TROPICAL CYCLONES

Tomonori Matsuura and Michiaki Yumoto
National Research Institute for Earth Science and Disaster Prevention, Tsukuba, Japan

Keywords: Tropical cyclones, Typhoon, ENSO, Interdecadal variability, Global climate change

Contents

Summary

Tropical cyclones are the most devastating of all natural disasters in terms of the loss of human life, property damage, and other economic consequences. Knowledge of tropical cyclones is incomplete and improvement can only be made through theoretical, observational, as well as modeling, studies. This paper reviews the characteristics of tropical cyclones and discusses their activity from a global perspective. The activity of tropical cyclones is related to atmospheric and oceanic circumstances and hence, can depend on the climate changes statistically such as ENSO (El Niño-Southern Oscillation), interdecadal variability, and global warming. It is suggested that the variability of sea-surface temperature (SST) and that of large-scale atmospheric circulations are main causes of the climatic variability of tropical cyclone activity.

1. Introduction

Tropical cyclones can create landslides, floods, and other related natural disasters that result in extensive damage to the economy and loss of human lives. For example, losses of human lives due to the storm surge associated with a cyclone in Bangladesh in 1998 were on the order of 130,000. In late October 1998, one of the largest hurricanes in the 20th century, Hurricane Mitch, caused great losses of human lives and devastating economic losses in Central America. In Japan, Typhoon Bart led to a storm surge in Shiranui Town, Kumamoto Prefecture in September 1999 and claimed many human lives.

Approximately 80 tropical cyclones reach the level of tropical storm intensity annually in the world. About one-third of all tropical cyclones in the world occur in the Western

North Pacific, and its average annual birth rate is 27.2 during the 30-year period, 1971-2000.

The research of tropical cyclones has been conducted in several inter-related areas: observations to understand the actual circumstances; theory; modeling to understand the mechanism; and numerical simulation to forecast the tropical cyclone activity. Observations of tropical cyclones can be made using many techniques such as rawinsonde, artificial satellite, and radar. Recently, an observation of the three-dimensional structure of a cyclone was made by an artificial satellite called TRMM, equipped with Precipitation Radar. The mechanisms of tropical cyclones are investigated through data regarding their generation, development, decay, and movement. The numerical modeling of tropical cyclone mechanisms have been based on geophysical fluid dynamics. However, since the amount of water-vapor is an important factor for tropical cyclones and the liquid-gas phase change occurs, the mechanisms are very complex. There are several ideas regarding the development of tropical cyclones. The ultimate objective of the research in this area is to forecast cyclone activity. This task remains formidable because of the insufficient computer technology, the lack of observational data, and insufficient knowledge of the underlying mechanisms.

It is known that the tropical cyclone activity varies at longer terms than inter-annual variations. One of the most important themes is to explore how the tropical cyclone activity changes when global warming occurs. In this article, we focus on the relationship between tropical cyclone activity and climate changes.

2. Classification of Tropical Cyclones

Tropical cyclones exist over the world's tropical oceans, and are called different names. The term "typhoon" is used for tropical cyclones generated and developed over the Western North Pacific Ocean. The severe tropical cyclones appearing in the Eastern North Pacific and the Atlantic Oceans are called “Hurricanes” and “Cyclones” in the Indian Ocean. In the Southern Hemisphere, for example in Australia, they are called “Tropical Cyclones." The World Meteorological Organization (WMO) divides tropical cyclone areas into several zones and establishes the center in each area. The Japan Meteorological Agency (Tokyo) is the local center for the Western North Pacific region, Hurricane Center of NOAA (Miami) for the North Atlantic and the Eastern North Pacific regions, and Indian Meteorological Agency for the Indian Ocean. These organizations collect and disseminate information for tropical cyclones. The classification of tropical cyclones is different among the organizations, as summarized in Table 1. Hereafter the term "typhoon" is used in place of the generic term "tropical cyclone."

3. Typhoon mechanisms

3.1 Typhoon structure

Rader and TRMM are able to observe fine structures such as cumulus convections, spiral bands, and wall clouds in the typhoon.

Intensity	Western North Pacific	Eastern North Pacific	Western South Pacific, South East Indian Ocean	North Atlantic	North Indian Ocean	South West Indian Ocean
< 34 kt ~17 m/sec	low pressure area or tropical depression	tropical disturbance or tropical depression	tropical disturbance or tropical depression	tropical disturbance or tropical depression	low pressure area or tropical depression or deep depression	tropical disturbance or tropical depression
34-47 kt (17-22 m/sec)	tropical storm	tropical storm	tropical cyclone	tropical storm	cyclonic storm	moderate tropical storm
48-63 kt (23-32 m/sec)	severe tropical storm	tropical storm	severe tropical storm	tropical storm	severe cyclonic storm	severe tropical storm
64-129 kt (33-65 m/sec)	typhoon	hurricane	hurricane	hurricane	severe cyclonic storm with a core of hurricane winds	tropical cyclone (64-9 kt), intense tropical cyclone (90-115 kt), very intense tropical cyclone (115 kt)
≧130 kt (65 m/sec~)	super typhoon	hurricane	hurricane	hurricane	severe cyclonic storm with a core of hurricane winds	very intense tropical cyclone

Table 1. Classification of tropical cyclones based on maximum surface wind speed.

However, we first discuss the large-scale structure of the developed typhoon and the oceanic structure beneath the typhoon. At the same time, the typhoon structure reproduced by a Coupled Atmosphere-Ocean General Circulation Model (CGCM) is discussed.

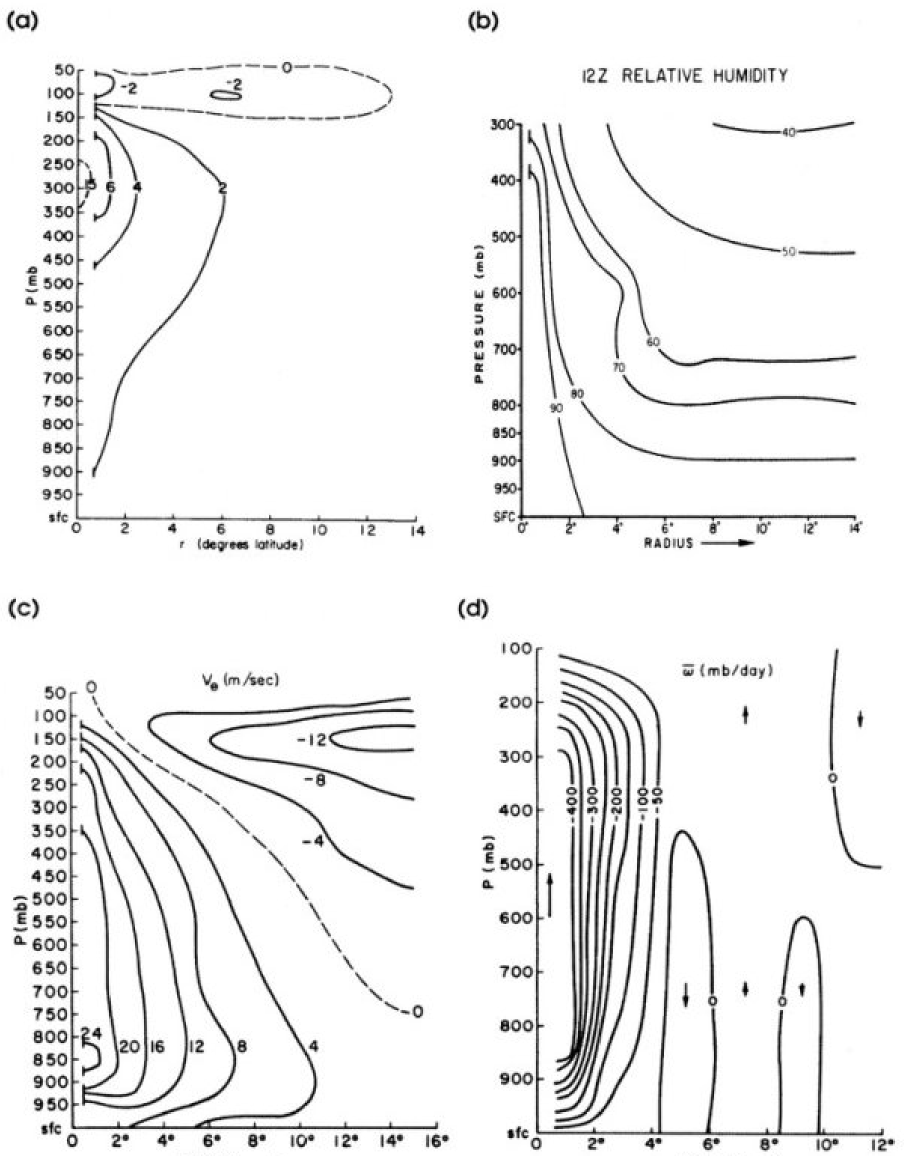

Figure 1. Two-dimensional cross section of an observed Typhoon (after Frank, 1977). (a) Temperature anomaly (°C), (b) relative humidity (%), (c) tangential wind (m s^{-1}), and (d) vertical velocity (hPa day^{-1}).

<u>Temperature fields</u>

As shown in Figure 1a, a typhoon is a warm-core vortex throughout the troposphere and the maximum temperature anomaly exceeding 10 °C occurs at about 250-hPa level (~ 10.4km). The high temperature anomaly in the typhoon core is called the “warm core”. Cumulus convection occurs in the neighborhood of the core due to upward winds and the latent heat releases into the atmosphere associated with the condensation of water vapor. When this situation lasts for a long time, the warm core is formed due to the combined effects of heat transport by the convection and the latent heat emission. The warm core maintains low pressure because of high temperature anomalies.

Relative humidity

The strong convection regions have much higher mean relative humidity than the surrounding tropical atmosphere. Figure 1b shows a mean cross section of the relative humidity. The most prominent feature of the humidity profile shows that the mean humidity exceeding 90 % extends up from surface through 400-hPa level (~ 7.2km) in the core region (~ 100 km). This implies that entrainment of dry air does not greatly hamper cumulonimbus convection in this inner region. The positive humidity anomaly extends outward through the active convective region.

Wind fields

The most prominent feature of the typhoon structure is the intense tangential wind field whose cross section is shown in Figure 1c. A broad lower tropospheric cyclone extends outward to 1 000 km or more and the tangential velocity increases inward. Not shown in Figure 1c, however, in the eye of typhoon where its velocity is extremely reduced. The tangential velocity is negative, i.e. anticyclonic, in the upper troposphere and far from the typhoon core. The intensive clockwise circulation has a peak about at 150-hPa level (~ 13.6km) and there, the radial velocity is outward. On the other hand, the radial velocity of the bottom boundary layer in the troposphere is inward.

Vertical motion

A cross section of the vertical motion field is shown in Figure 1d. Strong upward vertical motion exists from the wall of eye to about 4° radius (~430km). It is known that there exists downward vertical motion in the eye of typhoon. From 4-6° (430km~645km), there is moderate subsidence below 400 hPa indicating the mean location of the most regions. The converging air toward the eye wall in the boundary generates upward vertical motion within about 4° and the upward vertical motion diverges at about 150-hPa level.

Ocean structure beneath the typhoon

Typhoons emerge over the ocean. Sea-surface temperature (SST), heat flux, and humidity from the sea surface play important roles in the typhoon genesis and development. When the typhoon migrates over the ocean, SST and/or the temperature profile of upper ocean change. Figure 2 shows SST and the temperature profile of Typhoon Tess, which moved toward the northwest at 6 cm s^{-1}. Typhoon Tess caused SST cooling over a region of about 200 km width: the maximum SST response was estimated to be –4 °C and occurred roughly 75 km to the right of the track. As shown in Figure 2b, the upwelling in the ocean occurred in phase and of roughly equal amplitude from the base of the mixed layer to the 17 °C isothermal line.

Typhoon structure of a CGCM

Figure 3a shows the vertical section of a model typhoon on 29 October of model year 4 of the NIED CGCM run. The section shows both the atmospheric and ocean structure of the typhoon. This typhoon is representative of those simulated by the CGCM, and was formed at 150 ºE and 10 ºN on 22 October. The typhoon then moved northwards, arriving in the vicinity of Japan on 29 October (Figure 3b).

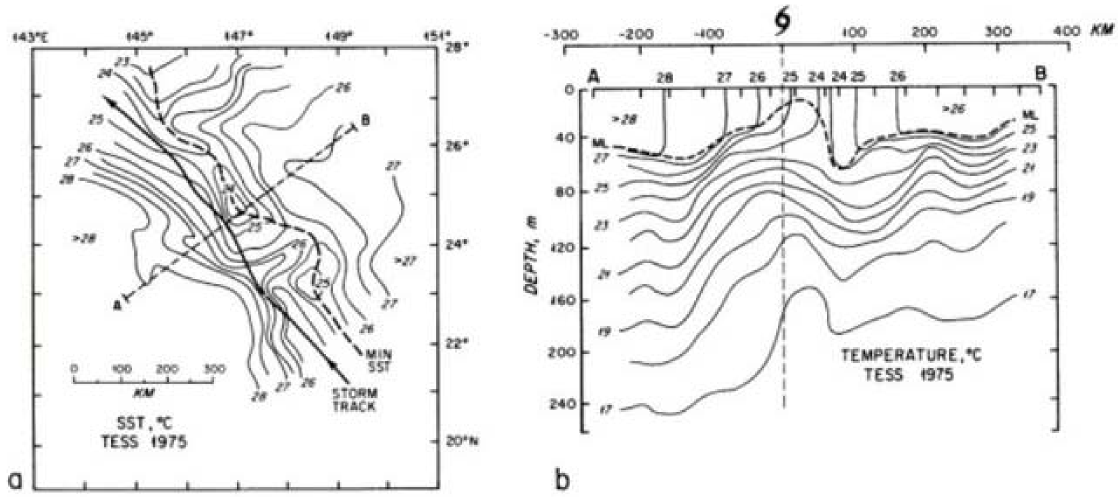

Figure 2. SST (a) and oceanic temperature (b) cross-sections around the track of Tess (after Pudov, et al., 1979).

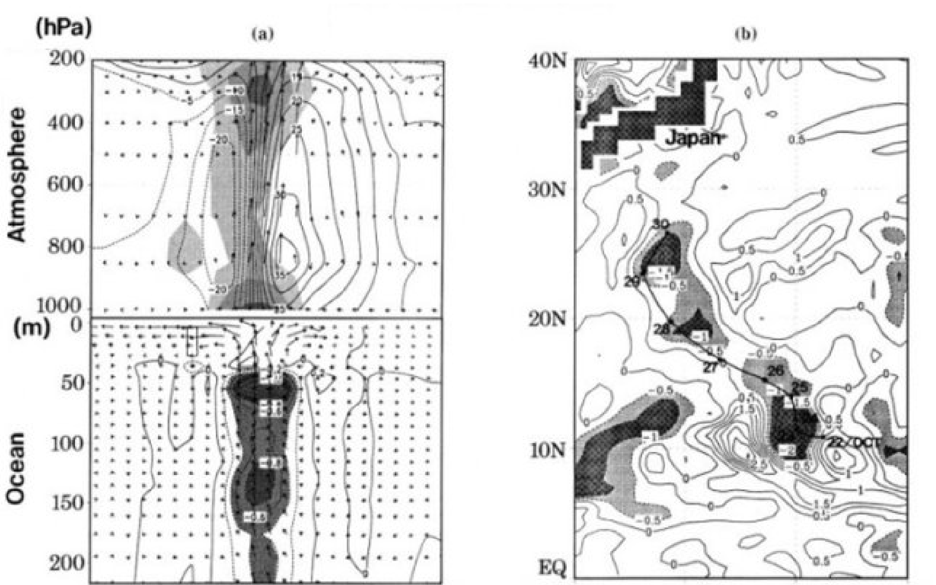

Figure 3. Atmosphere and ocean vertical section for a representative model typhoon (a) and its track (b). (a) Atmosphere: Meridional wind profile (contour interval is 5 m s^{-1}), temperature anomalies (light shaded> 4 °C, middle shaded > 6 °C, and dark shaded> 8 °C) and vertical wind vectors. Ocean: SST anomalies (contour interval is 0.2 °C; -0.8 °C < dark shaded < -0.4 °C, -0.8 °C < light shaded < -0.1 °C) and vertical vectors (u, $3{\leftrightarrow}10^3$ W). (b) Migration of typhoon and ocean temperature anomalies at 50 m depth. Dark shading < -1.0 °C and –1.0 °C < light shading < -0.5 °C. A solid line depicts the track of the model typhoon from 22 to 30 October model year 4.

The winds of the model typhoon blow cyclonically, with a maximum magnitude greater than 35 m s^{-1}. The wind speed on the right side of the typhoon track is stronger than on the left side. Although the model typhoon does not exhibit an eye, the sea level pressure drops sharply at the core, and the maximum wind velocity appears at the location where an abrupt gradient in sea level pressure exists. These features are similar to observed typhoons (cf. Figure 1). Moist air converges in the lower atmosphere, rises in the core of the typhoon, and diverges at 200-hPa level (~ 11.8km) (see Figure 1a). In particular, the temperature anomalies exceed 8 ºC at 200~300-hPa level (11.8 ~ 9.2km) in the core of the typhoon. However, this is because the horizontal resolution of model is too coarse to resolve its eye in the CGCM.

The ocean's response to the model typhoon includes strong mixing from the surface to about 50 m and a divergent Ekman drift is induced in the upper ocean by cyclonic wind stresses. In this manner, the seasonal thermocline upwells beneath the core of the typhoon (see Figure 3a). The characteristic variation of the upper ocean beneath the model typhoon is similar to that beneath observed hurricanes and typhoons (cf. Figure 2). Ocean temperature anomalies below a depth of 50 m (the seasonal thermocline) decrease over 1 ºC due to upwelling beneath the core of the typhoon (136 ºE - 137 ºE). Figure 3b shows that the temperature of the upper ocean decreases several degrees Celsius in the neighborhood of the typhoon track. Interestingly, the coldest temperature anomalies appear in the ocean area on the right side of the typhoon track during 27 to 30 October when the typhoon was in a mature stage and its forward speed was medium (~ 5 m s^{-1}). This is because the wind speed of the typhoon was more intensive on the right side of its track than that on the left side and the strength of mixing and upwelling became asymmetric. Moreover, the wind stress strengthened the inertial current on the right side of the typhoon and weakened it on its left side. In general typhoon activity decreases SSTs through changes in air-sea heat exchange, vertical mixing, and upwelling.

3.2 Typhoon genesis and development

Although typhoon genesis and development are usually discussed from the viewpoint of basic dynamics and thermodynamics, first we explain them descriptively. Then, the environment of global atmosphere, which may affects on the typhoon genesis and development, is discussed.

Typhoon genesis is especially favored in the tropical zone between 10 °N to 20 °N. In these sea areas, SSTs exceed values as high as 26 °C. Cumulous convection occurs actively in these sea areas. The typhoon-scale motion coexists with cumulonimbus and develops interactively – the clouds supply latent heat energy to the typhoon, and the typhoon supplies the fuel, in the form of moisture, to the clouds. It is not known how the cloud cluster affects tropical cyclones and hence, the mechanism of clustering should be investigated. Now, the development of typhoons is explained if once the "infant" typhoons are formed. Once the "infant" typhoon is formed in the high SST area, evaporation from the sea surface activates and vapor amount increases in the low atmosphere. Simultaneously upward vertical motion becomes stronger. While water vapor rises, clouds occur through condensation. Then, since latent heat release in the core and the air temperature increases, a warm core forms as described in subsection 3.1. The pressure is lower in the warm core, where rising motion exists, than that in the environment. The low atmospheric air converges because it flows from high pressure to low pressure. If this event occurs within several degrees latitude from the equator, it becomes only a storm and does not develop to the typhoon stage. If it forms farther than 5° latitude from the equation, however, the converging atmospheric flow turns on cyclonically due to the Coriolis force. The atmospheric air, which converges to the vortex center, rises and then the upward motion is strengthened. This system is a positive feedback mechanism from which the typhoon develops.

Two representative mechanisms are suggested to explain the positive feedback. The first is called the conditional instability of second kind (CISK). The theory of CISK shows that the positive feedback is closely linked among the first circulation (tangential wind), inflow derived from the friction in the boundary layer, and cumulous convection in the inner core. Another is called finite-amplitude “wind-induced surface heat exchange (WISHE)” in which water vapor from the sea surface to the low level atmosphere interacts nonlinearly with the tangential wind. The typhoon develops from this mechanism of positive feedback.

It is noted that some favorable conditions of atmosphere and ocean are needed for the typhoon development as follows. First, an ocean temperature of at least 26 °C is needed down to a depth of about 60 m. The energy source of typhoons is latent heat, which is released to the atmosphere through the condensation of water vapor. In general, evaporation is active with increase of SST and water vapor is included more in the atmospheric boundary layer. Second, the atmosphere must be capable of permitting deep convection to occur: The stratification of atmosphere should be kept conditionally unstable so that cumulus convection occurs. Third, the dynamic balance of typhoon is approximated by the gradient relation and the Coriolis force plays an important role. Therefore, typhoon does not form over the equator but forms mainly northward of 5 °N. Fourth, there is a requirement for the prior existence at low altitude of a rather substantial level of cyclonic vorticity. Seventy percent of typhoons occur at monsoon shear lines and monsoon confluence zones during May to September annually. Fifth, vertical shear of the horizontal wind should be small for the typhoon generation in order for incipient warm air to accumulate. From the previous discussion, we can see that typhoon genesis is influenced by the large-scale atmospheric and oceanic circumstances.

3.3 Typhoon migration

Approximately 5 typhoons generated in tropical areas strike Japan annually on the average. Most damage from the typhoon occurs after landfall. Hence, a prediction of typhoon track plays an important role in the typhoon forecast. In order to predict the typhoon track, first it is necessary to understand the mechanism of typhoon migration. It is possible to classify three main tracks of typhoons in the Western North Pacific (WNP): The westward migration and landing on the southeast Asia, the northwestward migration and turning toward northeast, and those tending to take irregular courses.

The typhoon track is principally determined from mean atmospheric currents. The mean currents are defined by vertical integration from 700-hPa level (~ 3km) to 500-hPa level (~ 5.6km). Then, in summer when the North Pacific High covers the southern sea off

-

-

-

Bibliography

Diaz, H.F. and Pulwarty, R.S. (Eds.) (1997). *Hurricanes: Climate and Socioeconomic Impacts*, New York, Springer--Verlag. [This book is a collection of contributions on scientific knowledge and societal impacts of hurricane activity in the Atlantic]

Frank, M.W., (1977). The structure and energetics of the tropical cyclone, Paper: Storm structure. Monthly Weather Review, 105, 1119-1135. [This paper indicated the large-scale structure of tropical cyclones composited from 10 years of northwest Pacific rawinsonde data.]

Lander, M.A. (1994). An exploratory analysis the relationship between tropical storm formation in the western North Pacific and ENSO. Monthly Weather Review, 122, 636-651. [This paper described the relationship between typhoon activity and ENSO during 32-year period 1960-1992 in detail.]

Pudov, V. D., Varfolomomeev A.A., and Fedorov, K.N. (1979). Vertical structure of the wake of a typhoon in the upper ocean. Okeanologiya, 21, 142-146. [This paper reported the hydrographic survey for project Typhoon ’75.]

Biographical Sketches

Matsuura was born in Numazu in Japan, and received his B.S., M.S., and Ph. D. from Kyushu University. He is presently the project leader of “ A study of Disaster Prediction in Global Hydrological Processes” Program at the National Research Institute for Earth Science and Disaster Prevention (NIED). First he has researched the oceanic themes of coastal engineering and geophysical fluid dynamics at Ibaraki University (1983-1989). He has joined a project of Science and Technology Agency in Japan “Dynamics and Predictability of ENSO System” as a group leader at NIED (1994-1998). His major work is to develop a high-resolution Coupled General Circulation Model of NIED and investigate the relationship between the synoptic weather phenomena and the climate changes using it.

Michiaki Yumoto received his B.Sc. from Shizuoka University and his M.Sc. and D.Sc. from

Kumamoto University. He was a staff at the Earth Science and Technology Organization of Japan (1997-1998). He worked in the National Research Institute for Earth Science and Disaster Prevention (NIED) of Japan, first as a supporting staff (1998-2000), then has been employed as a special researcher (2001). He is investigating the relationship between the activities of tropical cyclone over the western North Pacific and global climate changes, using data from the observations during the 50-year period 1951-2000 and the simulation of a high-resolution Coupled General Circulation Model of the NIED.