CHAPTER 8

General Circulation of the Atmosphere and Ocean

43. GENERAL CIRCULATION OF THE ATMOSPHERE

The word *circulation* here simply refers to motion (sometimes it is used in a narrower sense, to mean motions around closed trajectories, or 'circulation wheels'). It is convenient to divide atmospheric motions into *small-scale motions*, with scales $L$ much smaller than the effective thickness $H$ of the atmosphere (defined, for example, by formula (2.6)), *meso-scale motions*, with $L$ of the order of $H$ or several times larger than $H$, and *large-scale motions*, with $L \gg H$ (Kolesnikova and Monin, 1965). The latter include global circulations, of the zonal and monsoon types, as well as synoptic processes, that is, eddies and Rossby waves, barotropic with scales of the order of $L_0 = c_0/f$, where $c_0 = (gH)^{1/2}$, and baroclinic with scales of the order of $L_R = HN/f$. The statistical ensemble of large-scale atmospheric motions constitutes the general circulation of the atmosphere.

The atmospheric circulation on Earth, Mars, and Venus originates because of the baroclinicity of the atmospheric gases (the dependence of $\rho$ on $T$ of type (1.7)), due to the spatially inhomogeneous heating of these gases by the long-wave radiation of the underlying surface and by the direct short-wave radiation of the Sun. Air expands when heated, and air masses rise, so that at a given height the pressure increases. This pressure rise at elevations in warm regions forces air at high levels to flow into cool regions. At lower levels there will then be a compensating downflow of air into warmer regions. This circulation between the equatorial zone and the middle latitudes on the Earth is known as the *trade winds* (a representation first formulated by Hadley in 1735; subsequent investigators introduced additional 'wheels' of the meridional circulation).

On Mars and Earth the Coriolis force turns the flow of air from the equator to the poles at high levels toward the east, producing a westerly transport of air in the upper atmosphere of the middle latitudes (and a westward component of the surface trade winds in the tropics). Meteorological measurements have shown, however, that the 'wheels' of the meridional circulation are too weak to account for the very strong zonal circulation observable in the Earth's atmosphere (including the subtropical jet streams at latitudes of around $\pm 35^\circ$ and heights of about 12 km, which have an effective width of 300 to 400 km, a thickness of 1 to 2 km, and a velocity of 60 to 80 m/s, although a speed as high as 190 m/s has been recorded).
A quantitative explanation of the zonal circulation is obtained only if the role of synoptic processes is taken into account. The first to do this was Defant (1921), who interpreted the synoptic eddies as being a kind of large-scale turbulence (see Section 37), causing meridional heat transfer (Defant estimated the effective transfer coefficient to be $\rho v \sim 10^8$ g/(cm s)). Jeffreys (1926) suggested that this also makes a major contribution to the meridional fluxes of angular momentum.

One of the first to offer a systematic fluid-dynamical description of the general circulation of the atmosphere was Kochin (1936). He assigned a major role to the forces of eddy viscosity, which he took to be comparable to the Coriolis force (rather than to the inertial forces, as in boundary-layer theory). Moreover, Kochin showed that the appropriate simplified equations of fluid dynamics can be used to calculate the three-dimensional fields of the velocity and density, in terms of the specified field of the surface pressure $p_s$ and the specified temperature field $T$. The next step was taken by Blinova (1947), who appended to the equations of Kochin the equation of heat influx and, taking the continents and oceans into account, calculated the mean annual three-dimensional field of $T$ and $p_s$ (in which, in particular, all the so-called centers of action of the atmosphere were obtained theoretically for the first time, these being quasistationary subtropical anticyclones and subpolar cyclones); later she also computed their annual variation.

Any complete theory of the general circulation must include the feedback between the zonal circulation and synoptic processes. On the one hand, the zonal circulation is baroclinically unstable, with respect to small nonzonal disturbances (see Dikii’s theorem in Section 12), which grow at the expense of the available potential energy to become synoptic eddies (Bjerknes, 1937). On the other hand, the statistical ensemble of synoptic eddies may transfer angular momentum to the latitude zones with jet streams, that is, it may act like a ‘negative viscosity’ and thus transfer its kinetic energy to the zonal circulation (Rossby, 1941, 1947).

The unusual effect of a ‘negative viscosity’ can be explained as follows: the axes of the crests of the Rossby waves, which are oriented from the tropics toward the subtropical jet stream (toward the north in the Northern Hemisphere), tend to slope predominantly toward the current (they point toward the northeast). Thus angular momentum ahead of the Rossby troughs, where it is higher (since the flow is close to zonal), is transferred to the jet stream (northward), whereas behind the troughs, where it is lower (flow close to meridional), angular momentum leaves the stream (southward). The total effect over the entire wave amounts to a transfer of angular momentum to the jet stream.

Following Monin and Seidov (1982), we will present a simplified qualitative model describing the enhancement of a jet stream by negative viscosity in a fluid layer of constant depth that is uniform along the vertical. The density $\rho$ is assumed to be a function only of the temperature $T$. The origin of the horizontal coordinates $(x, y)$ is on the stream axis, the $x$ axis points east, and the $y$ axis points north. We assume that

$$T = \text{const} - T_0 \sin \frac{\pi y}{2Y}; \quad U = - \frac{\alpha g \varepsilon}{f} \frac{\partial T}{\partial y}; \quad |y| \leq Y,$$

(43.1)

where $U$ is the velocity of the thermal wind, and $\alpha$ is the coefficient of thermal