Like the SAO, the theoretical understanding of the QBO is that it is forced by momentum transfer by vertically propagating waves forced in the lower atmosphere, interacting with the mean flow. The dynamical theory of the QBO is explained in detail elsewhere.

**See also**
Middle Atmosphere: Planetary Waves; Polar Vortex; Quasi-Biennial Oscillation; Semiannual Oscillation.

---

**Quasi-geostrophic Theory. Wave Mean-Flow Interaction.**

**Further Reading**

---

Monsoon derives from the Arabic word ‘mausam’, meaning season, and in its broadest definition describes those climates that are seasonally arid. As shown in Figure 1, many regions of the tropics and subtropics experience a rainy summer season and a dry winter season, although regions close to the Equator can often experience two rainy seasons; e.g., equatorial east Africa with its ‘long’ (March–May) and ‘short’ (October–December) rains. The main driver of this marked seasonality in rainfall is the change in the distribution of surface heating between winter and summer, primarily associated with seasonal variations in the position of the sun. Because of this close relationship with the solar seasonal cycle, the start of the rainy season often begins with remarkable regularity each year.

Although Figure 1 shows that many regions are seasonally arid, the more precise definition of a monsoon climate, as proposed by Ramage, identifies South Asia, Australia, and Africa as having distinct monsoons. Ramage’s criteria for a monsoon to exist are as follows:

1. Prevailing wind direction shifts by at least 120° between January and July.
2. Prevailing wind direction persists for at least 40% of the time in January and July.
3. Mean wind exceeds 3 m s⁻¹ in either month.
4. Fewer than one cyclone–anticyclone alternation occurs every 2 years in either month in a 5° latitude-longitude rectangle.

These criteria essentially demand that a monsoon be characterized by a wind regime that is steady, sustained and therefore inherently driven by the seasonally evolving boundary conditions, such as land or ocean surface temperatures. It excludes most extratropical regions that are characterized by synoptic weather systems with alternating cyclonic–anticyclonic circulations.
Figure 1 Mean precipitation distributions for northern winter (January–February; upper panel) and northern summer (July–August; lower panel) at the height of the monsoon season (units: mm day$^{-1}$). (Data source: Global Precipitation Climatology Project.)

Figure 2 Mean winds at 925 hPa for northern winter (January–February; upper panel) and northern summer (July–August; lower panel) at the height of the monsoon season (units: m s$^{-1}$). (Data source: Reanalyses from European Centre for Medium Range Weather Forecasts for 1979–93.)
Based on these criteria, Figure 2 shows that this major reversal in the seasonal wind regimes only occurs over (1) India and South-East Asia, (2) northern Australia, and (3) West and central Africa. These three regions constitute the major monsoons of the global circulation. Although the Americas and South Africa also experience a strong seasonal cycle in rainfall, the prevailing wind direction is largely unchanged between winter and summer (Figure 2), and so strictly speaking cannot be classified as monsoon regions. The name ‘monsoon’ is often used to denote the rainy season, but in fact can relate to both extremes of the seasonal cycle. The term winter monsoon is used in South-East Asia to describe the dry, north-easterly winds that prevail over the northern Indian Ocean and South China Sea during boreal winter (Figure 2, upper panel).

For a monsoon to be established, a thermal contrast between the land and ocean must exist. This occurs when large land masses, such as Asia, Africa, and Australia, heat up rapidly during the spring and summer (Figure 3). Since the thermal inertia of the land is much less than the surrounding oceans, the continents respond much more rapidly to the seasonal cycle in solar heating, setting up large temperature gradients. These hot land masses draw humid air in from the surrounding oceans, like a massive sea breeze (Figure 2). As the moisture-laden air reaches the warm land, it rises, the moisture condenses, and the rainy season begins. By contrast, in winter the land becomes much cooler than the surrounding oceans and cold, dry air then flows from the land out over the ocean. Often the two monsoons, winter and summer, are closely linked with the winter monsoon of one hemisphere feeding the summer monsoon of the other. For example, in the Asian–Australian monsoon system, the dry air from the winter continent flows across the Equator toward the summer hemisphere (Figure 2), picking up moisture from the warm oceans and feeding the monsoon rains over the summer continent.

A critical factor that determines the generation of a monsoon is the geographical orientation of the oceans and continents. The strongest monsoons occur where there is a pronounced north–south distribution in land and ocean that can take advantage of the north–south progression of the solar seasonal cycle. As Figure 3 shows, the largest land–sea temperature contrasts occur over the seasonally arid regions of North Africa, India, and Australia, during the months preceding the summer monsoon. These very warm temperatures lead to the development of thermal lows which serve to pull in air from surrounding regions. Once the monsoon is established and the rains begin, the land

---

**Figure 3** Surface temperatures for early austral summer (November–December; upper panel) and boreal summer (May–June; lower panel) at the onset of the monsoon (units: °C). (Data source: Reanalyses from European Centre for Medium Range Weather Forecasts for 1979–93.)
surface temperatures tend to cool due to the increased soil wetness, but the atmospheric warming from latent heat release associated with the monsoon rains (Figure 1) maintains the low-pressure regions (Figure 4) which continue to drive the monsoon winds.

Although this classic description of monsoons provides the fundamental basis for their existence, there are important regional differences associated with the shape of continents, orography (particularly mountain barriers), and ocean temperatures. For the
Asian summer monsoon, the Tibetan plateau acts as an elevated heat source which clearly influences the establishment and maintenance of the monsoon circulation. The seasonal heating of the plateau leads to a reversal of the meridional temperature gradient which extends throughout the troposphere (Figure 5). This reversal is instrumental in triggering the large-scale seasonal change in the circulation over East Asia, with the poleward transition of the subtropical jet and the onset of the monsoon over the Indian subcontinent.

The importance of this deep warm core over South Asia is demonstrated in Figure 6, which shows the winds in the free troposphere at 700 hPa. These winds can be compared with the boundary layer winds at 925 hPa in Figure 2. It is only for the domain of the Asian monsoon that the seasonal reversal of the winds is seen extending above the boundary layer into the free troposphere. This is important because it is only when there is advection of moist air through a substantial depth of the troposphere that sustained monsoon rainfall is achieved.

The significance of the Tibetan plateau is further demonstrated when a comparison is made between the summer monsoons of South Asia, northern Australia, and West Africa. In the absence of an orographic heat source, the seasonal reversal of the meridional temperature gradient through the depth of the troposphere is barely evident over Australia and West Africa. This is despite the very substantial surface warming of Australia and North Africa shown in Figure 3. The effect of the confinement of the seasonal reversal in the meridional temperature gradient to the near-surface layers over Africa and Australia can be seen in the winds at 700 hPa (Figure 6). Unlike South-East Asia, there is no seasonal reversal of the winds in the free troposphere so that a deep moist layer is not established in the same way as over South Asia. Consequently, the monsoon rains of West Africa and Australia are not as intense, nor do they extend as far polewards.

Monsoons are crucial elements of the global circulation and monsoon rainfall provides the water needed by over 60% of the world’s population. Understanding and predicting how monsoons may change from year to year, and the result of global warming are key scientific, economic and societal issues. The management of water resources is a top priority for monsoon-affected countries to enable the population to survive from one rainy season to the next. Food production in seasonally arid areas is also inherently risky. By the end of the dry season, the soil is parched and planting cannot begin until the rains arrive. A late or weak monsoon can lead to a short or poor growing season and hence low yields. Agricultural failure has a profound effect on the economy of monsoon-affected countries, such as India, where farming accounts for 30% of the gross domestic product and 67% of the workforce.

---

**Figure 6** Mean winds at 700 hPa for northern winter (January–February; upper panel) and northern summer (July–August; lower panel) at the height of the monsoon season (units: m s$^{-1}$). (Data source: Reanalyses from European Centre for Medium Range Weather Forecasts for 1979–93.)
Dynamical Theory

P J Webster and J Fasullo, University of Colorado – Boulder, Boulder, CO, USA
Copyright 2003 Elsevier Science Ltd. All Rights Reserved.

Elements of a Monsoon Circulation

A monsoon is a circulation system with certain well-defined characteristics. During summer, lower tropospheric winds flow toward heated continents away from the colder oceanic regions of the winter hemisphere. In the upper troposphere the flow is reversed, with flow from the summer to the winter hemisphere. Precipitation generally occurs during summer, centered in time on either side of the summer solstice and located over the heated continents and the adjacent oceans and seas in the vicinity of a trough of low pressure referred to as the ‘monsoon trough’. Most summer rainfall is associated with synoptic disturbances that propagate through the region. However, these disturbances are grouped in periods lasting from 10 to 30 days. Such envelopes of disturbed weather and heavy rainfall are referred to as ‘active periods of the monsoon’. The intervening periods of mini-drought are referred to as ‘monsoon breaks’. The location of the monsoon trough and axis of heavy monsoon precipitation is generally well poleward of the position of the oceanic intertropical convergence zone (ITCZ), within which the majority of tropical oceanic precipitation occurs. For example, the rainfall associated with the South Asian monsoon falls at the same latitudes as the great deserts of the planet.

Monsoon systems are associated with colocated pairs of continents such as Asia and Australia, or continents straddling the Equator such as north-west and south-west Africa, and North and South America defining, respectively, the Asian–Australian monsoon system, the West African monsoon, and the American monsoon. Each system is different in terms of intensity and circulation characteristics. For example, the northern arm of the American monsoon is a relatively weak counterpart of the other major monsoon systems and there does not appear to be a discernible cross-equatorial component during the summer. In that sense, the North and South American monsoons may be thought of as almost separate entities. Rainfall that occurs over the continents that span the Equator (e.g., equatorial Africa and South America, and Indonesia) is not strictly monsoonal and possesses double rainfall maxima occurring with the equinoxes. Monsoon climates, on the other hand, possess a single solstitial rainfall maximum, while solstices demark the dry seasons for equatorial climates.

Basic Driving Mechanisms of the Monsoon

It is helpful to consider first a simple prototype geography that will allow us to identify the basic elements of a monsoon system. The geographical model we adopt is an oceanic planet with a continental cap extending from the subtropics to the pole in one hemisphere. After establishing the important processes that drive the monsoon for this simple geography, we will return to the consideration of local influences.

Monsoons arise from the development of cross-equatorial pressure gradients produced or modified by the following physical properties of, or processes associated with, the land–ocean–atmosphere system: differential heating of land and ocean produced by the different heat capacity of land and water; the different manner in which heat is transferred vertically and stored in the ocean and the land; modification of differential heating by moist processes; the generation of meridional pressure-gradient forces resulting from the differential heating; and the meridional transport of heat in the ocean by dynamical processes. Each of these processes and properties has to be considered relative to the rotation of the planet, and the influence