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CURRENT PROBLEMS IN RESEARCH

General Atmospheric Circulation of the Tropics

The meridional cell is a useful model, but many new hypotheses await testing by adequate observations.

Herbert Riehl

In science, we are always interested in a well-ordered simple package whenever such a package appears to be in the offing. There has been widespread belief that the general circulation of the tropics meets these requirements. The weather observations which have been gathered in increasing volume in the upper air over the tropics during the last 15 years, however, have thrown doubt on the validity of such a simple view. They appear to call for a more complex approach to an ultimate understanding of the tropical atmospheric machinery and of the interaction between tropical and temperate latitudes. The question now is: Must we really accept an increased order of difficulty, or can the evidence of the new observations be reconciled with the older approach? If it can be, the chances of arriving, within the next decade, at a definite solution of the problem of the general circulation of the tropics would be greatly enhanced.

In one respect the story has not changed; the tropics are a heat source for the atmosphere of higher latitudes. This fact, in broad terms, has been recognized for centuries. Further, circumnavigation of the oceans by sailing vessels led to recognition of a second fact: the tropics also are the source of momentum for the westerly winds prevalent especially in temperate latitudes. Essentially, half of the globe has winds from the east at the surface (Fig. 1), and the other half has winds from the west. Surface drag acts to retard all winds and bring air toward stagnation. Therefore, momentum in the direction of rotation of the earth's axis (toward the east) is given up by the atmosphere to the earth outside of the tropics and taken up from the earth inside the tropics. For balance, momentum must flow poleward across the subtropics.

Thus, we have a geophysical coincidence in the location of heat and momentum sources for the atmosphere. This fact must be rated as one of the basic peculiarities of our present-day planet, one that is highly influential in governing life in the tropics. A second peculiarity, relevant here and to be explored, is the fact that the surface of the tropics is mainly (about 80 percent) oceanic.

Simple Cell Model

A realistic model of the tropical general circulation must do the following: (i) Explain the principal observed circulation features, and (ii) permit export of heat and momentum to the northern and southern latitudes beyond. We can evolve a simple and very clear picture with three assumptions: (i) Steady state prevails except for diurnal and seasonal changes; (ii) variations with longitude are small as compared to variations with latitude; (iii) no cross-equator coupling exists, again apart from seasonal changes and possible interaction on very long time scales (of the order of years and up). Assumption (i) will be supported by most travelers to the tropics; assumption (ii) means that, while the strength of the trade winds may differ in the Atlantic and Pacific oceans, the significant point is that such a wind system exists in both oceans; assumption (iii) rests on the fact that, in a broad sense, the general circulation of both hemispheres is symmetrical with respect to the "meteorological equator" at 5 degrees north latitude.

Granted these assumptions, the general problem of the tropical general circulation, involving time and three space coordinates as independent variables, is reduced to two independent variables in space—latitude and height. We may, then, represent the salient features of the tropical atmosphere in vertical cross section (Fig. 2).

The basic feature in Fig. 2 is a "meridional circulation cell," with equatorward branch in the surface layer, return branch centered at 40,000 feet, ascending branch in the heart of the tropics, and a descending branch—not closed off from higher latitudes—at the limit of the tropics. The temperatures are highest near the equator and decrease toward the poles; near the surface, cool air from outside the tropics is carried equatorward and warmed; in the return branch some heat is lost to space as a result of radiation.

The sense of the circulation is dictated by ascent where the air is warmest and least dense. Here the heat gained by the air over the oceans during equatorward passage—largely through evaporation, and manifest as an increase in moisture content of the atmosphere—is released through precipitation in cumulus clouds. The other circulation branches follow through continuity. Subtropical deserts and equatorial rainbelt provide the best

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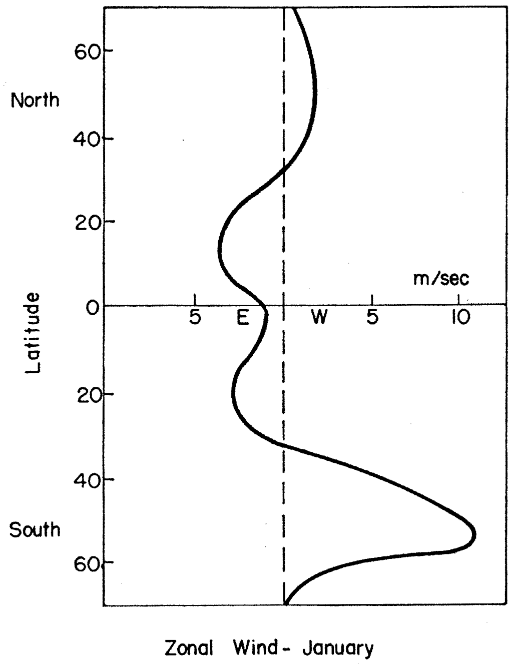


Fig. 1. Mean distribution of zonal wind speeds at the surface over the oceans in January. *E*, wind from the east; *W*, wind from the west.

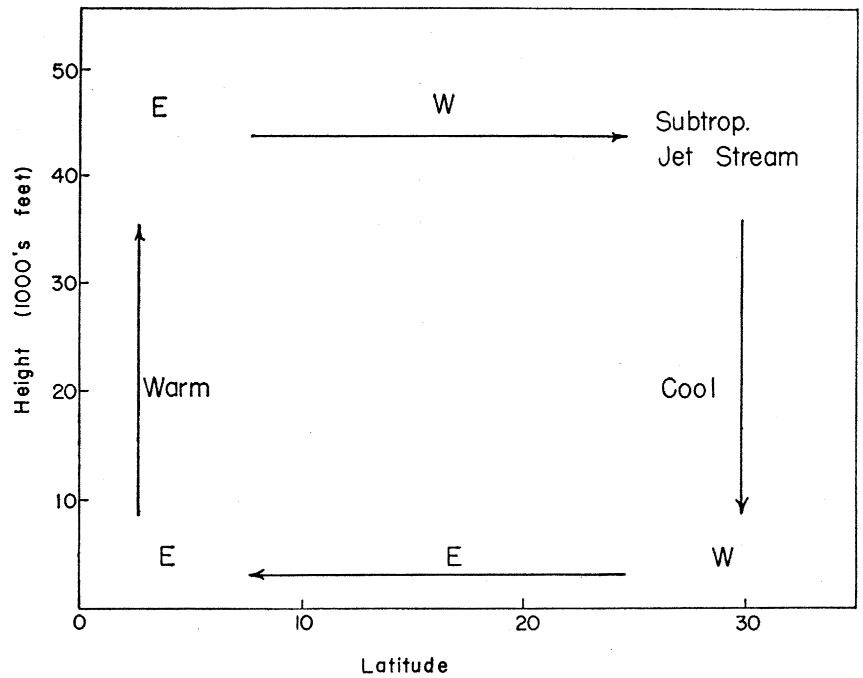


Fig. 2. Scheme of the simple meridional cell. *E*, winds from the east; *W*, winds from the west.

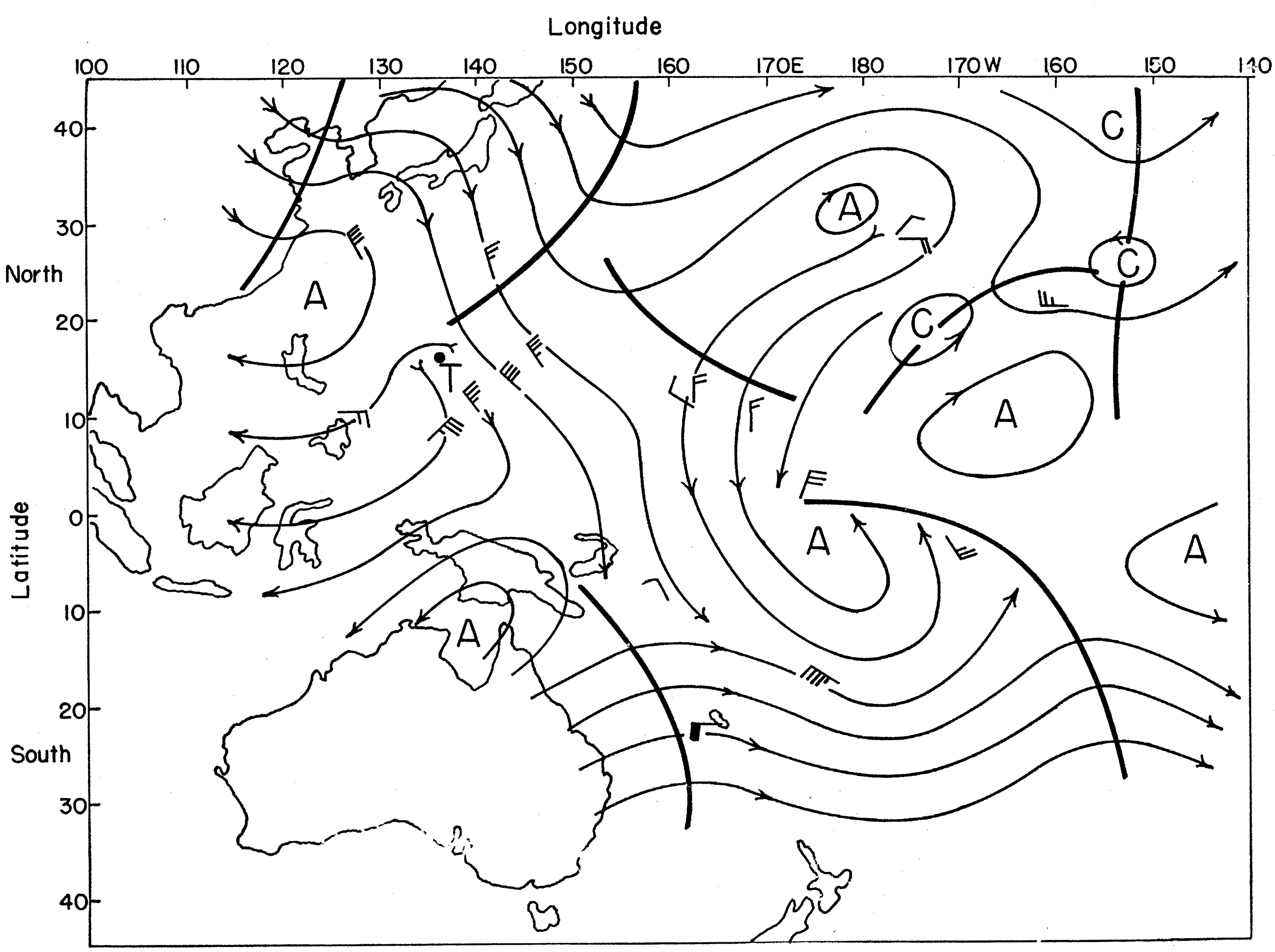


Fig. 3. Typical wind flow at altitude 40,000 feet over the Western Pacific Ocean, illustrating eddying motion and flow across the equator. Heavy lines indicate maximum cyclonic curvature. *A*, anticyclonic center; *C*, cyclonic center. Map of September 1945.

evidence for the existence and location of the vertical branches.

What can be said about the significance of the meridional cell?

1) Despite the temperature decrease upward, the poleward branch carries more heat than the equatorward branch. The high altitude of the return flow must be taken into account. This produces potential energy transport poleward, and this transport is the dominating term in computations of complete heat balance.

2) With the ascent of light air near the equator and the descent of heavier air on the margins of the tropics, the circulation acts to convert a small fraction of the potential energy gained during the equatorial ascent to energy of motion. This sustains the tropical wind system against frictional dissipation of kinetic energy.

3) The air in the return branch, well removed from the surface, tends to conserve its angular momentum. The earth's angular momentum is highest at the equator, where the distance from the earth's axis of rotation is greatest and where a point on the earth revolves at about 1000 miles per hour. As the air travels toward higher latitudes, where the angular momentum of the earth becomes increasingly smaller, it should turn toward the east. We should observe winds from the west near 40,000 feet, which rapidly increase in strength as they approach the poleward boundary of the cell. Such winds are indeed observed, and at the poleward margin of the tropics, above the horse latitudes, the subtropical jet stream has been discovered.

In contrast, the equatorward branch near the surface is in contact with the ground. According to the principle of conservation of momentum, huge easterly winds should appear in the tropics. But, due to the boundary stress, momentum from the west is transferred to the atmosphere, and the easterlies are held to the strength of the pleasant breezes of the trades (Fig. 1).

With this reasoning, the observed distribution of east and west winds is deduced qualitatively from the meridional cell. The resulting vertical shear of the zonal winds is such that angular momentum is carried poleward, since the surface equatorward flow is associated with easterly winds and the poleward branch, with westerly winds.

The foregoing, in essence, summarizes the simple cell theory; it is a closely knit story which, qualitatively, hangs well together. Mathematical models in which the chain of reasoning is put into quantitative form have been developed. Circulations such as those outlined in Fig. 2 have been produced successfully in laboratory experiments on rotating fluids with equatorial heat source and polar cold source (*1*). It would be very interesting now to investigate long-period weather trends in middle latitudes—trends of a month or longer—with reference to the tropical cell. If we postulate variations in the intensity of the cell on this time scale, changes in heat export and momentum export from the tropics would undoubtedly occur. But serious difficulties have come to light which lead us to inquire whether the entire simple cell model should not be discarded.

Objections to Simple Cell Model

No one will insist that the assumptions on which the model is based hold rigidly. It is merely expected that effects due to departures from the assumptions will be small relative to the effects due to the mean circulation. But there, precisely, doubt has arisen.

The assumptions break down strikingly near latitude 30°, where the tropical cell ends. How are heat and momentum transported there? An answer has been found for the Northern Hemisphere, based on the increased network of upper-air stations around the subtropical belt during the last 15 years. Balloons are sent up, usually twice daily, to measure pressure, temperature, humidity, and wind over at least the lower nine-tenths (by weight) of the atmosphere. These observations have shown that, at least at the boundary of the tropics, the flow is not steady but is "turbulent," in horizontal planes. Trains of waves and vortices, with dimensions of the order of 1000 miles, produce alternating northerly and southerly wind components around the belt. The magnitude of these components is 10 meters per second, as compared with 1 meter per second for the meridional cell. Now, in line with expectations from the source and sink locations, winds from the south carry higher heat and momentum than winds from the north. This correlation, though far from perfect, is sufficiently high to account for the bulk of the poleward flow of heat and momentum (see *2, 3*). With this mechanism, turbulent transport by means of lateral eddies—turbulent, because net mass flow is not considered—replaces transport by means of correlations along the vertical in the simple cell, which does require net mass flow at any level.

The next question is: How important is the mechanism just described within the tropics proper? Near the surface the evidence is negative. Wind systems such as the northeast trade and monsoon are among the steadiest on earth. During winter, equatorward flow occurs at almost all meridians. In the low levels, then, the meridional cell definitely represents more than just the statistical average of all kinds of variable wind fluctuations. In the upper troposphere, however, large wind eddies and restlessness of flow occur often (Fig. 3). The scanty evidence suggests that these eddies often extend across the equator. With this, several of the premises underlying the cell hypothesis are placed in jeopardy. Other evidence, mainly from precipitation data, also points to variability of weather elements within the tropics, though on varying time scales. India's food supply hangs in balance each year as the yield of the monsoon rains is awaited with anxiety. Even Honolulu, in the center of the trades, has experienced annual precipitation ranging from 10 to 47 inches in 70 years. Variability over shorter time intervals is still greater.

Lateral turbulence, as depicted in Fig. 3, transports momentum more effectively than heat; the correlation between the north-south wind component and temperature diminishes rapidly from the subtropics equatorward. It will be difficult to eliminate poleward energy transport by the meridional circulation as a major factor in the heat budget, even though the flow of the return branch is not uniformly distributed around the tropics but occurs preferentially in a few narrow poleward-directed channels (*4*).

In addition, an entirely different mode of heat transfer has lately attracted the attention of meteorologist and oceanographer: transport within the oceans. Consider a schematic ocean basin (Fig. 4). In the broadest sense the surface water masses follow the imposed air circulation, clockwise in the Northern Hemisphere. This leads to poleward transport of warm water over the western parts of the oceans, and to equatorward transport of cool water from the north over the eastern parts; hence the shape of the isotherms in Fig. 4. That warm and cold currents exist

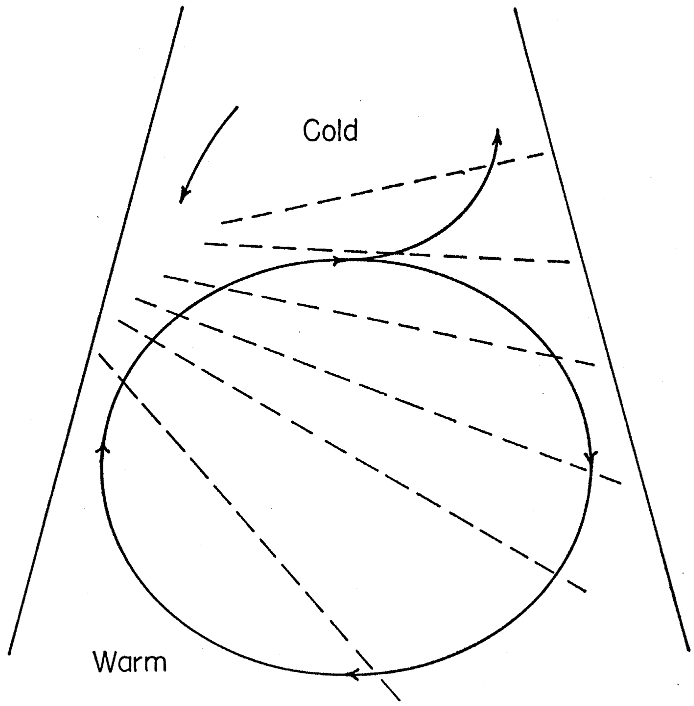
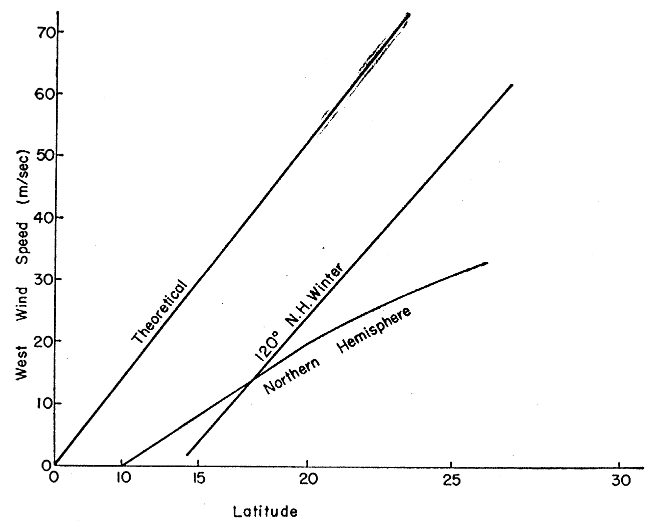


Fig. 4 (left). Ocean basin with mean current drift and isotherms (dashed lines). Fig. 5 (below). Theoretical profile of west-wind speed with latitude, under the requirement of conservation of momentum, given zero wind at the equator, together with two profiles observed at altitude 40,000 feet. [*Tropical Meteorology* (*14*)]



has been known for a long time. But only recent calculations have suggested that as much as 25 percent of the equatorial heat excess may be exported by these currents. It is tempting to speculate on the impact of variations in this heat flow which may be brought about by changes in the intensity of the clockwise atmospheric circulation over the oceans. No doubt such variations have an impact on atmospheric circulation anomalies of middle latitudes, and hence they will be an important factor in long-range weather prediction when the data necessary for computations become available.

In view of the foregoing considerations we should, perhaps, carry forward investigations of the tropical general circulation mainly by computing fluxes of turbulence, a task which will be difficult until we have a great many more data for the vast tropical area. Yet, this may be as exaggerated an approach to the atmospheric circulation of the tropics as rigid adherence to the meridional cell. After all, the climatic scheme of subtropical deserts, trade-wind belt, and equatorial rain zone does prevail and attest to the validity of the mean-circulation scheme of Fig. 2. This indisputable fact, together with reluctance to part with the mean cell hypothesis as a definite and possibly very sharp tool for gaining insight into the nature of the tropical circulation, has prompted further examination of the simple cell hypothesis.

Subtropical Jet Stream and Transverse Mass Circulation

As is well recognized (*5*), the principal difficulty of the cell hypothesis is the postulate of poleward-moving rings of air which conserve their angular momentum. This postulate requires huge westerly wind speeds in the tropics and phenomenal speeds at higher latitudes. Actual profiles of zonal wind with latitude fall far short of the profile demanded by the conservation of momentum principle, with the notable exception of the profile for East Asia (Fig. 5). Bjerknes proposed to relax the requirement of poleward-moving rings of air by taking advantage of the existence of subtropical high-pressure centers in both northern and southern oceans. Consider Fig. 6. Air moving northward at point *B* is subjected to a westward-directed pressure force. This force acts to decrease the angular momentum of the air at point *B*; the air can then move northward without the necessity of turning eastward with excessive speed. The converse applies at point *A*. In this way, the standing pattern of high-pressure centers facilitates north-south exchange of air.

With the increase of upper-air data in the 1950's, and especially with the introduction of radar-type equipment to measure upper-atmosphere winds, the subtropical jet stream has emerged as a definite feature useful for delineating the poleward boundary of the tropics. During the winter of 1955–56 this current had the mean position and wavelike shape shown in Fig. 7. In a broad sense, this configuration recurs annually during the winter. Figure 7 clearly shows how nature has responded to the momentum problem. A strong subtropical velocity maximum exists at about the altitude of the core of the poleward branch of Fig. 2, but this maximum undulates with longitude, and it is in phase with the pressure field, so that angular momentum is abstracted during poleward flow and added during equatorward flow.

These observations suggest that it may be of value to examine some aspects of the tropical circulation in a curvilinear coordinate system following the waves of the subtropical jet stream, rather than in spherical polar coordinates, which has been the usual practice. It is certainly desirable to have a latitude representation in any coordinate system, because the gradients of the earth's momentum and of solar radiation lie in that direction. But the merits of using spherical coordinates as a means for describing and analyzing general circulations have not been investigated as such. Nothing need prevent us, in principle, from choosing reference frames suitable for summarizing observational features in any desired way.

Introduction of curvilinear coordinates following the subtropical jet stream was suggested by the use of such coordinates in a rotating dishpan experiment with three steady waves (*6*). These waves may be treated by statistical methods as turbulence elements in a polar coordinate system or in a system of curvilinear coordinates following the waves (Fig. 8). When heat transfer is computed in these two coordinate systems, the results are as follows. In polar coordinates, heat transfer is effected mainly through the correlation of inward-directed flow with high temperature, and vice versa (Fig. 9). In curvilinear coordinates, it is produced by a cell similar to that of Fig. 2, except that the mass flow is computed normal to the *s*-axis of Fig. 8 rather than normal to latitude circles.

This computation points out that, at the present stage of our thinking, characterization of a fluid—at least of the steady-state type—is not absolute but is dependent on the choice of reference system. Mathematically, the transports computed from all reference systems must, of course, agree. But it is evident that the success of a particular investigation may depend critically on the reference frame used. In the case under discussion, the entire single-cell model of the tropical circulation can be saved—if that is desired—by viewing the problem as one requiring curvilinear rather than spherical coordinates. Eventually, of course, the reasons for the observed position and wave structure of the subtropical jet stream must be understood. But lack of a complete solution at this time need not prevent our taking advantage of this structure for computations on the tropical circulation.

When the curvilinear reference frame relative to the subtropical jet stream is adopted—with validity over a distance of at least 1000 miles equatorward from the jet axis—a mass circulation is obtained (*7*) which, in large measure, accomplishes the heat and momentum transfer postulated in the single-cell model. Further, a release of potential energy is computed which is greater by about an order of magnitude than that required to maintain the motion against friction. This release of potential energy is considerably larger than the production of kinetic energy by the meridional motion, as computed by Palmén *et al.* (*8*). It actually has the magnitude which Pisharoti (see *2*) has estimated is required for the maintenance of the whole extratropical circulation against friction. This shows clearly that the tropical wind systems are not driven by energy released in middle-latitude disturbances, as has been suggested, but that the tropics make an important and, as Krishnamurti points out, a variable contribution to maintenance of the temperate-zone winds.

A calculation showing the maintenance of the temperature structure equatorward of the subtropical jet stream may serve as an example of computations performed in the curvilinear system. In the sinking branch of the tropical cell (Fig. 2), in the curvilinear frame of reference, air is compressed because of motion toward higher pressure. This produces heating and tends to increase the temperature of the whole tropical atmosphere in the descending branch. For a steady temperature field, radiation cooling must balance this compression heating. If such balance is not achieved, at least roughly, then temperature advection by unsteady flow must be an important factor in the circulation. As seen in Fig. 10, balance is achieved within reasonable limits, and the computation may be taken as supporting the validity of the simple-cell approach.

These calculations, plus others, demonstrate that the concept of a thermally induced mass circulation as the basis of the tropical general circulation may be upheld. The future will show whether this approach is rewarding as compared with the turbulence concept, which will certainly be explored, if only because it lends itself easily to computation on large computers. Some of the possibilities that may be explored with the cell model are outlined later in this article. At present, let us ask merely whether a cell model will still serve to represent the main circulation features when heat and momentum sources are separated. Opportunity for a test of such a situation arises during the Northern Hemisphere summer, when the center of the heat source shifts from the equatorial zone to the subtropics over the continents of Asia and Africa and when, in addition, the heat source becomes elevated toward the middle (by weight) of the troposphere over the mountain ranges and high plateaus of Asia. Analogy with Fig. 2 suggests a cell with a structure like that shown in Fig. 11, in which, however, the heat source is situated at the latitude of smallest earth's momentum. Studies of the Asian tropics, undertaken primarily by Koteswaram (*9*), have confirmed the validity of this structure from the upper-air observations available since the middle of the 1950's. The analogy between summer and winter cell models can be carried very far. It also suggests that the precise location of momentum sources and sinks relative to a heat source is not significant with respect to the existence of vertical cells produced by heat sources.

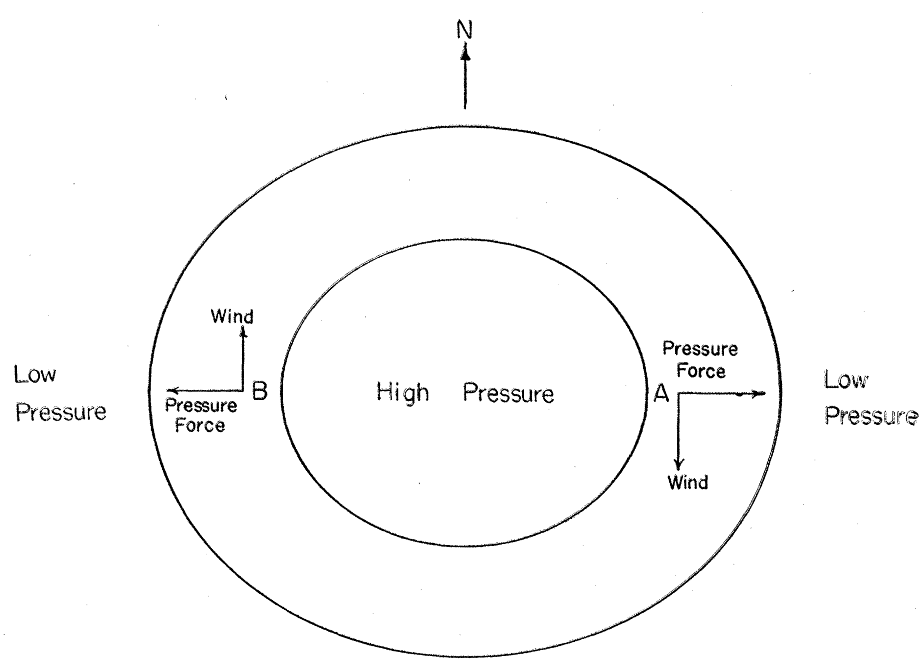


Fig. 6. Scheme showing meridional mass exchange, without the requirement of conservation of momentum due to a subtropical high-pressure center. [Bjerknes *et al.* (*2*)]

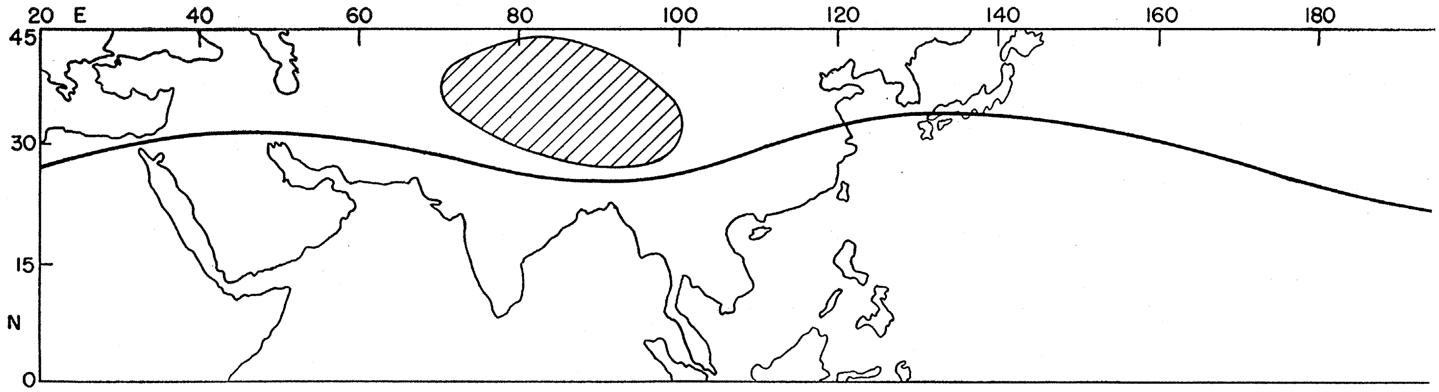


Fig. 7. Axis of the subtropical jet stream at altitude 40,000 feet during the winter of 1955–56. [Krishnamurti (7)]

Vertical Heat Transfer

Up to now I have spoken of the tropical heat source as self-evident, an assumption made frequently without qualification. A more detailed look, however, reveals quickly that determination of the exact ways in which the tropical atmosphere does become a heat source is a challenging research problem.

In the tropics, as elsewhere, the atmosphere is a radiational cold source. Long-wave radiation going to space greatly exceeds the direct absorption of solar short-wave radiation within the atmosphere. The real recipient of excess heat is the earth itself, which in the tropics, as noted before, is about 80 percent covered by water. It is the transfer of heat from ocean to air that establishes the atmospheric heat source. Contact heating of air particles at the interface produces some of this transfer, but the bulk of it is derived through evaporation of water from the oceans. This water is held in vapor form in the atmosphere, and its "latent heat" is eventually released through condensation during ascent in cumulus clouds.

According to current theory, the sensible heat flux is proportional to the temperature difference between sea and air, the surface wind speed, and a roughness parameter characteristic of the ocean surface. Evaporation is proportional to the vapor-pressure difference between sea and air, to wind speed, and to the roughness parameter.

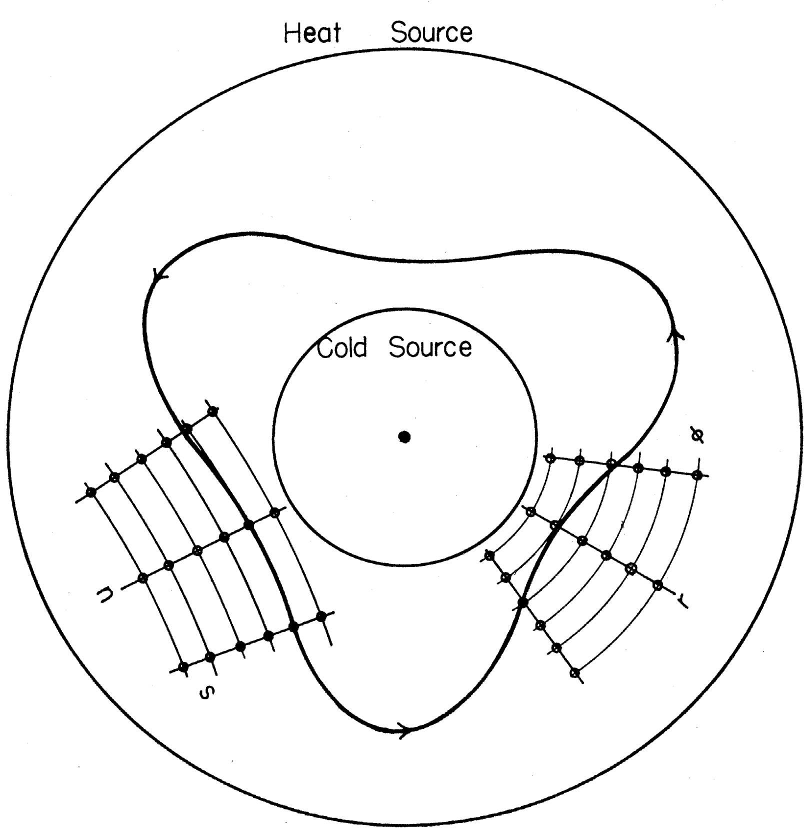


Fig. 8. Outline of a dishpan surface with a three-wave jet-stream axis, and two types of coordinate systems used in making the computations. [Riehl and Fultz (6)]

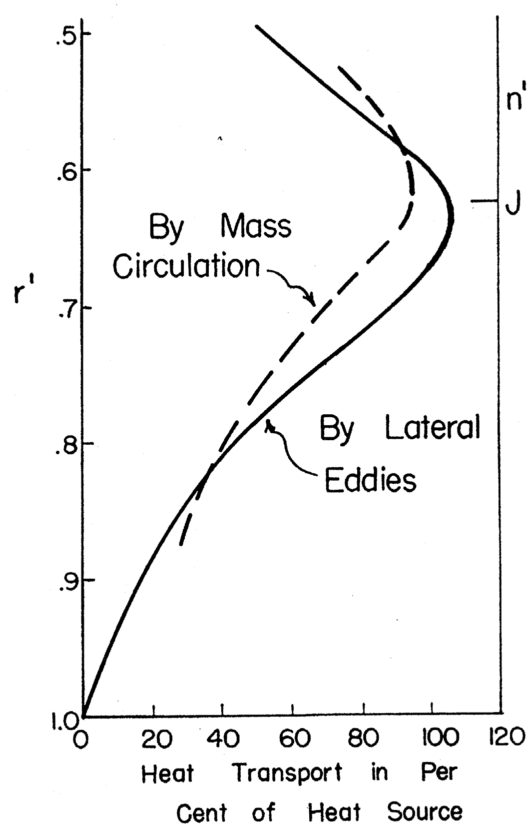
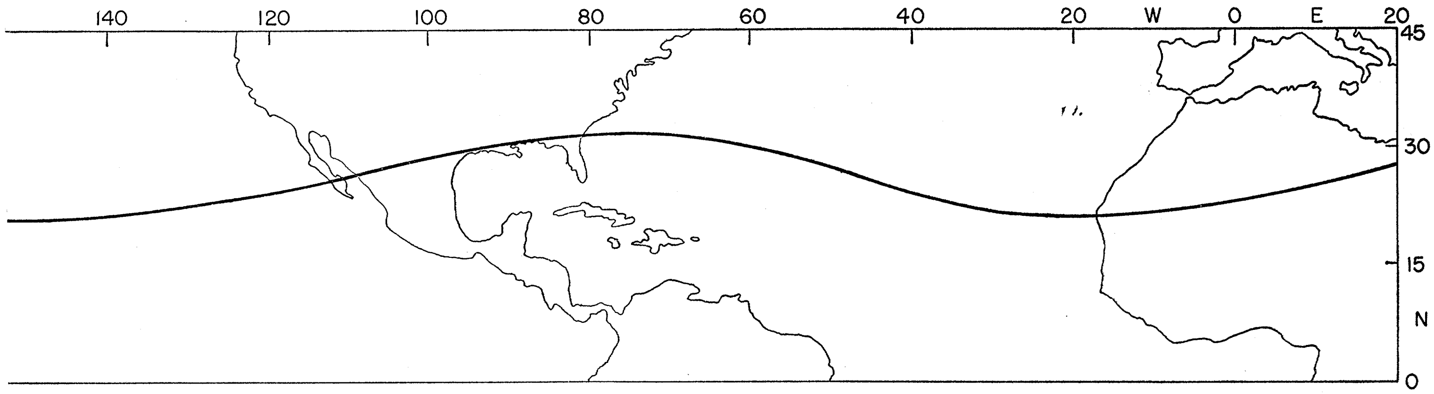


Fig. 9. Heat transport in the dishpan experiment: by lateral eddies in polar coordinates and by mass circulation in curvilinear coordinates.



It is assumed, further, that the air temperature is not higher than the ocean temperature, since this would strongly inhibit buoyant motions in the surface layer. If these hypotheses on exchange at the interface are correct, the heat transfer depends partly on atmospheric and partly on oceanic properties. Clearly, a tropical atmospheric heat source does not exist a priori or automatically. The atmosphere itself exercises considerable control over where and when strong or weak heat flux from sea to air will take place.

The mechanisms by which the heat gained from the earth is distributed to the high atmosphere present challenging problems, except possibly in the layer below the cloud base, usually at about 2000 feet in the trades. There the atmosphere is sufficiently well mixed so that diffusion by eddies of relatively small, though variable, size may be postulated. For upward transport beyond the cloud base, let us consider first the ascent of air with surface properties typical of, say, the Caribbean Sea in summer. The ascent of this air, when there is no mixing with the environment, is given by the solid curve of Fig. 12. The break in temperature lapse rate at 930 millibars denotes the cloud base; from this point upward condensation occurs. The dashed curve shows a mean Caribbean atmosphere in summer, which is very similar to mean atmosphere computed over comparable parts of other oceans in summer. By and large, the two curves of Fig. 12 have the same shape; this observation has led to the general conclusion that the condensation process is the main factor in shaping the vertical temperature structure over the tropical oceans.

Let us now return to the circulation cell of Fig. 2. In view of the steady state postulated for the cell, particles rising from the surface in the equatorial zone actually should follow paths similar to those depicted in Fig. 12 and establish the temperature structure of these paths as the climatically observed structure in the rising part of the cell. Until recently, it was generally assumed that such was the case. But diligent study of data from many thousands of

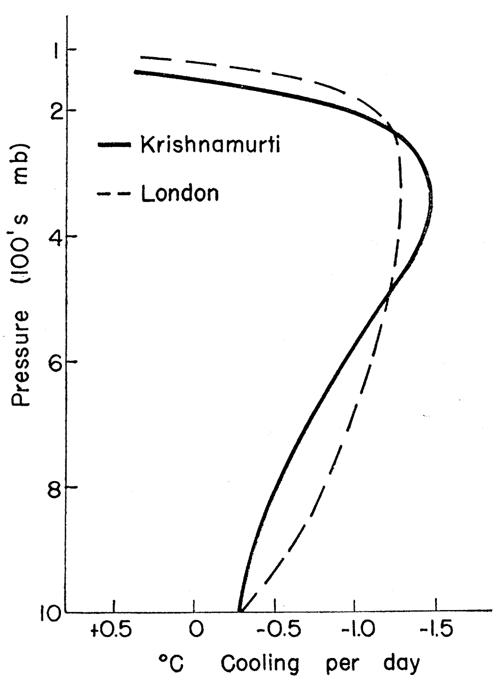


Fig. 10. Radiation cooling equatorward of the jet axis, required for heat balance [Krishnamurti (*7*)] and mean radiation cooling in the subtropics in winter [London (*12*)].

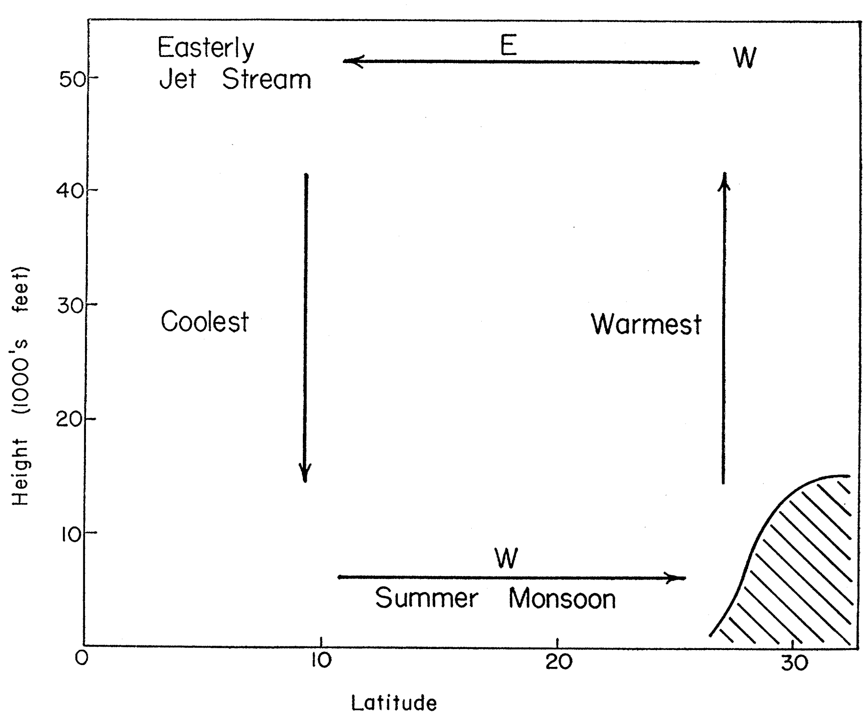


Fig. 11. Scheme of simple meridional cell south of Asia during the summer. *E*, winds from the east; *W*, winds from the west. The shaded area shows mountains.

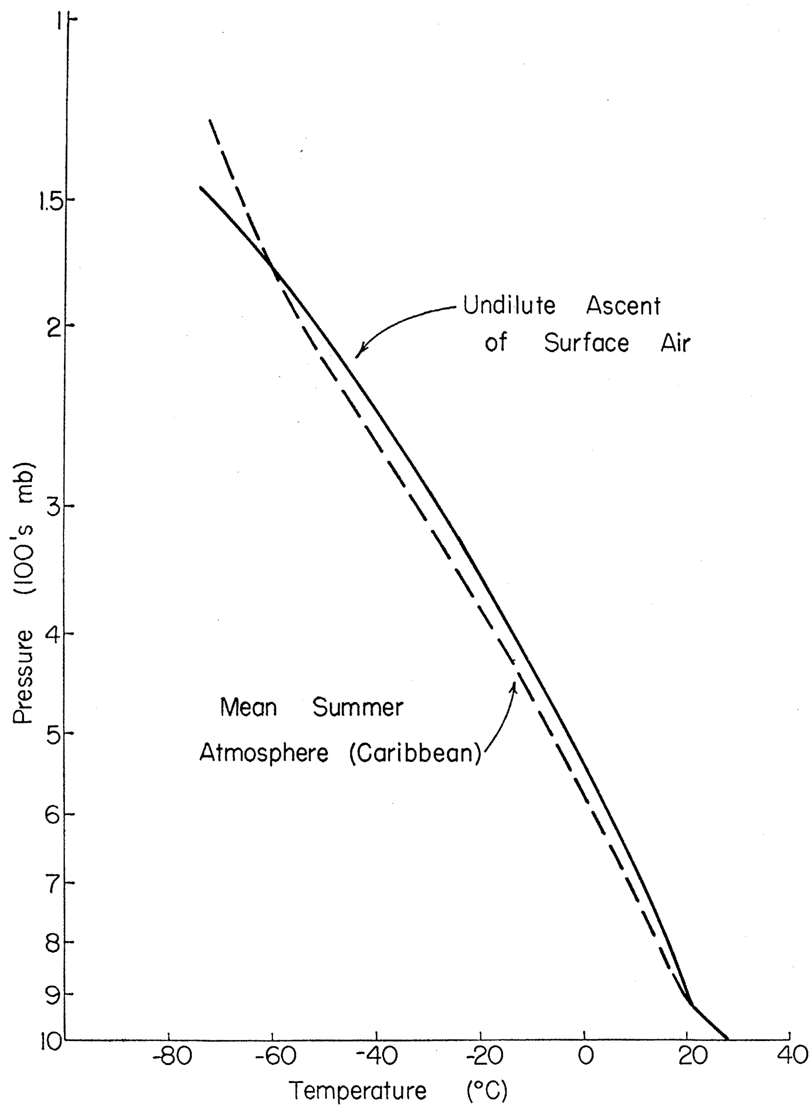
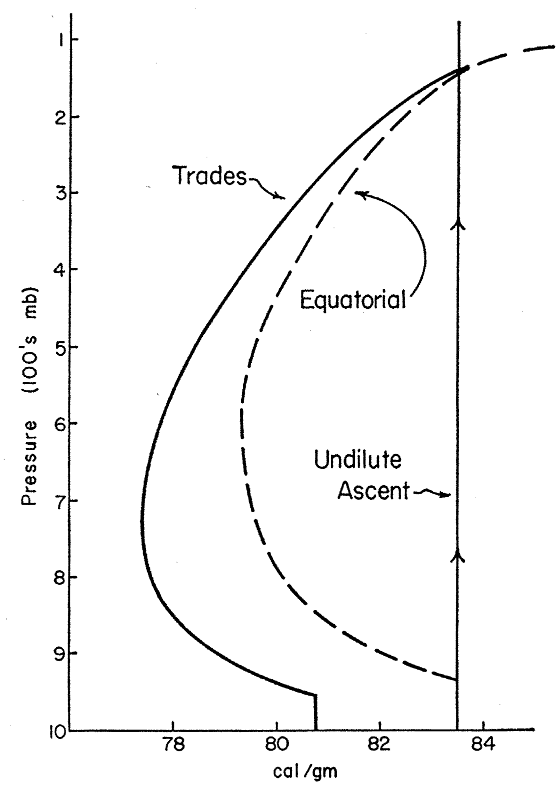


Fig. 12 (left). Temperature structure obtained against the logarithm of pressure (essentially height) during the ascent of surface air over the Caribbean Sea in summer, and as measured in the mean from sounding balloons.

Fig. 13 (right). Total energy content of the atmosphere (expressed in heat units) as a function of pressure (linear scale) for the trades, for the equatorial zone, and for the case of ascent of surface air without mixing. [Riehl and Malkus (*11*)]



balloon ascents has uncovered hardly any individual soundings which show this structure. One could fall back on the fact that in the equatorial zone, as elsewhere, ascent of air to high levels does not occur uniformly over the entire area (although the concept of random convection was widely held at one time) but that ascent is concentrated in weather disturbances which cover no more than one-tenth of the whole equatorial area. However, even soundings taken in such disturbances do not conform to the expected structure. Instead, the picture presented by Fig. 13 occurs regularly. In this diagram, the total energy of the air has been expressed in heat units (calories per gram). The energy forms considered are specific enthalpy, potential energy, and latent heat energy. The straight-line ascent at constant energy content corresponds to the undilute ascent shown in Fig. 12; the other curves give the mean structure of equatorial and trade-wind zones. It follows that, in the equatorial zone, energy flows down-gradient in the lower part of the atmosphere and upgradient at higher elevations.

This is a most unexpected conclusion for conditions at the heat source. If the circulation seen in Fig. 2 is superposed on this mean structure, it appears that energy must be transported upward across, say, the 500-millibar surface at 79.5 cal/g and exported poleward near 200 millibars at 82.0 cal/g. We are thus left with a deficit which is augmented by the radiational cold source within the upper atmosphere. Clearly, the cell concept fails to provide for heat balance here and must at least be amplified by an assumption of turbulence transport. Noting this, let us inquire how turbulence plus net mass transport can produce the required heat transport, where, to compound the difficulty, the transport must be in part down-gradient and in part upgradient. Before we do so, may I comment that problems of such complexity are common in meteorology. At times it has been said that progress in this field is slow. Perhaps the problem just outlined will explain why things have not always advanced as speedily as one might have wished.

The difficulty really is restricted to the layer above 600 to 500 millibars, in which the total energy content of the air increases upward. Lower down, cumulus clouds abound over those portions of the tropical oceans where an active heat source exists. The fundamental work of Stommel (*10*) has made it clear that these clouds are an effective means of funneling heat upward and thus imparting it to the environment through mixing. In turn, this mixing reduces the buoyancy of the cumuli, and, on the average, their tops are found near the layer of minimum energy content (Fig. 13).

This observation, by itself, does not solve the very interesting question of why the mixing process described does not continue all the way to the top of the troposphere. At this stage of our knowledge it is possible merely to postulate a mechanism which can establish the observed structure of the tropical atmosphere. Let us assume that a small fraction of the cumulus clouds becomes much larger in horizontal extent than most, with diameters of several kilometers as compared with hundreds of meters for the vast majority of the clouds. Then, mixing with the environment at the edges of these larger clouds will require some time before environmental air can penetrate to the center of an updraft and reduce the buoyancy there. Hence, if the buoyancy acceleration is large enough to permit the air in the core to acquire speeds sufficient for escape to high levels before its buoyancy is eroded, then the energy content of this air upon arrival at the upper levels would be typical of the surface layer. Actually, the time needed by buoyant elements to travel from the cloud base to the high troposphere is of the order of half an hour or less. This time scale is satisfactory for the mechanism just described, and the mechanism has been postulated as the means by which the whole equatorward mass flow is brought to high levels (*11*). The concentration of the poleward return current near 200 to 150 millibars—that is, near the top of the troposphere—supports this view.

The foregoing hypothesis implies the existence of two effective heat source locations, one near the surface and one near the tropopause. Heat is transported upward through mixing by cumuli in the low layers and transported downward by compression heating of turbulent elements from the high troposphere (Fig. 14). The tropopause itself is in equilibrium with the surface; it has the same heat content and represents, in the mean, the highest altitude to which air can penetrate from the ground.

If the hypothesis just outlined holds, a few thousand large clouds in the tropics will suffice to act as heat and mass funnels connecting equatorward and poleward branches of the mass circulation cell. The area covered by such ascending shafts is likely to be no more than 1 per mille of the area of the equatorial zone, in view of the strong vertical velocities in the large clouds. Therefore, the chance of balloon release into one of these updrafts is extremely small; moreover, releases often must be postponed during heavy rain at the release site. It is consequently evident why almost none of the many daily soundings show an atmospheric structure similar to that of the straight-line ascent in Fig. 13, and why the hypothesis is virtually without direct verification. This difficulty may be overcome now through cloud photography by satellite, when pictures are of sufficiently high quality to permit a count of the large clouds.

From the foregoing discussion it might be inferred that these large clouds form by random selection from millions of small cumuli. This, indeed, was the viewpoint held about tropical convection during the early part of this century. However, ample evidence exists to demonstrate that these clouds form in zones of mass convergence associated with weather disturbances which, roughly, have the same dimension as those of higher latitudes. Further, some types of disturbances, though well developed only in the high atmosphere, suppress cloud development almost to the ground, even in the presence of a surface heat source. Where clouds do occur, they tend to be arranged in lines, usually parallel—and more rarely normal—to the shear of the horizontal wind with height, and parallel to the wind itself in the absence of pronounced shear. Wide clear areas are situated between these "cloud streets." Such grouping of clouds shows the value of laboratory experiments on convection cells carried out over many years and should encourage continued experimentation. As yet, the occurrence of the streets is still problematic, but experiments may contribute toward a solution.

Quantitative work on atmospheric cloud streets in the tropics, from small cumuli to deep cloud bands in hurricanes, has been started. Notably, Woods Hole Oceanographic Institution, under the leadership of J. S. Malkus, has made an extensive photographic survey in the middle of the tropical Pacific, where land influences are nil. In the past, such influences have only too often distorted the conclusions of observers. Cloud systems were measured and found to be structured in close relation to the general air flow, from the ground to an altitude of 40,000 feet, especially at the latter altitude. There was even an area several hundred miles wide west of Hawaii which was almost cloudless during one traverse, hardly what one would expect in the trades. The area of the equatorial "convergence zone" was observed to have a cloud structure that was very variable in time and space, in agreement with all qualitative observations of the last 20 years.

In the future, photographic experiments logically will be coordinated with satellite photography. The combination should go far toward establishing the visible structure and motions of the cumuli which effect the vertical heat transport, and toward showing this structure in the frame work of the broader-scale array of convective clouds.

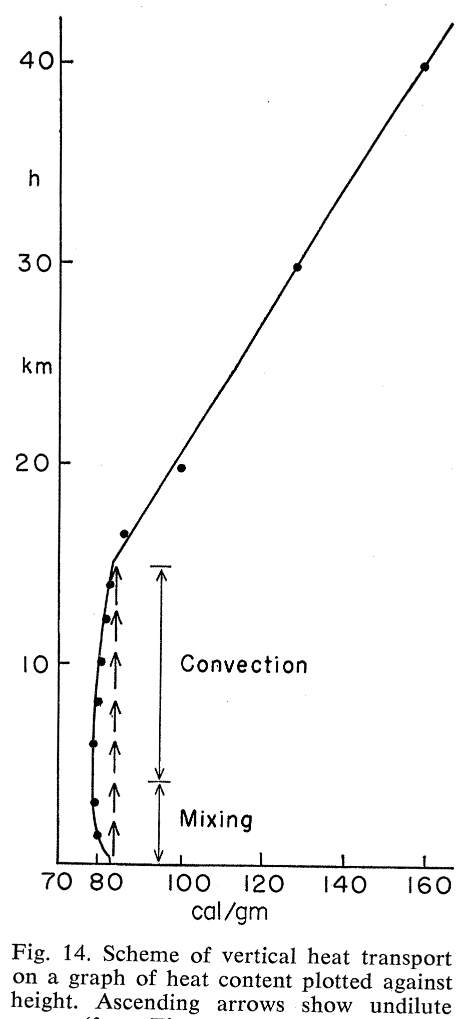


Fig. 14. Scheme of vertical heat transport on a graph of heat content plotted against height. Ascending arrows show undilute ascent (from Fig. 13). In the stratosphere, heat content decreases downward linearly from the top zone of the ozone layer, and heat may flow downward along this gradient. [Riehl and Malkus (*11*)]

The Next Decade

In this article I have attempted to show that there is no shortage of ideas which may be brought to bear on the subject of the general circulation in the tropics. A serious handicap, however, is lack of adequate observations to test hypotheses satisfactorily. The years from 1945 to 1960 may be regarded as the era of initial attempts to establish the processes of the tropical general circulation by computational means. If the next decade is to bring these attempts to fruition, a drastic change in the observational program must occur. The most encouraging feature of recent years has been improvement in the quantity and quality of weather data from many tropical regions, especially of upper-air data. This hard core of basic and indispensable observations must be at least doubled if reliable calculations of tropical weather processes are to be made.

As the reader may suspect, a substantial contribution to knowledge is expected from satellite observations, because of the nature of these data and because satellite observations will be made over the oceans and large continental areas where routine weather observations are inadequate. The actual heat source of the earth-atmosphere system in the tropics has never been measured. It is computed by an intricate chain of calculations (see *12*) which contains many assumptions, especially about cloud cover. The satellites will make direct measurements of incident solar radiation, reflected solar radiation (albedo), and long-wave radiation, on a continuing basis. These measurements should yield information on albedo and tropical heat source for the whole tropical belt, for hemispheres, and for continents and oceans, season by season, and information about specific large atmospheric disturbances.

Most intriguing, perhaps, is the possibility that there are variations in albedo and net heat source, say, from one January to the next, for the tropics as a whole and for specific regions. Such variations should have an impact on the tropical circulation cell. It may be that the intensity of this circulation responds, possibly with a substantial lag, to variations in net heat source. Weather and circulation anomalies in the temperate zone of one or both hemispheres may follow. But what is the origin of variations in net heat source? Changes in cloud cover are thought to be the most likely cause of variations in albedo. Since the atmospheric circulation itself controls the cloud cover, as far as is known, fluctuations in heat source may be internally produced, Then again, the atmospheric control may not be so perfect as has been assumed. Factors such as ascent to the surface of subsurface water masses in the oceans may play a substantial role in regulating cloudiness.

It is idle to carry speculation very far in matters where numerous variables exercise partial control of weather and also interact with one another. Two firm statements can be made. Information on the heat source as a function of time and space is imminent. But this information, taken alone, will not solve the atmospheric problems. It must be analyzed in conjunction with adequate observations on the circulation of the troposphere, the poleward heat and momentum fluxes, and the air-sea energy and momentum exhange. Advances in ocean buoy design hold much promise of great strides in knowledge of the interface processes. While the buoy program may be pursued mainly by those concerned with oceanography and related activities, establishment of a far-flung network of buoys over the oceans will also provide the surface-exchange data required as input for atmospheric calculations.

The main residual difficulty is the prohibitive cost of establishing an adequate network of balloon sounding stations. At present, all possible alternatives must be explored, even though they may provide only partial data. Successful flights of balloons floating with the wind at constant pressure over long tracks have attracted much attention in recent years. The outlook for the operationally proven design is poor, since the balloon package is heavy and regarded as a hazard to aviation. But the balloon program has provided stimulus for an ingenious new design of lightweight, super-pressure balloons (*13*). As many as 2000 such balloons circling the globe at one time at various altitudes are envisioned; information from them would be gathered by orbiting satellites. In a sounding system such as Lally's lies the brightest present hope for obtaining extensive wind and temperature data from all parts of the tropics. Further, it may turn out that balloons will shun certain areas and circulation systems, while congregating in others. This would provide direct evidence of the location of the highly important areas of horizontal divergence and convergence. In some areas and at some altitudes the balloons may cross the equator readily and indicate the extent of coupling between hemispheres.

Moreover, the data from the balloon flights may answer highly interesting questions, such as the following: Is there a circumpolar belt with winds from the west in the high troposphere over the equator? Westerly winds have been measured at many locations, but at present we do not know whether these westerlies extend around the globe over the equator, as they do in middle latitudes. Verification of the existence of an equatorial westerly belt would be an outstanding discovery, for its angular momentum would exceed the maximum angular momentum of the earth and hence could not be gained by contact with the ground. Can a dynamical model be devised to explain such a belt? Undoubtedly, a fundamental advance in knowledge of atmospheric dynamics should result from the impact of such challenging observations. And since there is a belt of eastward-propagating disturbances on the equator of the sun, this advance should also contribute to the understanding of solar dynamics.

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