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The atmosphere of the earth*

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Abstract

The processes by which the movements at the surface of the earth due to its rotation around the polar axis can influence the atmosphere above are considered in detail. It emerges that the fast-moving areas in the equatorial belt on the surface of the earth play a highly important role in determining the behaviour of the atmosphere. The jet-stream in the sub-tropical regions, the westerly zonal winds in the region of middle latitudes and the easterly surface-winds in the equatorial belt are explained on this basis and shown to stand in close relationship with each other. The winds observed in the polar belt are also discussed and explained.

1. Introduction

It is proposed in this address to consider the following questions and endeavour to find answers to them. The earth revolves around its polar axis once in every twenty-four hours; does the atmosphere which is a gaseous mantle enveloping the globe rotate with it and in the same manner at all elevations and in all latitudes? What are the considerations which determine the behaviour of the atmosphere in this respect? What are the observable consequences of any differences between the globe and the atmosphere in the speed of their movements around the polar axis? In dealing with these questions we have necessarily to leave out of consideration, the complexities in the behaviour of the atmosphere at various times and at various places which manifest themselves as the phenomena of the weather. It is these latter phenomena and the interpretations of their origin which are the preoccupations of the meteorologist who watches the weather and seeks to forecast the changes in it. But it is not impracticable to regard the manifestations of weather as variations from a standard state of the atmosphere which may be defined as its average taken over a sufficient range of time and over a sufficiently extended area of the surface of the earth. In other words, we consider the behaviour of the earth's atmosphere in its broadest aspects, taking a global and long-term view of the subject.

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2. The atmospheric rotation belts

In dealing with the problems set forth above, it is necessary at the very outset to recognize that the atmosphere which envelops the globe cannot be considered for the present purposes as a single entity. The reason for this is that all the factors which influence or can influence the atmospheric movements vary enormously over the surface of the earth. Among them we may mention particularly the actual speed of movement of the surface arising out of the rotation around the polar axis, as well as the rate at which this speed alters as we move longitudinally along the surface. The insolation by solar radiation and the magnitude of its variation during the year with the seasons are also very different in various regions. The speed of movement as well as the magnitude of the insolation are both functions of the latitude. Hence, and to avoid any suggestion of arbitrariness, we partition the surface by drawing circles of latitude which are equally spaced. We thus obtain the following areas on the surface exhibiting distinctive features.

Firstly, we have the region which we designate as the equatorial belt and which includes the entire area comprised between the circles of latitude 30° north and south of the equator. This forms a single continuous surface which occupies one-half of the entire superficial area of the globe. The speed of movement is a maximum, viz, 465 metres per second at the centre of the belt which is the equator. The speed falls off quite slowly at first, to 457 metres per second at 10° latitude and to 437 metres per second at 20°. The drop in speed then becomes rather more rapid. It is 403 metres per second at the circles of 30° latitude which are the extremities of the belt on either side of the equator. The equatorial belt is also distinguished by its being the recipient of the maximum amount of solar radiation at all seasons of the year.

Secondly, we have the belts of middle latitude comprised between the latitudes of 30° and 60° on either side of the equator. Each of these belts covers an area which is roughly one-sixth of the total area of the globe. The speed of movement is substantially less than in the equatorial belt, and also falls off steeply from 403 metres per second at 30° to 233 metres per second at 60°. The insolation of the belts of middle latitude is also notably less than that of the equatorial belt and progressively diminishes as we move polewards. It also shows large differences between the summer and winter months.

Thirdly, we have the polar belts, by which term we refer to the parts comprised between the latitudes of 60° and 90°. These are of relatively small area, each being about one-fifteenth of the earth's surface. The speed of movement of the ground falls off from 233 metres per second at 60° to 120 metres per second at 75° and becomes zero at the poles. The insolation of this belt when summed up for the whole year is much less than that of other areas on the surface of the earth. The insolation also shows large variations with the season of the year and actually vanishes during the long polar nights.

3. Rotational coupling of earth and atmosphere

A clear understanding of the manner in which the rotation of the globe influences its gaseous envelope is of the utmost importance in the present context. The forces in the nature of a frictional resistance which operate at and near the surface of contact when there is a relative motion between ground and air obviously play an important role. But this role is purely a negative one. In other words, the frictional forces act merely as a check on the relative motion, their direction being reversed when the sign of the relative motion alters. The frictional forces cannot set up or maintain a steady state of relative motion, and when such a state exists, we have to look elsewhere for an explanation of its cause or origin. It is also necessary to remark that the range of action of the frictional forces on the atmosphere is strictly limited. Some idea of this range can be obtained from observations on the manner in which the strength of a wind alters as we approach nearer the ground or move away from it. This effect is found to depend on the actual strength of the wind, on the roughness of the ground and on other factors. It may be inferred from the observations that the frictional resistance is effectively restricted to comparatively low levels in the atmosphere. A hundred metres above ground is a fair estimate of the height up to which the frictional forces dominate the behaviour of the wind, while a kilometre may be put as the upper limit of the height beyond which their effect may be considered as negligible.

But we shall be wholly in error if we were to assume that the atmosphere at all levels above one kilometre from the ground can be regarded as a completely free medium on which the rotation of the ground below is without influence. In reality, the state of the atmosphere in its higher levels is influenced and indeed fully determined with reference to the rotation of the ground below by processes of a quasi-permanent nature which we shall now proceed to describe and discuss.

4. The vertical transport of momentum

The atmosphere when in contact with land or water heated by solar radiation takes up both moisture and thermal energy. When the temperature of the air is thereby raised sufficiently with respect to that of the superincumbent layers, its equilibrium becomes unstable, and masses of air break off and move upwards, expanding as they go, thereby maintaining an equality of pressure with their surroundings. The expansion results in an adiabatic cooling and this suffices to check the upward movement beyond a certain height. But if the initial moisture content of the heated air is sufficient, part of it condenses out to form fine droplets of water which remain in suspension. The heat of condensation of this water is released, thereby warming the air and enabling it to mount up to still higher levels. This upward movement of heated air accompanied by the formation of clouds is a familiar phenomenon and may reach up to great heights. The important aspect of it from our present point of view is that it involves a vertical transport of momentum from the rotating earth to the upper levels of the atmosphere by a process which is both quick and efficient. The actual momentum transported by an individual parcel of air may be small. But a great many parcels keep going up, and their total effect would evidently be cumulative when summed up over a long period of time. The final result would be to bring the air at all levels up to which these processes operate into a definite relationship with the ground below in its rotatory movement about the polar axis of the earth.

5. The origin of the jet-stream

The equatorial belt on the surface of the earth plays a highly important role in terrestrial meteorology. This is a consequence of several factors, viz., the large area and central position of the belt, the high speed of its surface movement, and, above all, the fact that its insolation is more intense and much more constant through the year than that of other areas on the globe. Of particular importance in the present context is that the insolation is a maximum at the equator itself and changes but slowly within the range of ten degrees of latitude on either side of the equator. But the insolation falls off rapidly as we proceed to higher latitudes.

In the circumstance stated above, it is fully to be expected that a powerful updraft of heated air from the area in the equatorial belt comprised between the latitudes of 10° north and 10° south of the equator would be a constant feature throughout the year. The association of such heated air with water vapour would enable this updraft which carries with it the momentum of a surface-speed of 465 metres per second to reach great heights. This would also result in heavy precipitation, an inference which is strikingly confirmed on an inspection of a map showing the distribution of rainfall over the surface of the earth. The regions of heavy rainfall with a precipitation exceeding two metres of water per annum are all found in the belt of latitudes between 10° north and 10° south of the equator. The northern parts of South America, the equatorial regions in Africa, Ceylon, Malaya, Sumatra, Java, Borneo, Celebes and New Guinea, are all regions of such heavy rainfall and lie within this range of latitudes. Indeed, outside this range, there are few areas in which there is such heavy rainfall ascribable to convectional precipitation.

It is evident that when an updraft of air from the latitude belt between 10° north and 10° south of the equator reaches the higher levels of the atmosphere, there would arise a drift of air outwards from these regions towards latitudes north and south of the equator. Two questions then arise. At what level would this outward flow commence, and how far outwards would it extend? To the first question, the answer evidently is that the outward flow would commence at the level at which the updraft has lost its driving force. The atmospheric temperature at the equator falls to the freezing point of water at a level of some five kilometres above ground. It falls further to $-20°$ C at 8 kilometres, to $-30°$ C at 9 kilometres and to $-40°$ C at 11 kilometres. It is evident that at a height of about 10 kilometers above ground level at the equator and in all neighbouring regions, the entire content of moisture in the air would have been frozen out. The motive power for any further upward movement would then have practically disappeared. It may therefore be justifiably assumed that the horizontal drift would manifest itself principally at a height of some 10 kilometres from the ground but might extend a little both above and below that height. It is also evident that the air thus moving north and south at high levels cannot subside or sink to lower levels in latitudes where there is even a moderate updrift of heated air. We may therefore normally expect the movement to extend over the whole of the equatorial belt, viz., upto 30° of latitude or even beyond.

As the cumulative effect of the mixing with high-speed air from the equator, the air between 0° and 30° latitude at and near the 10 kilometre level would acquire a speed of approximately 465 metres per second or close to it. The difference between this speed and that of the ground below would appear as a circumpolar or zonal wind in these latitudes. The difference would be small in regions quite close to the equator. But as we proceed further north or south of the equator, the ground speed falls off rapidly, and the difference would be perceived as a circumpolar westerly wind of considerable force. If the speed of 465 metres per second is maintained upto the limits of the equatorial belt, viz., 30° north or south, the circumpolar or zonal wind would have a speed in those latitudes of $(465-403)=62$ metres per second or 140 miles per hour.

6. The westerly winds in middle latitudes

When the flow of air at high levels near the equator towards the north or south reaches latitudes where it does not meet with any updraft from below, the air-stream would subside to lower levels and at the same time become more diffuse. The belts of middle latitudes would thereby become the recipients of fast-moving air from the equatorial belt. The admixture of such air with the more slowly moving air in those latitudes would result in the atmosphere in these areas moving faster than the ground below. As a consequence, these regions would exhibit westerly zonal winds which may be considered to be downward and poleward extensions of the high-level stream in the equatorial belt. The westerly zonal winds would extend down to ground level but their speeds would diminish in the lower levels. The winds would evidently be strongest in latitudes between 30° and 45° (north or south) and become weaker as we proceed further polewards.

7. The easterly surface-winds

The void in the atmosphere left by the streaming upwards of heated air from near the equator has, of necessity, to be filled up by air moving in towards the equator at various levels. Some of this replacement may be effected in the equatorial belt by an inflow in the marginal regions at various levels. But a substantial part of the air needed must come in at and near the ground level. Admixture of air from the higher latitudes with the atmosphere nearer the equator would reduce the speed of rotation of the atmosphere in the lower levels. Hence, at these levels, zonal easterly winds would be perceived.

8. Winds in the polar belt

The difference between the heating effect of solar radiation in the belt of mid-latitudes and in the polar belt is sufficiently great to allow of a circuit of convection being established in these areas. Warm air goes up into the troposphere from the belt of middle latitudes. Its replacement has to be effected by colder air moving in from the polar regions. Since the surface speeds of movement are very low near the poles, the air drifting away from the poles would result in reducing the surface-speeds of the atmosphere with which it mixes. Hence, we would have a regime of easterly surface-winds in the polar belt. The warm air going up from mid-latitudes has necessarily to find its way back into polar belts. This can be achieved by its going to the tropopause level and then drifting polewards and then slowly subsiding into the polar area. As the air thus going up is derived from the mid-latitudes where the surface speeds are much higher than in the polar belt, it follows that westerly winds with considerable speeds would be perceived as blowing over the polar areas at high levels.