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"Climatic Asymmetries Relative to the Equator"

G. PHILANDER
Princeton University
Princeton, New Jersey
USA

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Climatic Asymmetries relative to the Equator

S.G.H.Philander
T. Li
G. Lambert
R.C.Pacanowski[*]

Atmospheric and Oceanic Sciences Program
Princeton University, Princeton,N.J.
[*]Geophysical Fluid Dynamics Laboratory/NOAA
Princeton, N.J.

Although solar radiation is symmetrical about the equator and has a maximum there, the coast of Panama is a tropical jungle with plentiful rainfall, whereas the coast of Peru, at the same latitudes but south of the equator, is a barren desert. Such climatic asymmetry is present in both the eastern tropical Pacific and Atlantic, regions with a surprisingly prominent annual (rather than semi-annual) cycle at the equator even though the sun "crosses" that line twice a year. These curious features , evident in figure 1, depend on the global distribution of continents, on the coastal geometries of western Africa and the Americas, and on unstable interactions between the ocean and atmospheree, interactions that involve low-level stratus clouds.

In a world that is perfectly symmetrical about the equator, the climate could nonetheless be asymmetrical if symmetrical conditions were unstable to perturbations. But why would the processes that lead to asymmetries be more effective in some longitudes than others? Why are asymmetries in sea surface temperatures , rainfall and cloudiness most prominent in the eastern tropical Pacific and Atlantic Oceans? Figure 1(a) shows that the northern rather than southern hemisphere is favored with the warmest waters. Why is that hemisphere, which also has the heavier rains, favored over the other? The answers to these questions must involve the distribution and the geometries of the continents but first we need to investigate the processes that can convert symmetric conditions into asymmetric ones.

From an atmospheric point of view, the climatic asymmetries of the eastern tropical Pacific and Atlantic can be attributed to the asymmetry in sea surface temperatures. Atmospheric convection that involves rising air, cumulus towers and heavy rains occurs over the warm waters off Panama, not the very cold waters off Peru. The rising air is sustained by convergent low-level winds. From an oceanic point of view those winds cause the observed sea surface temperature pattern. The northward winds that prevail south of the convective region drive oceanic currents with a northward component. That component is small far from the equator because the Coriolis force deflects the wind-driven currents. As the equator is approached, and the Coriolis force becomes small, the northward component of the currents gains in speed and attains a maximum at the equator where the Coriolis force vanishes. This means that the northward currents are divergent south of, convergent north of the equator. They therefore cause the upwelling of cold water, and cause low sea surface temperatures, south of the equator but are responsible for downwelling and warm surface waters north of the equator[1,2] Hence the winds determine the surface temperature patterns. They also depend on those patterns, as explained earlier. This circular argument suggests that interactions between the ocean and atmosphere are at the heart of the matter. Similar interactions influence the ocean-atmosphere response to seasonal variations in solar radiation in the eastern equatorial Pacific and Atlantic but not the Indian Ocean. This can be inferred from the high correlations evident in figures 1 (c and d) which show seasonal variations in the sea surface temperature, and the zonal component of the wind, at two locations on the equator: at 110°W in the eastern Pacific and at 30°W in the Atlantic. Once again it appears that the winds both cause and are caused by the sea surface temperature variations. Intriguingly, this is the case where climatic asymmetries are large but is not the case at the island Gan in the Indian Ocean. There the correlation between the zonal wind and sea surface temperature is low, a semi-annual harmonic is dominant, and the annual harmonic is minimal (figure 1b). What is special about the eastern tropical Pacific and Atlantic for those to be the preferred regions of ocean-atmosphere interactions? How do those interactions give rise to an annual harmonic at the equator?

The ocean-atmosphere interactions[3] that are relevant to the phenomena under consideration here have the following effect on a perturbation to symmetric conditions, a perturbation that displaces the warmest waters, initially at the equator, slightly northward (say). The southerly winds that converge onto the displaced warm waters (where the air rises into convective clouds) causes low sea surface temperatures south of the equator, cold surface waters north of the equator for reasons mentioned above. The resultant sea surface temperature gradient creates pressure gradients in the lower atmosphere that intensify the northward winds[4] which in turn strengthen the temperature gradient and so on. In this positive feedback, divergent surface currents cause a decrease in sea surface temperatures[3]. The feedback is therefore most effective where the thermocline is shallow. (The thermocline is the layer of large vertical gradients that separates the warm surface waters from the cold water at depth.) The thermocline happens to be shallow in the eastern tropical Pacific and Atlantic

Oceans because the Trade winds that prevail over the Atlantic and Pacific drive the warm surface waters westward and expose cold water to the surface in the east. Hadley explained why such winds would prevail in the tropics on a water covered globe. (The conservation of angular momentum requires westerlies in the earth's middle latitudes, easterlies in the tropics.) The extent to which the presence of continents modifies the Trades is minimal over the tropical Atlantic and Pacific Oceans but is enormous in the Indian sector where cross-equatorial monsoons are the dominant winds. (Depending on the season, they blow to or from the Indian subcontinent whose seasonal temperature fluctuations are much more extreme than those of the adjacent ocean.) Because of the monsoons, the thermocline in the Indian Ocean is essentially uniformly deep along much of the equator. Hence the global distribution of continents, by determining where Trades and where monsoons prevail, determines where the equatorial thermocline is shallow -- in the eastern tropical Pacific and Atlantic -- and hence where air-sea interactions can create climatic asymmetries. Those interactions favor neither hemisphere. Why then are warmest waters north rather than south of the equator?

Asymmetries of the time-averaged state

To investigate the specific aspects of the continental geometry that cause climatic asymmetries we start with a General Circulation Model of the atmosphere that reproduces realistic surface winds if the observed sea surface temperature patterns are specified as a lower boundary condition[7]. In the following numerical experiments, in which the annual mean solar radiation is specified as forcing function, the model calculates the winds when sea surface temperature is strictly a function of latitude and is symmetrical about the equator. (The specified sea surface temperatures correspond to the time-averaged temperatures observed along the date-line and in the northern hemisphere.) The continents are deformed in various ways as shown in figure 2 and the land is assumed to be flat in all the calculations to be described here. In figure 2(b) the shape of the continents is idealized so that coastlines are either lines of longitude or circles of latitude. In such a world, climatic asymmetries persist in the eastern tropical Atlantic because of the bulge of west Africa. Although the solar radiation is symmetrical about the equator, the west African land surface attains a temperature far higher than that of the ocean to the south. This contrast is similar to that which causes a land-sea breeze or the monsoons. In figure 2 (b) the winds over the eastern equatorial Atlantic are seen to aquire a component towards the bulge, a component that is absent from the winds over the eastern equatorial Pacific. In this model, with specified sea surface temperatures, the modification to the winds is modest but it could be amplified considerably if the winds were allowed to influence the ocean. The northward winds can cause oceanic upwelling and cold surface waters, not only to the south of the equator as explained earlier, but especially along the southwestern coast of Africa where they drive northward oceanic currents that the Coriolis force deflects off-shore. That deflection induces coastal upwelling and low sea surface temperatures. A decrease in sea surface temperatures magnifies the land-sea contrast which intensifies the northward winds, causing even lower sea surface temperatures and so on.

In figure 2(b), the Pacific Ocean has practically no asymmetry in the winds. We next explore whether the asymmetry that exists in reality could be caused by the greater land area of the northern hemisphere. To eliminate possible effects of the local coastal geometry, we changed the Americas in such a way as to preserve the land area of each latitude while making the western coast coincide with a line of longitude. In such a world, shown in fig 2(a), the winds over the eastern tropical Pacific do not appear to acquire any asymmetry that the various feedbacks mentioned earlier could amplify. In this model, at least, the climatic asymmetry of the eastern Pacific is not attributable to the greater land area of the northern hemisphere.

The final experiment explores how the inclination of the western coast of the Americas to lines of longitude affects the winds. Although a comparison of figures 2 (b and c) indicates that the winds over the tropical Pacific hardly change when the coast is inclined, that view is a strictly atmospheric one. From an oceanographic point of view there is a critical change when the coast is inclined: the northeast Trades to the north of the equator become essentially perpendicular to the coast while the southeast Trades to the south of the equator are parallel to the coast. It is well-known that winds parallel to a coast drive an oceanic jet in that direction. Because of the Coriolis force, the flow veers offshore so that cold water from below rises to the surface. That can happen south of the equator where the wind is parallel to the inclined coast but not to the north where the wind is perpendicular to the coast. Thus the winds will cause the surface waters to be cold off the coasts of Ecuador and Peru, warm off the coast of Panama.

In principle ocean-atmosphere interactions ought to amplify the modest asymmetries introduced by continents when sea surface temperatures are symmetrical about the equator. However, calculations with a coupled ocean-atmosphere model (which previously was used in realistic simulations of the Southern Oscillation and El Nino8) indicate that the interactions mentioned earlier are not very effective amplifiers, not unless another feedback involving stratus clouds is taken into account. Decks of low-level stratus clouds cover the oceans off the coasts of Peru, California and Angola. Whereas the deep convective clouds over the warmest waters are associated with the release of substantial amounts of latent heat that drive atmospheric motion, the stratus clouds over the cold water are so shallow and thin that they merely increase the albedo of the earth. They are nonetheless important for the maintenance of the climatic asymmetries because they are involved in a crucial feedback. The clouds depend on the vertical temperature gradient of the lower atmosphere and become more dense the colder the sea surface. Enhanced cloudiness shields the ocean from solar radiation, causes even lower sea surface temperatures, and thus leads to more cloudiness and so on. Although our atmospheric model satisfies most of the conditions for the clouds to form -- a temperature inversion in the lower atmosphere and subsiding air aloft -- its vertical resolution is too coarse for the humidity to reach a critical value for stratus clouds in any one layer. An empirical formula for cloudiness in terms of the vertical temperature gradient and subsidence in the lower troposphere -- it was derived on the basis of satellite and other measurements -- was adopted to enable the model to take the clouds into account. A coupled ocean-atmosphere model with such stratus clouds, forced with the annual mean solar radiation which is symmetrical about the equator, reproduces a reasonably realistic asymmetrical climate as shown in figure 3 (Philander et al, manuscript submitted).

The annual cycle at the equator

Various factors can cause an annual cycle on the equator. One is the ellipticity of the earth's orbit which causes the earth to be closest to the Sun in January, furthest in July. Another is the asymmetry of the continents relative to the equator. (We just found that that asymmetry can give an asymmetric response to symmetric forcing.) A third possibility is the asymmetry of the time-averaged climate. To explore these possibilities, we rely on a simplified coupled ocean-atmosphere model, similar to that of Cane and Zebiak[9,10], in which the time-averaged states of the ocean and atmosphere are specified. The forcing is seasonally varying solar radiation with a time-average that is zero. Our results (Li and Philander, manuscript submitted) indicate that by far the most important reason for the annual cycle at the equator is the asymmetry of the time-averaged state. Consider for example how the response to the seasonal forcing changes when the time-averaged winds change from being symmetrical about the equator to asymmetrical. If the winds are symmetrical, then their meridional component, on the average, vanishes at the equator; it is southward during the southern summer, northward during the northern summer. (That is the case in the Indian Ocean.) However, if the time-averaged winds at the equator are northward, as they are in the eastern Pacific and Atlantic, then a superimposed seasonal cycle causes intense northward winds (in August), weak northward winds in (February). Hence the wind speed at the equator can have an annual cycle and, because wind speed controls evaporation from the ocean, surface temperatures too can have an annual cycle. Figure 4 shows the seasonal variations of sea surface temperature in our model when a realistic, asymmetrical time-averaged state is specified, and when the forcing is strictly anti-symmetrical about the equator. The dotted line is the result when, in the oceanic component of the model, only evaporation affects sea surface temperatures. The effects of oceanic upwelling are included in the solid line of figure 4. The dashed line, which has a realistic amplitude for the annual cycle at the equator, is obtained when the model takes into account that the cold surface waters favor the formation of low-level stratus clouds which lower temperatures further. A prominent (and realistic) feature of the simulation is a signal (in sea surface temperature and the zonal component of the wind) that propagates westward at 60 cm/sec along the equator. This signal involves ocean-atmosphere interactions that are symmetrical about the equator[3].

In summary, climatic asymmetries relative to the equator depend on several factors. First the global distribution of continents determines where monsoons and where Trade Winds prevail and hence determines variations in the depth of the warm surface layer of the ocean. In regions where the surface layer is shallow, ocean-atmosphere interactions plus a variety of feedbacks including ones that involve stratus clouds, amplify modest perturbations that introduce asymmetries about the equator. The most important sources of asymmetric perturbations are the west African bulge to the north of the equator in the Atlantic, and the slope, relative to a meridian, of the western coast of the Americas in the Pacific. Asymmetric time-averaged conditions permit a non-zero response at the equator to annual variations in solar radiation that vanish at the equator. Two factors that could affect climatic asymetries of the time-averaged state were ignored in these calculations and remain to be explored: mountains, especially the Andes and Himalayas, and the effect of the seasonal cycle on time-averaged conditions. Both are likely to be very important in the Indian sector.

Figure Captions

Figure 1(a) Time-averaged sea surface temperatures for the period 1950 to 1979[11]. The contour interval is 1 °C. Dashed contours are 27°C and 29°C. In the lower panels the solid lines are for sea surface temperature in degrees Centigrade; the dashed lines are for the zonal component of the windstress in dynes/cm^2 . Time, in units of a month, starts on 1 January in all three cases. The measurements were made on the equator at (b) the island Gan in the Indian Ocean (70° W) by Knox[12] starting in 1973; (c) at 110° W in the eastern Pacific by Halpern[13] and McPhaden and McCarty[14] starting in 1985; and (d) at 30°W in the Atlantic by Weingartner and Weisberg[15] starting in 1983.

Figure 2. Surface wind vectors as calculated by an atmospheric General Circulation Model, for different continental geometries. The specified sea surface temperatures vary only with latitude and correspond to those observed along the date line.

Figure 3. Sea surface temperatures as simulated by a coupled ocean-atmosphere model forced with the time-mean solar radiation. The contour interval is 1 °C and temperatures exceeed 28°C in the shaded area. The model includes a parameterization for stratus clouds.

Figure 4. Seasonal variations in sea surface temperatures (in degrees Celsius) at 0°N 100°W as simulated with a coupled ocean-atmosphere model in which the specified time-mean state is realistically asymmetrical relative to the equator. The sea surface temperature variations are determined strictly by evaporation in the case of the dotted line, by evaporation and oceanic upwelling in the case of the solid line, and by evaporation, upwelling and the presence of low-level stratus clouds in the case of the dashed line. The forcing is that component of the annually varying solar radiation that is strictly antisymmetrical about the equator. In this model the western coast of the Americas coincides with a meridian.

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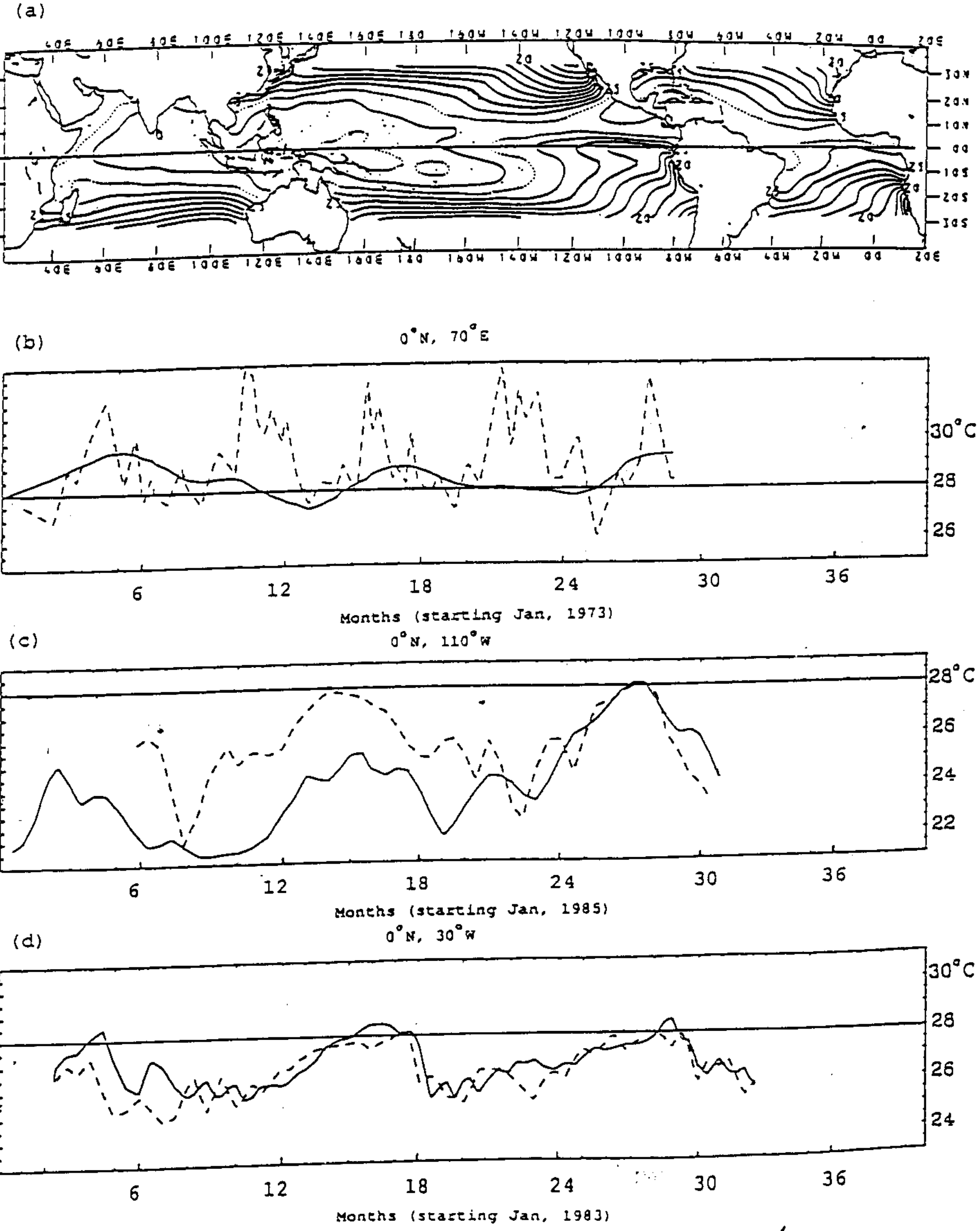(a)
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Months (starting Jan, 1973)
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Months (starting Jan, 1985)
(d)
0°N, 30°W
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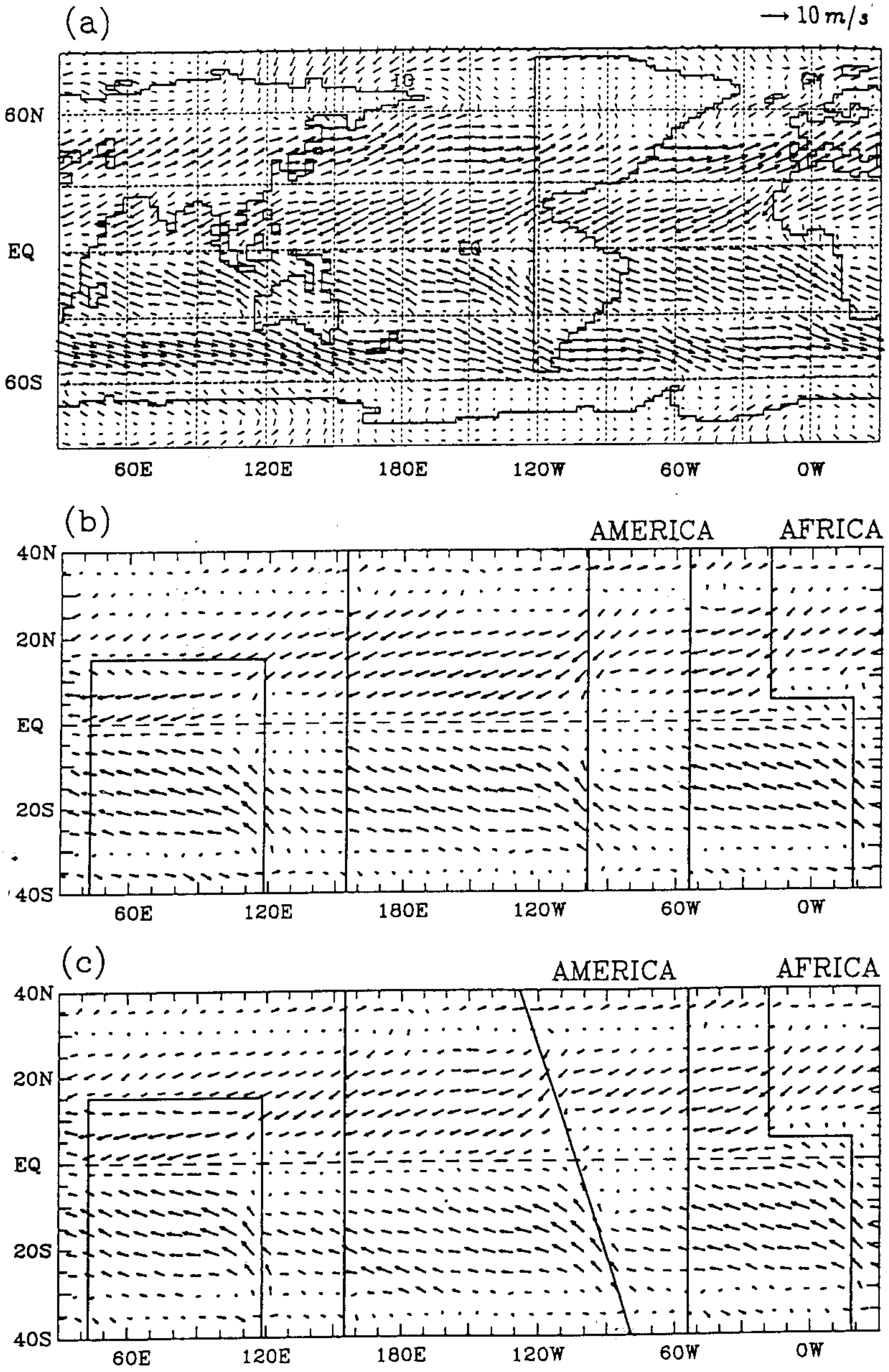
Months (starting Jan, 1983)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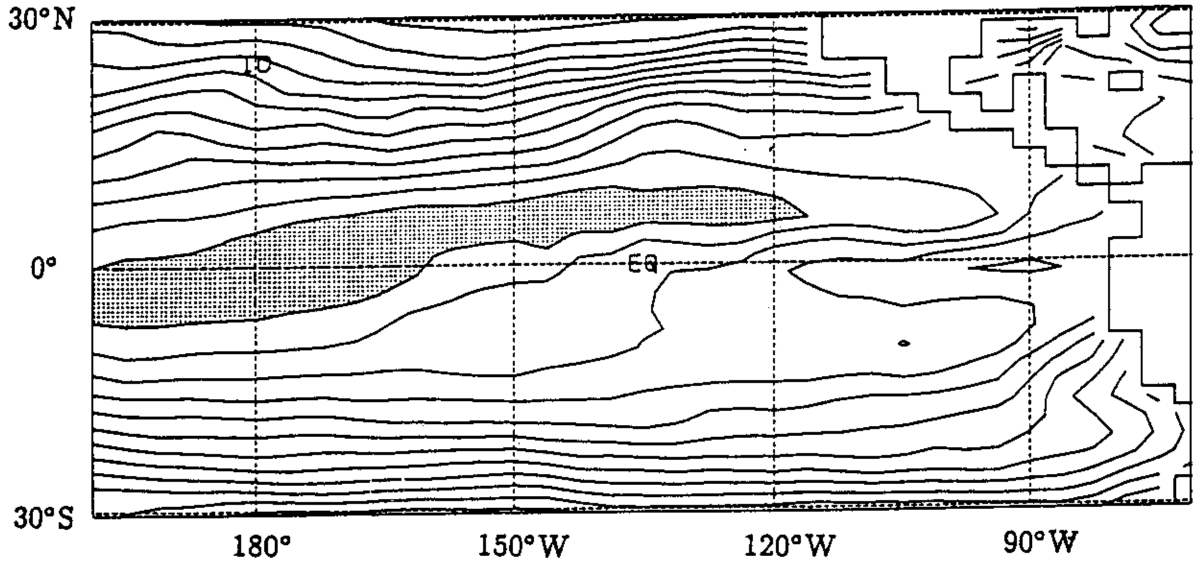
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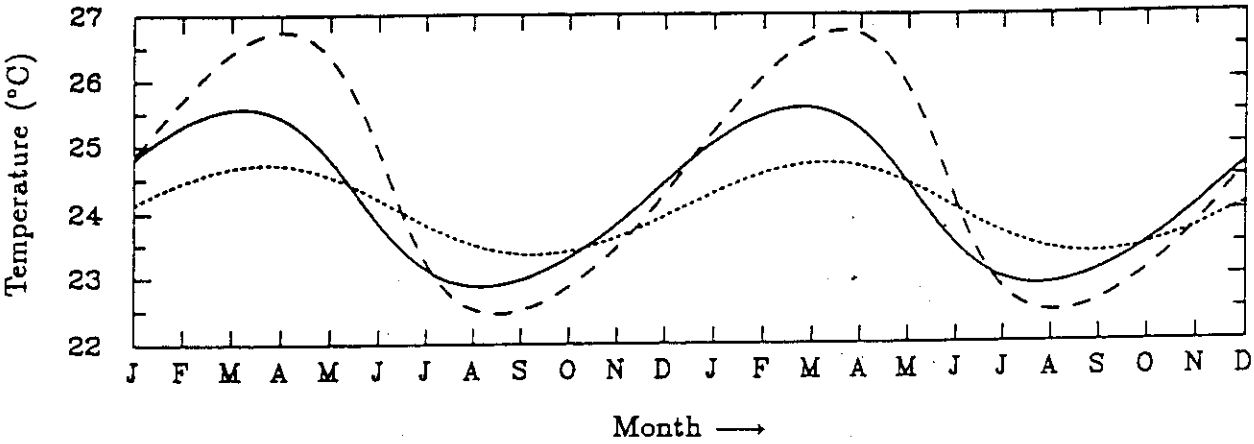
Temperature (°C)
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