1C.4 Tropical cyclone climatology in a global warming climate as simulated in a 20km-mesh global atmospheric model

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1. INTRODUCTION

To understand the possible changes in tropical cyclones in a greenhouse-warmed world remains a high priority issue from both scientific and socio-economic viewpoints. Studies on this issue have been undertaken with global climate models (*e.g.*, Broccoli and Manabe, 1990; Haarsma *et al*., 1993; Bengtsson *et al*., 1996; Krishnamurti *et al.,* 1998; Sugi *et al*., 2002; Tsutsui, 2002; Yoshimura *et al.,* 2005) and regional nested models (*e.g.*, Knutson *et al.*, 1998; Knutson and Tuleya, 1990, 2004; Walsh and Ryan, 2000). A typical resolution of most of the global models was not enough finer than 100 kilometers, which made it impossible to represent the inner structures of a tropical cyclone. In this study, we use a 20km-mesh global atmospheric model, and performed two sets of 10-year time integration to investigate possible changes in intensity of the tropical cyclones in a future warmed climate. This will add a scientifically more reliable insight into our current understanding on the issue.

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2. DESCRIPTION of EXPERIMENTS

The model used in this study is an Meteorological Research Institute (MRI)/Japan Meteorological_Agency unified model originated from the operational numerical weather prediction model with some modifications for a climate research objective (Mizuta *et al.,* 2006). The time integration was accelerated with the introduction of a vertically conservative semi-Lagrangian scheme (Yoshimura and Matsumura, 2005), which allows nearly 4 hours of wall-clock time for a 1-month time integration with a time step of 360 seconds by using 30 nodes of the Earth Simulator. The model is configured with the horizontal spectral truncation of TL959 (equivalent to about 20 km mesh) and 60 vertical levels with the model top at 0.1 hPa. The cumulus parameterization used is a prognostic Arakawa-Schubert scheme (Randall and Pan, 1993; Arakawa and Schubert , 1974).

The experiments follow the so-called "time-slice" method (Bengtsson *et al.,* 1996; IPCC, 2001). First, a 10-year present-day experiment was conducted with the forcing of the observed climatological sea surface temperature (SST) average from 1982 to 1993. Next, an SST change between the future (average over 2080-99) and the present (average over 1979-98) experiments was added onto the observed SST. The SST change was predicted by the MRI-CGCM2.3 (Yukimoto *et al.,* 2005) on the basis of the IPCC A1B emission scenario (IPCC, 2000) with the CO_2 concentration nearly doubled around the 2080-99 period and the global mean surface air temperature rising by 2.5 degrees. Under the SST condition, the model was integrated over 10 years as a future global-warmed climate experiment. In the future experiment, the concentrations of greenhouse gas and the aerosols are taken from the values of the year 2090 in the A1B scenario.

The tropical cyclones in both experiments are searched in the 45S and 45N latitudinal belts over the ocean. The initial position of each tropical cyclone was limited to the region between 30S and 30N. The tracking method is basically the same as those used by Sugi *et al.*(2002), and explained in Oouchi *et al.* (2006).

3. RESULTS

3.1 An example of a tropical cyclone rainfall Morphology

Compared to previous climate models with a coarser mesh, an advantage of using the 20km-mesh model is the improvement in the representation of the inner structures of a tropical cyclone. To gain insight into some morphological aspects of the improvement, a typical tropical cyclone in the present-day experiment is shown in Fig. 1. The figure illustrates (a) the 6-hour averaged rainfall amount over a western North Pacific region near Japan, (b) the 6-hour averaged rainfall amount near a tropical cyclone in the mature stage, (c) a temperature anomaly at 925 hPa as a deviation from the displayed area mean, (d) the water vapor mixing ratio at 925 hPa, and (e) the velocity at 925 hPa. The area displayed in panels (d) and (e) is an expanded view of the area surrounded by thick-dashed lines in panel (b). In panels (d) and (e), the distribution of the precipitation is also plotted with white contours.

Figure 1a demonstrates that the 20km-mesh model reproduces a variety of precipitation features with wide-ranging scales and a hierarchy, including a remnant of the precipitation from a frontal system stretching across the Pacific coastal region of Japan, a tropical cyclone on its way to Japan, and some organized cloud ensembles located to the south of the tropical cyclone. In the following, the typical hierarchy of the simulated precipitation features in the tropical cyclone is described. In Fig. 1b, it is evident that a comma-shaped stronger rainfall region, labeled A, spreads immediately outside of the lowest surface pressure region. Region A may be likely to correspond to the eyewall of the tropical cyclone. In the northeastern to eastern quadrant of the lowest pressure center, spiral-form rainbands B and C are present. Although not shown, an examination of the time sequence of B and C reveals that the rainbands, as they develop, move inward so as to eventually merge into the innermost eyewall area. Although the present 20km-mesh global model does not incorporate any sophisticated cloud micro-physics to allow a full-scale comparison of the simulated behaviors of the rainbands with the observations, it can be inferred that, in the organization and maintenance of B and C, some meso-beta scale thermodynamical processes are at work, even if not as elaborately as in non-hydrostatic tropical cyclone models. In Fig. 1c, conspicuous negative temperature anomalies coincide with the stronger rainfall regions corresponding to A, B, and C. These negative anomalies may partly originate from the evaporation of the rainwater from A, B, and C. At the eastern edge of rainband C, the boundary layer is relatively moist (Fig. 1d), and the low-level flow is from the southeast (Fig. 1e). These conditions may be favorable for the maintenance of rainband C. It is interesting to note that rainband C is represented not as a homogeneous rainfall area but as an ensemble of substructures with varying rainfall intensity. The substructures are indicative of cellular convective structures, which are embedded in observed tropical cyclone rainbands (*e.g.*, Willoughby *et al.*, 1984). Thus, the typical inner structure of a tropical cyclone is captured more reasonably compared to the previous coarser-mesh climate models in which the representation of the inner structure, including the eye, has been somewhat elusive (Krishnamurti *et al.,* 1989). Within the present purpose of investigating the tropical cyclone climatology, the simulated inner structure of a tropical cyclone provides an important improvement over those in previous studies.

3.2 Intensity

The annual mean numbers of the simulated tropical cyclones for the "present-day (green lines)" and "future (red lines)" experiments are plotted against the observation (dotted, black). In Fig.2, a two-sided Student's t-test was applied to the difference between the "present" and "future" curves to check the statistical significance. In deriving the significance level, storm results aggregated for the entire storm season each year were used as the sample elements of the t-test (n1=n2=10, for each 10years time integration). The segment of the graphs satisfying 95% significance level are marked with open and closed circles. The circles on thin/thick lines denote that the trend of frequency increase/decrease in the future experiment are statistically significant (95% level). Focusing on the global frequency, it is noteworthy that the maximum surface wind speeds in the present simulation are generally lower than those that are observed. The model is likely to underestimate the surface wind speeds and, therefore, the intensity of the tropical cyclones. The discrepancy may originate from some insufficient performance of the physical schemes in the 20km-mesh model, including the cumulus parameterization.

Here, the focus is on the comparison of the wind speeds between the present and future experiments. It is evident in Fig. 2 that the simulated change in the number of tropical cyclone occurrences in the globe is different in tropical cyclones of intense (> 43 m s^{-1}) and weak-to-moderate(< 43 m s^{-1}) classes. In the future experiment, tropical cyclones of the intense class increase in number, while those of weak-to-moderate class decline. In particular, the statistically significant (at 95% confidence level) increase is found for the class of 45-60 m s^{-1}. A similar contrasting trend of frequency change in the "weak-to-moderate" and "intense" class is equal across most of the ocean basins (not shown), though detailed estimates of its statistical significance may require a larger sampling number; the current result is highly dependent on the variance in the number sampled among the basins (Fig. 2). The result is consistent with the finding from a lower-resolution (T106) GCM (Yoshimura *et al.* ,2005) for the frequency change and from the regional model (Knutson *et al.,*1998) in that the more intense tropical cyclones are likely to increase under the greenhouse-warmed climate.

4. DISCUSSION and REMARKS

The results suggest that more intense tropical cyclones will increase in the future greenhouse-warmed climate. The finding is in agreement with previous studies using regional models (Knutson *et al.*, 1998, Walsh and Ryan, 2000, Knutson and Tuleya, 2004) as well as a theoretical estimation using the thermodynamical factors relevant to tropical cyclone (Emanuel, 1987; Holland, 1997; Henderson-Sellers *et al.*, 1998). The present study supports the finding in a more comprehensive manner because of the long-term climate integration with the 20km-mesh models*1. Another advantage of our model in coping with this problem would be that the dynamical effects of the environmental flow of a tropical cyclone, including the effect of vertical shear, might be represented consistently throughout the integration period. This feature should be checked in a future study. The importance of the effects in assessing the influence of global-warming upon the intensity of tropical cyclones was suggested by Walsh and Ryan (2000), but these effects have not been incorporated in most of the past modeling studies.

It is noteworthy that the downscaling from low to high (fine) resolution AGCM alone does not resolve all the problems around accurate tropical cyclone projection. Even in the context of climate statistics, we found that the model still has some shortcomings in capturing the observed geographical distribution, frequency, and intensity of a tropical cyclone (Oouchi *et al.*, 2006). In particular, the deficiency of the intense (*e.g.*, high wind speed of more than 60 m s^{-1}) tropical cyclone in difficult to understand. One may argue that the use of 20km mesh is still coarse for representing mesoscale features of tropical cyclone. Compared to non-hydrostatic model, the resolution is unarguably coarse to capture the internal structures of convections and intensities that can affect evolution of tropical cyclone. Relevantly, one may question the validity of the cumulus parameterization used in such a “high-resolution” hydrostatic model because moist process plays key role in the development of tropical cyclone. It will be important to clarify the extent to which the cumulus parameterization and other physical schemes are involved in the success of the reliable projection of tropical cyclone.

In addition to identifying the caveats in the model schemes, comparison of the results with observational studies are essential to deepen our understanding of the issue. Evidence is emerging that the tropical cyclone activity in the past 30 years in the North Pacific and North Atlantic or in the globe is increasing significantly and that the storms are characterized by greater duration and intensity, which are attributed, at least partially, to anthropogenic activities (Emanuel, 2005; Webster *et al.*, 2005). Some of the results from the 20km-mesh AGCM experiments are basically in line with the observational findings, as discussed in Oouchi *et al.* (2006).

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*1 For those interested in the performance of the 20km mesh AGCM in a present-climate mode, see online at http://www.mri-jma.go.jp/Project/RR2002/k4-1-en.html

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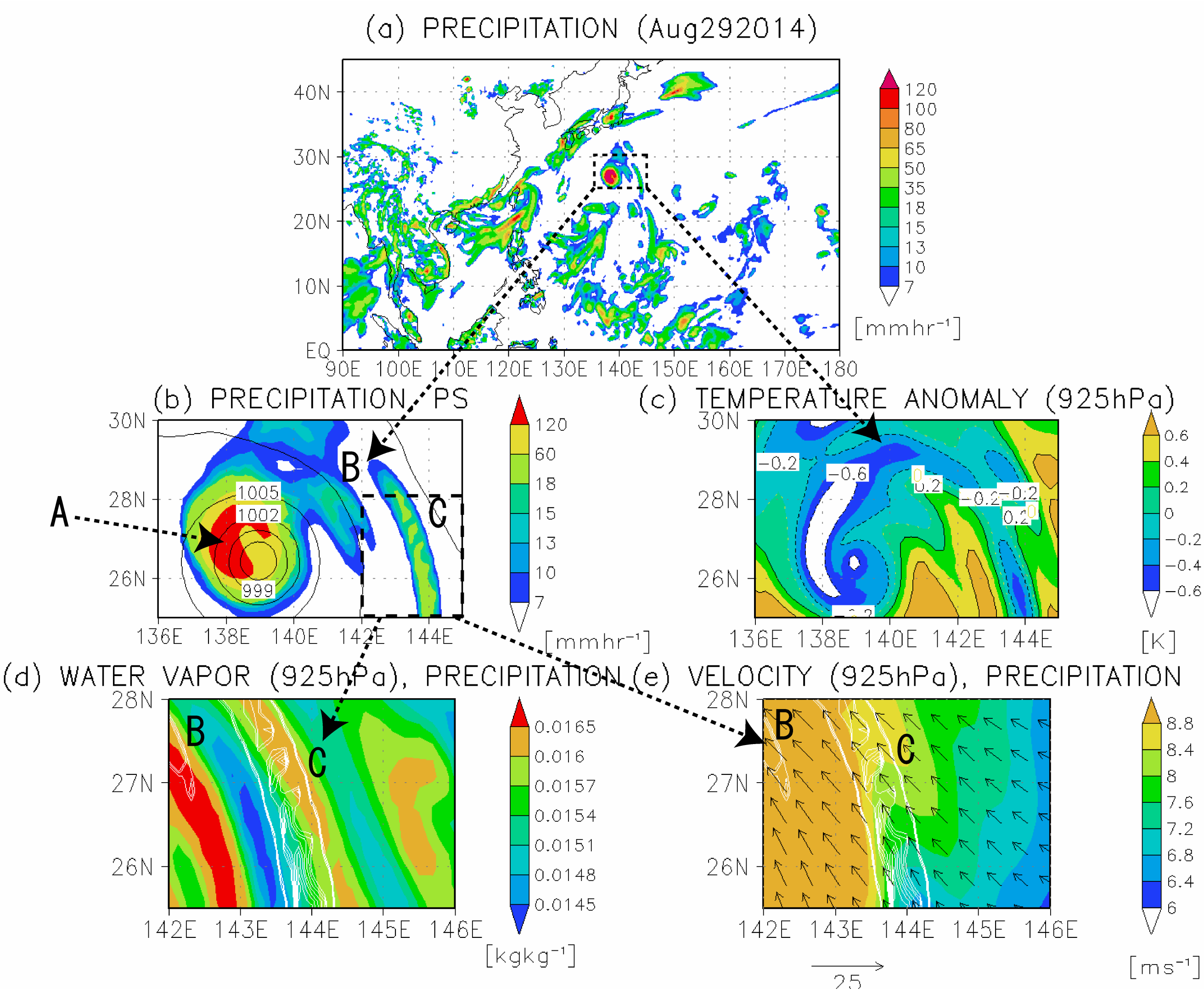

Figure 1 Horizontal view of a tropical cyclone simulated in the present-day experiment (Aug 29, 7th year of the time integration): horizontal distributions of (a) 6-hour averaged precipitation amount in mm hour^{-1} in the near-Japan, and northwest Pacific region. The rest of the panels focus on a tropical cyclone,displaying (b) 6-hour averaged precipitation amount in mm hour^{-1} (shaded) and surface pressure (contour), (c) temperature anomaly at 925hPa in K, (d) water vapor mixing ratio at 925hPa in kg kg^{-1} (shaded) and precipitation amount (white contour), and (e) horizontal velocity at 925hPa in m s^{-1} (shaded and arrows) and precipitation amount in mm hour^{-1} (white contour). The domain of panel (d) and (e) is an expanded view of the region surrounded by a dotted box in panel (b).

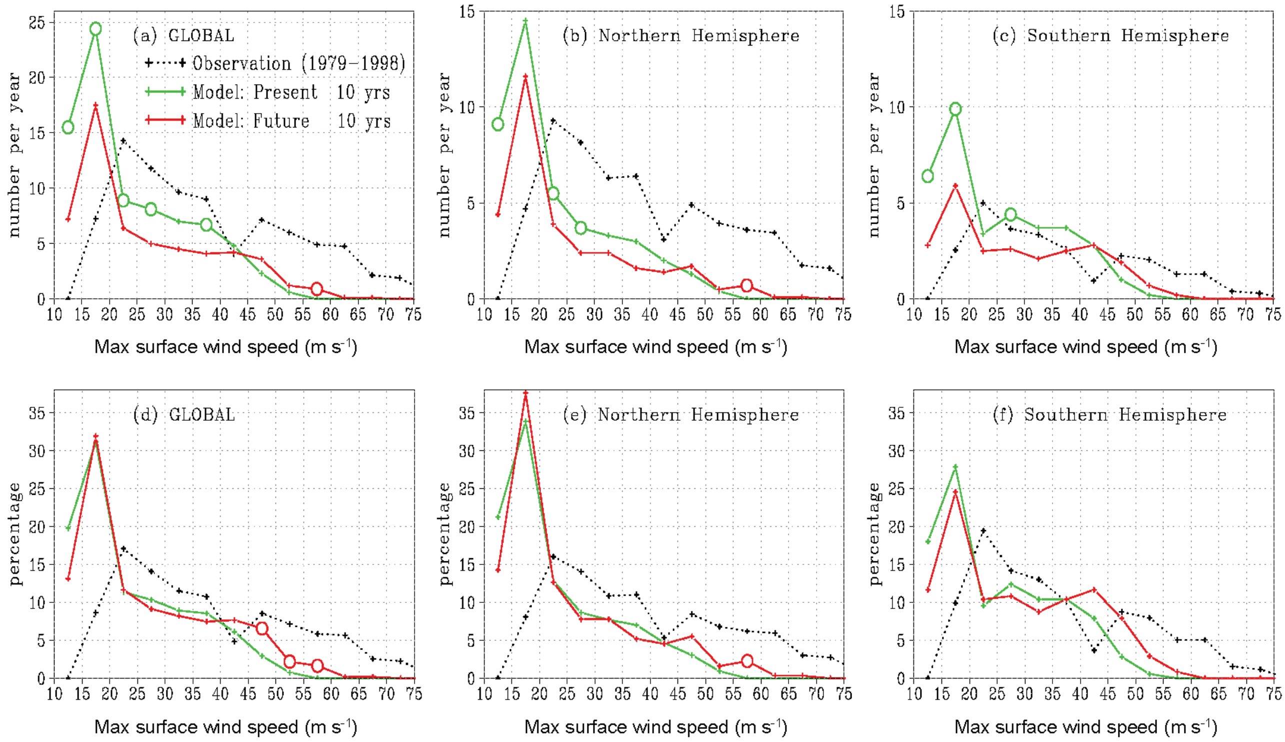

Figure 2 (a,b,c) Annual mean occurrence frequency, (d,e,f) Occurrence rate (%) normalized by the total number of simulated tropical cyclones counted in the region specified as functions of the tropical cyclone intensities (abscissa) for (a,d) global, (b,e) Northern Hemisphere, and (c,f) Southern Hemisphere. The abscissa is the largest maximum surface wind speed, and the maximum wind speed attained in the lifetime of a tropical cyclone is plotted. Dotted lines indicate the observation; results from the present-day experiment are shown by thick solid lines, and those from the future experiment, by thin solid lines. For the difference between the "present" and "future" results, the plot at the 95% statistical significance level is marked with an open or closed circle (according to a two-sided Student's t-test). Note that plots from the observation include no tropical cyclone with the maximum surface wind speed at less than 17.2 m s^{-1}.