Large-Scale Circulation Anomalies Over the Tropics during 1971–72

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ABSTRACT

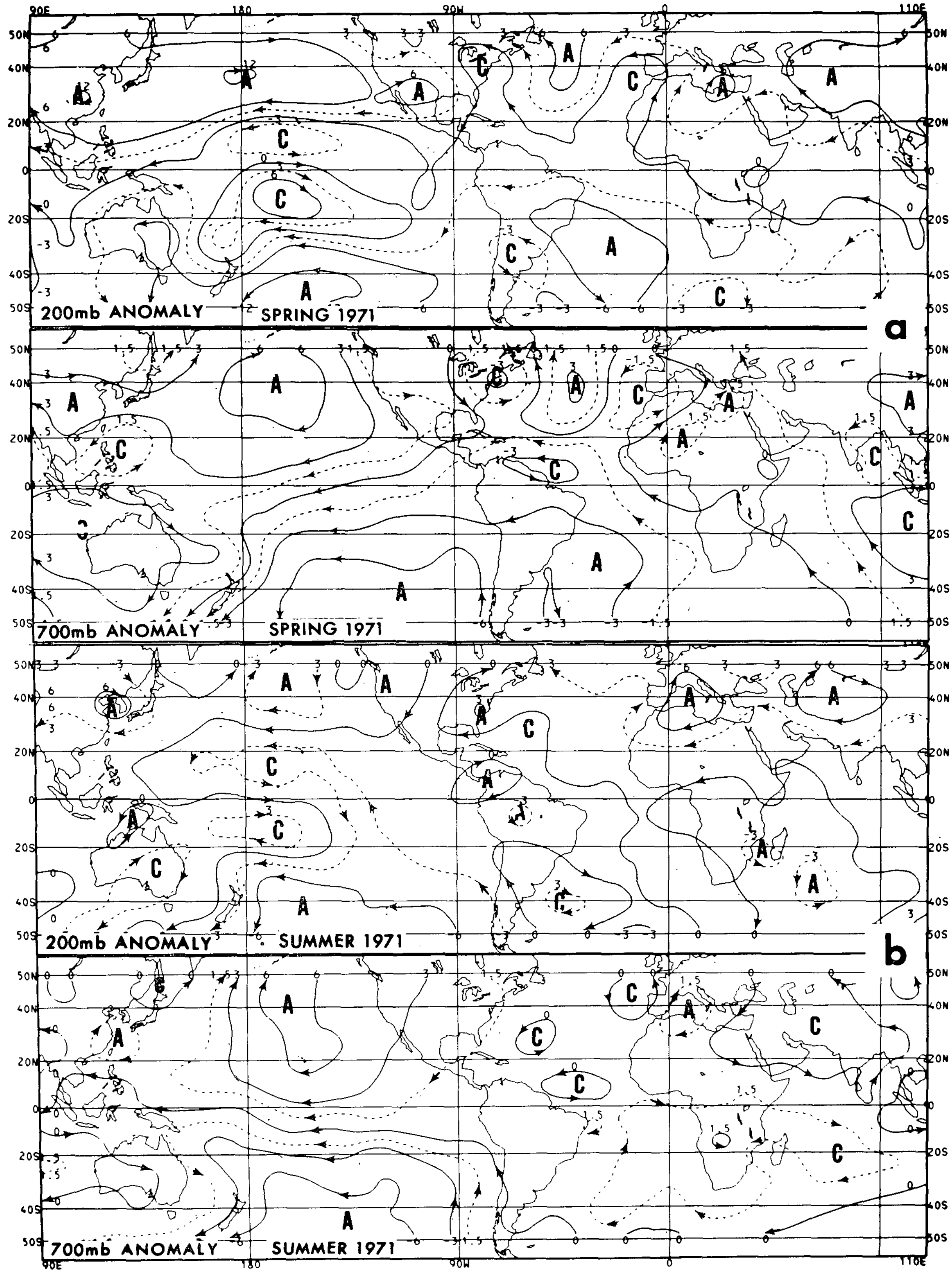
The authors have been monitoring the large-scale circulation over the tropics since 1968 through use of operational tropical wind analyses prepared by the National Meteorological Center. Seasonal and monthly anomaly charts of the tropical circulation at 700 and 200 mb have been prepared using four-year seasonal and monthly means as a preliminary "normal." A sequence of seasonal anomaly charts is used here to describe the highly anomalous tropical circulation during the northern summer of 1972 and its antecedents. During this season the trades were weaker than "normal" over most of the Pacific with both the North and South Pacific anticyclones displaced poleward. In the upper troposphere the anomalous flow was anticyclonic over the Central Pacific reflecting the weakness of the mid-oceanic troughs north and south of the equator. From the eastern Pacific eastward across the Atlantic, Africa, and the Indian Ocean the flow at upper levels north of the equator was westerly relative to normal, signifying a notable reduction in the strength of the summertime "monsoon" easterlies over Africa and the Indian Ocean. The evolution of these striking circulation anomalies from a substantially different initial state a year earlier and their association with sea-surface temperature variations over the equatorial Pacific are discussed.

1. Introduction

Some of the most dramatic weather events of the past decade occurred during 1972. This was especially true for the tropics during northern summer[1] of 1972. Satellite photography indicates that convection was widespread over much of the tropical North Pacific. Over Southeast Asia and the Philippines, heavy rains and floods occurred. In the eastern South Pacific the El Niño current displaced the usually dependable Peru-Chile current. Rains over normally arid Peru were reported as the heaviest in 40 years. While tropical storm activity was frequent over the eastern North Pacific, Atlantic tropical storms were very few in number. Over North Africa, south of the Sahara, extremely devastating drought characterized the "rainy season" (United Nations, 1973; World Meteorological Organization, 1973). Likewise, relatively dry conditions prevailed over India where the monsoon was delayed and much weaker than normal. These large-scale weather anomalies had a profound effect upon many human activities, particularly the world's food production during 1972. In the future, the impact of such anomalies is expected to be even greater because of rapidly increasing population pressures. Consequently it is becoming imperative that the large-scale variations in weather and associated atmospheric circulations be monitored on a comprehensive global scale and that methods for their long-period prediction be developed.

Our purpose is to describe many of the pertinent large-scale circulation events over the tropics and temperate regions of both Northern and Southern Hemispheres during 1971 and 1972. Heretofore the large-scale circulation over the tropics and many portions of temperate latitudes of the Southern Hemisphere have been only imperfectly observed. In recent years, the situation has been improving, first with increased aircraft observations in some areas and secondly with wind estimates derived from cloud motions obtained from the geosynchronous satellites. Thus it is now becoming feasible to monitor the large-scale flow with present operational tropical analyses. We have used the National Meteorological Center's (NMC) objective tropical analysis (Bedient *et al.*, 1967)—hereafter referred to as the Bedient analysis—to construct monthly and seasonally averaged wind fields since 1968. Recently the characteristics of two of these monthly wind fields (February 1969 and February 1971) were examined (Krueger and Winston, 1974). Inspection of such monthly and seasonal fields indicates that, just as in middle and high latitudes, the "climatological forcing" is so strong that monthly and seasonal means for different years grossly resemble each other. Consequently it is useful to remove the climatology and examine the anomalous part of the circulation. At higher latitudes this is

[1] All seasonal references in this paper are with respect to Northern Hemisphere seasons (e.g., summer 1972 refers to June, July, August 1972; winter of 1972 refers to December 1971, January and February 1972).


90E
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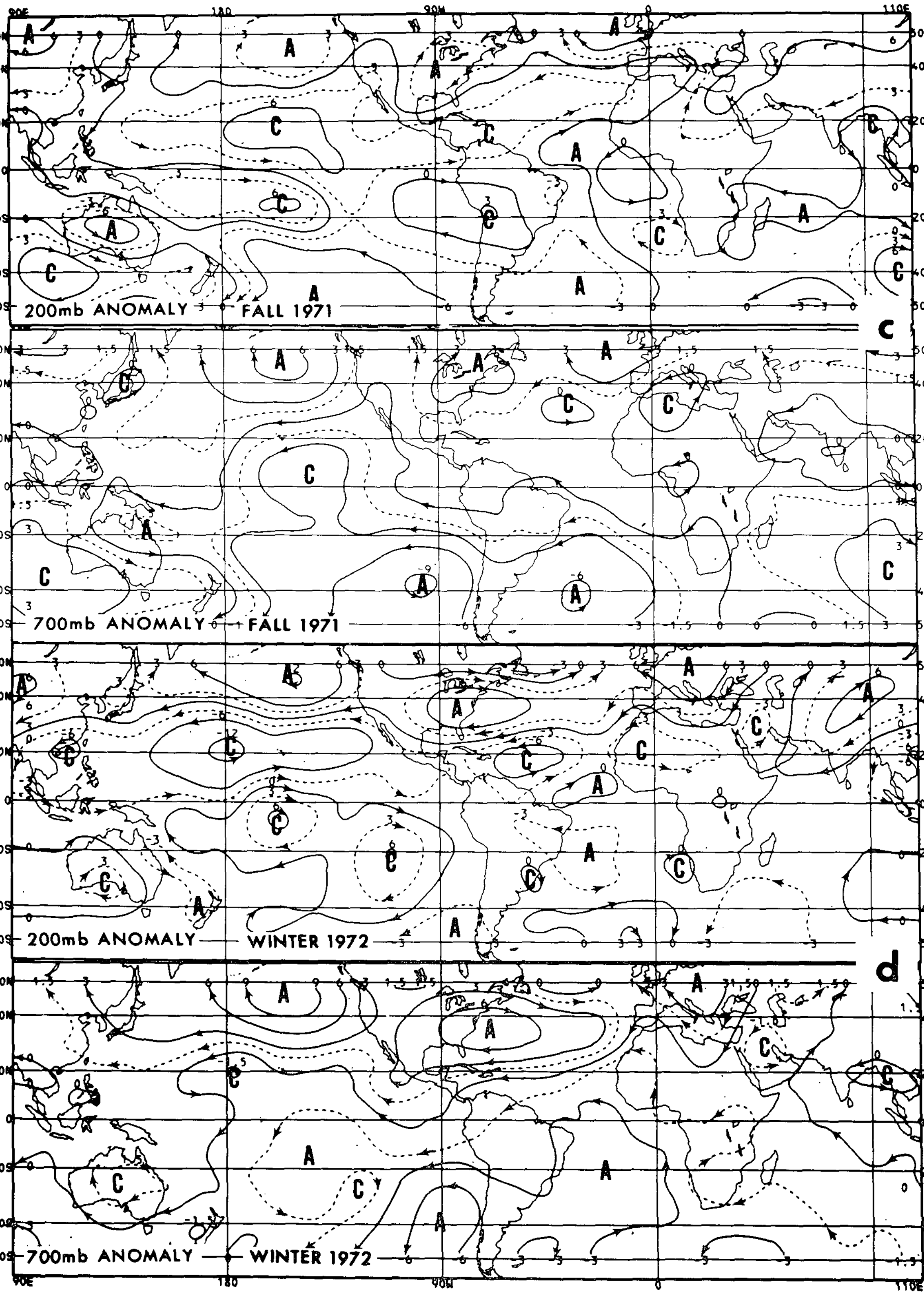
200mb ANOMALY FALL 1971
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700mb ANOMALY FALL 1971
200mb ANOMALY WINTER 1972
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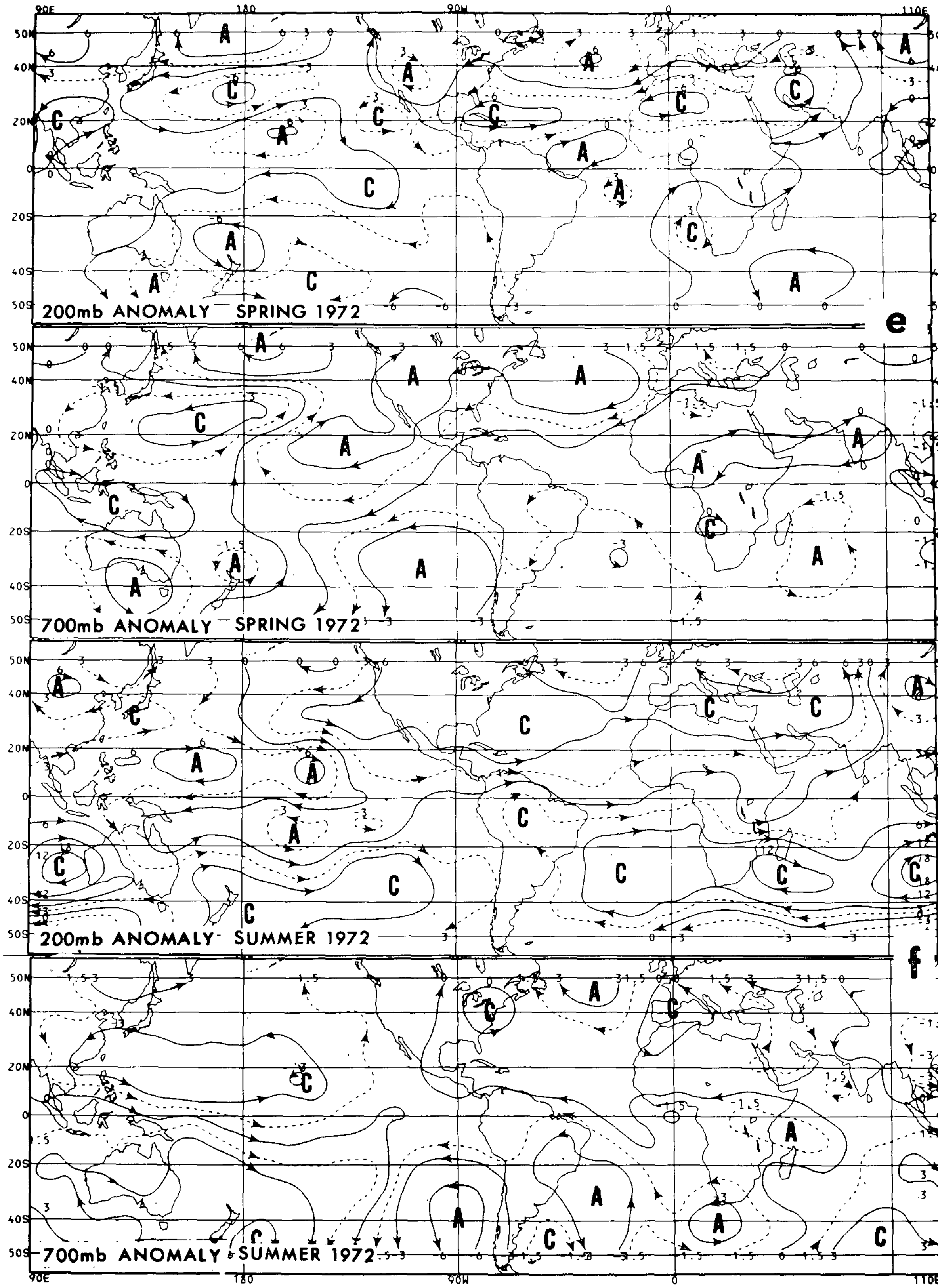

FIG. 1. Seasonal 200 and 700 mb circulation anomalies for spring 1971 (a) through summer 1972 (f). Contour interval is 6×10^6 m^2 s^{-1} at 200 mb and 3×10^6 m^2 s^{-1} at 700 mb. Intermediate contours indicated by dashed lines. Letters "A" and "C" indicate centers of relative anticyclonic and cyclonic circulations. Contour interval of 6×10^6 m^2 s^{-1} per 10° of latitude corresponds to an anomalous wind of 5.4 m s^{-1}.

usually done by removing the climatological mass field and inferring geostrophic anomalous flow. At low latitudes this procedure is not appropriate, so instead one must compute the anomalous flow $\mathbf{V}'(x,y,p,t)$ directly from the wind field, $\mathbf{V}(x,y,p,t)$ as follows:

$$\mathbf{V}'(x,y,p,t)=\mathbf{V}(x,y,p,t)-\bar{\mathbf{V}}(x,y,p),$$

where

$$\bar{\mathbf{V}}\equiv 1/N\,\Sigma\mathbf{V}(x,y,p,t)$$

is the appropriate climatology over a period N. Since only four years of the Bedient analyses were available at the beginning of this phase of the project, this period was used as the base period, or "climatology."

While one can draw streamlines of the anomalous flow, we have chosen to display the anomalous streamfunction instead (Fig. 1). Derivation of this field is straightforward and, in essence, it is obtained from a relaxation technique applied to the vorticity of the *anomalous* wind. It should be kept in mind that there are still major data voids, especially over the Southern Hemisphere, and consequently the anomalous flow may show little deviation from "climatology" in some areas. Considerable caution is therefore recommended in interpreting these maps. However, the major circulation anomalies described here are believed to be quite representative.

The low-latitude circulation during summer 1972 will be described first and compared with that for the previous year. This will be followed by a discussion of the evolution of this highly anomalous circulation.

2. The anomalous circulation of summer 1972

The anomalous flow for summer 1972 (Fig. 1f) contrasts dramatically with that of the previous summer (Fig. 1b). In particular, the high-level circulation over the central Pacific was completely opposite. Instead of cyclonic anomalous flow north and south of the equator with westerlies over the equator, as occurred in 1971, there was high-level anticyclonic anomalous flow at approximately 15°N and 15°S with relative easterly flow along the equator and strong westerlies near 25°N and 25°S (Figs. 1f and 4). Also note from the 700 mb anomalous flow (Fig. 1f) how weak the trades were over most of the equatorial Pacific, particularly in contrast to the anomalous easterlies at 700 mb the previous year (Fig. 1b). These 700 mb winds of summer 1972 averaged as much as 3 m s^{-1} below the 4-year mean, and appear as a relative westerly current extending from southeast Asia to near 120°W. To the north, a zonally oriented cyclonic anomaly extending from China to Hawaii

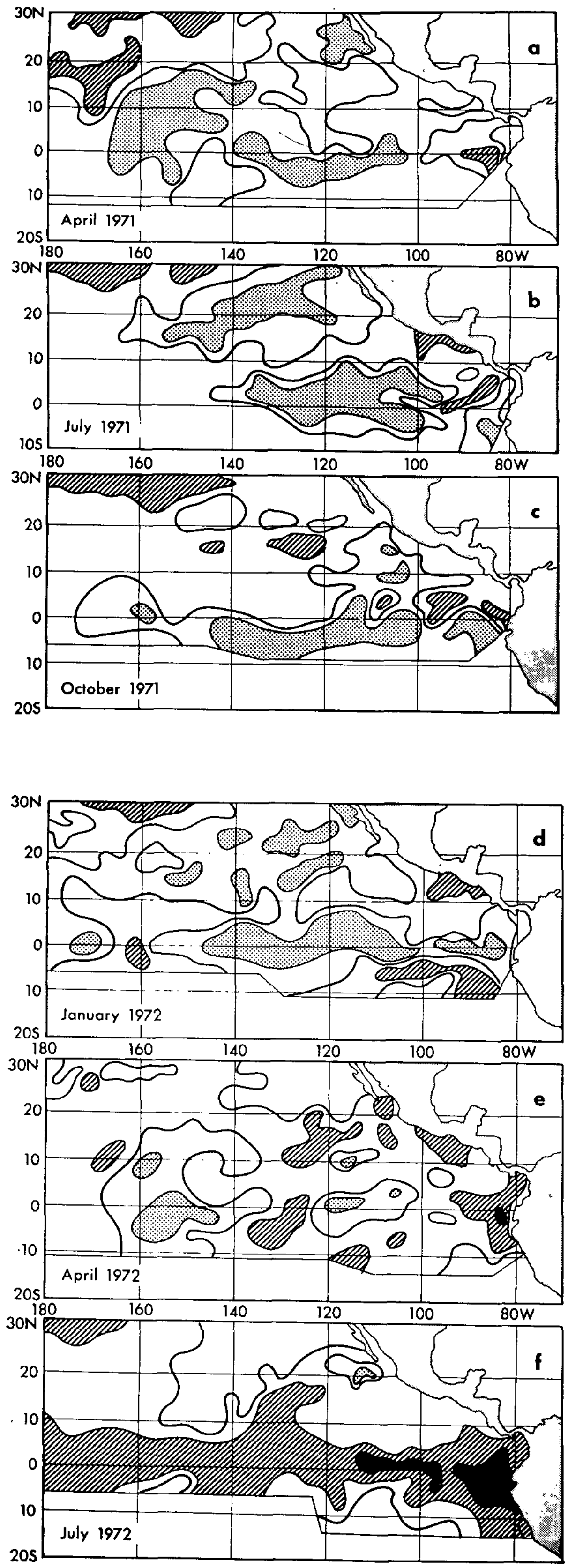

FIG. 2. Sea-surface temperature anomaly for the eastern tropical Pacific for spring 1971 through summer 1972 (Laurs, 1971–72). Areas with temperatures more than 1°C above normal are hatched. Heavier shaded areas are greater than 3°C above normal. Stippled areas represent temperatures more than 1°C below normal.

was directly underneath the aforementioned 200 mb anticyclonic anomalous flow. Satellite imagery indicated that convective cloudiness in the intertropical convergence zone (ITCZ) was frequent and occurred north of the equator where the 700 mb anomalous flow was westerly and cyclonic, while that at 200 mb was easterly and anticyclonic (Fig. 1f). Sea-surface temperature averaged more than 1°C above normal from the date-line to South America (Fig. 2f) in contrast to the below normal temperatures occurring a year earlier (Fig. 2b).[2] To a large extent these represent temperatures above 28°C and imply a high surface equivalent potential temperature in the northern ITCZ. This suggests that condensation heating over a warmer-than-normal sea surface played an important role in maintaining this anomalous circulation. Note that while positive sea-surface temperature anomalies were greatest in the eastern tropical Pacific (Fig. 2f)—during July, for example, they were as much as 5°C above normal near the Galapagos—these correspond to a temperature of only 25°C, which is probably not high enough for any significant deep convection to occur.

Over the eastern South Pacific, the trades remained south of normal where they averaged as much as 3 m s^{-1} above the 4 yr mean. Accordingly the South Pacific anticyclone was south of normal. Also the South Atlantic anticyclone was south of normal. These southward displacements, which are indicative of Southern Hemisphere mid-latitude blocking, are clearly shown by the extensive 700 mb anticyclonic anomalous circulations at 30–40°S extending from the East Pacific to Africa.

It is interesting to note that while the South Atlantic anticyclone was displaced south of normal, the equatorial easterlies over eastern South America were stronger than normal. They flowed inland near the mouth of the Amazon with speeds as high as 2 m s^{-1} above "normal." The low tropospheric easterlies over the western Arabian Sea and Africa between the equator and 20°N were also stronger than average, in contrast to the relative westerly flow of summer 1971. Over Africa, in particular, the anomalous 700 mb easterlies may have inhibited the onshore flow of moist tropical Atlantic air and instead spread dry Saharan air over most of the Sahel, thus contributing to the extremely devastating drought of that summer.

Superimposed upon these anomalous lower tropospheric easterlies was a high-level relative westerly current that extended from the east Pacific halfway around the earth. In particular, relative westerly flow occurred over Africa, the Arabian Sea, and India, where the high level flow is normally easterly and makes up the tropical easterly jet. Not only was this easterly jet weak, but the Asiatic monsoonal circulation from which this jet emanates was also weaker than normal. Evidence of this is the 200 mb cyclonic anomalous circulation located southeast of the Caspian Sea where the monsoonal upper level anticyclone is usually located.

The low-level cyclonic circulation usually present over India during summer was also weak, as was the southwesterly flow over the Arabian Sea. This current appears to have been displaced southward as a result of the northerly flow emanating from an anticyclonic anomaly located over the USSR. This anticyclonic anomaly appears to have persisted from a blocking anticyclone that established itself over eastern Europe during the previous winter. It spread cool air, which continued into the summer, as far south as Iran and Afghanistan. This very likely played an important role in inhibiting the Asiatic monsoon in the summer of 1972.

3. Evolution of the tropical circulation during 1971–72

The very long-period evolution of this highly anomalous circulation is also of considerable interest. While the circulation patterns during spring and summer 1971 were rather similar in many respects (Figs. 1a and 1b), a major change, particularly over the Pacific, appears to have begun during fall 1971. In retrospect these changes appear to have ushered in the anomalous circulation regime of 1972. In particular, the large anticyclonic anomalies that characterized the lower tropospheric circulation over the Pacific during the previous two seasons moved apart, leaving a broad area near the equator with reduced tradewind flow (Fig. 1c). However, strong anomalous easterly flow set in from California to Hawaii in the Northern Hemisphere and west of Chile over the Southern Hemisphere.

During winter 1972, the eastern North Pacific and Bermuda anticyclones intensified. In fact the 700 mb anomaly centers in these areas represent major circulation anomalies (Fig. 1d). Namias (1972) has indicated that the eastern Pacific and Bermuda anticyclones were 1.3 and 2.0 standard deviations respectively above their winter means. He has suggested that the abnormally strong east Pacific anticyclone drove a stronger and colder California current southward along the coast and then southwestward out into the Pacific. The abnormally strong Bermuda high was accompanied by stronger than normal trades across the Caribbean. Wind speeds here averaged as much as 4 m s^{-1} above normal. As this anomalous current flowed across Central and northern South America it turned southwestward towards the equator and appeared to merge south of the equator with the anomalous flow from Chile. Surprisingly, the trade flow just south of the equator over the eastern Pacific does not appear weaker than "normal" despite the

[2] Sea-surface temperatures were obtained from Laurs (1971–72) and include tropical Pacific data only east of 180°.

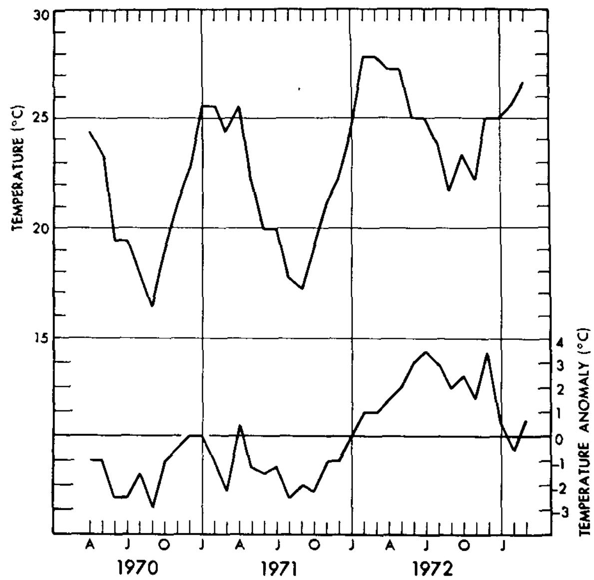

FIG. 3. Sea-surface temperature and its anomaly at 5°S, 85°W. Data from Laurs, 1971–72.

weakening of the South Pacific anticyclone (Fig. 1d). However, a relative weakness in the flow occurred at 5–10°S between the strong trades near Central America and the southern trades, which continued south of normal and averaged 4 m s^{-1} above the mean near 20°S. Thus the curvature of the wind profile over the eastern Pacific was large.

Such a large-scale shift in the major wind systems as occurred during fall and winter would be expected to have important consequences for the major oceanic gyres, which are largely wind-driven. Accordingly, the southeastward shift of the South Pacific anticyclone towards the coast of Chile during autumn suggests a parallel shift in the Peru-Chile current system and a weakening of the South Equatorial Current over the eastern Pacific. It is recognized that the equatorial current system, in particular, is to a large extent dependent upon the wind stress curl or the curvature of the wind profile rather than the local wind stress (Munk, 1950). Wyrtki (1974) has emphasized that fluctuations in the equatorial currents are more influenced by the position of the tradewinds than their strength. Equatorial countercurrents tend to occur where the trade flow is relatively weak, for it is at this location that they are least opposed by the wind (Sverdrup, 1947; Neumann and Pierson, 1966; Wyrtki, 1974). Usually a minimum in the tradewind flow occurs 5–10° north of the equator and, as is well known, is accompanied by the Northern Equatorial Countercurrent (Wyrtki and Kendall, 1967). Less is known about equatorial countercurrents in the Southern Hemisphere although they have also been documented (Tsuchiya, 1970). It is, of course, unknown whether a South Equatorial Countercurrent formed over the eastern Pacific during early 1972, but the relative minimum in the easterly flow at 5–10°S referred to earlier raises this interesting possibility. At any rate, the poleward shift of the tradewinds both north and south of the equator over the Central Pacific with a parallel shift in the North and South Equatorial Currents very likely resulted in a more complex current system near the equator than normally occurs. Consequently, during fall and winter of 1971–72 conditions became favorable for reduced equatorial upwelling, and an increase in sea-surface temperature began over much of the tropical Pacific (Fig. 3).

With the North Pacific high displaced north of normal, the zonally oriented 200 mb cyclonic anomaly center was also displaced northward to about 20°N (Fig. 1d). Note how this anomaly trough is located above or just south of the strong easterly anomalous flow at 700 mb. Associated with this displacement, the high-level equatorial westerlies shifted northward over the Central Pacific. Two-hundred millibar wind speeds near 10–15°N averaged as much as 5 m s^{-1} above normal during the season. Since the low-level anomalous flow was easterly, the vertical wind shear was also stronger than normal (6 m s^{-1}), indicating a cold anomaly center and a strong meridional thermal gradient across this westerly stream (Fig. 4). Note that the northern cyclonic anomaly center was displaced westward with respect to that over the Southern Hemisphere, indicating that the northern mid-Pacific high level trough was west of normal. Accordingly the high level equatorial confluence was reduced.

Above the strong trades south of the Bermuda high the upper level anomalous flow was also cyclonic with relative westerly flow over northern South America. Relative westerly flow, in fact, occurred at equatorial latitudes from Indonesia eastward to North Africa.

During spring 1972, low-latitude westerly flow at 200 mb continued to be strong across the Atlantic and extended as far east as the Arabian Sea (Fig. 1e). Over the central Pacific, however, the tropical westerlies continued to shift northward. Note in Fig. 4 how the northern edge steadily moved from about 10°N

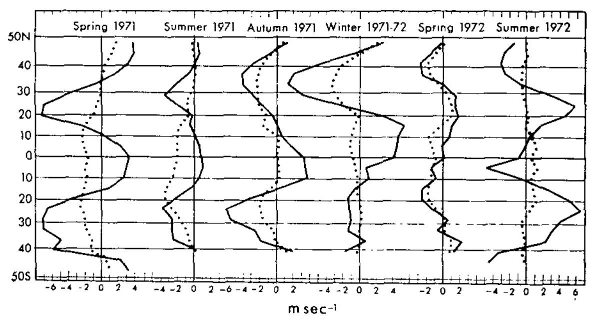

FIG. 4. Profiles of seasonal mean zonal wind anomaly over the Pacific between 160° and 110°W at 200 mb (solid) and 700 mb (dotted) between spring 1971 and summer 1972. Note contrast between spring-summer 1971 and summer 1972 at 200 mb.

during the previous summer to 20–25°N in spring 1972. As this westerly current shifted completely into the Northern Hemisphere, the flow over the equator became easterly at most longitudes. Concurrently, the cyclonic anomaly associated with the high level mid-oceanic trough shifted northwestward to near 30°N, 175°E, and a major anticyclonic anomaly formed south of Hawaii. This was accompanied by widespread cloudiness and convection. The steady shift of the westerlies from the equator northward during the past four seasons suggests that this anticyclonic circulation anomaly, located on the south side of the maximum westerlies, actually had its origins in the cyclonic anomaly center that had previously been south of the equator.

The tradewind flow was weak over the western Pacific—note the anomalous westerly flow at 700 mb from Southeast Asia to 170°E (Fig. 1e). Surprisingly, the tradewind flow temporarily strengthened over the central Pacific, however. These strong trades apparently maintained active oceanic upwelling, since a cold pool existed along the equator in this sector despite the warming off the coast of Ecuador and Peru (Fig. 2e). Apparently the trades do not necessarily slow down at all longitudes during a weakening of the Walker circulation.

Over Central America the tradewind flow weakened as the Bermuda high shifted into the central Atlantic. Despite this, an anomalous current continued its equatorward flow and appeared to merge with the southern trades near 110°W. South and east of the Galapagos the flow continued weak, and the southern equatorial convergence that had formed during late winter gradually extended itself towards northern Peru. Most of the convection associated with the southern ITCZ occurred during February and March when the sea-surface temperatures peaked at about 28°C (Fig. 3). Note that the anomaly continued to rise, however. Despite this, the ITCZ over the eastern Pacific reformed north of the equator during April.

4. Conclusion

The charts shown in Fig. 1, which represent the first tropical circulation anomaly maps, demonstrate that it is now possible to monitor the large-scale circulation over the tropics with conventional objective wind analyses. They also indicate that significant large-scale circulation anomalies occur over the tropics and undergo a very slow evolution—often taking as long as several years to complete a cycle. These circulation anomalies are in turn accompanied by large-scale anomalies in condensation heating. The major circulation anomalies during 1972 were associated with a major shift in the tropical energy sources, and it appears that the change toward this circulation regime may have begun late in 1971 following large-scale poleward displacements of the major centers of action over the North and South Pacific. Why such similar shifts should occur both north and south of the equator is unclear, but at any rate they were associated with a weakening of both the atmospheric and oceanic equatorial circulations over the Pacific as well as a rise in sea surface temperatures (Laurs, 1971–72) and probably also in equivalent potential temperatures in the planetary boundary layer. Enhanced tropical convection tapped this greater available energy, resulting in a greater amount of condensation heating over the Pacific. An interesting question presents itself—namely, did the greater condensation heating over the Pacific act to interfere with the convection normally occurring in the Indian monsoon? The number of heat sources around a latitude circle after all is probably limited and the circulations they produce undoubtedly interact in a rather complex way. These observed events in 1971–72 then raise the question as to how closely long-term fluctuations in the monsoon are tied to major ocean-atmosphere circulation interactions over the Pacific.

These and many other questions about the tropical circulations and their interactions with the rest of the global circulation must be examined much more fully to understand and to aid in prediction of the large-scale global circulation and weather variations. Continuation of this series of seasonal and monthly circulation anomalies is planned; also planned is a similar series of anomalies of the radiative energy budget (and cloudiness) as observed from satellites. Long series of such basic circulation and energy information will allow for much more advanced studies of large-scale interactions within the global circulation.

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REFERENCES

Bedient, H. A., W. G. Collins, and G. Dent, 1967: An operational tropical analysis system. *Mon. Wea. Rev.*, **95**, 942–949.

Krueger, A. F., and J. S. Winston, 1974: A comparison of the flow over the tropics during two contrasting circulation regimes. *J. Atmos. Sci.*, **31**, 358–370.

Laurs, R. M., 1971–72: Fishing Information Bulletin, National Marine Fisheries Service, Southwest Fisheries Center of LaJolla, Calif. (see monthly issues between March 1971–August 1972).

Munk, W. H., 1950: On the wind-driven ocean circulation, *J. Meteor.*, **7**, 79–93.

Namias, J., 1972: Experiments in objectively predicting some atmospheric and oceanic variables for the winter of 1971–72. *J. Appl. Meteor.*, **11**, 1164–1174.

Neumann, G., and W. J. Pierson, Jr., 1966: *Principles of physical oceanography.* Englewood Cliffs, N. J., Prentice-Hall, Inc., 545 p. (See pp. 450–453).

Sverdrup, H. U., 1947: Wind-driven currents in a baroclinic ocean; with application to the equatorial currents of the eastern Pacific. *Proc. Nat. Acad. Sci.*, **33**, 318–326.

Tsuchiya, J., 1970: Equatorial circulation of the South Pacific. In "Scientific Exploration of the South Pacific." Warren S. Wooster, Ed., National Academy of Sciences, Washington, D. C. 257 p.

United Nations, 1973: Development Forum. U. N. Centre for Economic and Social Information, Geneva. Vol. 1, No. 2, March (See: "Famine Weather: p 1, and "Was it really so bad" p 12).

World Meteorological Organization, 1973: Significant weather in 1972. *WMO Bull.* **22**, 99–107.

Wyrtki, K., 1974: Equatorial currents in the Pacific 1950 to 1970 and their relations to the trade winds. *J. Phys. Oceangr.*, **4**, 372–380.

Wyrtki, K., and R. Kendall, 1967: Transports of the Pacific equatorial countercurrent. *J. Geophys. Res.*, **72**, 2073–2076.