Assessing Impacts of Global Warming on Tropical Cyclone Tracks

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Summary

The impacts of human activities on the global climate have been of great concern since last century. Scientific researches have indicated that global warming associated with the global climate change can affect tropical cyclone activities. A new approach is proposed to assess the possible impacts of the global climate change on tropical cyclone tracks in the western North Pacific. In this approach, the climatological tropical cyclone motion consists of two parts: large-scale steering and the vector resulted from the interaction between tropical cyclones and their environment. The latter is assumed unchanged in the future climate state. The output of the Geophysical Fluid Dynamics Laboratory (GFDL) climate model is used to estimate the large-scale steering in the future climate state. By 2059, given that the formation locations remain the same as in the current climate state, the tropical cyclone activities in the western Northern Pacific will decrease, but favor a northward shift of tropical cyclone tracks. The storm activities in the South China Sea will decrease by 12%, while the Japan region will experience an increase by 12-15%.

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Submitted to *J. Climate.*

Dec. 2002

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ABSTRACT

A new approach is proposed to assess the possible impacts of the global climate change on tropical cyclone (TC) tracks in the western North Pacific (WNP) basin. The idea is based on the premise that the future change of TC track characteristics is primarily determined by changes in large-scale environmental steering flows.

It is demonstrated that the main characteristics of the current climatology of TC tracks can be derived from the climatological mean velocity field of TC motion by using a trajectory model. The climatological mean velocity of TC motion, which is composed of the large-scale steering and beta drift, is determined on each grid of the basin. The mean beta drift is estimated from the best track data, and the mean large-scale steering flow is computed from the NCEP/NCAR reanalysis for the current climate state. The derived mean beta drift agrees well with the results of previous observational and numerical studies in terms of its direction and magnitude.

The outputs of experiments A2 and B2 of the Geophysical Fluid Dynamics Laboratory (GFDL) R30 climate model suggest that the subtropical high will be persistently weak over the western part of the WNP or shift eastward during July-September in response to the future climate change. By assuming that the mean beta drift in the future climate state is unchanged, the change in the general circulation by 2059 will decrease the TC activities in the WNP, but favor a northward shift of typical TC tracks. As a result, the storm activities in the South China Sea will decrease by about 12%, while the Japan region will experience an increase of TCs by 12-15%. During the period of 2000-2029, the tropical storms that affect the China region will increase by 5-6%, but return to the current level during 2030-2059. It is also suggested that, during the period of 2030-2059 tropical storms will more frequently affect Japan and the middle latitude region of China given that the formation locations remain the same as in the current climate state.

1 Introduction

The impacts of human activities on the global climate have been of great concern since last century. Scientific researches have indicated that human activities are changing atmospheric composition in ways that are very likely to cause significant global warming. The United Nation's Intergovernmental Panel on Climate Change (IPCC) has speculated that climate change due to increasing amounts of anthropogenic greenhouse gases may affect tropical sea surface temperature (Houghton et al. 1996), and thus tropical cyclone (TC) intensity (Knutson and Tuleya 1999; Walsh and Ryan 2000).

By now we know little about the possible impacts of the climate change on TC tracks. Assessment of the global warming impacts on TC activity remains in embryo. Manabe et al. (1970) noticed for the first time that atmospheric general circulation models (AGCMs) are able to simulate model tropical storms that have a climatology and physical characteristics similar to those of real tropical storms. Studies have been conducted to investigate the variability of TC formation on various time scales in AGCMs (e.g., Broccoli and Manabe 1990; Wu and Lau 1992; Haarsma et al. 1993; Bengtsson et al. 1996; Vitart and Anderson 2001). According to Henderson-Sellers et al. (1998), however, current AGCMs cannot adequately simulate TCs to the degree that one can possibly say whether the frequency, area of occurrence, time of occurrence, mean intensity or maximum intensity of TCs would change in the global warming scenario. Considering that the large-scale atmospheric circulation simulated in GCMs may be more reliable than the model-simulated so-called TCs, Warrerson et al. (1995) calculated the indices for TC formation developed by Gray (1975) in an AGCM in an attempt to indirectly estimate TC formation numbers So far, little attention has been paid to the possible future changes in TC tracks.

The prevailing TC track is intimately linked to the mean large scale circulation patterns. Recently, Wang and Chan (2002) examined how El Nino/La Nina affect the TC activity over the western North Pacific. They found that during October of El Nino years tropical storms tend to recurve northward to extratropics, whereas during the October of La Nina years tropical storms more frequently take a westward (Fig. 1). In addition, the formation locations shifted eastward dramatically from El Nino to La Nina years. The changes in the large scale steering flows induced by El Nino forcing are evident (Fig. 2). The increased number of the northward turning tropical storms near Japan during El Nino years is consistent with the increased northward steering flows (the vertically averaged between 850 hPa and 300 hPa) (Fig. 2b). The decrease in the number of westward moving tropical storms from the Philippine Sea to the southeast Chinese coast during El Nino years is also in good agreement with the decrease of the easterly steering currents in the region (Fig. 2b). It is inferred that during a global warming background the large scale flow pattern changes may effectively change the tropical storm track and their impacts to human life.

Recent progresses in TC motion research have made it more meaningful to assess the future changes of TC tracks based on projected future changes in the general circulation. It is now generally recognized that two fundamental mechanisms operating in TC motion are (a) advection of the relative vorticity or potential vorticity associated with the TC by large-scale environmental flows (large-scale steering) and (b) propagation or beta drift that involves the nonlinear interactions among the environmental flow, the planetary vorticity gradient, and the vortex circulation (Wang et al. 1998). Numerical and observational studies suggest that the propagation component can be 2-4 m/s and it becomes important in causing a systematic deviation when the steering currents are weak (Wang and Li 1992; Wang and Holland 1996; Carr and Elsberry 1990; Franklin et al. 1996).

The insights gained from the TC motion research provide a basis for evaluation of the global warming impacts on TC tracks. In order to relate the climatology of TC tracks to the global climate change, we propose to define a climatological mean velocity of TC motion in a fixed reference frame relative to the earth. It is hypothesized that the mean velocity defined on specified grids can be used to derive the primary features of the climatological mean TC tracks. The mean velocity is also the sum of the climatological mean large-scale steering flow and beta drift. It is conceivable that the climatology of TC tracks may respond to the global climate change due to the resultant changes in large-scale steering flows.

Compared with the climate change, TCs are short-lived and transint phenomena. For a specific TC, it is extremely difficult to separate the environmental steering from the TC circulation. Many earlier efforts were mainly concentrated on searching for the steering flow from various observations. On the time scale of climate change, however, this problem is no more a roadblock because the transient tropical cyclones have been substantially removed from the climatological mean environmental flows. Recently, Wu and Wang (2001) have verified that there exits a steering level for a specific TC in the diabatic numerical experiments. Although such a steering level varies case by case, they showed that the steering level is located in the lower and midddle troposphere. As suggested by Holland (1993), the pressure-weighted mean flow from 850 to 300 mb will be taken as the steering flow.

In this study, an approach for assessing the impacts of climate change on TC tracks is proposed. Using this approach, the future changes of TC track is evaluated with the output of the Geophysical Fluid Dynamics Laboratory (GFDL) Rhomboidal 30 truncation (R30) coupled climate model (Delworth et al. 2002). Our focus is placed on the western North Pacific (WNP). The WNP basin experiences on average 26 tropical storms each year, accounting for about 33% of the global total. In East Asia, vulnerability becomes more and more pronounced due to recent fast population growth and economic development in the coastal region. Any possible climatological shift of TC tracks is of great importance to both the governments and the public. In particular, two questions will be addressed: 1) Will the typical cyclone tracks shift due to the climate change? 2) How will the primary pattern of the WNP TC track in response to the global climate change?

The paper is therefore organized as follows. Section 2 defines three parameters that measure the climatological characteristics of TC tracks. Section 3 shows how climatological characteristics of TC tracks can be derived from climatological mean velocity by using a trajectory model. In section 4 the climatology mean beta drift is retrieved and compared with results from the previous studies. Section 5 discusses to what extent the global climate change can modify the TC tracks. Concluding remarks are presented in section 6.

2 Climatology of TC motion in the western North Pacific

The climatological TC motion can be measured by the following three parameters: 1) frequency of TC occurrence in a specific location; 2) frequency of TC occurrence in a specified region; and 3) climatological mean velocity of TC motion.

The first is defined on each grid box to indicate the spatial distribution of TC activities. It is counted at a 6 hour interval and measures how frequently a specific grid box is affected by storms. The grid box is 2.5^o latitude by 2.5^o longitude in this study. Figures 3a and 4 show, respectively, the frequency of occurrence and the formation frequency in each grid box during July-September calculated using the Joint Typhoon Warning Center (JTWC) best track data from 1965 to 2000 . The starting year was chosen to be 1965 when satellite monitoring of weather events first became routine so that no TC would be missed. During the peak season from July to September, there are two maximum centers for TC occurrence, which are located to the east of Taiwan and the South China Sea, respectively. Although a maximum of the formation frequency (Fig. 4) coincides with the center in the South China Sea, the formation frequency only accounts for a very small fraction of the total frequency of TC occurrence. In other words, the first parameter is primarily a reflection of TC motion.

The second parameter measures how many TCs hit a specific region of interest. In general, a TC that forms over the WNP takes one of the three typical tracks: westward, northwestward, and northeastward recurving. Accordingly, it would affect the following regions: the South China Sea region (including Philippines), the coastal region of China (including the Taiwan island), and the Japan region (Fig.5). What we want to know is whether the typical tracks change in response to the global climate change. The percentage is calculated based on the total storms of the three categories. During the period of July-September, based on the best track data from 1965 to 2000, 14.1%, 37.9% and 47.9% of the storms affect those three regions, respectively (Table 1). It should be pointed out that a storm may be counted twice if it entered the South China Sea and then moved northward to enter the east coastal region of China.

The third parameter is also defined on each grid box. As done by Carr and Elsberry (1990), the TC motion is transferred into a fixed reference frame relative to the earth. The mean velocity of TC motion is calculated at each grid point based on all the storms that passed across a grid point. In the present study, a grid point represents a box of 2.5^o latitude by 2.5^o longitude. Figure 6 shows the mean TC translation vectors. Note that the mean translation vector is consistent with the seasonal mean steering flows. During the peak season (July-September), TCs occur frequently and the large scale flows are relatively steady. In this case, the climatological mean flows can be taken as the climatological steering flows. In other months, the climatological mean flows may not be a good indicator for the mean large-scale steering flows because TCs may not occur frequently enough to render a statistically reliable mean motion vector, or because the the large-scale flows are unsteady. Choice of the period of July-September is based on such consideration.

3 The trajectory model

In this section, we demonstrate the climatological features of the TC tracks can be deduced from climatological mean motion vectors by using a trajectory model. In this model, a TC is treated as a point vortex, and moves with the climatological mean translation velocity within a specified grid box. In other words all the storms located within the same grid box move at the same speed. To construct the climatology of TC tracks from the the climatological mean translation velocity, all the tropical storms that formed during the peak season of 1965-2000 are considered. The initial position of a storm is its location when it first achieved its tropical storm intensity. The trajectory calculations end when the storms move out of the domain of interest. For the grids on which the climatological motion vectors are not available, the velocity is taken as the sum of the mean steering flow and the mean beta drift that was computed by averaging the beta drift over all the grids on which the climatological motion vectors are available. With the simulated TC tractories, the frequency of TC occurrence can be derived as discussed in section 2. Figure 3b shows the simulated frequency of TC occurrence. It is nearly identical to Fig. 3a. The magnitude near the major center is slightly overestimated. It should be noted that the calculated trajectories are meaningful within the domain encircled by the contour of 40 since we assume that a reasonable estimate of the climatological motion vectors may not be available beyond the domain.

With the simulated trajectories, the numbers of TCs that affect the three regions mentioned above can be deduced. During the peak season, based on the simulated trajectories, 14.6%, 37.9% and 47.3% of the storms, affect the South China Sea, the coastal region of China, and the Japan region, respectively (Table 1). The differences between the simulated trajectories and the best tracks are within 1% of the error bars. It is shown that the first two parameters that indicate the climatological characteristics of TC tracks in the WNP can be well retrieved from the climatological mean velocity, and that the trajectory model provides a way to assess the response of TC tracks to the global climate change if the climatological motion velocities can be derived from climate models.

4 Retrieval of climatological beta drift

The propagation component of TCs has been extensively studied with barotropic and baroclinic numerical models. Due to the beta effect, even in a resting environment a TC would move northwestward in the northern Hemisphere (Adem 1956; Holland 1983). In a three-layer model, Shapiro (1992) found that the beta drift is about 2.4 m/s toward the north-northwest. Recently numerical studies (Wang and Holland 1996; Wu and Wang 2001) confirmed this finding. Although the influence of environmental flows varied in different models, especially for the vertical shears of the environmental flow, it is generally believed that beta drift can be affected by the large-scale environmental flow (Williams and Chan 1994; Wang and Li 1995; Li and Wang 1996; Shapiro 1992; Flatau et al. 1994; Wang and Holland 1996; Wu and Wang 2001).

Despite uncertainties involved in defining a large-scale steering flow, a persistent difference between the steering flow and the TC motion is found to be northwestward in the northern Hemisphere (Gorge and Gray 1976). Carr and Elsberry (1990) converted the composite rawinsonde studies to a north-oriented, earth-relative coordinate system and displayed the difference vectors between cyclone motion and the layer-mean (850 - 300 hPa) steering flow averaged over 5-7^o latitude band of the TC center. In agreement with the numerical studies, they found that the propagation is generally westward and poleward in each hemisphere with magnitudes ranging from 1-3 m/s. Franklin (1990) analyzed the case of hurricane Josephine and found that the difference ranges from 1.8 -3.7 m/s with the directions from 289-317°. Franklin et al. (1996) used Omega Dropwindsonde datasets for 10 Atlantic TCs and showed that the propagation vector has the mean orientation of 321° and mean magnitude of 3.2 m/s.

Following Holland (1993), a single large-scale steering flow is defined in this study as the pressure-weighted mean flow from 850 to 300 hPa (see also Carr and Elsberry ,1990). The climatological wind data from the NCEP/NCAR Re-analysis are based on 13-year average monthly fields from 1982 to 1994 with a uniform latitude-longitude 2.5° resolution. As mentioned above, the climatological mean propagation component can be obtained by removing the climatological mean steering flow from the climatological mean translation vectors shown in Fig. 6. As shown in Fig.7, the resulted mean beta drift is generally westward and northward, which is consistent with the previous observational studies (Carr and Elsberry 1990; Franklin et al. 1996) and numerical studies (Wang and Li 1992; Wang and Holland 1996). There are several vectors near the center of the subtropical high are eastward. This may be because the climatological steering flow is not well represented by the climatological mean flow. As we know, TCs usually cannot move into the center of the subtropical high. The mean orientation of the beta drift is 303° with a mean magnitude of 3.0 m/s. This compares well with the 321^o direction of the beta drift with a mean magnitude of 3.2 m/s found in Omega Dropwindsonde Datasets (Franklin et al. 1996). It is larger than the magnitude of 1-2.5 m/s from composite analysis (Carr and Elsberry 1990).

Chan and Williams (1987) and Wang and Li (1992) suggested that the beta drift was proportional to beta. The mean propagation components are averaged by latitudes to examine the latitudinal dependence. In the presence of environmental flow, the observed results differ from the numerical model studies; the northward component increases with latitudes (Fig.8). This agrees with Carr and Elsberry's finding that the beta drift direction rotates from northwestward to north-northwestward with latitudes. We find that the increase accompanies by the increase of the vertical shear of the zonal environmental flow. According to Wu and Emanuel (1993), Flatau et al. (1994), and Jones (1995), the vertical shear can significantly tilt a TC and then enhance the northward propagation. Wang and Holland (1996) suggest that the enhanced northward drift arises from the penetration flow of the upper-level anticyclone associated with TCs. Wu and Wang (2001) suggested that the resulting asymmetric circulation is responsible for the enhanced northward drift. Therefore the latitude-dependence may reflect the influence of the vertical shear of environmental flows. Furthermore, the meridional shear of the environmental flow, in particular the shear strain rate can significantly change the beta drift (Wang and Li 1995, Li and Wang 1996; Wang et al. 1997).

In this section, the climatological mean beta drift has been derived from the best track data. The derived beta drift agrees well with the previous numerical and observational studies in terms of its magnitude and direction. In addition, the influence of the vertical environmental shears on beta drift is also shown, which has been confirmed through various numerical model studies. These results suggest that the selected large-scale steering flow is reasonable.

5 Possible impacts of climate change

In section 3, it was demonstrated that the main climatological characteristics of TC tracks can be deduced from the climatological mean motion vectors. In order to obtain the future climatological features of TC tracks, the new climatological mean motion vectors in the projected future climate state must be constructed. As discussed in the previous section, the calculation of the large-scale steering flow is straightforward, while the construction of the future mean beta drift remains a challenge. Up to now it has been found that the beta drift can be affected by the strength of TCs, the vertical and horizontal shears of the environmental flows, and the relative vorticity gradient of the environmental flow. To simplify the analysis, it is assumed that the global climate change would only significantly modify the large-scale environmental flow on the zeroth order. The changes on the first order (horizontal and vertical shears) and on the second order (relative vorticity gradients) are neglected.

Numerical experiments A2 and B2

In order to assess the possible impacts of global change on TC tracks in the WNP, the outputs of the GFDL R30 climate model with IPCC scenario forcing A2 and B2 are obtained from the Internet at nomads.gfdl.noaa.gov. In the IPCC A2 scenario family, alternative energy technologies develop relatively slowly and fossil fuels maintain their dominant roles in the energy supply. Global CO_2 emission can increase by more than fourfold over their 1990 level by 2100. On the other hand, in the IPCC B2 world, dynamics of technological change continue along historical trends. With the continued growth of population and of income per capita, a steady increase of CO_2 emissions increase about twice the 1990 level by 2100.

The details of the R30 climate model have been reviewed by Delworth et al. (2002). The atmospheric component of the coupled model uses a spectral technique with Rhomboidal 30 truncation, which corresponds to a transform grid with a resolution of approximately 3.75^o longitude by 2.25^o latitude. The ocean component has a resolution of approximately 1.875^o longitude by 2.25^o latitude. Relatively simple formulations of river routing, sea ice, and land surface processes are included.

The A2 experiment experiences transient greenhouse gas levels based upon the IPCC A2 scenario. Similarly, the transient forcing derived from the IPCC B2 scenario were used in the B2 experiment. Because each of the various greenhouse gases (CO_2, CH_4, N_2O, halocarbons, etc.) are not carried separately in this version of the model, the greenhouse gas changes are applied as equivalent CO_2 increases. Aerosols are not prognostic variables in the model, so the direct effects of tropospheric sulfate aerosols are included as temporally and spatially varying changes in surface albedos consistent with the A2 or B2 forcing scenarios.

Possible impacts by 2059

The possible impacts of the global climate change on TC tracks were assessed for the following two periods: 2000-2029 and 2030-2060. The large-scale mean steering flows for experiments A2 and B2 were calculated the way discussed in the previous section. The climatological mean velocity of TC motion was constructed as the sum of the new climatological mean large-scale steering flow in the future climate and the climatological mean beta drift in the current climate.

Figures 9a and 9b show the deviations of the mean motion vectors or deviations of the large-scale steering flow during 2000-2029 from the current climate state in experiments A2 and B2, respectively. The anomaly patterns are similar in both experiments with the anomaly cyclonic circulation over the Taiwan island. During the peak season, the ridge line of the high (125-140°E) is usually located between 25°N and 30°N (Ding 1994). The anomaly cyclonic circulation suggests that the western part of the subtropical high is weak or shifts eastward in response to the global climate change. Since the subtropical high plays an important role in the TC tracks over the WNP basin, the resulting change will lead to corresponding changes in the climatological mean TC tracks.

In order to demonstrate the implications of the deviations of large-scale steering flows, the trajectories of TCs are calculated based upon the frequency and position of TCs formed during 1965-2000. As shown in Figs. 10a and 10b, the general patterns are very similar with two primary centers of TC activities located roughly in the same location as in Figs. 3a and 3b. No significant change in the TC activity centers occurs in both the experiments. In the South China Sea, the eastward anomalies of the large-scale steering flows suggest that the TCs tend to slow down and the TCs that form over the WNP have less chance to enter the South China Sea. In this case, the frequency increase due to the reduced westward movement is canceled by the decrease in the TCs that enter the South China Sea. As a result, there is no significant change in the frequency of TC occurrence in the South China Sea. The northeastward anomalies extending from the South China Sea to the region to the south of Japan, imply that TCs would have more chance to recurve and move northeastward in agreement with the increased frequency in the eastern part of the domain (Figs. 3 and 10).

The number of TCs that affect the western part of the basin will change in response to the chane in steering flows. In both experiments, as shown in table 1, the TC activities in the South China Sea decrease by about 10%, while the storms that affect the China region increase by about 5.3% and 6.2% in A2 and B2, respectively.

The storms that affect the Japan region also increase by 4 - 5%. The typical storm tracks shift to the middle latitudes due to northward anomalies in the steering flow.

During 2030-2059, the anomalies of the steering flows are very similar in experiments A2 and B2 (Figs.11a and 11b). The systematic northeastward deviations south of 25°N from the current climate state suggest that the TCs have more chance to recurve and affect the middle latitudes than those during 2000-2029. As a result, compared with Fig.3, Figs. 12a and 12b indicate that the frequency of TC occurrence over the western part of the WNP basin significantly decreases. In addition, as shown in Fig. 11, the northwestward anomalies in the steering flows over the East Sea and the region to the south of Japan suggest more TCs that can affects Japan and the middle latitude region of China. As shown in Table 1, the storms that affect the Japan region increase by about 13% compared with the the current climate state. Since more storms recurve to the Japan region, the storms that affect the China region decrease to the level of the current climate state. As a result, the TC activities will be significantly reduced in the South China Sea.

In summary, the TC activities during the period of 2000-2059 tend to decrease in the western part of the WNP basin, accompanying with a northward shift of the typical storm tracks. The TC activities increase by 12-15% in the Japan region, while decrease by about 12% in the South China Sea. In general the track shift results from the decrease of westward storms and the increase of storm that recurve to the middle latitudes. Mainland China region will first experience an increase during 2000-2029, and return back to the current level during 2030-2059. By year 2059, however, tropical storms may strike this region with higher latitudes than those in the current climate state.

6 Summary

An attempt is made to assess the possible impacts of the global climate change on TC tracks in the WNP. A climatological mean vector of TC motion on each grid point is first determined, based on all storms that passed across the grid point. The primary climatological features, such as the frequency of TC occurrence in a specific location and the frequency of TCs that enter a specified landfalling region or extratropics, can be derived from the climatological mean motion vector field. In order to assess the impacts of climate change on TC tracks, the mean motion vector in the future climate state is computed as to the sum of the future climatological mean large-scale steering flow and the mean beta drift. The mean beta drift was determined from current climatology and assumed unchanged. In other words, the influence of the global climate change on TC tracks are investigated by examining how the climate change alters the climatological mean steering flow.

The climatological mean beta drift was estimated from the best track data. The resulting beta drift is in good agreement with the previous numerical and observational studies in terms of the magnitudes and directions. It is also found that the vertical shears can have significant influence on the beta drift. The results agree with numerical studies (e.g., Wu and Emanuel 1993; Jones 1995).

Based upon the outputs of experiments A2 and B2 of the GFDL R30 climate model, it is found that the subtropical high in the WNP will weaken or shift eastward in response to the climate change. It is interesting that this change is nearly the same in experiments A2 and B2 although the CO_2 emission scenarios are different. Due to such a change, The TC activities in the South China Sea region will decrease by about 12% by year 2059, while the Japan region experiences a 12-15% increase. During the first period of 2000-2029, the tropical storms that affects the China region increase by 5-6%, but return to the current level during 2030-2059. It is suggested that during the period of 2030-2059 tropical storms that affect China and Japan tend to take more northward tracks.

It should be pointed out that the results should be interpreted in combination with the following assumptions made in this study. First, since the results are derived from the output of the GFDL climate model, the results are strongly affected by the accuracy of the model prediction. Second, the spatial distribution and frequency of TC formation are assumed to be the same as in the current climate state. Although Hendeson-Sellers et al.(1998) suggested that the broad geographic regions of cyclogenesis are not expected to change significantly, this has not been rigorously validated. Our experiments show that the results are not sensitive to slight shifts of the formation location (less than 2.5^o). However, climate change might change the distribution of the TC formation. Further study of the impacts in this regard is needed. Third, the response of the mean beta drift on the global climate change is not considered. As mentioned in section 4, the mean beta drift could be affected by the large-scale environmental flow through the vertical and horizontal shears, shear strains and vorticity gradients. Future study will include the outputs of different climate models and evaluate the model capabilities to simulate the large-scale circulation.

Acknowledgments. We are grateful for the permission to use the GFDL R30 model output. We'd like to thank Dr. A. Dai of NCAR and Prof. Jiaxi Song of National Marine environmental Research and Forecast Center of China for valuable suggestions during the initial stage of this work. Bin Wang acknoledges the support by Office of Naval Research under award No. N00014-021-0532. Thgis is the school of Earth and Ocean Science and Technology publication number XXXX and International Pacific Research Cenetr publication number YYY. The International Pacific Research Center is sponsored in part by Frontier Research System for Global Change.

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Table 1: Mean percentage of the TCs affecting the three regions (see text for experiment designs)

	South China Sea	China	Japan
Obs.	14.1	37.9	47.9
Sim.	14.6	37.9	47.3
A2 (30yr)	4.7	43.2	52.1
B2 (30yr)	4.6	44.1	51.3
A2 (60yr)	1.1	36.8	62.1
B2 (60yr)	2.1	37.9	60.0

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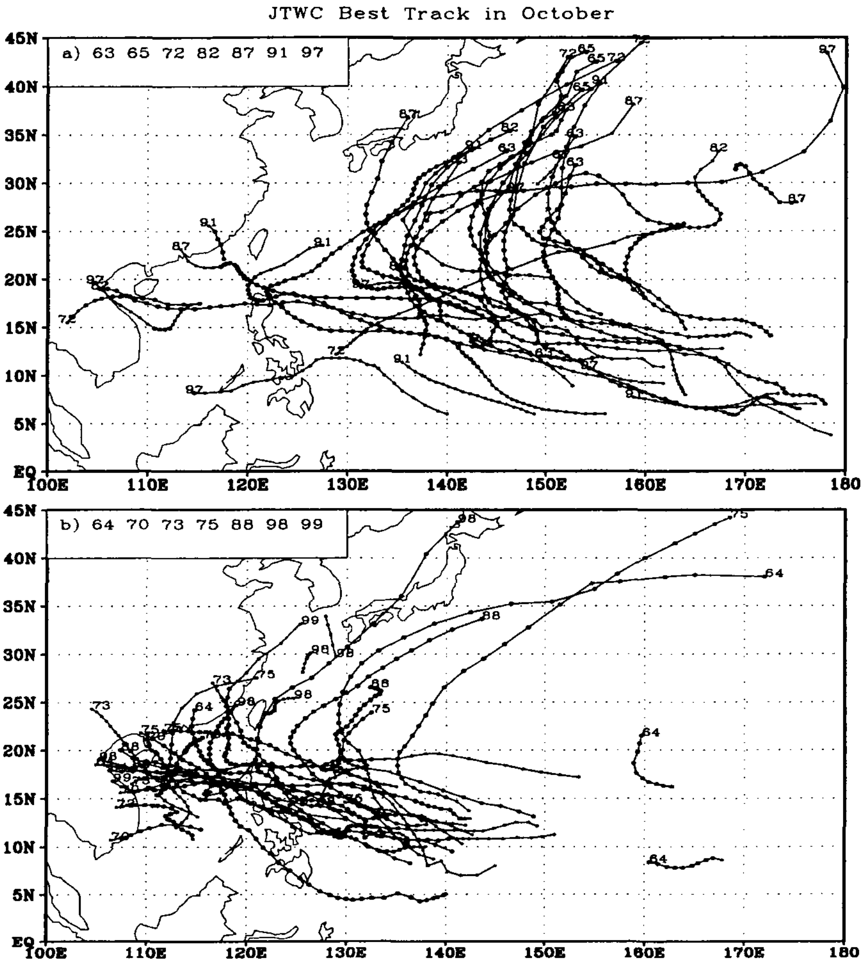


Figure 1: TC tracks (a) in the October of El Nino years (63, 65 , 72, 82, 87, 91,97) and (b) in the October of La Nina years (64, 70, 73, 75, 88, 98, 99).

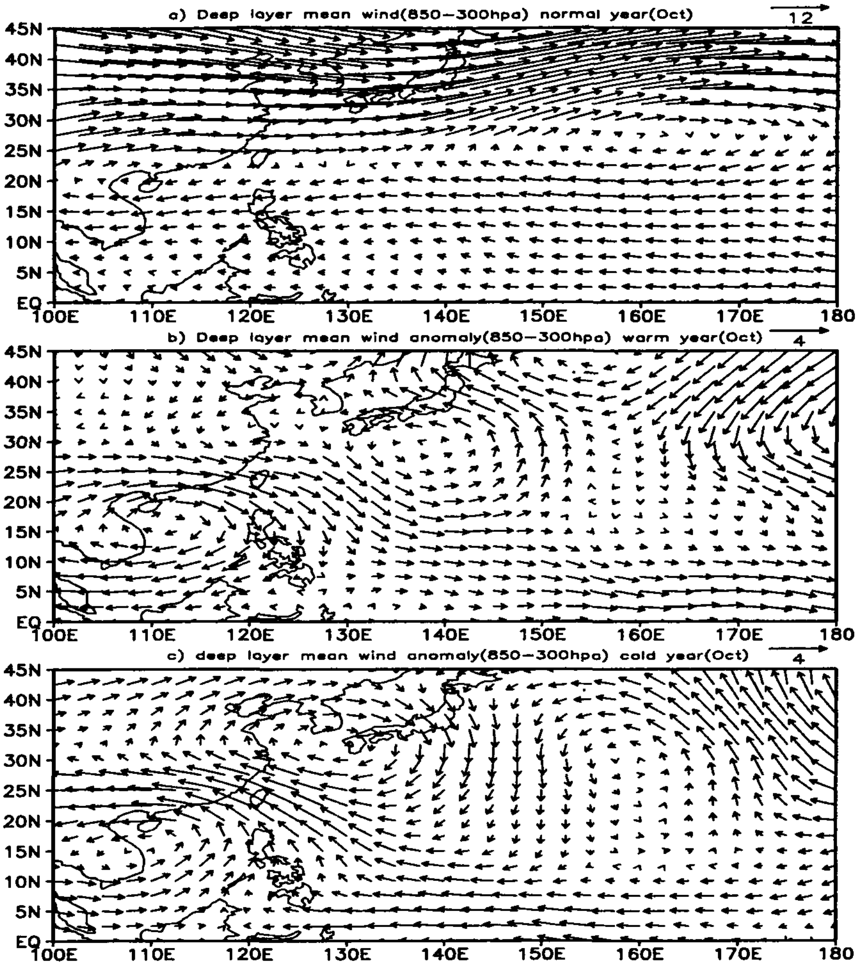
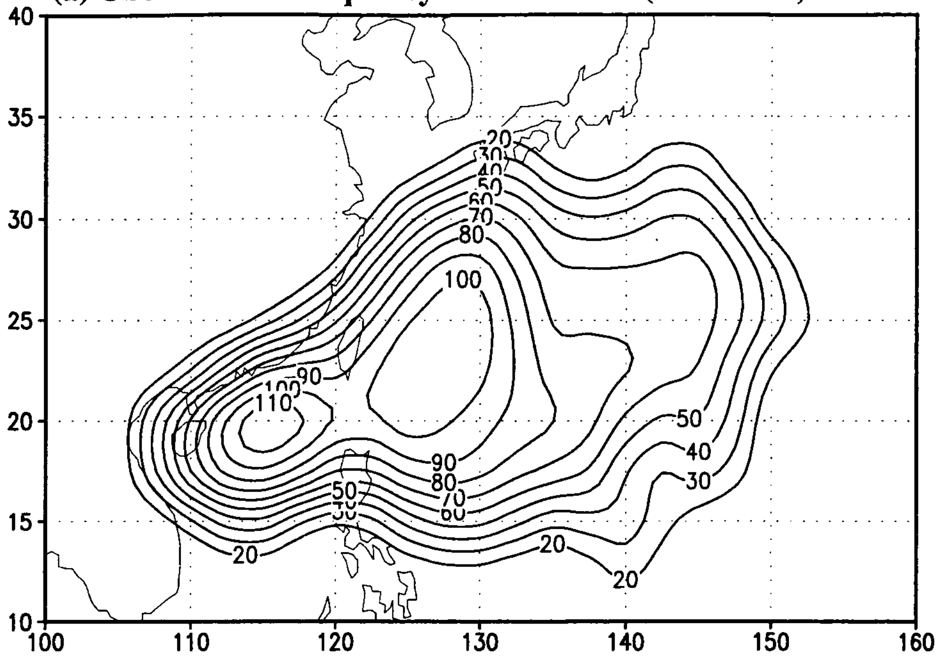


Figure 2: (a) Climatological layer mean (850-300 mb) flows in the October, (b) layer wind anomalies in the October of El Nino years (63, 65, 72, 82, 87, 91,97), and (c) in the October of La Nina years (64, 70, 73, 75, 88, 98, 99).

(a) Observed TC frequency of occurrence (1965-2000)



(b) Simulated TC frequency of occurrence

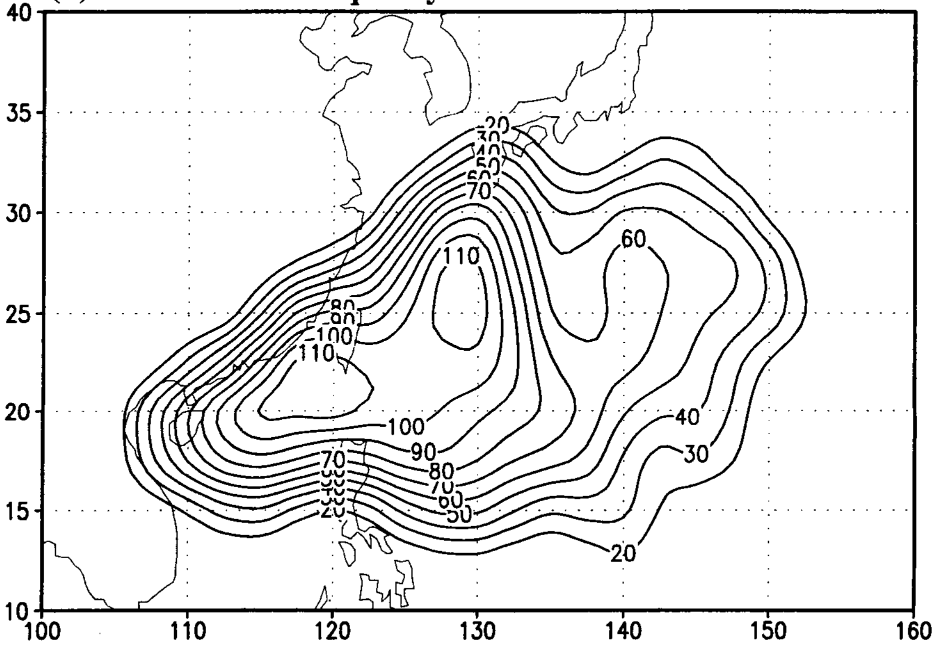


Figure 3: Distribution of the frequency of TC occurrence at 2.5 latitude by 2.5 longitude grid in the typhoon peak season (July to September) derived from (a) the JTWC best track data from 1965 to 2000 and (b) from the trajectory model.

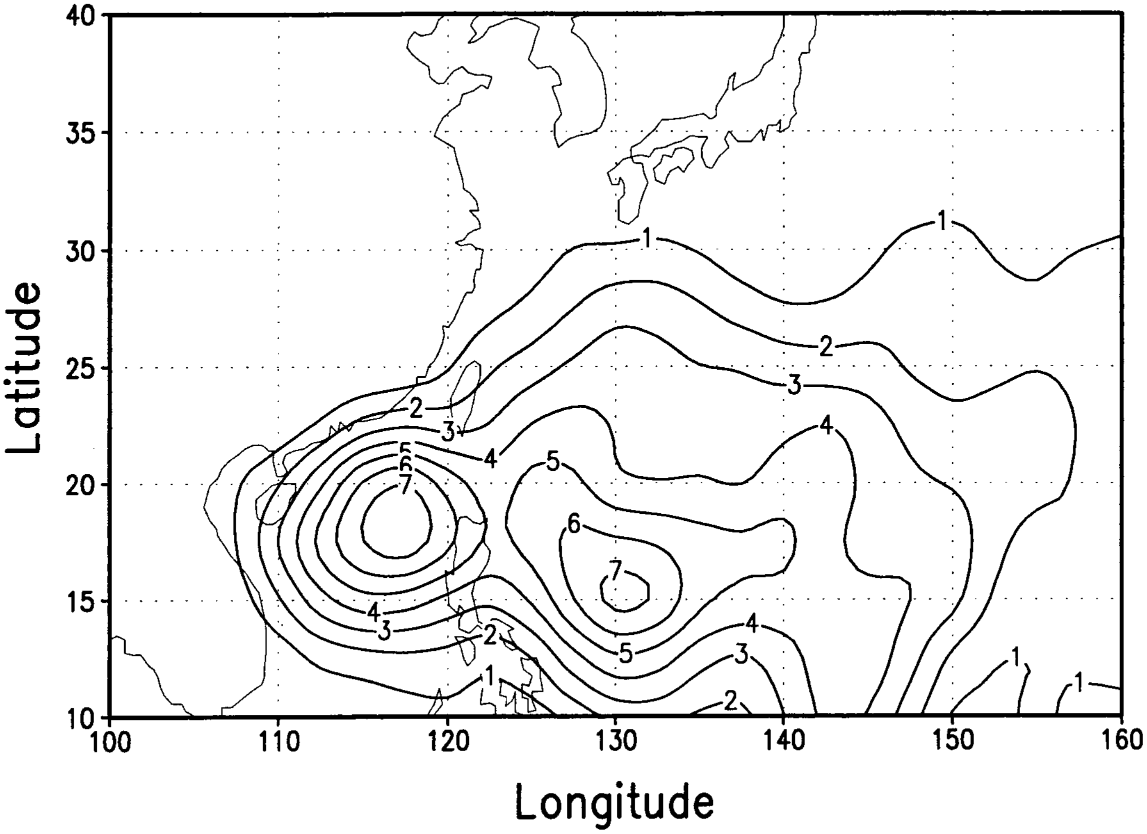


Figure 4: Distribution of the TC formation frequency at each 2.5 latitude by 2.5 longitude grid in the typhoon peak season (July to September) derived from the JTWC best track data from 1965 to 2000.

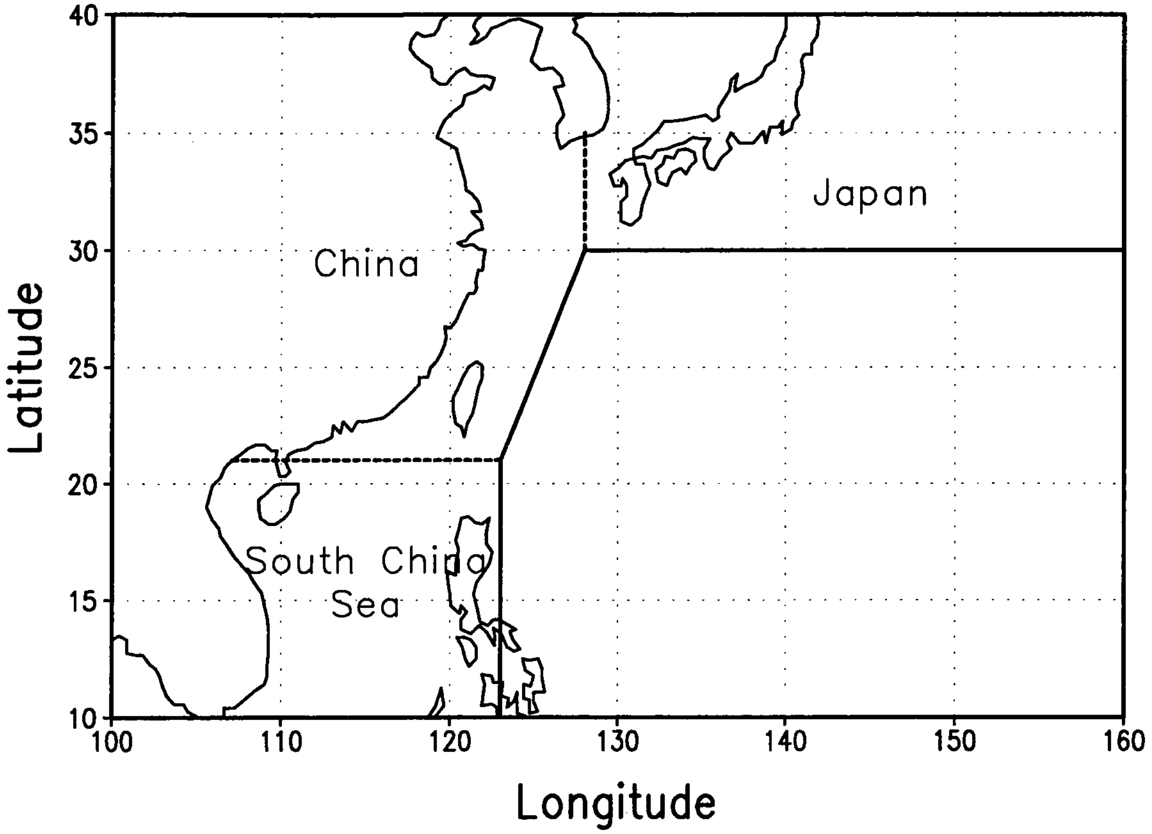


Figure 5: Schematic of the regions where the possible impacts of the global climate change on TC tracks are investigated. The three region are the South China Sea, the eastern coastal region of China (China) and the Japan region (Japan).

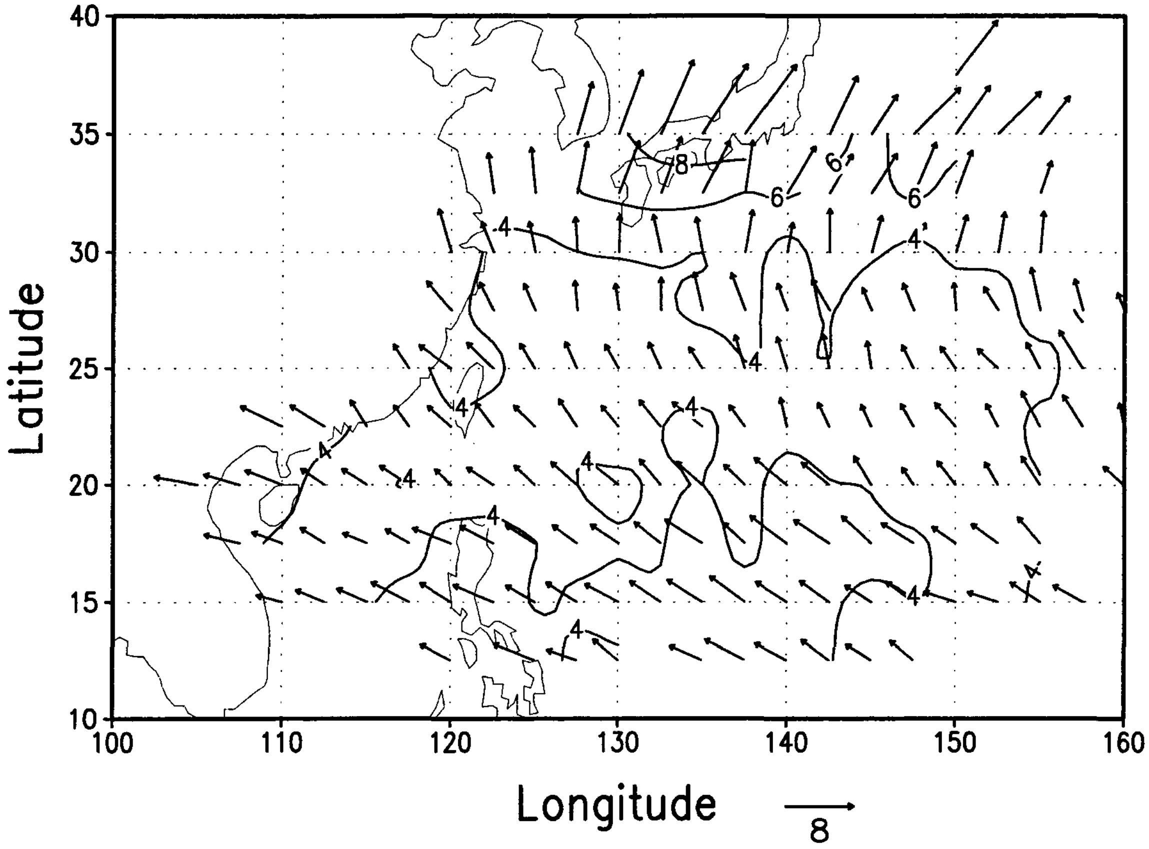


Figure 6: Mean TC translation vectors (m/s) in the typhoon peak season derived from the JTWC best track data from 1965 to 2000.

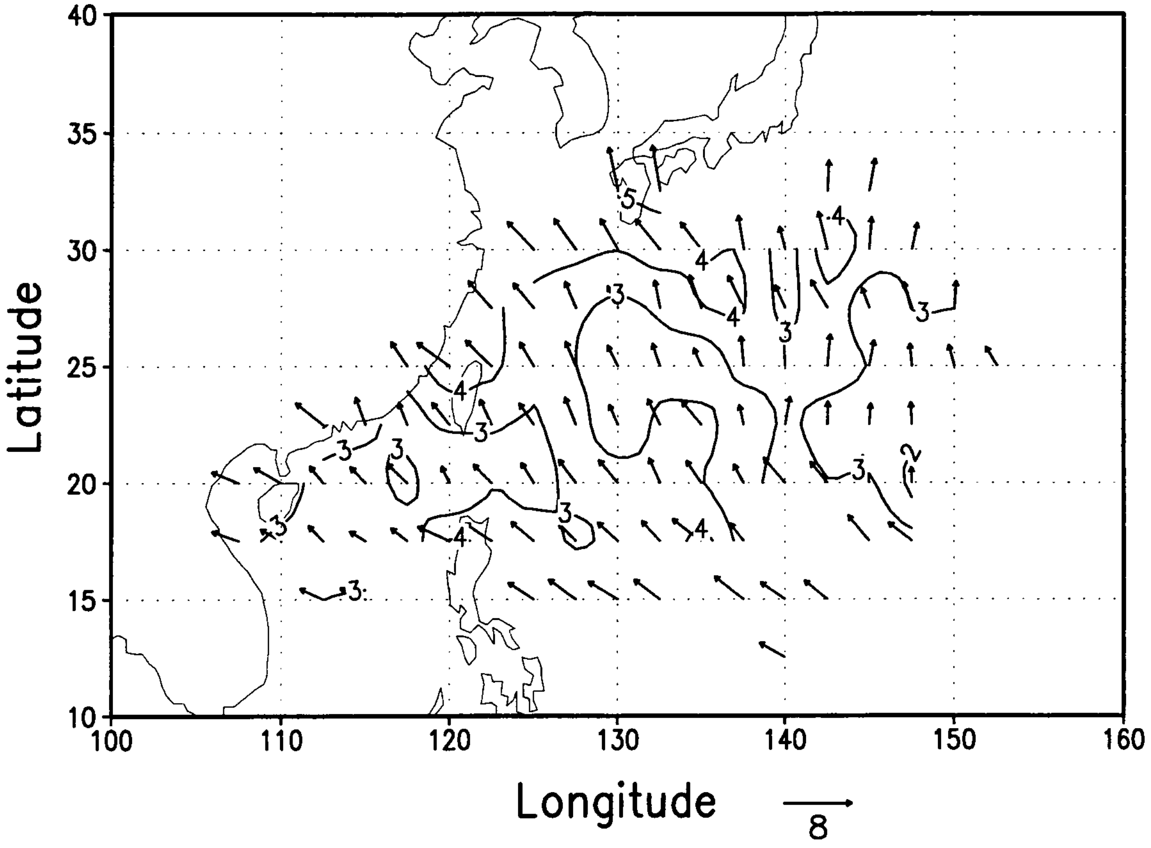


Figure 7: Mean propagation vectors (m/s) in the typhoon peak season derived from the JTWC best track data from 1965 to 2000. Each grid point has at least 40 samples.

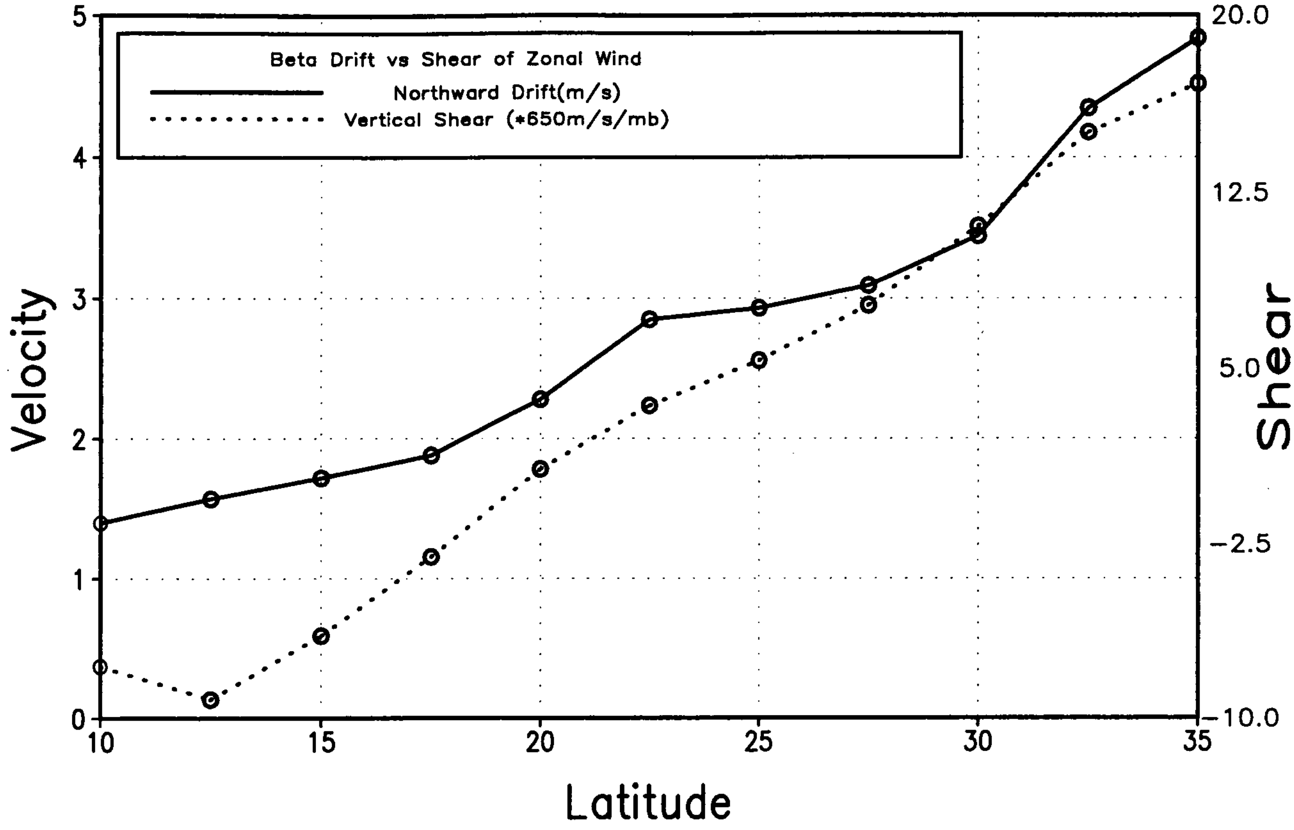
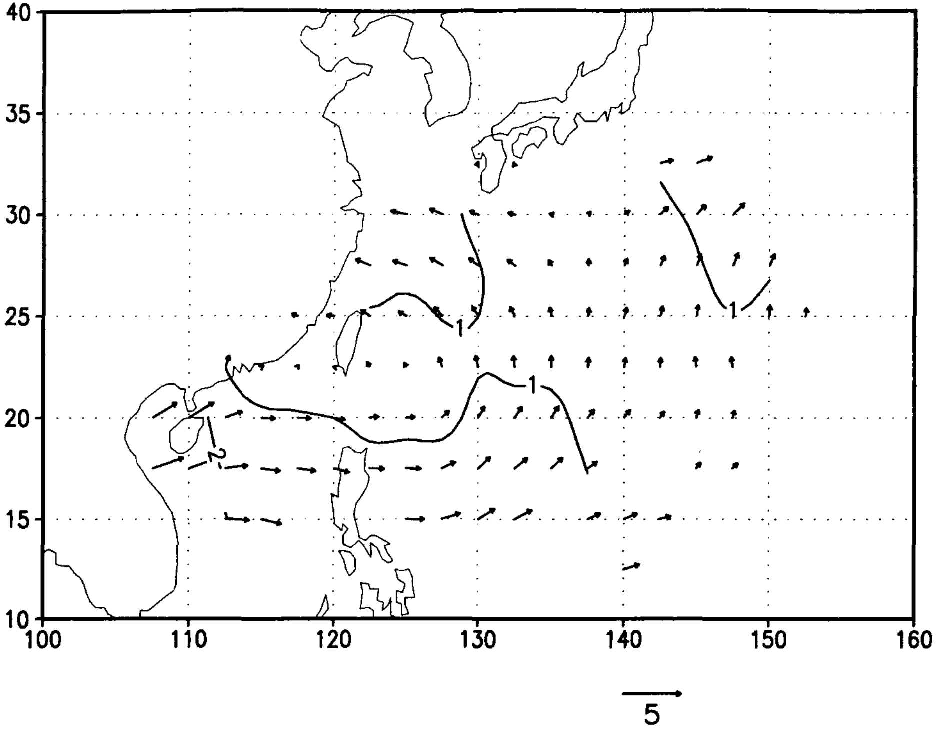


Figure 8: Northward beta drift and vertical shear of the zonal mean environmental flows as a function of latitude.

(a) Experiment A2



(b) Experiment B2

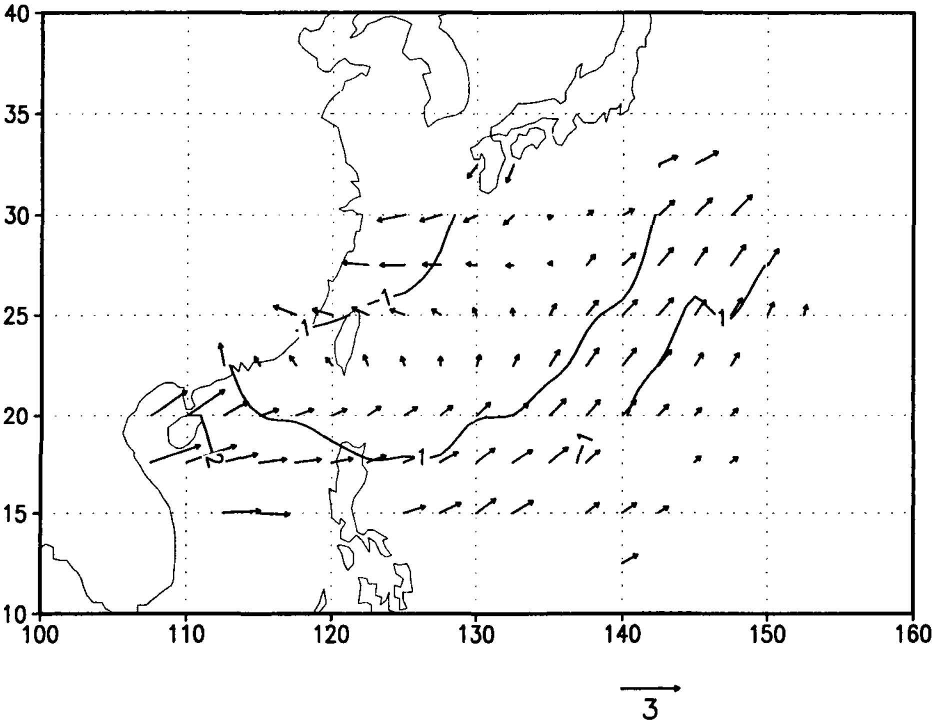
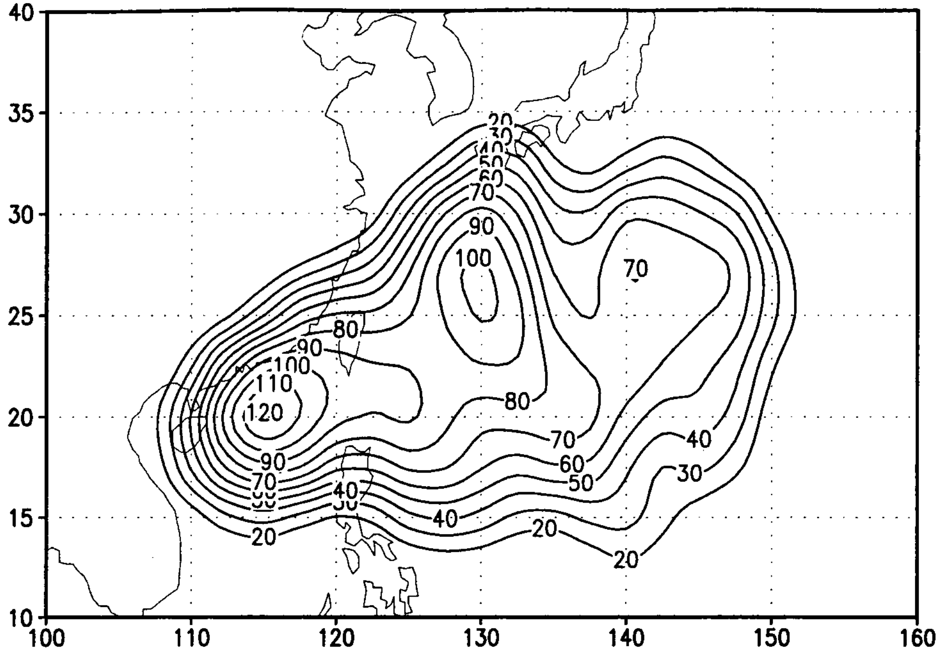


Figure 9: Difference of TC translation speeds (m/s) from the current climatological mean from July to September in (a) experiment A2 and (b) experiment B2 during the period of 2000-2029.

(a) Experiment A2



(b) Experiment B2

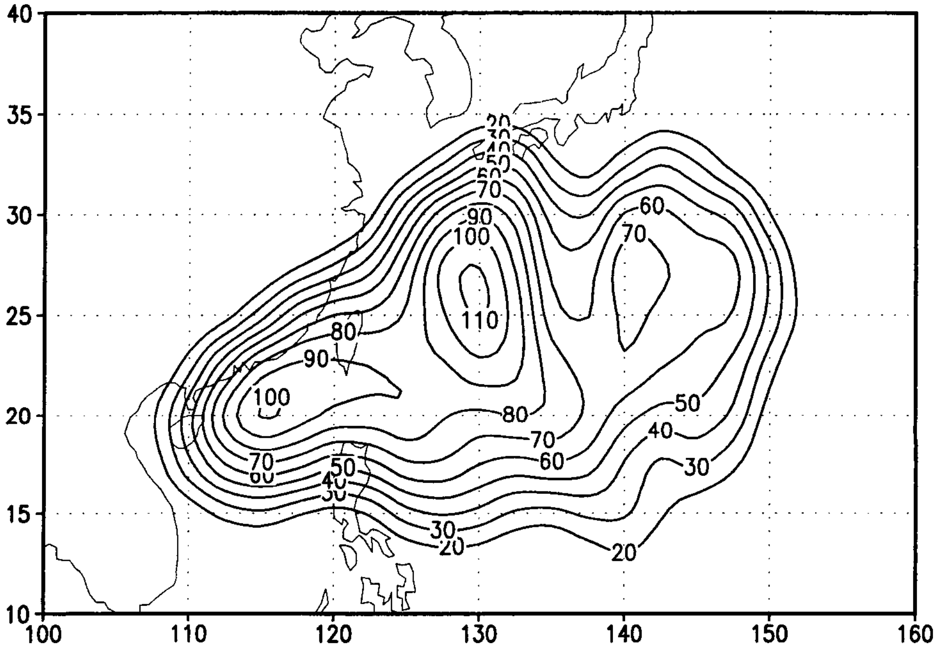
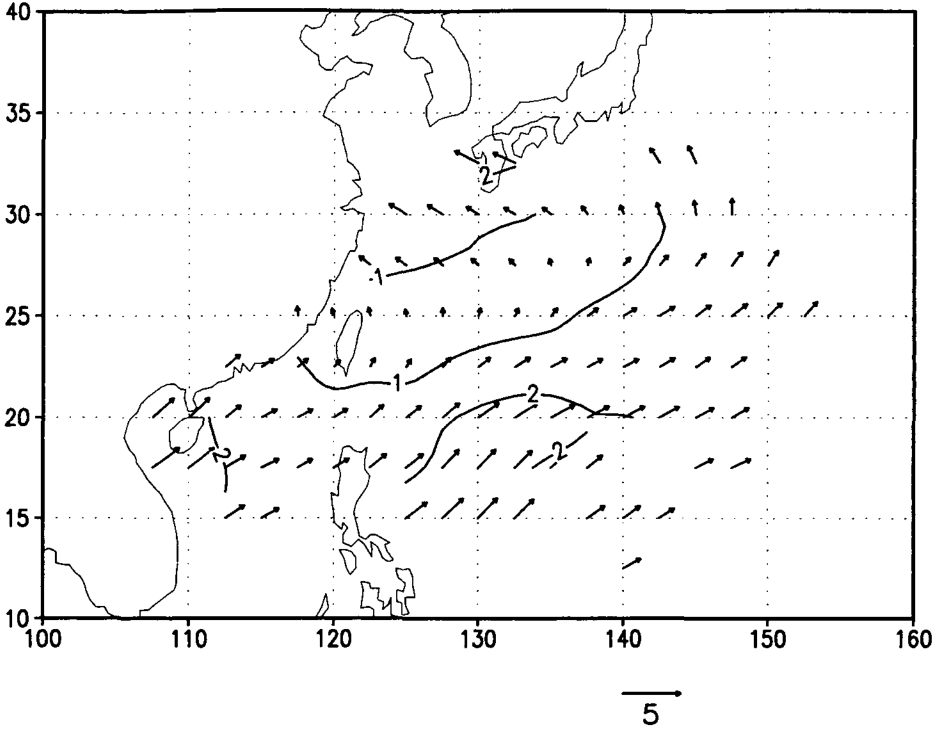


Figure 10: Simulated distribution of TC ocurrence at each 2.5 latitude by 2.5 longitude grid from July to September in (a) A2 and (b) B2 during the period of 2000-2029.

(a) Experiment A2



(b) Experiment B2

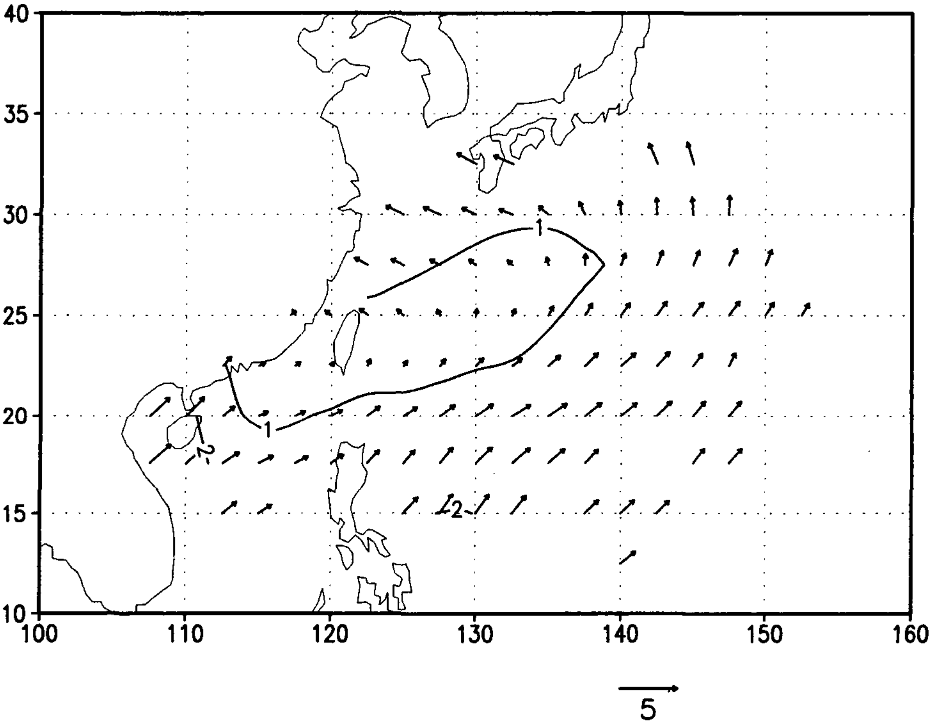
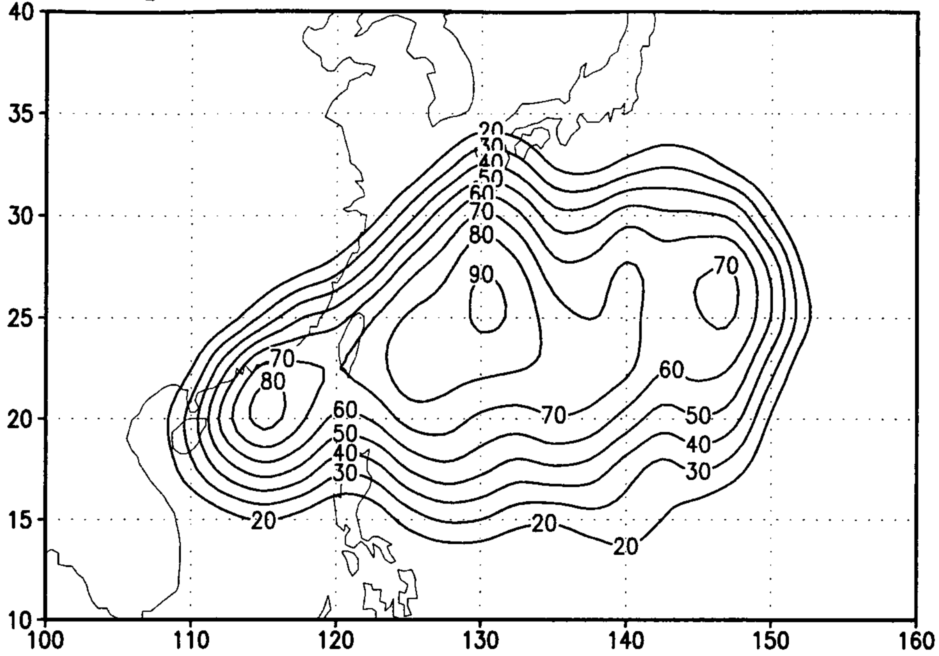


Figure 11: Difference of TC translation speeds (m/s) from the current climatological mean from July to September in (a) experiment A2 and (b) experiment B2 during the period of 2030-2059.

(a) Experiment A2



(b) Experiment B2

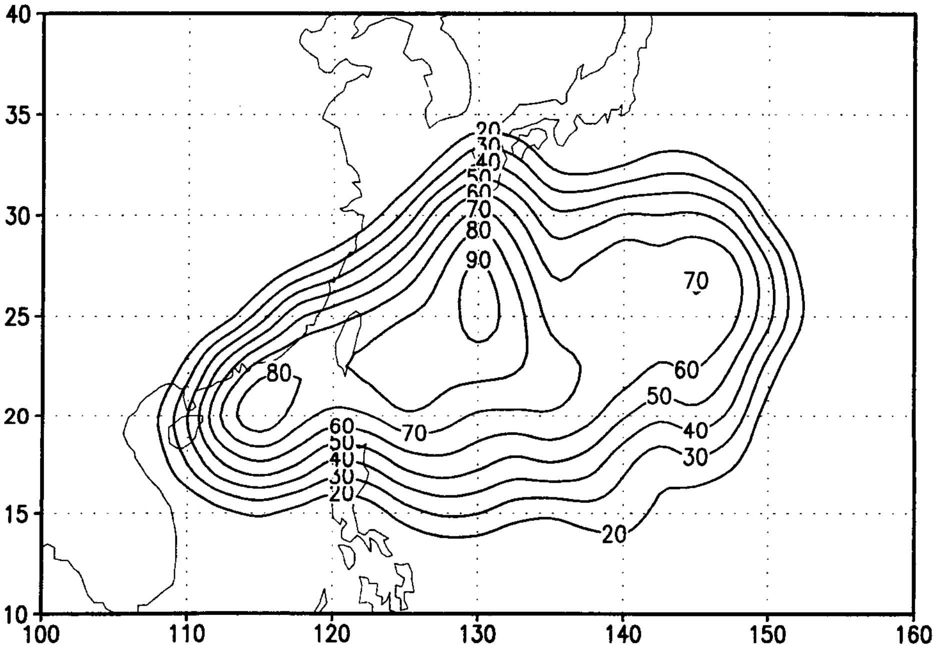


Figure 12: Simulated distribution of TC ocurrence at each 2.5 latitude by 2.5 longitude grid from July to September in (a) A2 and (b) B2 during the period of 2030-2059.