6. TROPICAL CYCLONES

6.1. INTRODUCTION

The term “tropical cyclone” applies to a non-frontal low pressure system of synoptic-scale, developing over tropical or subtropical waters and having a definite organized circulation. However, the term is generally used in a more restrictive sense to include only potentially destructive warm-core systems; thus, the operational definition excludes monsoon depressions, mid-tropospheric and subtropical cyclones.

Warm-core tropical cyclones are the most destructive weather phenomena for their size in the tropics. These weather systems function as natural, but very inefficient, “heat engines”. Most of the latent heat energy that is released is expelled high in the atmosphere. Only a small percentage of the energy is converted into kinetic energy in the form of wind and waves. Nevertheless, the destructive power of an intense tropical cyclone is awesome, with surface wind speeds near the cyclone center often exceeding 100 knots. Torrential rains falling from the spiral convective cloud bands several hundreds of miles from the center can cause flash flooding and landslides. The storm surge propagating ahead of the cyclone can completely inundate low-lying coastal areas. The combined effects of destructive winds and phenomenal seas can swamp and sink vessels unfortunate enough to be caught in its path.

The combination of potentially destructive winds, rains and high seas poses a threat to life and property that cannot be ignored. The following examples of tropical cyclone destruction clearly illustrate this point:

1737 - Calcutta, India: 300,000 people killed,

1876 - Backergunge, India: 100,000 to 400,000 people killed,

1944 - Philippine Sea: three U.S. Navy destroyers sunk and 800 lives lost,

1970 - East Pakistan: 300,000 people killed,

1974 - Darwin, Australia: 90 percent of the city destroyed,

1977 - Near Andhra Pradesh, India: 10,000 people killed,

1991 - Bangladesh: 138,000 killed.

6.2. TERMS AND DEFINITIONS

Most countries within JTWC’s AOR are actively involved in tropical cyclone forecasting. A lack of standardized terminology can be a source of confusion when interpreting bulletins from other forecasting agencies or when exchanging information with foreign meteorologists. To minimize such confusion, JTWC adheres to definitions and classifications adopted by the U. S. National Weather Service. Forecasters are to interpret bulletins from other countries in terms of reported maximum sustained wind speeds and apply the appropriate U. S. definition. Note that NAVPACMETOCCEN WEST/JTWC uses a one minute maximum sustained wind average as opposed to the ten minute wind average used by WMO International warning agencies. When exchanging information with foreign meteorologists, stress the use of maximum sustained 1-minute winds rather than classification terms. Maximum sustained wind speeds provide a common reference for exchange and interpretation of tropical cyclone information. Table 6.1 provides a summary of standard and non-standard tropical cyclone classifications.

Table 6.1 Tropical Cyclone Classifications

Standard:	United States (maximum sustained 1-minute mean surface wind speed in knots)		
		Tropical depression	<34
		Tropical storm	34 to 63
		Typhoon/Hurricane	>63
	World Meteorological Organization (maximum sustained 10-minute mean surface wind speed in knots)		
		Tropical depression	<34
		Tropical storm	34 to 47
		Severe tropical storm	48 to 63
		Typhoon (or local synonym)	>63
Non-Standard:	JTWC (maximum sustained 1-minute mean surface wind speed in knots)		
		Super typhoon	>129
	Mauritius and Southwest Indian Ocean (maximum sustained 10-minute mean surface wind speed in knots)		
		Tropical depression	<34
		Moderate tropical depression/storm	34 to 47
		Severe tropical depression/storm	48 to 63
		Tropical cyclone	64 to 90
		Intense tropical cyclone	91 to 115
		Very intense tropical cyclone	>115
	India, Bangladesh and Pakistan (maximum sustained 10-minute mean surface wind speed in knots)		
		Depression	<28
		Deep depression	28 to 33
		Severe cyclonic storm	48 to 63
		Severe cyclonic storm with core of hurricane force winds	>63

The following is a list of terms/definitions used by JTWC:

Best Track -- A subjectively smoothed path (versus a precise and very erratic fix-to-fix path) used to represent tropical cyclone motion.

Binary Interaction -- The interaction between two tropical cyclones (more commonly known as the Fujiwhara effect) when they are within about 750 nm of each other that usually results in the storms rotating cyclonically (occasionally they may rotate anticyclonically) about a central point between them. This interaction may end in one of three ways:

1. The destruction of one vortex (by movement over land or dissipation, for example);
2. By merger of the two cyclones; or
3. By escape.

The Fujiwhara effect refers specifically to the interaction between two cyclonic vortices, where mutual attraction and coalescence takes place (Brand, 1970; Dong and Neumann, 1983, Lander and Holland, 1993).

Center -- The vertical axis or core of a tropical cyclone that is usually determined by cloud vorticity patterns, wind and/or pressure distribution (i.e. isobaric pattern).

Explosive Deepening -- A rapid decrease in the minimum sea-level pressure of a tropical cyclone at the rate of 2.5 mb/hr for 12 hours or 5.0 mb/hr for at least six hours (Dunnavan, 1981).

Extratropical -- A term used in warnings and tropical weather summaries to indicate that a cyclone has lost its "tropical" characteristics. The term implies both a poleward displacement from the tropics and the conversion of the cyclone's primary energy source, the release of latent heat of condensation, to baroclinic instability. It is important to note that cyclones can become extratropical and still maintain winds of typhoon or storm force.

Eye -- The central area of a tropical cyclone that is more than half surrounded by a wall cloud.

Intensity -- The maximum sustained 1-minute mean surface wind speed, typically within one degree of the center of the tropical cyclone.

Maximum Sustained Wind -- The highest surface wind speed averaged over a one-minute period of time. (Peak gusts over water generally average 20-25 percent higher than sustained winds.)

Mei-yu Front -- The term "mei-yu" is the Chinese expression for "plum rains". The mei-yu front is a persistent east-west zone of disturbed weather during spring which is quasistationary and stretches from the east China coast, across Taiwan and eastward into the Pacific Ocean south of Japan.

Monsoon Depression -- A tropical cyclonic vortex characterized by:

1. Its large size, (the outer-most closed isobar may have a diameter about 600 nm),
2. A loosely organized cluster of deep convective elements,
3. A low-level wind distribution which features a 100-nm diameter light-wind core which may be partially surrounded by a band of gales, and
4. A lack of a distinct cloud system center.

Note: Most monsoon depressions which form in the western North Pacific eventually acquire persistent central convection and accelerated core winds marking its transition into a conventional tropical cyclone.

Monsoon Gyre -- A mode of the summer monsoon circulation in the western North Pacific characterized by:

1. A very large nearly circular low-level cyclonic vortex that has an outer-most closed isobar with a diameter on the order of 1200 nm,
2. A cloud band rimming the southern to eastern periphery of the vortex/surface low,
3. A relatively long (two week) life span. (Initially, a subsident regime exists in its core and westerly and northwesterly quadrants with light winds and scattered low cumulus clouds; later, the area within the outer closed isobar may fill with deep convective cloud and become a monsoon depression or tropical cyclone.), and
4. The large vortex cannot be the result of the expanding wind field of a pre-existing monsoon depression or tropical cyclone.

Note: A series of small or very small tropical cyclones may emerge from the "head" or leading edge of the peripheral cloud band of a monsoon gyre (Lander, 1994).

Rapid Deepening -- A sharp decrease in the minimum sea-level pressure of a tropical cyclone at the rate of 1.25 mb/hr for 24 hours (Holliday and Thompson 1979).

Recurvature -- The turning of a tropical cyclone from an initial path toward the west and poleward to a subsequent path toward the east and poleward, after moving poleward of the mid-tropospheric subtropical ridge axis.

Reverse-oriented Monsoon Trough -- The distinguishing characteristics of the a reverse-oriented monsoon trough are:

1. A SW-NE orientation (as opposed to the normal NW-SE of the trough axis) and
2. The penetration of the trough axis into subtropical areas which are normally the province of easterly flow.

Significant Tropical Cyclone -- A tropical cyclone becomes "significant" with the issuance of the first numbered warning by the responsible warning agency.

Size -- The areal extent of a tropical cyclone, usually measured radially outward from the center to the outer-most closed isobar. Based on an average radius of the outer-most closed isobar, size categories in degrees of latitude are as follows:

1. 1° to 2° = very small,
2. 3° = small,
3. 4° to 5° = medium (average),
4. 6° to 9°= large, and
5. 10° or greater = very large (Brand, 1972 and a modification of Merrill, 1982).

Strength -- The average wind speed of the surrounding low-level wind flow, usually measured within one to three degrees of the center of a tropical cyclone.

Subtropical Cyclone -- A low pressure system that forms over the ocean in the subtropics and has some characteristics of a tropical circulation but does not contain a central dense overcast (CDO). Although occasionally associated with an upper-level cold low or low-level baroclinicity, a sub-tropical system can still transition to a tropical cyclone if organized deep convection develops and persists, resulting in a warm innercore.

Super Typhoon -- A typhoon with maximum sustained 1-minute mean surface wind speed of 130 kt or greater.

Tropical Cyclone -- A non-frontal, migratory low-pressure system, usually of synoptic scale, originating over tropical or subtropical waters and having a definite organized circulation.

Tropical Depression -- A tropical cyclone with maximum sustained 1-minute mean surface wind speed of 33 kt or less.

Tropical Disturbance -- A discrete system of apparently organized convection, generally 100-300 nm in diameter, originating in the tropics or subtropics, having a non-frontal, migratory character and having maintained its identity for 12-24 hours. It may or may not be associated with a detectable perturbation in the wind field. It is the basic designation which, in successive stages of development, may be classified as a tropical depression, tropical storm, typhoon or super typhoon.

Tropical Storm -- A tropical cyclone with maximum sustained 1-minute mean surface wind speed of 34-63 kt, inclusive.

Tropical Upper-tropospheric Trough -- A dominant climatological system and a daily upper-level synoptic feature of the summer season, located over the tropical North Atlantic, North Pacific and South Pacific Oceans (Sadler, 1979). Cold-core vortices embedded in the TUTT are generally referred to as TUTT cells or TUTT lows.

Typhoon -- A tropical cyclone with maximum sustained 1-minute mean surface wind speed of 64 to 129 kt, inclusive. West of the 180°, they are called typhoons and east of the 180°, they are called hurricanes.

Wall Cloud -- An organized band of deep cumuliform clouds that immediately surrounds the central area of a tropical cyclone. The wall cloud may entirely enclose or only partially surround the center.

6.3. DEVELOPMENT CLIMATOLOGY

Five of the seven major ocean basins for tropical cyclone development occur within JTWC's AOR. The AOR experiences an annual average of 56 tropical cyclones which is 72% of the average annual global total of 78 tropical cyclones (reaching tropical storm intensity or greater (Fig 6.1)). The western Northern Pacific basin, which includes the South China Sea (development area), is by far the most active with an annual average of 26 tropical storms and typhoons (33% of average annual global total). See (Fig 6.2) for the frequency of occurrence of tropical storm or typhoon force winds by month for each major basin (Neumann, 1993). A discussion of these areas follows:

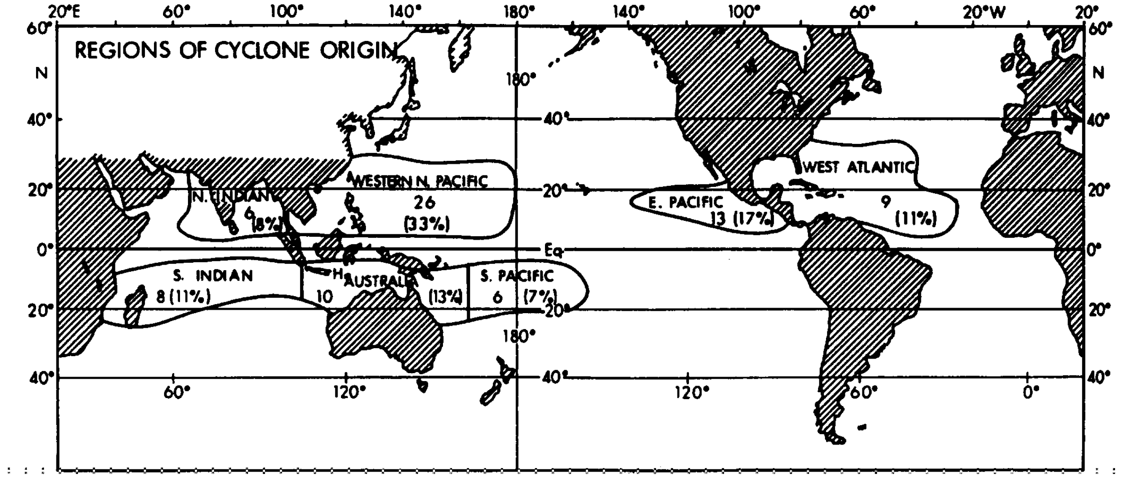

Figure 6.1 Average annual number (and Percentage of global total) of tropical cyclones that reach tropical storm or greater intensity in each development area for 1958 to 1977 (from Gray, 1978)(AWWS/TR95/001, 1995)

Western North Pacific Ocean -- This region experiences more than twice as many tropical cyclones as any other development area and is the only area in which tropical cyclones can occur in any month of the year. August is normally the most active month, and 90% of the storm activity occurs during the period May through December. More than 80% of tropical disturbances that reach depression stage further intensify into tropical storms or typhoons, and two-thirds of the tropical storms eventually reach typhoon intensity.

South China Sea -- Data for this region is normally included with those of the western North Pacific. However, stratifying data from the two areas reveals that the South China Sea experiences a slight double maximum in storm formation -- the first in May and the second in September. This double maximum is related to the northward and southward oscillation, respectively, of the monsoon trough.

Bay of Bengal -- Two distinct tropical storm seasons occur in the Bay of Bengal:

1. Pre-monsoon period from April to June.
2. Post-monsoon period from September through December.

In contrast to tropical storm activity, the development of tropical cyclones that reach only the depression stage occurs in all months except March, with most occurring in the northern Bay of Bengal during the southwest monsoon and early post-monsoon period from June to October.

Arabian Sea -- The Arabian Sea has the fewest cyclones of all regions with an average of slightly over one depression and one tropical storm per year. The region also experiences two seasons (April to June and September to December) associated with the monsoon transition seasons and the seasonal movements of the monsoon trough.

Southwestern Indian Ocean -- This area includes the Southern Hemisphere - Indian Ocean area from the coast of Africa to 100° East and experiences an average of eight cyclones per year of tropical storm intensity or greater. A significant increase in the number of storms reported in this basin has occurred subsequent to the advent of continuous satellite coverage. The season extends from December to April, with over 70% of the storms occurring from January to March.

Australian/Southeastern Indian Ocean -- This basin includes the southern Indian Ocean from 100°-142° East and is an area that has shown a marked increase in tropical storm observations in recent years due to the availability of satellite imagery. The season extends from December through April, with most storms occurring from January to March.

Australian/Southwestern Pacific Ocean -- This area includes the Southern Pacific Ocean area east of 142° East. This basin averages about seven tropical cyclones per year, and the monthly occurrence of tropical cyclones is similar to the South Indian Ocean frequency. Nearly 75% of the tropical cyclones in this area occur from January through March. There is a tendency for these tropical cyclones to form simultaneously in both the North and South Pacific during the transition months (April, November and December).

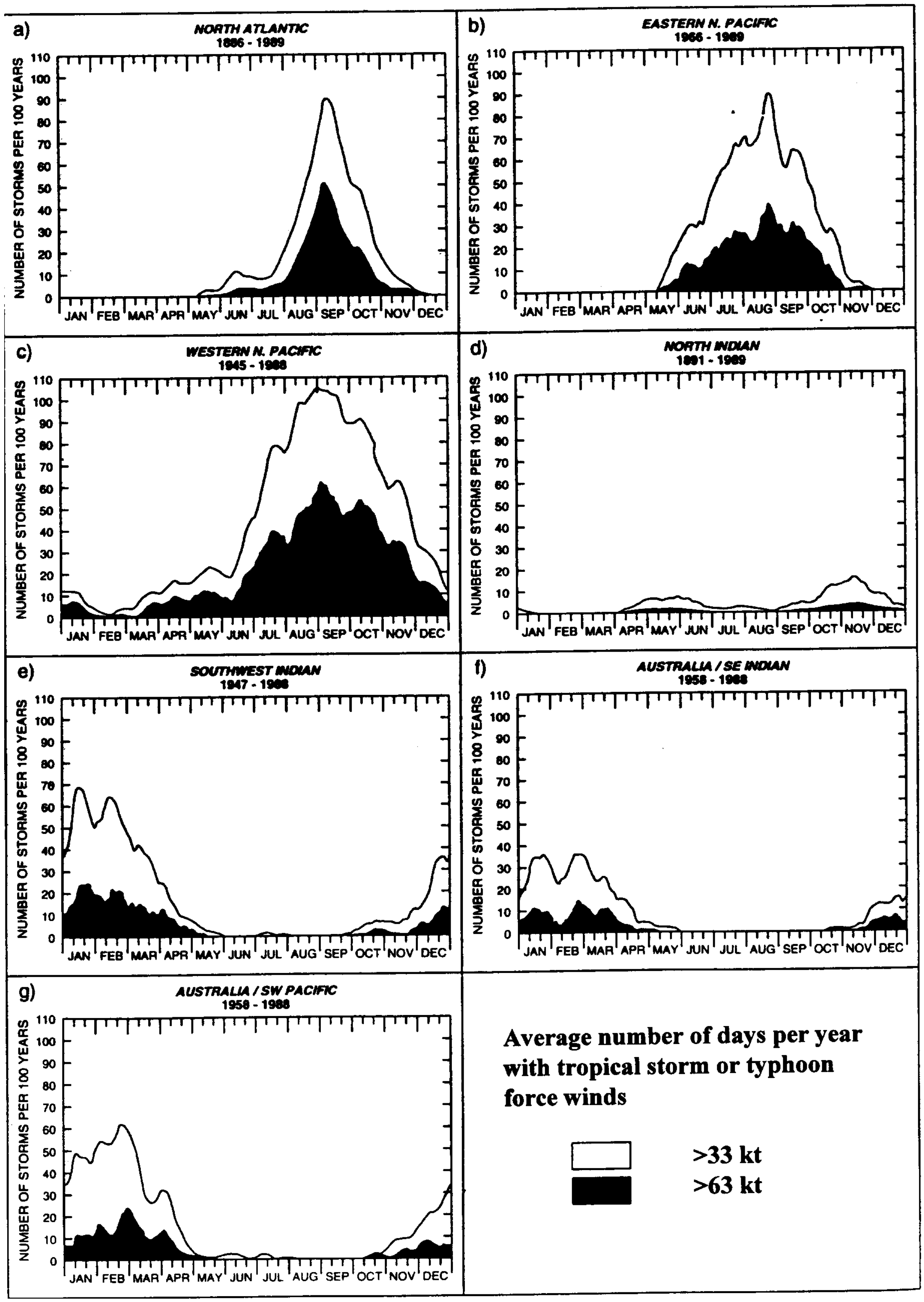

Figure 6.2 Seasonal tropical cyclone frequency for (a) North Atlantic, (b) eastern North Pacific, (c) western North Pacific, (d) North Indian, (e) Southwest Indian, (f) Australia and Southeast Indian reagions, (g) Australian and Southwest Pacific. Upper and lower bounds refer to maximum winds of at least 34 kt and 64 kt, respectively. Data has been smoothed over a 15 day period (from Neumann, 1993)(modified from WMO/TD-No.693, 1995).

6.4. STRUCTURE

The physical structure of mature tropical cyclones has been studied in detail. NAVPACMETOCCEN WEST/JTWC Guam's forecasters use their understanding of typical features of tropical cyclones to interpret available satellite and synoptic data. A discussion of typical structure follows.

A mature tropical cyclone can be divided into four general parts:

1. An outer region with inward increasing cyclonic winds and limited convection extending 176-264 nm from the center,
2. An inner belt in which winds reach typhoon intensity and convective activity is concentrated in spiral rainbands,
3. A ring-shaped wall cloud region characterized by maximum wind speeds and violent convective activity, and
4. A central eye inside a transition zone through which there is a rapid decrease in wind speed. The eye is characterized by light winds, the absence of strong convection and confused seas.

The winds of a tropical cyclone consist of cyclonic inflow near the surface, rising motion in the eyewall and rainbands, outflow at the top of the storm and sinking motion some distance away. (Fig 6.3) shows a modeled cross-section of the motion, clouds and pressure within a tropical cyclone.

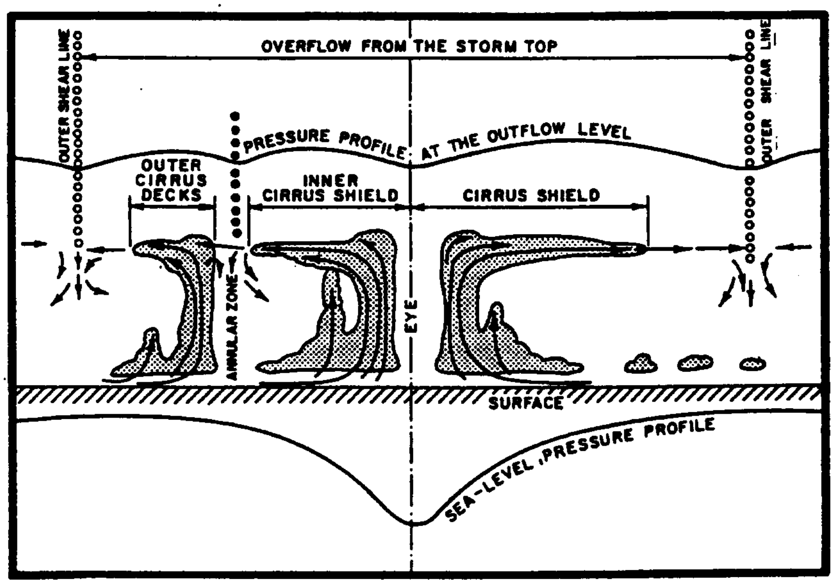

Figure 6.3 Schematic vertical cross-section of air flow, cloude and pressure from model typhoon (After Fujita et al.)(modified from AWS/TR-95/001,1995.

Tangential velocities increase rapidly in the inflow layer, remain relatively constant in the eye wall to a height of about 19536 ft (5954 m), then gradually decrease with height up to the outflow level. At the outflow level, wind speeds decrease rapidly and change direction from cyclonic to anticyclonic.

Horizontal surface wind distribution from a typical Northern Hemisphere tropical cyclone is depicted in (Fig 6.4). Note the asymmetrical distribution of wind speeds. Maximum winds are located to the right of the storm track due to the tropical cyclone's forward motion being added to the storm's wind speed in that sector.

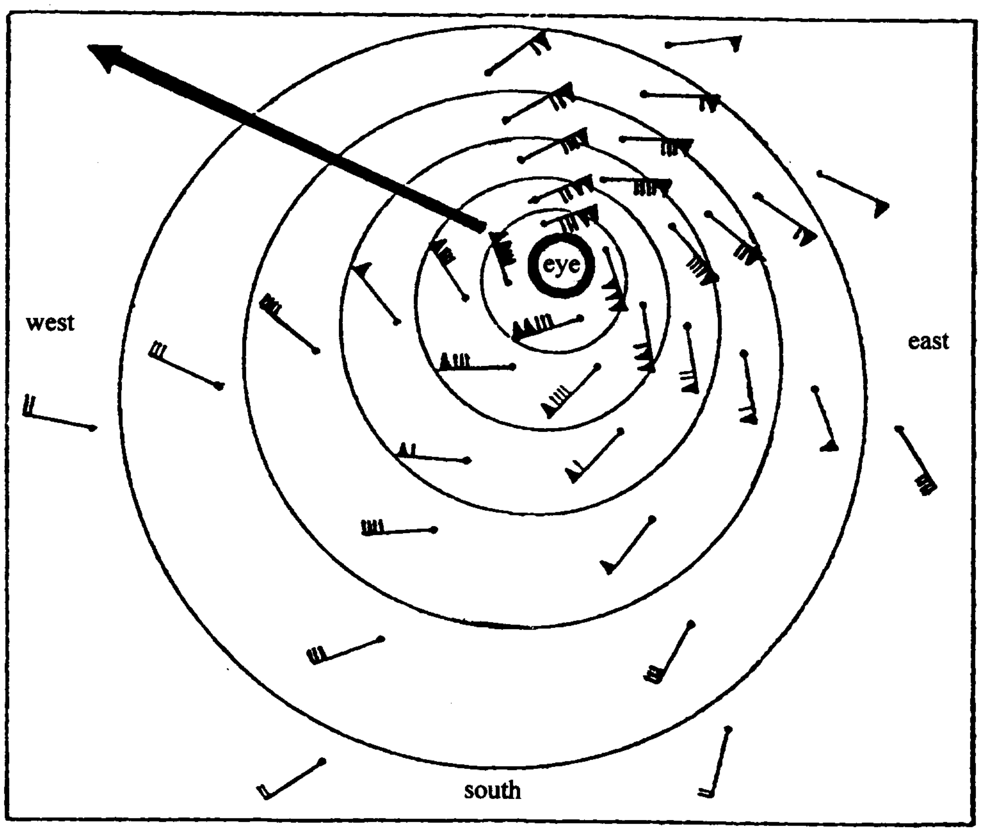

Figure 6.4 Wind circulation around and "average" 150-knot typhoon in the Northern Hemisphere. The nested circles show a tighter pressure gradient to the northeast of the center of the circulation. Note the wind blows accross the isobars towards the eye. The solid arrow indicates typhoon's direction of motion along track.

6.5. FORMATION AND DEVELOPMENT

The primary indicator of impending tropical cyclone development is the existence of persistent low-level convergence in an area of favorable conditions. Typhoon Duty Officers use an empirically developed "Tropical Cyclone Formation Alert Checklist" to assign points to the relative strengths of the conditions of tropical cyclone genesis. A Tropical Cyclone Formation Alert (TCFA) is issued once a minimum number of points is reached. The TCFA is discussed in more detail later. Since all tropical cyclones develop in limited areas and are highly seasonal, specific environmental conditions are required to accomplish the transition from a loosely organized convective disturbance to an intense vortex. By examining the climatology of cyclone genesis in relation to large-scale variables, some of the important physical relationships associated with cyclone formation can be inferred.

The large scale climatological parameters associated with tropical cyclogenesis are summarized as follows:

1. Warm Seas -- A large ocean area is necessary with surface temperatures warm enough to provide sufficient moisture and sensible and latent heat such that when air is lifted from near the surface and expands pseudo-adiabatically, it will remain warmer than the surrounding tropical atmosphere to a height of about 39,600 ft (12,069 m). Minimum sea surface temperatures of 79°F (26° C) are required.

2. Minimum Coriolis Parameter -- Almost all cyclones are observed to form poleward of 5° latitude, since a strong rotation in the wind field can be generated only where the Coriolis parameter exceeds a certain minimum value.

3. Weak Vertical Wind Shear -- Weak vertical wind shear through a deep tropospheric layer is necessary to permit vertical development of the cyclone. Strong shear can displace the deep convection and the associated warm column away from the low-level circulation, resulting in weakening or dissipation of the system.

4. Pre-existing Disturbance -- Cyclonic horizontal wind shear or a low-level surface vortex is required to initiate convergent flow near the surface. Deep convection can then become concentrated and the latent heat released can result in the development of a warm-core system.

5. Divergence Aloft -- An anticyclone or well-defined ridge near the 200-mb-level transports excess heat and mass away from the system center, allowing continued decrease in the central pressure. Some systems develop beneath a pre-existing upper-level anticyclone and eventually link up with it. Those systems located in low- or no-vertical wind shear environments develop their own upper-level anticyclone.

Although the above criteria exists over a large portion of the tropical oceans for extended periods of time, tropical cyclogenesis remains a relatively infrequent occurrence. Gray (1975) hypothesized that cyclones only form during periods when the above conditions depart significantly from their regional climatological means. See (Fig 6.5) for certain regions of the world that have atmospheric conditions that are favorable for these significant departures.

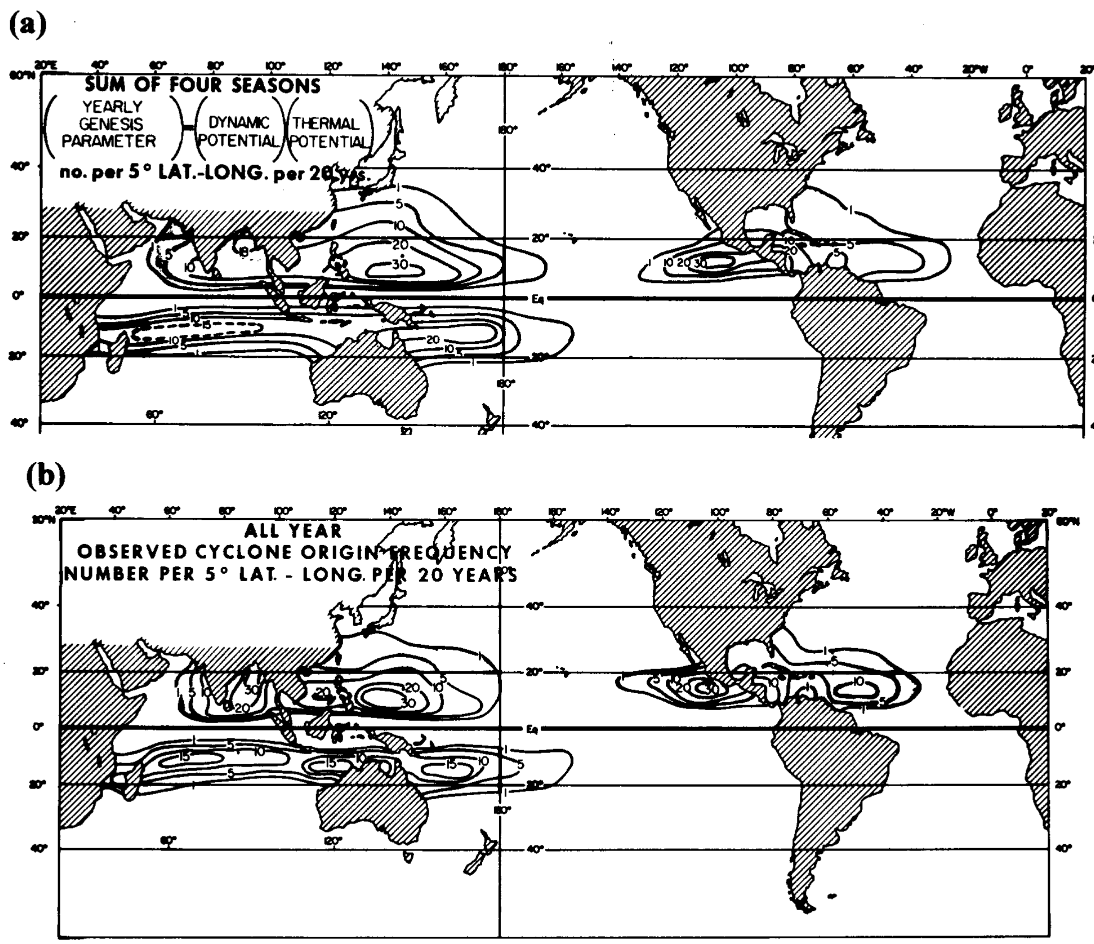

Figure 6.5 (a) Annual genesis parameter as defined by Gray (1975) and (b) observed tropical cyclone formation frequency expressed in turms of occurrence per 20 years with 5 degree lat.-long. areas (Gray, 1975).

There are certain environmental patterns or phenomena that create conditions favorable for tropical cyclone genesis:

1. Monsoon Trough Development -- The monsoon and near-equatorial troughs are seasonal phenomena that are related to the season. In the spring and early summer, solar heating near the equator produces the near equatorial troughs. As the summer continues, the trough moves poleward. Westerly wind bursts further contribute to the development of the monsoon tough. The summer and early autumn monsoon trough is, without doubt, the greatest breeder of tropical cyclones.

2. Tropical Upper-tropospheric Trough (TUTT) -- A surface disturbance can be induced by upper-level divergence associated with the eastern side of a cyclonic cell in the TUTT (Sadler, 1976). This type of development occurs most frequently during the August to October timeframe due to the strength of the TUTT and accounts for 10% to 20% of the tropical cyclones that develop. These disturbances, which usually occur between 15° to 25° North, undergo the following three stages of development shown in (Fig 6.6):

3. Low-level Westerly Surges -- Tropical cyclone development can be initiated by a westerly wind surge or "burst" equatorward of the monsoon trough or near-equatorial trough axis (Keen, 1982; Lander, 1990).

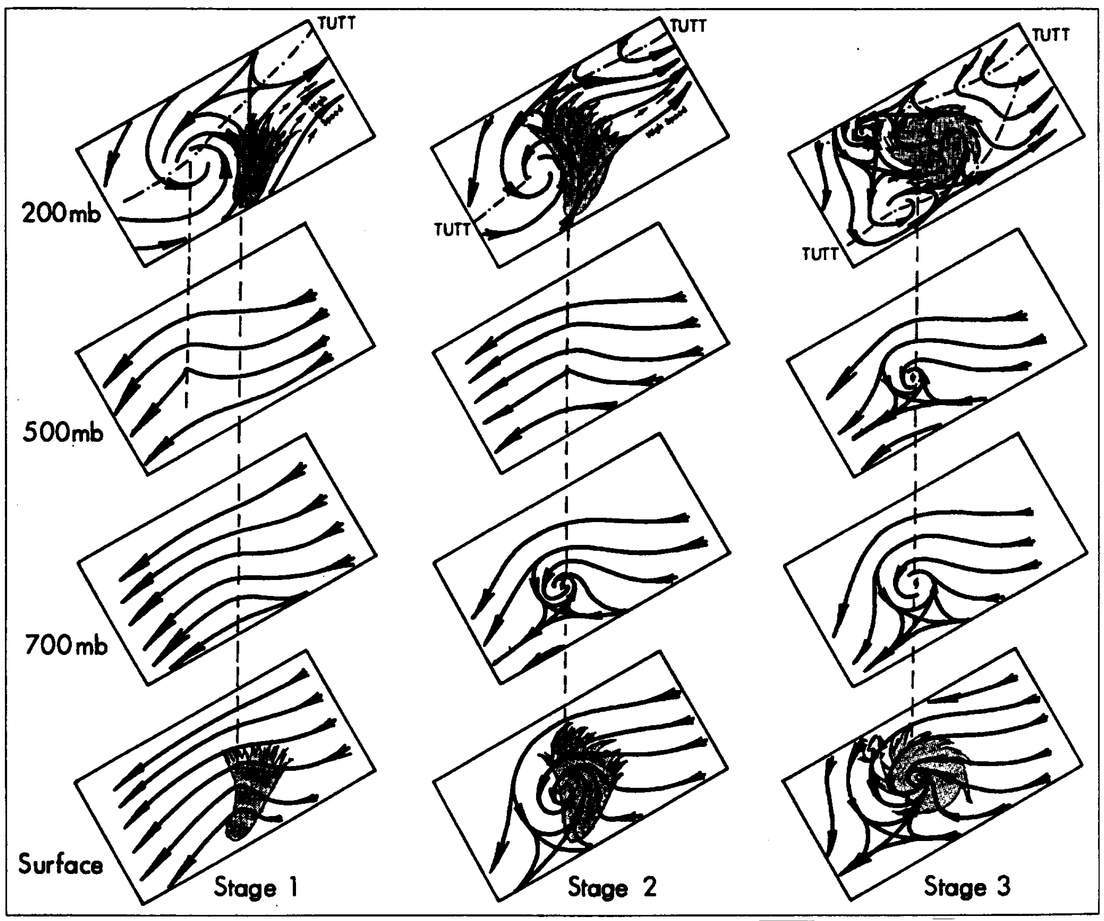

Figure 6.6 Schematic model of a tropical cyclone initiated by an upper-tropospheric low (Sadler, 1976).

6.6. DISSIPATION AND EXTRATROPICAL TRANSITION

Tropical cyclones ultimately either dissipate or transform into extratropical cyclones. Dissipation is primarily due to two effects:

1. Interaction with land masses, which:
   a. cuts off the main source of fuel for the heat engine (the latent heat release from the warm moist air off the ocean) and
   b. introduces increased frictional effects and disruption to the low-level inflow.
2. Strong vertical wind shear, which:
   a. strips away the persistent central clouds and
   b. destroys the vertical circulation that is needed to maintain the cyclone's heat engine.

6.7. MOTION

The movement of a tropical cyclone (TC) was formerly believed to be determined primarily by four major factors:

1. Coriolis effect,
2. Asymmetrical distribution of pressure falls about the cyclone center,
3. Integrated steering flow from the surface through the upper troposphere, and
4. Interaction with other systems.

Additionally, numerous studies have shown that the size of the TC affects its propagation relative to the environmental steering and may significantly alter its environment (Carr and Elsberry 1994; Chan and Williams 1987; Fiorino and Elsberry 1989). This interdependence of TC track, intensity and size has lead to the JTWC's adoption of the **"Systematic and Integrated Approach to Tropical Cyclone Track Forecasting" (Carr and Elsberry 1994)** as its primary forecasting technique. The details of the "Systematic Approach" cannot be adequately addressed in this document. The "Systematic Approach" defines a set of conceptual models (TC-environment models) to assist the forecaster in formulating a comprehensive understanding of how the mutual influence of the TC and its environment determines TC motion.

The general principles describing model group interaction and evolution with time completes the "Systematic Approach." The conceptual models are organized into three groups:

1. Environmental Structure -- Characterizations of environmental flows, excluding the symmetric circulation of the TC. Two subsets, based on scale, define the environment:
   a. Large scale environmental surroundings based on the existence and orientation of various synoptic features, such as cyclones, anticyclones, ridges and troughs are called **Synoptic Patterns**.
   b. Smaller areas within synoptic patterns are called **Synoptic Regions** and characterize directions of steering.
2. TC Structure -- Characterizations of the intensity and size of the symmetric TC. The TC structure is defined by its size (Midget, Small, Average, and Large) and intensity (Exposed Low Level, Tropical Depression, Tropical Storm, Typhoon, Intense Typhoon).
3. TC-Environment Transformation -- Characterizations of one- and/or two-way advections or energy exchanges between the TC and the environment. Five transformation models are defined:
   a. Basis Beta Effect Propagation
   b. Vertical Wind Shear
   c. Ridge Modification by Large TC
   d. Monsoon Gyre-TC Interaction
   e. Tropical Cyclone Interactions

6.8. TRACK TYPE

There are four tropical cyclone track categories with various types and locations of synoptic features associated with each category of motion:

1. Straight Runner **--** TC's embedded in the deep easterly flow equatorward of a continuous mid-level subtropical ridge.
2. Recurver **--** TC's that move around the western edge of, or through breaks in, the mid-level subtropical ridge. The track changes orientation from westward and poleward to eastward and poleward.
3. North Oriented **--** TC's embedded in a reverse oriented trough. Low latitude TCs may move eastward before developing a slow, somewhat erratic northward track. Other storm TCs will slow their westward motion and assume a northward track.
4. Other/Erratic Mover **--** TC's embedded in weak or aclimatological steering flow. Examples include:
   a. TUTT-induced TC's that form near the axis of the subtropical ridge or TC's in the summer that form along the monsoon trough and track to the north or northeast and don't recurve.
   b. TC's in the South China Sea are often of this variety.

The average or preferred tropical cyclone tracks are shown in (Fig 6.7).

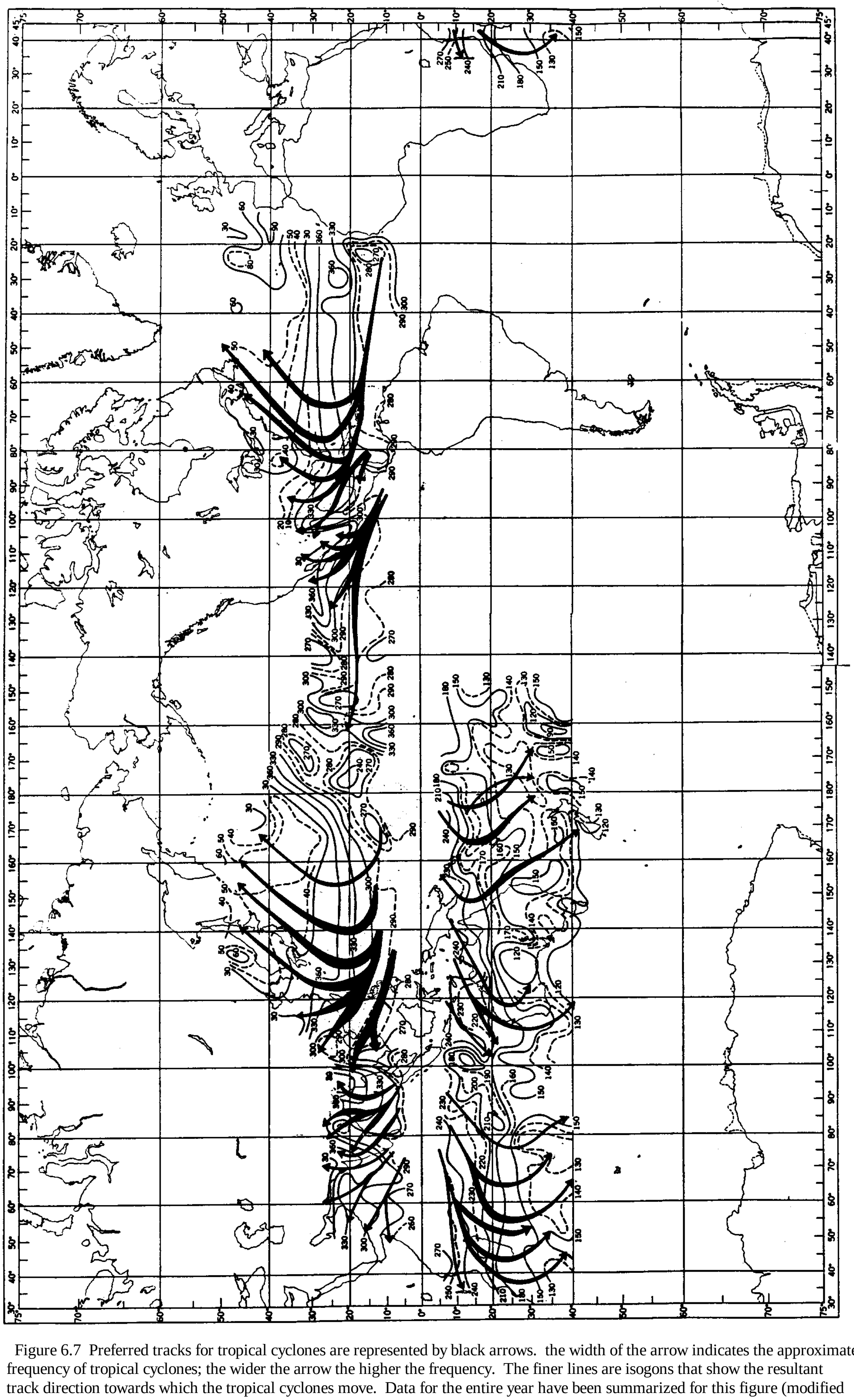

Figure 6.7 Preferred tracks for tropical cyclones are represented by black arrows. the width of the arrow indicates the approximate frequency of tropical cyclones; the wider the arrow the higher the frequency. The finer lines are isogons that show the resultant track direction towards which the tropical cyclones move. Data for the entire year have been summarized for this figure (modified from NAVAIR 50-1C-61, 1974).