GENERAL CIRCULATION

Mean Characteristics

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Introduction

0154-P0005 The atmosphere of the Earth has a diverse range of motions. The general circulation refers to the larger-scale motions that have horizontal length scales greater than 1000 km and persist for a season or longer. In addition, this term includes all processes necessary to explain sufficiently, or maintain directly, the large-scale circulation.

0154-P0010 The general circulation encompasses more than simply the movement of the air. Understanding the circulation requires the examination of many other atmospheric quantities. Large-scale circulations are created by imbalances in the radiation fields that lead to temperature gradients that the atmosphere tries to eliminate. The circulations that develop are limited by various physical constraints such as energy balance, mass balance, and angular momentum balance. So, while the primary scope of this article is to descibe the mean properties of the circulation, it is also necessary to consider related variables that are directly observed. The related variables reveal the constraints on the circulation and the underlying laws of dynamics and thermodynamics. Other articles on the general circulation discuss how the circulation is maintained and how it can be simulated.

0154-P0015 The general circulation of the atmosphere has complex structure in all dimensions as it evolves over the seasons. To make a discussion of this subject manageable, it is traditional to examine first the properties of the general circulation when longitudinal averages are taken. Longitude averages are commonly labeled "zonal means." Zonal means provide a useful starting point since many atmospheric variables have much symmetry in the longitudinal direction. For example, contours of temperature in the upper troposphere are oriented east–west to a large degree. Zonal means reduce the information that one needs to view in order to visualize the circulation. However, zonal averages miss important phenomena that can be seen in time averages. Time means reveal longitudinal variations that must be taken into account in order to understand both the properties and the maintenance of the zonal mean state.

The general circulation undergoes seasonal change. 0154-P0020 In many fields the seasonal change is much less in the Southern Hemisphere. The difference arises because the middle latitudes in the Southern Hemisphere have a much higher fraction of ocean coverage than those in the Northern Hemisphere. Land and ocean have different thermodynamic properties: heating and cooling are more readily mixed through a greater amount of mass in the ocean than on land; and the albedo of land can change drastically with season, unlike that of the ice-free ocean. These factors magnify seasonal change over land.

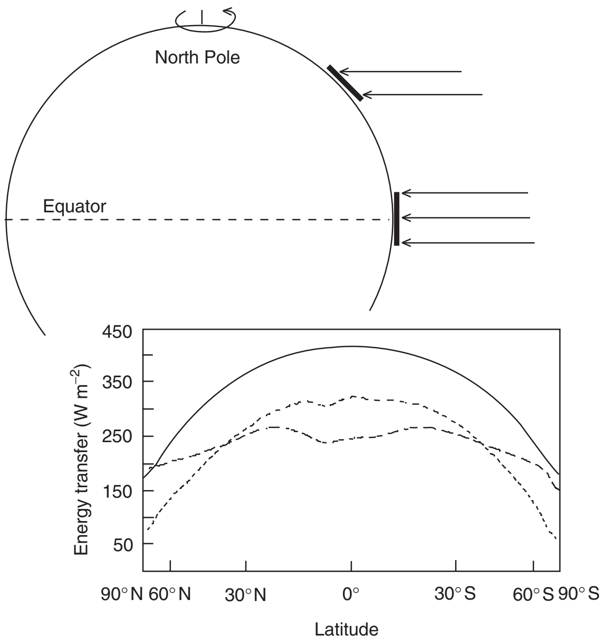
The difference in middle latitude land coverage has 0154-P0025 another implication. There are more major mountain ranges in the Northern Hemisphere. The mountains, together with differences that arise between land and sea areas, lead to more prominent planetary waves in the Northern Hemisphere. In contrast, many fields in the Southern Hemisphere tend to be more zonally uniform.

Longitudinal Average Characteristics

Radiation and Temperature

A discussion of the general circulation usually starts 0154-P0030 with radiation, since the distribution of radiation absorbed and emitted is the ultimate driving mechanism for the circulation.

The Earth (including its atmosphere, solid, and 0154-P0035 ocean parts) absorbs radiation emitted by the Sun. While the Earth rotates about an axis that is tilted with respect to the Sun, the Equator is perpendicular to the Sun's rays on an annual average. Simple geometry (see **Figure 1**) shows that the amount of solar radiation reaching unit area on the Earth diminishes from the Equator to the poles. The amount of solar radiation absorbed is influenced by the reflectivity of the Earth's surface, the amount of cloud cover, and the path length through the atmosphere. On an annual average, the amount of radiation absorbed decreases greatly from the Equator towards each pole. The rate that absorption decreases with latitude is greater in polar than in tropical regions.



0154-F0001 **Figure 1** Schematic diagram of solar radiation reaching the Earth at an equinox. Inset: latitudinal distribution of incoming solar (solid line), absorbed solar (short dashed line), and terrestrial emission (dashed line). Data redrawn from Barkstrom B, Harrison E, and Lee R III (1990) *EOS Transactions* 71(9): 249, 299, 304–305.

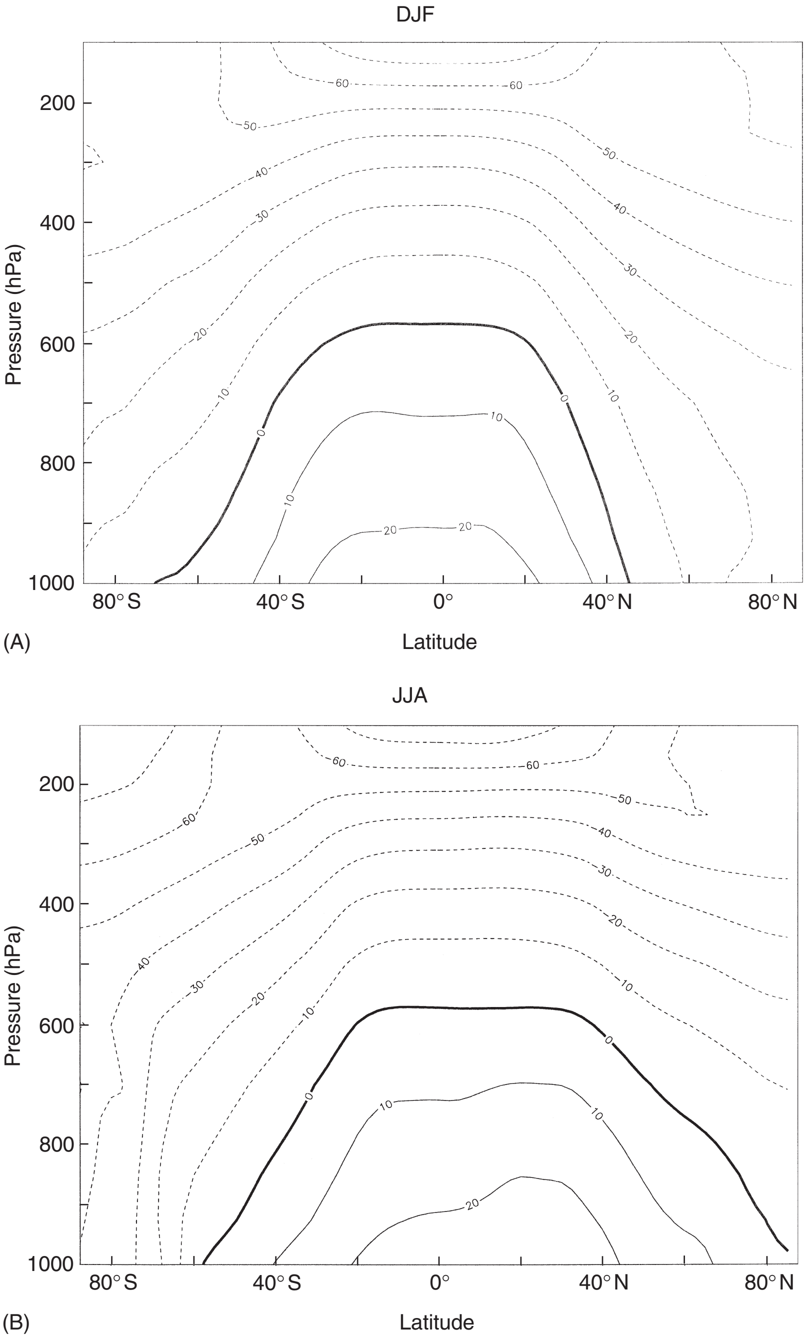
0154-P0040 The radiant energy absorbed is balanced by the energy emitted by the Earth back to space. Like the absorbed solar radiation, terrestrial emission also decreases from the Equator towards each pole on an annual average. The terrestrial emission is governed by the temperature and the radiative properties of the emitter. Emission comes from the surface of the Earth as well as from the atmosphere. For equivalent radiative properties, more radiant energy is emitted from objects that are hotter. Thus, the terrestrial emission is consistent with the tropics being warmer than the polar regions. However, the emission does not change with latitude nearly as fast as does the absorption. There is therefore a net radiation surplus in the tropics and deficit in the extratropics. A poleward energy transport is required, which has implications for the temperature field. The terrestrial emission means that temperatures are lower in the tropics and warmer in the polar regions than they would be without heat transport. While some transport occurs via the oceans, the remainder occurs in the atmosphere, and so the atmosphere must have a circulation. Further complicating the issue, the atmosphere may transport the heat by direct means (termed sensible heat transport) or by transporting water (termed latent heat transport). In the latter process heat is gained or released through a phase change of the water. Thus, the distribution of radiation implies links to temperature, velocity, and moisture fields.

Temperature In the troposphere and lower stratosphere, absorption and emission of radiation alters the air temperature at a rate of a few degrees per day. This change of air temperature is generally small compared with the difference between the equatorial regions and the polar regions. Hence, the radiant energy absorption and emission do not create large temperature differences between the daylight and night sides of the Earth. Therefore, much about the atmosphere's thermal structure is seen in a zonal mean. 0154-P0045

Seasonal averages for winter and summer temperature are displayed in **Figure 2**. The following properties are evident from the figure: 0154-P0050

1. Temperature decreases with increasing height. The rate of decrease (equal to the opposite of the lapse rate) is greater in the troposphere and notably less in the stratosphere. Temperature increases with height in the tropical lower stratosphere. The lapse rate is less than the lapse rate for neutral stability; the atmosphere is therefore statically stable on the large scale.
2. The tropopause marks the boundary between the stratosphere and troposphere. The zonal mean tropopause is not level, but ranges from 6–8 km in polar regions to 16–18 km in the tropics.
3. In the troposphere, zonal mean temperature along an isobaric surface decreases towards each pole. The rate of decrease (the meridional gradient) is small in the tropics and larger in the middle latitudes (30–60° N or S). The gradient is stronger during winter, with the exception of the sharp gradient near the Antarctic coast. The temperature change from Equator to pole is also greater at the surface than in the middle troposphere.
4. The coldest temperatures are in the winter polar region and near the equatorial tropopause.
5. In much of the lower stratosphere, the zonal mean temperature gradient is reversed from the troposphere. The reversal is evident in much of the tropics and middle latitudes. The main exceptions are the higher latitudes and part of the Southern Hemisphere middle latitudes during winter.

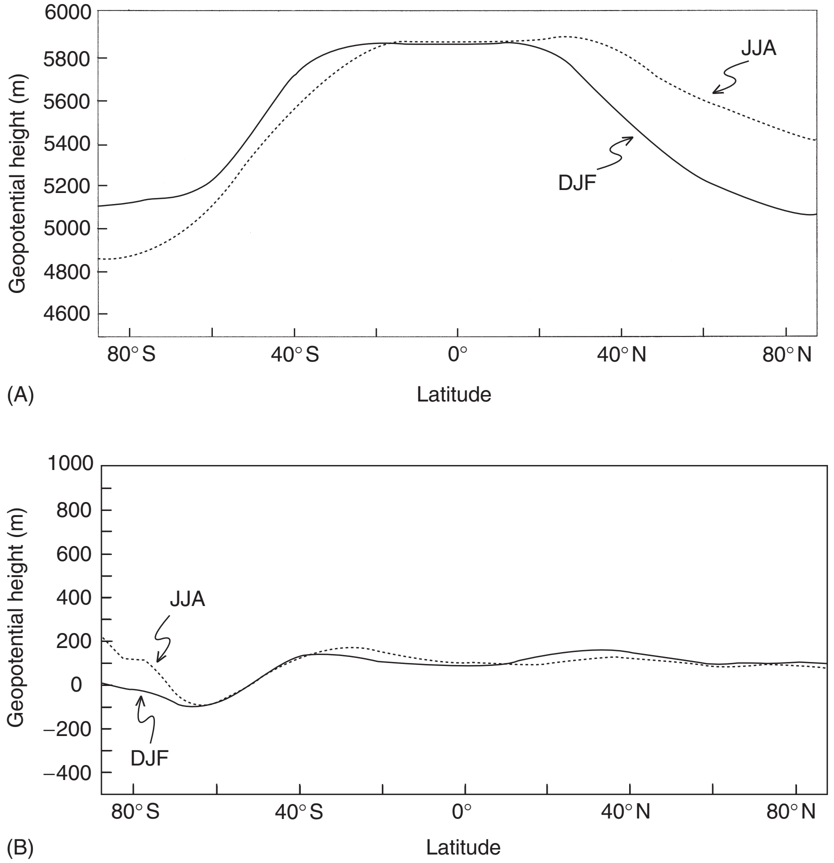
Mass fields The temperature field is related to the mass fields in several ways. For example, the hypsometric equation demonstrates that the spacing between isobaric surfaces is proportional to the mean temperature of the air between those surfaces. In the troposphere, air is warmer in the tropics, thus the vertical distance between any two isobaric surfaces 0154-P0055



0154-F0002 **Figure 2** Zonal mean temperature during (A) December–February and (B) June–August. Units are degrees Celsius. National Center for Environmental Prediction/National Center for Atmospheric Research (NCEP/NCAR) reanalysis data 1979–99.

(the 'thickness') is larger than in the extratropics. Since the variation of surface pressure over the Earth is rather small, this implies that the altitude of a constant pressure surface (200 mbar, say) on average increases from Pole to Equator.

0154-P0060 The zonal mean geopotential heights of the 500 and 1000 hPa surfaces are shown in **Figure 3**. The 500 mbar surface is representative of geopotential height surfaces in much of the troposphere and lower stratosphere. At 500 mbar, the geopotential heights are greater in the tropical regions with lowest values near the poles. The gradient between Equator and pole is strongest in the middle latitudes. The 1000 mbar height pattern is representative of the mass field near the surface. The surface pattern is quite different from levels above: pressure is relatively low along the



0154-F0003 **Figure 3** Zonal mean geopotential heights in m (A) at 500 hPa and (B) 1000 hPa. Solid line is for December–February and dotted line is for June–August. NCEP/NCAR reanalysis data 1979–99.

Equator and in middle latitudes; pressure is highest in the subtropics.

Zonal Velocity

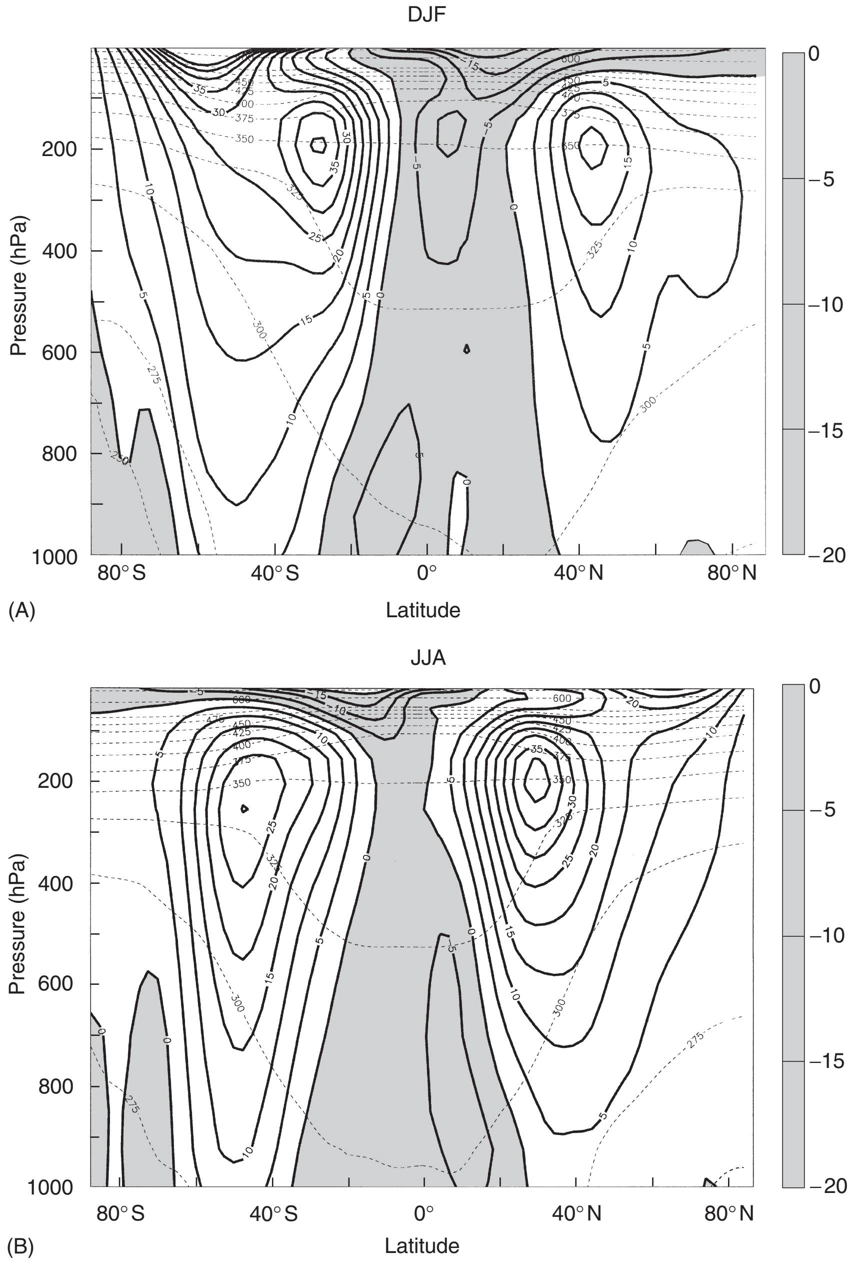
0154-P0065 The zonal wind is directed positive when blowing towards the east. Outside the equatorial region, the mass and wind fields are in approximate geostrophic balance. The meridional gradient seen in the tropospheric geopotential height fields implies a westerly wind that is stronger in middle latitudes. At the surface, comparatively weak winds are expected.

0154-P0070 The thermal wind relation states that vertical "shear" of the zonal wind is proportional to the meridional gradient of temperature and inversely proportional to the Coriolis parameter. The temperature gradient in much of the troposphere is directed equatorward, an orientation implying westerly wind shear. Since the tropospheric temperature gradient is stronger in middle latitudes, one expects the westerly shear to be stronger there as well. The temperature gradient reverses in the tropical and middle latitudes of the lower stratosphere, implying easterly shear. Therefore, one anticipates westerly winds to increase with height in the troposphere and to decrease above it, in the lower stratosphere. In short, the stronger westerly winds tend to occur at tropopause level.

Another constraint on the zonal wind is angular momentum balance. If the winds at the surface were everywhere westerly, say, then those winds would apply a net torque upon the surface of the Earth. A net westerly torque would speed up the rotation of the Earth and the days would be getting shorter. However, the angular momentum of the Earth is essentially constant. Thus the areas of easterly winds must be balanced by areas of westerly winds at the surface. 0154-P0075

The zonal mean of the zonal wind is shown in **Figure 4** for winter and summer. Areas that are shaded indicate easterly winds. The following properties are evident from the figure: 0154-P0080

1. The surface winds are generally easterly in the tropics, which make up approximately half of the surface of the globe. The surface winds are westerly primarily in the middle latitudes.
2. The winds generally gain a westerly component with elevation. For the tropical troposphere, the



0154-F0004 **Figure 4** Zonal mean zonal wind (solid contours; in m s^{-1}) with potential temperature (dashed contours; in K) for (A) December–February and (B) June–August. Areas of easterly winds are shaded. NCEP/NCAR reanalysis data 1979–99.

easterly wind decreases with increasing elevation. For much of the middle latitudes, the westerly wind increases with height until the tropopause. Above the tropopause, the shear reverses and westerlies decrease with increasing height. The principal exception is the middle latitudes of the Southern Hemisphere in winter. These properties, including the exception, are anticipated from the temperature gradients.

3. In the high-latitude winter stratosphere, westerly winds increase with height. It is difficult to see with the vertical coordinate chosen, but these westerly winds are associated with the polar night jet. That jet reaches maximum speed in the upper stratosphere (10–30 hPa level).
4. The subtropical jets are prominent maxima at the midlatitude tropopause. These jets are stronger and migrate to a lower latitude in winter. In the Southern Hemisphere during winter, strong winds of the polar night jet extend into the upper troposphere, creating the impression that there are two tropospheric jets on upper-level isobaric charts.

Meridional Circulations

0154-P0085 The meridional wind is comparable in magnitude to the zonal wind in many instances. However, if the meridional wind is geostrophic, then a zonal average is the integral (with respect to longitude) of a longitudinal derivative. Unless a mountain is intercepted, this integral must be zero because the integral completes a circuit. Since the total wind is nearly in geostrophic balance outside the tropics, the zonal mean meridional wind is very small outside the tropics.

0154-P0090 Since the observed lapse rate is less than the dry adiabatic lapse rate, it follows that vertical motions are resisted. One consequence is that vertical motions are far smaller in magnitude than are horizontal motions on this large scale. Large-scale vertical motion cannot be measured directly since it is smaller than the errors of the observing systems. Vertical velocity can be estimated indirectly from quantities that are measured with some confidence. One procedure is to estimate the meridional winds from an equation for angular momentum balance and then deduce a streamfunction in the meridional plane. An alternative procedure is to input observed fields into a primitive equation general circulation model and let the model deduce the vertical motion. The latter procedure obtained the motions shown in **Figure 5**.

0154-P0095 The zonal mean motions in the meridional plane have the following properties:

1. The motion is organized into distinct patterns commonly referred to as meridional cells. The most prominent cells occur in the tropics and are often called the "Hadley" cells. In the middle latitudes of each hemisphere is found a weaker circulation, usually called the "Ferrel" cell.
2. The meridional cells are much stronger during winter both in terms of the areal extent they occupy as well as the vigor of the circulation. The winter Hadley cell has significant flow across the Equator.
3. The Hadley cell circulates in an intuitive sense: Rising motion occurs where the atmosphere is warmer, and sinking motion where it is cooler. The temperature distribution over the globe is statically stable in the dry sense. However, in the lower tropical troposphere the air is very moist and nearly neutral with respect to a psuedoadiabatic lapse rate. The upward motion of the Hadley cell is driven by latent heat release as water vapor is converted into precipitation. Precipitation is therefore expected to be a maximum in the tropics. In order to overcome the moist static stability and entrainment as air parcels rise into the upper tropical troposphere, the rising motion is embedded within thunderstorms. These thunderstorms occupy a very small fraction (about 0.5%) of the tropical surface area. Air parcels in the poleward-moving branch of the Hadley cell cool radiatively; as their potential temperature decreases, these parcels sink.
4. In the Ferrel cell air appears to rise where temperatures are cooler and sink where they are warmer. This Eulerian mean motion should not be confused with the actual paths of air parcels. In middle latitudes parcel motions are strongly influenced by baroclinic waves. When an average is taken around a latitude circle at constant pressure the resulting mean has the sense given by the Ferrel cell. Such a mean does not reflect the motions of air parcels. On the other hand, if an average is taken along constant entropy surfaces (isentropic coordinates), it reflects the nearly adiabatic motion in the eddies, and the resulting mean meridional circulation has the same sense on the Hadley circulation.
5. The radiative energy distribution requires a meridional circulation to transport heat poleward. The meridional motions of the Hadley cell transport the same mass poleward as southward (ignoring the mass due to moisture). The Hadley cell has a net heat transport because the upper-level air has higher moist static energy than does the lower-level air. In the case of the Ferrel cell, the frontal systems have strong heat fluxes that can be deduced from westward tilts with height of the trough and ridge axes of these waves.

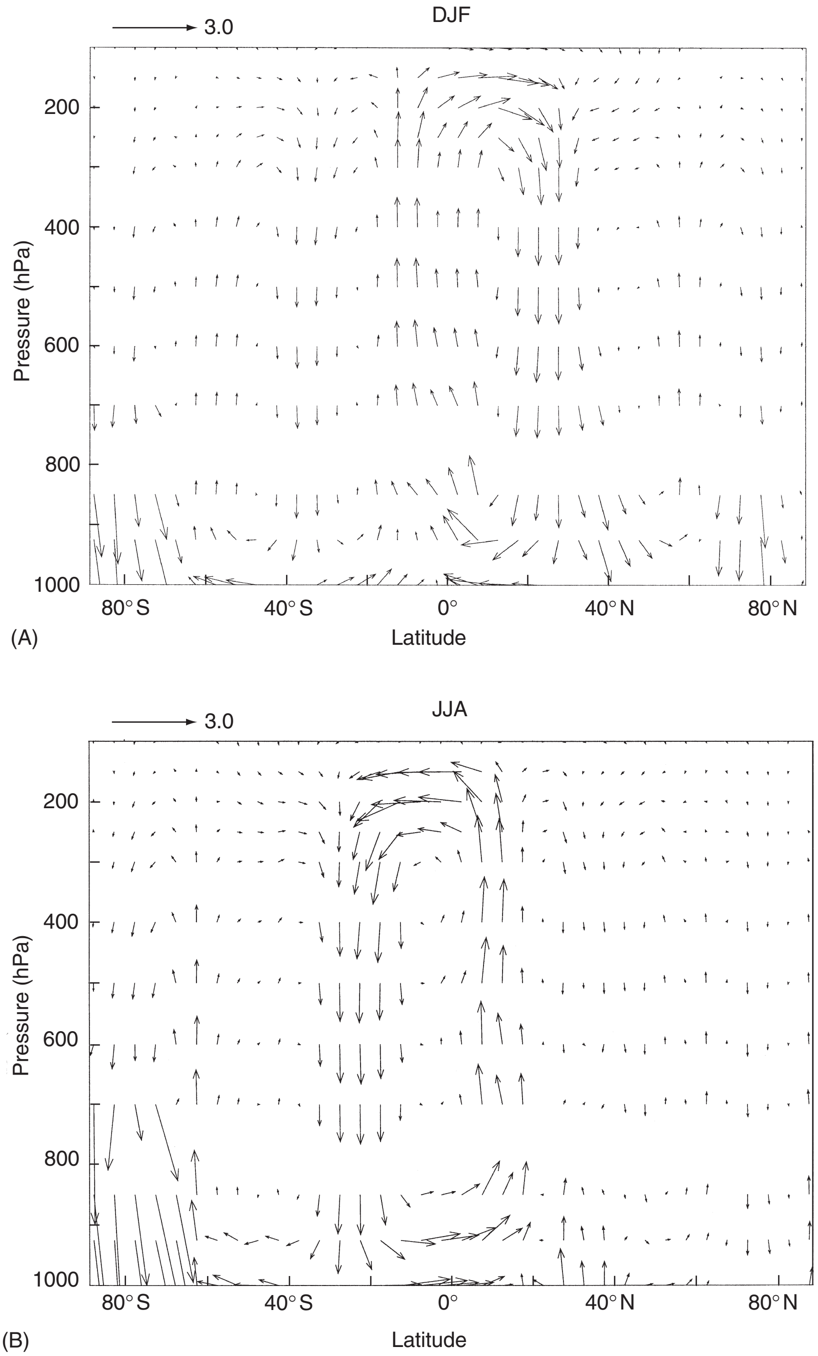
Precipitation

Precipitation is linked to the general circulation in several ways. **Figure 6** shows the zonal mean distribution of precipitation. The largest precipitation occurs in the tropics and is associated with the rising branch of the Hadley cells. In some seasons, two equatorial maxima are found, the explanation for which becomes clear when time mean fields are considered. Where sinking motion is seen in the meridional cells, precipitation is suppressed. Secondary maxima occur in middle latitudes that are superficially linked to the rising branch of the Ferrel cells, but are more properly associated with the extratropical cyclones. 0154-P0100

Time Average Characteristics

Midlatitude Planetary Waves and Storm Tracks

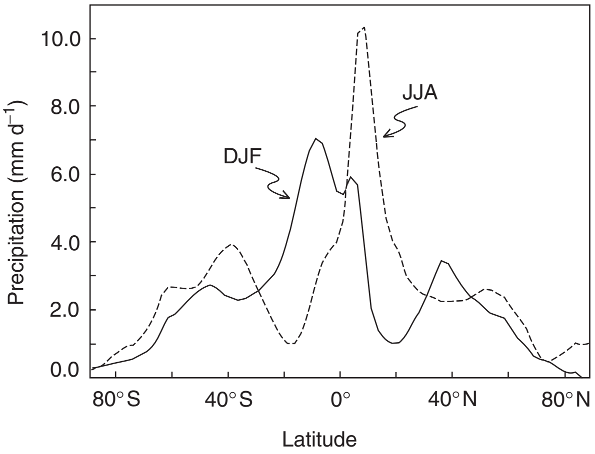
The mass and temperature fields have significant longitudinal variation. Away from the surface, the time mean pattern is characterized by long waves. The 500 hPa geopotential height (**Figure** 7) is typical of the troposphere. Prominent troughs are seen near the midlatitude east coasts of Asia and North America. The temperature field beneath (e.g., at 700 hPa) also 0154-P0105



0154-F0005 **Figure 5** Zonal mean meridional circulations for (A) December–February and (B) June–August. Vectors for $p > 800$ hPa over Antarctica should be ignored. Vectors based upon NCEP/NCAR reanalysis data 1979–99.

has troughs near these regions. A weaker geopotential trough occurs over the Mediterranean and north-west Africa. At the base of each trough the height contours are more closely spaced; from geostrophic balance wind speeds would be expected to be relatively stronger there. Ridges are found in between, most prominently in north-western North America and Europe. In summer, the North American trough remains visible owing to the Baffin and Greenland ice sheets.

Most of the weather in the middle latitudes is created by travelling frontal cyclones. These cyclones interact with the planetary wave pattern in various ways. Cyclones prefer to form, propagate and decay in specific regions. Generally speaking, cyclogenesis is favored in three types of regions: near the east coasts of 0154-P0110



0154-F0006 **Figure 6** Zonal mean precipitation in mm d^{-1} for December–February (solid line) and June–August (dotted line). CMAP 1979–99 data used.

continents, on the lee side of major mountain ranges, and where large-scale surface temperature gradients are strong. Most of these regions coincide with the locations of longwave troughs. The last type includes the area south of Africa and much of the southern Indian Ocean. The cyclones generally progress eastward and poleward as they evolve. In the Northern Hemisphere cyclones often merge with or supplant the 'semi-permanent' Aleutian and Icelandic lows (**Figure 8**). The storm tracks show up in the precipitation fields (**Figure 9**) as bands of heavier precipitation in the middle latitudes across the oceans. Precipitation is also enhanced where westerlies encounter mountain ranges of North America and western Europe.

Subtropical Highs

0154-P0115 At the surface one finds prominent high-pressure regions in the subtropics (**Figure 8**). A three-way balance between the pressure gradient, Coriolis, and turbulent drag forces implies divergence at a surface high. Surface divergence is consistent with the sinking, and here it is the sinking branch of the Hadley cells. The sinking is apparent in **Figure 10** as areas where upper-level divergent winds converge. When longitude is included, the subtropical highs have a clear preference for the eastern sides of the major ocean basins. The mechanisms felt to be responsible for this preference are associated with the colder ocean temperatures at these longitudes. The colder temperatures foster low stratus clouds, which in turn create a net radiative cooling of the air. As the air cools, it sinks. The areal extent of the highs is influenced by other factors such as the midlatitude storm tracks and tropical convection. In summer, these factors allow much greater expansion of the subtropical highs in the Northern than in the Southern Hemisphere. The tropical convection, mainly equatorward and to the west of the subtropical high, feeds the circulation supporting the high; this link is observable in the divergent winds.

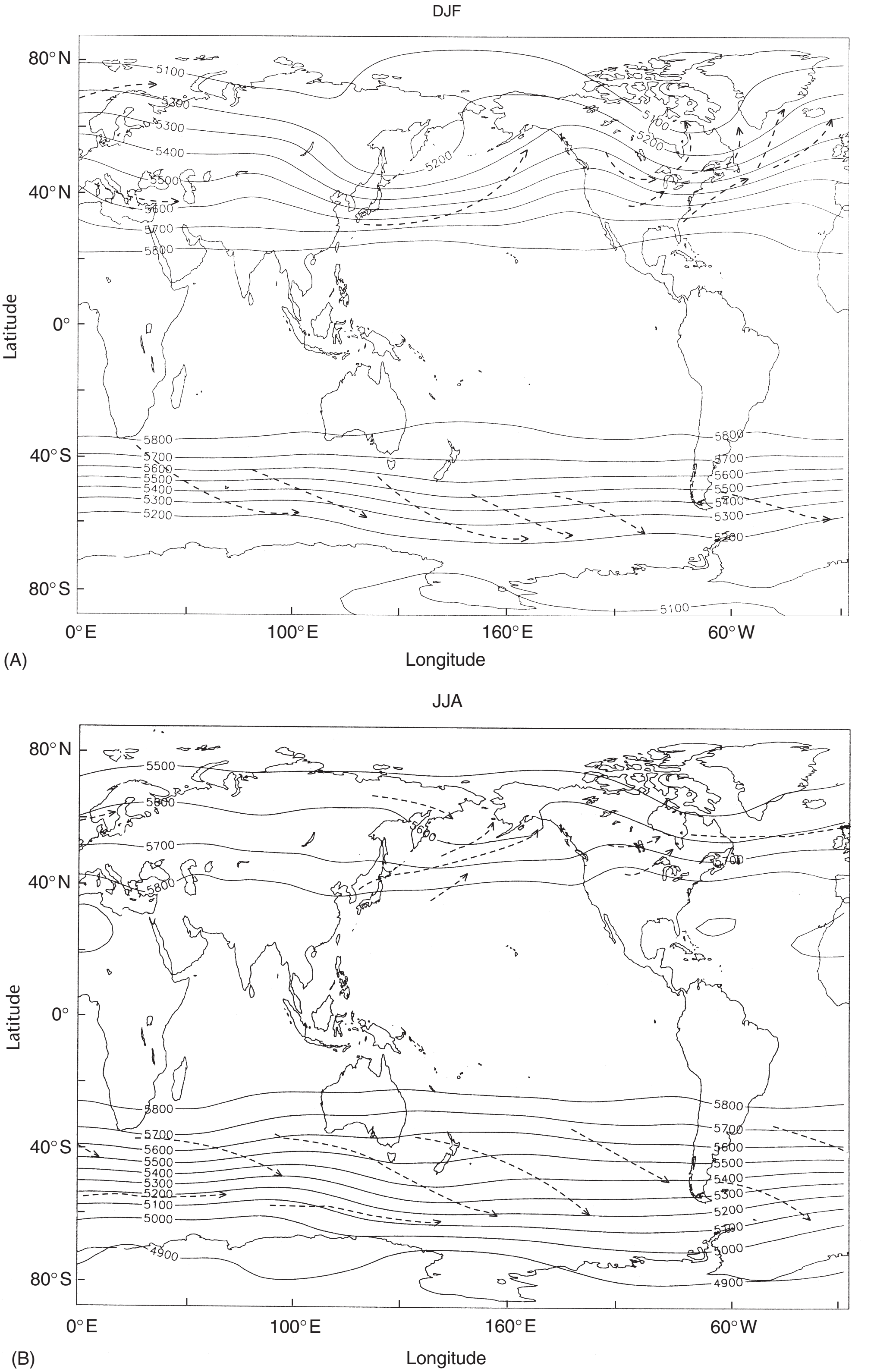
Divergent Tropical Circulations

The zonal mean Hadley circulation implies vigorous upward motion near the Equator and that motion is driven by precipitation. The time mean precipitation, **Figure 9**, has a clear preference for tropical land areas and regions of warmest sea surface temperature. In northern summer, precipitation is greatly enhanced over India, while at other longitudes it remains closer to the Equator, resulting in the double maximum seen in **Figure 6**. The upward motion has similar zonal variation. 0154-P0120

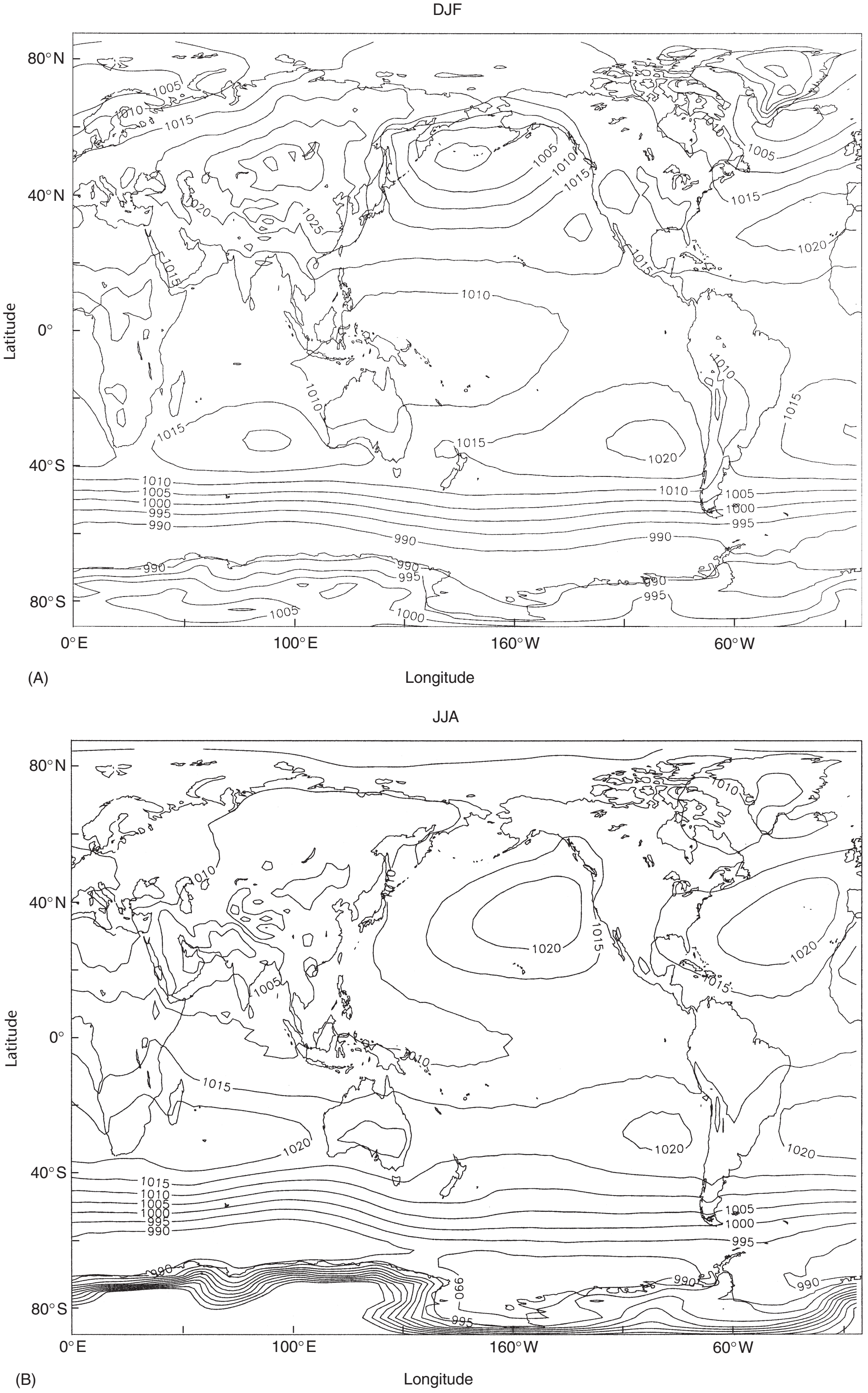
The Hadley cell upward motion is part of the divergent winds of the tropics. Diverging arrows in **Figure 10** imply rising motion below. Following the divergent wind vectors appears to connect areas of preferred rising with the sinking above the subtropical highs. Some divergent winds are poleward and thus consistent with the Hadley circulation at 200 mbar. The strongest areas of divergence in **Figure 10** overlie South-east Asia and Indonesia and Amazonia. In northern summer, the South-east Asian Monsoon is prominent. The figure also shows prominent east–west motion in the Pacific that is generally referred to as the "Walker" circulation. The Walker circulation apparently connects sinking over the subtropical highs of the eastern Pacific with the far western Pacific precipitation. The rising air is fed by low-level convergence that results from ageostrophic motions that occur for relatively low surface pressure. Observations show a large correlation between heavier precipitation in Indonesia, lower pressure there, and stronger Pacific subtropical highs. 0154-P0125

Subtropical Jet Streams

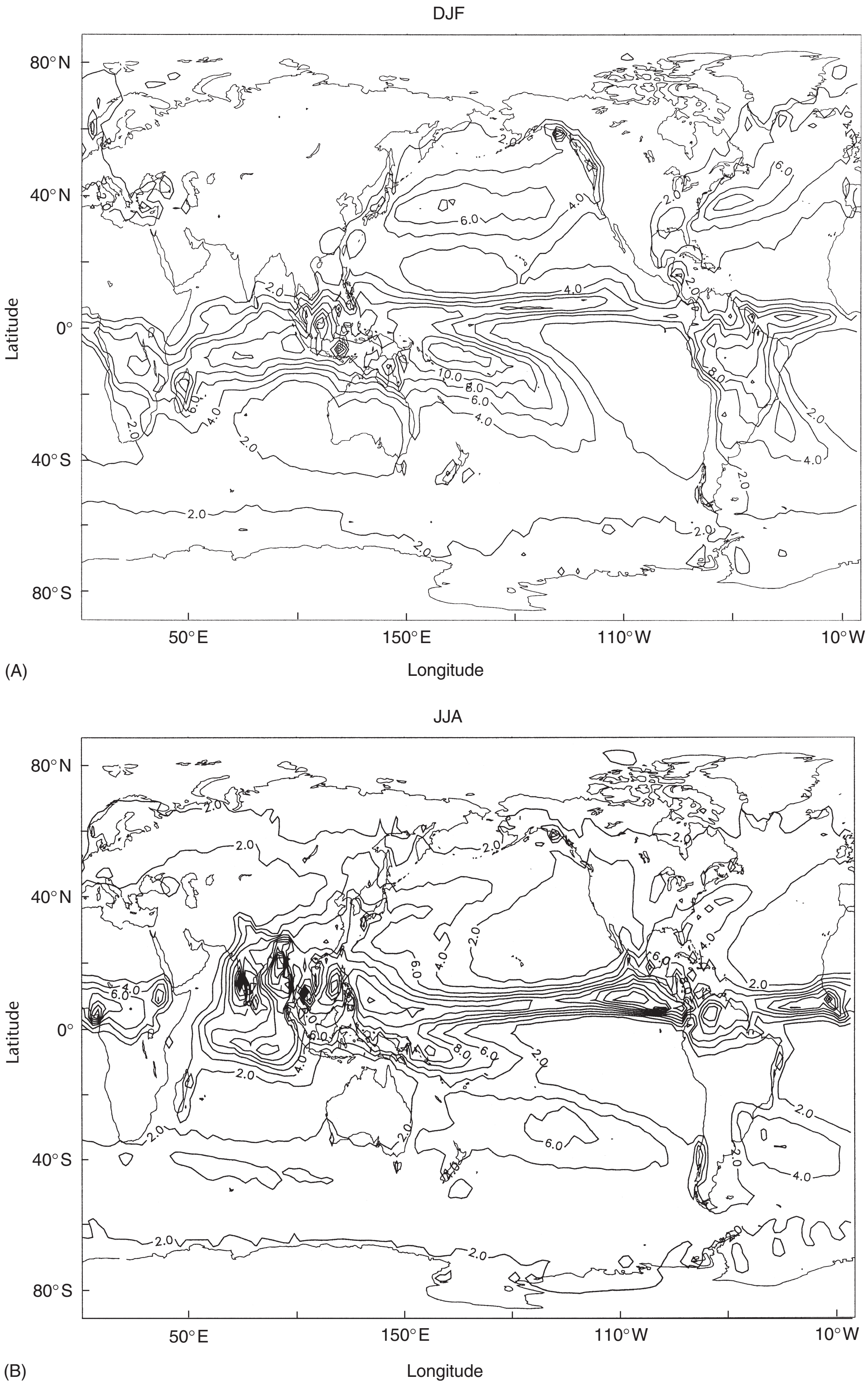
Zonal variations of the subtropical jet streams are linked to many of the phenomena discussed above. The time mean wind speed is plotted in **Figure 11**. The jet streams have relative maxima near the east coasts of Asia and North America. These maxima are much stronger during winter. The height gradients are stronger there as well, consistent with geostrophic balance. Stronger portions of the jet streams occur in the middle latitudes of the Southern Hemisphere. Further south (near 60° S) is another maximum during southern winter that extends into the high stratosphere (where it becomes the polar night jet) on a time average. 0154-P0130



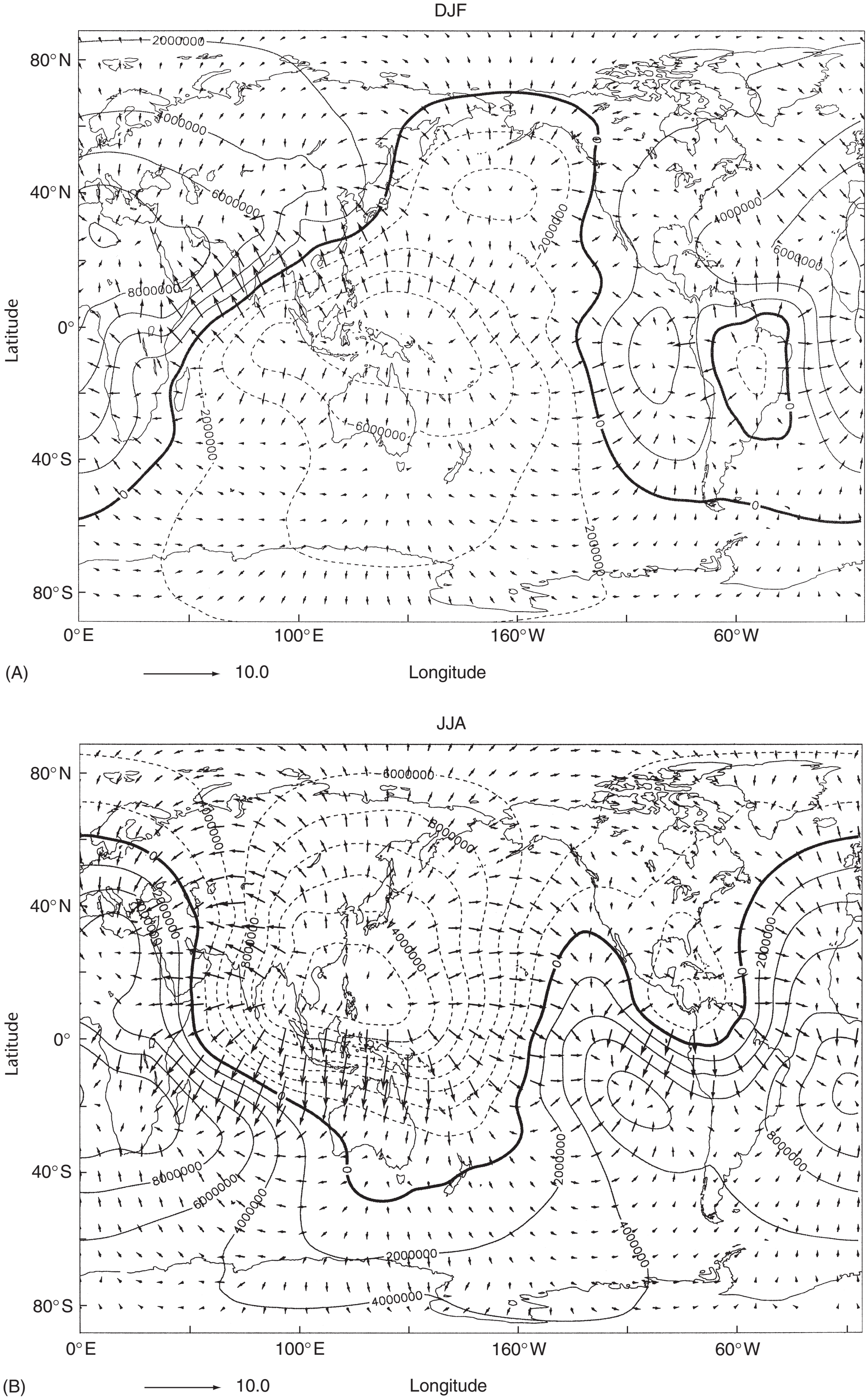
0154-F0007 **Figure 7** Time mean geopotential heights of 500 mbar surface for (A) December–February and (B) June–August. Interval is 100 m. NCEP/NCAR reanalysis data 1979–99. Major extratropical cyclone storm tracks are also marked using dashed arrows; tails located in regions preferred for cyclogenesis and heads in regions preferred for cyclolysis. The tracks are highly idealized and are deduced from various sources, including: Simmonds I and Murray R (1999) *Weather Forecasting* 14: 878–891; Sinclair M (1995) *Monthly Weather Review* 123: 1601–1619; Whitaker L and Horn L (1984) *Journal of Climatology* 4: 297–310.



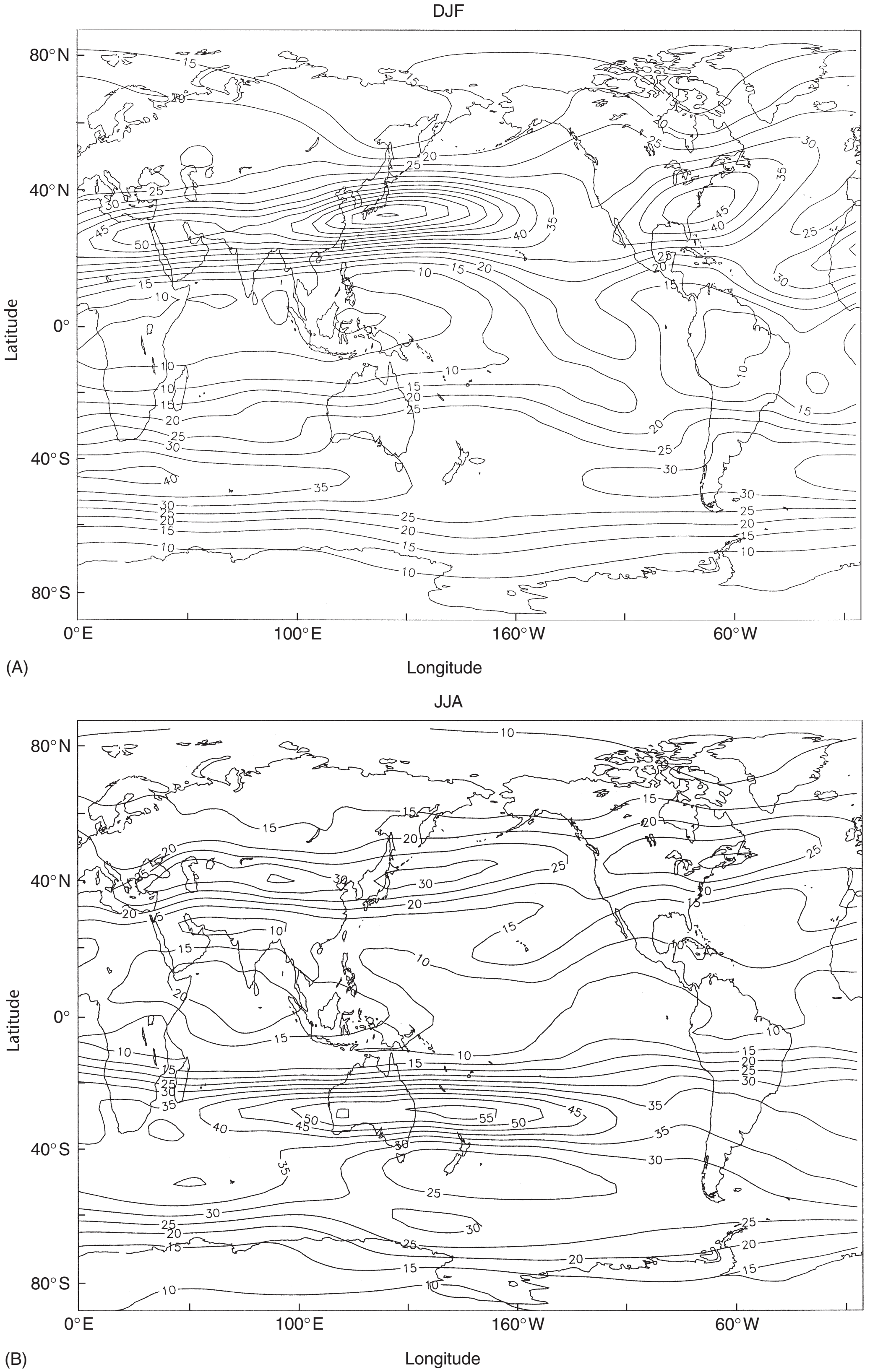
0154-F0008 **Figure 8** Time mean sea level pressure for (A) December–February and (B) June–August. Interval is 5 mbar. NCEP/NCAR reanalysis data 1979–99.



0154-F0009 **Figure 9** Time mean precipitation for (A) December–February and (B) June–August. Interval is 2 mm d^{-1}. CMAP 1979–99 data used.



0154-F0010 **Figure 10** Time mean divergent wind (arrows) and velocity potential (contours) at 200 mbar during (A) December–February and (B) June–August. The longest arrow is approximately 10 m s^{-1} and the contour interval is 2×10^6 m^2 s^2. NCEP/NCAR reanalysis data 1979–99.



0154-F0011 **Figure 11** Time mean horizontal wind at 200 mbar for (A) December–February and (B) June–August. Interval is 5 m s^{-1}. NCEP/NCAR reanalysis data 1979–99.

0154-P0135 The divergent winds of the Hadley cell advect planetary angular momentum poleward and thereby strengthen the subtropical jets in preferred regions. In the case of east Asia, divergent flow northward from the Indonesia region during northern winter builds higher pressure to the south east of the Asian longwave trough. This amplifies the height gradient on the south-east side of that trough (e.g. **Figure** 7A). The divergent flow southward from the Indonesia region leads to the stronger jet over Australia.

See also

Dynamic Meteorology: Balanced Flows and Potential-Vorticity Inversion (0140); Overview (0138); Primitive Equations (0139); Waves and Instabilities (0141). **General Circulation:** Energy Cycle (0155); Overview (0153). **General Circulation Models** (0157). **Hadley Circulation** (0161). **Middle Atmosphere:** Zonal Mean Climatology (0227). **Monsoon:** Overview (0235). **Planetary Atmospheres:** Mars (0312); Venus (0313). **Radiation Budget:** Planetary (0335). **Synoptic Meteorology:** Weather Maps (0397). **Tropical Meteorology:** Tropical Climates (0416).

Further Reading

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