HURRICANE DEVELOPMENT[1,2]

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(Manuscript received 22 September 1958)

ABSTRACT

Latest available compilations confirm that mean hurricane frequencies vary widely within the tropics. Referred to a standard unit area, hurricanes (typhoons) are three times as likely to develop in the western North Pacific as in any other generating area.

Numerous published analyses indicate that an intensifying upper trough in low latitudes may, through an energy dispersion mechanism, sharpen the next downstream trough. The resultant pressure fall in the downstream trough, should it overlie a low-level cyclonic disturbance, might be enough to trigger hurricane development in the disturbance.

Frequent energy dispersion from a vigorous persistent upper trough in the central North Pacific could account for the high frequency of west Pacific typhoons.

1. Introduction

Although much remains unknown, investigators generally agree on some of the requirements which must be satisfied if a hurricane (typhoon) is to form. Palmén [30] lists the following:

1. "Sufficiently large sea or ocean areas with the temperature of the sea surface so high (above 26 to 27C) that an air mass lifted from the lowest layers of the atmosphere (with about the same temperature as the sea) and expanded adiabatically with condensation remains considerably warmer than the surrounding undisturbed atmosphere at least up to a level of about 40,000 ft."
2. "The value of the Coriolis parameter larger than a certain minimum value, thus excluding a belt of the width of about 5 to 8 deg lat on both sides of the Equator."
3. "Weak vertical wind shear in the basic current, thus limiting the formation to latitudes far equatorwards of the subtropical jet stream."

To this should be added:

4. Tropical storms form only in pre-existing low-level disturbances [37].

In 1948, Riehl [36] outlined a typhoon-development mechanism. He postulates that a low-level disturbance tends to deepen when it moves beneath a divergent northerly stream associated with a high tropospheric cyclone. The cyclone might have already intensified after superposing on a mid-latitude disturbance. In the two cases of cyclogenesis used to illustrate the hypothesis, analysis shows upper disturbances moving west at about 15 kn and overtaking slower moving low-level disturbances. Other investigators [17; 22; 24; 28; 35] describe hurricanes developing when upper lows or troughs often moved erratically or were nearly stationary. These reports, however, do not question Riehl's additional requirement for tropical cyclone development:

5. Upper outflow above the surface disturbance.

Outflow must exceed compensating inflow at other levels. Only if the central pressure falls sufficiently to transform the surface disturbance into a vigorous energy-producing circulation (addition of sensible and latent heat from the sea to the inflowing surface air), can a hurricane form and persist.

The remainder of this paper relates frequencies of tropical-cyclone formation in various regions to geographical distribution of the five requirements listed above, discusses the transformation of cold-cored into warm-cored cyclones, and bases a development hypothesis on analyses published by other investigators.

2. Regional distribution of tropical cyclone development

The tropical oceans may conveniently be divided into twelve regions. Except for the South Pacific, each has provided a wealth of data on tropical cyclones (maximum winds usually above Beaufort force 8). Table 1 lists for each region the mean annual frequency of tropical storms and hurricanes, and the extent of sea with summer surface temperatures above 26C (requirement 1) lying poleward of 5 deg lat (requirement 2) and equatorward of the summer position of the subtropical ridge at 300 mb (requirement 3). Column 7 shows the mean annual frequencies of tropical storms per million km^2 delimited by require-

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[1] This research has been supported by the Geophysics Research Directorate, Air Force Cambridge Research Center, Air Research and Development Command, under Contract AF 19(604)–1942.

[2] Contribution No. 8 of the Hawaii Institute of Geophysics.

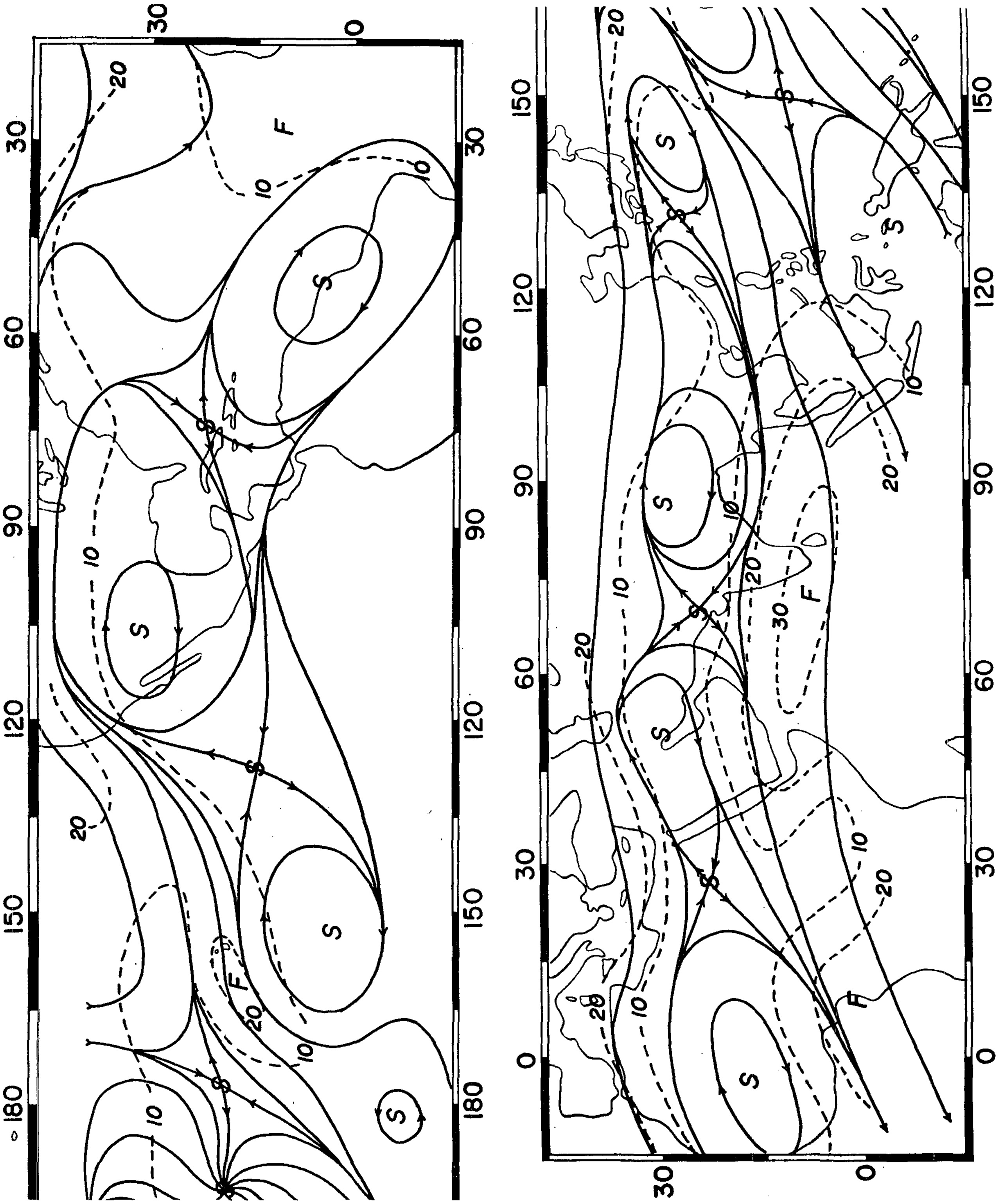

FIG. 1. Mean resultant wind field at 200 mb for July 1951 (after Gilchrist[16]). Isotachs labelled in m sec^{-1}. Centers of minimum wind speed denoted by "S," centers of maximum wind speed by "F."

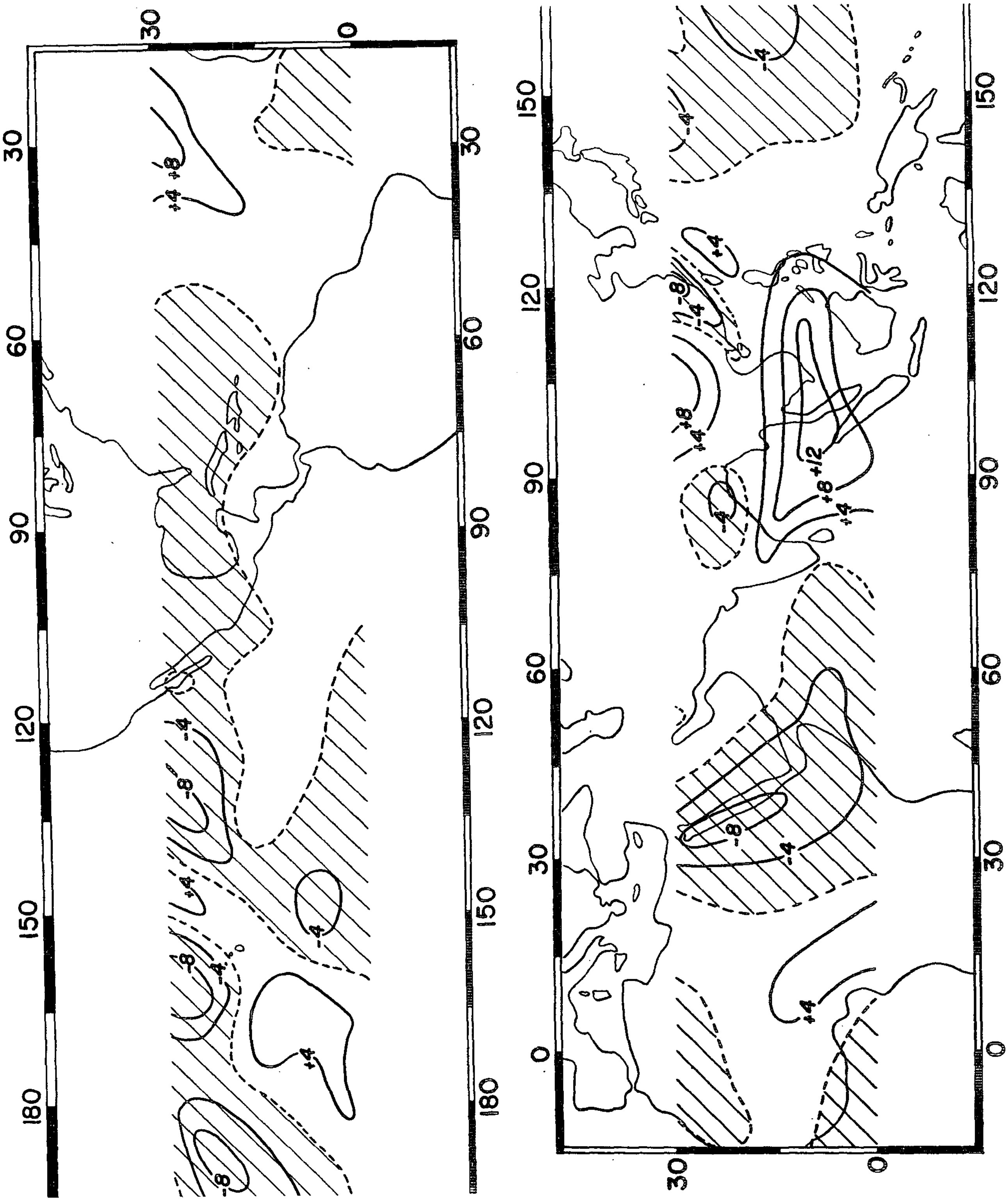

FIG. 2. Mean divergence field at 200 mb for July 1951. Divergence isopleths labelled in units of 10^{-6} sec^{-1}. Negative areas shaded.

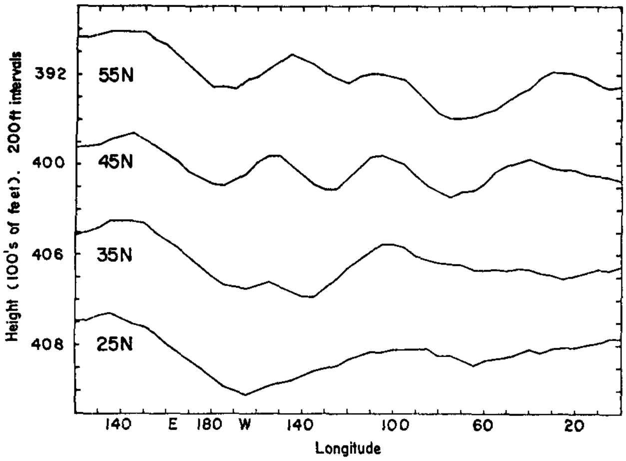

FIG. 3. Mean latitudinal pressure-height profiles at 200 mb for summer (July, August, and September, three years).

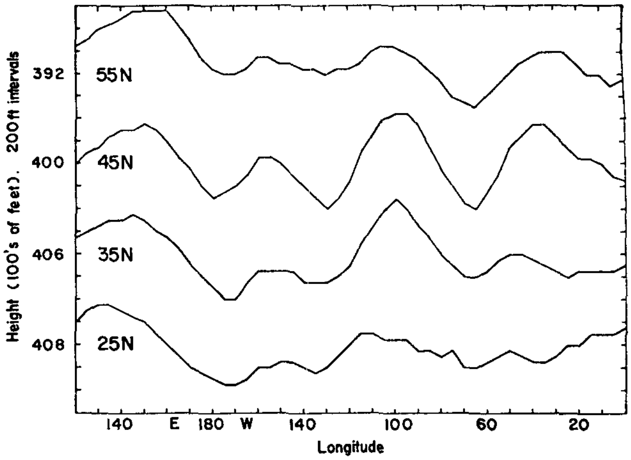

FIG. 4. Mean latitudinal pressure-height profiles at 200 mb for July and August 1957.

ments 1 and 2. Columns 9 and 10 show the frequencies of tropical storms and hurricanes per million km^2 delimited by requirements 1, 2 and 3 (data were insufficient to allow Southern Hemisphere regions to be included in these columns). Column 10 shows that, referred to a favorable area of constant size, hurricanes develop three times as commonly in the western North Pacific as in other regions. Despite possible variations in intensity criteria and land-mass boundary effects, this frequency difference is large enough to be significant. Since only a small fraction of low-level tropical disturbances intensify into hurricanes (requirement 4), high-level flow patterns (related to requirement 5) may yield clues to the sharp interregional variability of hurricane occurrence.

3. Climatology of the 200-mb flow in summer

Gilchrist [16] presents mean resultant 200-mb winds for July 1951. Supplementary data for other summer months were added, and streamline-isotach (fig. 1) and divergence (fig. 2) analyses were made. As might be expected, anticyclones cover the continents (above low-level heat lows) and extend ridges over the western oceans; troughs are found over the cool eastern oceans. A vigorous trough extending from Alaska to Indonesia and markedly divergent flow west of 150E dominate the Pacific. *No features of comparable magnitude appear elsewhere in the tropics.*

In July 1951, only one tropical depression and one typhoon formed in the west Pacific and no tropical cyclones in other regions. Since the month was rather inactive, its wind patterns were checked to see whether they generally typified the summer months. From 200-mb monthly mean charts published in the Monthly Weather Review, mean pressure-height profiles along 55N, 45N, 35N and 25N were constructed for nine summer months, July through September (fig. 3). Profiles south of 25N could not be determined. Over the Pacific, troughs on either side of the oceanic ridge in middle latitudes merge into a single dominant trough at 25N–165W. Over the Atlantic, the oceanic ridge disappears toward the south, a weak trough is found at 25N–65W and the eastern Atlantic is quite featureless. Thus the pressure-height profiles attest to the climatological significance of the July 1951 200-mb wind patterns.

From July through September, at the height of the summer monsoon, an immense surface-heat low is centered over northern India. Above it, at 200 mb, a vigorous anticyclone dominates south and southeast Asia and the Pacific west of 140E. Strongest winds occur over southern India and the Bay of Bengal where horizontal thermal gradients are steepest. Easterlies exceeding 50 kn are often reported [21]. Further east, over China and the China Seas, thermal gradients are flatter and 200-mb winds, generally from northeast, are lighter. Winds also diminish to the west, over the Arabian Sea and Arabia. The upper tropospheric part of the monsoon circulation is thus persistently divergent east of the Indian peninsula and as persistently convergent west of the peninsula.

A pronounced trough over the central Pacific separates the Asiatic anticyclone from a somewhat weaker North American anticyclone. Hubert [18] suggests that as the trough tends to persist throughout the year [8] it may well be maintained by large scale features of the general circulation. There is little land in the Far East south of 20N. Consequently, temperature and pressure diminish toward the equator in summer, and the trough orients northeast-southwest.

Two heat sources, over South America at about 10N and over Africa at about 15N, influence the Atlantic circulation. The upper anticyclones over North and South America and over Africa are so close that neither troughs nor divergence persist over the Atlantic.

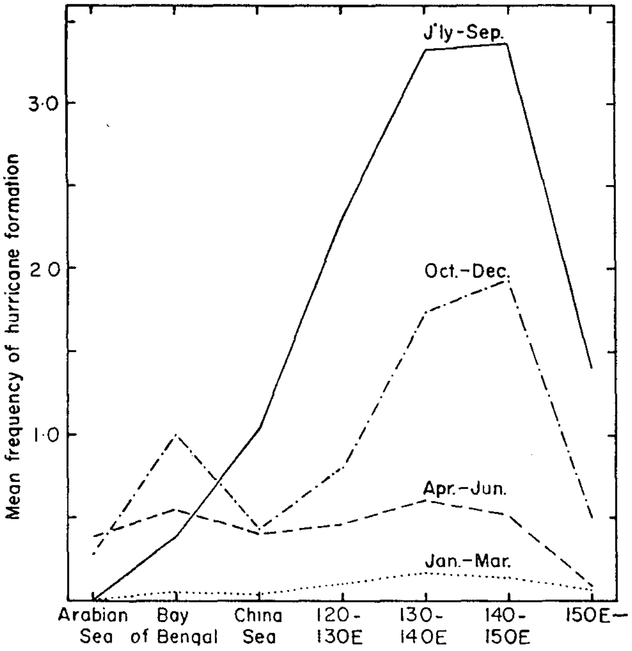

FIG. 5. Mean frequency of hurricane formation (by seasons) over the western Pacific, the Bay of Bengal, and the Arabian Sea.

4. Northern-hemisphere hurricanes

Fig. 5 shows the frequency distribution of typhoon and hurricane development by longitude strips for the western North Pacific (1924 to 53) and for the Bay of Bengal and the Arabian Sea. Fig. 6 expresses mean monthly hurricane developments for each northern-hemisphere generating region as percentages of the total number of hurricanes forming in the region. As in fig. 5, the western Pacific is divided into 10-deg-longitude strips.

Western Pacific.—As far-eastern meteorologists have known for many years [15; 29], a significant frequency maximum is found between 130E and 150E where two-thirds of all typhoons develop. Since this zone differs little from areas to the east and west in sea-temperature distribution or in numbers of low-level disturbances, it seems reasonable to conclude that the typhoon-development peak stems from upper tropospheric causes.

The mid-Pacific upper trough (MPT), described in the preceding section, resembles other major semi-permanent troughs. Upper cyclones move into it and intensify, move away from it and often dissipate. Simpson [41] publishes a frequency table for cut-off lows at 300 mb which shows that cyclogenesis often occurs in the trough.

Three separate energy sources may inject cyclonic vorticity into the low-latitude portion of MPT:

1. Mid-latitude cyclones which intensify as they move into the northern part of the trough.

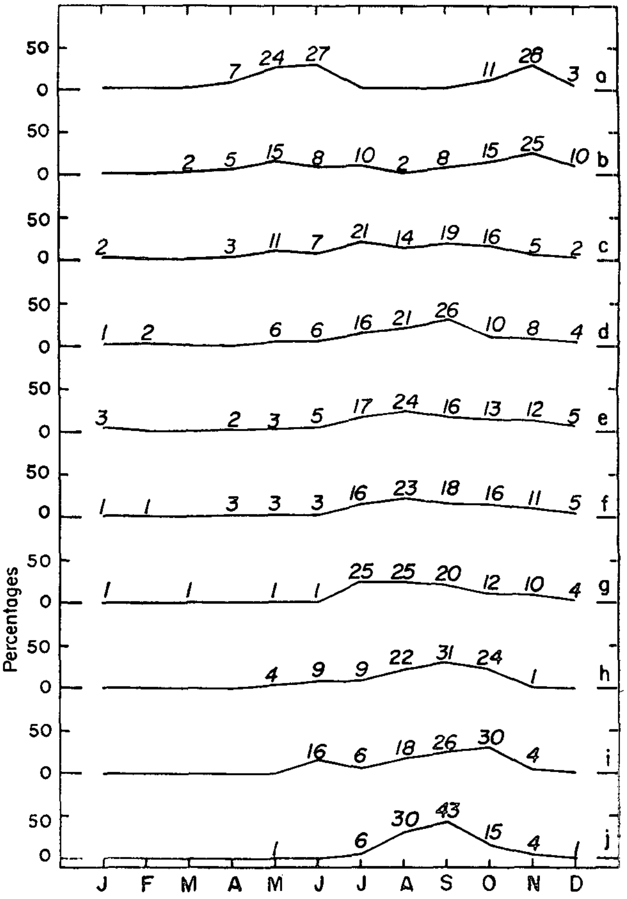

FIG. 6. Mean monthly variability of hurricane development in the Northern Hemisphere, expressed as percentages of the total in each generating area.

Areas:
a. Arabian Sea
b. Bay of Bengal
c. China Sea
d. W. Pacific from 120E to 130E
e. W. Pacific from 130E to 140E
f. W. Pacific from 140E to 150E
g. W. Pacific east of 150E
h. E. Pacific
i. Gulf of Mexico and Caribbean
j. Atlantic

2. High-level equatorial cyclones which develop in the MPT south of 20N and may be directly linked to fluctuations in solar activity [32].
3. High-level anticyclones in the Southern Hemisphere which have been observed to intensify, extend across the equator, and affect the MPT.

Averaging fails to hide activity in the MPT. Mean upper cyclones were centered near Wake Island (19.3N–166.6E) in July 1951 (fig. 1) and 250 mi south of Wake Island in November 1952 [20].

During periods of increased cyclonic activity in the MPT, upper northerly flow west of the trough is often divergent and according to Riehl would aid intensification of underlying disturbances into typhoons. Since the MPT usually lies between 165E and 170E at 20N, maximum typhoon development might be expected within ten degrees to the west. However, fig. 5 shows maximum development centered about 142E.

Synoptic situations associated with eleven west-Pacific typhoons have been analyzed and published [17; 22; 28; 36]. Whenever typhoon winds set in, a vigorous upper (30,000 or 40,000 ft) cyclone was centered 20 to 25 deg east of the surface circulation, its median position being 15N–163E, or very close to the usual location of the MPT (see fig. 1). In no case did northerly flow which was part of the circulation of the upper cyclone appear to overlie the developing typhoon. In most cases, a well-marked ridge had formed west of the upper cyclone and the surface disturbance was found west of the ridge axis beneath either southeast flow or an upper trough.

McCreary and Wharton [23] note that horizontal wind shear at 30,000 ft between Wake Island and Eniwetok (11.3N–162.3E) is generally anticyclonic prior to mid-April and generally cyclonic thereafter. Meager data suggest that reversion to anticyclonic shear occurs in December. Thus, the season of maximum activity in the low latitude portion of the MPT includes the west Pacific typhoon season.

The high rate of typhoon development in the western Pacific probably stems directly from the persistent MPT, a unique feature of the tropical upper troposphere.

China Sea.—West of 130E, typhoons develop much less often. Over the China Sea during August, shear between the generally weak south or southwest surface monsoon and the upper north-easterlies reaches a maximum. This is reflected in a weak secondary typhoon-frequency minimum.

The winter monsoon is established by November and surges of cold air and southward drift of cold water inhibit development over the China Sea. Only 9 per cent of all China Sea typhoons form in winter compared with 18 per cent for the region east of 130E.

Central Pacific.—East of the MPT, southwesterlies prevail at high levels and often tend to be convergent. Vertical shear between them and the strong northeast trades helps make hurricane development extremely rare.

In 1957, an unprecedented three hurricanes and two tropical storms developed between 140W and 160W. Data are almost nonexistent south and east of Hawaii, and detailed analysis of these storms will be impossible. However, mean 200-mb latitudinal profiles for July and August 1957 (fig. 4) reveal that the mid-latitude trough in the eastern Pacific persisted to low latitudes. Frazier [12] says "The increased activity (in the eastern Pacific during 1957) was associated with the trough along the west coast of North America which has been rather persistent and well developed, especially at the lower latitudes throughout the summer and fall seasons." Thus, in 1957, when a trough similar to the MPT lay across the tropical eastern Pacific, the region to the west experienced abnormal hurricane activity.

Bay of Bengal.—Upper divergence over the Bay of Bengal is strongest in summer at the height of the monsoon. Despite this, excessive vertical wind shear between the lower and upper branches of the monsoon tends to inhibit hurricane development. Spring, before the monsoon reaches full strength, is more favorable; fall is still more favorable for, in October to December, low-level flow is weak and generally convergent and the upper southwesterlies over the southern Bay are divergent [34].

Arabian Sea.—Upper convergence (fig. 2) and the strong vertical-wind shear of the monsoon circulation ensure that no hurricane ever forms in the Arabian Sea during summer. Although the situation is slightly less unfavorable in spring and autumn, the region has the lowest frequency of hurricane development of all northern-hemisphere generating regions (table 1).

Atlantic, Caribbean, Gulf of Mexico and eastern Pacific.—These may be termed "average" hurricane areas (table 1). No major persistent features dominate flow at upper levels. Judging from numerous synoptic studies, *moving* upper-level disturbances predominate, accidentally affecting moving surface disturbances to trigger hurricanes.

Published analyses [11; 14; 19; 27; 38; 39] indicate that, as in the western Pacific, hurricanes usually develop beneath flow from a southerly quarter to the west of an upper ridge. Gentry [14], describing the Cedar Keys hurricane of August 1950, tentatively suggests that westward energy dispersion at upper levels may have triggered its development. Dunn *et al*, [11] hypothesize that eastward energy dispersion in the westerlies may have been responsible for the rapid intensification of hurricane "Greta."

Although the North American summer monsoon is weak and fitful compared with its Asiatic counterpart, it may influence the seasonal distribution of hurricane development. The North Atlantic has a mid-summer development maximum. On the other hand, over the western Caribbean and Gulf of Mexico (which may correspond to the Bay of Bengal) and to a less extent over the eastern North Pacific (resembling the Arabian Sea) storms develop more often in late summer and early autumn and a weak secondary frequency maximum is evident in early summer.

5. Southern-hemisphere tropical cyclones

McRae [24] points out that, of eight severe tropical cyclones he analyzed in the southwest Pacific in 1955–56, seven formed beneath poleward flow at 200 mb and only one beneath equatorward flow.

TABLE 1. Regional frequency distribution of tropical storms (Beaufort force >8) and hurricanes.

						Seas with mean summer surface temperatures above 26C lying poleward of 5° lat.		Seas with mean summer surface temperatures above 26C lying poleward of 5° latitude and equatorward of the subtropical ridge at 300 mb.		
	Region	Mean annual number of storms and data sources	Years of record	Mean annual number of hurricanes and data sources	Years of record	Area (millions km²)	No. of storms per million km² per year	Area (millions km²)	No. of storms per million km² per year	No. of hurricanes per million km² per year
Northern Hemisphere	(1) Arabian Sea	1.3 [25]	56 1881–1937	0.7 [25]	56 1881–1937	2.7	0.48	2.7	0.48	0.25
	(2) Bay of Bengal	5.4 [25]	57 1887–1935	2.0 [25]	57 1887–1935	3.4	1.58	3.4	1.58	0.58
	(3) South China Sea	3.4 [4]	70 1884–1953	1.9 [4]	30 1924–1953	3.3	1.03	3.3	1.03	0.58
	(4) Pacific Ocean west of 170E	18.6 [4]	70 1884–1953	17.5 [4]	30 1924–1953	15.6	1.19	11.6	1.61	1.51
	(5) Pacific Ocean east of 170E	5.7 [26]	31 1910–1940	2.2 [26]	31 1910–1940	19.0	0.30	8.3	0.70	0.26
	(6) Atlantic Ocean west of 70W	3.6 [5]	64 1887–1950	2.3 [10]	50 1901–1950	5.2	0.69	4.4	0.82	0.52
	(7) Atlantic Ocean east of 70W	3.7 [5]	64 1887–1950	2.5 [10]	50 1901–1950	12.7	0.29	5.8	0.64	0.43
Southern Hemisphere	(8) Indian Ocean west of 90E	4.7 [25]	87 1848–1935			10.7	0.44			
	(9) Indian Ocean east of 90E	2.1 [3]	38 1919–1956			7.2	0.29			
	(10) Pacific Ocean west of 150W	4.0 [13]	16 1940–1956			12.4	0.32			
	(11) Pacific Ocean east of 150W	0 [26]				5.2	0			
	(12) Atlantic Ocean	0 [9]				4.1	0			
	1	2	3	4	5	6	7	8	9	10

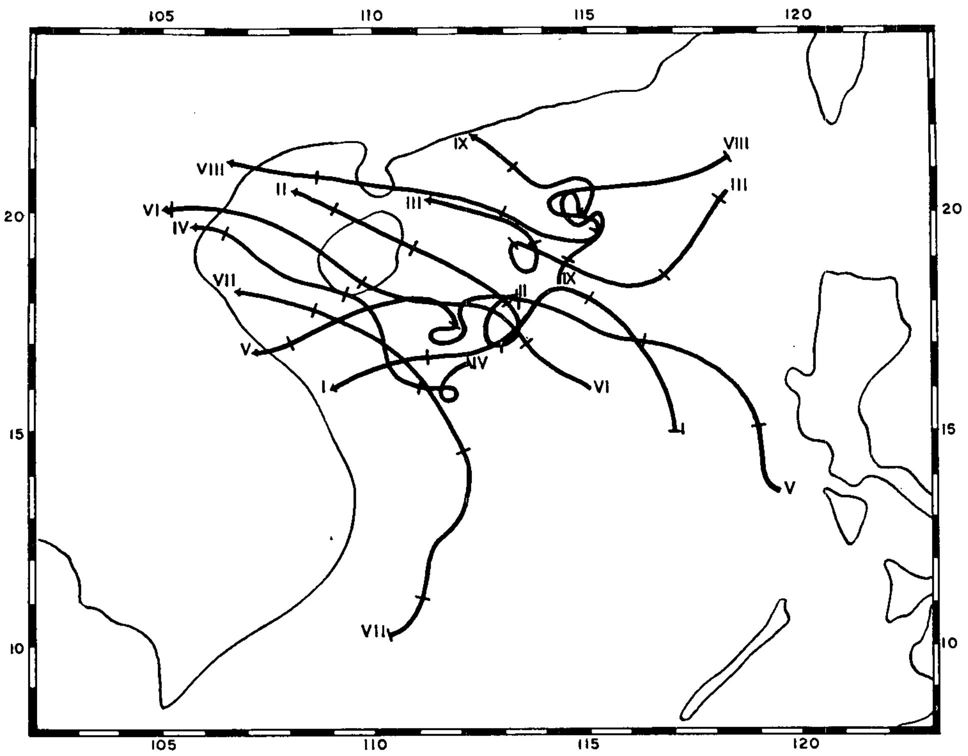

FIG. 7. Tracks of China Sea storms which changed from cold- to warm-cored. 0000 GCT positions marked.

Storm no.	Duration	Maximum observed surface wind (kn)
I	19–21 September 1948	35
II	8–12 June 1950	25
III	16–20 June 1951	35
IV	6–9 August 1951	25
V	2–7 September 1951	30
VI	16–19 September 1952	30
VII	14–17 June 1953	38
VIII	28 June–1 July 1953	33
IX	2–5 June 1955	50

Intensification usually occurred below a region of divergence on the warm side of the subtropical jet-stream axis. The divergence resulted from increasing amplitude of a long-wave trough or the formation of a cut-off low.

Monsoons probably do not distort distribution noticeably since all generating areas show a sharp mid-summer frequency maximum. The relatively low totals suggest the absence of persistent triggering systems.

6. Transformation of cold-cored cyclones

Palmer [31] and Simpson [40] describe tropical and subtropical cold-cored cyclones of the central and eastern Pacific. These "Kona" storms which originate in the upper troposphere may occasionally build down to the surface where their circulations are characterized by a broad central region of light winds bordered on the north and east by a belt of stronger winds and heavy rain.

Unless a Kona storm receives fresh injections of cold air, latent heat released by condensation will gradually warm the central regions of the storm which may eventually change into a weak warm-cored disturbance. Simpson says "Isolated reports from some Kona cyclones have indicated that occasionally the lower layers of the vortex experience sudden and marked deepening with subsequent intensification of the circulation." As an illustration, he describes a storm whose center crossed the island of Oahu on 26 March 1951. Presumably, this was the best example available. Nevertheless, pressures did not fall below 1000 mb nor winds exceed 50 kn.

Similar tropical cyclones which began as cold-cored systems and ended warm-cored have been observed in the China Sea (fig. 7). Despite a dense ship reporting

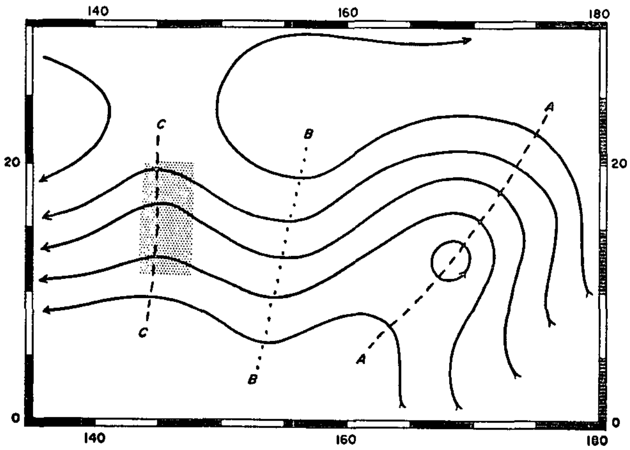

FIG. 8. Schematic streamline representation of a common west Pacific sequence at 30,000 or 40,000 ft leading to typhoon development.

Cyclonic vorticity increases in trough AA resulting in downstream energy dispersion which sharpens ridge BB and intensifies the next downstream trough CC. The pressure fall along CC may trigger any low-level cyclonic disturbance in the shaded area into a typhoon.

network, none of the nine storms shown reached hurricane strength.

Typhoon "Carmen" in November 1952 [28] and hurricane "Greta" in November 1956 [11] seem to have been originally upper cold cyclones which gradually weakened and became warm-cored. Then, apparently responding to an upstream increase in high-level cyclonic vorticity, they grew to full hurricanes. The complete sequence from upper cyclone to hurricane is prolonged and very rare. However, forecasters should not ignore the possibility.

7. The hurricane trigger

Priestley [33] emphasizes that upper divergence and lower convergence occur almost simultaneously. However, for a hurricane to develop and persist, low-level convergence must lag sufficiently behind high-level divergence to allow an appreciable pressure fall. Riehl's development hypothesis implies that the lag is enough when independent high- and low-level disturbances move together and divergent equatorward flow is superimposed on the surface disturbance. Unfortunately, the examples quoted above (if representative) indicate that only a rare hurricane, which generally develops poleward of the subtropical ridge, fits Riehl's model.

Possibly the slow relative movement of upper and lower disturbances in the tropics (usually less than 15 kn) allows insufficient lag between divergence and compensating convergence for the necessary surface pressure fall.

Energy from an intensifying upper trough or cyclone is propagated at group velocity and almost always travels much faster than the originating disturbance. Mid-latitude experience [2] would suggest that, in low latitudes also, the divergence field cannot adjust rapidly enough to prevent deepening in the next downstream trough. Thus, a low-level disturbance located on or near the trough axis might deepen and develop into a hurricane (fig. 8).

The independent analyses already referred to [17; 22; 28; 36; 11; 14; 19; 27; 38; 39], as well as a paper by Cressman [6], support this hypothesis which must, however, be considered highly tentative since 24-hr chart intervals make it difficult to determine the sequence of events accurately, while no one has as yet analyzed low-latitude energy-dispersion quantitatively. Nevertheless,

1. Equatorward (poleward) of the subtropical-ridge hurricane development in a surface disturbance most often occurs beneath poleward (equatorward) flow shortly after an upper trough or cyclone intensifies to the east (west);
2. Some surface depressions whose circulations extend weakly into the high troposphere or former upper cyclones which have become warm-cored may transform into hurricanes if they are located downstream from an intensifying upper cyclone or trough;
3. The most active hurricane generating area in the world, between 130E and 150E in the tropical North Pacific, is approximately one wave length downstream from the most persistent and active upper trough in the tropics;[3] and
4. Hurricane winds usually first appear in a storm's northeast quadrant where presumably vertical shear is least;

Riehl states that superposition of low and mid-latitude disturbances often precedes hurricane development. Certainly superposition might well initiate energy dispersion. Solar variations, too, might increase upper cyclonic vorticity in very low latitudes [32].

8. Concluding remarks

1. Northern-hemisphere hurricane-generating regions were defined as the areas enclosed by the 26C mean summer sea-surface isotherm, 5 deg lat, and the subtropical ridge aloft. On a unit generating area basis, hurricanes are three times as likely to form in the western Pacific as anywhere else. This feature appears related to a persistent mid-Pacific high tropospheric trough which has no counterpart over the other oceans.
2. Summer-monsoon circulations may affect tropical disturbances. In mid-summer, shear between surface

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[3] Ohmstede and Dean (28) in their careful analyses of 30,000 ft winds over the Pacific for October and November 1952 delineate four wave families (two cyclones with an anticyclone between) in the tropical central Pacific. The median latitude of the low centers was 18N and of the highs, 6.5N while the median wave length was 24 degrees of longitude.

southwesterlies and upper easterlies hinders hurricane development over the China Sea and the Bay of Bengal and convergent upper easterlies over the Arabian Sea completely stop development there. A secondary mid-summer hurricane-frequency minimum for the Gulf of Mexico and the Caribbean may stem from the weaker North American monsoon.

Tropical cyclones in the Southern Hemisphere show a mid-summer frequency peak, indicating relatively little monsoon effect.

3. An upper cyclone which extends its circulation to the surface may eventually possess warm-core characteristics. However, for it to intensify into a hurricane, upstream development of a high-level cyclone seems necessary. Complete transformation from upper cyclone to hurricane is prolonged and extremely rare.

4. Only if compensating low-level convergence lags behind upper divergence can the surface pressure fall sufficiently to establish a hurricane circulation. The disturbance producing the divergence must initially be independent of the surface disturbance. Energy propagated from a newly intensified upper trough or cyclone and travelling faster than the initiating disturbance may trigger a hurricane beneath the next downstream trough which is where energy dispersion deepening would be expected. Although energy dispersion might trigger hurricanes throughout the tropics, it has no other quasi-stationary low-latitude source comparable in activity to the mid-Pacific trough.

Arakawa [1] has made a mathematical study of low-latitude waves. Low-latitude energy dispersion and favored wave lengths also merit investigating.

5. The important problem of trans-equatorial interaction and the phenomenon of "double vortices" [7] are not treated here. IGY data should facilitate a new attack.

6. Nowhere in the tropics are data at 300 and 200 mb sufficient to guarantee correct analytical solutions. Hence, preconceived notions and an inevitably subjective approach affect analyses and conclusions. It is hoped that concentrating almost entirely on the published analyses of others has reduced the chances of deductive error. Ideally, tropical meteorologists without proprietary interest in the hypotheses this paper advances should now test them on a large sample of hurricanes and typhoons.

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