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Tropical cyclones, oceanic circulation and climate

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1. Introduction

Tropical cyclone, also popular known as hurricane or typhoon, is a non-frontal synoptic scale warm-core system characterized by a large low-pressure center. It forms over most of the world's tropical waters between about 5° and 22° latitude in an environment with sufficient sea surface temperature (>26.5°C), moisture instability and weak vertical shear, including North Indian, western North Pacific, eastern North Pacific, North Atlantic, South Indian and western South Pacific (Fig.1). Environmental conditions in the eastern South Pacific and South Atlantic are not favorable for the tropical cyclone's genesis. Thus, so far there has only been one documented tropical cyclone in the South Atlantic basin and it was quite weak. Mostly for the purpose of providing useful warnings, tropical cyclones are categorized according to their maximum wind speed. Tropical cyclones, with maximum winds of $17 ms^{-1}$ or less, are known as tropical depressions; when their wind speeds are in the range of 18 to 32 ms^{-1}, inclusive, they are called tropical storms, whereas tropical cyclones with maximum winds of 33 ms^{-1} or greater are called hurricanes in the western North Atlantic and eastern North Pacific regions, typhoons in the western North Pacific, and severe tropical cyclones elsewhere.

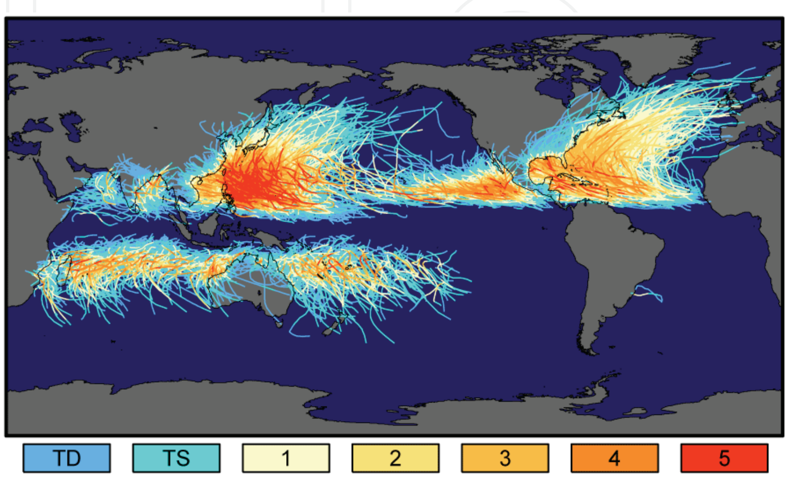

Fig.1. The tracks and intensity of nearly 150 years of tropical cyclones.
(http://earthobservatory.nasa.gov/IOTD/view.php?id=7079)

A tropical cyclone is driven principally by heat transfer from the ocean. Thus, the genesis and development of the tropical cyclones and its variability of number and intensity are influenced by the oceans importantly.
Meanwhile, a tropical cyclone can affect the thermal structure and currents of the upper ocean. Beginning with the observations published by Leipper (1967), a number of studies have been made in order to understand the various aspects of the ocean response to tropical cyclones (e.g. Price, 1981; Black, 1983; Greatbatch, 1983; Ginis, 1995; Jacob et al., 2000) and the tropical cyclone-ocean interaction (Chang & Anthes, 1979; Sutyrin & Khain, 1979; Ginis et al., 1989). It became obvious that the tropical cyclones have a profound effect on the uppermost 200-300*m* of the ocean, deepening the mixed layer by many tens of meters, cooling the surface temperature by as much as 5°C, and causing near-inertial surface currents of 1-2ms^{-1}, detectable at depths up to at least 500*m* (Withee & Johnson, 1976). However, most of the previous studies focused on the local response of the ocean to the passing tropical cyclone. Relatively little is known about the influence of tropical cyclones on the mean climatology. Emanuel (2001) estimated the oceanic heat transport induced by tropical cyclone activity, comparable the observed peak meridional heat transport by the Meridional Overturning Circulation (MOC) as estimated by Macdonald & Wunsch (1996), suggesting that tropical cyclones may play an important role in driving the thermohaline circulation and thereby in regulating climate.
As we known, the world's oceans is an extremely important part of the Earth's climate control system because the world's oceans carry roughly half of the net equator-to-pole heat flux necessary to balance the meridional distribution of net radiative flux at the top of atmosphere (Macdonald & Wunsch, 1996) and thus play a critical role in setting the global temperature distribution. Furthermore, tropical cyclones threaten lives and property because of their high winds, associated storm surge, excessive rain and flooding, and ability to spawn tornadoes. Of all the natural phenomena that affect our planet, tropical cyclone, which account for the majority of natural catastrophic losses in the developed world, is among the most deadly and destructive. It is therefore of critical importance to understand the mutual influence of the tropical cyclones, oceanic circulation and climate.
Our discussion here focuses on the role of tropical cyclones in regulating the general oceanic circulation and climate, section 2, and the effects of the ocean on tropical cyclones, section 3.

2. The role of tropical cyclones in regulating oceanic circulation and climate

2.1 It's role in ENSO

El Niño/Southern Oscillation (ENSO) is a climate pattern that occurs across the tropical Pacific Ocean on average every four years, but over a period which varies from two to seven years. ENSO is composed of an oceanic component, called El Niño (or La Niña, depending on its phase), which is defined as a warming or cooling of at least 0.5°C (0.9°F) averaged over the east-central tropical Pacific Ocean, and an atmospheric component, Southern Oscillation, which is characterized by changes in surface pressure in the tropical Western Pacific. Measurements from satellite, ships, and buoys reveal El Niño to be a complex phenomenon that affects ocean temperatures across virtually the entire tropical Pacific, also affecting weather in other parts of the world. People are gradually interested in El Niño just because it is usually accompanied with abnormality of global circulation (Horel & Wallace, 1981).

It has been recognized that tropical cyclones, strong nonlinear events in the low and mid-latitudes in the weather system, can influence ENSO greatly. Most tropical cyclones form on the side of the subtropical ridge closer to the equator, then move poleward past the ridge axis before recurving into the main belt of the westerlies. It is well known that surface westerlies on the equator are an essential part of the development of El Niño events. Several studies have pointed out that a single tropical cyclone can also generate significant equatorial westerlies (Harrison & Giese, 1991; kindle & Phoebus, 1995). Gao et al. (1988) proposed a triggering mechanism of the near-equatorial cyclones on El Niño. They pointed out that the near-equatorial tropical cyclones developing equatorward of 10°N can intensify equatorial westerlies and produce Kelvin waves, which propagate to the South American Coasts in about 2-3 months, inducing SST to rise there. According to their result, the near-equatorial cyclones play an essential role in El Niño in its beginning, continuous, and developing period.
Sobel & Camargo (2005) argued that western North Pacific tropical cyclones play an active role in ENSO dynamics, by helping a warm event which is already taking place to persist or strengthen. They proposed that tropical cyclones in the western North Pacific can produce equatorial surface westerly anomalies near the dateline, and an associated SST increase in the central and eastern Pacific. These signals are of the right sign to contribute to the enhancement of a developing El Niño event.

2.2 Tropical cyclone-induced mechanical energy input and its variability

According to the new theory of oceanic general circulation, external sources of mechanical energy are required to maintain the quasi-steady oceanic circulation. Wind stress and tidal dissipation are the primary sources of mechanical energy. However, tropical cyclone, a vitally important component of the atmospheric circulation system at low- and mid-latitudes, may be an important mechanical energy source, which have been ignored because in the commonly used low spatial resolution wind stress data, these strong nonlinear events are smoothed out. Nillson (1995) estimated the energy input to the inertial waves induced by tropical cyclones theoretically as 0.026 TW, while Shay & Jacob (2006) estimated as 0.74TW using the averaged downward vertical energy flux of 2ergs cm^{-2} s^{-1} based on the observational data profile during the passage of the hurricane Gilbert.
Based on a hurricane-ocean coupled model (Schade & Emanuel, 1999), the mechanical energy input to the world's oceans induced by tropical cyclones was estimated (Liu et al., 2008). As shown in Fig.1, tropical cyclones vary greatly in their location and strength and its activity is different each year; thus, for the study of their contribution to the general oceanic circulation and climate, the most objective approach is to estimate the annual mean contribution from these storms. Then the energy input to the ocean induced by over 1500 tropical cyclones from 1984 to 2003 was calculated:
(a) One of the major forms of energy transfer from wind to the ocean is through surface waves. The annual energy input to the surface waves induced by tropical cyclones averaged from 1984 to 2003 is 1.62TW.
(b) The wind energy input to the surface currents, including both the geostrophic and ageostrophic components, by tropical cyclones is 0.1TW.
(c) Tropical cyclones are excellent generators of near-inertial motions, which are the most likely contributor to the subsurface turbulence, internal waves, and the subsurface diapycnal mixing, because of their large wind stress that change on the inertial time scale.

The generation of inertial motions by tropical cyclones has been discussed in previous studies (e.g. Price, 1981, 1983). The energy flux due to wind forcing associated with tropical cyclones averaged from 1984 to 2003 is 0.03TW.
(d) Tropical cyclone-induced cooling in the upper ocean is a striking phenomenon, which has been documented in many studies. Within the vicinity of a tropical cyclone, strong winds blowing across the sea surface drive strong ocean currents in the mixed layer. The vertical shear of the horizontal current at the base of mixed layer induces strong turbulence, driving mixing of warm/old water across the mixed layer base (Emanuel, 2005). As a result, sea surface temperature is cooled down. Most importantly, the warming of water below the mixed layer raises the center of mass, and the gravitational potential energy (GPE) of the water column is increased. According to the calculation, the annual mean GPE increase induced by tropical cyclones averaged from 1984 to 2003 is 0.05TW.
The relationship between the increase of GPE and the energy input to the near-inertial currents and the surface currents for each individual tropical cyclone over the past 20 years are demonstrated in Fig. 2a and 2b, respectively. It is clearly seen that the near-inertial energy input alone cannot account for the increase of the GPE when the hurricanes are strong. The ratio of GPE increase to the wind energy input to the near-inertial currents and the total surface currents versus normalized PDI (power dissipation index: $PDI \equiv \int_0^{T_{life}} v_{\max}^3 dt$, , which indicates the strength of the tropical cyclones) are shown in Fig. 2c and 2d, respectively. For weak tropical cyclones the increase of GPE is limited and it may be dominated by the contribution from the near-inertial energy from the wind.

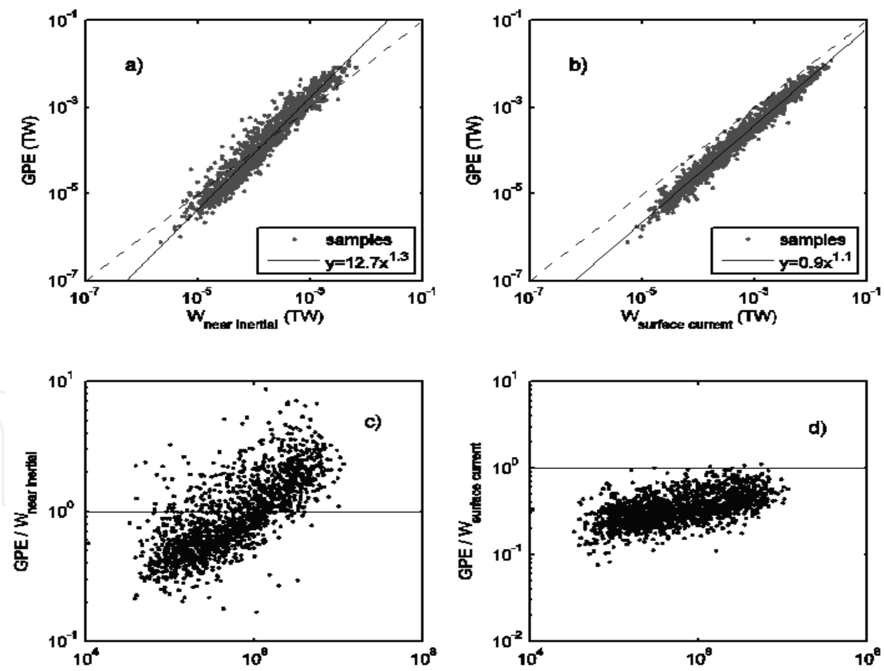

Fig.2. Relationship between the increase of GPE and the energy sources from the hurricanes: (a) GPE vs near-inertial components; (b) GPE vs wind energy input to the surface currents; (c) the ratio of GPE increase to near-inertial energy from the wind vs PDI; and (d) the ratio of GPE increase to energy input from the wind input to the surface currents vs PDI. In the upper panels the solid lines indicate best-fit power laws (Liu et al., 2008).

For hurricanes, however, the near-inertial energy from the wind can only supply a small portion of the energy needed for GPE increase, and the remaining portion of energy should be supplied by subinertial components of the wind energy input to the surface currents. Therefore, when the hurricane is strong, wind energy input to the subinertial motion is not totally dissipated in the mixed layer; instead, it contributes to the increase of GPE. Moreover, the conversion rate of kinetic energy input from the wind to GPE also increases as the strength of the hurricane increases.

The distribution of the energy input to the near-inertial motions from tropical cyclones averaged from 1984 to 2003 is shown in Fig.3. It is readily seen that most of this energy is distributed in the latitudinal band from 10° to 30°N in the western Pacific and in the North Atlantic, with approximately half of the total energy being input into the western North Pacific (The distribution of the other forms of energy generated from tropical cyclones has similar patterns).

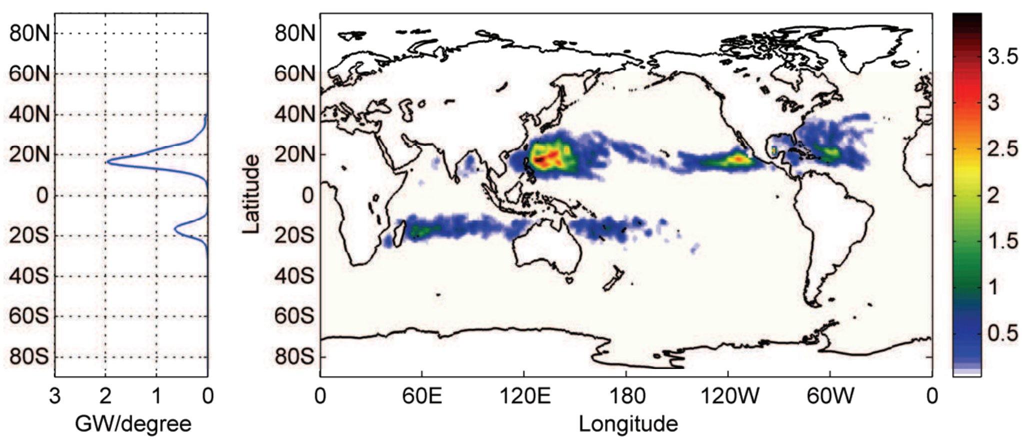

Fig. 3. (right) Energy input to near-inertial motions induced by tropical cyclones averaged from 1984 to 2003 (units: mW m^{-2}); (left) the meridional distribution of the integrated energy. (Liu et al., 2008)

According to the previous studies, the energy input induced by smoothed wind stress to the surface geostrophic currents is estimated as 0.88TW (Wunsch, 1998), the energy input to surface waves is 60TW (Wang & Huang, 2004a) and the energy input to Ekman layer is about 3TW, including 0.5-0.7TW over the near-inertial frequency (Alford, 2003; Watanabe & Hibiya, 2002) and 2.4TW over the subinertial range (Wang & Huang, 2004b). It seems that the energy input by tropical cyclones is much smaller than that from smoothed wind field. However, it may also have a non-ignorable role in the oceanic circulation and climate. Figure 4 shows the distribution of the energy input to surface waves (induced by NCEP-NCAR wind field and tropical cyclones) averaged from 1984 to 2003. The left panel is the meridional distribution of the zonally integrated results, where the blue line is the energy input from the smoothed wind field and the red line is the total energy input. From the meridional distribution, it is readily seen that the energy generated by tropical cyclones greatly enhances the energy input at the midlatitude. In the latitudinal band from 10° to 30°N, tropical cyclones account for 22% increase of the energy, and in the western North Pacific, they account for 57% increase of energy, compared with results calculated from smoothed wind data. Although the total amount of energy input by tropical cyclones is much smaller than that by smoothed wind field, it may be more important for many applications including ecology, fishery, and environmental studies since they occur during a short time period at the midlatitude band where stratification is strong.

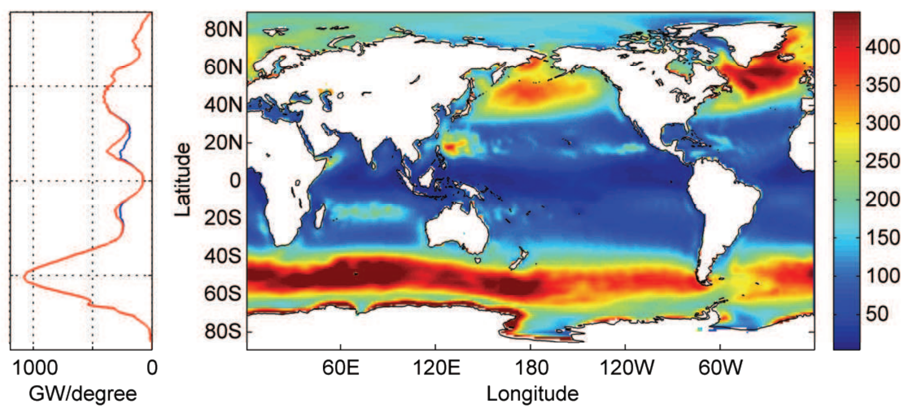

Fig. 4. (right) Distribution of energy input generated from smoothed wind field and tropical cyclones to surface waves averaged from 1984 to 2003 (units: mW m^{-2}) and (left) the meridional distribution of the zonal integrated energy source. The blue line is the energy input generated by smoothed wind stress, and the red line is the total energy input, including contributions due to tropical cyclones. (Liu et al., 2008)

Emanuel (2001) argued that subtropical cyclones are one of the strongest time-varying components in the atmospheric circulation. Accordingly, great changes in energy input to the ocean induced by tropical cyclones are expected. Figure5 shows the decadal variability of the normalized annual mean energy input to the ocean induced by tropical cyclones, the energy input to the ocean based on the NCEP-NCAR wind stress dataset (Huang et al., 2006), the normalized PDI and the normalized number of global tropical cyclones. The energy input from tropical cyclones show strong interannual and decadal variability with an increasing rate of 16% over the past 20 years, which is similar as the variability of the PDI, and the correlation coefficient is 0.92. That is, the energy input induced by tropical cyclones depends upon the strong hurricanes. Moreover, the energy input is also associated with the number of tropical cyclones in each year, and the correlation coefficient is 0.33. In addition, it can be readily seen that the energy input from tropical cyclones varies much more greatly than that from smoothed wind field, which may have an important role in the climate variability.

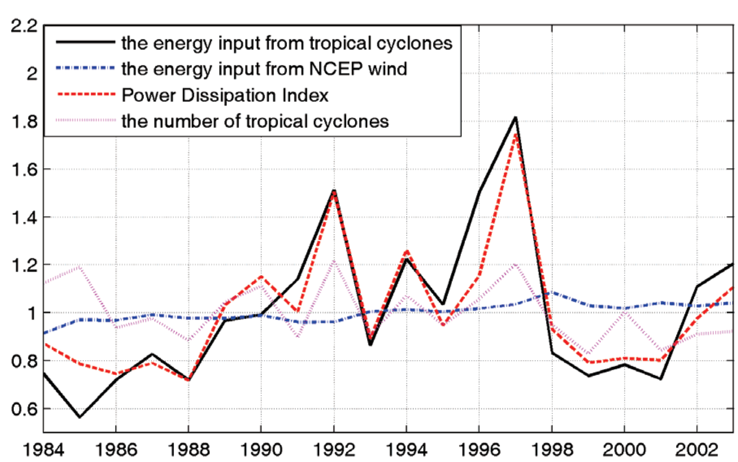

Fig.5. The normalized annual-mean energy input to surface waves from hurricane (black solid line), from the NCEP-NCAR wind stress dataset (blue dash-dot line), the normalized PDI (red dashed line) and the number of tropical cyclones (magenta dotted line).

2.3 The mixed layer deepening induced by tropical cyclones

The strong activity of tropical cyclones can deepen the mixed layer at low- and mid-latitudes. Huang et al. (2007) have shown that the mixed layer deepening at low and middle latitudes can enhance the meridional pressure difference and thus the overturning circulation and poleward heat flux, and at the same time, take less mechanical energy to support to subsurface diapycnal mixing. Then a natural question is, how much do the tropical cyclones contribute to the mixed layer deepening at low and mid-latitudes at the global scale?

Owing to the strong wind associated with tropical cyclones, mixing in the ocean is greatly enhanced, deepening the mixed layer. The mixed layer deepening for an individual tropical cyclone is defined as the difference between the initial mixed layer depth and the maximal mixed layer depth obtained from the model at a given station during the whole process of the passing through of a tropical cyclone. However, there is a possibility that several tropical cyclones passed through the same grid point within one year, each time the mixed layer deepening is denoted as dh_j. If there are N tropical cyclones that passed through this grid in one year, the total mixed layer deepening at this grid is $dH = \sum_{j=1}^{N} dh_j$, and the distribution in the world's oceans is shown in Fig.6. The maximum mixed layer deepening induced by tropical cyclones is on the order of 100m. It is readily seen that the mixed layer deepening induced by tropical cyclones accumulates at low- and mid-latitude, which may be much important for the meridional overturning circulation, and thus the climate.

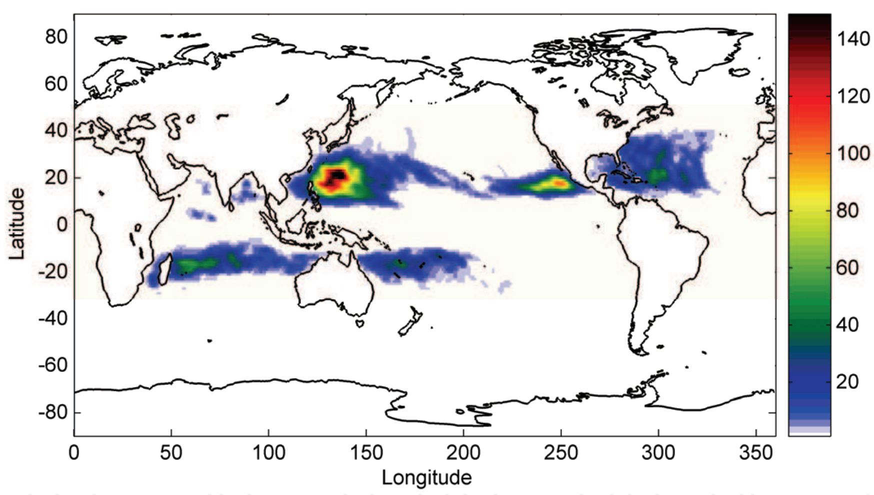

Fig.6. Annual mean (accumulated) mixed layer deepening (*m*) induced by tropical cyclones averaged from 1984 to 2003. (Liu et al., 2008)

In general, with the passing of a tropical cyclone, the mixed layer depth can be increased remarkably. Furthermore, after the passing through of the tropical cyclone, the mixed layer gradually relaxes back to the initial state. Woods (1985) have demonstrated that the mixed layer deepening/shoaling process can play the most important critical roles in watermass formation. The deepening of the mixed layer enables a mass exchange from the pycnocline, leading to obduction, which indicates the irreversible mass flux from the permanent pycnocline to the mixed layer; on the other hand, mixed layer retreating leaves water mass behind, leading a mass flux from the mixed layer, and thus an enhancement of subduction, which indicates the irreversible mass flux from the mixed layer to the permanet pycnocline.

Thus, the mixed layer deepening/shoaling process induced by tropical cyclones may be an important mechanism for the watermass formation/erosion. The total volume flux of mixed layer deepening induced by tropical cyclones is estimated as 39 Sv (1 Sv=10^6 m^3 s^{-1}), with 22.4 Sv in the North Pacific. Qiu and Huang (1995) discussed subduction and obduction in the oceans; they estimated that the basin-integrated subduction rate is 35.2 Sv and obduction rate 7.8 Sv in the North Pacific (10° off the equator). That is, the total rate of mixed layer deepening induced by tropical cyclones is approximately 50% of the subtropical water mass formation rate through subduction and it is much larger than obduction.

However, the volume flux of mixed layer deepening induced by tropical cyclones cannot be simply regarded as the induced subduction/obduction rate enhancement. In the study of water mass movement, the upper ocean can be divided vertically into four layers: the Ekman layer, the mixed layer, the seasonal pycnocline, and the permanent pycnocline. Water parcels entrained into the mixed layer during the passage of tropical cyclones may be originated from the seasonal pycnocline, rather than from the permanent pycnocline; similarly, water parcels released during the mixed layer retreating period may be re-entrained into the mixed layer downstream. On the other hand, the subduction/obduction rate for the stations near the passage of tropical cyclone can also be affected if the subducted/obducted water parcels pass through the typhoon region during the mixed layer deepening period, which can re-entrain the water parcels in the pycnocline to the mixed layer. However, so far how to estimate the subduction/obduction enhancement induced by tropical cyclones remains unclear. Consequently, the mixed layer deepening and shoaling process induced by tropical cyclones must have a major impact on water mass balance in the regional and global oceans, which needs our further study and water mass balance without taking into consideration of the contribution of tropical cyclones may not be acceptable.

2.4. The vertical diffusivity induced by tropical cyclones

Ocean mixing affects global climate because it is linked to the ocean's ability to store and transport heat (Wunsch & Ferrari, 2004). The winds associated with tropical cyclones are known to lead to localized mixing of the upper ocean (Price, 1981; Jacob et al., 2000; D'Asaro, 2003). Furthermore, they are important mixing agents at the global scale. Sriver & Huber (2007) estimated the vertical diffusivity induced by tropical cyclones based on the temperature data. However, the assumption that all mixing in a given year is achieved during the single largest cooling event may underestimate the vertical mixing rate induced by tropical cyclones.

In our study, the vertical diffusivity averaged over the lifetime of a tropical cyclone can be defined by the following scaling: $k = wdh$, where dh is the mixed layer deepening due to cyclone stirring, and $w = dh / T_{life}$ is the equivalent upwelling velocity averaged over the life cycle of tropical cyclone. However, for the study of oceanic general circulation, it is more appropriate to define the contribution due to each tropical cyclone in terms of the annual mean vertical diffusivity

$$k_j = w_j \cdot dh_j = dh_j^2 / T_{year} \tag{1}$$

The annual meaning (accumulated) vertical diffusivity is defined as

$$k = \sum_{j=1}^{N} k_j = \frac{1}{T_{year}} \sum_{j=1}^{N} dh_j^2 \tag{2}$$

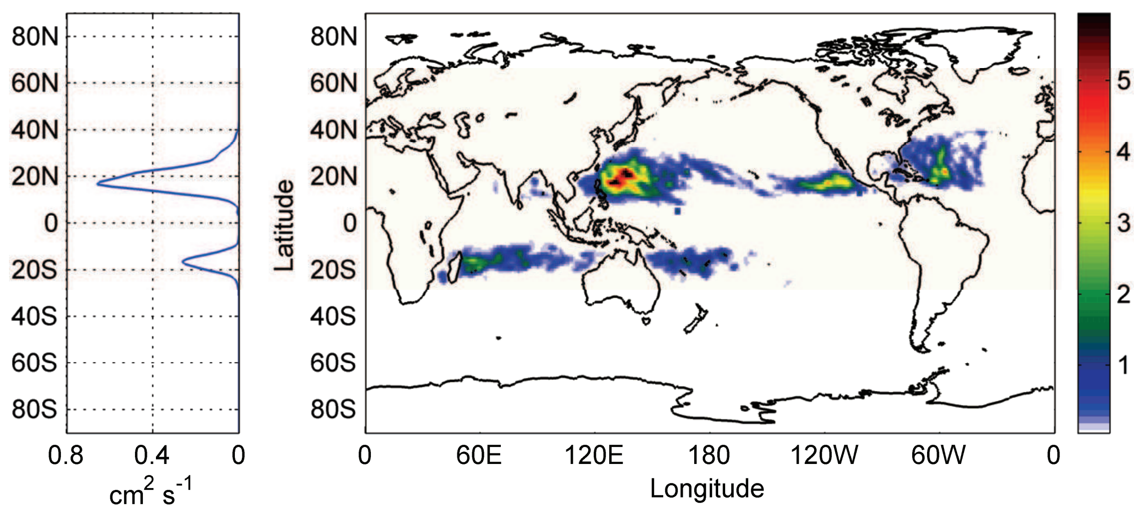

Fig. 7. Annual-mean vertical diffusivity induced by tropical cyclones from 1984 to 2003 (units: 10^{-4} m^2 s^{-1}): (right) the horizontal distribution and (left) the zonally averaged vertical diffusivity. (Liu et al., 2008)

The horizontal distribution of the tropical cyclone-induced vertical diffusivity is shown in Fig. 7. It indicates that vertical diffusivity induced by tropical cyclones is on the order of (1-6)$\times 10^{-4}$m^{2}s^{-1}, which is approximately 10 to 100 times larger than the low environmental diffusivity (0.05-0.1) $\times 10^{-4}$m^{2}s^{-1} observed in the subtropical ocean below the mixed layer. Thus, the winds associated with tropical cyclones generate strong, near-inertial internal waves, making them efficient upper ocean mixers. Although the hurricane-induced mixing takes place in a vertical location in the water column quite different from that of deep mixing induced by tides, they all contribute to the maintenance of the oceanic general circulation and climate. Climate is especially sensitive to mixing variations in the tropical ocean (Bugnion et al., 2006) because this region of strong stratification is the most efficient place for mixing to drive strong heat transport (Scott & Marotzke, 2002; Nof & Gorder, 1999, 2000; McWilliams et al., 1996). The cyclone-induced mixing is a fundamental physical mechanism that may act to stabilize tropical temperature, mix the upper ocean, and cause amplification of climate change (Sriver & Huber, 2007).

3. How the tropical cyclone's behavior is affected by the ocean?

During the past decade or so, many researchers have suggested that because of global warming, the sea surface temperature will likely increase, which will then lead to an increase in both the number and intensity of tropical cyclones (Chan & Liu, 2004). Emanuel (2005) found that the hurricane power dissipation, which indicates the potential destructiveness of hurricanes, is highly correlated with tropical sea surface temperature, reflecting well-documented climate signals. Moreover, the total power of dissipation has increased markedly since the mid-1970s due to both longer storm lifetimes and greater storm intensities. Thus, it was proposed that the future warming may lead to an upward trend in tropical cyclone destructive potential. Sriver and Huber (2006) further proposed that a 0.25°C increase in mean annual tropical sea surface temperature corresponds roughly to a 60% increase in global Power Dissipation of tropical cyclones. Webster et al. (2005) showed that in an environment of increasing sea surface temperature, a large increase was seen in the number and proportion of hurricanes reaching categories 4 and 5 while the number of cyclones and cyclone days has decreased in all basins except the North Atlantic during the past decade. However, in the more recent work published by Emanuel et al. (2008), based on a new technique for deriving hurricane climatologies from global data, he stated that global warming should reduce the global frequency of hurricanes, though their intensity may increase in some locations.

Emanuel (2001) argued that tropical cyclones are one of the strongest time-varying components in the atmospheric circulation. The interannual variations of tropical cyclone activity received much more attention. Among these, most studies focus on the effect of the El Niño/Southern Oscillation (ENSO). ENSO affects tropical cyclones strongly in several basins, though its influence is different in each.

For the western North Pacific, during warm ENSO events, there is the eastward and equatorial shift in genesis location of tropical cyclones and longer lift span (Wang & Chan, 2002). However, due to the differences in data and technique, the results about the influence of ENSO on the frequency of tropical cyclones may be somewhat controversial. Chan (1985, 2000), Wu& Lau (1992), and others reached a common conclusion that the number of tropical storm formation over the western North Pacific is less than normal during El Niño years. However, in more recent work (Chan & Liu, 2004; Camargo & Sobel, 2005), it is shown that the mean annual tropical cyclones in the western North Pacific is higher (lower) during El Niño (La Niña) year.

For the eastern North Pacific, the formation points shifts west, more intense hurricanes are observed, and tropical cyclones track father westerward and maintain a longer lifetime in association with warm ENSO events (Schroeder & Yu, 1995; Irwin & Davis, 1999; Kimberlain, 1999) . Moreover, in the South Pacific, tropical cyclones originated farther east, resulting in more storms in the eastern South Pacific and fewer in the western South Pacific during El Niño years (Revell & Goulber, 1986).

In the North Atlantic, when El Niño is present, there are fewer and/or weaker storms and its genesis father north (Gray et al., 1993; Knaff, 1997).

4. Conclusions

Climate variability and any resulting change in the characteristics of tropical cyclones have become topics of great interest and research. As we discussed above, the climate signals, including ENSO, global warming, can greatly influence the tropical cyclone activity, including its number and intensity. On the other hand, a tropical cyclone can affect the local thermal structure and currents of the upper ocean, which has been discussed much in the previous studies. However, relatively little is known about the influence of tropical cyclone activity on the oceanic circulation and climate. Therefore, in this study we mainly focus on the role of tropical cyclones in regulating the general oceanic circulation and climate.

The tropical cyclones can influence the oceanic circulation in many aspects: 1) Tropical cyclones play an essential role in modulating, even triggering ENSO; 2) Tropical cyclones are an important mechanical energy sources required to maintain the quasi-steady oceanic

circulation. 3) Mixed layer deepening induced by tropical cyclones at low and midlatitudes can enhance the meridional pressure difference and thus the overturning circulation and poleward heat flux. Moreover, the mixed layer deepening/shoaling processes induced by tropical cyclones can also affect the water mass formation/erosion, which need the further study. 4) Tropical cyclones can lead to strong localized mixing which affects global climate.
Nevertheless, these studies are only the first step toward unraveling the complicated roles of tropical cyclones in the oceanic circulation and climate system. Many important questions remain unclear at the present time. For example, tropical cyclones are active only for a small fraction of the annual cycle. How do the energy input and the increase of vertical diffusivity induced by tropical cyclones over a small fraction of time in a year affect the general oceanic circulation? How do the mixed layer deepening/shoaling processes induced by tropical cyclones affect the formation/erosion, and then the subduction/obduction? To answer these questions further study is clearly needed.

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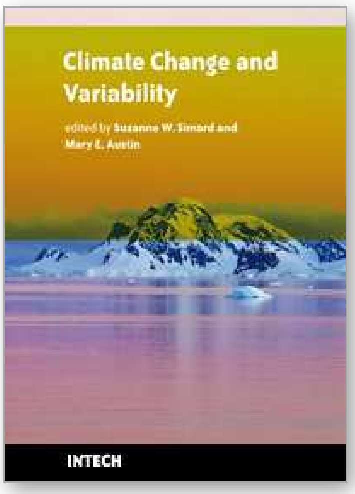

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Climate change is emerging as one of the most important issues of our time, with the potential to cause profound cascading effects on ecosystems and society. However, these effects are poorly understood and our projections for climate change trends and effects have thus far proven to be inaccurate. In this collection of 24 chapters, we present a cross-section of some of the most challenging issues related to oceans, lakes, forests, and agricultural systems under a changing climate. The authors present evidence for changes and variability in climatic and atmospheric conditions, investigate some the impacts that climate change is having on the Earth's ecological and social systems, and provide novel ideas, advances and applications for mitigation and adaptation of our socio-ecological systems to climate change. Difficult questions are asked. What have been some of the impacts of climate change on our natural and managed ecosystems? How do we manage for resilient socio-ecological systems? How do we predict the future? What are relevant climatic change and management scenarios? How can we shape management regimes to increase our adaptive capacity to climate change? These themes are visited across broad spatial and temporal scales, touch on important and relevant ecological patterns and processes, and represent broad geographic regions, from the tropics, to temperate and boreal regions, to the Arctic.