TROPICAL METEOROLOGY

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PREFACE

In July, 1943, the author first saw the tropics when he arrived in Puerto Rico to join the staff of the Institute of Tropical Meteorology, newly founded through the initiative of Professors C. G. Rossby and H. R. Byers as a cooperative project of the Universities of Chicago and Puerto Rico. On the first evening some of the staff walked along the beach and admired the beauty of the trade cumuli in the moonlight. Well schooled in the ice-crystal theory of formation of rain, they had no suspicions about these clouds with tops near 8,000 feet where the temperature is higher than +10°C. Suddenly, however, the landscape ahead of them began to dim; then it disappeared; a roar approached as from rain hitting roof tops. When some minutes later they stood on a porch, drenched and shivering, they had realized that cloud tops with temperatures below freezing were not needed for the production of heavy rain from trade-wind cumulus.

There and then the question arose: How is it with the other theories in so far as they concern the tropics? In the past, weather and circulation in low latitudes had been regarded as steady except for occasional hurricanes. The urgent demand of the U.S. Army Corps for research in tropical meteorology, which had provided the impetus for founding the institute, belied the old descriptions. Military forces conducting war in the tropics undeniably found that "weather" on a serious scale did occur in that part of the world. What brought it on, and how could it be predicted?

One thing leads to another. It is well known that the low latitudes furnish a large fraction of the heat needed to balance the radiation deficit elsewhere. If conditions are not steady but variable within the tropics, could one still maintain that the tropics are without influence on variations of the general circulation in middle and high latitudes? The last ten years have shown repeatedly that the investigator of the general circulation cannot proceed like a physicist who turns on a well-controlled flame underneath a tank and then proceeds without further reference to the flame.

The eventual outcome of the many studies that have their roots in the early 1940's cannot now be foreseen. But the progress since those days, attained by research in many parts of the world, has been as swift and far-reaching as one could possibly expect. The new information is scattered throughout many journals and research papers difficult to secure for student bodies. As time passes, it has become increasingly hard to teach a course in tropical meteorology, especially on the undergraduate level. Plans for this book ripened slowly with the growing need.

Since the text deals with a specialty, knowledge of elementary meteorology as available in several basic texts and many instruction programs is assumed. Every effort, however, has been made to avoid complicated concepts or to discuss their physical significance in a simple way. The use of mathematics has been held to a minimum but, contrary to initial plans, could not be avoided entirely. Meteorology today is engaged in a vigorous effort to emancipate itself from the qualitative stage and become quantitative. This is achieved by the formulation and application of usually simple equations. The reader would be done anything but a service if this growing trend were eliminated from the book by a tour de force, if, for instance, the explanation and subsequent application of the theorem of conservation of potential vorticity were omitted.

Instruction programs, such as those leading to the master's degree, must allocate time for the large number of subjects of modern meteorology in some reasonable proportion. The book therefore attempts to hold the subject matter to what can be covered in one semester containing 45 to 50 lectures. It also tries to give a complete survey of the field, since most meteorologists and workers in allied sciences who may not have an opportunity to return for university training would wish to obtain such general coverage. These two aims limited the amount of material that could be taken up in each chapter. A full treatment of tropical storms alone would require as many pages as are contained in the whole present book. It is hoped that achievement of the dual purpose that has governed the selection of material will outweigh the shortcomings and omissions which in a new subject necessarily must be great.

Wartime experiences and subsequent research have shown spectacularly that there is far more to the subject of formation of clouds and rain than 100 per cent relative humidity. A presentation of the advances in cloud physics, especially the formation of rain from warm clouds, is essential. Since the author has not had experience in this field, it seemed advisable to have the subject handled by a person of authoritative standing. The author was fortunate in securing the collaboration of Dr. Raymond B. Wexler of Harvard University and Massachusetts Institute of Technology.

The influence of many persons and agencies combines to lead to the eventual preparation of a book. Before 1947, the author's work in

tropical meteorology was made possible through support of the U.S. Army Air Forces and the U.S. Weather Bureau. Since 1947, research in the tropical field at the University of Chicago has been sponsored generously and consistently by the Office of Naval Research. Professors C. G. Rossby and H. R. Byers made the arrangements that permitted the author to enter tropical meteorology and continue in the field. Early stimulation in Puerto Rico came from Clarence E. Palmer, first director of the Institute of Tropical Meteorology, and Gordon E. Dunn of the U.S. Weather Bureau. In recent years, the author has enjoyed increasing contact with the program of marine meteorology in the trades conducted by Woods Hole Oceanographic Institution. Just prior to concluding his work on this manuscript he was fortunate in being able to visit a new expedition for the study of cumulus clouds under the leadership of Dr. Joanne S. Malkus. Many discussions at the University of Chicago have served to form and clarify the author's viewpoints. He is especially indebted to his colleagues T. C. Yeh, N. E. LaSeur, and Chas. L. Jordan.

Finally, the permission of several publishing houses to reproduce certain figures is acknowledged gratefully, as is also the manuscript assistance of Dr. Ernst Moll.

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CONTENTS

CHAPTER 1

WINDS AND PRESSURE

Some people say that the Tropics of Cancer and Capricorn bound the area within which to limit tropical meteorology. Others point to the 30th parallel, which divides the earth's surface between pole and equator in equal halves. Anyone living in the marginal belt will find both definitions arbitrary. The state of Florida certainly experiences tropical weather in summer but rarely in winter. In northern India and Pakistan forecasters reckon with "western disturbances" in the dry season.

If we define the tropics as that part of the world where most of the time the weather sequences differ distinctly from those of middle latitudes, the dividing line between easterlies and westerlies in the middle troposphere serves as a rough guide of the boundaries. Choice of this fluctuating line allows for seasonal variations and for differences between one part of the world and another in the same season. The tropics so outlined will be our major concern. But we are also interested in the connections between tropical and temperate zones. No part of the atmosphere exists alone or can be understood without considering a wider area. Both synoptic and climatic data of this book, therefore, include a portion of the middle latitudes.

Pressure and Wind Profiles at the Surface

Average weather conditions generally change much more with latitude than with longitude. From early times, men have so viewed the climate and coined names such as "doldrums" and "trades." As our first step we shall ascertain the mean conditions in these broad belts.

Sea-level Pressure. In the subtropics, often called "horse latitudes," each hemisphere has a pressure maximum at sea level in both seasons (Fig. 1.1). Between these "subtropical highs" a region of lower pressure is found near the equator—the "equatorial trough" commonly known as the doldrums. The trough is centered near 5°S in January and near 12–15°N in July. It migrates through 20° latitude between seasons; this migration influences the seasonal march of cloudiness and rainfall and the formation of tropical storms. In the annual mean, the trough lies near 5°N rather than on the geographical equator. This latitude has been named the "meteorological equator."

The subtropical high-pressure ridges reflect the asymmetry with respect to the geographical equator. The southern ridge is situated 5° latitude closer to it in the mean than the northern one. Both ridges are an equal distance from the meteorological equator. The width of the belt between ridges and equatorial trough, largely occupied by the trades, is identical in the yearly mean in both hemispheres (30°). But this width undergoes a distinct seasonal variation; although the subtropical ridges shift in phase with the equatorial trough, their displacement amounts to little more than 5° latitude, while that of the trough is 20°. In consequence the intervening belt is much broader in the winter (35°) than in the summer hemisphere (25°).

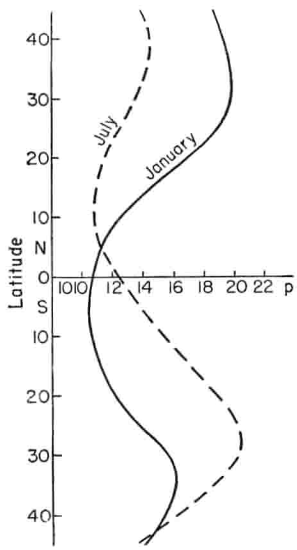

Fig. 1.1. Mean sea-level pressure (mb).

At the subtropical-ridge lines, pressure is practically equal in both hemispheres, varying from 1015 mb[1] in summer to 1020 mb in winter. We observe that the whole tropical belt changes accordingly. In each hemisphere, the mass in the tropics decreases from winter to summer. Because this mass does not escape completely to the polar regions (34),[2] a net export takes place from summer to winter hemisphere across the equator.

Resultant Winds. If we wish to make statements about the wind field that are as quantitative as those just made about the pressure, we must confine our attention to the oceans. The *Atlas of Climatological Charts of the Oceans* (40) contains extensive statistics on wind and other weather elements in "squares" bounded by 5° latitude and longitude intervals. Similar statistics over land do not exist and would be very hard to compute. Oddly enough, less is known about the circulation over wide continental stretches than over remote ocean areas crossed by shipping lanes. Local topography exercises a strong influence on the wind at any land station; the difference in ground friction alone renders a combination of ocean and land winds impossible. So we shall restrict the analysis to the oceans. A glance at world streamline charts (Fig. 1.7), however, reveals that the wind belts over land are quite similar to those over the oceans.

[1] NOTE ON UNITS. In meteorology, there exists a grotesque confusion in respect to units. We have temperature in °C, °A, °F; pressure in mb, mm, and inches of mercury; length in cm, inches, feet, km, land miles, nautical miles, etc.; these units and others occur in any number of combinations. Nothing is more annoying than the time constantly lost by everyone through unnecessary conversions; adoption of one world-wide system of units should be achieved by the profession.

[2] Figures in parentheses refer to the references listed at ends of chapters.

A plot of the direction of the resultant wind vector against latitude (Fig. 1.2) looks quite unconventional for meteorology. It features straight lines with abrupt breaks rather than smooth curves as in Fig. 1.1. Separation between the wind belts is very sharp. At the edges of the diagram, we see the beginnings of the polar westerlies. These lie about 5° closer to the equator in winter than in summer. Next comes a break in wind direction across the subtropical ridges. It is significant

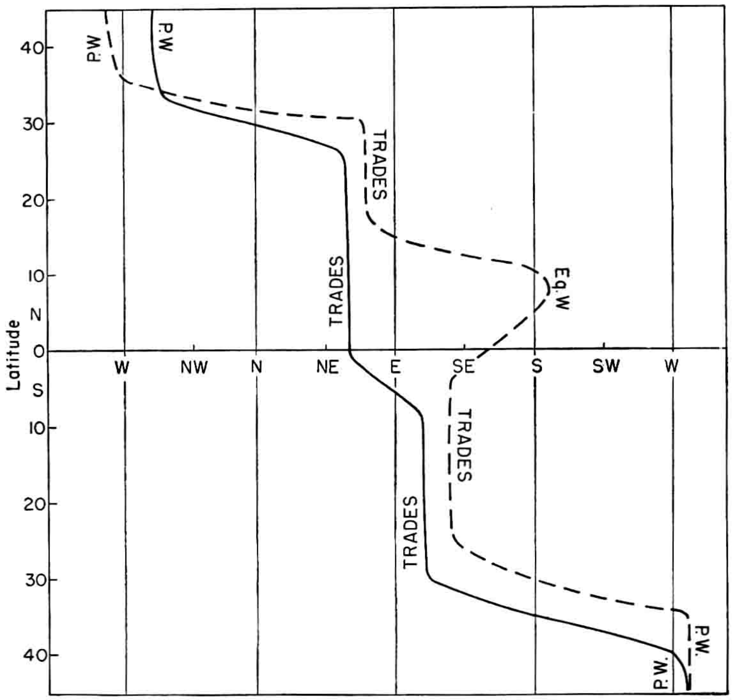

Fig. 1.2. Resultant surface-wind direction for January (*solid*) and July (*dashed*).

that winds turn from west to east through north in the northern hemisphere and through south in the southern hemisphere. This implies a net flow of air through the subtropical high-pressure belt, a flow directed toward the equator in both hemispheres.

The trades occupy the bulk of the tropics. Broadly speaking, they blow from ENE in the northern hemisphere and from ESE in the southern hemisphere. But the flow points a little more toward the equator in winter than in summer. The average wind direction in the northern hemisphere is 50–60° in winter and 70° in summer;[1] in the southern hemisphere it is 120–130° in winter and 110° in summer. Thus, northern

[1] Measured clockwise from north on the 360° compass.

and southern trades blow across the latitude circles in the mean with equal angles: 30–40° in winter, 20° in summer.

Up to this point the symmetry in the pressure fields of both hemispheres relative to the meteorological equator has held true in the wind field. A marked difference appears at the equatorial margin of the trades. In January, the break in wind direction between the trades occurs quite properly near 5°S. In July, however, southerly flow occupies the belt 0–15°N, and the resultant direction even is west of south between 5 and 10°N. Here the method of averaging around latitude circles is not satisfactory. The westerly component arises as the southern trade makes wide incursions into the northern hemisphere on a clockwise curving path (Fig. 1.7). These incursions take place only in limited belts of longitude, mainly in the Indian Ocean. If this ocean were excluded from the computation, the July curve would be very different between the equator and 15°N.

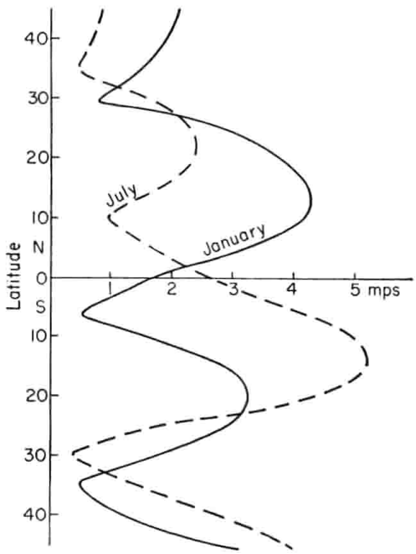

Fig. 1.3. Resultant surface-wind speed (mps).

Turning next to the resultant wind speed (Fig. 1.3), we observe four belts of high speed in each season—the trades and polar westerlies. Regions of low speed are interspersed in the subtropics and near the equatorial trough. Both trades and westerlies increase in strength from summer to winter; the intensity of the trades nearly doubles. In the northern hemisphere the highest speed is 2.4 mps in summer and 4.3 mps in winter; in the southern hemisphere 3.3 mps in summer and 5.3 mps in winter. The increase in both cases is 2 mps. We find that the speed of the southern trade exceeds that of the northern by 1 mps in both seasons and that the latitude of strongest trade in both hemispheres shifts about 10° equatorward from summer to winter.

The foregoing applies to the *resultant speed.* This, however, may not tell us much about the *average speed* of the winds, *i.e.*, the mean of all wind speeds regardless of direction. We know that the subtropical ridge oscillates northward and southward many times in the course of one winter. It is possible that in consequence the subtropical latitudes experience alternating east and west winds of considerable strength but that these winds cancel when the resultant is taken. We should call such a regime unsteady. In contrast, a region with relatively constant wind direction has a steady regime.

Climatology offers several methods to determine steadiness of the winds. One measure is the correlation between average and resultant wind speed. This correlation has been computed for July by dividing the tropics into three portions with the help of Fig. 1.7: the belt within 5° of the equatorial trough, the belt from the equatorward margins of the subtropical ridges to the poleward limits of the map, and the intervening trade-wind belt. The linear correlation coefficients are 0.70, 0, and 0.94, respectively. It follows that winds in the subtropics are highly variable. Near the equatorial trough the variability is less; in the trade-wind zone winds are steady.

We have set down numerically the experience of the old seafarers, who often spent anxious days in the horse latitudes and doldrums but sailed the trades with little concern. Profiles of wind constancy against latitude (Fig. 1.4) further confirm this. Constancy here is defined as the per cent frequency of all observations with wind direction within 45° of the most frequent direction, or mode. For instance, if the wind at some station blows most often from NE and it blows anywhere between N and E 75 per cent of the time, the constancy is 75 per cent. The profiles of Figs. 1.3 and 1.4 are very similar. High resultant speeds coincide with high constancy and low resultant winds with low constancy. This relation holds for the regional distribution so that the isotachs of Fig. 1.7 might, with some approximation, have been labeled lines of equal constancy.

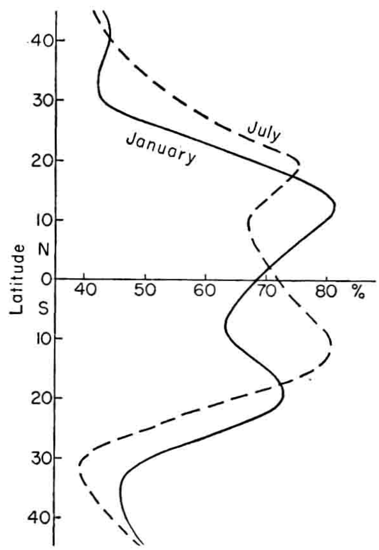

Fig. 1.4. Constancy of surface wind (per cent).

In the trades the constancy attains 80 per cent; in no other regime on earth do the winds blow so steadily. Life has adjusted to this uniform wind stream in numerous ways. On many islands the towns lie on the leeward side, which affords better protection to shipping from wind and ocean. Many busy airports have only one runway along the direction of the resultant wind, though this at times has proved a mistake.

The steadiness also introduces a certain monotony in trade-wind weather. The author recalls from his days in Puerto Rico that there always was a great deal of excitement in the office during one of the rare "interruptions of the trade."

Resultant Wind Components. Latitudinal profiles of the resultant wind components play a role in a variety of problems such as the general circulation and the distribution of cloudiness and rainfall. The mean meridional circulation (Fig. 1.5) has formed a cornerstone of many theories since the days of Hadley. It is quite surprising that no one has computed its actual strength before 1950 (22, 26, 27). Before accepting

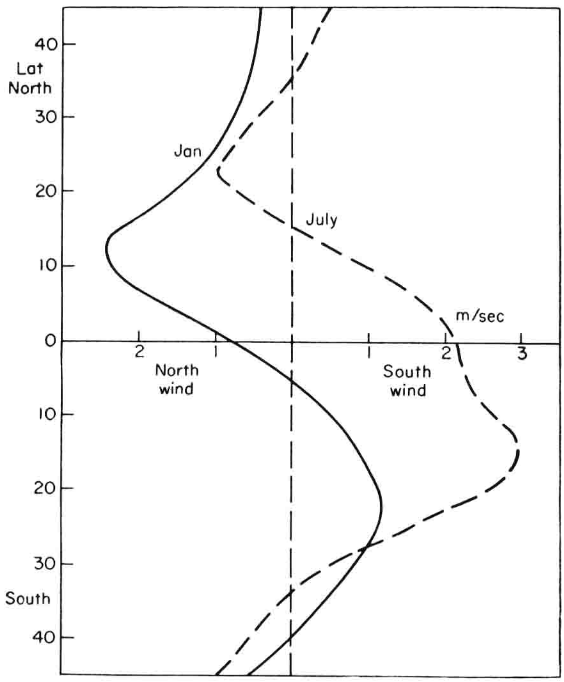

Fig. 1.5. Mean meridional wind (27).

the curves of Fig. 1.5, some checking is necessary. North and south components could alternate around the globe on any latitude circle so that the resultant could be a statistically insignificant difference between large numbers. We can make a test by counting on each latitude circle the number of 5° latitude-longitude squares with north and south components (Table 1.1).

Equatorward components dominate so strongly that the validity of Fig. 1.5 in the trades during winter is assured. Farther poleward the mean meridional circulation becomes very small; in the summer hemisphere north and south components alternate much more. Here the statistics are less impressive. We conclude that the tropics contain only

TABLE 1.1. NUMBER OF 5° LATITUDE-LONGITUDE SQUARES WITH (*A*) MEAN POLEWARD AND (*B*) EQUATORWARD WIND COMPONENT IN THE TRADES, IN WINTER

	A	*B*
July:		
5–10S	4	54
10–15S	2	58
15–20S	1	54
20–25S	7	50
January:		
5–10N	3	53
10–15N	0	59
15–20N	0	54
20–25N	0	52

one large circulation cell—in the winter hemisphere. There, a broad sweep of air around the globe flows toward and beyond the equator at considerable speed (2–3 mps). In the subtropics air crosses the sub-

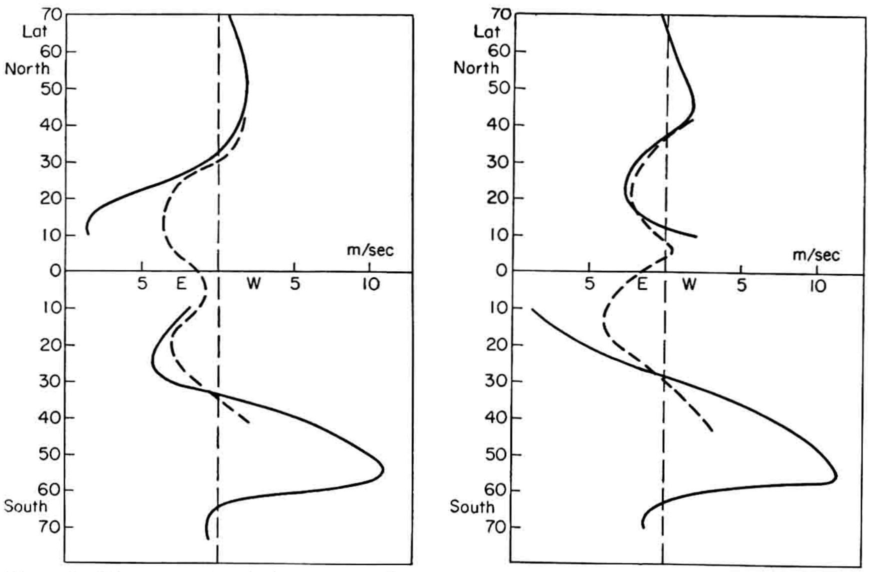

Fig. 1.6. Mean zonal wind (mps, *broken*) and geostrophic wind (*solid*) (17). *Left:* January. *Right:* July.

tropical ridge from the westerlies to the trades; the latitude separating equatorward and poleward wind components lies 5° or more poleward from the high-pressure ridge. In the equatorial zone the crossover latitude from north to south components is 5°S in January and 15°N in July, in good agreement with the equatorial-trough positions.

Turning to the zonal component (Fig. 1.6), an east wind of 1.5–2 mps blows on the equator in both seasons (17). Such an east component is not found on all stellar bodies of which we have knowledge. In the observable layers of the sun's atmosphere the equatorial drift is westerly; a westerly circulation also has been produced in rotating dishpan experiments. Scanty data for the planet Mars, however, suggest equatorial easterlies (13); the general circulation resembles that of the earth to a remarkable extent, for there are not only equatorial easterlies but also cellular subtropical ridges.

Figure 1.6 includes geostrophic wind profiles to latitudes 10°. Agreement between observed and computed winds is good at the subtropical ridge. Equatorward from the subtropics the gap between geostrophic and actual winds widens. Below latitudes 20°, the geostrophic computation is quite useless as an indicator of true resultant winds in winter. Comparison of instantaneous geostrophic and observed winds yields similar results (Chap. 7).

World Distribution of Winds and Pressure

Anyone who sets out to prepare a set of charts such as Figs. 1.7–1.8 will soon realize that this is not a small or wholly satisfactory task. Although every atlas or textbook carries some picture of the mean wind field, there are important differences, not easy to reconcile. This book draws mainly on the *Climatological Atlas* (40) for the oceans and several special publications (3, 9, 18, 32, 33, 37–39, 43) for the land areas.

Analysis of Fig. 1.7 was carried out with the streamline technique developed by V. Bjerknes (1) and extensively applied to tropical work by Palmer (21). Chapter 7 contains a description of the technique. In view of our computations of wind constancy, the streamlines in the trades represent mean air trajectories; those of the subtropics merely indicate net mass displacements. Nevertheless, the anticyclonic singular points in the eastern parts of the subtropical oceans are one of the most striking features of the maps. Such singular points occur in all oceans in both seasons except the south Indian Ocean in July. There the data suggest an anticyclonic line source of streamlines. All subtropical cells execute the seasonal shift deduced before.

The streamlines which emanate from the subtropics diverge widely as they pass through the trades, especially in the southern hemisphere in summer. Approaching the equator, they curve clockwise over the eastern parts of the oceans. Eventually the SE trades move from SW, W, and even NW in some areas. This turning is often ascribed to monsoonal effects; a portion of the trades, called "deflected trades," is thought to be drawn toward the heated continents. Freeman (11) has suggested

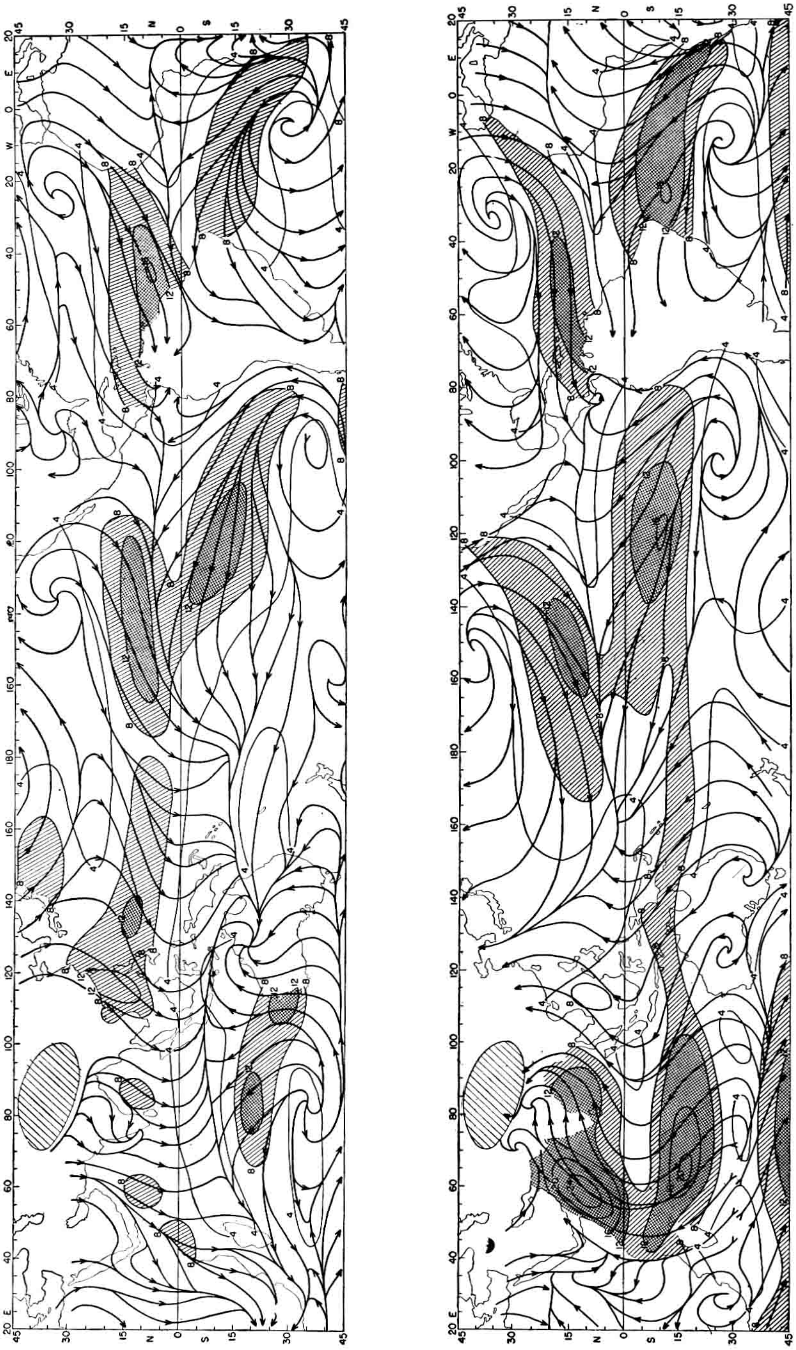

Fig. 1.7. Resultant streamlines and isotachs. *Top:* January. *Bottom:* July. Light shading denotes areas with wind speed greater than 8 knots; heavy shading, greater than 12 knots.

another explanation, at least for the west coast of South America; this explanation is based on the idea of hydraulic-pressure jumps under an inversion. Various facts cast doubt on the monsoon theory of the deflected trades. For instance, the northern-hemisphere air executes a corresponding turning—counterclockwise in this case—in the middle of the Indian and Pacific Oceans in January. There can, however, be no doubt that the charts prove the existence of monsoons; air flows toward the continents in summer and from the continents in winter.

In general, the equatorial trough is situated where the streamlines from both hemispheres converge. Its position is clear-cut in January, apart from the central south Pacific, where a convergence line oriented SE–NW emanates from the subtropics and becomes part of the equatorial trough between 160°W and 180°. The trough slopes from ENE to WNW over all three oceans. This implies a northward shift from east to west across the continents, evident over Africa (20° latitude) and Australia (10°).

In July the trough can be located with ease only over Africa, the Atlantic, and the Pacific to about 150°E. In the eastern hemisphere it lies over the mainland of Asia and appears in the streamlines only over India and Pakistan, where detailed data exist. Analysis is most difficult in the western Pacific. The zone of streamline convergence that extends southeastward from Korea does not represent the mean position of the equatorial shear lines found on daily charts. These lines extend, on the average, across the Philippines and the South China Sea. Winds are highly variable in the western tropical Pacific; large typhoons are frequent, and the mean streamlines probably reflect the influence of these storms.

Low resultant speeds prevail in the subtropics and in the equatorial trough, high resultant speeds in the trades just as in Fig. 1.3. Each trade region contains definite centers of high speed (and high wind constancy) that reach 12–16 knots. Speeds are highest over the Indian Ocean in July—more than 24 knots in the Persian Gulf.

Figure 1.8 shows the relations between world streamlines and isobars. This set of charts was difficult to draw, especially in the equatorial zone, where pressure gradients are weak. Many published maps leave this area blank. The oceanic isobars are based on analyses in several publications (30, 31) and on additional pressures recorded largely at island stations and collected in "World Weather Records" (7). After completion of preliminary isobars the author superimposed them on the previously finished streamlines; definite relations between the two sets of lines appeared which resemble those found on daily charts. The subtropical ridges coincide fairly well with the anticyclonic singular points. In the trades, air blows across the isobars toward lower pressure; the equatorial troughs as determined from streamline and isobaric analysis coincide