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Tropical Cyclone Forecasters Reference Guide
3. Tropical Cyclone Formation

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13. ABSTRACT (*Maximum 200 words*)

One of the keys to safe and successful naval operations in the tropics is a thorough understanding of tropical meteorology. The Tropical Cyclone Reference Guide is designed primarily as a ready reference for midlatitude forecasters required to provide tropical meteorology support to staff commanders. This report presents a comprehensive overview of tropical cyclone genesis forecast support and is Chapter 3 of the reference guide. Subjects discussed include tropical cyclone genesis forecast products, major warning center operations, tropical cyclone genesis terminology, and significant ranges of tropical cyclone genesis phenomena by basin that could be encountered in the world marine environment.

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TROPICAL CYCLONE FORECASTERS REFERENCE GUIDE

3. TROPICAL CYCLONE FORMATION

Tropical cyclone formation is one of the least understood topics of tropical meteorology. This is due in large part to the complexity of the formation process and the sparsity of data in the tropics (Ooyama, 1982). Research indicates that approximately 80 % of all tropical cyclones form in or just poleward of the Inter Tropical Convergence Zone (ITCZ)/monsoon trough (Gray, 1968). Current thinking indicates this is in response to the larger amounts of low-level vorticity in this region. Most of the remainder (about 10 %) form from disturbances embedded in the easterly trade wind flow near the Tropical Upper Tropospheric Trough (TUTT). While the advent of satellite imagery has provided a wealth of data to aid research on this topic, it has also lessened the need for short range forecasting of tropical cyclone formation. Nevertheless, predicting formation remains an important subject.

1. FACTORS AFFECTING TROPICAL CYCLONE FORMATION

There are two primary influences on tropical cyclone formation: internal and environmental influences. The consensus is that these two influences are equal in importance during the initial formative stages of a tropical disturbance. There is a requirement for some type of mechanism which will enhance the low-level convergence and increase the organization associated with a developing tropical disturbance or convective cloud cluster. This enhancement is usually attributed to an external influence, but as the disturbance becomes more organized and self-sufficient, the importance of the environment in maintaining the disturbance's structure lessens, but still has a large influence.

Since tropical cyclones have been observed to develop from the inner core outward and also to decay from the inner core outward, it is important to understand the internal processes associated with tropical cyclone development. For brevity, only those factors which pertain to initial formation will be mentioned here.

1.1 Overview of Tropical Cyclone Formation

Pre-existing low-level disturbances and the associated convective cloud clusters occur quite frequently over tropical oceans. The latent heat released by these convective cloud clusters warms the upper-troposphere (500 - 200 mb) during the initial development stages. A warm core develops resulting in increased upper level height fields and increased divergence aloft, which lowers the surface pressure. The atmosphere responds to the lower pressure with increased convergence in the low-levels, which enhances the convection. Additionally, due to the earth's rotation, the converging air begins to rotate cyclonically and a tropical disturbance/ depression is formed. Whether or not this disturbance/depression continues to develop is dependent on the surrounding environment's ability to sustain favorable conditions in the vertical column.

1.2 Dynamics of the Vertical Column

In the 1940s and 50s it was hypothesized that for the above process to occur, some type of upper-tropospheric outflow pattern developed over a disturbance which triggered a corresponding area of low-level convergence. Gray (1968) suggests that compensation for mass convergence and divergence at any level must always occur at a higher level; and that the initial formation stage of a tropical disturbance is the result of a pre-existing area of low-level convergence that develops in an environment favorable for the accumulation of heat within a vertical column. This type of environment is characterized by areas of weak vertical wind shear (Fig. 3.1). If heating in the vertical column is allowed to persist, a tropical cyclone may form (Fig. 3.2).

1.3 Thermodynamic Requirements for Formation

The formation of tropical cyclones whose circulation extends through most of the troposphere is the most difficult task that the tropical atmosphere performs. It is seldom accomplished. The crucial problem in understanding the cyclone formation processes is that of understanding how the 500-200 mb levels can increase their enthalpy (thermodynamic energy). It appears that this can only be accomplished in areas of weak vertical wind shear. These are areas where the upper tropospheric environmental winds, and the disturbance from which the cyclone forms, move with very much the same direction and speed (Gray, 1975).

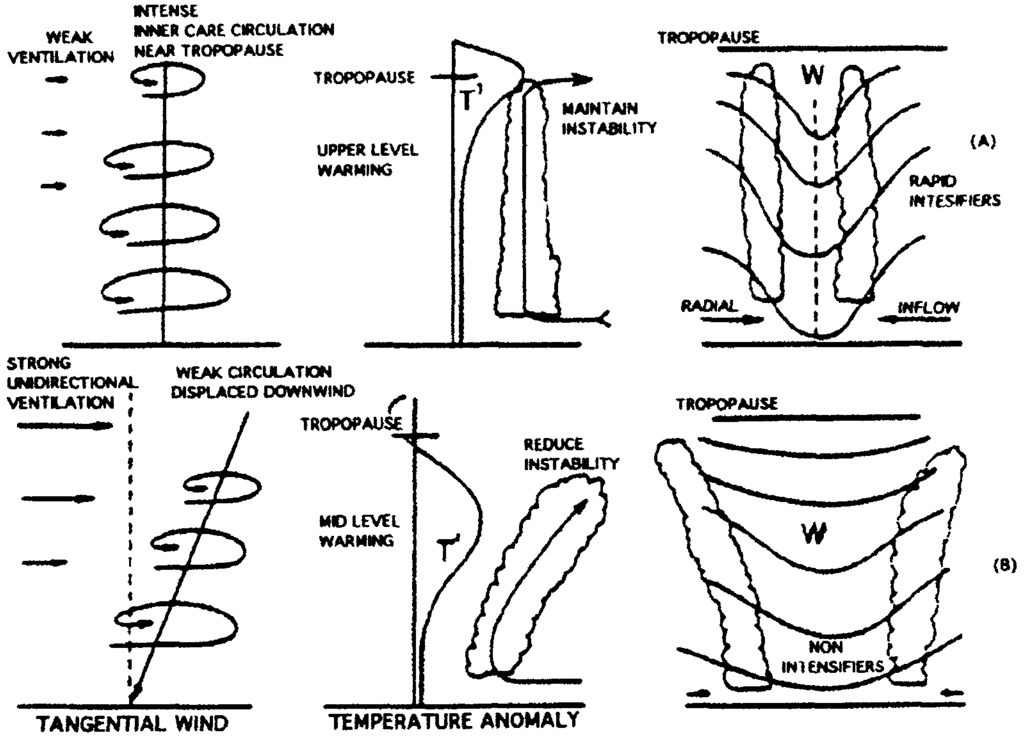

Figure 3.1. Depiction of favorable (top panels A) and unfavorable (bottom panels B) conditions for tropical cyclone development (Mundell, 1990).

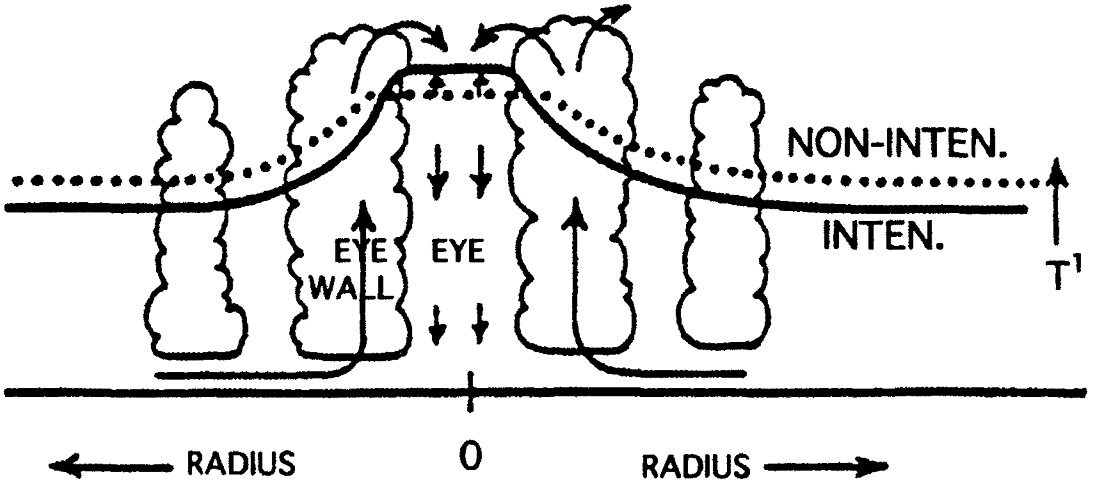

Figure 3.2. A vertical cross section of an established tropical cyclone (Mundell, 1990).

1.4 Ventilation

Current thinking also acknowledges that upper-level flow patterns are important in the formation of a tropical cyclone. Upper-level anticyclonic flow over a pre-storm disturbance and small vertical shear combine to form a favorable environment for formation. Many times, upper-level anticyclonic flow is accompanied by large vertical shear which inhibits tropical cyclone formation. In situations where vertical shear is weak, upper-level flow can ventilate the pre-storm disturbance. In simple terms, if the latent heat released in the upper-troposphere is carried away faster than it can be replenished by the low-level convergence and resulting convection, the disturbance will not develop. Additionally, if an upper-level outflow pattern does not develop after the initial disturbance occurs, the system will retain too much mass in the upper-levels and discourage continued low-level convergence (Gray, 1975).

1.5 Summary

Obviously the above descriptions are over-simplified since only a small portion of tropical cloud clusters develop into tropical cyclones. The thermodynamics (i.e., warming of the atmosphere) of the developing and non-developing clusters are nearly equal. Research at Colorado State University has concluded that the choice between which clusters do or do not develop is largely determined by the surrounding environment, with horizontal and vertical wind shear playing the largest roles (Gray, 1979).

2. ENVIRONMENTAL INFLUENCES

A series of Colorado State University research projects determined that there are six environmental factors which influence tropical cyclone formation (these are discussed below). In general, all six of these parameters are satisfied over the tropical oceans at any given time, especially during the summer months. Thus, there must be a change (increase or decrease) in one or more of these variables for the formation of a tropical cyclone. Typically, low-level vorticity and vertical wind shear are the most variable parameters, and thus are closely monitored for changes which lead to a favorable environment for tropical cyclone formation.

2.1 Earth Vorticity

It has been observed that tropical cyclones do not form within 3 degrees of the equator (Fig. 3.3 and 3.4). Apparently a certain critical value of earth's vorticity is required for the formation of tropical cyclones. However, the likelihood of formation does not necessarily increase with increasing coriolis parameter (i.e., moving away from the equator). Coriolis force is necessary for formation of a tropical cyclone, but it is not sufficient to produce tropical cyclone formation by itself.

2.2 Low-level Relative Vorticity

Tropical cloud clusters which develop into tropical depressions are always located in regions of low-level positive vorticity. Such regions include the ITCZ, monsoon trough, and the near equatorial trough (Gray, 1968).

2.3 Vertical Wind Shear

A primary factor in the formation of a tropical cyclone is the warming of a column of air by latent heat released during convection. If this heating occurs sufficiently, it will lower the surface pressure and begin a cyclonic circulation and inflow. Large values of vertical wind shear prevent this process from occurring since they remove heat from the air column. (Gray, 1968).

2.4 SST and Mixed Level Depth

Numerous studies have used exact numbers as a minimum SST criterion for tropical cyclogenesis. Typically these are in the range of 26-27 degrees C. Warm seas are prevalent over the mean formation areas (Fig 3.5). The warm ocean water must exist over a sufficient depth (e.g., 200 feet). As the tropical cyclone gains energy from the ocean, its winds also produce upwelling. If the upwelled water is too cool, the ocean may no longer be capable of sustaining the development process. Thus, a stationary cyclonic disturbance will not develop if the depth of the warm surface level is too shallow.

2.5 Potentially Unstable Atmosphere

Measured as the difference of equivalent potential temperature between the surface air temperature and 500 mb, this instability must typically be 10 degrees K or less for convection to occur. This critical value is usually satisfied over tropical oceans, and daily variations of the critical value are small (Gray, 1968).

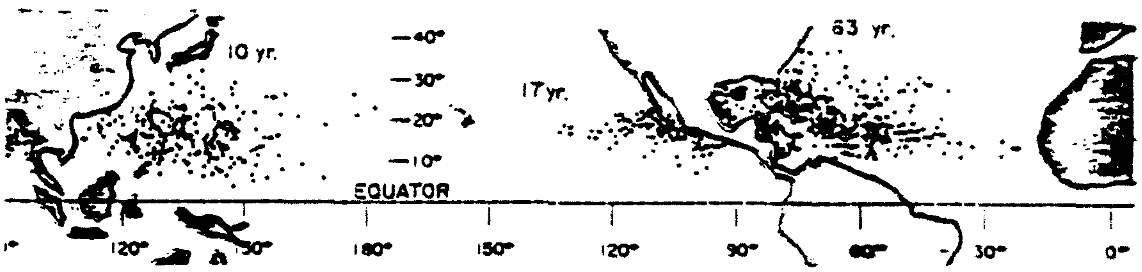

Figure 3.3. Location points of storms where hurricane intensity winds were first observed (Gray, 1968).

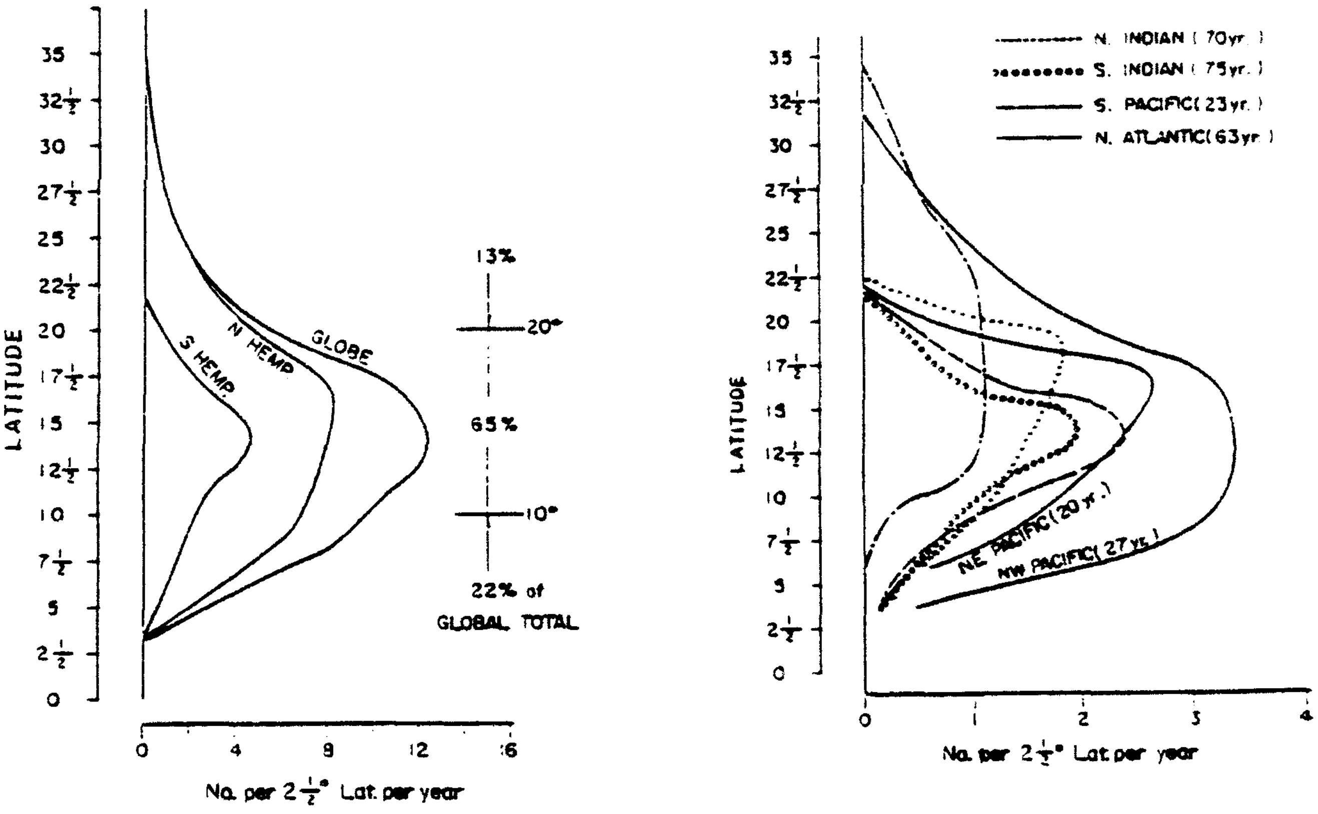

Figure 3.4(a) - Latitude at which initial disturbances which later became tropical storms were first detected. (b) - Latitude at which initial disturbances which later became tropical storms were first detected for the various development regions. Number of years in data average in parentheses (Gray, 1968).

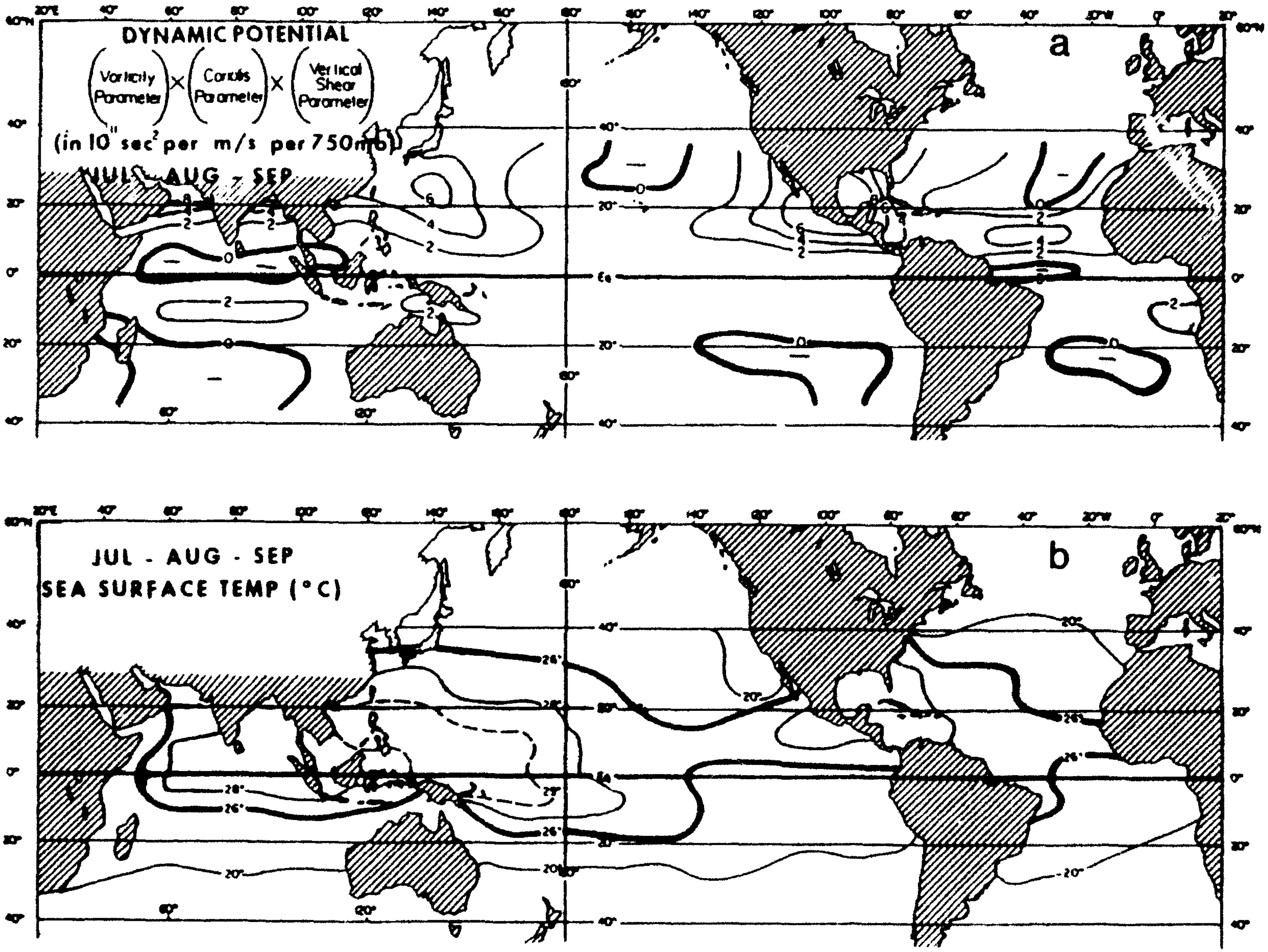

Figure 3.5(a). Global dynamic potential climatology. Positive values indicate areas with good tropical cyclone development potential. (b) Global sea surface temperature climatology. Areas with greater than or equal to 26C have good tropical cyclone development potential (Gray, 1968)

2.6 Mid-Troposphere Humidity

The higher the mid-level humidity, the longer a parcel of air can remain saturated as it entrains the surrounding air during its ascent. Vigorous convection occurs if the parcel remains saturated throughout its ascent. A relative humidity of 50-60 % at lower to mid-levels (700-500 mb) is often sufficient to keep a parcel saturated during ascent. This condition is regularly evident over tropical oceans (Gray, 1968).

3. DYNAMIC CONTRIBUTORS TO TROPICAL CYCLONE FORMATION

To effectively predict tropical cyclone formation the forecaster must be able to identify key dynamic contributors on available numerical analysis and prognostic charts. The following section discusses some of the most significant environmental influences on tropical cyclone formation.

3.1 Sources of Increased Low-level Vorticity

Cloud clusters which develop into tropical cyclones have approximately 2 to 3 times more low-level relative vorticity than those clusters which do not develop (Gray, 1979). Positive vorticity usually exists in the form of a low-level trough such as the ITCZ (doldrum trough), monsoon trough, or near equatorial trough. These are regions where the equator-ward flow from the subtropical ridges in each hemisphere meet (Fig 3.6). In some regions, these troughs and lines of convergence move across the equator to the summer hemisphere (Indian Ocean and Western Pacific). In other basins, the convergence zone remains north of the equator year round (Eastern Pacific and Atlantic). This failure of the convergence zone to move to the summer hemisphere is one of the reasons that no tropical cyclones form in eastern South Pacific and South Atlantic basins.

3.1.1 Low-Level Wind Surges

An increase in the relative vorticity for a low-level trough is usually the result of an increased convergence in the wind field. These increases are sometimes referred to as "surges" and can originate from three different sources.

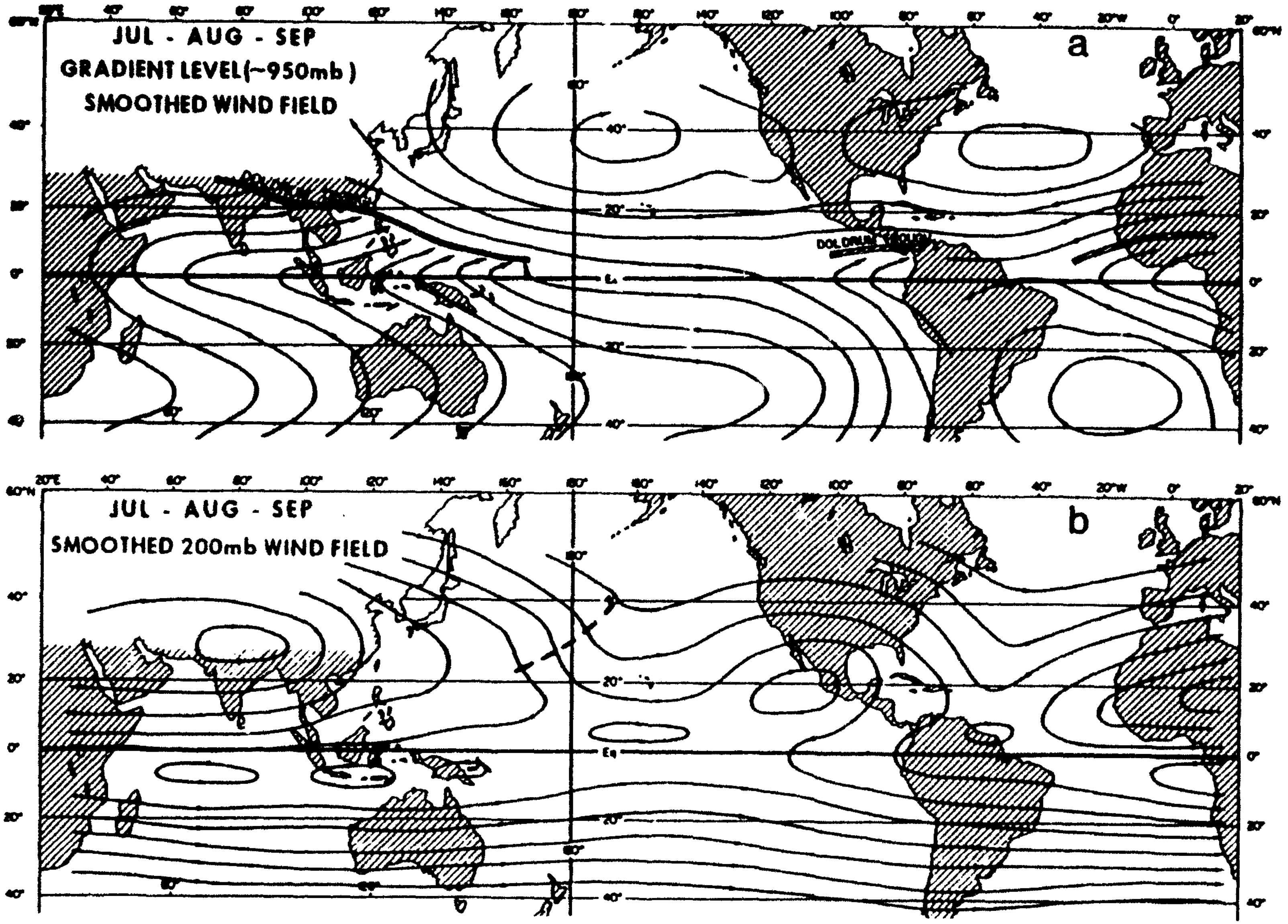

Figure 3.6(a). Gradient level smoothed wind field climatology. The areas labeled as doldrum troughs have larger values of low-level relative vorticity. (b) Smoothed 200 mb wind field climatology. The areas that coincide with the mean tropical cyclone genesis locations show weak winds and anticyclonic curvature (Gray, 1968).

a. Northeasterly Surges. Poleward of the low-level trough or convergence zone is the subtropical ridge. A strengthening or equatorward movement of the subtropical ridge can result in increased speeds in the tradewind easterlies. This in turn increases the horizontal wind shear at the trough, thereby generating more relative vorticity.

b. Southwesterly Surges. Another frequently occurring source of increased low-level vorticity is a surge in the cross-equatorial monsoon. During the Northern Hemisphere summer, flow from the Southern Hemisphere crosses the equator and turns, becoming westerly along the southern portion of the equatorial trough (Figs. 3.7, 3.8). As mid-latitude systems affect the subtropics of the Southern Hemisphere (winter), anticyclogenesis behind cold fronts increases the southerly winds, which cross the equator and become southwesterly creating a surge in the cross-equatorial monsoon. These surges usually cause increased convection in the equatorial trough and can lead to the formation of a tropical cyclone. While these surges are observed most frequently in the western North Pacific summer, they also occur frequently in the South Pacific summer as well.

c. Surges Associated With Monsoon Depressions. The final mechanism which is associated with surges in the cross-equatorial monsoon is observed when the southwesterlies intensify and deepen significantly over the Philippines and eastward. For this to occur, an area of persistent low pressure must exist that can temporarily compete with the Asian Heat Low for the low-level flow from the Southern Hemisphere. Such persistent lows are observed in two forms.

The first, intense and relatively concentrated, is the tropical cyclone. As these systems move west of 140E and usually north of 15N, they can produce moderate to strong surges that are the primary weather producers for the Philippines in the summer.

The second surge producer is not so intense, but is massive, with 4 to 8 mb pressure falls covering hundreds of thousands of square miles of the western Pacific. These rapid, large-scale pressure falls occur an average of twice a year east of the Philippines, usually in late July or early August, and appear to be related to very intense cold-core cyclones in the TUTT which build all the way to the surface. As winds accelerate into this low pressure area, a monsoon depression forms around the low, frequently in a wave-like pattern. Because deep monsoon surges produce gale and frequently storm force winds, they significantly increase low level vorticity and present a formidable hazard to shipping and aircraft.

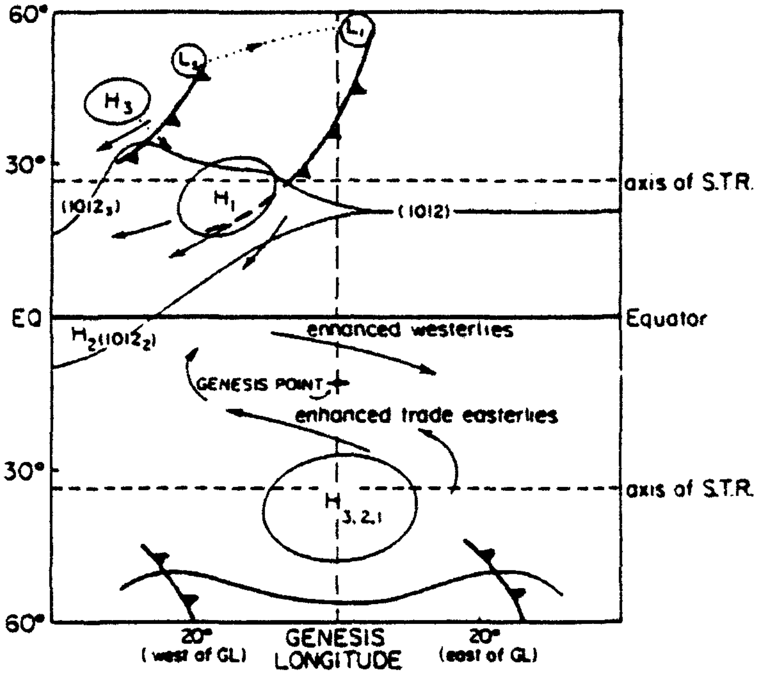

Figure 3.7. Idealized surface wind chart showing the positions of important synoptic scale features 3-1 day(s) before Southern Hemisphere tropical cyclone genesis. Subscripts denote day number before genesis (Love, 1985).

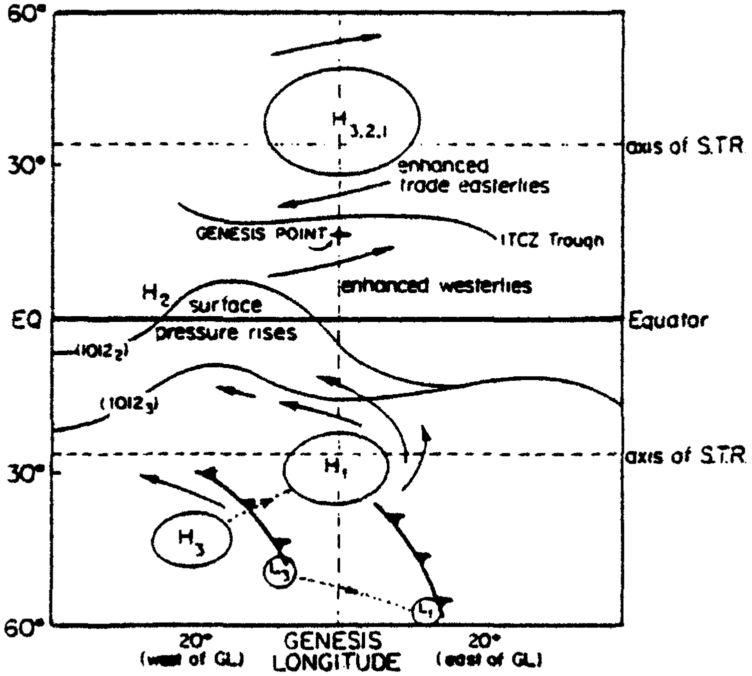

Figure 3.8. Idealized picture chart showing the positions of important synoptic features 3-1 day(s) before Northern Hemisphere tropical genesis (Love, 1985).

Monsoon depression development produces a highly asymmetric wind pattern. Winds are weak in the center and on the northwest semicircle, but strong in the southeast semicircle. Maximum winds are displaced as much as 150 nm from the circulation center. Only after the cold-core low weakens and retreats upward, can a tropical cyclone develop beneath the convection (usually located on the strongly divergent southeast side of the upper-level low) as described by Sadler (1976a & b).

The intensity of the monsoon surge is related to the overall pressure gradient, but the relationship is not straightforward. That these surges occur instantaneously and extend thousands of miles in the horizontal suggests that a complex Hadley-Walker circulation solenoid is in some way involved (Guard, 1982).

d. Satellite Indications of Surges. While surges into the monsoon trough can be traced to their origin, they are sometime difficult to detect in real time. One indication of the existence is a convective burst. This burst is often observed in the monsoon trough when the low-level surge arrives. Composite studies of the cloud cluster vertical motion also show the existence of a convective burst prior to the actual development of a tropical cyclone (Lee, 1989a & b).

3.2 Vertical Wind Shear

As previously stated, latent heating is one of the primary ingredients in tropical cyclone formation. The latent heat released from cumulus convection can lower the surface pressure and begin a cyclonic circulation and low-level inflow. But in order for this event to occur, the heat generated by the convection must not be removed. For example, if the cloud cluster disturbance travels at nearly the same speed as the environmental flow in which it is embedded, its heating will not be removed with respect to the disturbance center. However, if it is too slow, the heating in the upper troposphere will be carried away by the mean flow. Thus, there must be nearly zero vertical wind shear in the area of cyclogenesis. Figure 3.9 shows computed heating profiles for the three shear situations. Note that in the "No Ventilation" case, a surface pressure fall of 4-5 mb would occur over three days (Gray, 1975), while no pressure falls would occur under the third case.

In addition to small values of vertical wind shear near the disturbance center, Gray (1979) has shown that the orientation of the horizontal gradient of zonal vertical wind shear is also important. Figure 3.10 shows that in those cloud clusters which develop, the

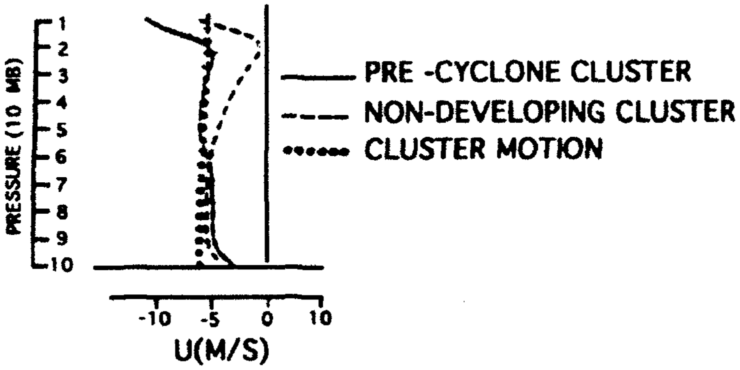

Figure 3.9. Vertical variation of the zonal wind velocity in the western North Pacific cloud clusters and the typical westward propagation of these cloud clusters. Note that the 200-500 mb zonal velocity of the pre-cyclone cluster is very close to that of the cluster westerly movement (Gray, 1968).

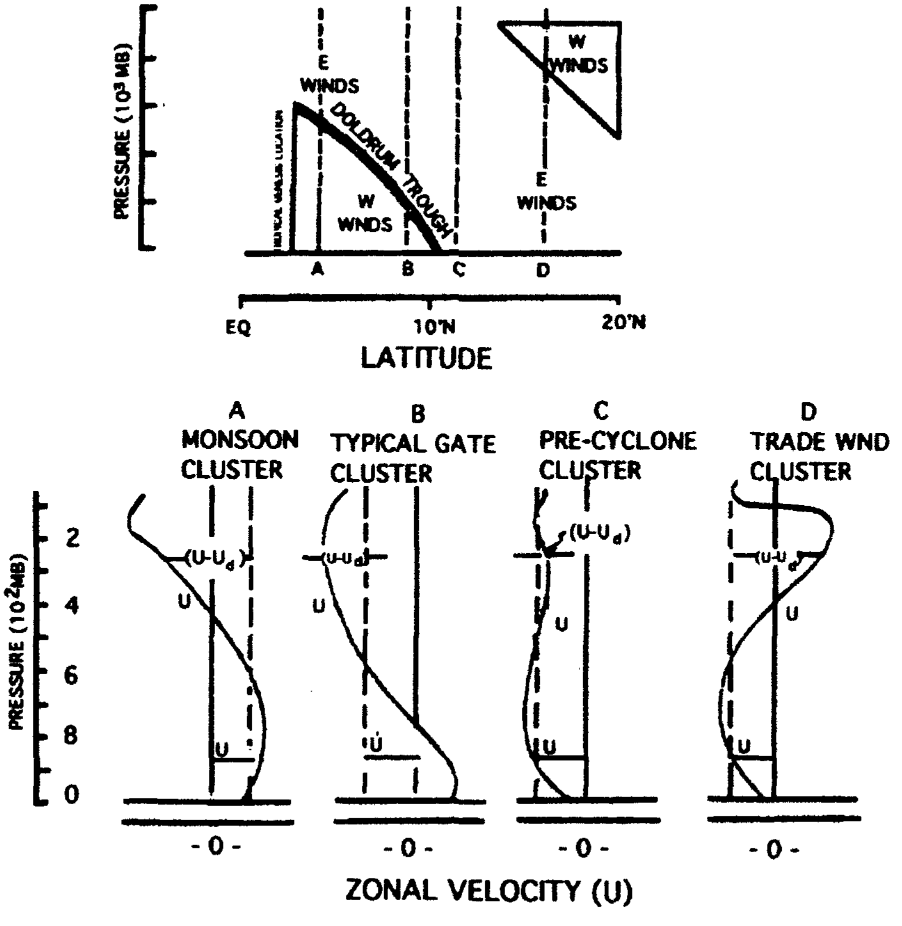

Figure 3.10. North-south cross-section of the typical locations of various classes of tropical cloud clusters relative to the doldrum equatorial trough and the usual zonal winds present with these systems (top diagram). The bottom diagram portrays the vertical distribution of typical zonal wind velocity (U) occurring with different A to D types of cloud clusters whose general location is specified in the top diagram. The usual zonal cluster velocity is designated U d and the difference in cloud cluster and environmental wind velocity at any level is given by (U-U d) (Gray, 1968).

magnitude of zonal vertical wind shear determines the extent to which the cloud cluster is ventilated. If the cloud cluster ventilation is small, as in the third diagram from the left, heat and moisture can accumulate and development can occur. In the Northern Hemisphere, this implies westerly shear (westerlies aloft, easterlies below) to the north and easterly shear to the south. This pattern is satisfied if a low-level cyclonic rotation is overlaid by an upper-level anticyclone. Initially it was thought that the upper-level anticyclone was a result of the heating from the incipient tropical cyclone. But recent studies have shown that a small amount of anticyclonic rotation must exist prior to development of a tropical disturbance.

By rearranging the terms in the vertical wind shear equation, Gray and Frank (1978) summarized this parameter as the difference of the low-level (e.g., 900 mb) and upper-level (e.g. 200 mb) relative vorticity average over an appropriate radius (2-6 degrees). They found this value to be three times larger for developing systems than for those which did not develop.

4. REGIONAL TROPICAL CYCLONE FORMATION CLIMATE

Some general conclusions can be drawn from the global distribution of tropical cyclone origin locations (Fig. 3.11). The most obvious is that tropical cyclone formation is confined to a region approximately 3ON and 30S, with 87% of the origin points located

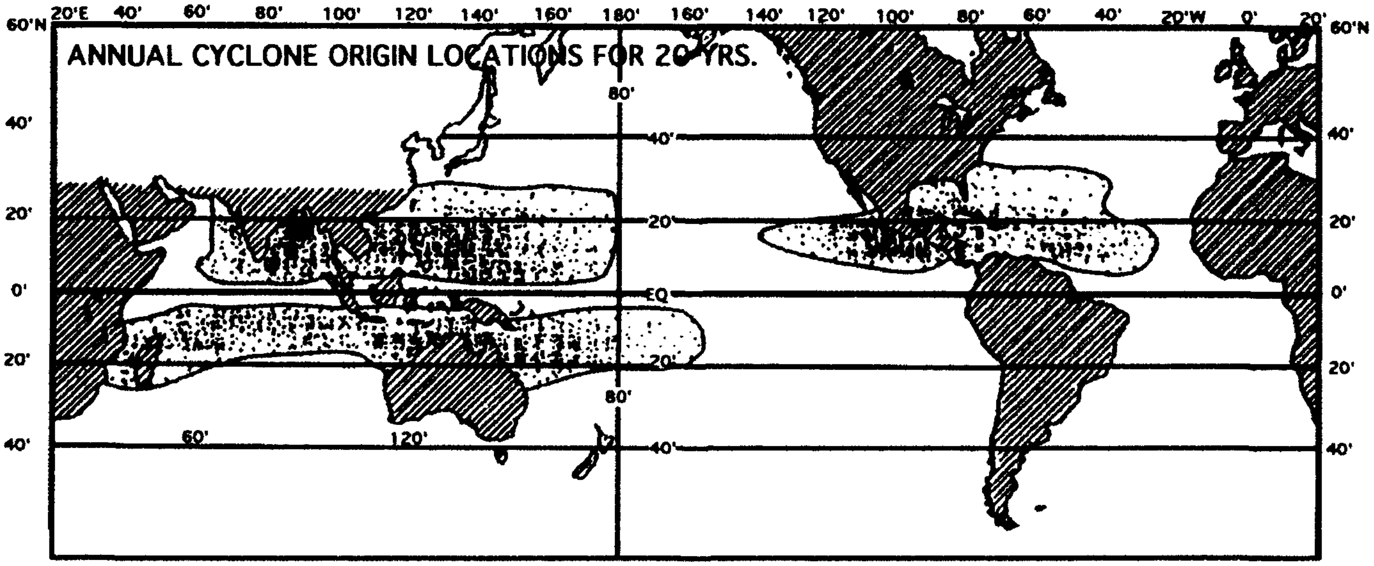

Figure 3.11. Annual cyclone origin locations for 20 years (Gray, 1968).

within 20 degrees of the equator (Gray, 1968). Also noted is the lack of tropical cyclones near the equator, as well as in the eastern South Pacific and South Atlantic basins. The reasons for these distributions are discussed in Section 2.

According to Gray (1968, 1975) approximately 80 tropical cyclones reach tropical storm intensity (34 kts or greater) each year around the globe. There is an average annual variation of only plus or minus 7% (Elsberry et. al., 1987), which implies that seasons with low frequencies in one basin are compensated somewhat by higher frequencies in other basins.

Because of the varied topography, geography, oceanography, and large scale flow patterns, the causes of tropical cyclone formation may vary from basin to basin. Some of the physical processes that cause formation do not occur in certain basins, while formation in others is possible all year.

4.1 Western North Pacific

The most active of all basins, the western North Pacific, contains approximately one-third of all tropical cyclones each year. Gray (1968) speculates that this is due to the low values of vertical shear rather than high values of low-level vorticity. This basin also contains very warm ocean temperatures over a broad area, adding to the favorable conditions for formation. Tropical cyclones may form during any month of the year, but there is a pronounced maximum during the months of July through October.

Most of the tropical cyclones in this region originate from within the monsoon trough (80%) , which typically lies across the South China and Philippine Seas. The low-level monsoon trough migrates across the equator during winter months (Fig. 3.12a & b). However, at times a near-equatorial trough still exists during the winter and can lead to tropical cyclone formation. There is some disagreement as to the exact mechanism which leads to tropical cyclone formation within the monsoon trough. Case studies by Fett (1968) show two vortices which form within the ITCZ, while Heta (1990) states that most tropical cyclones in the 1980 season formed from an easterly wave-like disturbance in the ITCZ.

Harr and Elsberry (1990) showed that the mechanism responsible for an enhanced monsoon trough also dictates the track that the incipient cyclone will take. If the monsoon trough is enhanced by easterlies along the southern periphery of the subtropical ridge, then

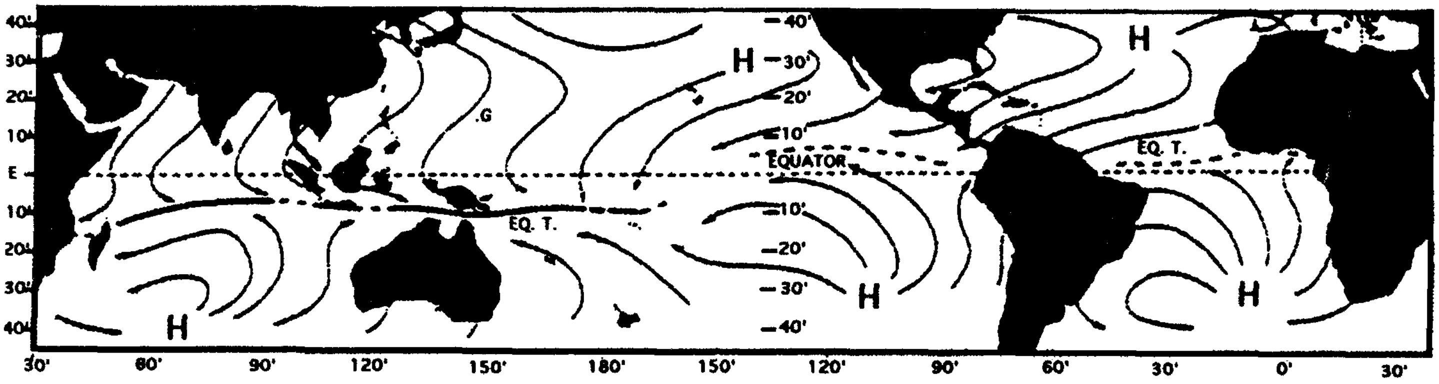

FIGURE 3.12A-IDEALIZED MONTHLY MEAN FLOW CONDITIONS FOR JANUARY. THE HEAVY SOLID LINE REPRESENTS DOLDRUM EQUATORIAL TROUGH; THE HEAVY DASHED LINE REPRESENTS TRADE WIND EQUATORIAL TROUGH.

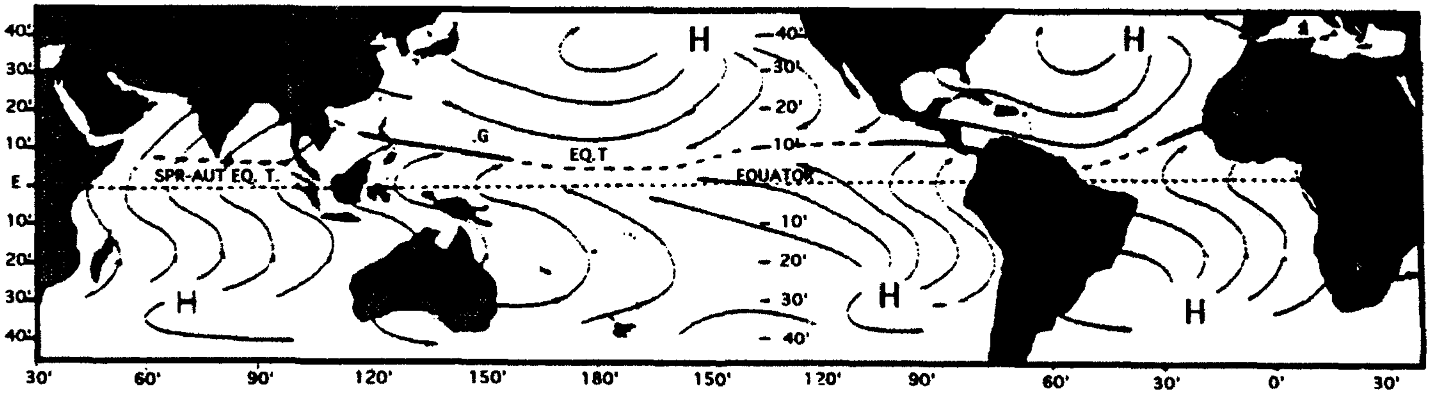

Figure 3.12(a). Idealized monthly mean flow conditions for January. The heavy solid line represents doldrum equatorial trough; the heavy dashed line represents trade wind equatorial trough. (b) Idealized surface mean flow conditions for August. The heavy solid lines represent doldrum equatorial trough; the heavy dashed line represents trade wind equatorial troughs. The very heavy dashed line over the North Indian Ocean represents the average position of the equatorial trough in spring and autumn (Gray, 1968).

the developing cyclone will most likely follow a straight path. However, if a surge in the cross-equatorial monsoon is responsible for the monsoon trough enhancement, then the cyclone will often recurve.

Another common mechanism for tropical cyclone formation is the Tropical Upper Tropospheric Trough (TUTT) . As discussed in Section 2, the TUTT extends from the mid-latitudes of the eastern North Pacific to the tropical western North Pacific. When the western end of this trough lies to the north of the monsoon trough (Fig. 3.13), it aids development through three influences.

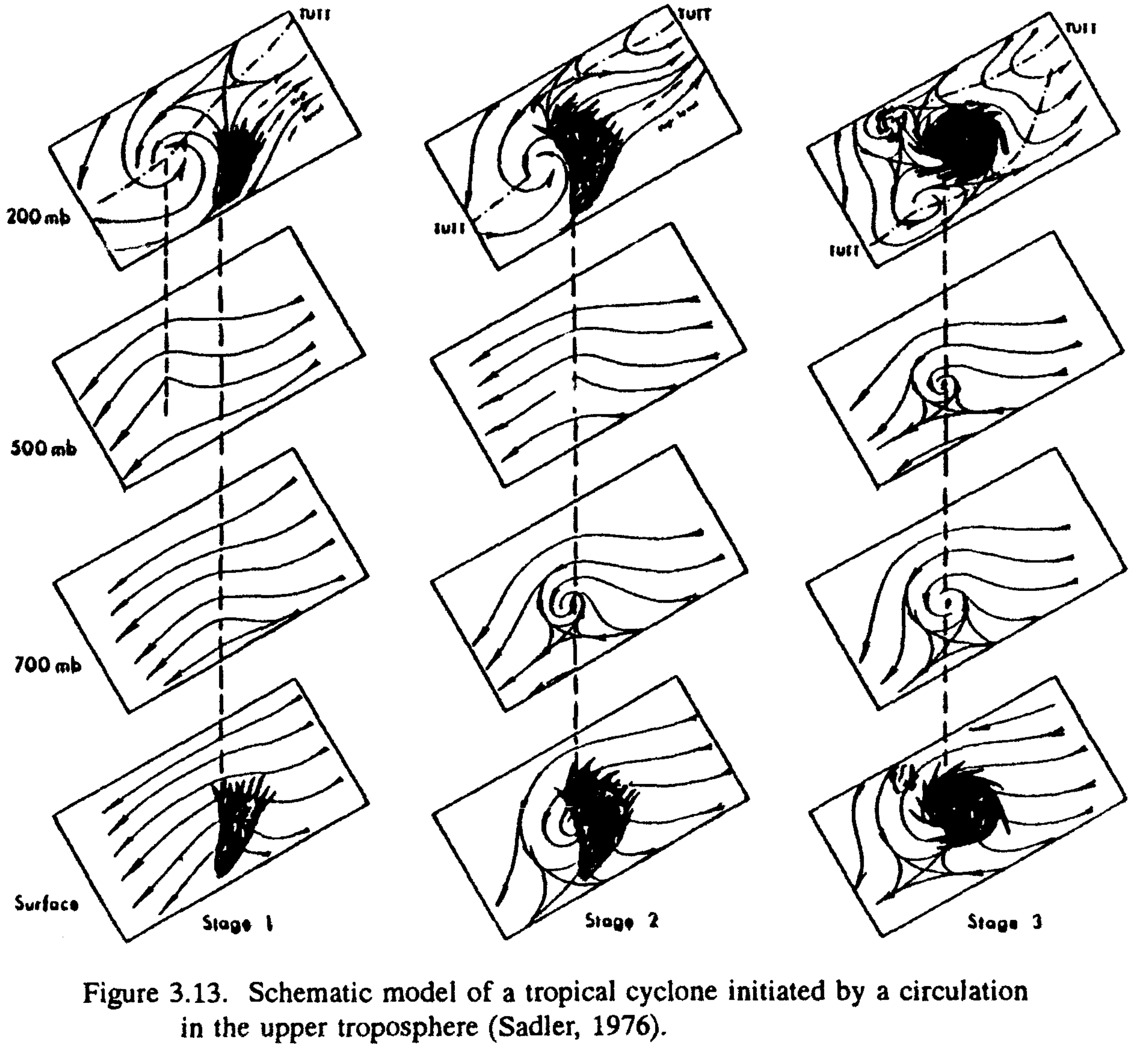

Figure 3.13. Schematic model of a tropical cyclone initiated by a circulation in the upper troposphere (Sadler, 1976).

a) Upper-level divergence provided by the westerlies equatorward of the trough.

b) The upper-level sub-equatorial ridge is superimposed over the low-level trough, which decreases the vertical shear over the trough.

c) A channel to the westerlies (Fig. 3.14) provides increased outflow for the evacuation of mass from the disturbance.

Figure 3.14 shows a schematic model of tropical cyclone formation induced by a TUTT cell. Note that the cyclonic circulation of the TUTT cell does not transform into the tropical cyclone. Rather, the divergence pattern associated with the TUTT cell induces the cyclone and provides an outflow channel for the mass built up due to low-level convergence. Sadler has done extensive work in TUTT/tropical cyclone interrelationships and provides convincing cases, complete with satellite imagery and synoptic charts (see Sadler 1974, 1976a&b).

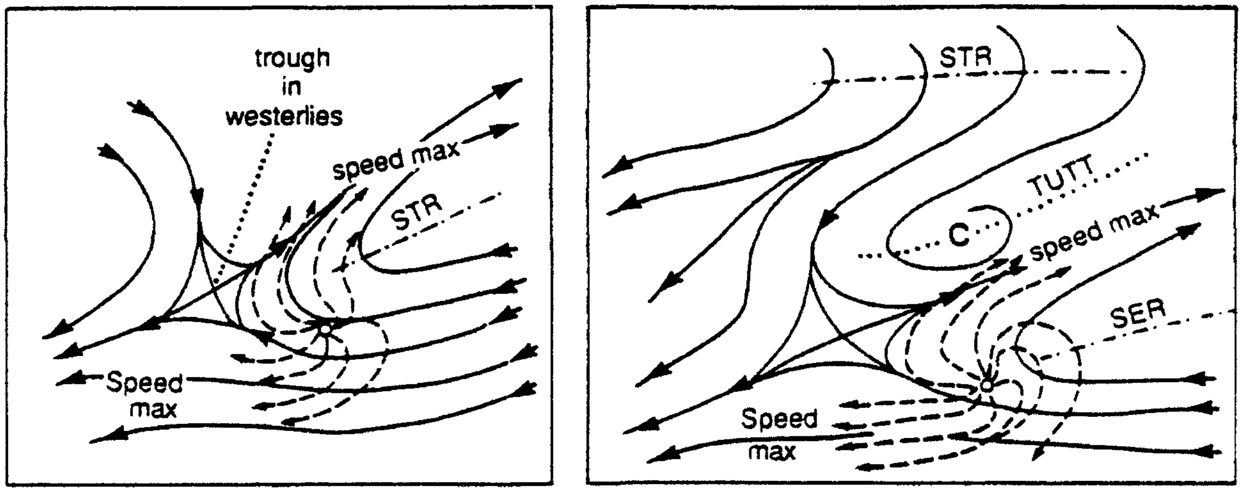

Figure 3.14. Two synoptic models of upper-level environmental flow patterns that are associated with enhanced tropical cyclone intensification (Sadler, 1978). STR is Subtropical Ridge; SER is Subequatorial Ridge; and TUTT the Tropical Upper Tropospheric Trough.

4.2 North Indian Ocean

There are actually two tropical cyclone areas in the North Indian Ocean, the Arabian Sea and the Bay of Bengal. There are about 5-6 times more tropical cyclones in the Bay of Bengal. This is also the basin where tropical cyclones do the most damage due to the combined effects of terrain, geography, and lack of communications. More than 200,000 people perished in the Bhola cyclone of 1970 in Bangladesh.

There are two tropical cyclone seasons in the North Indian Ocean, namely, before and after the summer monsoon (Fig. 3.12). The maximum occurrence is in November with a secondary maximum in May. Tropical cyclone formation is suppressed during the monsoon season. The reason for the decreased activity is two fold. Firstly, the ITCZ migrates northward to a location over the Indian subcontinent. This decreases the moisture supply necessary for tropical cyclone formation. Secondly, there is a large vertical wind shear during this season, with the southwesterly monsoonal flow underlying the upper-level easterly jet. This vertical wind shear inhibits tropical cyclone formation by removing the heating due to convection, which is necessary to lower the surface pressures and create a cyclonic circulation.

During the spring months (April to June), low-level westerly flow covers most of the basin and the monsoon trough is weak. The conditions which favor formation occur when the low-level ridge near 2ON strengthens producing easterly flow over the tropical waters. The observing stations Port Blair (station id: 43330) and Bangkok (station id: 48455) should be monitored for a change from westerly to easterly flow.

The fall months (mid-September to mid-December) are the most active season. The monsoon trough has migrated south and is typically oriented east-west over the open water. Its position changes from approximately 2ON at the beginning of the season to 5N by the end. Easterly flow to the north of the trough and westerlies to the south are ideal for tropical cyclone formation. The subtropical upper-level ridge overlies the monsoon trough resulting in reduced vertical shear.

The monsoonal trough (or ITCZ) is the primary factor in tropical cyclone formation for this basin. As seen in Section 2, this trough crosses the equator during the winter months (mid December to April). Thus, cyclones are rare during this time. They occur when the cross-equatorial buffer system is displaced northward temporarily. Such systems rarely achieve significant intensity.

As in other basins, development of a tropical cyclone within the monsoon trough is the result of enhanced low-level convergence (vorticity). The easterlies to the north of the trough are enhanced by cold surges from an Asian anticyclone which strengthens the subtropical ridge. The equatorial westerlies can also increase due to an anticyclonic surge in the Southern Hemisphere. Another mechanism observed in this basin is the development of a tropical cyclone in the South Indian Ocean. This enhances the equatorial westerlies and can lead to the formation of a "twin" in the Northern Hemisphere.

4.3 Southwest Indian

Statistics on this basin are poorly documented. As mentioned in the previous section, the ITCZ is migratory over the Indian Ocean (Fig. 3.12). Thus, tropical cyclone occurrence in this basin is largely confined to the months of October through April (85% occur December-March), with a very distinct maximum in January. The locations of formation follow the movement of the ITCZ, reaching south of 10S in the middle of the summer.

One area of particular interest is the Mozambique Channel. Between November and December, the low-level flow in this area changes from southeasterlies to cross-equatorial northerlies. In this situation, cyclones readily form where the two flows meet (Fig. 3-11). The flow returns to southeasterly by April, ending tropical activity in this area.

4.4 Australia

The Australian basin is often divided into three areas: northwest Australia, Gulf of Carpentaria, and northeast Australia (Fig. 3.15). Each area has some unique features with respect to formation as well as motion. The tropical cyclone season for the northwest area is concentrated in the 3 month period of January - March, whereas the other two areas have significant activity from December - April. Figure 3.16a & b shows the frequent occurrence of tropical storms in the Gulf of Carpentaria. Due to the restrictive size of the Gulf, tropical cyclones are much less frequent. Note the high concentration of tropical cyclones off the northwest coast of Australia.

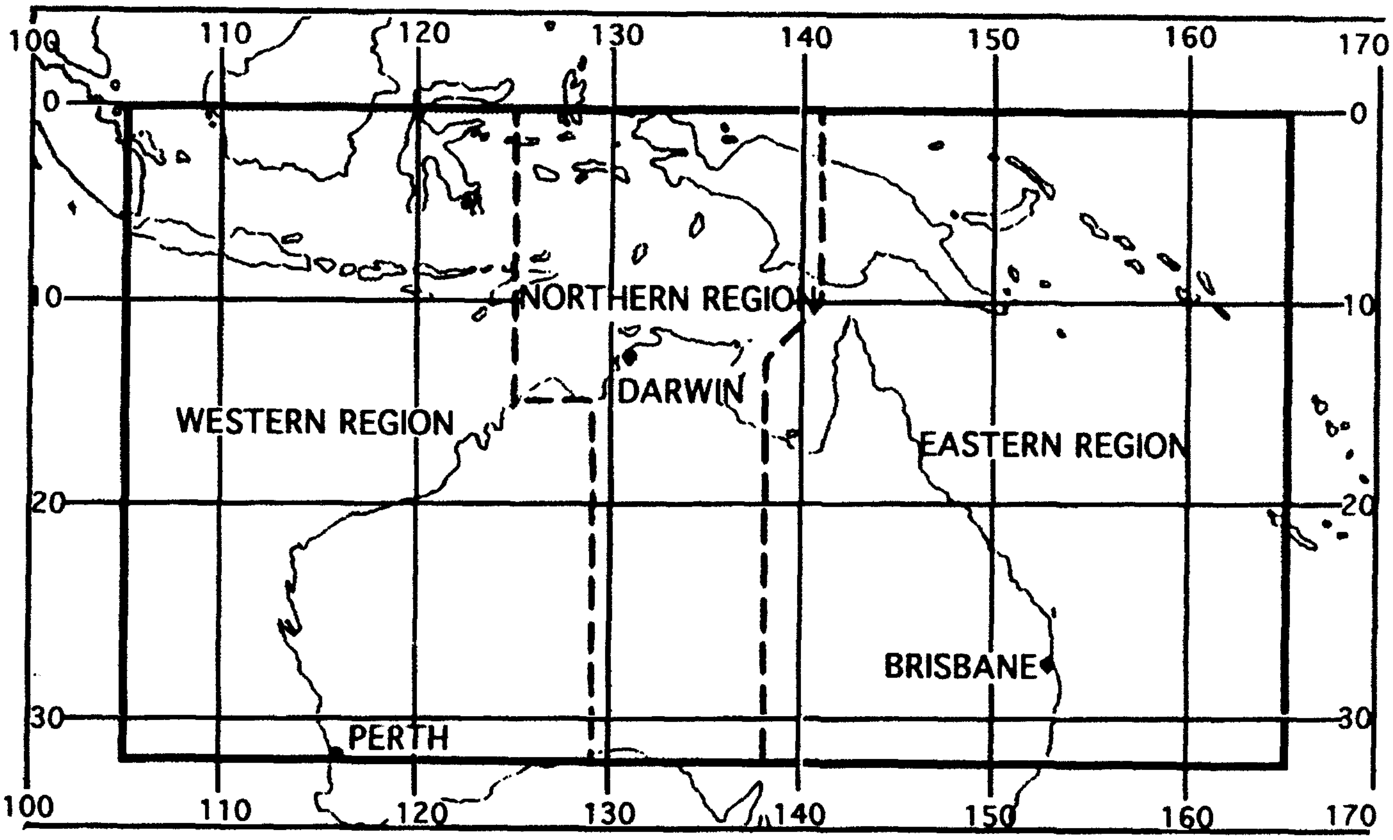

Figure 3.15. Boundaries of the Australian area and the local regions adopted for this section of the reference guide (Neal and Holland, 1977).

Figure 3.17 shows the distribution of tropical cyclone formation points for the Australian basin for a 20 year period. Of note is the large number of formation locations near the coastline (49% within 300 km), which is somewhat unique to this basin.

The remaining charts in Figure 3.18 show the monthly tropical cyclone formation locations, along with the 27 degree C SST isotherm and the monsoon shear line. Note that the monsoon trough moves over the Australian continent during the summer months. Even so, it is still active, since moisture is supplied by the northwesterly monsoonal flow.

A study by Mcbride and Keenan (1982) showed that of the 38 formation cases analyzed, 32 (84%) had their pre-cyclone cloud cluster traced back to the monsoon trough. More than half of the formation cases in the northwest basin originated in the monsoon trough over land. This is of particular interest since there is the natural tendency to only examine oceanic areas for possible tropical cyclone formatio

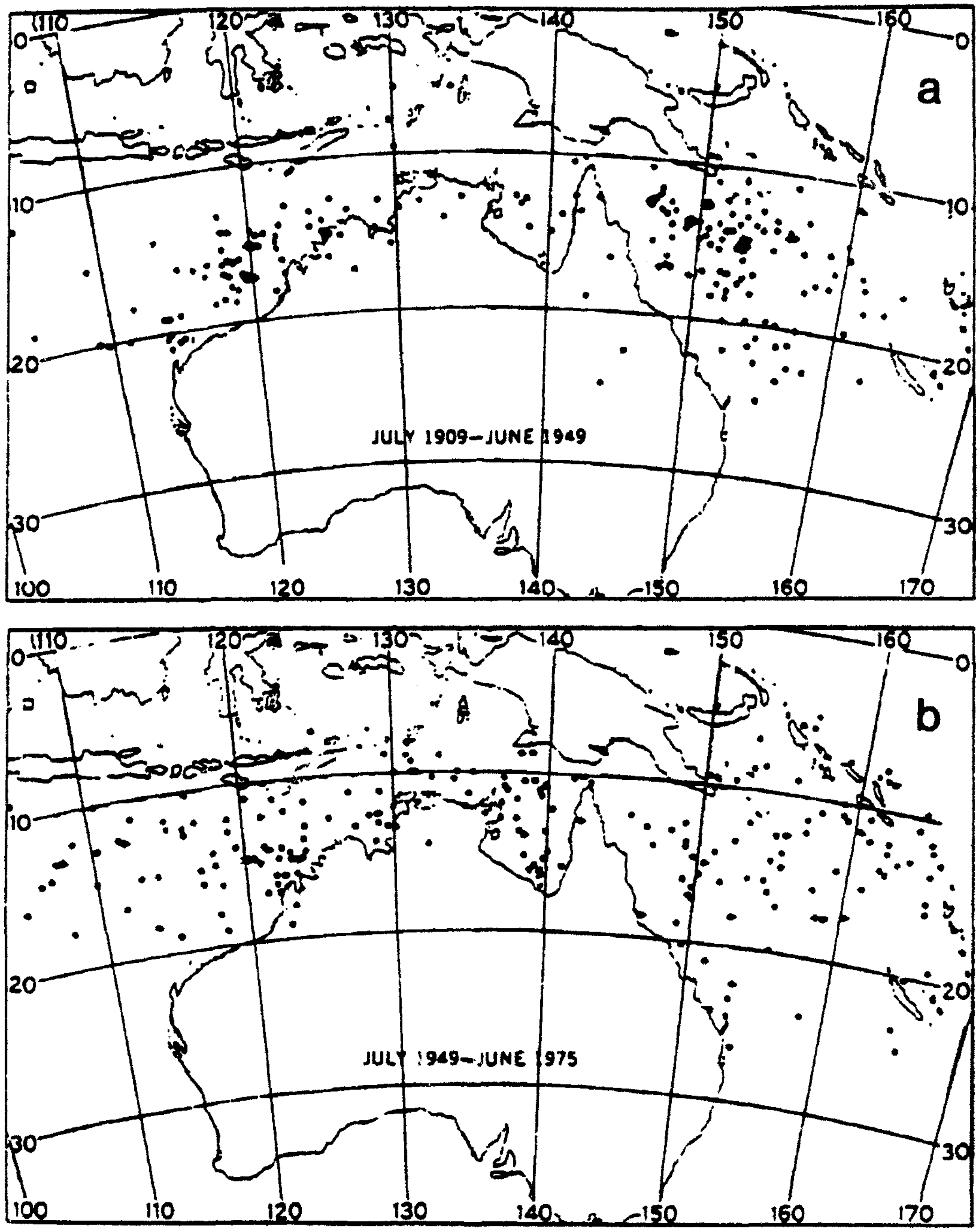

Figure 3.16. Points of origin of tropical cyclones: (a) July 1909-June 1949; (b) July 1949-June 1975 (Neal and Holland, 1977).

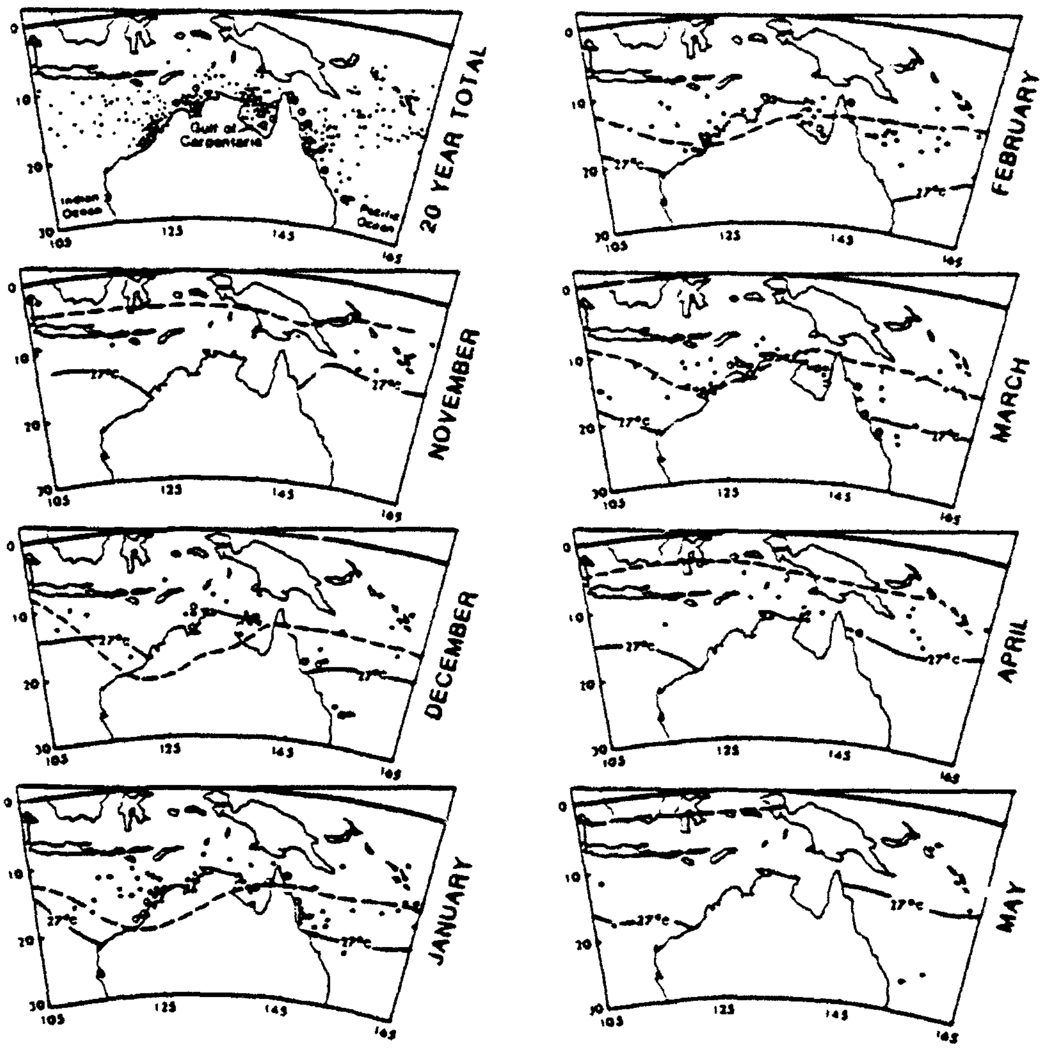

Figure 3.17. Point of origin of tropical cyclones in the region 105 to 165E for the 20 year period July 1959 to June 1979 (Mcbride and Keenan, 1982). (Circles show points of regeneration. Also shown are the mean position of the 27C sea-surface temperature isotherm (solid) and the monsoon shear line (dashed)).

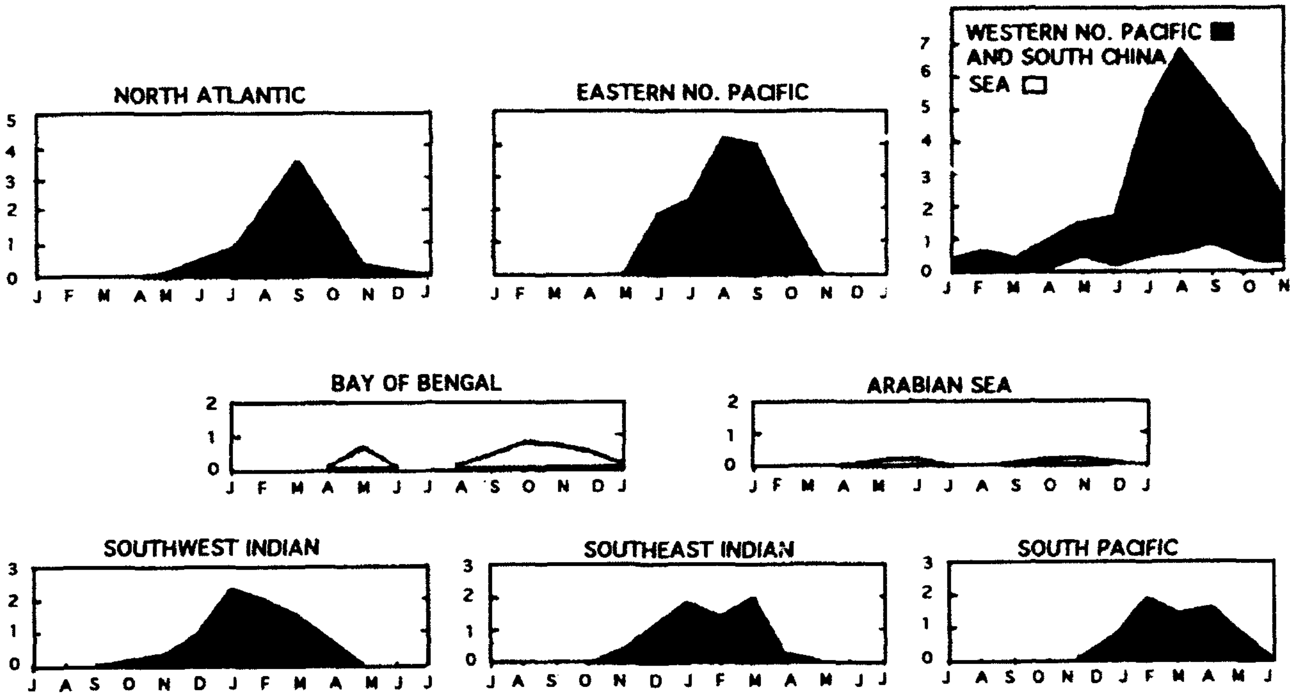

Figure 3.18. Average monthly frequency of tropical cyclones of tropical storm or greater intensity in each development area. Abscissas start with January in Northern Hemisphere areas and July in Southern Hemisphere areas (AWS-TR240, 1971).

Examination of formation locations and 200 mb troughs revealed that slow developing systems (those tracked for 3 days or more before achieving tropical depression stage) have upper-level troughs over them. Fast developing systems (tracked 1 day or less) have a trough positioned such that there is northward (equatorward) flow to the west and southward (poleward) flow to the east of the incipient disturbance. Also, the fast developers have a much slower change in the upper-level synoptic pattern.

Although the model of the TUTT was derived using North Pacific ocean data, the TUTT has been observed in the South Pacific. It is primarily applicable to the Coral Sea and can lead to formation as far south as 25S.

Another unique aspect of the Australian basin is the frequency of regeneration of tropical cyclones. On the average, 1.3 cyclones (12%) annually regenerate after crossing over the Australian continent. This typically occurs with systems entering or leaving the Gulf of Carpentaria. Examinations of synoptic charts show that while over land, these systems maintain their large scale tropical characteristics, with maximum intensity at 700 mb and a warm core above that level.

4.5 South Pacific

The distinction of the boundary between the Australian and South Pacific basins is often unclear and typically overlaps. Tropical cyclones usually occur west of 160W between 5S and 20S. However, during El Nino years, tropical cyclone formation occurs further north (closer to the equator) and east, with some tracks extending as far as 135W.

The main factor in tropical cyclone formation east of the Coral Sea is the South Pacific Convergence Zone (SPCZ). This zone occurs where the southeast trades from transitory anticyclones to the south meet with the semipermanent easterly flow from the eastern South Pacific anticyclone (see Chapter 2). Note that the SPCZ exists in summer and winter, with approximately the same orientation and location. It is often distinct from the ITCZ over Australia, but at times they become one continuous zone of convergence.

Of the numerous depressions which form along the convergence zones, typically 4-5 per year develop into tropical cyclones, although some years have has as many as 12 cyclones. Tropical cyclones are uncommon north of 5S. Those which occur poleward of 20S and east of 160W or develop during the winter are rarely severe, but may become so as they reach the extratropical latitudes.

4.6 North Atlantic

The Atlantic basin is probably the most widely studied in the field of tropical meteorology. However, many of the factors which involve tropical cyclones are unique to this basin. This prevents some research from being generalized to other basins.

The annual number of tropical cyclones in this basin is highly variable, with a range from 1 to 21 cyclones. The season typically extends from June through October. The location of cyclone formation varies during the season. During the early part of the season (i.e., June), formation usually occurs in the SW Caribbean and Gulf of Mexico. As the season progresses, development shifts to the central Atlantic east of the Lesser Antilles. By late September, the western Caribbean once again becomes the favorable location for tropical cyclone formation. This shift in formation location is largely due to the movement of the equatorial trough, vertical wind shear, and the strength of African waves (Gray, 1968).

Slightly more than half of the tropical cyclones which form in this basin originate from African tropical waves (Avila, 1990). This number may be slightly low due to methods of analysis in the 1960's and 70's (Avila, personnel communication). The remainder of the tropical cyclones in this basin form in response to midlatitude frontal systems and upper-level cold lows (i.e., TUTT cells).

4.7 Eastern and Central North Pacific

Of all tropical cyclone basins in the world, the eastern (east of 14OW) and central (14OW - 180E/W) North Pacific was the least understood until the advent of satellite imagery in the 1960's. Since then, it has been discovered that there are nearly twice as many tropical cyclones in this basin as previously thought. This makes it the second most active basin in terms of tropical cyclone development. It also is the most densely concentrated area in terms of tropical cyclone occurrence. An average of 6 cyclones pass near 15N 11OW each year.

Nearly all formation in this area takes place in the ITCZ. On mean surface wind charts, there exists a col in the ITCZ. West of the col, the ITCZ is merely a confluent zone, also referred to as a tradewind trough. To the east, the cross equatorial flow turns westerly and directly opposes the flow from the north. Within this region is the main area of formation. The location of this col moves during the season, expanding the formation area to 130W during the summer and moving to 90W during winter.

As in the western North Pacific, there is some disagreement as to the actual cause of tropical cyclone formation. Some argue that easterly waves from the Caribbean Sea traverse the isthmus of Central America and generate tropical cyclones in the eastern North Pacific. (Avila 1990). Others discount the easterly wave theory and hypothesize that the disturbances generate within the ITCZ itself. Thus, there is a need for detailed observations and case studies to resolve the questions concerning tropical cyclone formation in this region.

Although the ITCZ in this region remains north of the equator during the entire year (Fig. 3.11 & 3.12), tropical cyclone formation is restricted to the months of May - November. Only one cyclone has formed in this region outside this time frame since 1949. During the winter, the ITCZ shifts south, away from the warmest ocean waters, and becomes much weaker. Additionally, vertical wind shear in the area increases during the winter months, making tropical cyclone formation unlikely.

The trade wind trough of the central North Pacific can initiate tropical cyclogenesis. Development in this area averages 3 cyclones per year. Activity is restricted to the months from July - November.

4.8 Other Basins

Since the advent of geostationary satellite imagery, observers have noticed disturbances with tropical cyclone characteristics in the South Atlantic. Yet, no tropical cyclones have been officially recorded in this basin. Although the conditional stability of the region is favorable for tropical cyclone formation, large vertical shear prohibits further development. The same reasoning applies to the central North Pacific. However, tropical cyclones frequently occur in this basin. Most of them are generated in the eastern North Pacific and then move westward into the western North Pacific.

As previously mentioned, tropical cyclones are observed in the eastern South Pacific as far east as 135°W during El Nino years. Typically, however, the sea surface temperatures of the eastern South Pacific are too cold for tropical cyclone formation to occur.

4.9 Annual Variation

It has long been recognized that the number of tropical cyclones in a given region varies from year to year. The exact causes of this remain largely unknown. However, some work in this field has yielded some promising results. Gray (1984a&b) has developed a method for predicting in May the number of tropical cyclones that will occur in the North Atlantic during the period of June - November. A similar application to the western North Pacific has been less successful.

4.10 Seasonal Variation

The number of tropical cyclones in a given region also varies based on the time of year. Figure 3.18 indicates the frequency of tropical cyclone development has a definite seasonal maximum. This maximum is associated with the location of the thermal equator as it moves north and south with the seasons. A 1971 Joint Typhoon Warning Center research initiative indicates that the amount of time required for a tropical disturbance to develop into a tropical storm or typhoon is much shorter in the summer than in the winter (Table 3.1).

Table 3.1. Rate of intensification statistics for 1971 tropical cyclone.

TIME PERIODS	JAN FEB MAR	APR MAY JUN	JUL AUG SEP	OCT NOV DEC	ANNUAL AVERAGE
INITIAL DETECTION TO TROPICAL DEPRESSION	5.2 DAYS	4.0 DAYS	2.6 DAYS	2.0 DAYS	3.0 DAYS
INITIAL DETECTION TO TROPICAL STORM	6.5 DAYS	6.0 DAYS	3.8 DAYS	3.5 DAYS	4.3 DAYS
INITIAL DETECTION TO TYPHOON	-----	8.6 DAYS	5.3 DAYS	4.8 DAYS	6.0 DAYS
TROPICAL DEPRESSION TO TYPHOON	-----	4.6 DAYS	2.7 DAYS	2.8 DAYS	3.0 DAYS
TROPICAL STORM TO TYPHOON	-----	2.6 DAYS	1.5 DAYS	1.3 DAYS	1.7 DAYS

5. EFFECTS OF LONG TERM ATMOSPHERIC OSCILLATIONS

It has been observed that large scale global variations in atmospheric phenomena are related to changes in the frequency of tropical cyclone genesis. The following section discusses these relationships.

5.1 El Nino/Southern Oscillation (ENSO)

The ENSO phenomenon is covered more thoroughly in Section 2. This section deals with the effects of ENSO on tropical cyclone formation in various ocean basins. The El Nino event is characterized by warmer SST's in the eastern South Pacific and anomalous winds over much of the equatorial Pacific. It influences tropical cyclone formation in the western North Pacific (Chan, 1985), South Pacific (Revell and Goulter, 1986), and even the North Atlantic (Gray, 1984a&b).

During the peak phase of the El Nino (usually occurs during the months of July - October), anomalous westerly winds near the equator extend to the dateline in the western North Pacific. This acts to enhance the ITCZ in this area, making it more favorable for formation of tropical cyclones. During El Nino years, the equatorial region of 150°W - 1800° should be monitored closely increased tropical cyclone activity.

Another effect of the El Nino circulation is an equatorward displacement of the South Pacific Convergence Zone (SPCZ). In addition, the waters of the eastern South Pacific are warmer. Revell and Goulter (1986) noted that during such years, tropical cyclones form closer to the equator and farther east. Regions such as French Polynesia, which are typically unfavorable for tropical cyclones due to a strong upper-level trough, experienced 6 tropical cyclones between February-June 1983.

The eastern North Pacific is also affected by the El Nino phenomenon. The ITCZ in this region is displaced south of its normal latitude to approximately 5N. Additionally, the warm ocean anomaly of El Nino extends to near 20N, which enhances the possibility of tropical cyclone formation. The result is an average increase of 2 tropical cyclones during El Nino years. Cyclones also develop closer to the equator and farther west than during a normal year (Chan, 1985).

5.2 Quasi-Biennial Oscillation (QBO)

It has been observed that winds in the equatorial stratosphere oscillate from easterly to westerly and back on the time scale of approximately two years. This phenomenon has been shown to have an impact on the frequency of tropical cyclones in the Atlantic (Gray, 1984; Shapiro, 1989). Hurricane activity is more frequent when the 30 mb stratospheric winds are westerly. The pattern has also appeared in a study of the western North Pacific (Chan, 1985) and North Indian Ocean (Subbaramayya and Rao, 1984), but was not investigated.

The exact mechanism by which the QBO affects tropical cyclones in the troposphere is still unknown. The oscillation signal is strongest at 30 - 50 mb, but is virtually undetected at 100 mb. The most likely explanation is that the QBO affects the upper tropospheric winds, modifying the vertical wind shear.

5.3 Global Scale Oscillations

In addition to the above mentioned oscillations, studies have shown various other oscillations to occur in the tropics, with time scales of anywhere from 2 weeks to 60 days. These oscillations are typically tracked by increased (or decreased) convective activity in a longitudinal belt. Their exact effect on tropical cyclone formation is unknown. Gray (1979) pointed out that tropical cyclone activity in the summer hemisphere tends to cluster into active and inactive periods. One possible explanation is a global scale oscillation which makes conditions favorable or unfavorable for tropical cyclone formation.

6. FORMATION FORECASTING PROCEDURES

All major tropical cyclone forecast centers follow certain procedures when producing their daily forecasts. An understanding of these procedures is necessary if the forecaster is to provide the best meteorological recommendation possible when operating in tropical cyclone regions.

6.1 Formation Forecast Procedures at JTWC

At both NHC and JTWC the primary method of tropical cyclone formation forecasting and detection is through use of geostationary satellite imagery. Hourly satellite imagery is monitored for increased convective activity associated with areas of disturbed weather in the tropics. JTWC monitors surface/gradient level data for areas with persistent low-level circulations and relatively low sea-level pressures. Areas where the pressures continue to fall and winds increase are watched. Mid-level analyses are performed to identify closed circulation or troughing. Upper-level analyses are used to identify weak vertical wind shear, TUTT interactions and anticyclone development.

Each feature described above can be an indicator of tropical cyclone development and is discussed in the tropical weather advisories applicable for the basin. Table 3.2 is an example of a Tropical Cyclone Formation Alert (TCFA) Checklist used at JTWC to assess the current situation.

Table 3.2. TCFA Criteria List -- WESTPAC/NORTH 1.0.

MONTH/DAY/HOUR__________ APPROXIMATE SURFACE POSITION__________

Point Value		Item:
		I. SFC/GRADIENT
2	A.	A circulation is evident in the wind field
4	B.	A circulation has been evident for 24 hours
4	C.	Environmental MSLP - Center MSLP = 4 MB (EST)
3	*D.	Westerly SFC/Gradient Level Wind of at least 10 KTS, is south of the tropical disturbance, and within 05 degrees of center.
1	*E.	Any wind associated with center is at least 20 KTS.
2	*F.	Any wind associated with center is at least 25 KTS.
3	*G.	Any wind associated with center is at least 30 KTS.
1	*H.	24-hour pressure decrease at nearby station (within 05 degrees)=2MB.
3	*L.	24-hour pressure decrease at nearby station (within 05 degrees)=3MB
1	*J.	EST. MSLP of tropical disturbance is < 1008 MB.
2	*K.	EST. MSLP of tropical disturbance is < 1006 MB.
3	*L.	EST. MSLP of tropical disturbance is < 1004 MB.
		II. 500 MB:
1	A.	There is evidence of at least a trough.
2	B.	There is evidence of a closed circulation.
		III. 200 MB:
1	A.	*TUTT to northwest of the tropical disturbance*
3	B.	Evidence of an anticyclone over the center of the tropical disturbance.
1	C.	200 MB wind over center < 25 kts.
		IV. SST:
1	A.	SST > 28 C
		V. SATELLITE DATA:
1	*A.	The tropical disturbance has persisted for at least 24 hours.
2	*B.	The tropical disturbance has persisted for at least 48 hours
3	*C.	The tropical disturbance has persisted for at least 72 hours.
1	*D.	DVORAK classification of at least T0.5
2	*E.	DVORAK classification of at least T1.0
4	*F.	DVORAK classification of at least T1.5
2	*G.	DVORAK classification of at least T2.0 (& indicates a warning should be issued)
		VI. MISCELLANEOUS:
3	A.	Double vortex interaction (cross-equatorial) exists.
5	B.	Tropical disturbance is within 72 hours of a DOD resource.
2	C.	Synoptic circulation and satellite fix are consistent in location (within 02 degrees)
1	D.	20 kt synoptic reports within 3 degrees of the satellite fix (does not apply to winter gales).

64	TOTAL POINTS POSSIBLE (If value is 35 or greater, issue an alert)	

NOTE: The list is progressive in certain categories. If the tropical cyclone is designated a "t1.5", then it would receive 7 points: 1 for being at least a t0.5, 2 for being at least a t1.O, and 4 for being at least a t1.5(1+2+4=7).

JTWC issues a daily narrative message, describing areas of significant tropical activity and evaluating potential for development into significant tropical cyclones. The words "poor," "fair," and "good" describe potential for development. "Poor" describes a tropical disturbance in which meteorological conditions are currently unfavorable for development. "Fair" describes a tropical disturbance in which meteorological conditions are currently favorable for development but significant development has not commenced. "Good" describes the potential for development of a disturbance covered by a TCFA. JTWC issues the ABPW10 (Significant Tropical Weather Advisory for the Western Pacific) message at 0600Z for the western North Pacific and Southern Hemisphere east of 135E, and the ABIO10 (Significant Tropical Weather Advisory for the Indian Ocean) message at 1800Z for the North Indian Ocean and Southern Hemisphere west of 135E.

When a tropical disturbance is listed as a suspect area on one of these advisories, JTWC must maintain continuity as to the disposition of the disturbance. In addition, this message will be re-issued if one of the suspect areas is upgraded. For example, if a suspect area goes from a poor to a fair the ABPW10/ABIO10 will be re-issued. If a suspect area goes from a fair to a good, the ABPW10/ABIO10 will be referenced in the TCFA that is issued to cover the area. This TCFA is considered the re-issued advisory.

6.2 Formation Forecasting Procedures at NHC

The following information is derived from Sheets (1990) and the National Hurricane Operations Plan (Office of the Federal Coordinator for Meteorological Services and Supporting Research, 1991). At NHC a 24 hour continuous watch is maintained in the satellite analysis unit. This group is responsible for providing significant tropical weather advisories for the eastern Pacific and the Atlantic. Geostationary satellite imagery is monitored for tropical weather activity on a continuous basis. This information is used in conjunction with synoptic observations and aircraft data to determine the occurrence of tropical cyclone formation. Satellite analysts work closely with tropical cyclone forecasters to determine when and where formation is likely to occur.

Several analyses are performed routinely for the NHC area of responsibility, primarily south of 40N to the Equator, the Caribbean Sea and the Gulf of Mexico. Analysis and interpretive products are distributed over national and international circuits. These products include tropical weather discussions for the entire area and Satellite Interpretation Messages (SIMS) issued every six hours. SIMS contain general information for the entire area and specific mesoscale discussions for Puerto Rico and the United States Virgin Islands, the Florida peninsula, and the northern Gulf of Mexico. In addition, synoptic surface analyses are completed and transmitted every six hours and an entire set of near surface, 200-mb, shear, deep-level mean, lower- and upper-level mean charts, heavily influenced by satellite derived data, are transmitted every 12 hours. Also, a detailed Gulf Stream and sea-surface temperature analysis for the Gulf of Mexico as well as general sea-surface temperature analysis are prepared thrice weekly and made available to marine interests through a dial-up system.

Marine forecast products include high seas forecasts issued at six hourly intervals for the North Atlantic south of 32N, the Caribbean Sea and the Gulf of Mexico as well as the eastern North Pacific east of 140W, and south of 30N. Aviation products include international area forecasts for essentially the same areas and international SIGMETS (bulletins describing weather hazards for large aircraft) for the San Juan, Miami, Houston and Oakland (south of 30N) flight information regions (FIRs) (Fig. 3.19).

NHC issues Tropical Weather Outlooks (TWOs) on the Atlantic and eastern Pacific daily during the hurricane season. They are transmitted at 0530, 1130, 1730, and 2230 Eastern Local Time in the Atlantic and at 0400, 1000, 1600, and 2200 UTC in the eastern Pacific. The outlook briefly describes both stable and potentially unstable areas out to 48 hrs. A monthly tropical weather summary of the Atlantic tropical cyclone activity is prepared and issued during hurricane season.

6.3 Formation Forecasting At CPHC

With regards to formation forecasting, CPHC operates essentially the same way as NHC. However, the number of products and the area of responsibility are significantly decreased for CPHC operations. In the central Pacific TWOs are transmitted by CPHC at 1000 and 2200 UTC and the outlook briefly describes both stable and potentially unstable areas out to 48 hours.

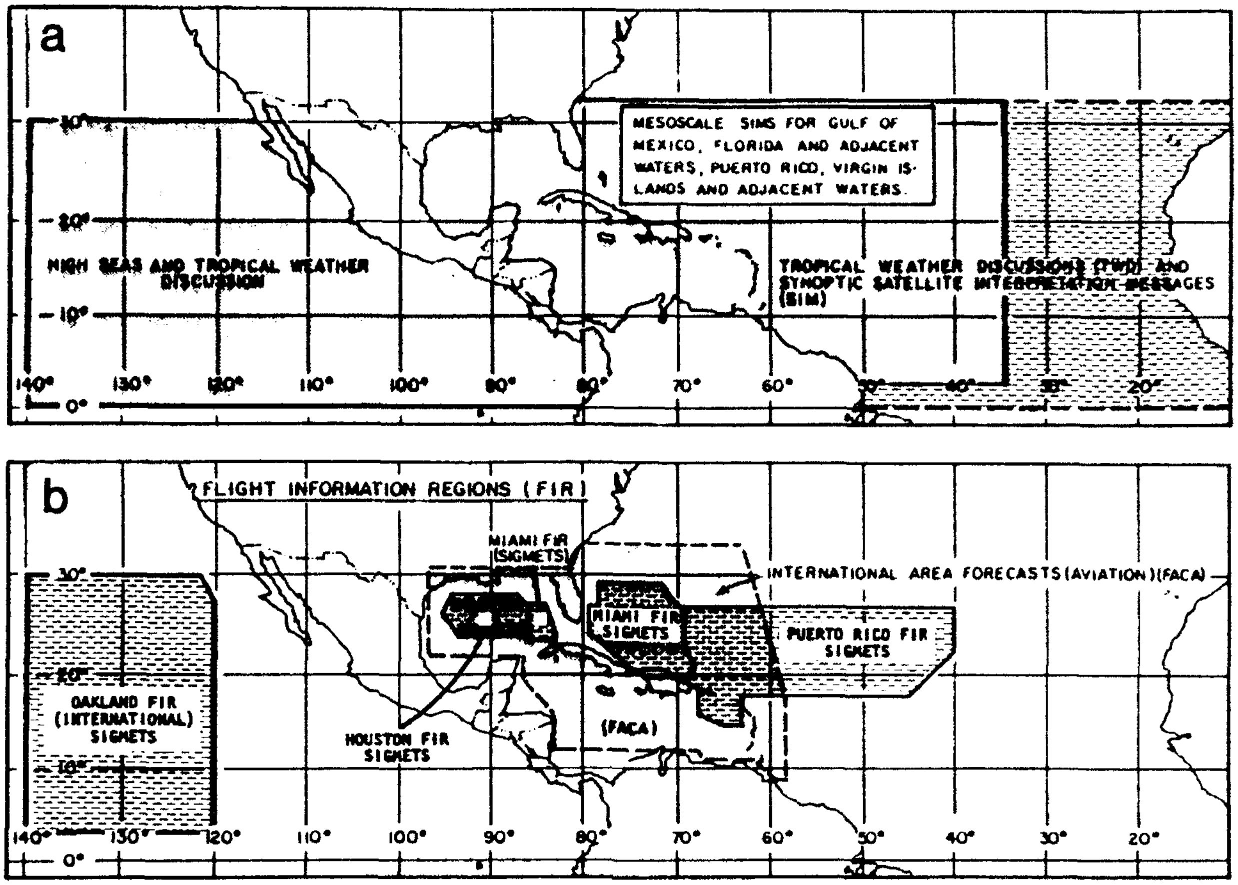

Figure 3.19. NHC areas of responsibility for (a) tropical analyses, interpretation products, and high seas; and (b) aviation forecasts and SIGMETS (Sheets, 1990).

6.4 Formation Forecast Procedures for Single Stations/Ships

When operating in the tropical waters, the following procedure is offered as a suggested approach to formation forecasting.

STEP ONE: Maintain a continuous plot of all suspect areas listed on the TWOs/Significant Tropical Weather Advisories. This plot should include a record of motion, changes in development potential and changes in estimated central pressure. This will allow the deployed forecaster the ability to track which areas the warning centers are monitoring with their more extensive data network and geostationary satellite imagery loops.

STEP TWO: Monitor the NOGAPS model for development of low-level circulations. A preliminary study of NOGAPS formation forecast capability during the 1991 tropical cyclone season indicated NOGAPS developed a circulation within five degrees of the actual formation location of a significant tropical cyclone in 7 of 10 cases. It was also observed that when the model predicted the development of a low-level circulation at 72 hours and it became more centralized at 48 hours and again at 24 hours, then formation was likely.

STEP THREE: Track areas where the numerical models are predicting low-level southwesterly equatorward and northeasterly poleward wind surges near pre-existing low-level circulation, and highlight areas of weak upper-level winds. These are areas where the formation potential is high.

NOTE: Current numerical model limitations only allow for forecasting two or three of the six suggested prerequisites for tropical cyclone formation. Current models predict surges in the low-level wind field which give forecasters the ability to identify areas where pre-existing low-level circulations will experience significant increases in low-level vorticity. These models also predict areas where weak upper-level winds are likely to occur which are often associated with weak vertical wind shear. When these areas of weak winds are in phase with pre-existing low-level circulations, tropical cyclone development potential increases.

6.5. Formation Forecasting Thumb Rules

1. Cloud clusters equatorward of the ITCZ rarely have a lifespan of more than 24 hours.

2. More than half of the formation cases in the Northwestern Australian basin originate in the monsoon trough over land.

3. 84% of formation cases in the Australian basin originate in the monsoon trough.

4. The conditions which favor formation in the North Indian Ocean during spring occur when the low-level ridge near 20°N strengthens, producing easterly flow over the tropical waters. The observing stations Port Blair (station id: 43330) and Bangkok (station id: 48455) should be monitored for a change from westerly to easterly flow.

5. Monsoonal flow from the Australian region into the western North Pacific occurs in three areas: east of New Guinea, west of New Guinea, and between Singapore and Borneo.

6. If the monsoon trough in the western North Pacific is enhanced by easterlies along the southern periphery of the subtropical ridge, then the developing cyclone will most likely follow a straight path. However, if a surge in the cross-equatorial monsoon is responsible for the monsoon trough enhancement, then the cyclone will often recurve.

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