CHAPTER III

THE ATMOSPHERIC CIRCULATION

In the previous chapter we introduced the physical laws which govern the circulation of the atmosphere, and the dynamic equations which express these laws in mathematical form. In this chapter we will describe some of the features of the circulation as revealed by observations. We will give particular attention to the fields of motion, temperature and moisture, averaged with respect to longitude and time.

Resolution of the Circulation

The observed fields of motion, temperature and moisture in the atmosphere cannot be represented by any simple analytic formulae, and quantitative statistics of the circulation are most easily presented in the form of tables or graphs. The three-dimensional spatial distribution of any particular static, such as the time-averaged wind velocity, can be reasonably well represented by a set of two-dimensional charts, which may be horizontal maps or vertical cross-sections. However, a collection of charts consisting of a separate set of maps or cross-sections for every statistic of interest would be altogether unwieldy, and it would be quite incomplete if the statistics were limited to such familiar quantities as means and standard deviations. While a map of the time-averaged field of motion might afford a good description of the trade winds, it would not reveal the prevalence of migratory cyclones in higher latitudes. Maps of covariances at suitable time-lags and space-lags might imply the existence of cyclones, but a map of cyclone frequency would serve the purpose more readily.

It will be convenient to classify the principal feature of the circulation into four categories, as follow :

1. *Features which appear when the variables are averaged with respect to time and longitude.* These are typified by the familiar trade winds. A time average may mean an average over all time, or over all year at a particular time of year. Some meteorologists prefer to restrict the term "*general circulation*" to features in this category, and it is these features which will receive the major attention in this monograph.
2. *Features in addition to those of the first category which appear when the variables are averaged with respect to time alone.* These are typified by the Asiatic summer and winter monsoons. Most of meteorologists include these as features of the general circulation.
3. *Features in addition to those of the first category which appear when the variables are averaged with respect to longitude alone.* These are typified by the familiar fluctuations of the zonal index. Studies of these features are ordinary regarded as general circulation studies by those engaged in them.
4. *Features in addition to those of the first three categories which appear when the variables are not averaged.* These are typified by migratory cyclones. Many of these features are ordinarily regarded as secondary circulations; some of their over-all statistical properties are frequently considered to be characteristics of the general circulation.

Following the modified notation of Starr and White [Starr and White 1954], we will let the notation as follow :

—	denotes the time average of any quantities,
′	denotes the departure of a quantity from its time average,
[ ]	denotes the longitudinal average of any quantities,
*	denotes the departure of a quantity from its longitudinal average.

It is evident that the operators $\overline{}$, $'$, [ ] and $*$ are commutative. By the use of these notations the wind field $\vec{U}$ may now be resolved according to the formulae

$$\vec{U} = \overline{\vec{U}} + \vec{U}' , \tag{3.1}$$

$$\vec{U} = [\vec{U}] + \vec{U}^{*} , \tag{3.2}$$

and thus, in greater detail;

$$\vec{U} = [\overline{\vec{U}}] + \overline{\vec{U}}^{*} + [\vec{U}]' + \vec{U}^{*\prime} , \tag{3.3}$$

Resolutions of the fields of temperature T, specific humidity q, and other quantities may be similarly performed.

Although the notation used in Eqs.(3.1) - (3.3) has been adopted by a number of meteorologists, there seems to be less uniformity in the accompanying terminology. We will refer to the fields of $\overline{\vec{U}}$ and $\vec{U}'$ in Eq.(3.1) as the long-term or time-averaged or standing motion and the transient motion. We will refer to the components $[u]$ and $[v]$ of $[\vec{U}]$ in Eq.(3.2) as the zonal circulation and the meridional circulation, and to the components of $\vec{U}^{*}$ as the eddies. We will also include the field of $[\omega]$ demanded by continuity as part of the meridional circulation. Thus the terms in Eq.(3.3) respectively the time-averaged or standing zonal and meridional circulation, the time-averaged or standing eddies, the transient zonal and meridional circulation, and the transient eddies.

The customary use of the terms zonal and meridional has led to some ambiguity. A *zone* generally means a latitude circle or a region extending along a latitude circle. *Zonal motion* generally means motion parallel to the zones, and is synonymous with u, while *meridional motion* means motions parallel to the meridians or meridional planes, and may be synonymous with v, or with ω. A *zonal average* generally means an average within zones, or with respect to longitude. The ambiguity arises in connection with the term "*zonal circulator*", which is sometimes used to mean the zonal motion u, sometimes the zonally-averaged motion $[\vec{U}]$, and sometimes zonally-averaged zonal motion $[u]$. We will use the term only in the last sense. Likewise we will use *"meridional circulation"* only to denote zonally-averaged meridional motion. The term *"mean meridional circulation"* has been used for the latter purpose, but it has also been used for the time-averaged meridional circulation. The frequently used term *"mean motion"* is not specific enough when both time averages and zonal averages are being considered.

The Balance Requirements

The application of the physical laws to the explanation of the observed circulation is the task which now confronts us. The most direct way to accomplish this task would be to solve the dynamic equations. At present we lack a suitable means of solution. We must therefore proceed more indirectly. In their usual form the dynamic equations enumerate the physical processes which directly affect any quantity. For example, the thermodynamic equation states that the temperature may be altered by advection, adiabatic compression or expansion, and net heating. It is sometimes possible to evaluate the long-term influence of each process affecting some features of the circulation by recourse to the observational data. In this section we will play attention on the balance requirements of some important processes which maintain the atmospheric circulation.

A. The Balance of Water

Consider the total mass of water contained in the region of the atmosphere north of a region latitude. This quantity may be temporarily increased by evaporation from the underlying Earth or decreased by precipitation falling to the Earth. It may also be increased or decreased by an inflow or outflow of moist air across the southern boundary. There is no necessity for the amount of evaporation taking place north of a given latitude to balance the amount of precipitation falling there, but, if the long-term average rates of evaporation and precipitation fail to balance, enough water must be transported within the atmosphere into or out of the region to balance the deficit or excess of evaporation. The need for this condition to be fulfilled constitutes the balance requirement for the transport of water in the atmosphere.

For computational purposes it is desirable to express the water balance in analytic form. If we integrate the general formula of the continuity equation over the volume of the region north of latitude ϕ_1, and then average with time, we find that

$$\int_0^{P0} 2\pi r \cos\phi_1 \left[\overline{\rho X v}\right] dz = -\int_0^{\infty}\int_{\phi_1}^{\pi/2} 2\pi r^2 \cos\phi \left[\overline{\rho\, dX/dt}\right] d\phi\, dz , \qquad (3.4)$$

where X is any scalar quantity.

$\left[\overline{\rho X v}\right]$ is measured at latitude ϕ, and it is assumed that there is no transport across the lower boundary by the motion of the atmosphere. An approximation to Eq.(3.4) obtained by integrating Eq.(2.36) over the mass of the region, using Eq.(2.37), is

$$\int_0^{P0} 2\pi a \cos\phi_1 \left[\overline{X v}\right] g^{-1}\, dp = -\int_0^{P0}\int_{\phi_1}^{\pi/2} 2\pi a^2 \cos\phi \left[\overline{dX/dt}\right] g^{-1} d\phi\, dp , \qquad (3.5)$$

If q represents the mass of water per unit mass of air, we obtain

$$\int_0^{P0} (dq/dt)\, g^{-1}\, dp = E_0 - P_0 , \qquad (3.6)$$

where E_0 is the rate of evaporation from the Earth,

P_0 is the rate of precipitation upon the Earth.

Equating X to q in Eq.(3.5), we obtain the water balance equation

$$\int_0^{P0} 2\pi a \cos\phi_1 \left[\overline{qv}\right] g^{-1}\, dp = \int_{\phi_1}^{\pi/2} 2\pi a^2 \cos\phi \left[\overline{E_0 - P_0}\right] g^{-1} d\phi , \qquad (3.7)$$

The left-hand side of Eq.(3.7) represents the total transport of water across latitude ϕ_1. The right-hand side has been used in constructing the transport curve in Fig.(3.2) from the values of E_0 and P_0 in Fig.(3.1). In most applications the horizontal transport of liquid and solid water is disregarded, and q is assumed to represent specific humidity.

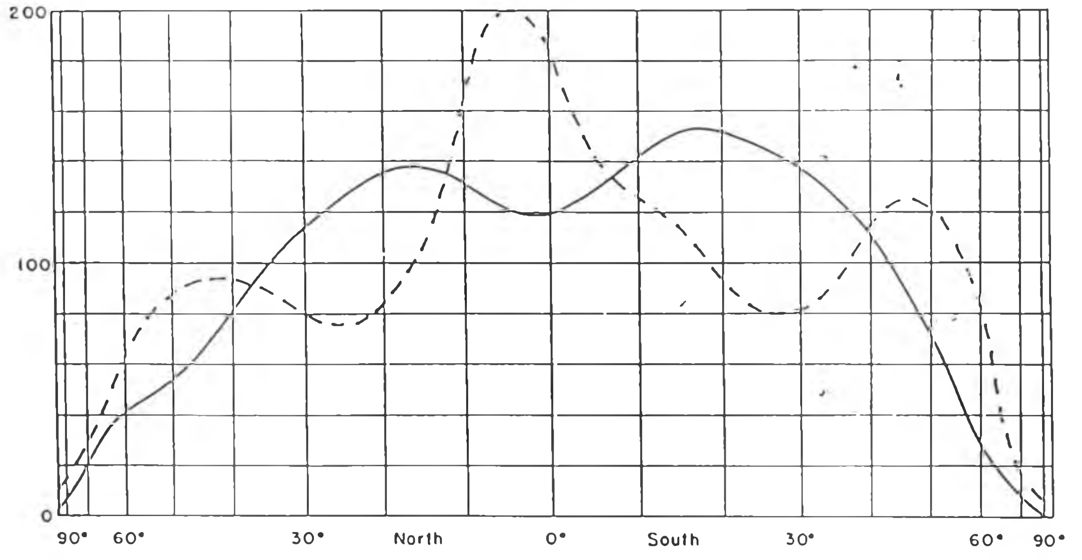


Figure 3.1 Average annual evaporation (solid curve) and precipitation (dash curve) per unit area. Values are in g cm^{-2} $year^{-1}$ (scale on left).

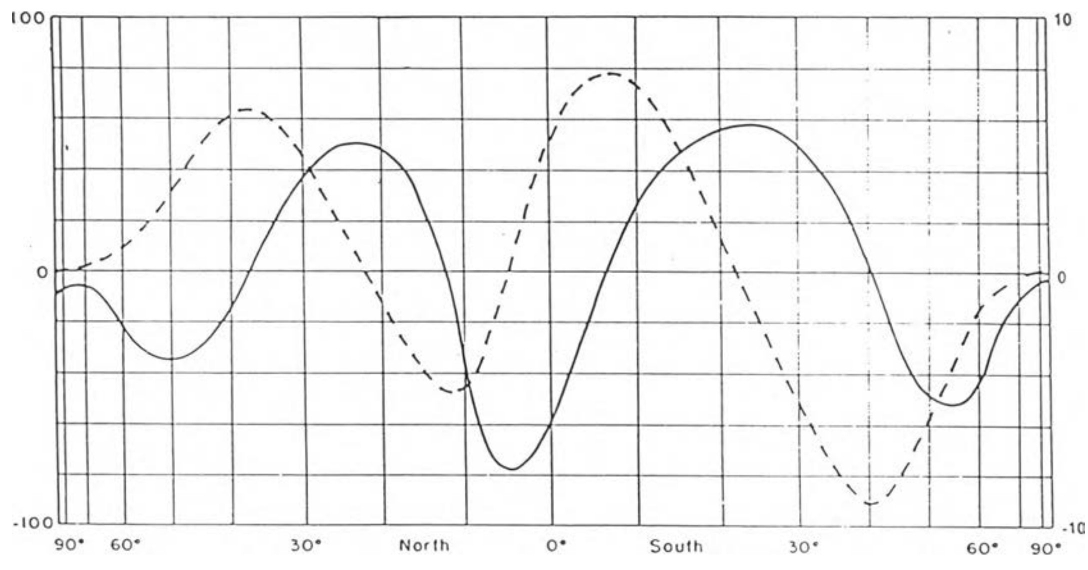


Figure 3.2 Excess of evaporation over precipitation (solid curve), in g cm^{-2} $year^{-1}$ (scale on left), and northward transport of water in the atmosphere required for balance (dash curve) in units of 10^{11} g sec^{-1} (scale on right).

B. The Balance of Absolute Angular Momentum

The balance of absolute angular momentum is analogous to that of water. Angular momentum may be exchanged between the atmosphere and the underlying surface, and it may be transported horizontally by the motion of atmosphere. Although individual masses of air do not conserve their angular momentum even approximately, still the pressure torque within the atmosphere transfers angular momentum only from longitude to another, while the frictional torque transfers its almost entirely from one elevation to another. Any net exchange of angular momentum with the underlying Earth by the region of the atmosphere north of a given latitude must therefore be balanced by a transport of angular momentum across that latitude. As Hadley noted long ago, the atmosphere exerts a westward frictional drag upon the Earth in the latitudes of the trade winds, whence angular momentum is transfered to the atmosphere from the Earth. In middle latitudes where the westerlies prevail, angular momentum is returned to the Earth. There is an additional weak transfer to the atmosphere in the polar caps.

The frictional drag is often spoken of as if it was the only means for exchanging angular momentum between the atmosphere and the Earth, but another mechanism can operate wherever there are mountains, hills, or small irregularities. If there is a horizontal pressure difference across a mountain range, the air will effectively push the mountain, and the rest of the Earth with it, toward lower pressure; the mountain therefore pushes the toward higher pressure. Although it seems natural to picture the air as piling upon the windward sides of mountains, and thereby augmenting the frictional torque, it is not obvious that this should be the ease, since many mountain masses are so large that the pressure difference across them depends mainly the positions of migratory cyclones and anticyclones.

Equating X to the absolute angular momentum M in Eq.(3.5), we find that

$$\int_0^{\infty} 2\pi r^2 \cos\phi_1 \left[\overline{quv}\right] dz + \int_0^{\infty} 2\pi r^3 \,\Omega \cos^3\phi_1 \left[\overline{\rho v}\right] dz$$

$$= \int_{\phi_1}^{\pi/2} 2\pi r^3 \cos^2\phi \left[\overline{T_{0\lambda}}\right] d\phi - \int_0^{\infty}\int_{\phi_1}^{\pi/2} r^2 \cos\phi \left(\Sigma\overline{p_E} - \Sigma\overline{p_W}\right) d\phi \, dz \;, \tag{3.8}$$

where Σp_E is the sum of the pressure on the east side of the mountains or other sloping terrain intersecting the latitude circle,

Σp_W is the sum of the pressure on the west side of the mountains or other sloping terrain intersecting the latitude circle,

$T_{0\lambda}$ is the eastward component of the frictional stress T_0 at the Earth's surface.

The terms on the left represent the transports of relative angular momentum and Ω - momentum.

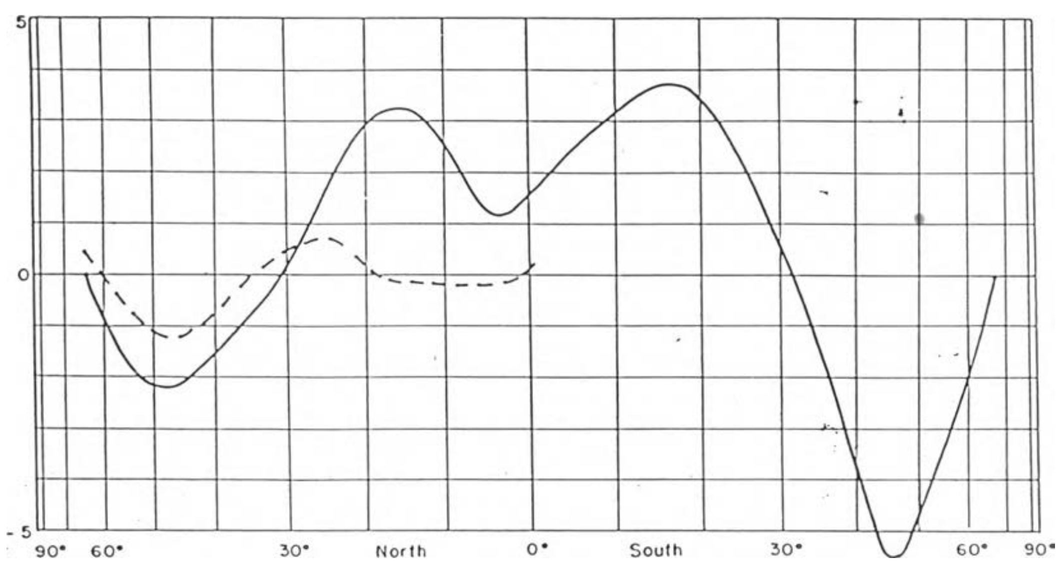


Figure 3.3 Average eastward torque per unit area exerted upon the atmosphere by surface friction (solid curve), and by mountains in the Northern Hemisphere (dash curve) in units of 10^8 g sec^{-2} (scale on left).

C. The Balance of Total Energy

The balance of total energy presents a more complicated problem. Not only does the atmosphere exchange energy with the underlying Earth, but both the atmosphere and the underlying Earth gain energy from the sun and lose it to outer space through radiation.

The incoming solar energy, which is the ultimate driving force for the atmospheric and oceanic circulations, is more intense in low than high latitudes. Some of this energy is reflected or scattered back to space and play no further role in the energy balance. The remainder is absorbed by the atmosphere and the Earth's surface is more intense in low latitudes. The energy re-radiated to space by the atmosphere and the Earth's surface is also more intense in low latitudes. Much of the outgoing radiation takes place from the uppermost layers of water vapour in the atmosphere; these extend to great heights in low latitudes and are therefore about as cold as the uppermost water

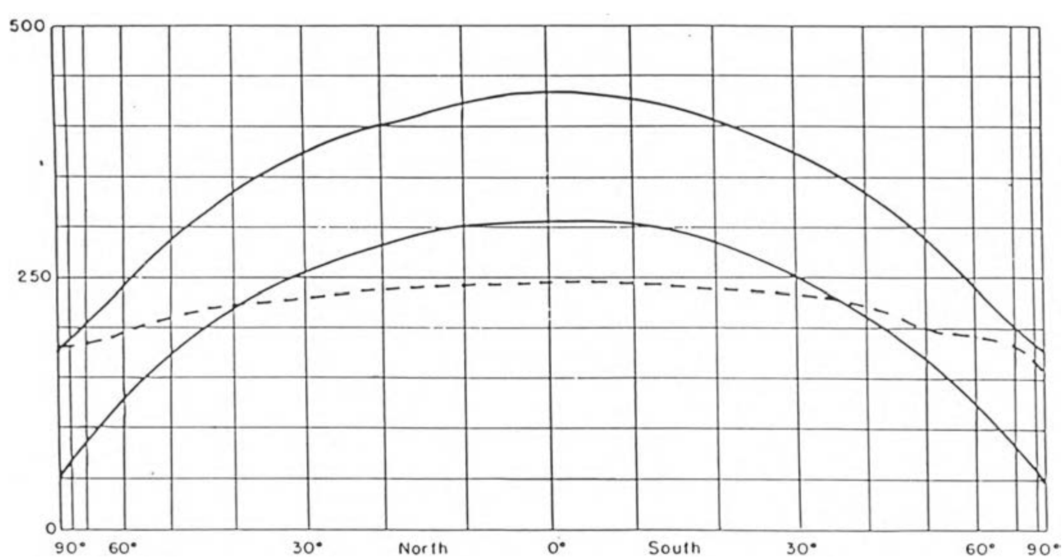


Figure 3.4 Average solar energy reaching the extremity of the atmosphere (upper solid curve), average solar energy absorbed by the atmosphere-ocean-Earth system (lower solid curve), and average infra-red radiation leaving the atmosphere-ocean-Earth system (dashed curve). Values are in watt m^{-2} (scale on left).

vapour in higher latitudes. The net result is therefore a considerable excess of heating in low latitudes. It follows that there must be a poleward transport or transfer of energy across virtually every latitude.

There are numerous estimates of the incoming and outgoing radiation. Fig.(3.3) is again upon the values compiled by Sellers [Sellers 1966] from a number of sources. Fig.(3.4) presents the net radiation and the required northward transport and transfer of energy. The principal features are gain the peak values in middle latitudes.

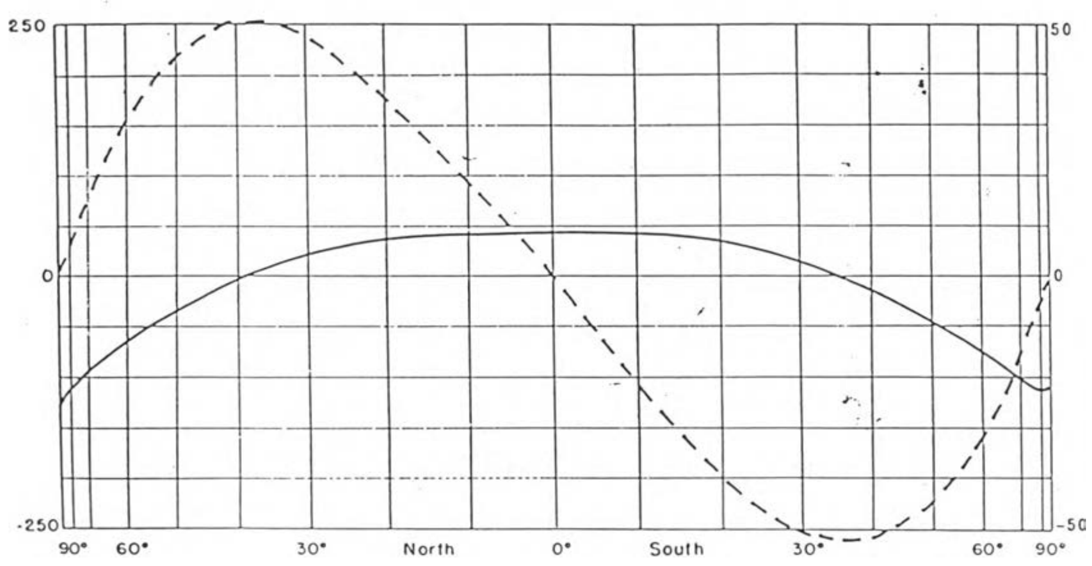


Figure 3.5 Excess of absorbed solar radiation over outgoing infra-red radiation (solid curve), in watt m^{-2} (scale on left); and northward transport of energy by the atmosphere and oceans required for balance (dashed curve), in units of 10^{14} watt (scale on right).

Since the atmosphere must satisfy the balance requirement for total energy, this requirement must also depend upon the choice of phase. If the liquid phase is chosen, the net radiation received or emitted by the atmosphere, the thermal internal energy transfered to the atmosphere from Earth, and the latent energy supplied to the atmosphere by evaporation must together be balanced by transports of sensible heat, potential energy, kinetic energy and latent energy within the atmosphere. If the gaseous phase is chosen, evaporation adds no energy to the atmosphere, but precipitation removes negative energy.

If we set X = K + Φ + I in Eq.(3.5), we find from Eq.(2.15) after some arrangement of terms that

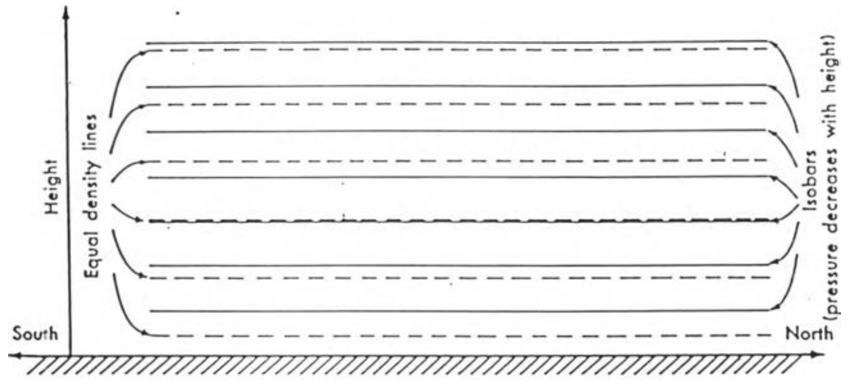
$$\int_0^{\infty} 2\pi r \cos\phi_1 \left[\overline{\rho\left(K + \Phi + I\right) v + pv}\right] dz = -\int_0^{\infty}\int_{\phi_1}^{\pi/2} 2\pi r^2 \cos\phi \left[\overline{Q + \vec{V}.\vec{F}}\right] d\phi\, dz\ , \tag{3.9}$$

The term pv on the left represents the work done against a unit area of the southern boundary by the pressure forces. Noting that for a dry atmosphere it would be proportional to, and additional to, the term ρIv, which would represent the transport of internal energy. For the real atmosphere pv is still proportional to the transport of thermal internal energy.

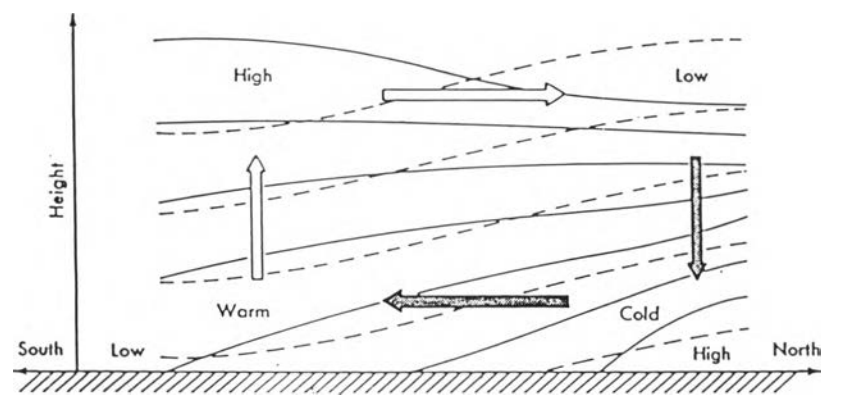
In the strictest sense Eq.(3.9) is not applicable, because the mass transport across the Earth's surface was neglected in deriving it. However, it may be used if I includes both thermal and latent internal energy, and if the gain of latent energy resulting from evaporation from the surface is included in Q. Alternatively, I may include only thermal internal energy, and the release of latent heat by condensation may be included in Q.

The General Circulation

The mean, worldwide distribution of winds is referred to as the *general circulation* [Miller 1966]. It is determined by averaging wind observations over long periods of time and thus represents the largest of the scales of motion. If the earth were not rotating and if the surface were homogeneous, the temperature difference between equator and poles would produce a thermal circulation cell in each hemisphere like that shown schematically in Fig.(3.6).



(a) Temperature uniform



(b) Temperature high in the south, low in the north

Figure 3.6 A schematic representation of the thermal circulation of atmosphere.

Near the surface of the earth, air would flow equatorward; heated by the warmth of the equatorial regions, it would rise and gradually move poleward, where it would sink, thus completing the circuit. Earth rotation and the non-uniform surface properties greatly modify this simple circulation pattern. Instead of one single cell in each hemisphere, there are three latitudinal cells and there are longitudinal variations around each hemisphere.

A schematic representation of the flow averaged over each latitude of the globe is shown in Fig.(3.7).

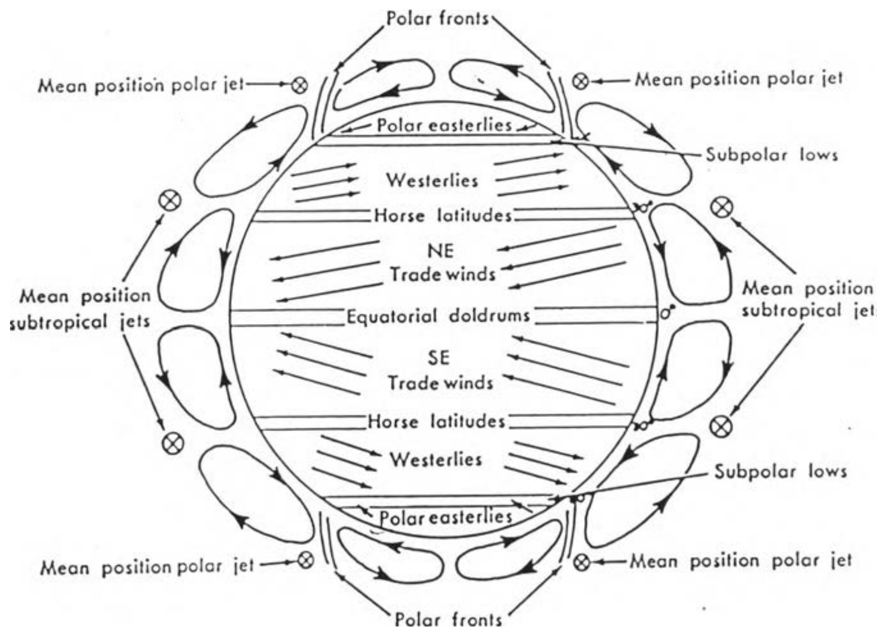


Figure 3.7 A schematic representation of the general circulation of atmosphere.

The horizontal flow is shown within the circle, while the net meridional circulation is depicted in the vertical cross section around the periphery. Near the equator there is a belt of low pressure; it is known as the doldrums, because the horizontal pressure gradient is generally weak here and winds are light and variable. It marks a zone where the wind belt to the north and south converge and rise. As a result, there are frequent heavy rain shower in the doldrums.

The 30°-wide belts to the south and north of the doldrums are noted for the remarkable persistence of the low-level winds. Winds from the east dominate both of these belts, the one in the Northern Hemisphere experiencing winds generally from the northeast, while southeast winds are found in the Southern Hemisphere belt. These wind are known as the *trade winds* because of the important role they played in opening up the New World when ships depended on sails.

A series of large high pressure areas (anticyclones) is located at about 30° N and another near 30° S. In these zones the mean vertical motion is one of descent, which inhibits the formation of clouds and precipitation. In this belt, along the eastern edges of the individual anticyclones, most of the world's great deserts are found. The light wins generally encountered in this belt have given rise to the name popularly applied to this subtropical high pressure zone: the horse latitudes. Spanish sailing vessels, carrying horses to the New World, on occasion were becalmed in one of these high centers and some of the animals had to be slaughtered as the supply of food became insufficient to complete the voyage.

Between 35° and 60° in both hemispheres, westerly winds prevail. Although they vary considerably between northwest and southwest, they usually have a component from the west. This zone is noted for its large number of moving cyclones and the changeable weather.

At 60° latitude, the subpolar lows form an almost continuous trough of low pressure in the Southern Hemisphere, but in the Northern Hemisphere there are two distinct semi-permanent low centers, one near the Aleutian Islands in the Pacific, and the other near Iceland in the Atlantic. Between the subpolar lows and the poles, high pressure areas dominate close to the surface, with weak easterlies. But these yield with increased height rather quickly to westerly winds, so that much of the middle and upper troposphere poleward of about 25° is dominated by west winds.