Feasibility study for downscaling seasonal tropical cyclone activity using the NCEP regional spectral model

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Abstract:

The potential use of the National Centers for Environmental Prediction (NCEP) Regional Spectral Model (RSM) for downscaling seasonal tropical cyclone (TC) activity was analyzed here. The NCEP RSM with horizontal resolution of 50 km, was used to downscale the ECHAM4.5 Atmospheric General Circulation Model (AGCM) simulations forced with observed sea surface temperature (SST) over the western North Pacific. An ensemble of ten runs for June–November 1994 and 1998 was studied. The representation of the TCs is much improved compared to the low-resolution forcing AGCM, but the TCs are not as intense as observed ones, as the RSM horizontal resolution is not sufficiently high. The large-scale fields of the RSM are examined and compared to both the AGCM and the European Centre for Medium-Range Weather Forecasts (ECMWF) reanalysis. The large-scale fields of RSM characteristics are in general similar to those of the reanalysis. Various properties of the TCs in the RSM are also examined such as first positions, tracks, accumulated cyclone energy (ACE) and duration. While the RSM does not reproduce the higher number of TCs in 1994 than in 1998, other measures of TC activity (ACE, number of cyclone days) in the RSM are higher in 1994 than in 1998. Copyright © 2006 Royal Meteorological Society

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1. INTRODUCTION

The western North Pacific is the basin with most tropical cyclone (TC) activity. Severe TCs or typhoons are a significant natural hazard for many Asian countries such as Japan, China, Philippines and Vietnam, making forecasting of seasonal tropical typhoon activity an important task. Operational forecasts (statistical and dynamical) of seasonal typhoon activity are currently available from: City University of Hong Kong (Chan *et al*., 1998, 2001; Liu and Chan, 2003), Tropical Storm Risk (TSR, 2006), IRI – International Research Institute for Climate and Society (IRI, 2006), ECMWF – European Center for Medium-Range Weather Forecasts (Vitart and Stockdale, 2001b; Vitart *et al*., 2003; Vitart, 2006). In this work, we are interested in examining the potential use of regional climate models in forecasting seasonal TC activity in the western North Pacific.

Many studies have analyzed the properties of cyclone-like structures in Atmospheric General Circulation Models (AGCMs), finding that the simulated TCs have properties similar to those of observed TCs (Manabe *et al*., 1970; Bengtsson *et al*., 1982; Broccoli and Manabe, 1990; Wu and Lau, 1992; Haarsma *et al*., 1993; Bengtsson *et al*., 1995; Tsutsui and Kasahara, 1996; Vitart

et al., 1997, 1999; Camargo and Sobel, 2004; Camargo *et al*., 2005). General circulation climate models have also been extensively used to study the influence of greenhouse gases on TC activity (Broccoli and Manabe, 1990; Ryan *et al*., 1992; Haarsma *et al*., 1993; Bengtsson *et al*., 1996; Royer *et al*., 1998; Druyan *et al*., 1999; Walsh and Ryan, 2000; Sugi *et al*., 2002; Walsh *et al*., 2004; Knutson and Tuleya, 2004; Walsh, 2004). Other climate influences on TCs, such as El Niño-Southern Oscillation (ENSO) and decadal variability, have been explored using both AGCMs (Wu and Lau, 1992; Vitart *et al*., 1997, 1999; Vitart and Anderson, 2001a) and coupled atmosphere–ocean models (Matsuura *et al*., 1999, 2003; Yumoto *et al*., 2003; Vitart *et al*., 2003). However, the modeled TCs have deficiencies related to the relatively low resolution of the models. In particular the model TCs tend to lack a distinct eye, eye wall and rain bands and have a larger horizontal scale than observed. The importance of high resolution for the realistic description of TCs is well-known (Kobayashi and Sugi, 2004), and resolution is at least one of the major reasons why low-resolution global reanalysis products do not describe TC activity well (Serrano, 1997; Fiorino, 2002; Cheung and Elsberry, 2002).

Dynamical downscaling using a regional model is a computationally efficient means of increasing the AGCM resolution in a limited area. In this approach, the regional climate model is forced by low-resolution fields from

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the AGCM. This method has been used in many problems, including seasonal precipitation forecasts over the northeast of Brazil (Sun *et al.*, 2005, 2006). The purpose of this work is to investigate whether the higher resolution of the regional model could improve upon the skill of the AGCM to simulate seasonal TC activity. The AGCM used here is the ECHAM4.5 developed at the Max-Planck Institute for Meteorology in Hamburg (Roeckner *et al.*, 1996). This model has been studied extensively in various aspects of seasonal TCs activity (Camargo and Zebiak, 2002; Camargo and Sobel, 2004; Camargo *et al.*, 2005) and is currently used operationally for experimental dynamical seasonal forecasts of TCs (IRI, 2006). The regional model used is the Regional Spectral Model (RSM) developed at National Centers for Environmental Prediction (NCEP) (Juang and Kanamitsu, 1994; Juang *et al.*, 1997; Juang and Hong, 2001). The dynamical downscaling is performed in the western North Pacific, where 30% of the global TC activity occurs and where typhoons have important societal impacts.

Previous studies have looked at the ability of regional models to represent TCs using reanalysis forcing (Landman *et al.*, 2005) and AGCM forcing (greenhouse gases effects on TC activity over the Australian region; Walsh, 1997; Walsh and Ryan, 2000; Nguyen and Walsh, 2001; Walsh and Syktus, 2003; Walsh *et al.*, 2004). Our aim here is to determine how successfully regional models can be used in operational settings to simulate the variability of seasonal TC activity. Recently, an inter-comparison of regional climate models over the Asian region results was discussed (Fu *et al.*, 2005), but the domain of that study is focused over the Asian continent and the RSM is not one of the regional models included in the project. In other recent downscaling studies the focus was to simulate the summer monsoon over China (Chan *et al.*, 2004; Liu *et al.*, 2006). One important issue that is also briefly discussed here is the influence of the choice of domain boundary on the regional climate model simulations (Seth and Giorgi, 1998; Landman *et al.*, 2005; Rauscher *et al.*, 2006).

The long-term goal of this study is to use a regional climate model to understand regional scale details of seasonal TC activity variability on seasonal and longer time scales. First, the basic properties of TCs simulated in the dynamical downscaling framework have to be studied, as well as the simulated regional circulation. With this aim, a few questions will be addressed here. The first question is: how well does the RSM represent typhoons, and does it improve upon the low-resolution AGCM? The second question is whether the RSM is able to independently form TCs in its domain, or whether it only provides more details about the TCs already present in the AGCM. The third (related to the second) is the performance of the RSM in simulating seasonal statistics of cyclones (typhoon number, intensity, tracks, interannual variability and genesis location).

In a recent paper, Castro *et al.* (2005) discuss the value added by dynamical downscaling to an AGCM. They concluded that surface boundary forcing is the dominant

factor in generating atmospheric variability for small-scale features and that it exerts greater control on the regional model solution as the influence of the boundary conditions diminish. In their analysis, the value added by the regional model is to resolve small-scale features that have a greater dependence on the surface boundary. As a possible solution for these issues, spectral nudging is suggested in Castro *et al.* (2005). The regional model used in this study (RSM) is a spectral model, which is a procedure similar to the spectral nudging.

In Section 2, we describe the numerical experiment in this study. In Section 3 the sea surface temperature (SST) and atmospheric conditions associated with the TCs in the two seasons considered are discussed. In Section 4 the RSM TC activity characteristics are discussed. In Section 5 sensitivity tests for domain choice are discussed and the conclusions are given in Section 6.

2. EXPERIMENT DESCRIPTION

The ECHAM4.5 AGCM was configured at triangular 42 (T42) spectral truncation, giving a spatial resolution of about 2.8 degrees latitude–longitude, with 19 vertical layers (Roeckner *et al.*, 1996). Multi-decadal ensemble simulations of approximately 50 years, forced by observed SST (Reynolds and Smith, 1994; Reynolds *et al.*, 2002), have been produced by the ECHAM4.5 AGCM. The different ensemble members are generated by having slightly different initial states, obtained by perturbing a set of self-consistent model fields from a previous integration of this model. The NCEP RSM (Juang and Kanamitsu, 1994; Juang *et al.*, 1997; Juang and Hong, 2001) with a horizontal resolution of 50 km is used to downscale ECHAM4.5 simulations over the western North Pacific. The regional model domain is 109.7 °E to 162.6 °W, and 1.2 °N to 42.1 °N, as shown in Figure 1.

The one-way nesting of the NCEP RSM into the ECHAM4.5 AGCM is different from conventional methods, which only use global model fields along the lateral boundary zone. The perturbation nesting method uses the global model output over the entire regional domain, not just in the lateral boundary zone. The dependent variables in the regional domain are defined as a sum of a perturbation and a base. The base is a time dependent field from the AGCM. Variability resolved by the RSM in the regional domain is defined as the perturbation. The nesting is done in such a way that the perturbation is nonzero inside the domain but zero outside the domain. Five prognostic variables from the global model outputs are used as the base fields in the RSM. They are zonal and meridional winds, temperature, humidity and surface pressure. Perturbations are often concentrated in the smaller spatial scales. In some cases, the perturbations can be strong at larger spatial scales as well (e.g. Sun *et al.*, 2006). All diagnostic variables (e.g. precipitation) are generated by the regional model itself. This spectral downscaling process is very similar to the spectral nudging discussed in Castro *et al.* (2005).
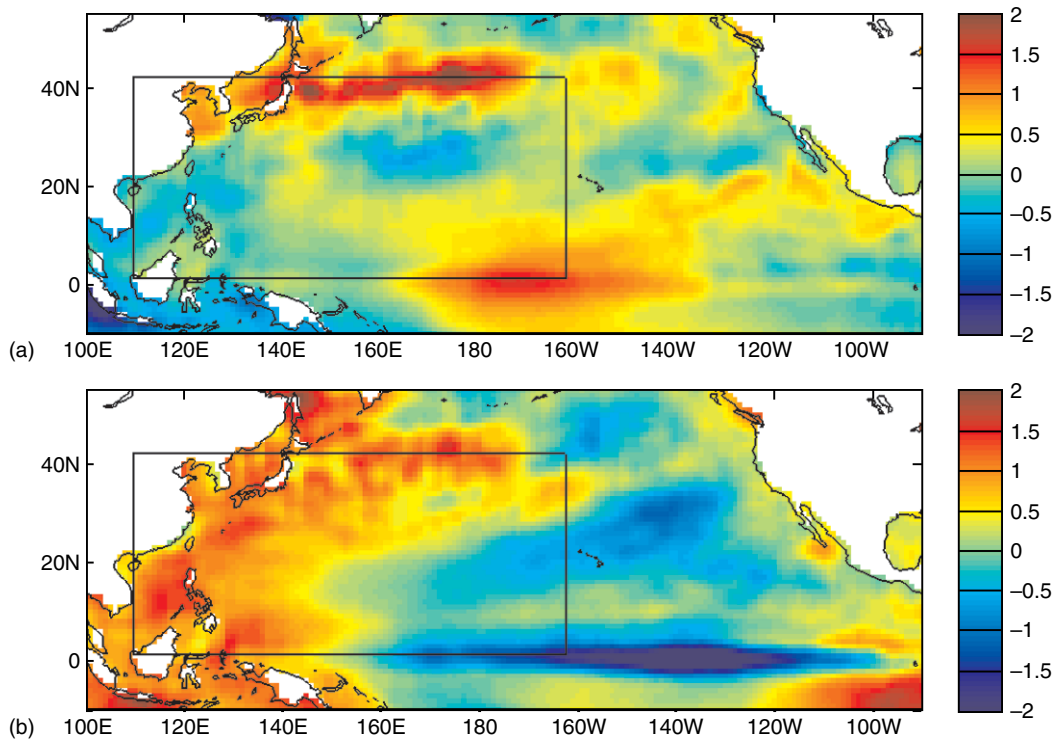
Figure 1. Observed mean sea surface temperature anomalies (in °C) in the period June–November 1994 (a) and 1998 (b). The domain used for the regional spectral model simulations is also shown in both panels.

The peak of the typhoon activity in the western North Pacific is July to October, though typhoons do occur in any month of the year as shown in Figure 2(b). We chose the period June to November, of 1994 and 1998 to use the RSM to downscale the ECHAM4.5 AGCM simulations. For each year, we used ten ensemble members of the ECHAM4.5 simulation, creating an ensemble of ten integrations of the RSM for each year.

The ECHAM4.5 has a reasonable TC climatology over the western North Pacific, underestimates the number of typhoons in the peak season (July–October), a common characteristic in low-resolution AGCMs (Camargo *et al.*, 2004a). The ECHAM4.5 has significant skill in simulating the interannual variability of the number of tropical storms and TCs in the western North Pacific (Camargo *et al.*, 2004a, 2005). However, ECHAM4.5 does not reproduce years with extreme numbers of named tropical storms. For this reason, we chose for this experiment 2 years with extreme numbers of named tropical cyclones (NTC): 1994 (high activity) and 1998 (low activity), as shown in Figure 2(a). The ECHAM4.5 does produce few TCs in the western North Pacific in 1998, but does not produce enough in 1994. One of the questions is whether the RSM can increase the number of simulated TCs in such a year. It was noticed that the analysis of the ECHAM4.5 by Camargo *et al.* (2004a, 2005) used 24 ensemble members while here only 10 ensemble members are used to force the RSM, because of computational resources constraints.

To define and track TCs in the models, we used objective algorithms (Camargo and Zebiak, 2002) based on prior studies (Vitart *et al.*, 1997; Bengtsson *et al.*, 1995).

Table I. Thresholds for vorticity (850 hPa), surface wind speed and anomalous temperature (700, 500 and 300 hPa) in the RSM and ECHAM4.5 (western North Pacific) models.

Thresholds	Vorticity (s^{-1})	Wind speed $(m\ s^{-1})$	Anomalous Temperature $(°C)$
RSM	4.9×10^{-5}	14.1	1.2
ECHAM	3.4×10^{-5}	12.0	1.9

The algorithm has two parts. In the detection part, storms that meet environmental and duration criteria are identified. A model TC is identified when chosen dynamical and thermodynamical variables exceed thresholds based on observed tropical storm climatology. Most studies (Bengtsson *et al.*, 1982; Vitart *et al.*, 1997) use a single set of threshold criteria globally; however, these do not take into account model biases and deficiencies. We use basin- and model-dependent threshold criteria, based on each model's climatology (for ECHAM4.5 and for the RSM) (Camargo and Zebiak, 2002). The threshold values for ECHAM4.5 in the western North Pacific and the RSM are given in Table I. In the tracking part, the tracks are obtained from the vorticity centroid, which defines the center of the TC, and relaxed criteria. The detection and tracking algorithms have been previously applied to a regional climate model forced by reanalysis data (Landman *et al.*, 2005) and to various AGCMs (Camargo and Zebiak, 2002; Camargo and Sobel, 2004; Camargo *et al.*, 2005).
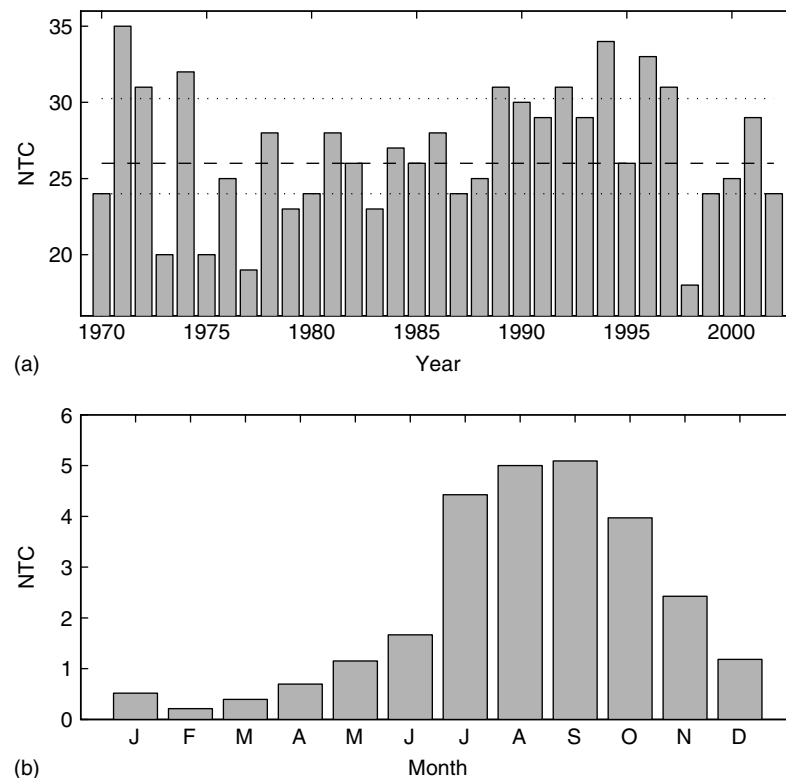
Figure 2. (a) Number of named tropical cyclones (NTC) per year, (b) average number of named tropical cyclones (NTC) per month in the western North Pacific in the period 1970–2002.

3. OCEANIC AND ATMOSPHERIC CONDITIONS

We begin by examining the SST and atmospheric conditions associated with TC formation for the two typhoon seasons studied. The SST anomalies, obtained from the Reynolds dataset (Reynolds *et al*., 2002), for JJASON (June–November) 1994 and 1998 are shown in Figure 1. In the summer and fall of 1994, the El Niño event of 1994/1995 was developing and positive SST anomalies in the central and eastern equatorial Pacific were observed. In contrast, in JJASON 1998, a long lasting La Niña event was developing, the SST in the Pacific warm pool were warmer than usual and negative SST anomalies in the central and eastern equatorial Pacific were evident. The western North Pacific SST anomalies were below normal (above normal) in 1994 (1998), associated with a high (low) number of typhoons. This association is consistent with the results of Chan and Liu (2004) and shows that in the western North Pacific the local SST does not determine the level of typhoon activity. Besides, there is an increase in the number of TCs in the western North Pacific during strong warm ENSO events (Wang and Chan, 2002). There is also a shift of TC activity to the southeast (northwest) in El Niño (La Niña) years (Pan,

The TC observational data was based on the Typhoon Warning Center (JTWC) best track dataset for the years 1994 and 1998 (JTWC, 2006). Tropical depressions are present in the best track dataset, but here only TCs with tropical storm intensity or higher are included.

1982; Chan, 1985; Chia and Ropelewski, 2002; Wang and Chan, 2002; Camargo *et al*., 2004b). This shift in TC genesis location in El Niño events leads to longer lived, more intense typhoons and therefore higher values of the accumulated cyclone energy (ACE) (Camargo and Sobel, 2005). A recent review of TC activity in the western North Pacific in interannual and interdecadal time scales is found in Chan (2005).

Besides SST, another important factor determining the amount of TC activity in a season is the vertical wind shear (i.e. the difference of the zonal winds at 200 hPa and 850 hPa). Previous studies (Gray, 1979; McBride, 1981) show that a favorable environment for genesis of typhoons is such that the vertical wind shear should be minimal near the center of the TC but large away from the center. In McBride (1981), one of the requirements for genesis is the existence of a large positive zonal shear to the north and negative zonal shear close to the south of the developing system. Figure 3 shows the zonal wind shear for JJASON 1994 and 1998 for the models (ensemble mean) and the ECMWF reanalysis (Uppala *et al*., 2005). Both the RSM and the AGCM capture the overall pattern of the zonal wind shear in both years. In 1994 there is a much larger region favorable for development – low shear and positive (negative) shear to the north (south) – than in 1998.

The difference of the surface pressure between 1998 and 1994 is shown in Figure 4 for the RSM and ECHAM4.5 models and for the ECMWF reanalysis. In all cases, 1998 (low TC activity) has higher values of surface
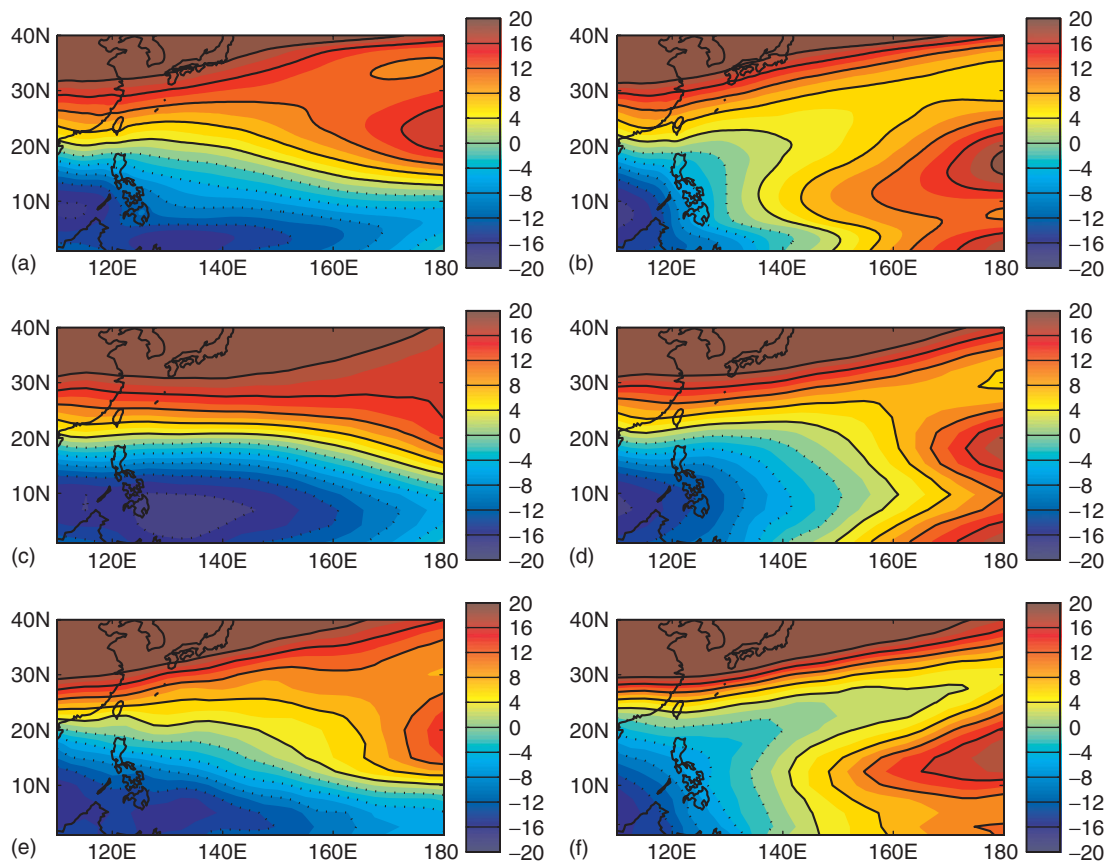
Figure 3. Vertical zonal wind shear (in m s^{-1}) of June–November 1994 (left panels) and 1998 (right panels) in the RSM ((a) and (b)), ECHAM4.5 ((c) and (d)) and ECMWF reanalysis ((e) and (f)). The vertical zonal wind shear is defined as the difference of the zonal winds between 200 and 850 hPa.

pressure than in 1994, showing a stronger subtropical high in the Pacific in that year. However, the RSM has a larger area of low surface pressure in the tropics than does either ECHAM or ECMWF.

In the northern summer, monsoonal southwesterly winds extend eastward from the Asian subcontinent. These near-equatorial westerlies meet the central Pacific easterlies on a moist confluence zone that is conducive to convection and wave accumulation (Holland, 1995; Sobel and Bretherton, 1999) and the formation of TCs (Briegel and Frank, 1997; Lander, 1996; Ritchie and Holland, 1999). In Figure 5, the zonal winds at 850 hPa are shown for the RSM and ECHAM4.5 modes and the ECMWF reanalysis in 1994 and 1998. The monsoon trough region in 1994 extends to the eastern part of the western North Pacific region, contributing to the high TC activity in that year. In contrast, the westerlies in 1998 only reached the Philippines region, leading to a much smaller region of confluence in the Pacific. The RSM zonal winds are very similar to the reanalysis in both years, with the exception of stronger westerlies around 110°E.

One of the factors important in the formation of TCs is the presence of cyclonic vorticity in lower levels. The vorticity at 850 hPa for 1994 and 1998 (not shown) shows larger values of cyclonic vorticity in 1994 than in 1998 in both models and observations. However, the patterns are quite distinct. While the RSM model has

a maximum around 10°N, from 150°E to 170°E, the ECHAM4.5 maximum occurs northeast of the Philippines (20°N, 135°E). The position of this vorticity maximum in the ECHAM4.5 model is similar to the maximum in the ECMWF reanalysis. However, neither model shows the vorticity maximum over the South China Sea, which is present in the Reanalysis.

4. CHARACTERISTICS OF RSM TROPICAL CYCLONES

4.1. Typical RSM tropical cyclone

A typical TC in the RSM and ECHAM4.5 models is shown in Figures 6 and 7, respectively. The instantaneous fields near a model TC are shown at the same time in the RSM and ECHAM4.5 models. Higher resolution leads to a much finer representation of the 850 hPa vorticity in the RSM compared with the ECHAM4.5. Also, the vorticity reaches much larger values in the RSM. Instantaneous precipitation and humidity values are also larger in the regional model, and there appears to be a rain band that was not present in the AGCM simulation. The maximum wind speed values are higher in the RSM representation of the storm, and there is a clear minimum in the center of the storm, an attempt by the RSM to produce the storm's 'eye'.
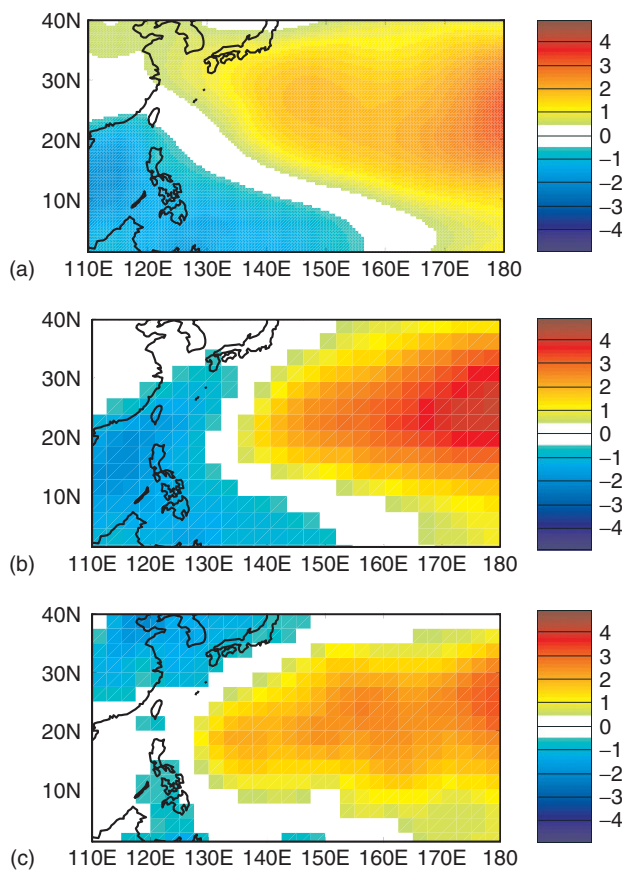
Figure 4. Surface pressure difference (in hPa) of JJASON 1998 and 1994 (a) RSM, (b) ECHAM4.5 and (c) ECMWF reanalysis.

Therefore, higher resolution gives a representation of the TC that is much more similar to reality than that obtained using a coarse resolution model. The next question to be answered is whether the higher resolution improves aspects of the model that are important for seasonal prediction of TC activity.

4.2. Number of tropical cyclones

In the 2 years chosen for our experiment, 1994 and 1998, there was a large difference in the number of NTCs in the observations in the period JJASON, namely 30 in 1994 and 16 in 1998. Table II shows the ensemble mean number of TCs in JJASON 1994 and 1998 for both models and the observations. The mean number of JJASON NTCs in the period 1970–2002 (more reliable data, postsatellite) in the western North Pacific is 22.6, and the standard deviation is 3.8. So both years have

Table II. Number of tropical cyclones per season (JJASON) in the models (ensemble mean) and observations in 1994 and 1998.

	1994	1998
RSM	36.3	39.3
ECHAM4.5	18.3	13.9
Observations	30	16

a number of TCs that differ from the historical mean by more than one standard deviation. In the period 1970–2002, 1998 had the lowest number of NTCs in the peak season (JJASON), while 1994 had the second highest, fewer only than 1971.

The mean number of JJASON TCs in the western North Pacific produced by the ECHAM4.5 using the average of 10 ensemble members in the period 1970–2002 is 16.8 (16.4 with 24 ensemble members), with a standard deviation of 1.7 (1.6 with 24 ensemble members). The ensemble mean number of TCs produced by ECHAM4.5 forced with observed SST (and 10 ensemble members) in JJASON 1994 and 1998 was, respectively, 18.3 and 13.9 (Table II), not as large a difference as in the observations, but the standard deviation is also lower. The difference between the ensemble mean number of TCs of ECHAM4.5 in both years is statistically significant at the 5% level using both the Wilcoxon rank sun test for the median of two distributions and the two-sample t-test for the mean of two distributions. It is interesting that although the ECHAM4.5, which is forcing RSM has a bias toward a low number of TCs, the RSM has a bias in the opposite direction, with too many TCs (Table II). Another interesting aspect is that ECHAM4.5 has more TCs in 1994 than in 1998, as is the case of the observations. In contrast, the ensemble mean number of TCs for the RSM is larger in 1998 than in 1994.

4.3. Tropical cyclones genesis locations

One of the crucial questions is whether the RSM model forms TCs independent of the global model. As we saw in the previous section, the RSM has more TCs per season than the ECHAM4.5. This means that the RSM is able to create at least a few TCs on its own. Let us examine the TC genesis locations. Figure 8 shows the first position of all TCs in the observations and in one of the ensemble members of the models. Note the formation of cyclones near the Philippines in the RSM, which does not happen in the ECHAM4.5. The first position density (not shown), constructed using all ensemble members confirms the formation of TCs in the RSM that did not exist in the ECHAM4.5 model.

Regarding the distribution of the genesis location of the TCs (not shown), the westward bias of the ECHAM4.5 model (Camargo et al., 2004a, 2005) is also present in the RSM model; while the southward bias is partially corrected, probably because of the finer resolution. In the observations, the genesis occurs further west in 1994 than in 1998, a feature that is reproduced in the ECHAM4.5 model, but not as well by the RSM model. In 1998, the observed genesis latitudes had a much smaller standard deviation (3.5°) than in 1994 (6.2°). The ECHAM4.5 model latitude distribution in 1994 is shifted equatorward in comparison with 1998, but the standard deviation in both years is much more similar than in observations (5.6°) and (5.2°), respectively.
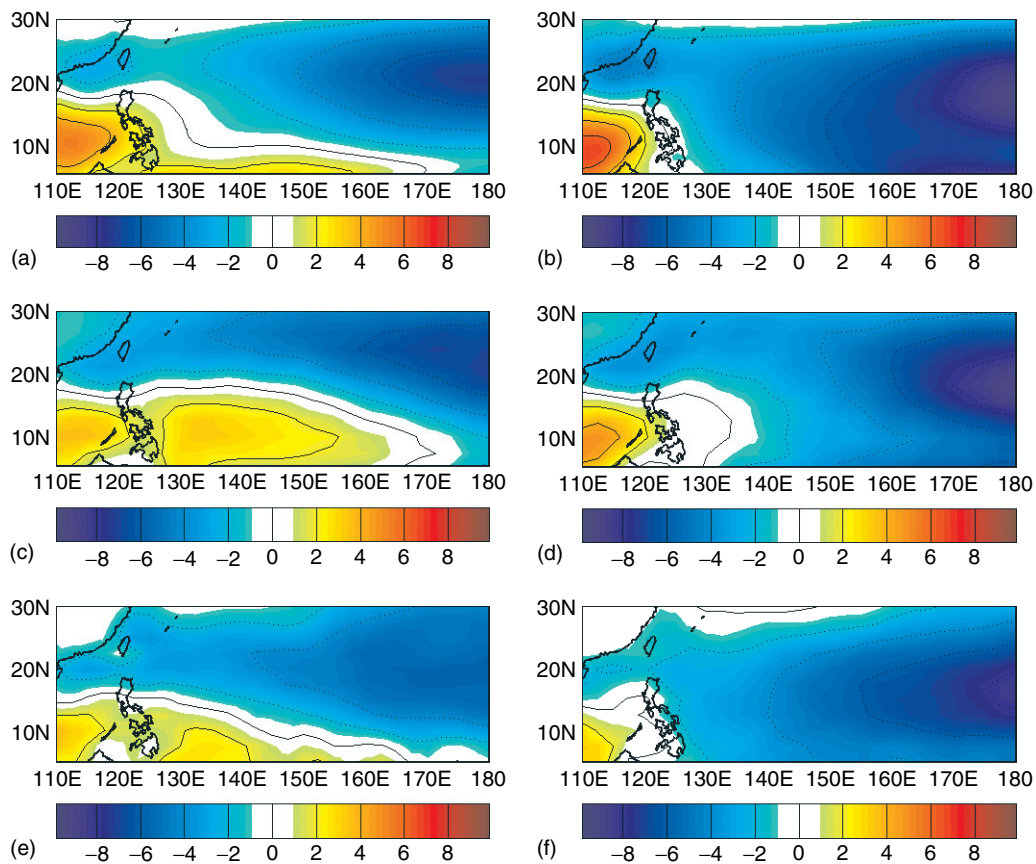
Figure 5. Zonal winds at 850 hPa (in m s^{-1}) for the season June–November: in 1994 (left panels) and 1998 (right panels) for the RSM (a) and (b), ECHAM4.5 (c) and (d), ECMWF reanalysis (e) and (f).
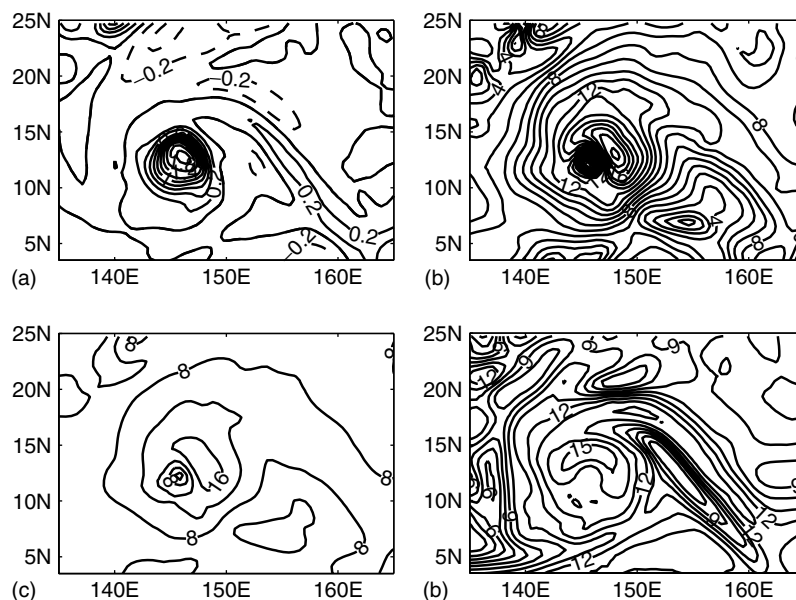

Figure 6. Typical fields of a RSM model tropical cyclone. (a) Vorticity at 850 hPa ($\times 10^{-4}$ s^{-1}), (b) wind speed at 1000 hPa (m s^{-1}), (c) precipitation (mm day^{-1}) and (d) specific humidity 850 hPa (g kg^{-1}), at 00 : 00 14 June 1994 in one of the ensemble members.

4.4. Tracks

Examining the tracks in the models and observations (Figure 9), we see that RSM has smoother tracks than does the ECHAM4.5, probably because of the higher resolution of RSM. However, the tracks still do not look very similar to the observed tracks, with very few TCs making landfall and with some TCs staying almost stationary for a few days, especially near the RSM boundaries.
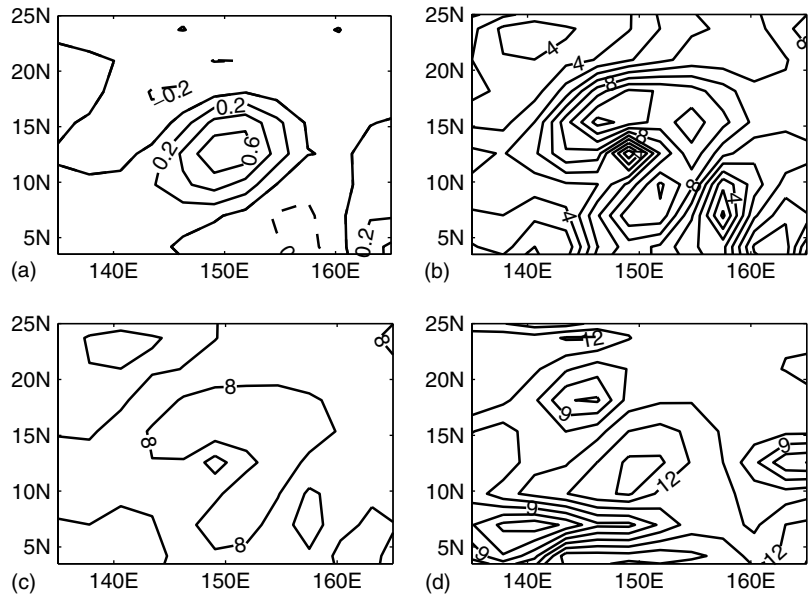
Figure 7. Typical fields of a ECHAM4.5 model tropical cyclone. (a) Vorticity at 850 hPa ($\times 10^{-4}$ s^{-1}), (b) wind speed at 1000 hPa (m s^{-1}), (c) precipitation (mm day^{-1}) and (d) specific humidity at 850 hPa (g kg^{-1}), at 00:00 14 June 1994 in the ensemble member that forces the simulation of RSM shown in Figure 6.

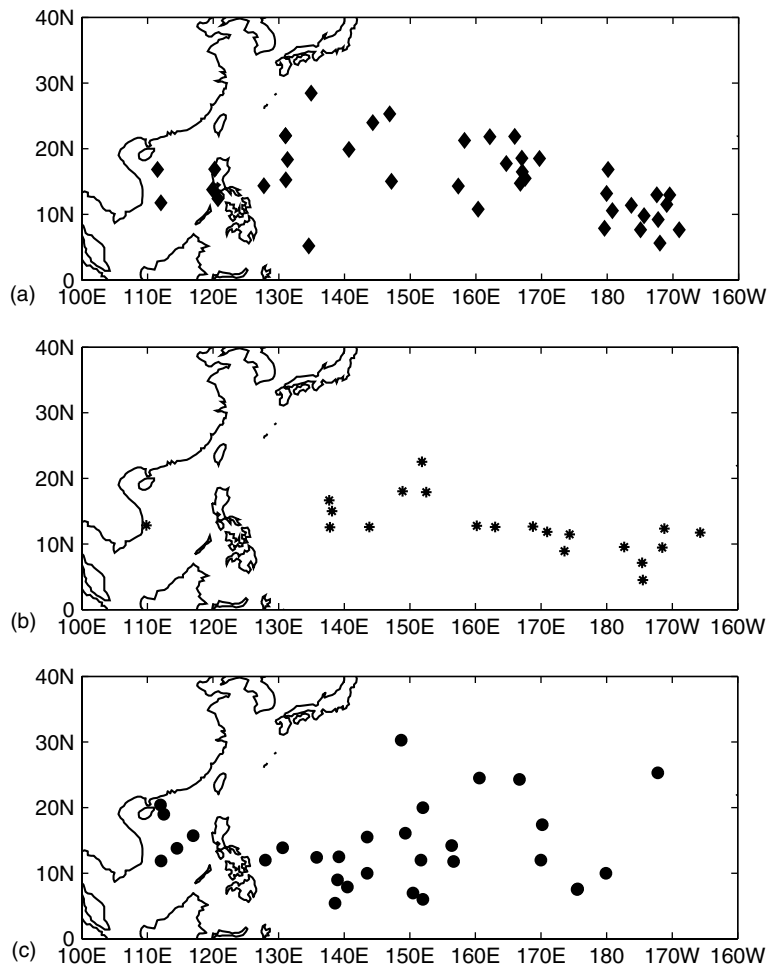Figure 8. First position of western North Pacific tropical cyclones for June–November 1994 in a single simulation from the (a) RSM, (b) ECHAM4.5 and (c) in observations. The ECHAM ensemble member shown in (b) forces the RSM simulation in (a).
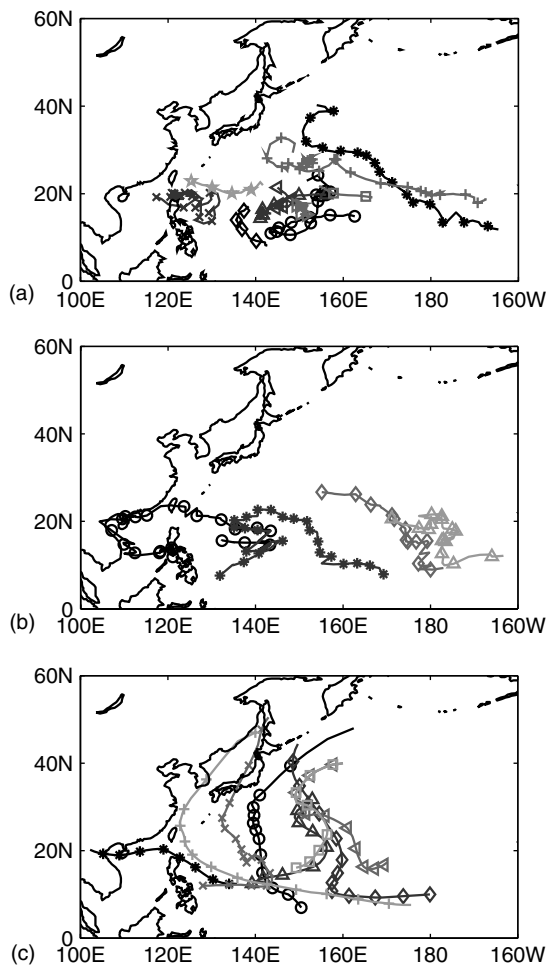
Figure 9. Tracks of western North Pacific tropical cyclones in September of 1994 in one of the ensemble members in the models (a) RSM, (b) ECHAM4.5 and (c) in observations. The ECHAM ensemble member shown in (b) forces the RSM simulation in (a).

Figure 10 shows the tracks density difference between 1994 and 1998. Both models have a higher density of tracks in 1994 than in 1998, as in the observations, as shown by the predominance of yellows and reds. However, while in the observations the maximum of the density difference is in the middle of the basin, both models tend to have an east–west pattern, with a higher density of tracks in 1994 in the east part of the basin and a predominance of tracks in the western part of the basin in 1998. This east–west pattern can also be noted when the tracks density of the observations for each year is examined (not shown), as well as in the statistics of the distributions, but is not obvious from the track density difference pattern. The east–west pattern in the track density is due to the southeast (northwest) shift of TC activity in El Niño (La Niña) events in the western North Pacific (e.g. Chia and Ropelewski, 2002). This shift in the location was reproduced in the RSM and ECHAM4.5 models mostly as an east/west shift in TC activity (Figure 10).

The RSM track density is maximum in locations more similar to the observations than in ECHAM4.5, which has
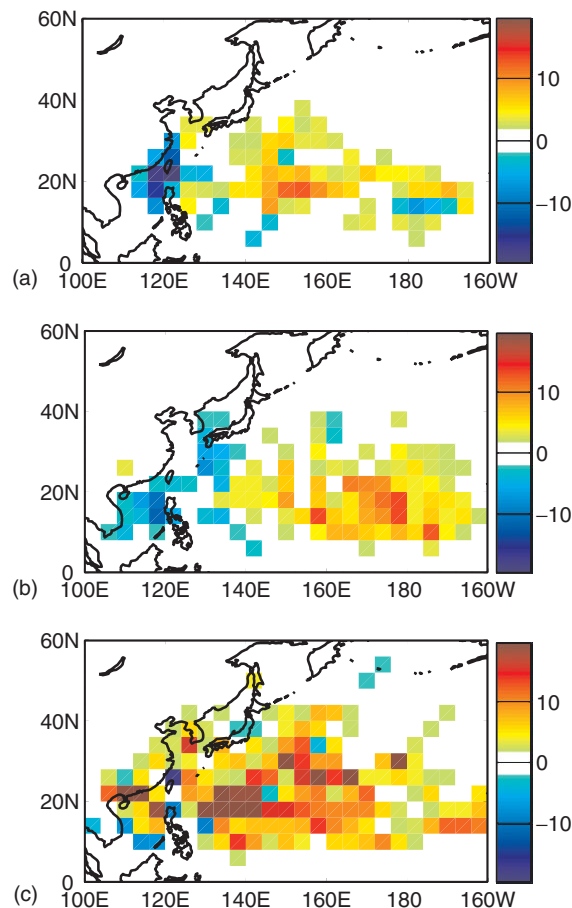

Figure 10. Track density difference of western North Pacific tropical cyclones in JJASON 1994 and 1998 ensemble mean in the models (a) RSM, (b) ECHAM4.5 and (c) in observations.

a known eastward bias (Camargo *et al.*, 2004a, 2005). In the RSM also the tendency of having nonzero track density values near the equator is also not present, while it occurs in the ECHAM4.5, due to the low resolution, as is typical of AGCMs TC activity at this resolution (Camargo *et al.*, 2005).

4.5. Tropical cyclone intensity

ACE (Bell *et al.*, 2000) is defined as the sum of the squares of the maximum wind of TCs active in the model at each 6-h interval. In the case of observations, only tropical storms or typhoons were considered, i.e. tropical depressions are not included in the calculation of seasonal ACE.

In both models, the seasonal ACE distribution is shifted to higher values in 1994, with both models having a wider spread among the ensemble members in 1998 (Figure 11(a)). Though both models have essentially the right behavior with lower seasonal ACE in 1998, because of the low resolution of both the ECHAM4.5 and RSM, seasonal ACE values in the basin per season are much smaller than the observed ACE value (Figure 11(b)). The seasonal ACE values of RSM are slightly larger than the case of ECHAM4.5. The models' ACE are too small during the most active months
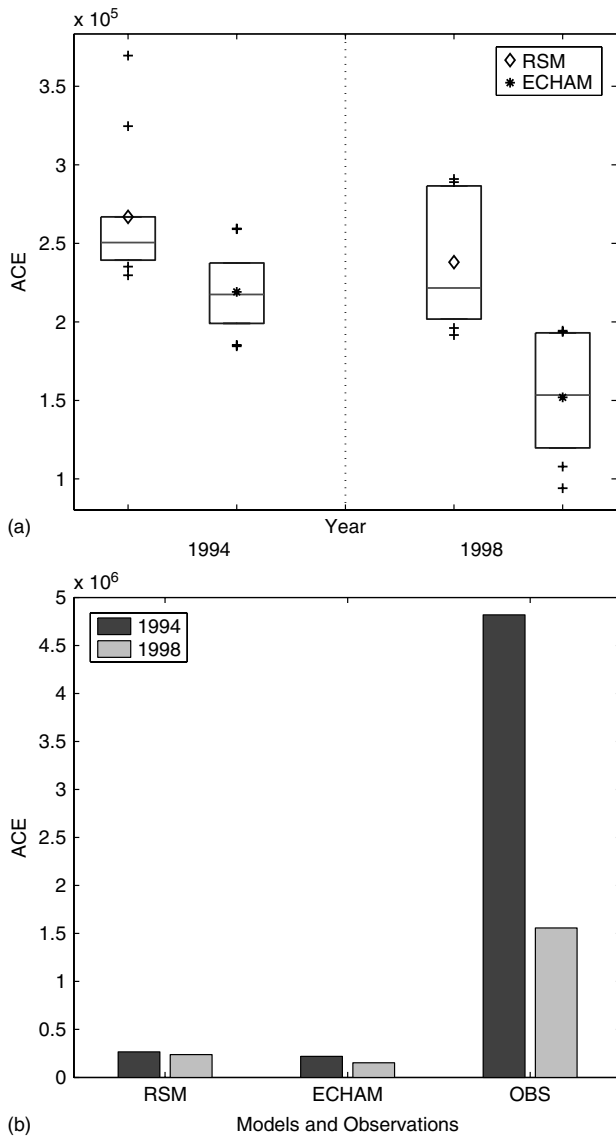
(a)

(b)

Figure 11. (a) Distribution of ACE per season (JJASON) in 1994 and 1998 of the 12 ensemble members of RSM and ECHAM4.5 models. The boxes show the 25th and 75th percentiles, the lines in the boxes mark the median, the asterisks and deltas the mean, and the crosses the values below (above) the 25th (75th) percentiles of the distributions. (b) ACE per season (JJASON) in 1994 and 1998 for the models (median of the ensemble members) and observations.

(July to October), but in the beginning and end of the season the models are comparatively too active, having a much flatter annual cycle than the observations (not shown).

Let us examine the characteristics of the intensity of the TCs in the RSM and ECHAM4.5 in more detail, by examining the distribution of the maximum wind speed and vorticity of all TCs of each model (Figure 12). The peak of the distribution of the RSM TCs wind speed occurs for smaller values than the peak of ECHAM TCs (Figure 12(a)), however, the distribution for RSM has a longer tail. In contrast, the distribution of the maximum vorticity of the TCs (Figure 12(b)) for the RSM is shifted to higher values and has a longer tail compared with ECHAM. Therefore, in terms of
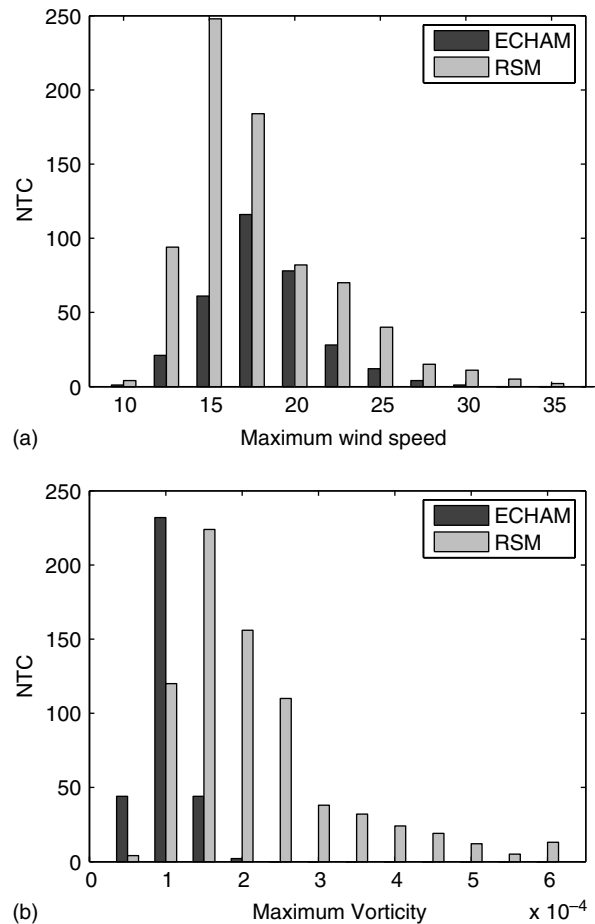

(a)

(b)

Figure 12. Distributions of (a) maximum wind speed (m s^{-1}) and (b) vorticity (s^{-1}) of the RSM and ECHAM4.5 tropical cyclones.

maximum wind speed most of the RSM TCs are weak, though a few of them do manage to intensify. In terms of vorticity, the RSM TCs are more intense than the ECHAM4.5 TCs, which is consistent with the smaller size of TCs in the RSM and not very high values of wind speeds.

4.6. Tropical cyclone duration

The lifetime distribution of the TCs in the models and observations is given in Figure 13(a). In AGCMs, the average TC lifetimes are larger than those observed (Camargo *et al.*, 2005), as shown in the case of ECHAM4.5 in Figure 13(a). The RSM lifetimes are much more similar to the observed ones, the downscaling correcting this bias of the AGCMs.

The number of days in which a TC is active in the base on a determined season (or month) is called the number of TC days. In terms of TC days, both models have a bias toward high values, especially in 1998, as shown in Figure 13(b). This high number of TC days is not because of the lifetimes of the RSM TCs, which are very similar to the observed, but rather to the high number of TCs generated by the model.
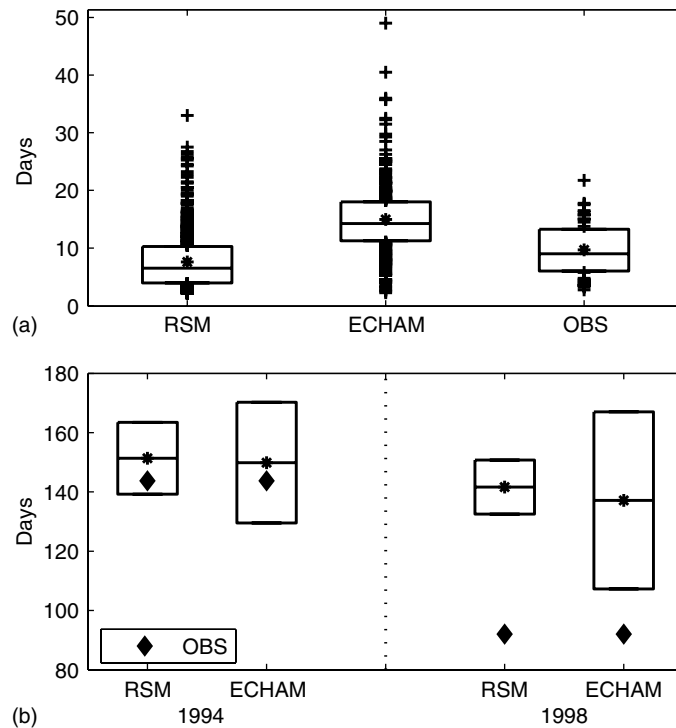
Figure 13. (a) Distributions of all tropical cyclones lifetimes in the RSM and ECHAM4.5 and observations. (b) Distributions of all tropical cyclone days per season in the models and observations in 1994 and 1998.
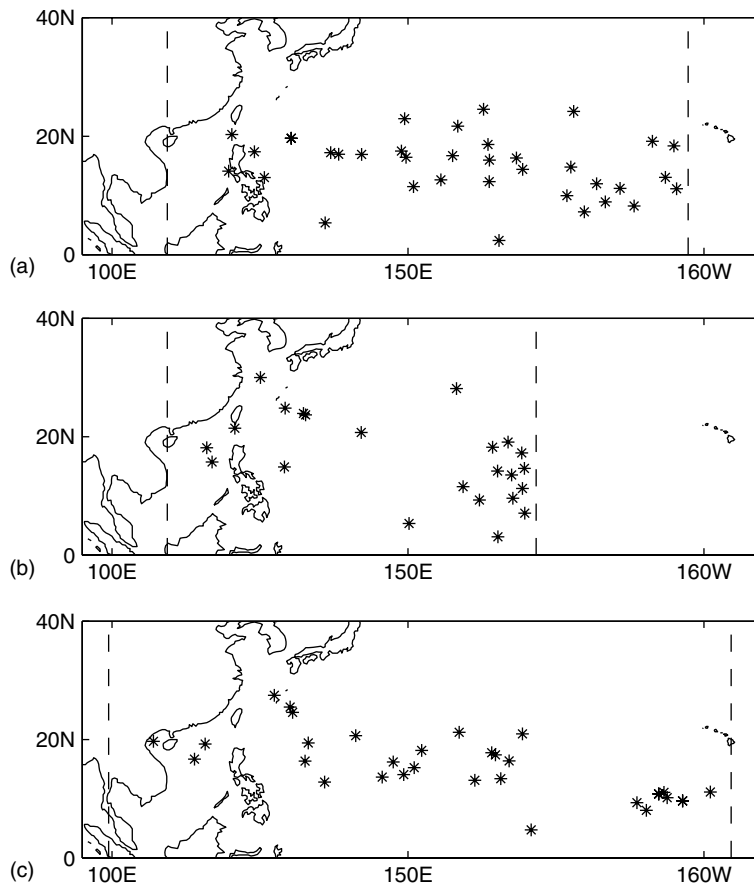

Figure 14. First position locations of RSM model tropical cyclones for the standard (a), small (b) and large (c) domains in JJASO 1994 for one ensemble member. The three RSM simulations were forced by the same ECHAM ensemble member. The dashed lines show the regional model longitudinal boundaries in each case.
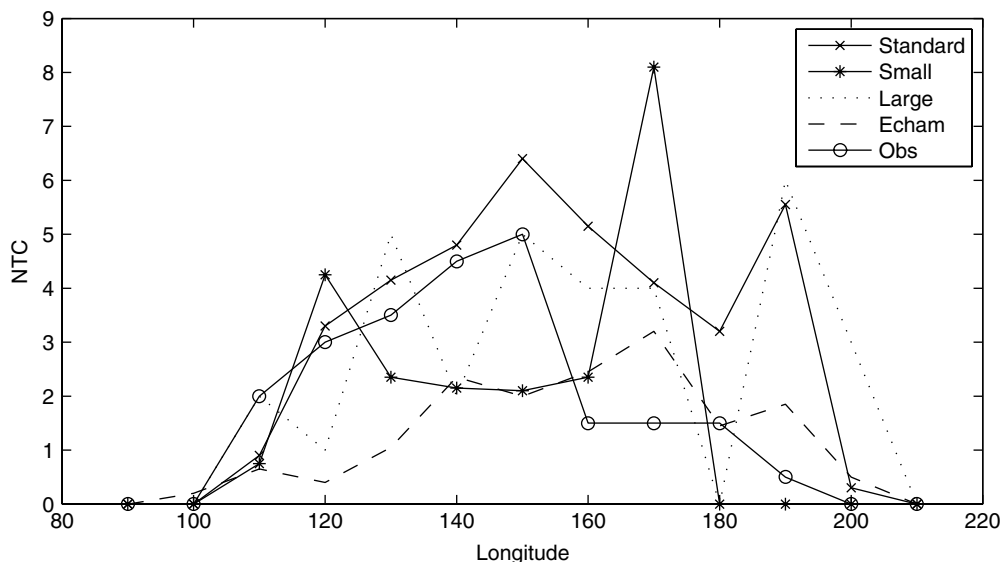
Figure 15. Mean number of tropical cyclones per longitude band in the RSM model (standard, small and large domains), the Echam4.5 model and in observations. In the case of the standard, small, and Echam4.5 models, ten ensemble members and two seasons were used in calculating the mean. The observations values are the mean of the two seasons. In the case of the large domain, it is the total number of genesis per longitude band in the 1994 season (one ensemble member only).

Table III. Boundary domain size of baseline simulations and sensitivity tests simulations with the RSM.

Type	Years	Ensemble Members	Longitude Range	Resolution (km)
Standard	1994, 1998	10	109.7 °E to 162.6 °W	50
Small domain	1994, 1998	10	109.7 °E to 171.7 °E	50
Large domain	1994	1	99.4 °E to 155.4 °W	50

5. SENSITIVITY TESTS

The regional climate model simulations are affected by domain size and location of the lateral boundaries (Seth and Giorgi, 1998). Landman *et al*. (2005), showed recently that the simulation of TCs by a regional climate model over the South Indian Ocean is strongly influenced by the position of the eastern boundary of the regional model domain, as many cyclones are advected through that boundary. In that study, it was also shown that the size of the domain also determined the ability of that regional model to simulate TCs tracks and landfall.

In contrast to Landman *et al*. (2005), a regional spectral model is used here, not a grid point regional model. In a regional spectral model, there is no buffer zone, as the spectral model is a perturbation model and it is forced with the large-scale fields throughout the domain, and not only in the boundaries. However, there are still boundary effects, as these perturbations are defined to be zero at the boundary. In previous studies (Juang and Kanamitsu, 1994; Sun *et al*., 2006), it was shown that the boundary effects are usually restricted to a very small (five grid points) region around the boundaries.

To evaluate how the results we obtained are dependent on the choice of the model boundary locations and size, we did two separate set of experiments, differing in the domain size and location.

In the first experiment (named 'small domain'), the eastern boundary of the domain was moved westward and the western boundary was kept in the same location; this experiment is named here. In the second experiment (named 'large domain'), the domain was expanded, with western (eastern) boundary shift westward (eastward). The details of these experiments are given in Table III.

In Figure 14 the genesis locations of the model TCs for the three different experiments are shown. The only difference among these experiments is the domain size of the regional model. In the three cases shown, the RSM was forced by the same ECHAM ensemble member in the June–November 1994 period. In the standard (a) and the small domain (b) experiments, there is a high concentration of genesis near the eastern boundary of both domains. The problem being more accentuated in the smaller domain (b). By having a larger domain (c), the genesis locations are spread more evenly. Note also the genesis of a TC west of Hainan island in the large domain (c), which was not possible to occur in the two other domains. In Figure 15, the mean number of TCs per longitude band in each case (including observations and the Echam4.5 model are shown). One notices that the genesis formation east of the dateline is very rare in observations. Also, it is clear that the ECHAM model has an eastward bias in
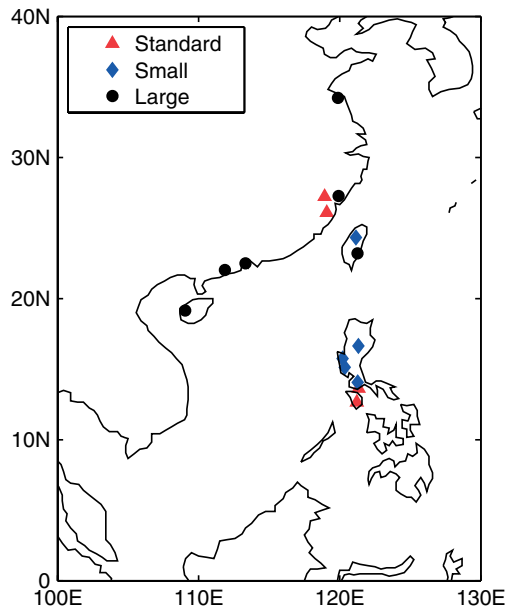
Figure 16. Landfall locations of the RSM model tropical cyclones for the standard, small and large domains, in JJASO 1994 for one ensemble member. The three RSM simulations shown are forced by the same ECHAM simulation.

genesis location (as discussed in Camargo *et al.* (2005)) and the RSM model forced by the large-scale fields of the ECHAM4.5 has the same eastward bias, accentuated near the regional model boundary. It is important to remember that in Figure 15, ten ensemble members and two seasons were used to calculate the mean in the case of the standard and small RSM domain, as well as for the ECHAM model. In contrast, the large domain uses only one season and ensemble member; and the observation of two seasons, and the curves in these cases are noisier.

In Figure 16, we show the landfall locations for each of the three domains forced by the same ECHAM ensemble member in the June–November period. With the extended domain, a larger number of landfalls occur in the Asian continent, compared with the smaller domains. Therefore, a domain choice with a westward extension would be fundamental for landfall probabilities studies.

6. CONCLUSIONS

In this paper, we explored using the RSM regional climate model to improve the TC activity forecasts in AGCMs. To do that, we forced the RSM in two typhoon seasons (June–November) with ten ensemble members of the AGCM. The two typhoon seasons chosen (1994 and 1998) have a high (low) typhoon activity, respectively.

Some of the aspects of the RSM TCs are indeed improved compared to the AGCM, because of the finer horizontal resolution. However, the signal in the difference of the number of TCs in the two seasons is not reproduced in the RSM, while it was present in the AGCM. In contrast, the TC activity in terms of track

density and ACE is indeed higher in 1994 than in 1998 in the RSM model.

Therefore, although the RSM does not produce more TCs in 1994 than 1998, in 1994 the TCs last longer and are more intense than in 1998, with an overall higher model TC activity in 1994 than in 1998, as in the observations. Though this result is not very encouraging, one has to keep in mind that only two seasons were analyzed and for a definite answer of the skill of the RSM many more years of simulation would be necessary.

We also discussed the effect of domain choice in our simulations. These sensitivity tests suggest that a larger domain would result in more realistic simulations than in the case of the standard domain used in this study.

Another point to keep in mind is that using a new version of the RSM could, in theory, improve the TC activity in the model. A parameterization of the convection-induced pressure gradient force (PGF) in convective momentum transport (CMT) was implemented in the new version of RSM. Inclusion of the CMT helps suppress spurious development of TCs. In the parameterization the PGF is assumed to be proportional to the product of the cloud mass flux and vertical wind shear. The new PGF parameterization helps increase hurricane intensity by reducing the vertical momentum exchange, giving rise to a closer comparison to the observations (Han and Pan, 2006).

NOTES

1. The ECMWF TCs seasonal forecasts are not public.
2. The 'small domain' experiment was actually our first choice of domain, and ten ensemble realizations of two seasons with this domain were performed. While analyzing the results of this experiment, we decided that a larger domain would be more appropriate and the integrations were then repeated with our standard domain. The 'large domain' experiment was performed with only one ensemble member in one season only, owing to computational time constraints.

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