinox (Fig. 2); also the distribution of potential temperature at the same epochs (Figs. 3 and 4).

The General Circulation of a Dry Atmosphere.

Finally, we have to consider what the circulation of the atmosphere would be in the supposed conditions of dry air. Looking at the diagram of the distribution of temperature, we see that an arrangement of the vertical columns of air round the pole would be the dominant feature, and therefore a vigorous west-to-east circulation round the pole in the upper atmosphere of the higher latitudes, compensated, as it must be, from the principle of conservation of moment of momentum, by a west-to-east circulation partly in the equatorial region.

There is also the flow of air down the polar slopes, which will certainly simulate the procedure which we attribute to the polar front. In the dynamical effects which they produce, the elevations at the poles are indeed the equivalents of very vigorous anticyclones, and the revolution of the earth will take care that the currents which they feed shall produce a circulation opposite to the westerly circulation under which they are formed.

There will be the discontinuities of temperature and of wind velocity typical of the polar front and the corresponding dynamical effects. Even if the earth went dry, the weather of the world would be of the same type as now in respect of general and local circulations; only as regards intensity would those circulations be affected.

If this conclusion be accepted, as I think it must be, we have next to think out what, after all, the effect of restoring the water would be, and then we shall have made a schematic representation of real weather. The thermodynamical aspect of the subject is treated in a paper on the energy of saturated air in a natural environment for the International Mathematical Association, in which the convective energy of a kilogram of air in virtue of its full complement of water vapour is represented by the area enclosed between the curve of environment and the adiabatic curve of saturated air drawn through the point at which saturation is assumed to exist. The amount of energy thus represented is found to vary from zero to 10,000 joules or more per kilogram.