DEVELOPMENT OF OUR KNOWLEDGE OF THE GENERAL CIRCULATION OF THE TROPICS

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1. INTRODUCTION

"The general circulation of the atmosphere means many things to many persons." Edward M. Lorenz, 1967

Once viewed by Hadley (1735) as so straightforward that it could be described in about 1000 words, the general circulation is now a subject so complex that it requires a major monograph for adequate treatment. As is implied in the quote by Lorenz, the bounds on what is included as part of the general circulation are indeed fuzzy. The "what" questions of the general circulation center on the description of "the time–averaged flow (of the atmosphere), where averages are taken over periods sufficiently long to remove the random variations associated with individual weather systems but short enough to retain seasonal variations" (Holton, 1979). However, as we move to the "how" questions of the general circulation, external factors must be dealt with to a greater or lesser degree. Foremost of these is solar radiation, the ultimate energy source for the general circulation. This is clearly an external parameter, independent of the general circulation itself.

A second set of external parameters are the surface boundary conditions, which play a fundamental role in the tropical circulation (Shukla, 1981). One may view the atmospheric general circulation in terms of the specific climatological boundary conditions, but in reality they are not independent of the circulation itself, but rather are determined in part by coupled atmosphere/ocean/land surface interactions. They are boundary conditions for the individual components of the climate system, but internal conditions in terms of the coupled climate system. Thus for a full description and understanding of of the processes of the general circulation we must address the entire system.

For example, the way in which the atmosphere responds to incoming solar radiation depends on how the incoming energy is processes through the climate system. We cannot adequately diagnose the heat balance of the atmosphere, including the required poleward transports by simply knowing the radiative imbalance at the top of the atmosphere. We also must know, direct or indirectly, the seasonal heat storage and poleward transport by the ocean. Just as General Circulation Models which began with only an atmospheric component (Phillips, 1956) have evolved into Global Climate Models with land and ocean components, so the concept of the general circulation has become intertwined with the concept of climate, and indeed might now be viewed as part of the climate problem. The spirit of this review reflects this point of view.

With such a broad conceptual framework, one can deal with only selected aspects of the subject in a review of this length. The particular features of the general circulation of the tropics which I have chosen to highlight are strongly skewed toward my own interests and research background in observational studies. This leaves a host of important topics either not addressed at all or treated in a highly cursory manner. Fortunately, many of these topics will be addressed in later lectures.

This review is therefore primarily descriptive in nature, i.e. the "what" and a little of the "how" of the tropical general circulation. It is hoped that it will provide useful background for subsequent lectures by my colleagues that will probe into the more profound "why" questions. Except for parts of the historical overview (Section 2), attention is limited to the tropics in general, and focused on the Equatorial Trough Zone (ETZ) in particular.

2. HISTORICAL OVERVIEW

"Every theory of the course of events in nature is necessarily based on some process of simplification of the phenomena and is to some extent, therefore, a fairy tale." Sir Napier Shaw, Manual of Meteorology (1936).

After providing a definition of the atmospheric general circulation, Holton (1979) went on to say that "A complete understanding of the physical basis for the general circulation requires a description involving the three spatial dimensions as well as time". This was certainly not the case for the "classical theory" originated by George Hadley (Hadley, 1735), which was widely accepted prior to the turn of the century. Skeptical of earlier explanations ("I think the causes of the general trade–winds have not been fully explained.") Hadley reasoned that the tradewinds are the lower branch of a hemispheric–wide thermal convection cell driven by the difference in solar heating between high and low latitudes. He considered transient disturbances to be irrelevant ornaments, uncoupled from the processes of the general circulation. He also believed that the zonal asymmetries of the circulation as well as the annual cycle were unimportant. Consequently, the general circulation could be described once and for all as a steady–state, zonally symmetric circulation.

Hadley's picture of the general circulation may seem naive to us today, but the explanation was not inconsistent with the knowledge of the time. The Coriolis force as well as the conservation of absolute angular momentum were yet to be properly understood (Hadley assumed that absolute velocity rather than absolute angular momentum was conserved). Moist thermodynamic processes were still unknown, as was the process of turbulent exchange. Finally, the circulation and the structure of the atmosphere above the surface were yet to be observed, and even the scattered surface observations were less than definitive.

Although Hadley's picture of a single hemispheric circulation cell was modified during the last half of the 19th century in order to bring it into conformance with new observations and the improved understanding of atmospheric processes, the general circulation continued to be viewed as a zonally symmetric feature by most authors, e.g. Thomson (1857), Ferrel (1859). In fact, the custom of viewing the general circulation as primarily a collection of zonally averaged statistics has continued long after of zonal asymmetries and transients were recognized as fundamental elements.

The early decades of the 20th century witnessed numerous futile attempts to salvage the classical framework in the face of increasing observational evidence that the picture was fundamentally flawed. The classical theory finally collapsed in the face of overwhelming evidence that the asymmetries and transients played a fundamental role in satisfying the balance requirements of the atmosphere. The general circulation was far more complex then Hadley had supposed.

2.1 Zonally Averaged Statistics: 1948–1970

The current observational picture has largely evolved since World War II. The initial advances were a consequence of the establishment of a near global rawinsonde network of upper air observations during the decade immediately following the war. The major scientific issues of the time centered on the relative importance of the symmetric component and the eddies, and the nature of the eddies and eddy transports, particularly the appropriateness of viewing and parameterizing them as large scale turbulence elements.

With the availability of large quantities of upper air data, it became clear that many of the zonally averaged quantities required to settle these issues could be evaluated reasonably well from the new observations. Analysis techniques to estimate transports by the transient and stationary eddies and the mean meridional circulation, based on Jeffries formulation in terms of mean and eddy correlation fluxes (Jeffries, 1926), were developed by Priestly (1949) and Starr and White (1954). Lorenz (1955) made a fundamental contribution to this effort through the formulation of the atmospheric energy cycle in terms of available potential energy. Many of the quantities in Lorenz' equations could also be estimated directly from the new observations.

Other post–war developments provided powerful research tools for gaining a deeper understanding of the new observational results. Prior to this time, subjective reasoning based on the governing equations, or analytic solutions of highly simplified models were the only means available for interpreting the observations. The development of dynamical weather prediction, and its' extension to the study of the general circulation (Phillips, 1956; Smagorinsky et al., 1965) provided a research tool of fundamental importance for studying the general circulation. These general circulation models, together with insight gained from rotating "dishpan" and annulus laboratory experiments (Riehl and Fultz, 1958; Fultz et al., 1959) allowed idealized atmospheres as well as approximations of the real atmosphere to be studied.

In many respects, the period 1948–1970 was a golden age in the description of the zonally averaged properties of the atmosphere, and many important papers and monographs resulted from this research. Although the observational picture has continued to be refined and extended, many of the salient features of the zonally averaged circulation were reasonably well described by 1970, at least in terms of the major questions of the time. The brilliant monograph by Lorenz (1967) beautifully summarized the current knowledge and understanding of the zonally averaged general circulation, and also provided an excellent review of the development of this knowledge.

Major features of the zonally averaged circulation of the Northern Hemisphere which emerged from these studies can be summarized as follows.

Angular Momentum Balance

a. The mean meridional circulation consists of three cells in each hemisphere; a dominant direct tropical cell circulation (Hadley cell), a much weaker indirect circulation in middle latitude (Ferrel cell), and a relatively insignificant high latitude direct cell.
b. Observations showed a maximum poleward eddy flux of angular momentum at about 30°N and a maximum flux convergence at about 45°N. The transport by the mean meridional circulation is not a significant fraction of the total angular momentum flux in extratropical latitudes.

Energy Cycle

a. The zonal mean radiative heating generates mean zonal available potential energy through a net heating of the tropics and cooling of the polar regions.

b. Baroclinic eddies transport warm air northward, cold air southward, and transform zonal available potential energy to eddy available potential energy.

c. At the same time eddy available potential energy is transformed into eddy kinetic energy by the vertical motions in the eddies.

d. The zonal kinetic energy is maintained primarily by the conversion from eddy kinetic energy through the correlation $u'v'$ (see Angular Momentum Balance).

e. The kinetic energy is dissipated by surface and internal friction primarily in the eddies (most of the surface dissipation takes place in the eddies rather than in the mean flow despite the fact that the mean flow kinetic energy is larger than the eddy kinetic energy).

f. In summary, the observed atmospheric energy cycle is consistent with the notion that the eddies which result from the baroclinic instability of the mean flow are to a large extent responsible for the energy exchange in the extratropical atmosphere.

2.2 Observing the Tropics: 1960–1990

"When you can measure what you are speaking about and express it in numbers, you know something about it; but when you cannot measure it, when you cannot express it in numbers, your knowledge is of a meager, unsatisfactory kind." Lord Kelvin (quoted by S. Petterssen in Weather Analysis and Forecasting, 2nd Edition, 1956).

While the rawinsonde network established after World War II was generally adequate for describing the general circulation over the extratropical Northern Hemisphere in some detail, the small number of stations in the Southern Hemisphere and over the Northern Hemisphere tropics left observational gaps which were too large for reasonable extrapolation between stations, thus precluding definitive quantitative results. For example, a total observational void generally existed over the crucial tropical sector extending from the coast of South American westward to Canton Island (near 170° W), more than one quarter of the distance around the earth.

The major advances in the description and understanding of the circulation of the tropics which have taken place during the past three decades coincide with, and are in no small measure the result of the era of satellite observations. The first meteorological satellite (TIROS–1) was launched on April 1, 1960. The initial operational product from this new observing system was a nephanalyses subjectively derived from the satellite television pictures. Time–averaged nephanalyses and brightness fields strikingly revealed the patterns of tropical cloudiness and convection, over both land and ocean. The comprehensive picture of time–space variability which the satellites provided lead to major advances in our qualitative understanding of tropical climatology. Among the most important developments was the clear indication of planetary–scale east–west circulation asymmetries in the equatorial belt, which lead J. Bjerknes (1969) to link tropical Pacific sea surface temperature (SST) variations and Walker's Southern Oscillation.

Our understanding of the structure and evolution of synoptic–scale features was greatly enhanced following the launch of the first geosynchronous satellite on December 6, 1966. Geosynchronous data, together with outgoing longwave radiation (OLR) data from polar orbiters have provided a comprehensive picture of synoptic cloud clusters as well as the 30–60 day variations in convection that are a prominent feature of variability over the Indian Ocean–western Pacific sector. They have also provided a basin–scale description of the evolution of the convection regimes over the tropical Pacific associated with the El Niño/Southern Oscillation (ENSO) cycle.

The information on rainfall variability from the early satellite products was indirect and essentially qualitative. The GARP Atlantic Tropical Experiment (GATE) conducted in 1974, provided the co–located satellite data and area–averaged precipitation estimates needed to develop an objective scheme for quantitative estimates of large–scale, time averaged precipitation over the global tropics (Arkin, 1979). The relative success of this technique, which derives precipitation estimates indirectly from cloud structure information provided by high–resolution geosynchronous IR and visible data, and the prospects for obtaining useful direct estimates of precipitation from operational microwave radiometers led the World Climate Research Programme (WCRP) to institute a Global Precipitation Climatology Project (GPCP). The objective of this program is to provide global rainfall analyses for the various WCRP research programs (Arkin and Ardanuy, 1989).

The value of satellite data has not been limited to the observation of cloudiness and the estimation of rainfall. SST is a most important element of the tropical general circulation. Estimates of SST derived from multi–channel satellite IR data, when used in tandem with the otherwise inadequate time/space distribution of ship observations, have provided a far better picture of the tropical SST field than previously available.

Atmospheric temperature profiles derived from satellite data are of less value in the tropics than in the extratropics. However, the wind estimates derived from cloud motion vectors, although of rather low quality, provide valuable information on the lower and upper tropospheric circulation over the vast ocean areas of the tropics where wind observations are otherwise unavailable.

Increasing interest in the role of the tropics in the general circulation, and the need for improving the physics of prediction models gave rise to a number of large–scale tropical field experiments during the late 1960's and 1970's. The Atlantic Tradewind Experiment (ATEX) (Augstein et al., 1973) and the Barbados Oceanographic and Meteorological Experiment (BOMEX) (Holland and Rasmusson, 1973) were conducted during the summer of 1969 in the eastern and western Atlantic tradewind belt, respectively, to examine the processes of sea–air fluxes, and the structure of the tradewind flow. The Global Atmospheric Research Program (GARP) Atlantic Tropical Experiment (GATE), which took place in 1974, was designed to resolve questions concerning the nature of tropical convective systems, i.e. cloud clusters. This was followed by the Monsoon Experiment (MONEX), another GARP program, designed to study aspects of the summer and winter monsoon. The decade of GARP experiments closed in 1979 with the First GARP Global Experiment (FGGE) during which the observational network over the tropics was substantially augmented.

The 1980's have been the decade during which interest in tropical coupled ocean/atmosphere interactions has come to the fore. This has resulted in the launching of the Tropical Ocean Global Atmosphere (TOGA) Program, which extends from 1985 through 1994. The fundamental objective of TOGA is the modelling and determination of the predictability of the coupled system, and an important aspect of the experiment has been the substantial augmentation of ocean observations over the tropical Pacific.

Even with the new satellite data, the description of the tropical circulation which can be gleaned from subjective or purely statistical analyses is limited. A good example is the divergent component of the circulation. An important development during the 1980's has been the steady improvement in the quality of the "model assimilated data sets" generated by global weather forecast centers. These analyses now appear to provide quite useful information on many important features of the tropical circulation, including the divergent wind field, which cannot be adequately defined by subjective analyses.

3. OBSERVATIONAL ASPECTS OF THE TROPICAL CIRCULATION

"The literature which may be classified under the heading 'equatorial trough' is abundant. Most remarkable is the extreme divergence of opinion concerning the nature, structure and life cycle of the disturbances in the trough zone. Complete models and life cycles cannot be presented. A regional treatment cannot be attempted. The reader will realize that here is indeed a rich field for research and discovery both empirical and theoretical." Herbert Riehl, Tropical Meteorology, 1954.

All things considered, the mid–1960's serve as a convenient point from which to measure the recent major advances in our knowledge of the tropical circulation. During the subsequent quarter–century, vast amounts of new data were synthesized into a far more extensive and coherent picture of the tropical circulation than existed at the time Riehl made the statement quoted above. This has been an exciting and rewarding effort, with the resulting advances in our knowledge of the tropical circulation rivaling in importance the post–war advances in the description of the extratropical circulation.

This section represents a broad brush, personal view of some salient aspects of the tropical circulation which have received considerable attention during the past quarter–century. Four themes will be emphasized.

The Annual Cycle and Zonal Asymmetries

Partly because of data limitations, many of the observational results during the immediate post–war period consisted of annually and zonally averaged statistics. Observational studies during the 1960's showed that annual averages often provided an incomplete or even misleading picture of the general circulation. Noteworthy in this regard were a pair of papers by Palmén and Vuorela (1963) and Vuorela and Tuominen (1964) which together showed the annually averaged Hadley circulation to be a relatively bland mix of vastly different seasonal circulations.

As work continued, the importance of the tropical annual cycle became increasingly clear. The annual cycle is not only a fundamental aspect of the mean circulation, but many aspects of low–frequency variability exhibit characteristic seasonal anomaly patterns, and the interannual time–scale ENSO cycle exhibits a preferred "phase–locking" with the annual cycle.

Once the annual variation of the Hadley circulation became clear, a new set of questions emerged regarding the interpretation of zonal averages that are derived from the vastly different monsoon, tradewind and continental circulation regimes (Lorenz, 1967). Was the annual cycle of the Hadley circulation primarily a reflection of the seasonal monsoon reversals, or was it also reflected in the tradewind belts? This question will be further examined in section 3.1.

The presence of the continents, with their uneven topography, contrasting surface thermal characteristics, and blocking effect on the ocean circulation leads to planetary–scale asymmetric features of the atmospheric circulation, i.e. the tradewind systems, monsoon, subtropical highs and oceanic convergence zones. Questions concerning the regional contributions to the zonally–averaged Hadley circulation are but one aspect of more general questions regarding the role of zonal asymmetries in the general circulation. In a seminal paper on large–scale tropical interactions, J. Bjerknes (1969) outlined a sweeping new conceptual framework which linked many of these features to ocean variability in a plausible manner. In fact, all four aspects of the general circulation which are being highlighted in this review were woven into Bjerknes conceptual framework. It seems difficult, in retrospect, to overrate the importance of this paper, for it had a profound effect on our view of the tropical circulation. It provided new insights into the importance of ocean–atmosphere coupling and its relationship to zonally asymmetric circulation features, and raised an entirely new set of questions to be answered. It marked the beginning of new directions in research on the tropical circulation which have exploded into a major scientific effort during the 1980's.

The Role of the Tropical Oceans

The circulation systems of the ocean and atmosphere are coupled through energy and momentum exchanges across the air–sea interface. The atmosphere "feels" the ocean at its lower boundary through the SST. The ocean, in turn feels the atmosphere through the surface wind stress, which drives the upper ocean circulation, and through the surface heat and salinity fluxes. Among the most important developments in our understanding of the tropical general circulation has been the recognition of the importance of coupled ocean/atmosphere interactions in the equatorial belt, and the emergence of at least a rudimentary understanding of some aspects of this dynamical coupling. The original stimulus for these developments was again Bjerknes' 1969 paper, which exposed the interannual time–scale ENSO cycle. It now seems clear that an understanding of the coupled annual cycle is also a requirement for understanding interannual variability, as the two seem to be intimately intertwined (Münnich et al., 1990).

The Tropical Hydrological Cycle

The fundamental role of tropical convection in the general circulation has long been recognized. Contrary to the situation in the extratropics, where the energy cycle can be described to a first approximation in terms of dry atmospheric dynamics and thermodynamics, the hydrological cycle is crucial to the tropical energy balance and general circulation. Major advances in the description and understanding of the tropical hydrological cycle in general, and tropical precipitation systems in particular have taken place since 1965.

The tropics are a region of net radiational heating, but this heating occurs primarily in the upper layer of the ocean. The atmosphere is in turn heated from below, principally through the transfer of latent heat by evaporation. The global hydrological cycle is most intense in the tropics and subtropics. The semi–arid subtropical oceans, where evaporation is much larger than precipitation, are the major source regions for atmospheric water vapor. Some of this moisture is transported poleward, where it condenses and releases its latent heat mostly in the storm tracks of the middle latitudes. Most of the moisture is swept by the planetary–scale tradewind systems into the convergence zones of the deep tropics, i.e. the low pressure regions which constitute the ETZ. Here, in the "firebox" of the atmospheric general circulation, the latent energy "fuel" from the tradewind belts, supplemented by local evaporation, is converted into sensible heat in the towering convective systems that populate the ETZ. Part of the sensible heat released in the summer hemisphere is transported into the winter hemisphere by the regional divergent circulations which together make up the upper branch of the wintertime Hadley cell.

The conventional scenario for large–scale tropical moisture transport and convergence was developed from observations in the northeast trades of the North Atlantic and North Pacific, where the tradewind flow converges into a trough zone (ITCZ) located in the same hemisphere. This equatorward low–level moist flow is confined beneath a tradewind inversion that is maintained as a balance between large–scale subsidence and small–scale upward transport and associated shallow convection (tradewind cumulus). The inversion increases in elevation as the air flows equatorward, loosing its identity as the air flows into the ITCZ.

The situation is more complex in the trans–equatorial monsoon circulations, and in the equatorial belt extensions of the southeast trades of the Southern Hemisphere. Here the air ultimately flows across the strong SST gradient on the north flank of the equatorial upwelling cold tongue, on its way to the Northern Hemisphere convergence zone (Deser, 1989).

This characterization of the tropical hydrological cycle is couched primarily in terms of large–scale, time averaged features. In reality, the time–averaged precipitation regimes derive from the individual contributions of synoptic cloud cluster "building blocks", which vary regionally in frequency, intensity and character. The nature of synoptic disturbances will be addressed in a subsequent lecture. Regarding their bulk properties, each transient synoptic system contains an area of deep convection generally referred to as a cloud cluster. The ensemble of cluster processes is quite complex, including downdrafts as well as updrafts, entrainment and stratiform precipitation. The latent heat release takes place primarily in the individual cumulus elements, i.e. the rising "hot towers" of the cluster. The upward mass transport by the convective systems, when averaged around a latitude circle, constitutes the upward mass flux of the the Hadley cell.

Hot towers are circulation features analogous to enclosed smokestacks. Malkus and Riehl (1958) recognized their importance as the mechanism for energy transport into the upper troposphere. This upward energy transport cannot be accomplished by large–scale upward motion because of the equivalent potential temperature minimum in the middle troposphere. This inconsistency was another fatal flaw in Hadley's picture which required zonally symmetric rings of rising air in the tropics.

Systematic Modes of Variability

An entirely new feature of tropical variability, the stratospheric QBO, was discovered in the early 1960s, and an explanation of the phenomenon was provided a few years later by Lindzen and Holton (Lindzen, 1987). It is now apparent that systematic, large amplitude modes of intraseasonal (Madden–Julian Oscillation) and interannual variability (the ENSO cycle) are also features of the tropical circulation. While these "oscillations" are far less regular than the QBO, they are nevertheless of great importance for global climate variability, and for understanding the behavior of the tropical circulation.

The revival of interest in the Southern Oscillation was another result of the insightful paper by Bjerknes (1969) in which he linked the Southern Oscillation atmospheric anomalies to interannual variations in equatorial Pacific SST, thus converting the Southern Oscillation into a part of the coupled ocean/atmosphere El Niño–Southern Oscillation (ENSO cycle). The existence of a remarkable tropical oscillation on the 30–60 day time–scale was discovered by Madden and Julian (1971, 1972). While the ENSO cycle owes its existence to coupled ocean–atmosphere interactions, the Madden–Julian Oscillation appears to evolve too rapidly to become dynamically coupled with the ocean. However, among the many intriguing results emerging from many studies during this decade is the remarkable similarity of evolution of the Madden–Julian "fast mode" and the ENSO cycle "slow mode" of atmospheric variability. The relationship between these two modes will be further addressed in section 3.2.

3.1 Zonally Averaged Features

The charts which accompany the discussion in sections 3.1 through 3.4 represent only a smattering of what is needed for a comprehensive description. There now exist a large number of atlases and monographs which together present a for more complete picture of the various aspects discussed. A few of these will be cited in the course of the discussion.

The low latitudes receive more incoming solar energy than do the polar regions. In addition, sea ice and snow cover reflect a much higher percentage of the solar radiation at high latitudes than do the darker, open waters of the low– and mid–latitude oceans. This further increases the latitudinal gradient of absorbed solar radiation. On the other hand, the latitudinal gradient of outgoing longwave radiation associated with the pole to equator temperature gradient is much flatter. This difference results is a latitudinally–varying radiative imbalance at the top of the atmosphere. There is net radiative heating at low latitudes and net cooling at high latitudes. Since the radiative imbalance must be offset by a poleward transport of energy, there exists a fundamental coupling between the radiation budget of the earth and the general circulation of the atmosphere and ocean.

The annual cycle is a fundamental element of the tropical general circulation which couples the circulation of the two hemispheres through inter–hemispheric shifts of the climatic zones and large seasonal cross–equatorial transports of mass, heat and moisture.

Figure 1 shows the mean northward energy transport by the atmosphere and oceans during the solstice seasons (December–February and June–August), as estimated by Carissimo and Oort (1985). Direct estimates of heat transported by the oceans have large uncertainties because of inadequate measurements of the ocean currents and thermal structure. Consequently, this quantity was obtained using computed values of ocean heat storage and the difference between the more accurately measured atmospheric energy transport and radiative imbalance. The quantitative values are not yet definitive, since sampling errors exist in the estimation of all the terms.

Even with the observational uncertainties, Fig. 1 clearly illustrates the importance of the tropical ocean as well as the atmosphere in the planetary heat balance. On a mean annual basis (not shown) there is a net heating in the tropics and transport from the

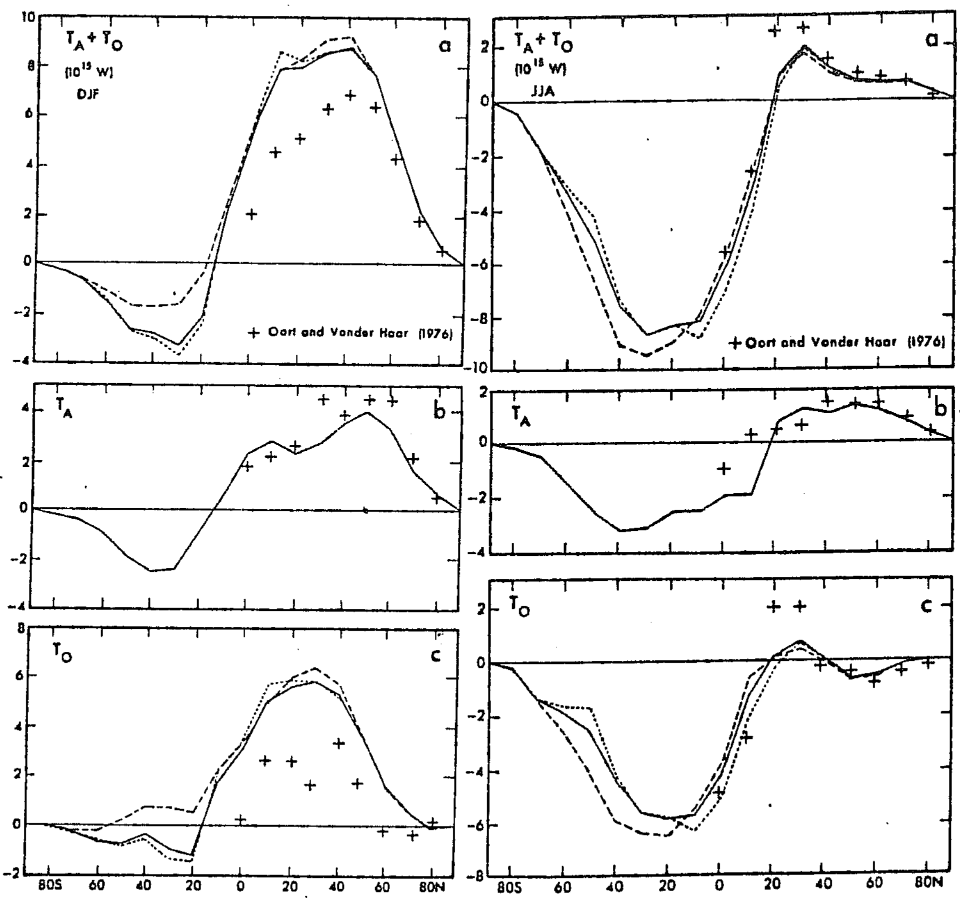


Fig. 1 Northward energy transports for December–February (left) and June–August (right). (a) total transport, (b) atmospheric transport (from Oort and Peixóto, 1983), (c) residual oceanic transport. In (a) and (c) the dashed, solid and dotted lines show the transports computed using oceanic storage values for the layers 0–112, 0–225 and 0–550 m, respectively. Values obtained by Oort and Vonder Haar (1976) are plotted for comparison. Units: 10^{15} W. (From Carissimo and Oort 1985).

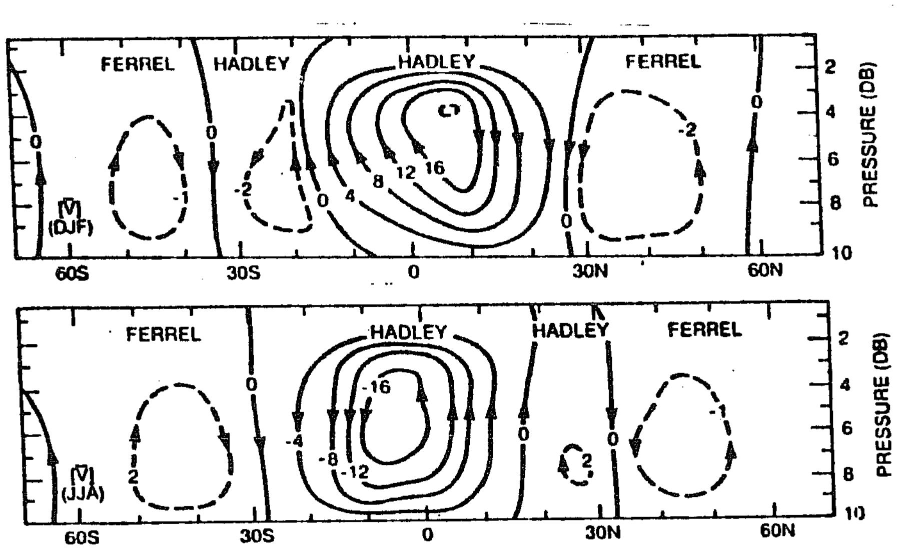


Fig. 2 Mean meridional circulation for December–February (upper) and June–August (lower) based on data provided by A. H. Oort. Units: 10^{10} kg/s.

equatorial belt to higher latitudes of both hemispheres (Carissimo and Oort, 1985). However, the mean seasonal transports which are shown on Fig. 1 are very different. There is a transport by both the ocean and atmosphere from the tropics of both hemispheres into the winter hemisphere extratropics during the solstice seasons. This illustrates the desirability of viewing the tropics of the two hemispheres as a single unit.

With a few notable exceptions such as water vapor variations between warm tropical ocean areas and dry desert regions, the tropical meteorological fields show much smaller horizontal and temporal variations than do the extratropical fields. Furthermore, the temporal and spatial correlations between the meridional component of flow and the temperature or specific humidity are relatively small in the tropics. Consequently, the zonally averaged horizontal eddy transports are relatively when compared to the extratropics, e.g. see Oort and Peixóto (1983). The strong Hadley circulation is the dominant factor in the zonally averaged circulation of the tropics.

Figure 2 shows estimates of the solstice season mean meridional circulation. Figure 3 shows the seasonal cycle of the zonally–averaged surface zonal and meridional components averaged over the ocean areas of the world. These figures again reveal that the average annual values are profoundly different from individual seasonal averages. Except for the brief late equinox season transitions, the winter hemisphere Hadley cell is dominant. During the solstice seasons the lower branch of the Hadley circulation transports a huge amount of water vapor into the zonally averaged ETZ of the summer hemisphere, while the upper branch in turn transports sensible heat back into the winter hemisphere.

Figure 4 shows the annual march of zonally averaged SST, while Fig. 5 shows the zonally averaged OLR. As noted before, it has been established empirically that OLR serves as a good index of time–averaged precipitation variability in the deep tropics. Low values of OLR indicate widespread deep convection and heavy precipitation; high values indicate the reverse. Even though the OLR average includes the continental areas as well as the oceans, there is a notable coincidence between the SST maximum, the OLR minimum, and the zonally averaged low–level convergence belt of the Hadley circulation. In fact, the zonally–averaged annual cycle of OLR is better phased with the delayed seasonal cycle of SST than with equatorial land surface temperatures, which more closely follow the annual cycle of insolation. This coherent pattern is clearly consistent with a zonally averaged direct thermal circulation, in which the zonally averaged SST gradient is the fundamental driving force.

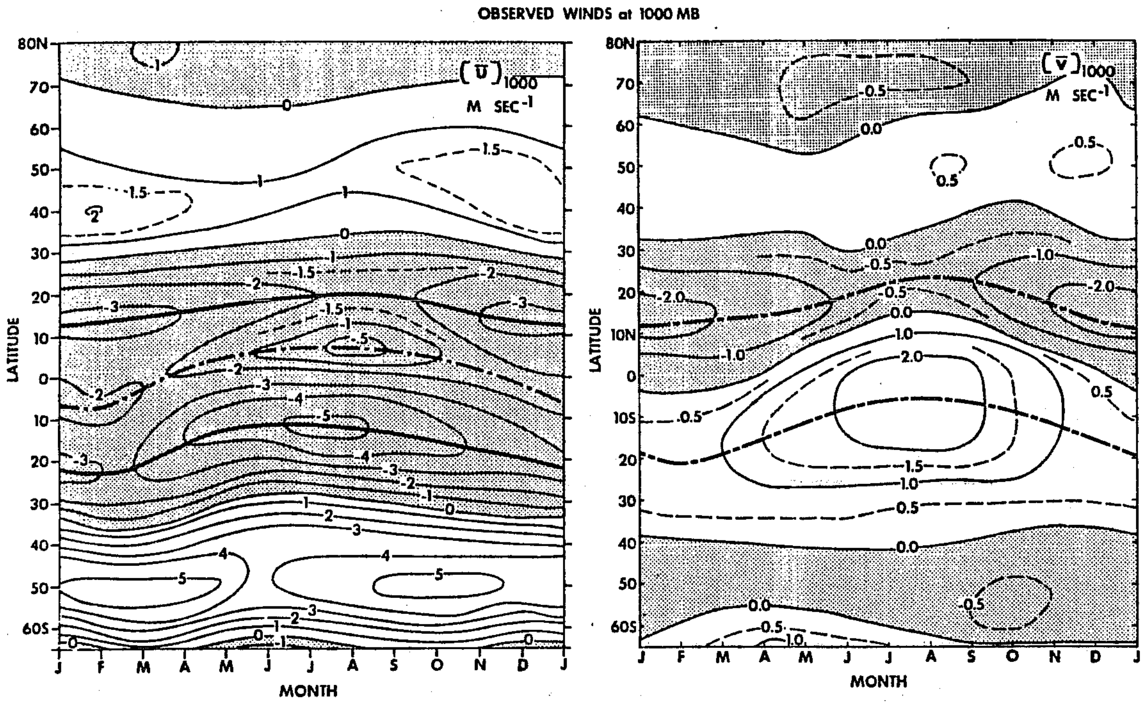


Fig. 3 Zonally averaged long-term monthly mean zonal (left) and meridional (right) components of the surface circulation over the oceans. Units: m/sec. (From Oort and Rasmusson, 1971).

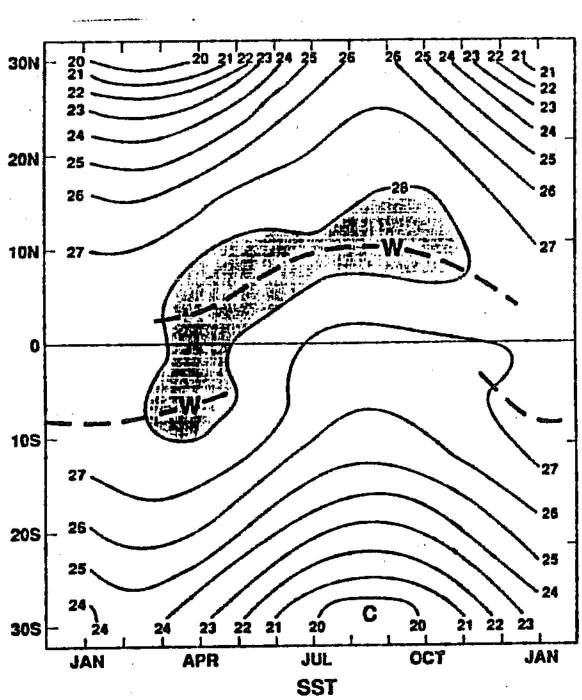


Fig. 4 Same as Figure 3 for SST. Units: °C. Values greater than 28°C are shaded.

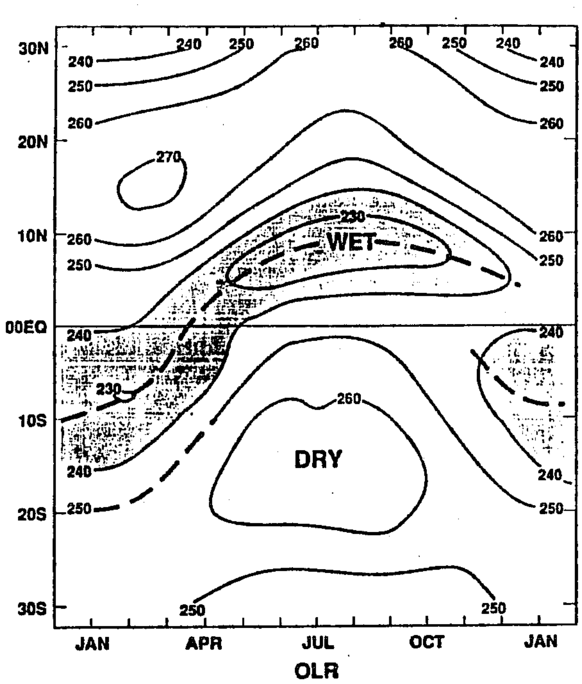


Fig. 5 Same as Figure 3 for OLR. Units: W/m^2. Values less than 240 W/m^2 are shaded.

Considering only the annual cycle of insolation, one might expect to see a dominant semi–annual harmonic in SST and precipitation in the equatorial belt. While the semi–annual harmonic is significant over the continents within about 5° of the equator, its' relative amplitude is generally small over the oceans (Halpert and Ropelewski, 1989). Nevertheless, there are asymmetries in the annual cycle. The well known asymmetry about the equator is apparent, with the annual average position of the SST and precipitation maxima located a few degrees north of the equator. Secondly, there is also a lack of seasonal symmetry in the OLR and SST averages. Specifically, the inter–hemispheric transition during the equinox equatorial crossing around April is somewhat smoother and more continuous than the reverse crossing late in the year, when the SST maximum and OLR minimum show a stronger tendency to "jump over" the equator.

To describe this behavior one must examine the SST annual cycle around the entire latitude circle. Figure 6 shows the zonally asymmetric distribution of SST along the equator. Relatively high temperatures occur over the Indian Ocean–west Pacific monsoon sector, while relatively low temperatures are found over the central and eastern Pacific and the Atlantic longitudes that are affected by equatorial upwelling. Over this sector, the SST annual cycle is predominantly under the domination of the large–scale circulation features of the Southern Hemisphere throughout the year, and exhibits a predominant annual harmonic. Colder water appears during the late southern winter, when the atmospheric circulation and the resulting upwelling that affects SST and the precipitation regime out to the dateline (Horel, 1982) is most intense. This feature will be further examined in the next section.

3.2 Surface Circulation Features

Because of the relationship of tropical convection to SST, and the fundamental importance of the latent heating as a determinant of the time–averaged circulation, it is convenient to begin a discussion of the surface circulation by first describing the tropical SST and precipitation fields.

Satellite "snapshots" reveal the basic mesoscale character of convective precipitation associated with tropical synoptic disturbances. When these "high frequency" variations are averaged over several weeks or longer, the large–scale, coherent rainfall patterns associated with the ETZ emerge. Figure 7 shows the mean OLR fields for the two solstice seasons. Experience suggests that areas in the tropics where time–averaged OLR is less than 240 W/m^2 generally correspond with the regions of mean upward motion and heavy convective rainfall.

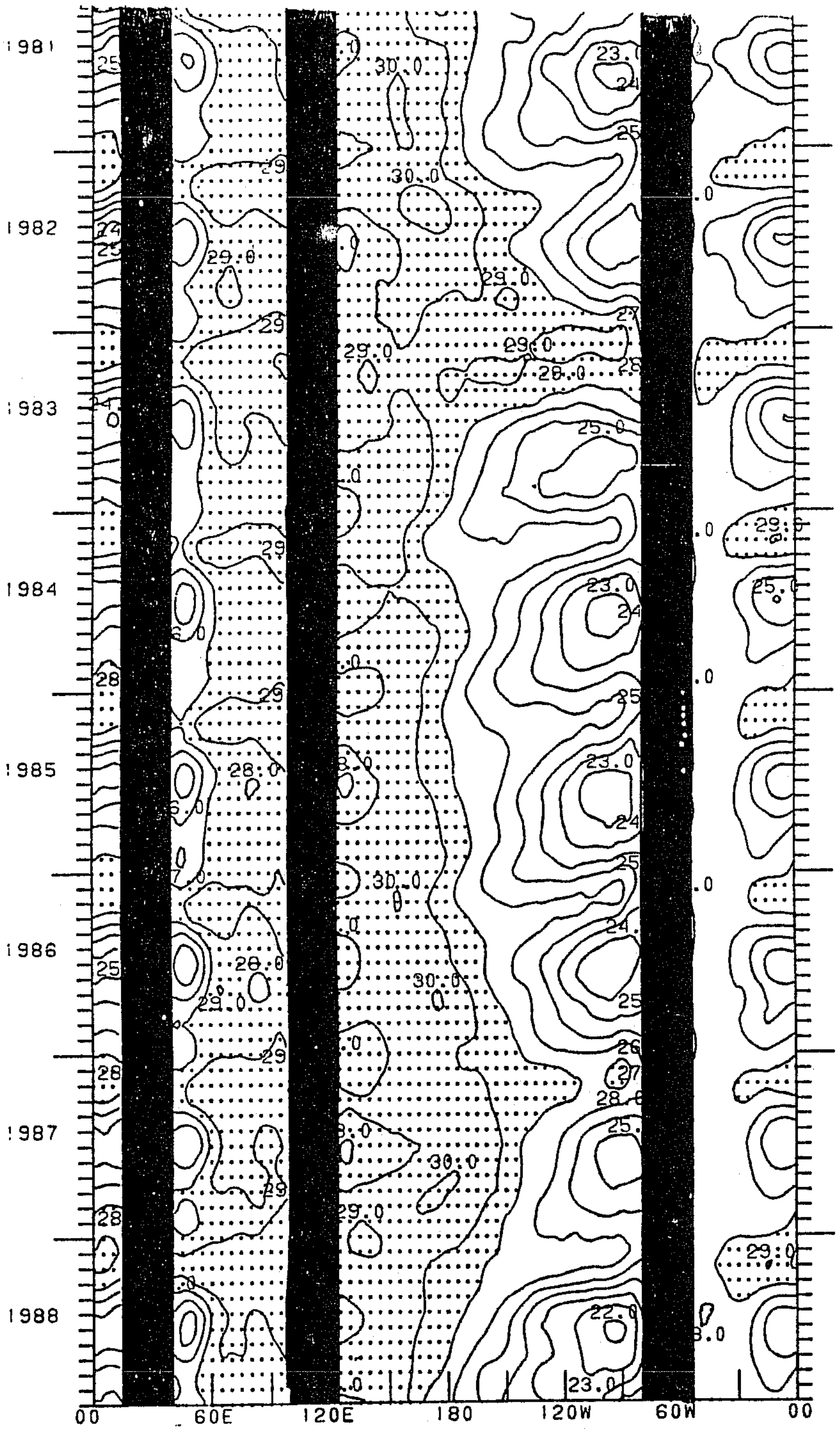


Fig. 6 Mean monthly values of SST. Units: °C. Values greater than 28° are hatched.

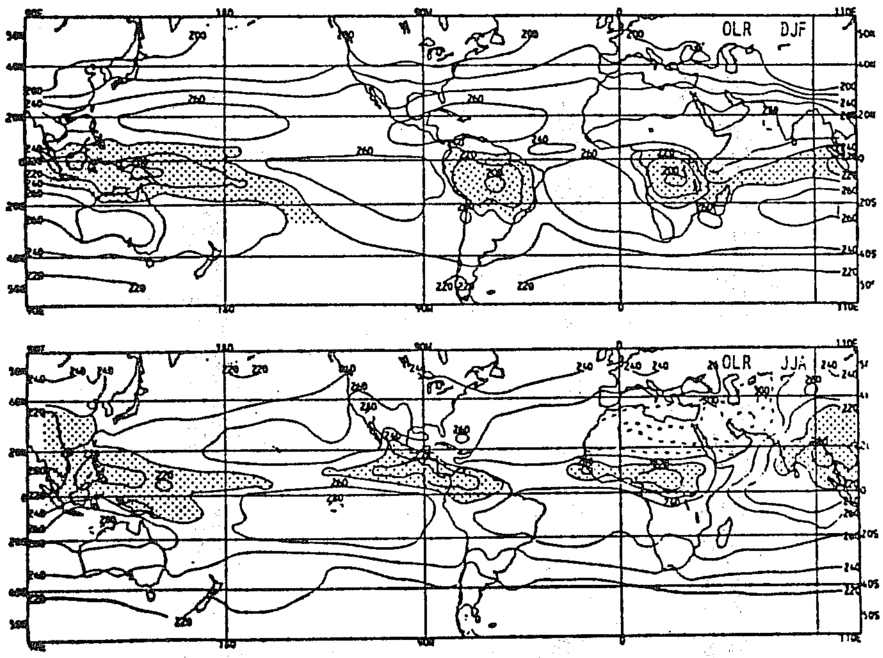


Fig. 7 Mean OLR for December–February (upper) and June–August (lower). Areas where OLR is less than 240 W/m^2 are stippled. Contour interval: 20 W/m^2.

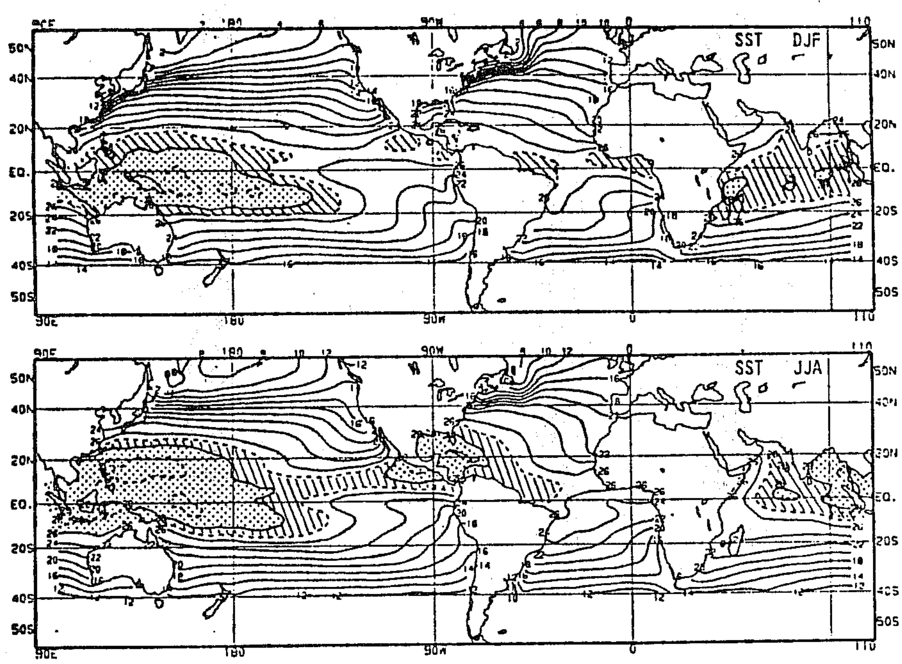


Fig. 8 Same as Figure 7 for SST. Units: °C. Contour interval: 2° C (solid). Areas where SST exceeds 28° C are stippled; areas between 27° C – 28° C are hatched.

One large–scale OLR minimum (precipitation maximum) is located over Africa, another over South America/Central America; both migrate north–south with the high sun season. The third and most extensive area is centered over the land areas and adjacent warm waters of the east Asian–Australian monsoon region, with eastward extensions along the the ITCZ north of the equator, and the South Pacific Convergence Zone (SPCZ) in the southwest Pacific. The three regions of heavy precipitation implied by the OLR mark the primary upward branches of the time–averaged direct thermal circulations of the tropics.

The tropical circulation and rainfall regime are closely related to the annual cycle of surface temperature, which, for most of the tropics, is SST (Fig. 8) Even though the annual cycle in tropical SST is relatively small, tropical convection is quite sensitive to these differences. Specifically, the tropical oceanic regions of OLR less than 240 W/m^2 lie mostly within the 28°C SST isotherm. The east–west SST difference between the upwelling region of the eastern equatorial Pacific, and the huge "warm pool" that overlays the west Pacific–eastern Indian Ocean monsoon region is particularly important. Comparison of Figs 7 and 8 reveals a good correspondence between the location and seasonal migration of the west Pacific–Indonesian warm pool and the monsoon precipitation regime. Thus, the time–averaged planetary–scale thermal circulations not only reflect the classical land–sea monsoon forcing, but also reflect the pronounced forcing due to large–scale SST gradients, the "oceanic monsoon effect", if you like.

The relationship between the annual cycle of SST, precipitation and surface circulation is further revealed by Figs. 9–11, which show mean monthly departures from the annual mean for SST, vector wind and OLR fields. The months of March and September were chosen for comparison because of their rough correspondence to the seasonal SST maxima and minima. (The phasing of the annual cycle over the equatorial oceans varies by one to two months (Halpert and Ropelewski, 1989)).

Like the comparable zonally averaged fields, there are many coherent features appearing on these charts which are worthy of note.

a. The annual cycle of the Hadley circulation is reflected in the low–latitude wind field over most of the tradewind belt, as well as over the monsoon sector. The annual cycle in the tradewind meridional flow is clearly related to the seasonally–varying SST gradient (Fig. 10).

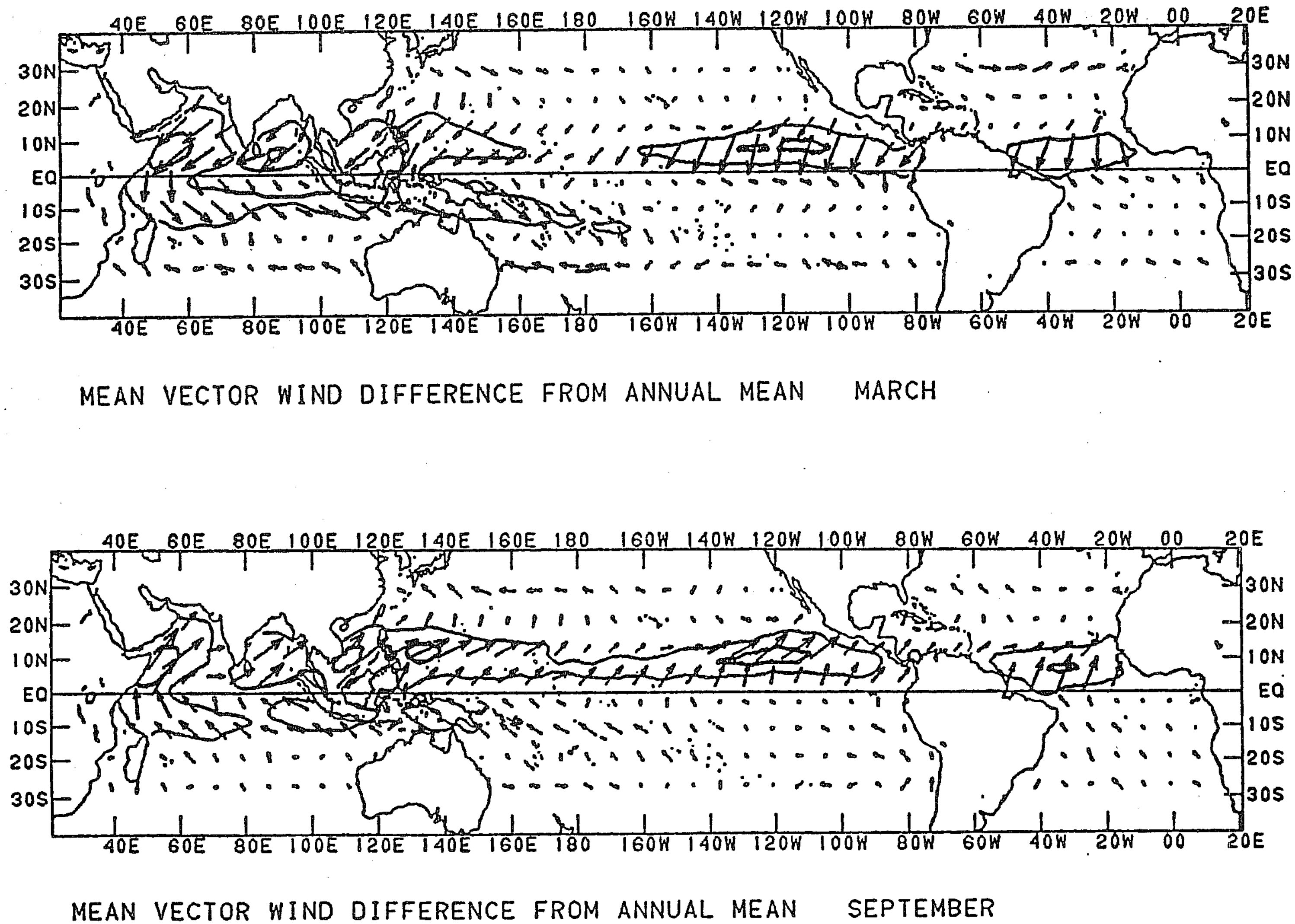


Fig. 9 Mean monthly surface vector wind difference from long term annual mean for March (upper) and September (lower). Contour interval: 2.5 m/s. (From Halpert and Ropelewski, 1989).

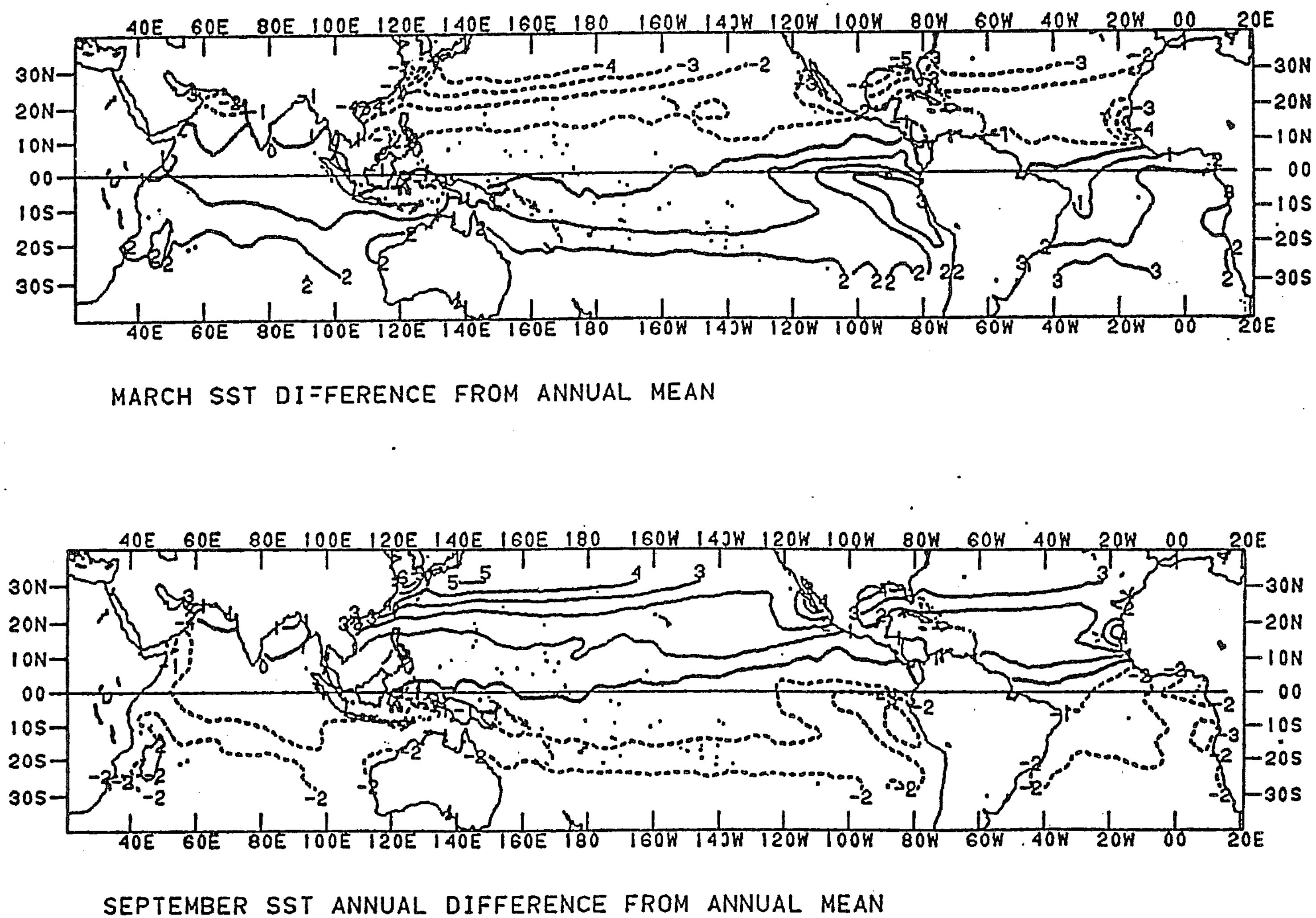


Fig. 10 Same as Figure 9 for SST. Contour interval: 1°C. Negative contours dashed. (From Halpert and Ropelewski, 1989).

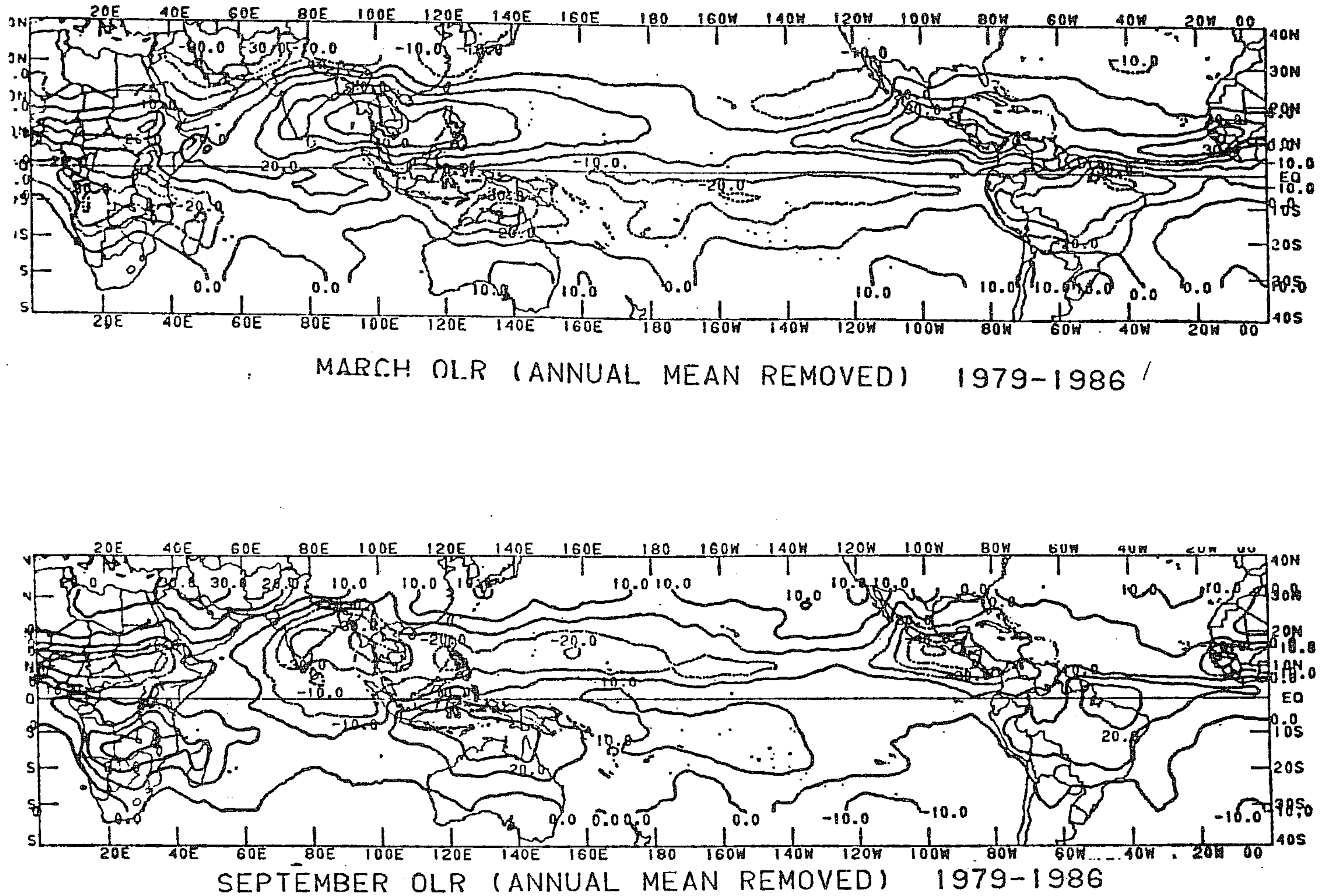


Fig. 11 Same as Figure 9 for OLR. Contour interval: 10 W/m^2. Negative contours dashed.

b. A consistent annual cycle is also reflected in the OLR fields across the Atlantic and Pacific. Although a convergence zone remains in the North Atlantic and northeast Pacific throughout the year, it varies in strength, being more intense in late summer–early autumn. This seasonal change in intensity is reflected in the OLR. An distinct summer convergence zone is rarely if ever observed over the South Atlantic, but a weak and evanescent convergence zone can be identified over the eastern south Pacific during March and April of some years.

The inter–hemispheric seasonal shift of the continental precipitation regimes also appears on the OLR charts. In this case the seasonal difference between the mid–solstice months of January and July, when land surface temperatures are highest, is more pronounced than that shown by the March–September charts.

c. The annual cycle of SST is not simply a rotation of the local annual cycle of solar radiation. First of all, in contrast to the continents, the semi–annual harmonic is relatively small over the equatorial belt. Secondly, while the basin–scale annual cycle of SST evolves as more or less a standing oscillation with an annual period, the pattern of evolution is quite different over the equatorial Atlantic and over a large area of the equatorial Pacific extending from the South American Coast westward along the equator to the dateline. Here, the annual cycle envolves as a westward propagating feature (Horel, 1982). There is clear evidence that ocean dynamics, in the form of seasonal variations in upwelling and advection plays a major and perhaps dominant role in the annual cycle of this large region.

This sector of the equatorial belt is under the domination of the large–scale Southern Hemisphere circulation throughout the year. The annual cycle in SST appears to be partly a response to the annual cycle of both local and remote wind stress forcing. Since the surface circulation over this region is strongly related to the SST gradient itself (see below), the effect of the wind field on SST will in turn result in changes in the wind field itself. SST is also related to the distribution of convection, particularly in the temperature range of 26° C to 29° C. SST distribution due to wind stress forcing will affect the precipitation regime, particularly over the central Pacific. Along with the SST, these modifications of convective heating may also modify the surface pressure gradient and therefore the circulation. This scenario is reminiscent of ENSO cycle interactions and suggests ocean/atmosphere dynamical coupling as an important annual cycle as well as interannual time–scale process in the equatorial Pacific.

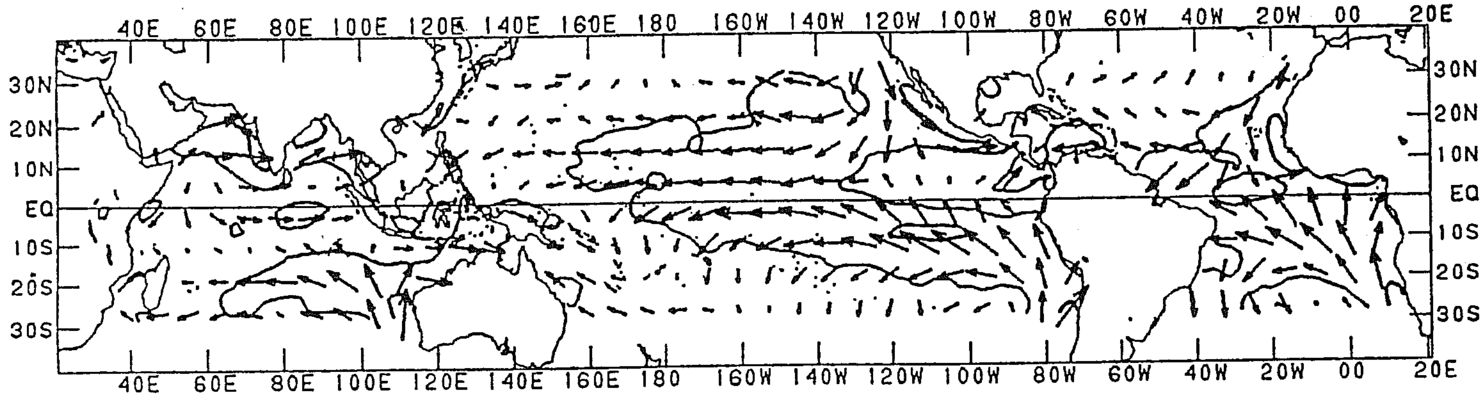
d. The relationship between the SST gradient and surface circulation is more clearly illustrated by Figs. 12 and 13, which show the mean monthly departures from the zonal means, i.e. the asymmetric component. The correspondence between the circulation and the SST gradient over the low–latitude Atlantic and the Pacific east of the dateline is striking! Over the western Pacific and Indian Ocean, where SST is high, and gradients are weaker, the relationship is less clear.

Lindzen and Nigam (1987) concluded that the low–level pressusre gradient and thus the circulation is largely determined by the SST by the SST gradient over much of the tropical oceans. The pattern over the Atlantic and eastern Pacific seems to be in at least qualitative agreement with the conclusion of Lindzen and Nigam. Broadly speaking, one might expect this direct thermal forcing to be most dominant in the dry low–regions where a mixed layer is capped by an inversion. Deser (1989) found this to be generally true, but also found that SST and pressure were better correlated than SST and wind, and attributed this to variations in factors such as boundary layer mixing. She found that the simple hydrostatic boundary layer relationship breaks down in the western Pacific, where, for example relativelly large ENSO cycle pressure changes are associated with small changes in SST. The western Pacific and the Indian Ocean would be the regions over which the relationship would be weakest due to convective heating and the forcing due to the land–ocean contrasts of the monsoon.

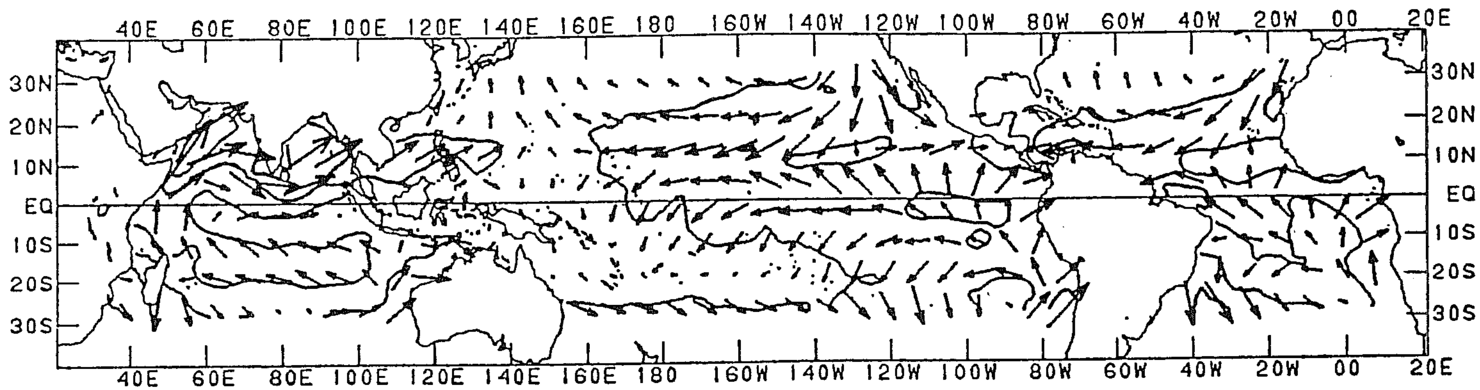
3.3 Upper Air Circulation

Both the climatological mean zonal flow and time–averaged anomalous circulation of the deep tropics exhibit a baroclinic structure reminiscent of the meridional profile of the Hadley circulation. Relative maxima and minima of reverse sign appear in the lower (surface–800 mb) and upper (150–300 mb) troposphere. This pattern is illustrated by Fig. 14 which shows the December–February seasonally averaged zonal flow at 850 mb and 200 mb derived from eight years of ECMWF analyses. Features of note include the following.

a. The baroclinic nature of the zonal flow in the deep tropics has been noted, and this can be contrasted with the in–phase (barotropic) structure of the extratropical zonal flow.

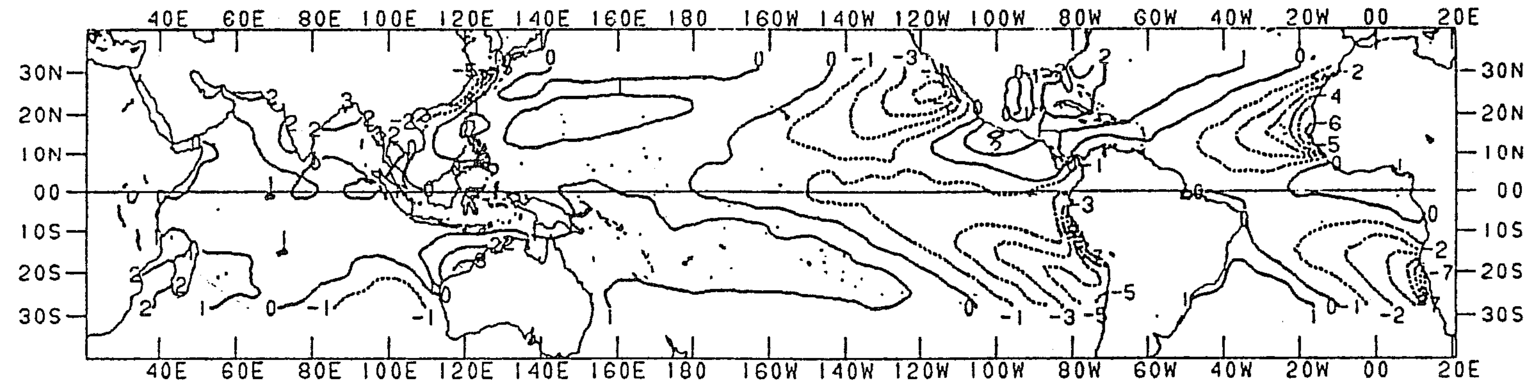


MARCH VECTOR WIND (ZONAL MEAN REMOVED)

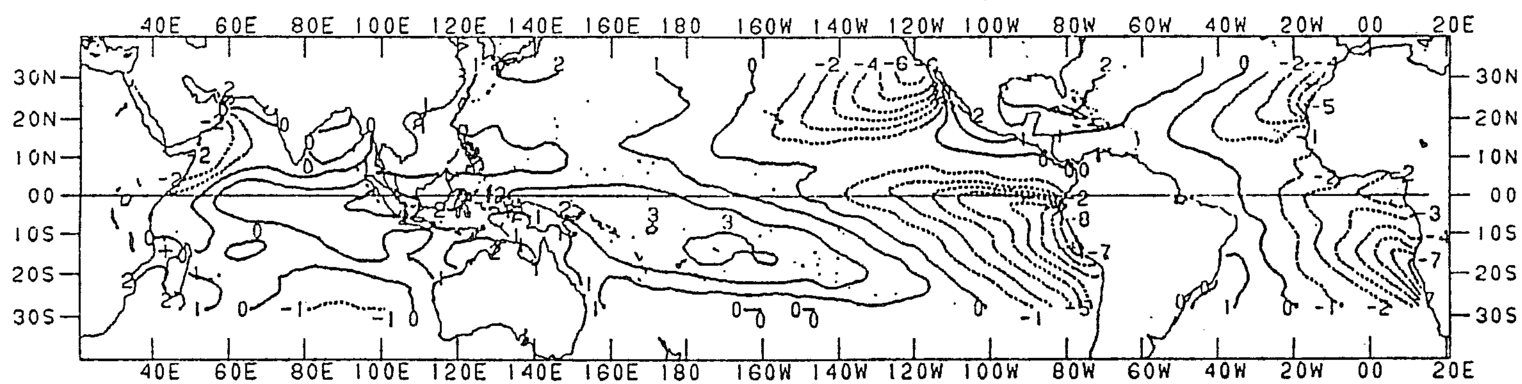


SEPTEMBER VECTOR WIND (ZONAL MEAN REMOVED)

Fig. 12 Mean monthly vector surface wind difference from the zonal mean. Contour interval: 2.5 m/s.



MARCH SST MEAN (ZONAL MEAN REMOVED)



SEPTEMBER SST MEAN (ZONAL MEAN REMOVED)

Fig. 13 Same as Figure 12 for SST. Contour interval: 1° C. Negative contours dashed.

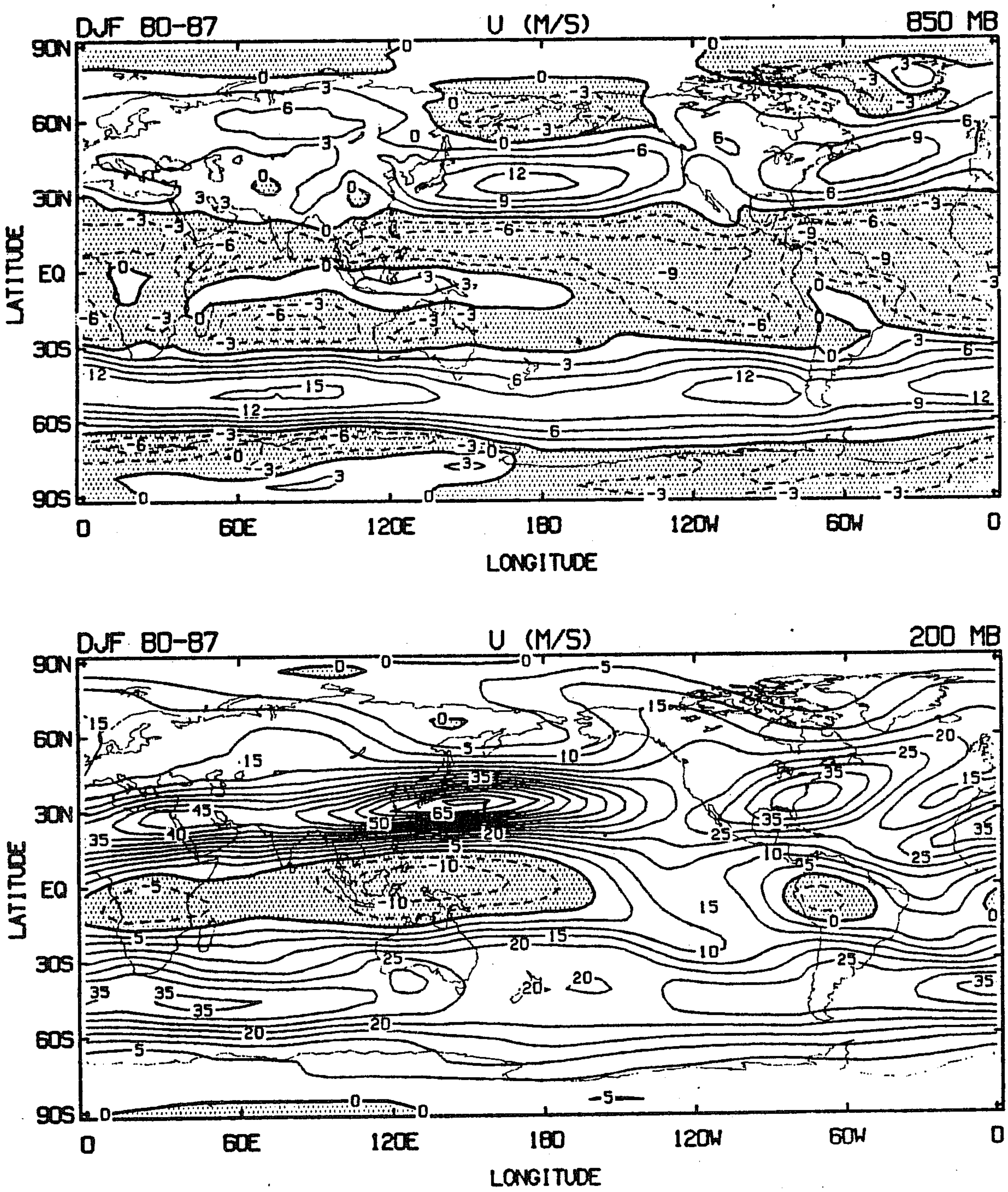


Fig. 14 Averaged 850 mb (upper) and 200 mb (lower) zonal flow for December–February based on eight years (1980–87) of ECMWF analyses. Units: m/s. Negative contours dashed. (From Schubert et al., 1990).

b. The 200 mb (850 mb) zonal flow of the deep tropics exhibits easterly (westerly) maxima relative to the zonal mean over Africa, South America and most notably over the Indonesian region. These extrema correspond to the three areas of maximum rainfall discussed in the previous section.

The time–averaged atmospheric circulation is basically driven by diabatic heating. The observed time–averaged tropical circulation is broadly consistent with conclusions from scale analysis (Hoskins, 1986) and simple model results, e.g. Matsuno (1966), Gill (1980), in showing that the atmospheric forcing which results from spatial variations in latent heating is the fundamental factor in the maintenance of the large–scale circulation features of the deep tropics.

The four year (1984–1987) average ECMWF 200 mb streamfunction (rotational component) and velocity potential (divergent component) fields for December–February and June–August are shown as Figs. 15 and 16. The December–February streamfunction shows anticyclones or ridges in the form of couplets that more or less straddle the equator over the three warm troposphere regions of heavy precipitation. The upper level easterly maxima are associated with these anticyclonic couplets. The position and relative intensity of these circulations change seasonally in association with the changes in intensity and inter–hemispheric shifts in the regions of heavy convection. The northern summer Asian monsoon high, with the Tropical Easterly Jet (TEJ) on its southern flank, is the strongest of these features.

The 200 mb divergent wind field has three tropical outflow regions which again correspond to the three regions of heavy precipitation. The monsoon sector outflow is clearly dominant, and the African outflow is weakest. There is meridional outflow from the convection regions to both hemispheres, but the trans–equatorial outflow from the summer hemisphere areas of heaviest convection to the winter hemisphere subtropics is clearly larger. This is reflected in the zonal average as the upper branch of the dominant winter hemisphere Hadley cell.

The divergent zonal flow in the equatorial belt is predominantly from regions of upward motion and convection to the largely rainless subsidence regions located over the cold ocean areas of the eastern Pacific and Atlantic. This circulation component can be identified with the Walker Circulation described by Bjerknes (1969). There has been considerable confusion over the years as to what is meant by the Walker Circulation. Bjerknes described it as a two–dimensional zonal–vertical circulation in the plane of the equator. Unfortunately, in his observational description he did not clearly distinguish between the rotational and divergent flow. Consequently, the Walker Circulation has

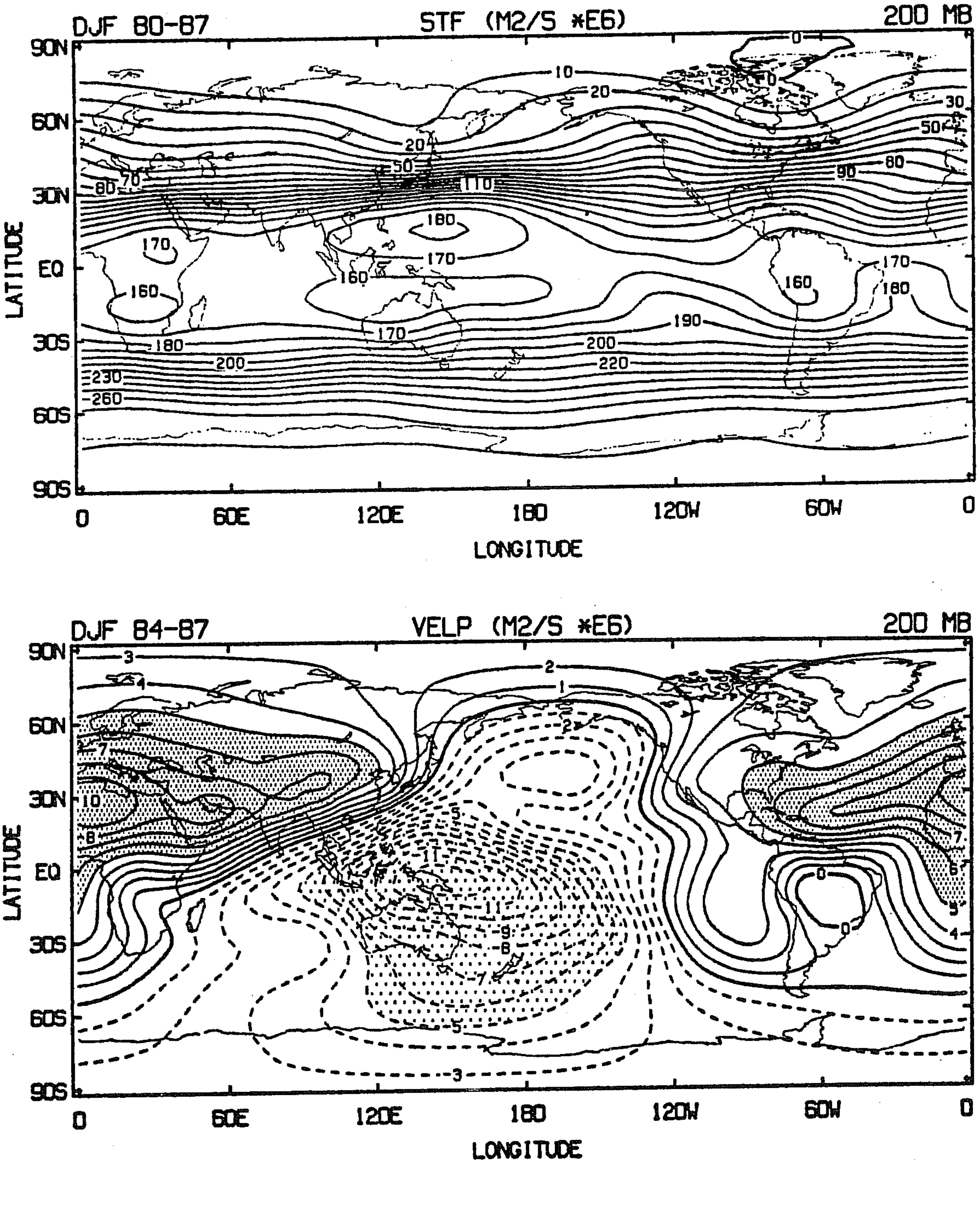


Fig. 15 200 mb streamfunction (upper) and velocity potential (lower) for December–January. The streamfunction is an eight year average (1980–87) while the velocity potential is a four–year averge (1984–87) of ECMWF analyses. Units: $m^2/s \times 10^6$. Negative contours dashed. (From Schubert et al., 1990).

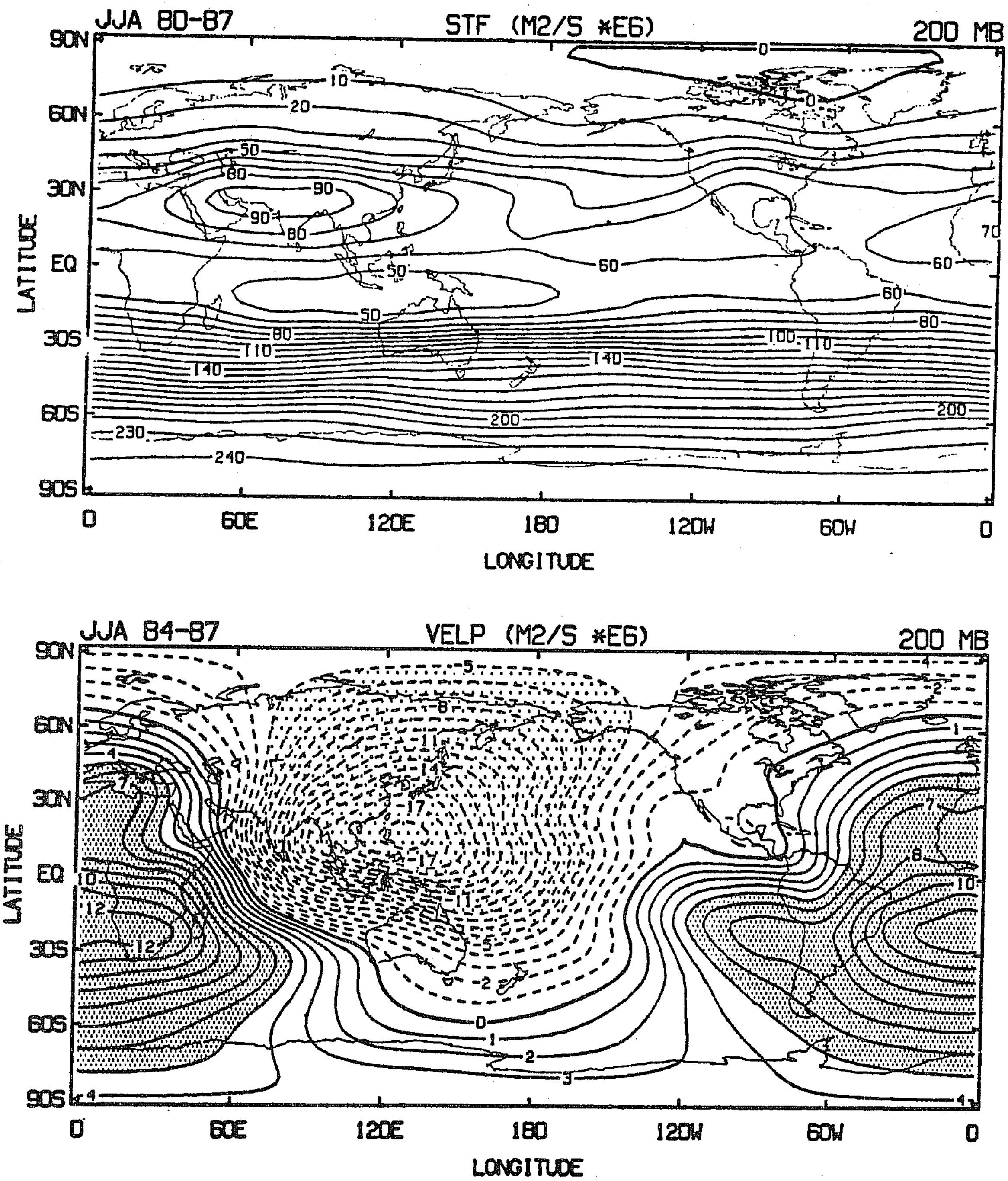


Fig. 16 Same as Figure 15 for June–August. (From Schubert et al., 1990).

often been equated with the total zonal flow in the equatorial plane. When this is done, the interpretation of the location of the upward and downward branches of the Walker Circulation will be totally incorrect, for as shown in Figs. 15 and 16, the relatively strong rotational flow is approximately in quadrature with the divergent Walker Circulation, i.e. the rotational flow maxima are located approximately over the the nodal points of the Walker Circulation.

3.4 Equatorial Trough Variability

The equatorial troughs and associated precipitation systems are a highly non–uniform feature of the tropical general circulation. They lie predominantly in the summer hemisphere, but the ITCZs of the eastern Atlantic and Pacific, and the SPCZ of the western South Pacific remain in the winter hemisphere in attenuated form. The troughs and trough–related precipitation generally coincide with an SST maximum over the ocean. The relationship between the thermal trough and precipitation is more variable over land, and depends to a large extent on moisture supply. Little precipitation is associated with the thermal trough over the arid regions of western Asia. During the rainy season over northern Africa, the thermal trough is located over the arid Sahara–Sahel, with the heavy precipitation displaced southward, into the moist airmass. Topography plays a role in the location of the monsoon trough over northern India.

There are significant regional variations in the nature and organization of ETZ precipitation systems. Although the ITCZs of the Atlantic and eastern Pacific received a great deal of observational and theoretical attention during the 1970s, the focus during the 1980's has shifted to the monsoon sector, which is the dominant region of atmospheric latent heating. This sector, which spans the longitudes of the Indian Ocean and west Pacific, is also the region where systematic modes of intraseasonal and interannual tropospheric variability are best developed.

The question arises as to how the intraseasonal and interannual modes should be viewed in the context of the general circulation. In the case of the tropical stratosphere, there seems little doubt that the QBO should be viewed as a fundamental feature of the general circulation, for it determines the very nature of the annual cycle during any particular year. While not so regular, the ENSO cycle would seem to fall into this category because of its fundamental relationship to the annual precipitation regime over large parts of the tropics. How the 30–60 day oscillations are to be viewed is less clear. It may depend on whether one views them as primarily a low frequency organizer of synoptic variability, similar to low frequency weather regimes in the extratropics, or whether they interact in a significant manner with the lower frequency ENSO cycle.

Figure 17 illustrates schematically the time/space hierarchal relationship between these modes of variability. The annual cycle is displayed as the outer ring to illustrate that it acts as a fundamental control, as least in terms of location and/or intensity of the other modes of variability. The next ring represents the ENSO cycle. The seasonally–related zonal migration of ENSO cycle anomalies in the equatorial belt, which exhibit a preferred phasing with the annual cycle, has been described by many authors, including Gill and Rasmusson (1983) and Rasmusson and Wallace (1983). The meridional migration of the basin–scale anomaly pattern a less well recognized aspect of the ENSO evolution. This feature is illustrated by a meridional OLR section averaged across the longitude sector 100°W–150°E (Fig. 18). Isolines are total OLR, rather than anomalies, in order to more clearly reveal the relationship between the mean annual cycle and precipitation anomalies.

The primary climatological convergence zone in the central and eastern Pacific remains north of the equator throughout the year. This is reflected as a persistent Northern Hemisphere OLR minimum (precipitation maximum) on Fig. 18. However, as discussed earlier, there is a relative north–south seasonal migration of the low–level convergence and precipitation belt that is superimposed on the annual mean pattern. This relative Hadley annual cycle is clearly reflected in Fig. 18 as an enhancement/diminution of rainfall in each hemisphere during its' local warm/cold season. During ENSO high index periods, the presence of cold upwelling water suppresses precipitation near the equator, and the Southern Hemisphere summer rainfall maximum is relatively short and often indistinct.

The ENSO cycle modification of the annual cycle during the 1982–83 and 1986–87 warm episodes is striking. There was a general increase in precipitation, particularly near and south of the equator during the southern summer, i,e. during the mature phase of a typical warm episode. The longitudinally–averaged precipitation anomalies migrated with the seasonal migration of the low–level convergence zone, i.e. with the seasonally varying Hadley component, and the anomalously high equatorial SST's allowed a continuous inter–hemispheric progression of the rainfall maximum (Compare with Figs. 4 and 5). Thus the basin–scale ENSO rainfall anomalies are tightly phased with the mean annual cycle, but the annual cycle is in turn modified by the ENSO cycle as indicated on Fig. 17.

The next ring on Fig. 17 represents intraseasonal oscillations. OLR data show that an individual oscillation typically first appears as a convective outburst in the western equatorial Indian Ocean, then migrates eastward, reaching maximum amplitude in the Indonesian–north Australian region after which it weakens or disappear over the central

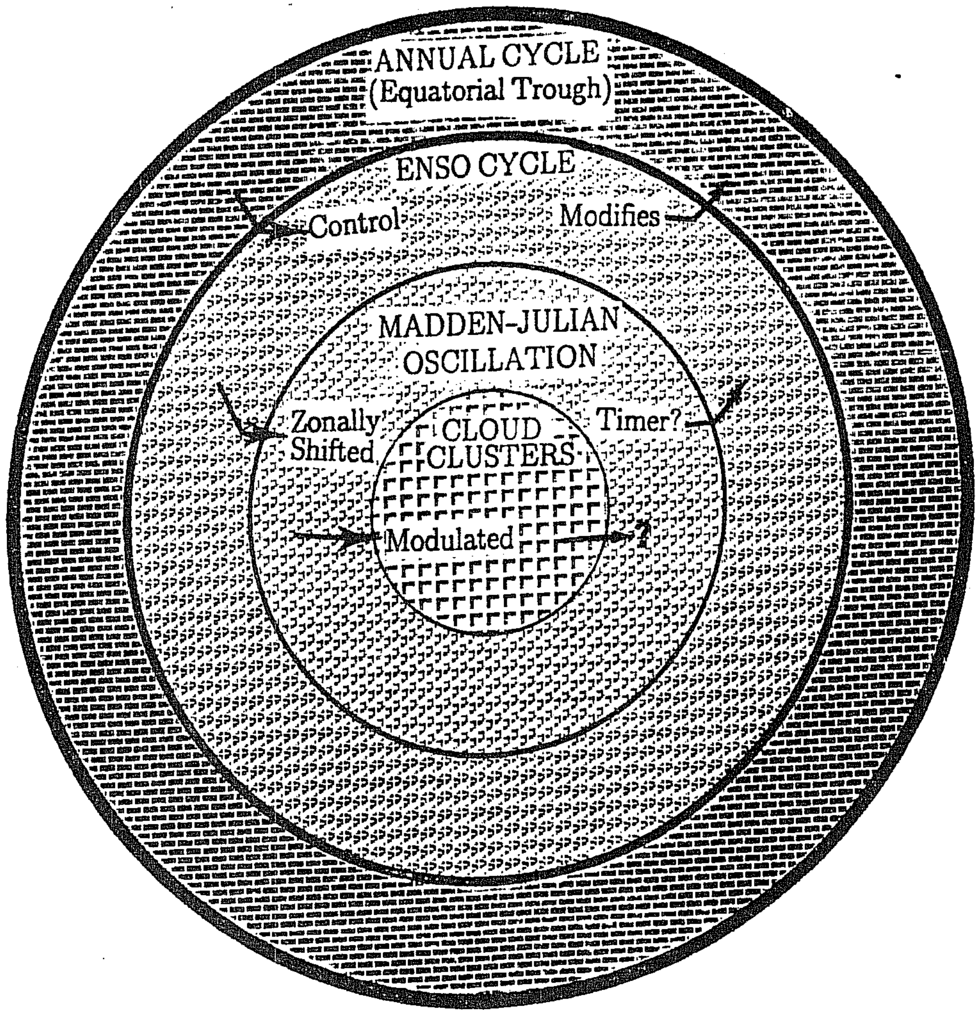


Fig. 17 Schematic representation of the hierarchy of equatorial trough variability over the Indian Ocean–west Pacific monsoon sector. (See text for discussion).

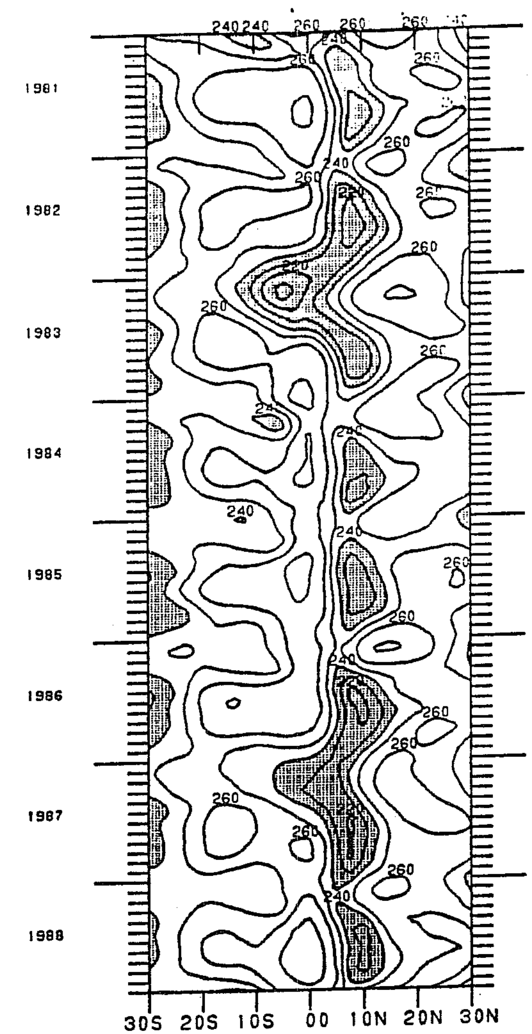


Fig. 18 Monthly averaged OLR for the sector 150°E to 100°W. Units: W/m^2. Values less than 240 W/m^2 are shaded.

and eastern Pacific. The area of maximum amplitude corresponds with the Indian Ocean–western Pacific region of high SST. Multi–year time series (Lau and Chan, 1986) strongly indicate that the area of maximum activity also shifts eastward and westward with the large–scale SST changes associated with the ENSO cycle. Thus the ENSO cycle, as well as the annual cycle plays a role in the positioning of the 30–60 day convective activity. The degree of feedback to the ENSO cycle is unresolved, and continues to be a lively topic of debate.

Finally, the inner circle represents the synoptic cloud clusters. The relationship between the 30–60 day convective activity and the individual cloud clusters has been stunningly described by Nakazawa (1988). His analysis of data from the Japanese geosychronous satellite showed individual synoptic cloud clusters moving westward through the envelope of 30–60 day convective activity. Each cluster first intensified and then weakened somewhat east of the comparable positions of its predecessor, thus forming an eastward propagating "supercluster" associated with the 30–60 day feature.

4. FINAL REMARKS

"Opinions of what constitutes the general circulation have never been static. A considerable shift of emphasis is anticipated in the years to come." Edward N. Lorenz (1970).

An attempt has been made to describe in a very broad brush manner our current knowledge of several aspects of the tropical general circulation. In some cases the current level of knowledge represents progress in the form of an improved description some generally known aspect of the circulation which was poorly documented and understood 25 years ago. An example is the nature of precipitation systems in the ETZ. However, in at least two notable cases, namely (1) the identification of an systematic intraseasonal mode of variability and (2) appreciation of the role of equatorial–belt ocean–atmospheric coupling, the relevant features and processes had yet to be discovered a quarter–century ago. Consequently, although we find ourselves with a vastly improved description and understanding of the tropical general circulation, new questions of fundamental importance have arisen which require answers. Taken together, they suggest that a fundamental current goal in the study of the general circulation of the tropics might be the description and understanding of the nature of the coupling between the ocean, atmosphere, and hydrological cycle on intraseasonal to interannual time–scales. The host of questions relating to this general topic seem destined, in our judgment, to occupy center stage for some time to come, most likely until some new aspect of the circulation is uncovered and interest shifts to a new set of questions.

Research interests and emphases are strongly influenced by available data. This is well illustrated by the changes in our view of the tropics which resulted from satellite observations. In his 1969 review which opened the Conference on the General Circulation of the Atmosphere, Lorenz (1970) speculated that "We shall become more and more interested in the cloud patterns for their own sake. Certainly the larger elements of the overall cloud picture are features of the general circulation." Satellite data have contributed greatly to the vast increase in our knowledge of tropical precipitation systems and the hydrological cycle of the tropics, as well as to our knowledge of the radiative balance of the atmosphere, a topic of central importance not addressed in this review.

The distinction between describing and understanding the atmospheric general circulation and describing and understanding the global climate has become blurred during the past two decades. This is true in both observational studies and general circulation/climate modelling. The availability of data from the new generation of satellites that is being planned for launch during the last half of this decade will open a new era in the observation and understanding of the global hydrological cycle and its role in climate dynamics. The first of these satellites will be the Tropical Rainfall Measurement Mission (TRMM), a joint Japanese–US mission planned for launch in 1996. TRMM will be an important stepping stone toward the concept of a Global Energy and Water Cycle Experiment (GEWEX). Lorenz (1970) also noted in his 1969 lecture that "The previous generation was greatly concerned with the dynamics of pressure systems and talked about high and lows. Today we have not lost interest in these systems but we tend to look at them as circulation systems. This change in attitude has lead to a deeper understanding of their dynamics. Perhaps the next generation will be talking about the dynamics of water systems." Could it be that GEWEX will lead us in this direction?

If past experience is any guide, the new interests and new directions which will emerge in general circulation research during the next generation will largely evolve from discoveries yet to be made. After all, who in 1965 anticipated the current intense interest in tropical coupled ocean atmospheric processes and the related El Niño and Southern Oscillation? After all, the common view at that time was that these phenomenological features were hardly worthy of serious attention by climate researchers, let alone as problems of the general circulation.

ACKNOWLEDGMENTS

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