

ZONAL WINDS AND JET-STREAMS IN THE ATMOSPHERE

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Received November 3, 1967

THE atmosphere of the earth is a gaseous mantle which completely surrounds the globe and is held down to the surface by its own weight. Being a compressible gas, its density is determined by the pressure of its own weight and is accordingly a maximum at the surface of the earth and rapidly diminishes as we proceed upwards, becoming very low at great heights. The atmosphere is carried round by the earth in its annual motion around the sun, and it is therefore appropriate to regard it as an integral part of the earth in much the same way as the land masses or the oceanic waters. But a difficulty arises when we seek to extend the same idea to the behaviour of the atmosphere in relation to the rotation of the earth about its polar axis. The atmosphere enjoys a freedom of lateral movement in all directions transverse to the surface of the earth. It also possesses no fixed external boundary. It follows that the atmosphere is not rigidly coupled in its rotation about the polar axis. The question thus arises to what extent does the atmosphere actually follow the rotation of the earth about the polar axis, and what are the observable consequences of any differences between the atmosphere and the earth in regard to this rotatory movement.

The issues stated above are obviously of fundamental importance. Unless the questions which have been asked are squarely faced and satisfactorily answered, it seems scarcely possible to discuss the problems of atmospheric behaviour meaningfully and to reach a clear understanding of the same. Strangely enough, the meteorologists who are professionally interested in the dynamic behaviour of the atmosphere and are perfectly well aware of the basic role played by the rotation of the earth in their subject, have apparently been content to assume that the atmosphere goes round with the earth unless specially disturbed from that condition. Why it should so behave and whether it actually follows the earth in its rotation at all levels and in all latitudes is the problem which we shall proceed to discuss.

The surface of the globe presents a wide diversity in its appearance at various places. In particular, the areas of land and water are distributed

in a very unequal manner in the northern and southern hemispheres. We shall, however, here ignore these differences and proceed to regard the surface of the earth as consisting of three distinct belts on each side of the equator, comprised respectively in the ranges of latitude from 0° to 30° , 30° to 60° and from 60° to 90° . The superficial areas of these three belts diminish quickly as we proceed from each to the next. Of particular importance also in relation to our present topic is the actual speed of motion at the surface of the rotating globe. This falls off as we proceed polewards from each belt to the next. It is 465 metres per second at the equator, 450 metres per second at 15° latitude and 403 metres per second at 30° latitude. In the second belt, the diminution of speed is much more rapid, being 329 metres per second at 45° and 232 metres per second at 60° . In the third belt it is still smaller, being 110 metres per second at 75° and zero at 90° . A further and highly noteworthy difference between the three belts is in respect of the heating of the surface of the earth by solar radiation and the turbulent movements in the atmosphere which arise by reason of its contact with the heated earth. These effects are highly pronounced in the first belt, moderate by comparison in the second belt, and relatively small in the third belt.

The coupling of the atmosphere to the earth in its rotation to the poles is attributable entirely to the forces acting at the surface of the globe when there is any movement of the air relative to the solid or liquid material with which it is in contact. We shall here ignore the part played by molecular viscosity. The interactions with which we are concerned express themselves by producing eddies or turbulence in the vicinity of the interface. The question arises, how far would the effect of such eddies or turbulence extend and what would be their ultimate effect on the movement of the air at considerable heights above the surface or in regions remote from the areas where there is relative movement.

Considerations of a very general nature suggest that the further away we move from the actual surface of the earth, the less and less would be the controlling influence of any particular area of the surface on the movement of the parcel of air immediately above it. *Per contra*, we are justified in assuming that the air at any given height would be influenced in its movements by the movement of areas on the surface of larger and larger extent as we proceed upwards. At sufficiently high levels, the effective areas on the surface may be expected to be of very considerable dimensions.

The approach indicated above leads us to certain inferences. As has been remarked above, the three parts of the surface of the globe between

0° and 30° , between 30° and 60° and between 60° and 90° , differ widely in those characteristics which may be expected to determine or influence the rotation of the atmosphere above the surface in those belts. We may therefore feel justified in drawing the inference that the atmosphere of the earth would exhibit these differences very noticeably in its rotational behaviour. In other words, we may expect to find three distinct belts of atmospheric rotation in each hemisphere, a broad belt extending on either side of the equator from 30° north to 30° south, a belt in the middle latitudes between 30° and 60° and the third belt between 60° and 90° . In the equatorial belt, the speed of atmospheric rotation would be a maximum, being everywhere nearly the same as the speed of movement of the surface at the equator itself. When we pass to the adjoining belt in the latitudes between 30° and 60° the speed of rotation may be expected to exhibit a large and sudden drop to a smaller value, since the speed of atmospheric rotation would be determined by the much lower speeds of the surface of the earth in these latitudes. Finally, when we pass to the third belt in the latitudes between 60° and 90° , we may expect a further and fairly sudden slowing down of the rotational movement, by reason of the large fall in the speed of movement of the surface as we move to the highest latitudes.

The existence of these belts in which the movement of the atmosphere parallel to the circles of latitude differs in speed from the surface of the earth below would reveal itself to an observer located in those areas as a zonal wind, blowing from the east or the west as the case may be, the speed of the zonal wind being the difference between the speeds of the atmosphere and of the earth. In the broad belt which extends from 30° north to 30° south of the equator where the surface speed is a maximum, we may expect the atmospheric speed to be also a maximum at the equator and to differ but little from the speed of the surface below. Accordingly, at the equator itself, there would be no zonal wind. But, as we move north or south of the equator, the atmospheric speed would be greater than the speed of the surface. Accordingly, we would have in these regions an easterly wind which gains strength as we proceed north or south and which may be expected to reach its maximum speed at or about a latitude of 15° north or south. Beyond this, the easterly wind would diminish in strength and vanish when we reach the limit of the equatorial belt of easterly zonal winds at 30° latitude.

In the latitude belts between 30° and 60° , north or south of the equator, considerations of the same nature as those stated above for the equatorial

belt indicate that an observer would find them to be regions in which there are zonal winds which appear to blow from the west. These winds would naturally be weak at the surface and might be expected to be absent at the boundary between the zones of easterly and westerly winds. The westerlies would become stronger as we proceed polewards from this boundary. The considerations already set out indicate that the westerlies would gain notably in strength as we proceed to higher levels above the surface. For, the influence of the slowly-moving surface areas on the air-speeds aloft would then progressively become greater.

We may also expect to meet with zonal winds in the latitude range between 60° and 90° . The speed of movement of the surface goes down to zero at the poles, but elsewhere would be finite. Hence, if we assume the atmospheric speed to be determined by some sort of averaging over the surface speed, the air-speed everywhere in this belt would be greater than the surface-speed. Accordingly, in this region we would meet with easterly zonal winds.

We now proceed to consider the question of the elevation up to which the atmospheric layers which rotate faster or slower than the surface of the earth below may be expected to extend. The transference of momentum from the surface upwards into the atmosphere is made possible by the process of eddy diffusion. Where this process comes to a stop, the transference of momentum will also cease.

As is well known, the atmosphere of the earth falls roughly into two divisions referred to respectively as the lower and the upper atmospheres. The dividing surface between them is called the tropopause; the region below is the troposphere and the region above is the stratosphere. The troposphere is characterised by its exhibition of a steady fall of the atmospheric temperature as we proceed upwards, while in the stratosphere the temperature does not exhibit this feature, but remains approximately constant. The most recent studies indicate that the tropopause has a multiple structure, there being three distinct parts of it, one at low latitudes, one in the middle latitudes, and the third in high latitudes. The first is at the highest level, 16 kilometres or more. The second is between 10 and 12 kilometres above the surface and the third between 6 and 8 kilometres.

The tropopause is usually identified as the boundary between the regions in which heat transfer is principally by convection and turbulence, and those

in which heat transfer is predominantly by radiation. On this basis, we can also identify the tropopause as the upper limit of the belts of air of which the speed of rotational movement differs from that of the surface below. It is readily understood on this basis why the tropopause exhibits a multiple structure as remarked above.

The recognition that there exist three wind-belts in the atmosphere with the characteristics already stated above enables a simple explanation to be given of the origin of the jet-streams which manifest themselves at fairly high levels in the atmosphere. There are two of these, viz., one known as the polar-front jet and the other as the sub-tropical jet. The location where these appear are the regions in the atmosphere where there is a steep fall in the atmospheric speed as we pass from one wind-belt to the next. This steep fall manifests itself as a large increase in the zonal wind-speed.