Pressure-Wind Relationships in the Equatorial Surface Westerlies

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ABSTRACT

Seasonally persistent westerly winds at the surface in the vicinity of the equator from 40E to 170E longitude are shown to be the generally predictable result of a geostrophically appropriate pressure gradient at latitudes higher than about 5° north or south, and a negative value of the second derivative of the pressure with latitude within about five degrees latitude of the equator. Existing empirical equatorial wind-pressure relationships are shown to be specific cases of these general relationships. The initiating mechanism for equatorial westerlies seems to be a movement of the equatorial trough more than five degrees of latitude from the equator.

1. Introduction

The existence of climatologically persistent westerly winds in the immediate vicinity of the equator had long been considered an anomalous and almost paradoxical situation, since it contradicted what appeared to be the normal confluence of easterly trade winds from both hemispheres and the asymptotic limits of the geostrophic wind-pressure relationship in the equatorial trough. Early explanations of the westerly regime, seemingly constrained by its observed close connection with the Indian monsoon, depended nearly exclusively on the changing sign of the Coriolis parameter with the cross-equatorial flow component provided by the continuous northward pressure decrease in the Arabian Sea in early summer.

More recent analyses of equatorial and tropical circulation systems have generally not dealt with equatorial westerlies *per se* but have rather considered the interaction of basic flow patterns relative to the generation and intensification of tropical vortices. Riehl (1948) makes such an assumption in discussing possible modes of typhoon formation both in the easterlies of the trade wind region and in the equatorial westerlies themselves. Palmer (1951) states that, at least in the western Pacific, equatorial westerlies are a consequence of vortex formation, and their appearance in averaged data is simply a statistical result, not necessarily a realized steady-state condition. Flohn (1960) explained the westerlies as a climatological result of the summer monsoon flow being turned eastward south of the equator, and the winter monsoon flow being turned eastward north of the equator so that in all seasons the cross-equatorial flow has a component from the west.

An alternate approach to the specific question of equatorial westerlies is a theoretical examination of wind-pressure relationships as the Coriolis parameter goes to zero. This however, has produced mixed results that often depend upon assumptions of highly artificial pressure distribution or upon extremely precise specifications of the initial conditions.

Crossley (1948) and Grimes (1951)—a summary of earlier work—obtained a pseudogeostrophic relationship valid in equatorial regions, in which the dynamic pressure and the absolute vorticity took the place of the pressure and the Coriolis parameter. Hollmann (1955) investigated the ageostrophic flow induced near the equator by a strictly zonal pressure gradient, and found that equatorward geostrophic flow invariably produced westerlies on the equator. Flohn (1955) presented an empirical correlation of precipitation and the zonal component of the wind consistent with the equatorial constraints on the equation of motion. H. Lettau (1956) examined the dynamics of high-level equatorial westerlies in terms of an interaction of adiabatic warming and a convergence of turbulent kinetic energy. Vander Elst (1960) considered the effect of inertial oscillations in equatorial wind fields, and concluded that westerlies were much more stable than equatorial easterlies.

Schmitz (1961), in defining conditions under which a stationary zonal current could exist on the equator, found that quasi-geostrophic westerly flow required an equatorial ridge, a result obtained empirically by Johnson and Morth (1960) from East African contour analyses. Rosenthal and Reeves (1967) in computing height patterns for specified wind fields found that these empirical wind-pressure relations could be generated through the use of appropriate wave parameters, but that in general it was difficult to devise pictorial models of the wind-pressure relationship in low latitudes.

While most of these analyses predict specific relationships between the wind field or streamline pattern and the height or pressure pattern, very little observational evidence is adduced to substantiate the theoretical predictions. To a large extent this is due to the fact that equatorial pressure observations are spatially not well distributed, and that synoptic-scale variations are small and often swamped by tidal and seasonal variations. Consequently, the data limitations often preclude any direct comparison on a quasi-instantaneous or synoptic time scale. It is, however, conceivable that the more precisely established mean equatorial flow pattern has a predictable relationship to the mean pressure pattern, and that if in addition the wind components can be expressed as linear functions of spatial derivatives of the pressure field, the observed relationships between the average conditions should also hold for synoptic and other short time scales.

2. The equations of motion

With the assumption of steady state flow in an inviscid hydrostatic atmosphere the equations of motion can be expressed as

$$\mathbf{V}\cdot\nabla u=-\alpha\frac{\partial p}{\partial x}+vf-wf' \tag{1}$$

$$\mathbf{V}\cdot\nabla v=-\alpha\frac{\partial p}{\partial y}-uf \tag{2}$$

$$\mathbf{V}\cdot\nabla w=uf', \tag{3}$$

where $\mathbf{V}$ is the three-dimensional velocity vector with components u, v, w; α is the specific volume of air; p is the atmospheric pressure, and f and f' are the Coriolis parameters appropriate to, respectively, a specified latitude and its co-latitude. At the equator as f goes to zero and f' reaches its maximum value, the equations indicate a balance between inertial terms, pressure gradient terms, and normally neglected Coriolis terms.

Some attempts have been made to use Eq. (3) directly (e.g., Flohn, 1955), since it has neither a singularity at the equator nor an explicit dependence upon the pressure distribution. It does, however, introduce a scale problem since it equates the order of magnitude of ∇w to that of the Coriolis parameter, so that $\partial w/\partial x$, for example, takes on values of the order of 1 m sec^{-1} per 10 km, which are much more appropriate to cumulus convection dynamics than to the longitudinally extended westerly regime.

Equations (1) and (2) introduce similarly troublesome scale considerations in an equatorial context when f goes to zero, although qualitatively, since $\partial p/\partial x$ is ordinarily an order of magnitude smaller than $\partial p/\partial y$ and of the same order as wf', it seems clear that horizontal gradients of the zonal wind can be expected to be much smaller than horizontal gradients of the meridional wind component; hence any region of westerly winds on or near the equator could very well be longitudinally extended, but should only be of limited latitudinal range.

A second difficulty related to the predictability of equatorial flow lies in the fact that the inertia terms include products of velocity components and gradients of velocity components, thus violating a basic principle that locally observable effects are produced by locally acting causes. This may lie at the root of the observation by Rosenthal and Reeves (1967) that only slightly differing flow fields generated widely differing contour patterns.

Since the equations of motion do not directly lead to useful results, we can apply Birkhoff's (1960) intuitively plausible hypothesis that the functions of rational hydrodynamics can be freely integrated, differentiated, and expanded in series or integrals. Assuming equilibrium conditions and constant density, differentiating Eqs. (1), (2), and (3) with respect to y produces

$$\alpha\frac{\partial}{\partial y}\left(\frac{\partial p}{\partial x}\right)=v\beta+f\frac{\partial v}{\partial y}-w\beta'-f'\frac{\partial w}{\partial y} \tag{4}$$

$$\alpha\frac{\partial}{\partial y}\left(\frac{\partial p}{\partial y}\right)=-u\beta-f\frac{\partial u}{\partial y} \tag{5}$$

$$0=u\beta'+f'\frac{\partial u}{\partial y}, \tag{6}$$

where β is defined as $\partial f/\partial y$ and β' as $\partial f'/\partial y$. In the vicinity of the equator, β depends only slightly on latitude and may be taken as equal to 2.3×10^{-13} cm^{-1} sec^{-1}, while β' is very nearly zero. With the further assumption that horizontal gradients of velocity components are negligibly small these equations may be summarized as

$$\alpha\nabla_h\left(\frac{\partial p}{\partial y}\right)=-\beta\mathbf{k}\times\mathbf{V}_g, \tag{7}$$

where $\mathbf{V}_g$ represents a horizontal equatorial geostrophic wind vector.

The derivation of Eq. (7) is quite straightforward and not particularly novel. It has, however, only rarely been tested with actual near-equatorial data. Jerlov (1953) applied it directly in a study of the equatorial countercurrent in the eastern Pacific and found that the velocities predicted were appreciably higher than those observed. H. Lettau (1956) took the vertical derivative of Eq. (7), expressed in terms of the temperature distribution in a hydrostatic atmosphere, to show that the observed high-altitude equatorial temperature field corroborated the existence of high-altitude westerlies. B. Lettau indicated that the climatological onset of large-scale northward cross-equatorial flow along the east coast of Africa coincided with the establishment of large positive values of $\partial^2 p/\partial x\partial y$ over the Arabian Sea.[1] In both cases the qualitative agreement was generally limited to

[1] B. Lettau, "Stream Function Analysis of the Indian Summer Monsoon," presented at the 5th Technical Conference on Hurricanes and Tropical Meteorology, 20–28 November, 1967, Caracas, Venezuela.

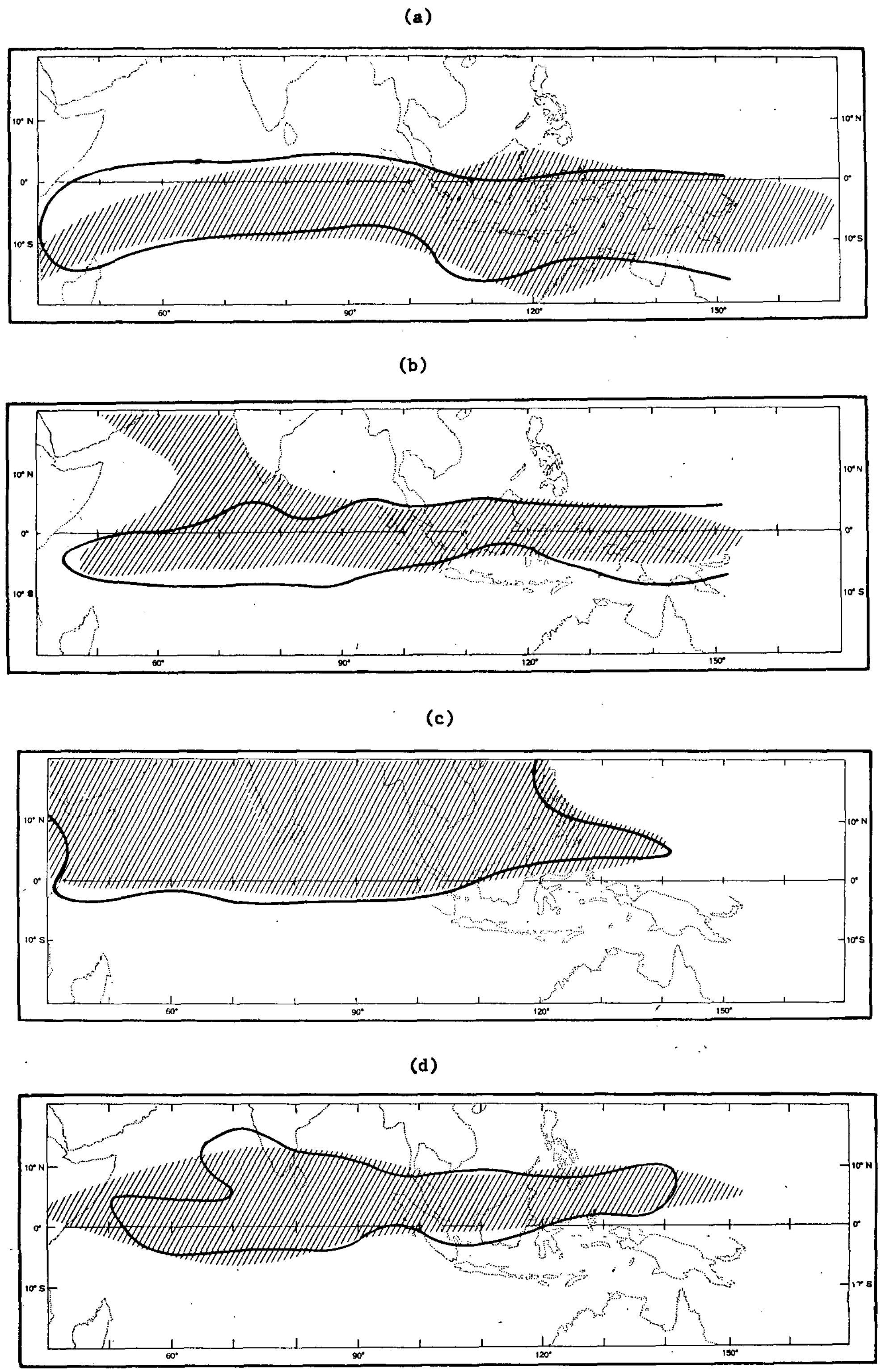


FIG. 1. The geographical distribution of observed westerly wind components at 900 mb (shaded) and 850 mb (solid line). a) January, b) April, c) July, d) October.

order-of-magnitude calculations, indicating however that even the spotty surface pressure data available should be sufficient to delineate the regions of equatorial surface westerlies.

3. The geographic extent of surface westerlies near the equator

While surface westerlies are found in three separate equatorial regions, in the Gulf of Guinea and over western equatorial Africa, in the eastern Pacific Ocean east of 120W, and in the Indian Ocean and western Pacific, the first two are relatively small and seasonally variable in extent. However, the Indian Ocean—western Pacific region extends from roughly 40E to 160E, persists through the year, and is anchored in summer at its western end by the distinctive summer monsoon wind pattern and pressure distribution. Primarily because of these three factors the present analysis will be restricted to that region.

The latitudinal extent of the westerly regime is presented in Fig. 1 for the months of January, April, July, and October. The gradient level winds (app. 900-mb) were obtained from Atkinson and Sadler (1970), and the 850-mb level winds from Ramage and Raman (1972). The indicated limits of the westerlies are determined by the equatorial locus of $u=0$.

It is clear that the westerly regime is in fact an equatorial one since in the absence of the disturbing influences of large land masses, the westerlies are confined to the zone between 10N and 10S latitude. At the time of the Indian summer monsoon the equatorial westerlies do merge with the geostrophic westerlies at higher latitudes to produce a latitudinally extended regime; however, the governing mechanisms must be different since geostrophic flow cannot persist into equatorial regions. The discrepancy between the two data sources in April in the region between 60E and 75E, and 10N and 25N is not particularly serious: the flow is largely meridional, with the streamlines drawn somewhat east of north in the 850-mb analysis, but somewhat west of north in the gradient level analysis, thus producing the isthmus of westerlies.

No distinction has been made in these figures between a latitudinal change in the sign of the zonal wind component due to succession of cyclonic vortices and cols, and that due to a downstream varying wind direction in an *equatorial buffer zone* (Conover and Sadler, 1960). In the first case the latitudinal wind shear is high and quasi-discontinuous, while in the second it is low and continuous as the zonal wind goes through zero. It appears that the occurrence of a line of vortices or a buffer zone is more directly related to the horizontal pressure distribution, and will be discussed in that context.

In January the region of westerlies is displaced into the Southern Hemisphere, and is bounded on the north by recurving monsoon flow and deflected Northern Hemisphere trade winds, and on the south by deflected Southern Hemisphere trade winds in the South Indian Ocean and a line of vortices over the northern coast of Australia. In April the meridional extent of the westerlies is reduced, and nearly its entire boundary consists of lines of equatorial vortices. The region is centered very nearly on the equator.

In July the region of equatorial westerlies is displaced into the Northern Hemisphere and merges with the geostrophic flow at higher latitudes. It is bounded on the south by recurving monsoon flow originating in the Southern Hemisphere which becomes westerly very nearly on the equator. The eastward extent of the equatorial westerlies reaches its minimum at about 140E; however, in the west the equatorial westerlies merge with the continental westerlies of Africa.

In October the region of equatorial westerlies is again well defined, but still displaced somewhat into the Northern Hemisphere. It is bounded on the south by deflected Southern Hemisphere trade winds, and on the north by a line of equatorial vortices. The maximum wind speeds observed in the equatorial westerlies occur at this time, with mean speeds in excess of 5 m sec^{-1} observed between 65E and 90E.

The differences between the two data sets in delineating the region of equatorial westerlies, with the one exception mentioned previously, are minimal and unimportant for the purpose of this study, and are largely the result of different interpolation techniques in data-sparse regions. Both sets indicate that surface westerlies are a non-transient, stationary, feature of the equatorial atmosphere, and must therefore exist in a pseudo-geostrophic framework.

4. The equatorial pressure distribution

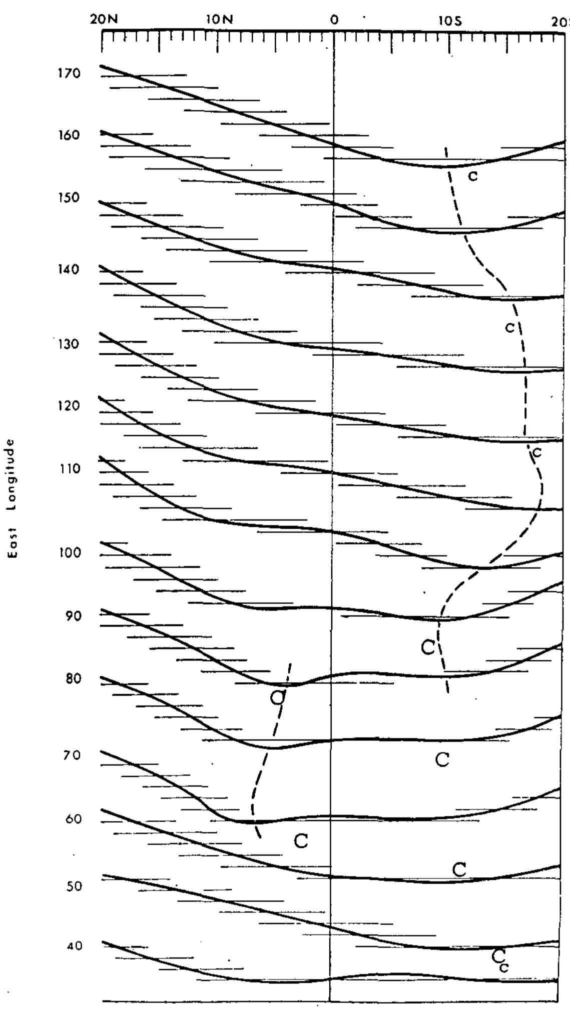
The most prominent feature of the equatorial pressure distribution is the equatorial trough—a globally extended zone of low pressure sandwiched between the subtropical high pressure belts. Historically the equatorial trough has been considered a single entity, and its longitudinal variations in position and its seasonal migrations have been extensively discussed in the literature. Unfortunately much of the discussion has been based upon longitudinal averages of pressure which effectively obliterate real regional differences and largely preclude empirical discussions of equatorial wind-pressure relationships. This submergence is particularly serious in the Indian Ocean region since it is here that deviations from the latitudinal mean position of the equatorial trough are a maximum.

The mean latitudinal profiles of the surface pressure from 40E to 170E longitude at 10° intervals for January, April, July, and October, are given in Fig. 2. The data for these profiles were taken from the *Marine Climatic Atlas of the World* (U. S. Navy, 1957). These show generally that the equatorial trough may be traced through this region, but the mean seasonal trough, as defined by Riehl (1954) for example, does not always coincide with the occurrence of lowest pressure between 20N and 20S latitude. These are definite indications that residual positions of the trough can be identified in the seasonal profiles, and that the apparent movement of the trough is the result of growth and dissipation at restricted latitudes.

In January the equatorial trough is situated between 8S and 18S, reaching its southernmost extent over northern Australia in the vicinity of 120E longitude, and coinciding quite well with the zone of equatorial vortices and the southern boundary of the equatorial westerlies. There is a secondary trough near 5N between 70E and 100E longitude with lower surface pressures than the primary trough, coinciding with a secondary region of equatorial vortices according to Ramage and Raman (1972).

In April the primary equatorial trough with its chain of equatorial vortices has moved to approximately 6S, and again defines the southern boundary of the equatorial westerlies. The secondary trough has maintained its longitudinal position, but extends northward into the Bay of Bengal between 80E and 90E longitude. The 900-mb analysis carries two cyclonic vortices at 12N, 76E, and at about 3N, 120E, along the northern boundary of the equatorial westerlies, while the 850-mb analysis carries two at about 7N, 85E and 4N, 110E. The more western of these two in each analysis lies within the Bay of Bengal extension of the equatorial trough, while the eastern ones, which are identified as equatorial vortices, and are located in the vicinity of Borneo do not correspond to a relative minimum in the latitudinal pressure distribution.

In July the equatorial trough can be traced within the equatorial region westward to about 130E longitude, but lies poleward of 20N between 120E and 40E, and the latitudinal pressure gradient is negative throughout nearly the entire region. Both analyses show a cyclonic vortex east of the Philippine Islands within the equatorial trough, and a single large persistent vortex near 65E just south of the equator. The southern boundary of the equatorial westerlies corresponds to the vestigial remnants of a Southern Hemispheric equatorial trough



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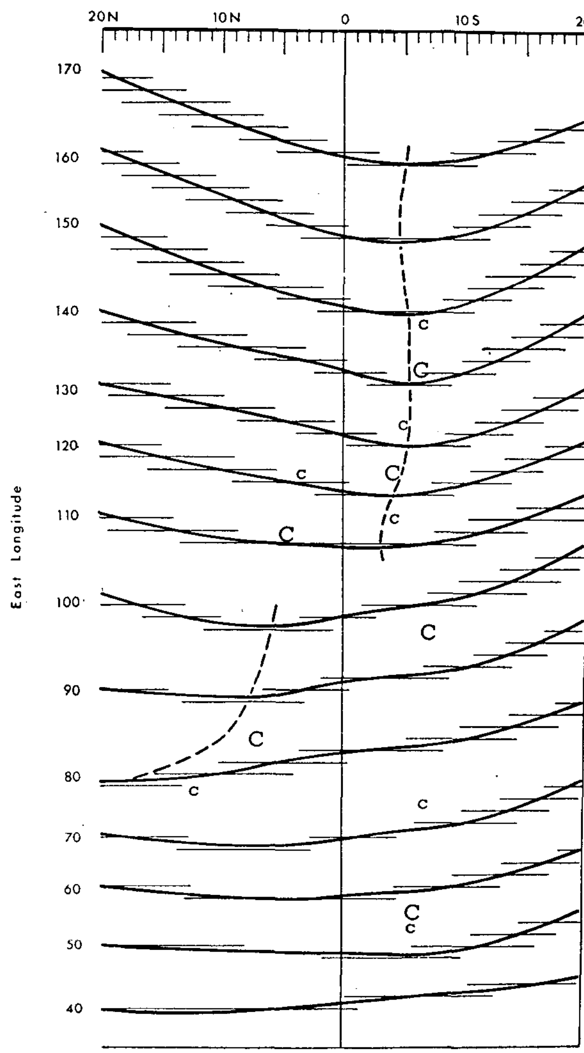

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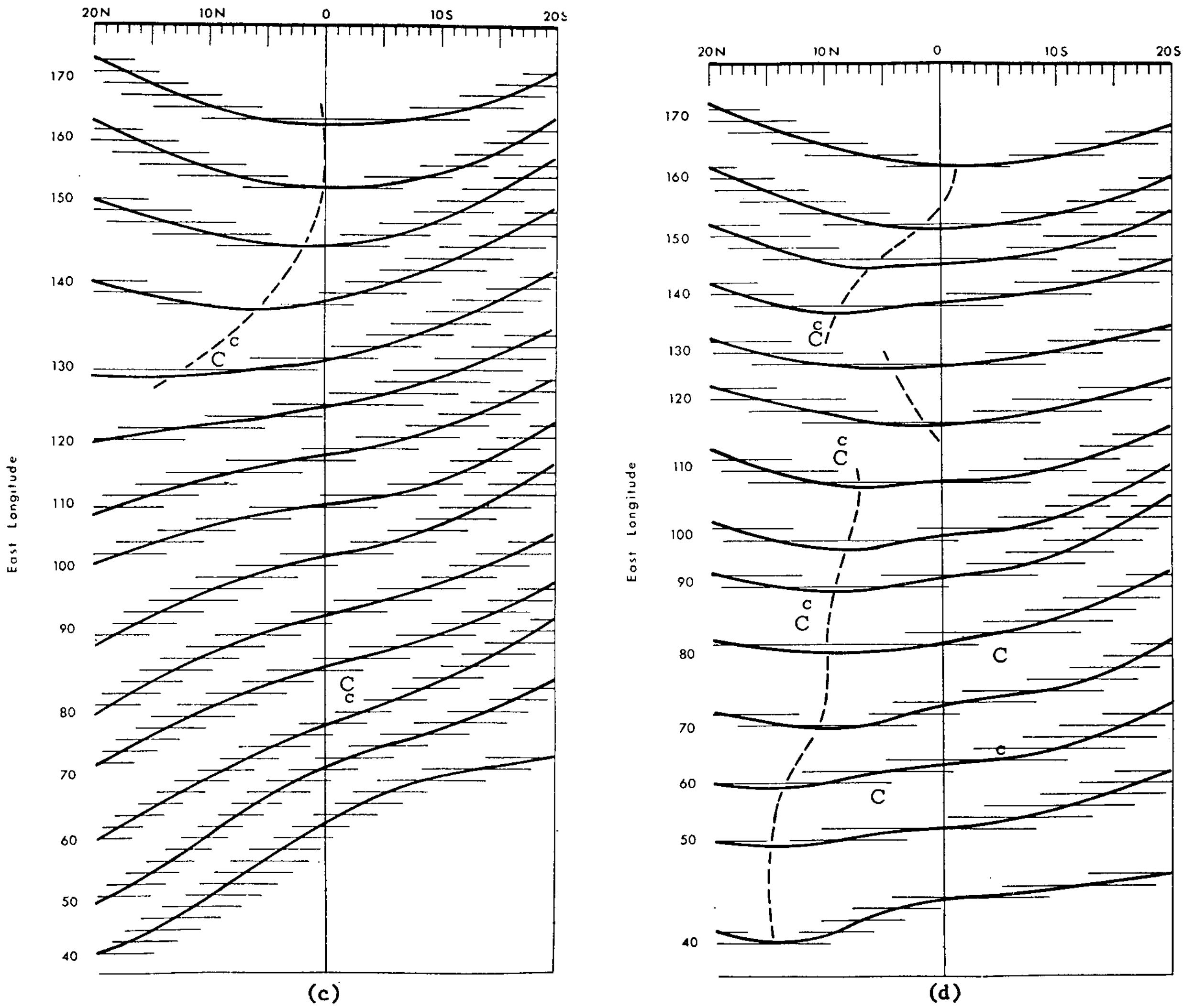


FIG. 2. The meridional pressure distribution at the indicated longitudes. The dashed line indicates the locus of lowest pressure; the symbol C indicates the location of cyclonic vortices in the streamline analysis; while the thin horizontal lines indicate increments of 1 mb. a) January, b) April, c) July, d) October.

which appears in the latitudinal pressure profiles only as an oscillation in the magnitude of the negative pressure gradient.

In October the equatorial trough is well-established in the Northern Hemisphere generally in the vicinity of 10N latitude. The single exception occurs between 120E and 130E longitude where the region of lowest pressure occurs between about 3N and the equator. An extended zone of equatorial vortices occurs with the trough and marks the northern boundary of the equatorial westerlies. The single cyclonic vortex on the southern boundary of the westerly regime, occurring at 5S, 77E in the 850-mb analysis and at 5S, 60E on the 900-mb analysis, can be traced through the intervening months to the two vortices in the July pressure distribution. Again in October these vortices mark the boundary between equatorial westerlies and easterlies, but do not coincide with a relative pressure minimum.

This examination of the seasonal pressure distributions in conjunction with the equatorial wind regime shows that the idea of geostrophic control of the zonal wind component is not a satisfactory one all the time. The association of an extended zone of cyclonic vortices at a boundary of the equatorial westerly regime with the equatorial trough is clearly consistent with a geostrophic model; however, extensive stretches of the boundary occur without a concomitant change in the sign of the pressure gradient. This is shown graphically in Fig. 3, which gives the latitudinal variation of the northward pressure gradient, together with the extent of the equatorial westerlies for each of the four months. Regions of geostrophic west winds in either hemisphere are shaded, and the boundaries of the equatorial westerly regime that are considered to be determined geostrophically are indicated by the heavy dashed lines.

In January the geostrophic regime extends along the entire southern boundary, and possibly one short segment of the northern boundary at 40E longitude. In April the geostrophic regime switches from the southern boundary from 150E to 110E longitude, to the northern boundary from 100E to 50E longitude. In July only the segment on the northern boundary from 140E to 130E longitude can be considered geostrophically determined because of the equatorial singularity, while in October most of the northern boundary is geostrophically determined the only exceptions being the segments from 110E to 130E longitude and from 50E to 40E longitude.

It is interesting to note that the geostrophically determined boundary only rarely occurs equatorward of 8° latitude, with most of the exception occurring in April. A working hypothesis may be formed from this observation; however, the equatorial limits of the geostrophic wind relationship defined in this way remain somewhat ambiguous.

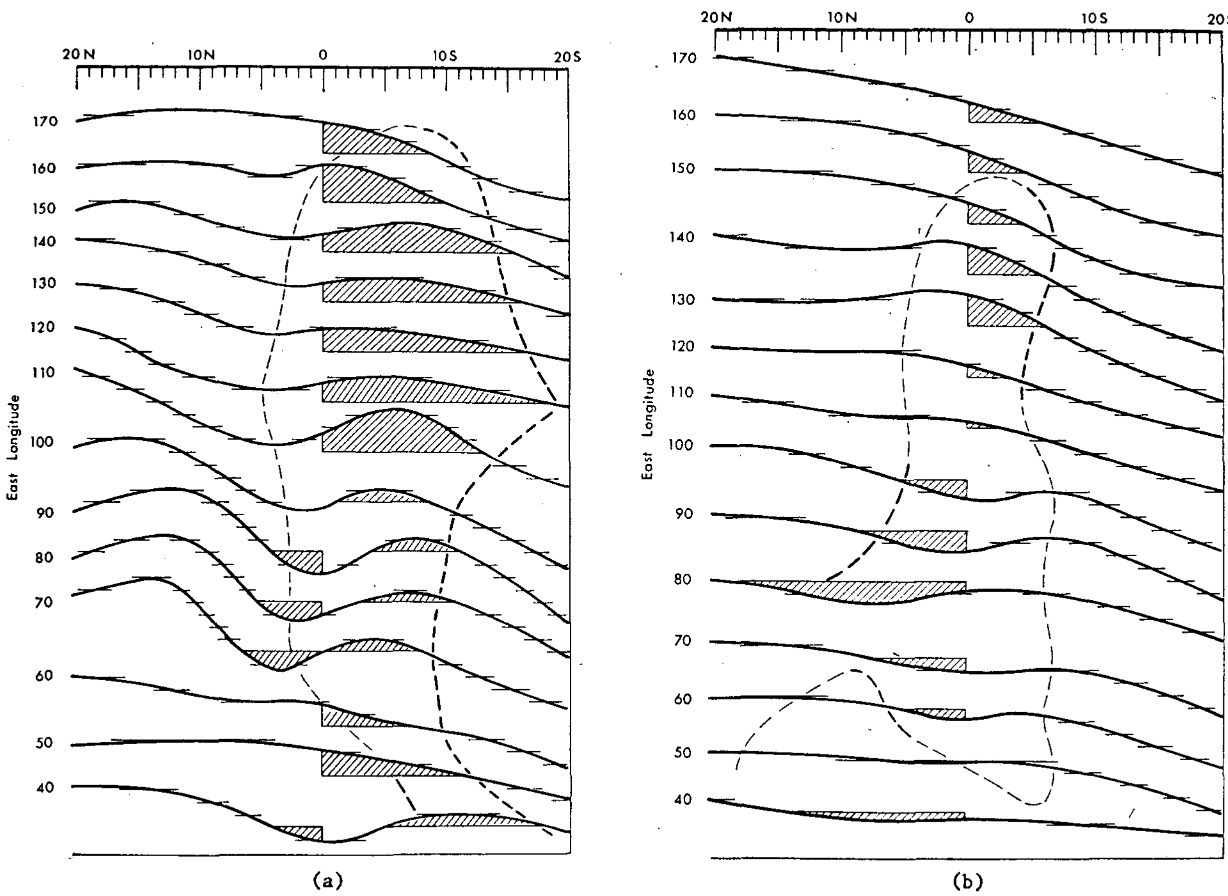
The complementary non-geostrophic boundaries of the equatorial westerly regime are given in Fig. 4, together with the meridional profiles of local values of the second derivative of pressure with respect to latitude. Regions with positive zonal wind components (negative second derivatives in both hemispheres) are shaded. The correspondence between these two is generally quite good, particularly in January and July when the zonal component is well established. The agreement is not nearly as good in April and October; however, it is clear that extended regions in which the wind direction changes smoothly downstream from easterlies to westerlies do not occur without a change in the sign of $\partial^2 p/\partial y^2$.

In January the northern boundary of the westerlies and the northern boundary of the negative second pressure derivative coincide from 150E to 70E longitude; their latitudinal position ranges from 2N to 5N latitude. The correspondence becomes less well marked at both the eastern and western extremes of the westerly regime.

In April the correspondence is best developed on the southern boundary from 100E to 60E longitude. Correspondence along the northern boundary is poor.

In July the southern boundary of the equatorial westerlies coincides very nearly with the southern margin of the negative second derivative of pressure from about 100E to 50E longitude. The latitudinal positions range from the equator to 2S latitude, and the correspondence again falls off at the extreme eastern and western ends of the westerly regime.

In October the correspondence along the southern boundary is reasonably good from 110E to 40E longitude, and along the northern boundary from 50E to 40E longitude. It is, however, questionable on both boundaries eastward of 120E longitude. The latitude of



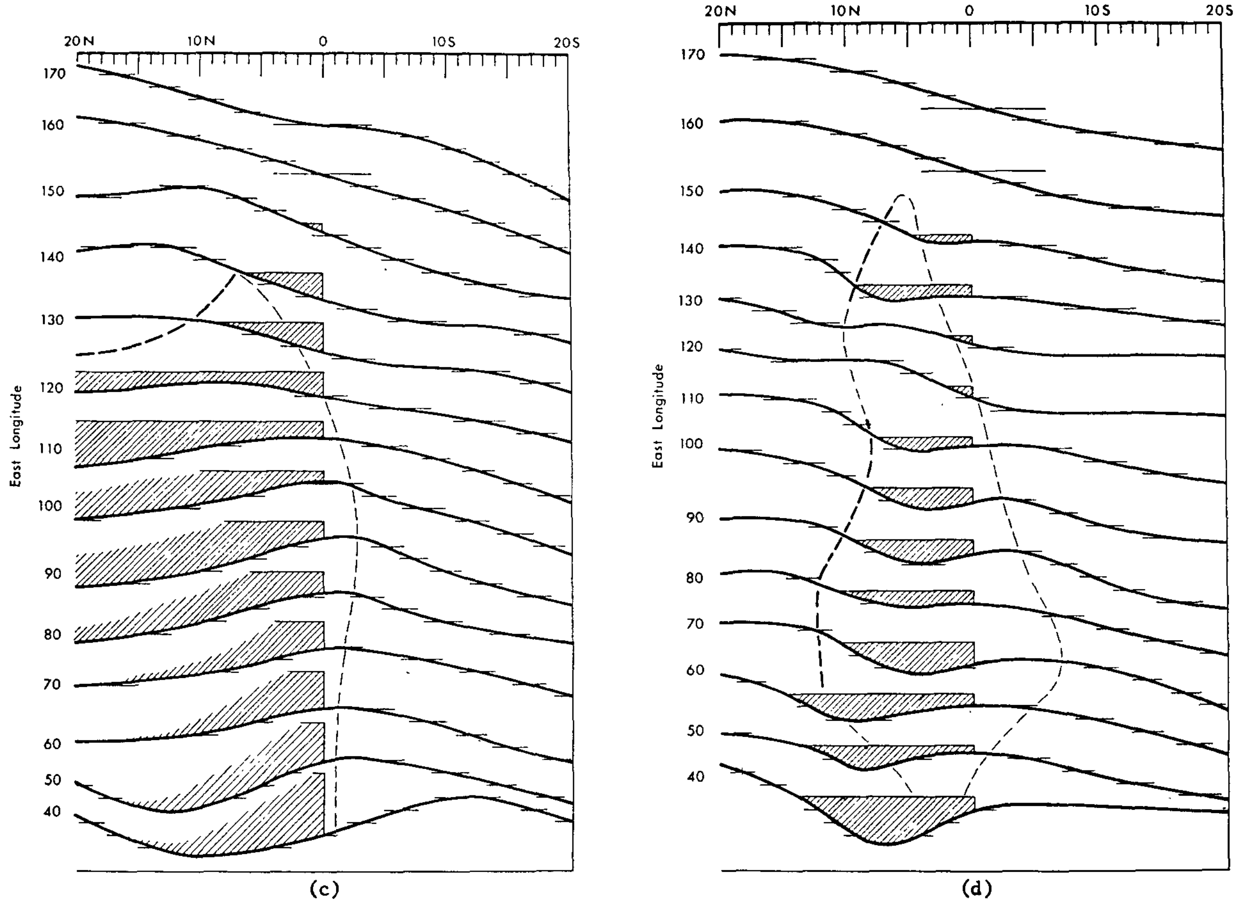


FIG. 3. The meridional pressure gradient distribution at the indicated longitudes. The shaded regions indicate geostrophic westerlies; the dashed line indicates the boundary of the observed westerlies at 900 mb (see text for additional explanation); the thin horizontal lines indicate increments of 0.1 mb/degree latitude. a) January, b) April, c) July, d) October.

the southern boundary ranges from the equator to 5S, well within the zone in which the equatorial wind-pressure relationship is expected to apply. The northern boundary eastward of 120E, however, lies near 10N, a latitude at which it is much more likely that the normal geostrophic regime would apply; therefore, the small belt of negative $\partial^2 p/\partial y^2$ at 120E and 130E appears to be an artificial result of the original pressure distribution.

5. Schematic conclusions and synoptic models

A number of empirical and analytical conclusions may be drawn from the above analysis. The ones classed as empirical are necessarily schematic and have only regional significance since they are predicated on the existence of an extended region of surface westerlies and a large seasonal variation in the position of the equatorial trough. Those classed as analytical follow from Eqs. (2) and (5) and are mathematical results which need not be realized in nature. Among the former are:

a) If the equatorial trough is located more than five degrees latitude from the equator in either hemisphere, it forms the poleward boundary of the region of equatorial westerlies.
b) If the equatorial westerlies straddle the equator, both boundaries are not geostrophically controlled at any given longitude; i.e., a true equatorial ridge does not exist within the study region. A possible exception, however, occurs in January from 70E to 100E longitude.
c) If a boundary of the equatorial westerlies lies within 5° of the equator, it corresponds to a change in sign of the second pressure derivative from negative to positive, with negative values occurring within the westerly regime.
d) Westerlies do not occur when the equatorial trough moves to within a few degrees of the equator, as it generally does east of about 150E longitude.

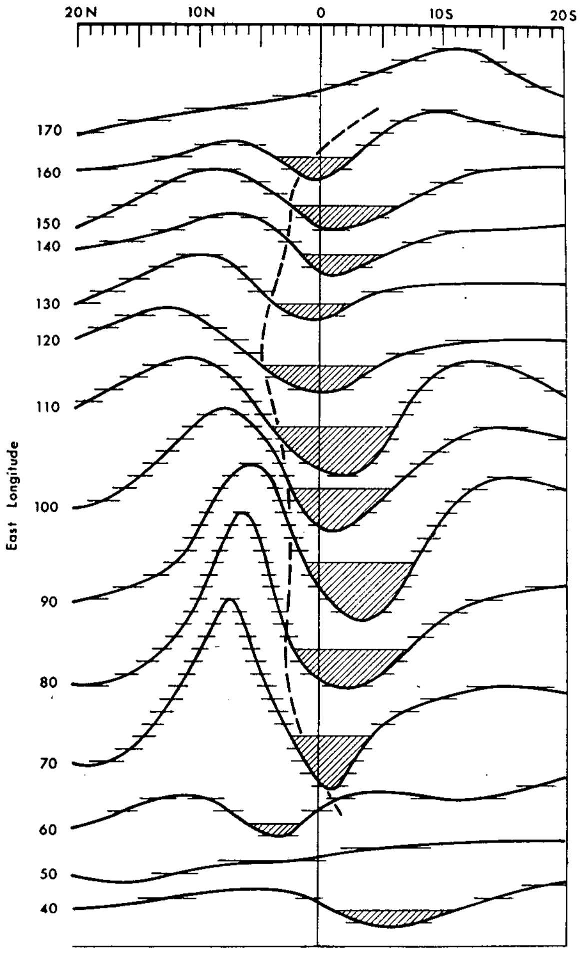
The strictly mathematical conclusions may be summarized in the following:

e) A circumscribed region of negative values of $\partial^2 p/\partial y^2$ in the vicinity of the equator requires that the latitudinal pressure gradient take on values that are least positive (most negative) along its northern boundary and most positive (least negative) along its southern boundary.

f) A similar region of positive values of $\partial^2 p/\partial y^2$ in the vicinity of the equator requires that the latitudinal pressure gradient take on values that are most positive (least negative) along its northern boundary and least positive (most negative) along its southern boundary.

Since the actual latitudinal pressure distribution is obtained by adding an arbitrary mean pressure gradient to the latitudinal integral of the pressure gradient, it is not surprising that the same observable result—either equatorial westerlies or easterlies—may result from a number of different pressure patterns. For example, if the mean pressure gradient is zero or very small, the westerly regime is associated with a true equatorial ridge separating two troughs, and the easterly regime with an equatorial trough. If the mean pressure gradient is approximately equal to the locally greatest positive or negative pressure gradient, the westerly regime is associated with a displaced equatorial trough in one hemisphere and a broad flat plateau in the opposite hemisphere. If the mean pressure gradient is greater than any locally observed values, the pressure will decrease continuously from one hemisphere to the other with, however, a greater horizontal packing of isobars in one hemisphere. The equatorial westerly regime is associated with the packing of isobars in the hemisphere of relatively lower pressure, while the easterly regime is associated with the packing of isobars in the hemisphere with relatively higher pressure.

These schematic results have many points of correspondence with the models of typical equatorial synoptic states developed by Johnson and Mörth (1960) and Johnson (1965), particularly with their basic *equatorial duct* and *equatorial bridge*, which correspond respectively to an equatorially-centered trough and ridge. The *equatorial step* model is equivalent to a parabolically varying pressure gradient, implying that $\partial^2 p/\partial y^2$ increases linearly northward. Since $\partial^2 p/\partial y^2$ passes through zero at the equator, geostrophic and equatorial westerlies are found in the Southern Hemisphere, and easterlies in the Northern Hemisphere. The



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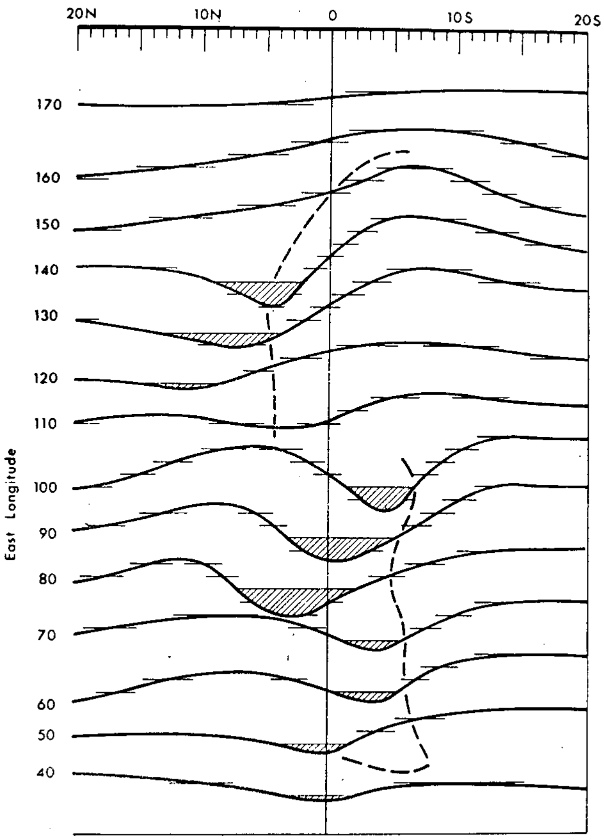

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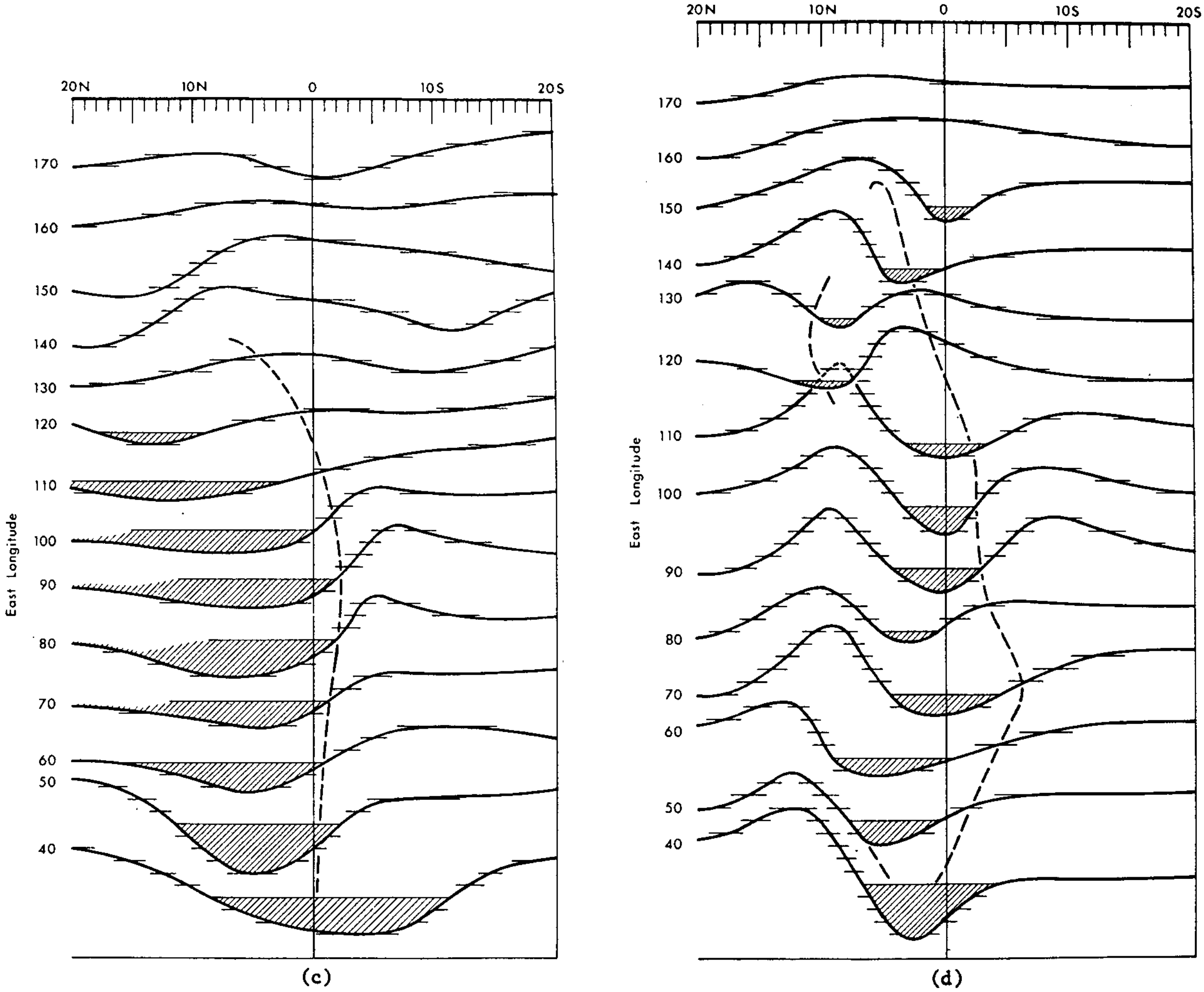

FIG. 4. The meridional distribution of $\partial^2 p/\partial y^2$ at the indicated longitudes. Negative regions are shaded; the dashed line indicates the observed boundary of the westerlies (see text for additional explanation); the thin horizontal lines indicate increments of 10^{-2} mb/(degree latitude)^2. a) January, b) April, c) July, d) October.

cross-equatorial drift model deals with the meridional rather than the zonal wind component; however, it is clearly consistent with Eq. (4) in its association with a non-zero value of $\partial(\partial p/\partial y)/\partial x$.

6. Summary

It has been shown that throughout the year the lateral boundaries of the extended region of observed surface equatorial westerlies in the Indian and western Pacific Oceans correspond closely either to a change in sign of the meridional pressure gradient, or to a change in sign of the meridional derivative of the pressure gradient. The former is a characteristic of the geostrophic approximation to the equation of motion, and occurs when the lateral boundary of the westerlies lies at latitudes higher than 5N or S, while the latter is a characteristic of the wind-pressure relationship obtained by differentiating the equations of motion with respect to latitude, and occurs when the lateral boundary of the westerlies lies between 5N and 5S.

Since it is not possible to devise a pressure pattern consisting of an equatorially centered trough *and* an equatorial region of negative $\partial^2 p/\partial y^2$, the location of the equatorial trough at latitudes higher than 5N or S appears to be one of the existence requirements for equatorial westerlies. It also seems reasonable to assume that in regions with a seasonally variable zonal wind component, the movement of the equatorial trough to latitudes higher than 5° is the initiating mechanism for equatorial westerlies.

A corollary to the above statement is that the geostrophic approximation is not valid between approximately 5N and 5S, and that occasional instances in which the ratio of the pressure gradient to the Coriolis parameter remains finite as f goes to zero, are ones in which the spurious appropriateness of the geostrophic approximation up to the equator itself masks the more general validity of the equatorial wind-pressure relationship that has been established here.

The overall congruence between the equatorial westerlies and the equatorial region of negative values of $\partial^2 p/\partial y^2$ implies very strongly that $\nabla_h(\partial p/\partial y)$ is in fact the key to a valid wind-pressure relationship on and near the equator.

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