EXPLORING THE FEASIBILITY OF REGIONAL TYPHOON MODELLING

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Abstract

An ensemble of typhoon events was examined to detect systematic skills and deficiencies of regional atmospheric models in dynamical downscaling these extreme weather phenomena from global reanalyses data. A regional atmospheric model hindcast was computed for the typhoon season 2004 for SE Asia and the western Pacific. Global reanalyses data were dynamically downscaled to a grid resolution of about 50 km and in a double-nesting approach to 18 km. Simulated typhoon tracks and intensities were compared to best track data. The comparison revealed improved SLP and near-surface wind values by the RCM compared to the reanalyses for most cases. The reanalyses showed smaller great circle distances to the best track data than the regional model. Precipitation patterns and rainfall amounts were simulated more realistically by the RCM using the higher resolution compared to the 50 km run. It is concluded that regional models can improve simulated typhoon developments from global forcing reanalyses data by giving lower core pressure and higher wind speeds and more realistic precipitation patterns even though these values still do not reach observed values.

1. Introduction

Tropical cyclones (TCs) pose a threat for flooding and for extreme weather conditions affecting the population living close to the coast. Global reanalysis data exist (e.g. NCEP-NCAR reanalyses, Kalnay et al. (1996)) which include a large number of TC on a low-resolution basis (e.g. 200 x 200 km). For extreme-weather events like typhoons this resolution is too coarse to simulate realistic low pressure cores and adjacent extremely high wind speeds. In this paper an approach for a dynamical downscaling system is presented which shall eventually lead to high-resolution atmospheric data which may serve as input data for wave, water level, or storm surge models. A similar dynamical downscaling strategy for the last decades was developed during the last years for western Europe (Feser et al. (2001); Sotillo et al. (2005), Weisse et al. (2005)), and for seasons in SE Asia (Lee et al. (2004); Kang et al. (2005)). The idea is to force large-scale synoptic information provided by reanalyses, such as prepared by NCEP-NCAR, upon a regional atmospheric model (RCM; von Storch et al. (2000); Miguez-Macho et al. (2004)). A similar approach was used by Wright et al. (2006) for oceanographic simulations. In the approach presented here the RCM is not only run with information along the lateral and lower boundaries but uses also a method called ”spectral nudging” (von Storch et al. (2000); Waldron et al. (1996)) in the regional model’s interior. This technique forces the simulated large-scale state in the RCM domain to be close to the analysed spacious weather phenomena. The large-scale state in the reanalyses is believed to be accurately described and homogeneous, while smaller scales may be less well described and subject to variations related to changing observational quality and distribution. Therefore the RCM results are nudged towards the reanalyses data by adding nudging terms to the RCM solution only for large spatial scales while the regional scales are left unchanged.

Camargo et al. (2007) analyzed the feasibility of downscaling a global model's seasonal tropical cyclone activity with observed sea surface temperatures using a regional model. Their results show that the representation of the tropical cyclones was improved but they were not as intense as observed cyclones. The regional model did not reproduce the lower number of tropical cyclones in 1998 (Nakazawa (2001)) compared to 1994. Landman et al. (2005) have demonstrated that even with a relatively coarse grid resolution of 60 km, tropical storms are satisfactorily described by a regional atmospheric model. A case study for dynamical downscaling of a single typhoon event was presented by Feser and von Storch (2007). Their results show that reanalyses reproduce the track close to observations while intensities and near-surface wind speeds show larger deviations. Using a RCM did not improve the track but yielded significantly lower core pressure and higher near-surface wind speed values. The method of Feser and von Storch (2007) shall be implemented to reconstruct tropical weather in SE Asia, but now for the last decades. Since hereby a major issue is the simulation of typhoons, the performance of the model is now analysed for one typhoon season with respect to typhoon tracks, sea level pressure (SLP) and 10 m wind speed statistics, and their precipitation patterns.

2. Model set-up and global forcing data

Global reanalysis data prepared by NCEP-NCAR (Kalnay et al. (1996), called NCEP reanalyses in the following) were dynamically downscaled using the state-of-the-art regional climate model (RCM) CLM (http://www.clm-community.eu), which is the Climate version of the operational weather forecast model Lokal Model (LM, Steppeler et al. (2003)) of the German Weather Service. Starting from the current model version 4.0, the LM and CLM are merged and the user is able to either select the climate or the forecast mode. The CLM is a RCM that can be run in hydrostatic or nonhydrostatic mode. Since 2005 it is the Community-Model of the German climate research. The model has been used for simulations on time scales up to centuries and spatial resolutions between 1 and 50 km. The advantages of this RCM are mainly the possibility to use it in nonhydrostatic mode when increasing the horizontal resolution as well as that spectral nudging (von Storch et al. (2000)) can be selected. It runs with standard parameterizations for physical processes; for convection the Tiedtke parameterization scheme (Tiedtke (1989)) was selected for this study. We analysed 12 typhoons between May and October of the typhoon season 2004. The selected typhoons were chosen according to the typhoons presented by Zhang et al. (2007). We intended to use their study as a high-quality comparison data set for the results of our simulations.

Two model set-ups were chosen for the regional model, one with a grid distance of 0.5°, which corresponds to about 50 km, and one with a grid distance of 0.165° equivalent to about 18 km (Figure 1). For the coarser 50 km run the NCEP reanalyses served as global input for the initialisation and the regional model boundaries. In addition to the usual forcing via the lateral boundaries a spectral nudging technique was applied for the whole model domain. This method adds nudging terms to the results of the RCM which 'nudge' the regional solution towards the forcing global model. The method was exclusively used for horizontal wind components, starting at a height of 850 hPa, and with increasing strength with height. Thereby we prevent the regional model from deviating from the global model for large spatial scales. For the NCEP reanalyses spatial scales larger than 6 grid points were considered reliably resolved (larger than about 800 km) and these spatial scales were nudged in the RCM simulation.

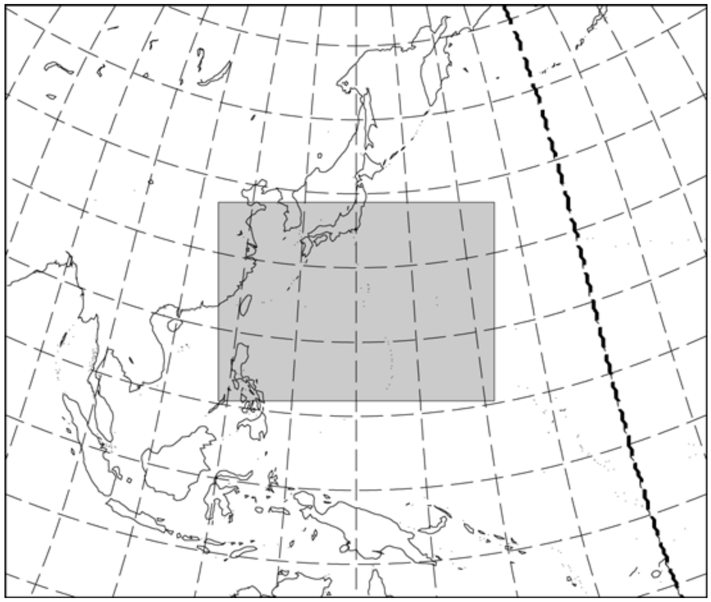

Figure 1 Model area for both regional CLM simulations. The larger area shows the model area of the 0.5° simulation, the smaller grey one the simulation area for the double nested 0.165° CLM run.

In a double-nesting approach a finer-resolution RCM run of 0.165° grid distance used the 0.5° RCM run as the forcing input. Once more the spectral nudging was applied, and again 6 model grid points were regarded reliably resolved by the forcing data. So this time spatial scales larger than about 300 km of the high-resolution run were nudged towards the forcing 50 km RCM simulation. The physical parameterizations were chosen like in the 50 km simulation.

3. Tracking

To identify the single typhoon events, a tracking algorithm was used that was described by Hodges et al. (1994) and Hodges et al. (1995)). For the 12 typhoons analysed, only 10 could be tracked in both the reanalyses and the regional model simulations, the other two were neither found in the reanalyses nor the RCM runs. For the RCM simulations the SLP data anomalies had to be low-pass filtered before the tracking to smooth the fields. For low-pass filtering a digital filter (Feser and von Storch (2005) was applied that removed spatial scales smaller than about 270 km for the 0.5° simulation and smaller than about 100 km for the 0.165° simulation. The tracking algorithm applied for the regional fields was used with the following search criteria: The tropical cyclones had to travel farther than 200 km in diameter, had to last longer than 8 hours, and the filtered SLP anomalies had to be lower than -300 hPa. For the reanalyses the tracking was done for sea level pressure (SLP) anomalies fields with search criteria that matched the ones for the RCM simulations. Since the data are 6-hourly and on a T62 grid with about 200 km grid distance no low-pass filtering was needed to smoothen the data before calculating the tracks. The model results were compared to “best track data” of the Japan Meteorological Agency (JMA, http://www.jma.go.jp/jma/jmaeng/jma-center/rsmc-hp-pub-eg/trackarchives.html). For this comparison first the tracks were selected and then the according full SLP and 10m-wind speed time series for the tracks were extracted from the simulations.

An overview over all 12 analysed typhoons of the 2004 season is given in Figure 2. The best tracks are shown as black solid lines, the reanalyses tracks as grey solid lines and the tracks of the regional simulation with 0.5° grid distance as grey dotted lines while the tracks of the 0.165° simulation are depicted as grey broken lines. Since the model area for the double nested simulation with 0.165° is much smaller than for the 0.5° simulation (see Figure 1), the tracks of the high-resolution run are only represented as long as they are located inside of the small simulation area. Most best tracks have a counterpart in both the reanalyses and the regional CLM data, only some typhoons were simulated just partly or not at all in the model runs.

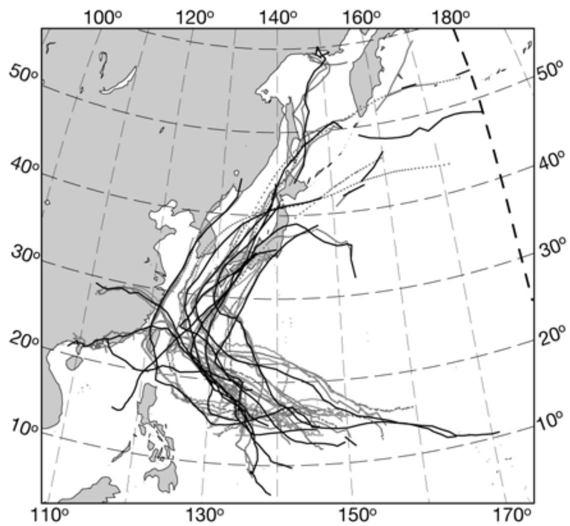

Figure 2 Overview for all 12 analysed tracks of the typhoon season 2004. Black solid lines show JMA best tracks, grey solid lines the reanalyses tracks, grey dotted lines the tracks of the 0.5° regional simulation, and grey broken lines the tracks of the regional 0.165° simulation.

4. Typhoon core pressure and near-surface wind speed

In the following modelled typhoon pressure and intensity evolutions are compared to best track data which were considered as being close to observations. Figure 3a shows the SLP for typhoon Dianmu (200406) from 06/11/2004 until 06/28/2004. This is an example for a typhoon representation close to the best track data in the RMC simulations. The JMA best track data reveal a large drop in SLP up to 915 hPa for the 16th of June 2004. This drop is only marginally recognizable in the reanalysis data, only values of about 984 hPa are reached. The regional simulations both with a grid distance of 0.5° and of 0.165° represent the drop in pressure with values of around 943 hPa and 936 hPa, respectively.

The wind speed for typhoon Dianmu (200406) is presented in Figure 3c. Like for the SLP results the reanalyses show only marginal higher wind speeds which peak at about 47 kt. The best track data has its maximum wind speeds on June 16 with 100 kt. The regional simulations reach much higher values than the reanalysis. The maximum wind speed amounts to about 87 kt for the 50 km simulation and about 3 kt higher values for the 18 km run.

An example for SLP and wind speed values which show a time lag and values with large differences compared to the best track data is shown in Figure 3b and Figure 3d for typhoon Songda. The best track data show two minimum pressure periods on September 1 and 5. Both the reanalyses and the RCM simulations drop off in pressure with several days time lag, reaching their minimum SLP values on September 8 with 969 hPa (NCEP), on September 5 with 957 hPa (CLM 0.5°) and on September 5 with 953 hPa (CLM 0.165°).

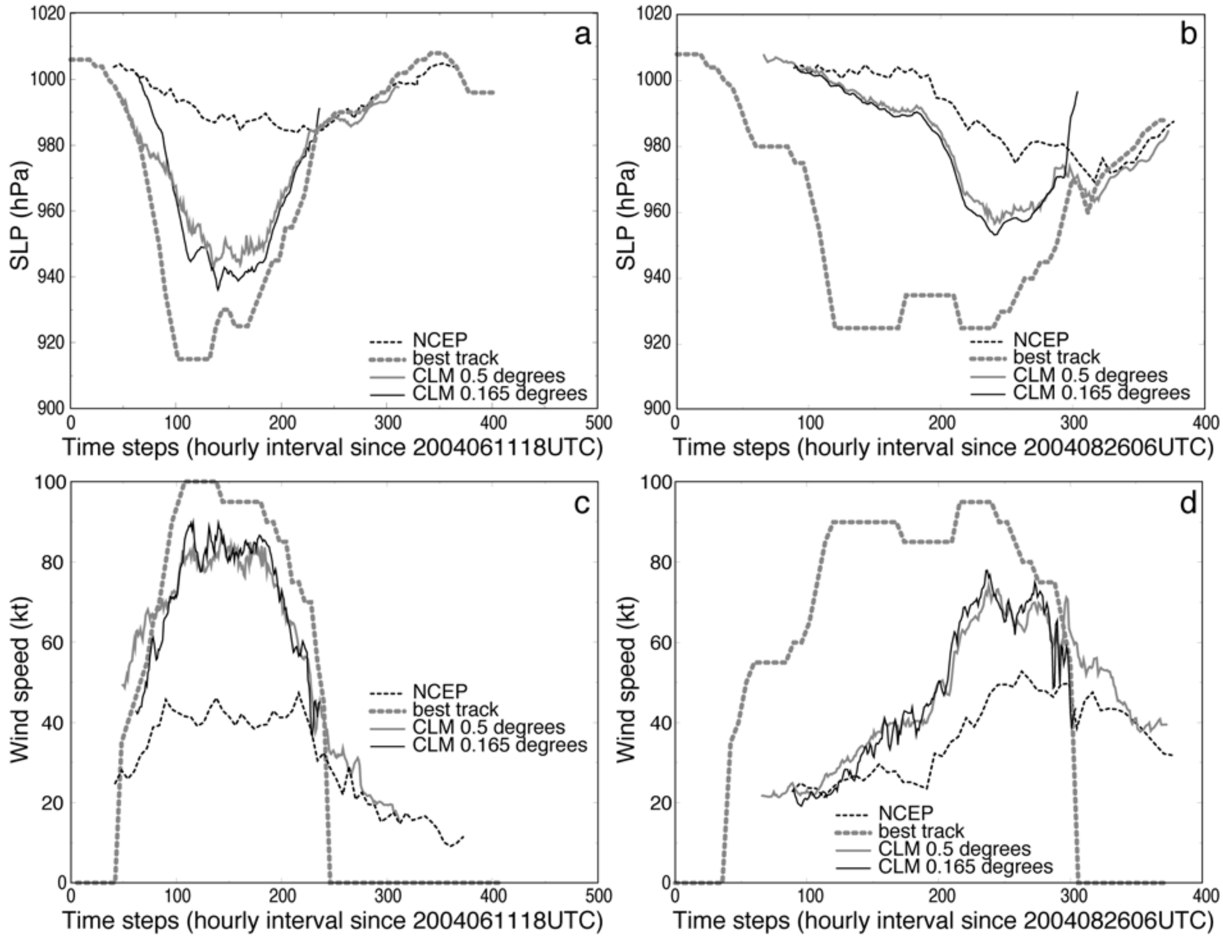

Figure 3 (a) SLP (hPa) evolution for typhoon Dianmu from June 11, 2004, 18 UTC, until June 28, 2004, 12 UTC. (b) SLP (hPa) evolution for typhoon Songda from August 26, 2004, 06 UTC, until September 10, 2004, 18 UTC. (c) 10 m wind speed (kt) evolution for typhoon Dianmu from June 11, 2004, 18 UTC, until June 28, 2004, 12 UTC (d) 10 m wind speed (kt) evolution for typhoon Songda from August 26, 2004, 06 UTC, until September 10, 2004, 18 UTC

Also, the great circle distance between the JMA best tracks and the tracks extracted from the model results was computed. The Haversine formula was calculated

$$\Delta\hat{\sigma} = \arccos(\sin\phi_s \sin\phi_f + \cos\phi_s \cos\phi_f \cos\Delta\lambda)$$

whereby $\phi_s, \lambda_s; \phi_f, \lambda_f$ are the geographical latitude and longitude of two points, $\Delta\lambda$ the longitude difference and $\Delta\hat{\sigma}$ the (spherical) angular difference/distance.

The time evolution for typhoon Dianmu is shown in Figure 4a. The tracks show quite large deviations in the beginning and smaller great circle distances during the development of the typhoon; while the RCM runs show some larger differences in the end as well. The regional model simulations show comparable distances (except for the very first period) with larger values than for the reanalyses. For typhoon Songda (Figure 4b) again the RCM simulations are quite close to each other while the reanalyses show smaller track deviations from the best track data.

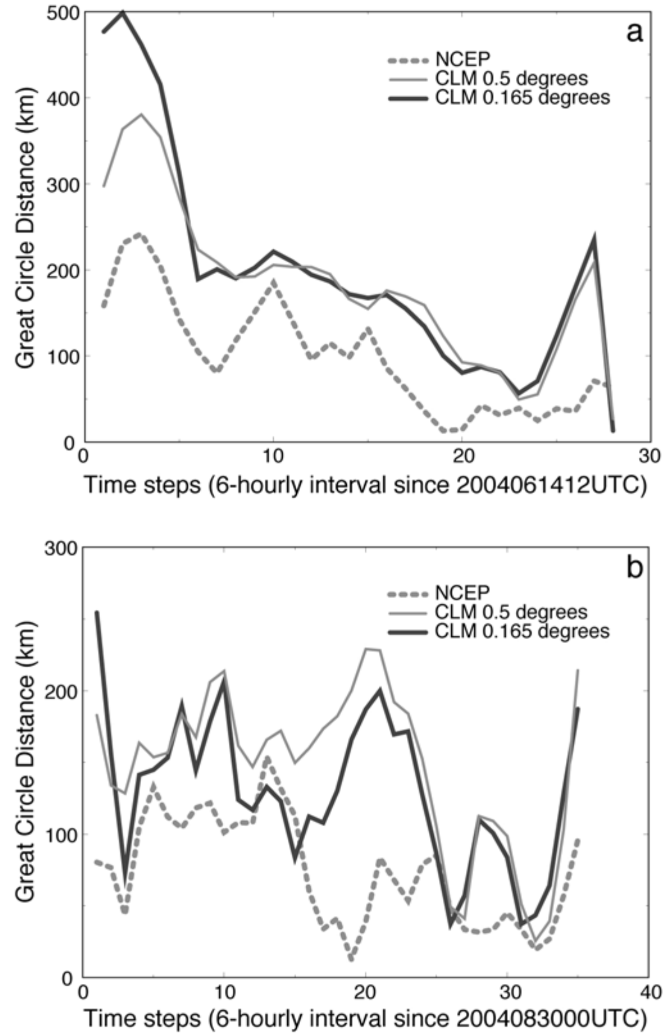

Figure 4 Great circle distance (km) between JMA best track data and the NCEP reanalyses (grey broken line), between JMA best track data and the 0.5° CLM simulation (grey solid line), and between JMA best track data and the 0.165° CLM simulation (black solid line) for (a) typhoon Dianmu from June 14, 2004, 12 UTC, until June 21, 2004, 12 UTC, and (b) for typhoon Songda from August 30, 2004, 00 UTC, until September 7, 2004, 18 UTC. The great circle distance was calculated according to the Haversine formula.

Table 1 shows the root mean square error (RMSE) for SLP and near-surface wind speed for all analysed typhoons. Typhoon Conson (200404) and typhoon Kompasu (200409) could not be tracked in both the reanalyses data as well as in the regional model runs. For the RMSE analysis only those time frames were chosen where all 3 model simulations (NCEP reanalyses, CLM 0.5° and CLM 0.165°) were simultaneously available. Since the high-resolution simulation of 0.165° is bounded to an area where mostly only the central part of the typhoon track was located these are the most difficult parts for the models to simulate with very low pressure cores and high wind speeds. Therefore the resulting values mostly do not represent the first and last days of the typhoon evolution where the models SLP and wind speed values generally are closer to the observations than during the peak periods of the typhoons.

Table 1 Root mean square error (RMSE) of SLP (hPa) and wind speed (kt) between JMA best track data and reanalyses as well as regional model simulations with 0.5° and 0.165° resolution. Also the mean great circle distance (GCD, km) between best tracks and the model simulations is given.

Typhoon Season 2004

Typhoon	Date	Model	RMSE SLP[hPa]	RMSE FF[kt]	GCD [km]
200406	06/11/2004	NCEP	53.83	46.32	98.53
	- 06/28/2004	CLM 0.5	25.49	14.34	183.21
		CLM 0.165	23.67	14.35	199.56
200407	06/21/2004	NCEP	23.16	33.59	121.57
	- 07/05/2004	CLM 0.5	12.17	20.48	134.54
		CLM 0.165	11.96	21.20	141.72
200413	08/06/2004	NCEP	24.03	34.87	186.45
	- 08/15/2004	CLM 0.5	14.84	22.84	393.48
		CLM 0.165	18.95	31.98	526.33
200415	08/14/2004	NCEP	13.72	21.64	148.03
	- 08/22/2004	CLM 0.5	9.64	14.77	254.16
		CLM 0.165	10.05	18.47	216.93
200416	08/18/2004	NCEP	60.14	53.99	106.20
	- 09/05/2004	CLM 0.5	40.61	34.20	200.21
		CLM 0.165	37.13	31.60	189.05
200417	08/18/2004	NCEP	20.02	31.82	145.84
	- 08/31/2004	CLM 0.5	14.04	19.67	262.65
		CLM 0.165	10.44	16.75	425.52
200418	08/26/2004	NCEP	58.27	50.14	74.08
	- 09/10/2004	CLM 0.5	48.02	39.38	146.81
		CLM 0.165	46.61	40.54	129.47
200421	09/19/2004	NCEP	46.82	46.35	51.08
	- 10/02/2004	CLM 0.5	44.67	46.80	351.35
		CLM 0.165	43.45	50.17	193.41
200422	10/03/2004	NCEP	30.66	33.48	57.80
	- 10/10/2004	CLM 0.5	31.76	39.00	321.03
		CLM 0.165	29.55	41.78	277.73
200423	10/12/2004	NCEP	35.95	37.59	99.73
	- 10/23/2004	CLM 0.5	24.14	26.08	184.47
		CLM 0.165	25.89	32.54	181.34

In all cases, except for Ma-On (200422), the SLP development is better described by CLM than by NCEP. In 7 out of the 10 cases, the high-resolution (0.165°) CLM performs better than the coarse (0.5°) CLM; in 3 cases the improved resolution does not lead to better results in terms of SLP (Figure 5a shows the according Brier Skill Scores of CLM versus NCEP). The result is less good for wind speed (see Figure 5b). In terms of this variable, CLM is not performing better than NCEP in 2 out of 10 cases; Usage of 0.165° grid-sizes leads to results closer to the best track numbers than 0.5° grid-sizes only in 2 out of 10 cases. In 8 of the 10 cases, the 0.5° CLM is performing better than the 0.165° CLM.

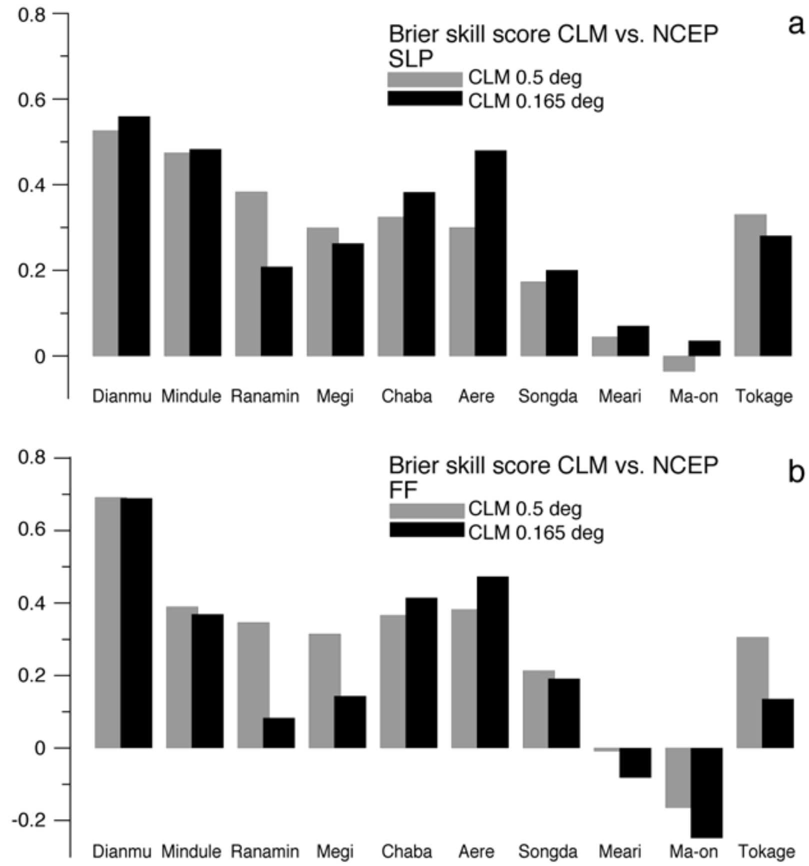

Figure 5 Brier Skill Score between JMA best track data and NCEP, CLM 0.5°, and CLM 0.165°, for (a) SLP and (b) 10 m wind speed for analysed typhoons, for values larger than 0 CLM is closer to the best track than NCEP, for 0 CLM is equally close to the best track as NCEP, for values smaller than 0 NCEP is closer to the best track than CLM.

The use of the regional model leads in most cases to deeper lows and stronger winds, compared to NCEP (Table 2); also the largest 6-hourly wind increases and pressure falls are stronger in case of the regional model. Thus, stronger tropical storms form in the regional model than in the NCEP re-analyses; the higher resolution leads to slighter deeper pressures, to slightly stronger winds than in the 0.5° resolution (7 times the 0.165° CLM leads to stronger maximum winds than the 0.5° CLM).

However, in all cases, the regional model underestimates the deepness of the cyclone and the strength of the maximum winds; in some cases, such as Meari (200421) or Ma-On (200422) the RCM TCs are severely too weak; in other cases, such as Dianmu (200406) the underestimate of maximum wind speed is only 10%.

Table 2 Minimum pressure, maximum pressure change within 6 hours, maximum 10m wind speed, and maximum 10m wind speed change within 6 hours for the selected tracks of the typhoon season 2004.

Statistics of Typhoon Tracks

Typhoon	Date	Model	min press[hPa]	max dp/dt	max$\|u\|$	max d$\|u\|$/dt
			[hPa]	[hPa/6h]	[kt]	[kt/6h]
200406	06/11/2004	best track	915	-15	100	10
	- 06/28/2004	NCEP	983	-4.5	47.3	7.1
		CLM 0.5	945	-7.0	85.3	6.4
		CLM 0.165	937	-9.6	88.1	9.7
200407	06/21/2004	best track	940	-10	95	10
	- 07/05/2004	NCEP	984	-6.2	41.4	11.0
		CLM 0.5	959	-6.2	67.3	7.8
		CLM 0.165	957	-9.8	72.5	8.9
200413	08/06/2004	best track	950	-10	80	10
	- 08/15/2004	NCEP	987	-5.6	38.5	4.1
		CLM 0.5	975	-4.5	55.9	6.2
		CLM 0.165	979	-6.0	50.4	7.1
200415	08/14/2004	best track	970	-5.0	65	10
	- 08/22/2004	NCEP	986	-4.2	42.6	9.9
		CLM 0.5	977	-5.1	64.1	9.8
		CLM 0.165	977	-5.3	59.5	10.5
200416	08/18/2004	best track	910	-20	110	20
	- 09/05/2004	NCEP	978	-6.9	53.0	7.1
		CLM 0.5	948	-7.1	80.0	8.7
		CLM 0.165	945	-8.9	85.0	13.0
200417	08/18/2004	best track	955	-5.0	80	5.
	- 08/31/2004	NCEP	988	-3.9	38.3	5.3
		CLM 0.5	980	-3.9	53.6	7.1
		CLM 0.165	972	-5.3	62.3	10.4
200418	08/26/2004	best track	925	-15	95	10
	- 09/10/2004	NCEP	969	-6.9	52.8	8.8
		CLM 0.5	957	-8.4	71.7	7.6
		CLM 0.165	953	-8.1	74.6	13.1
200421	09/19/2004	best track	940	-10	90	10
	- 10/02/2004	NCEP	998	-3.2	34.7	4.2
		CLM 0.5	997	-2.1	46.2	7.2
		CLM 0.165	1000	-2.2	28.6	7.7
200422	10/03/2004	best track	920	-15	100	15
	- 10/10/2004	NCEP	997	-4.0	32.4	5.6
		CLM 0.5	997	-2.7	36.8	9.1
		CLM 0.165	992	-2.7	39.4	11.5
200423	10/12/2004	best track	940	-10	85	10
	- 10/23/2004	NCEP	978	-5.0	55.2	6.1
		CLM 0.5	967	-3.8	65.4	6.7
		CLM 0.165	967	-5.0	62.2	8.0

5. Typhoon precipitation patterns

So far we focused on SLP and near-surface wind speed. But for typhoons one of the variables with most impact for the residents is rainfall. Zhang et al. (2007) showed satellite pictures and their own high-resolution reanalysis of rainbands for typhoons Tokage and Megi (see their Figure 6). For the current study precipitation rate plots of both regional model runs were prepared for both typhoons. Figure 6a shows large-scale and convective precipitation patterns for typhoon Tokage extracted from the CLM 0.5° simulation.

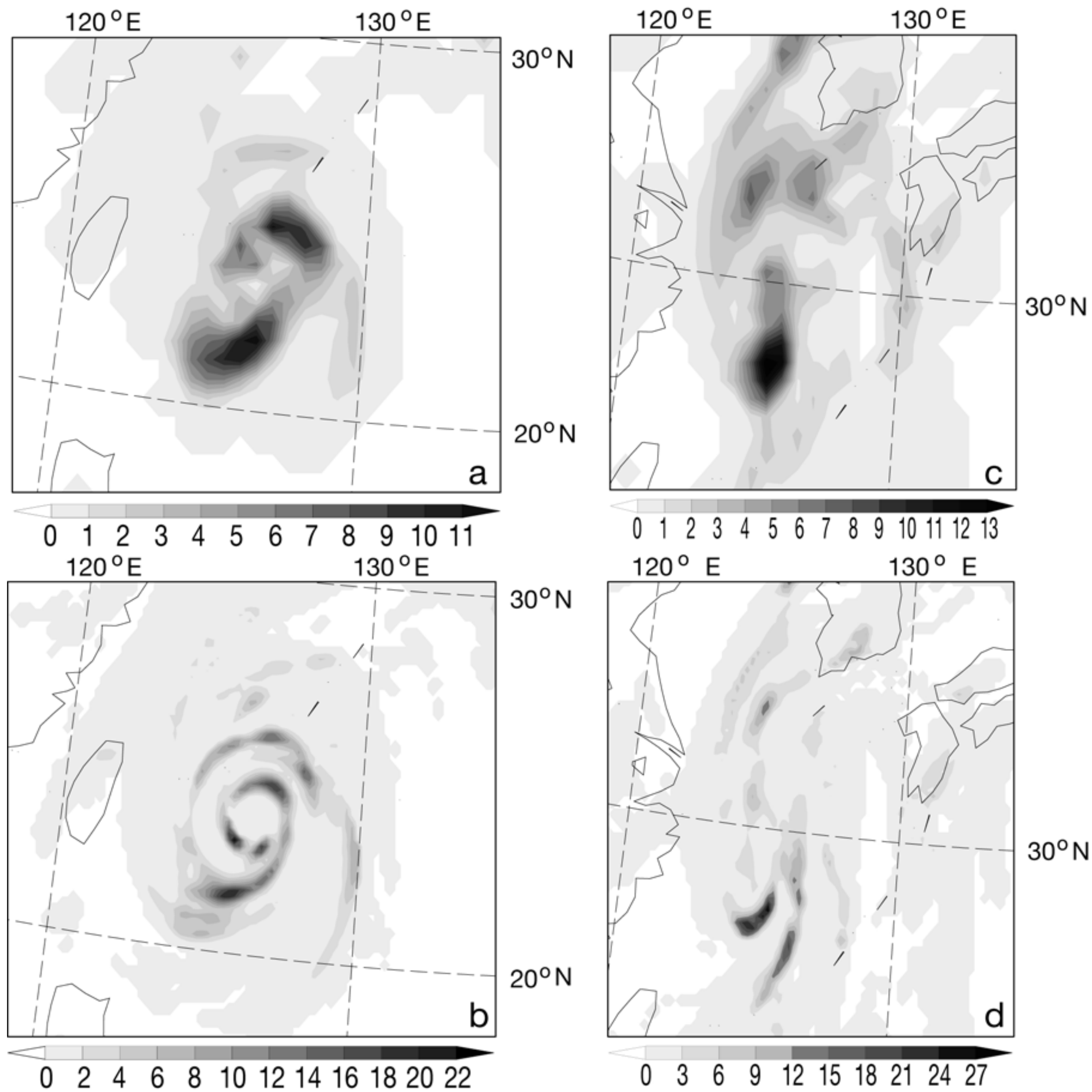

Figure 6 Precipitation rate (mm/h) for typhoon Tokage at 2004101821 UTC (left column) and typhoon Megi 2004081806 UTC (right column) given by the regional model at 0.5° resolution (upper row) and at 0.165° resolution (lower row).

The eye of the typhoon can be seen, whereby it is not as pronounced as in the satellite data. The outer convective rain bands are hardly noticeable, though. The satellite data showed a maximum

value of about 20 mm/h in the vicinity of the eye while the RCM only shows rates of up to 11 mm/h which are located farther away from the cyclone center. When turning to the results of the 0.165° RCM simulation (Figure 6b) the structure of the typhoon matches the observations a lot better, also the precipitation values are closer to the observed ones reaching maximum values of up to 22 mm/h close to the eye of the typhoon.
The high-resolution simulated spiralling rain bands look more similar to the satellite data as well. Figure 6c depicts a similar comparison of precipitation patterns for typhoon Megi in August 2004. A highly asymmetric spiral cloud band structure with maximum precipitation values of 30mm/h was depicted in the satellite data. The lower resolution regional simulation does show some asymmetric rainfall structures, but again the values are a lot lower than in the observations, reaching only 13 mm/h. The location of these precipitation maxima is hereby closer to the satellite data than for typhoon Tokage. The higher resolution run (Figure 6d) is closer to the satellite data both in pattern structure as well as in precipitation amounts, with maximum values of 27 mm/h. For the comparisons presented in this paper, the double nested, higher resolution simulation had its largest improvement compared to the 50km-run not in typhoon tracks, intensities or near-surface wind speed but rather in precipitation patterns and amounts.

6. Summary and Conclusions

In this paper the feasibility for computing a high-resolution hindcast of SE Asian weather was explored by analysing a sample typhoon season. The state-of-the-art regional climate model CLM was used to compute the year 2004 using NCEP-NCAR reanalyses as global forcing data. Two simulations were conducted, one with a grid distance of 0.5° and another one for a smaller model area nested inside the 0.5° simulation with a higher resolution of 0.165°. A spectral nudging technique was applied to prevent the regional model from deviating to great extent from the global model for large spatial weather phenomena. 12 selected typhoons of the typhoon season 2004 were considered. A tracking algorithm was used to identify typhoon tracks and to select the according SLP and near-surface wind speed values. Of the 12 considered typhoons only 10 were found in both the reanalyses and the RCM simulations.
A comparison of typhoon core pressure along the track revealed RCM values which were closer to the JMA best track data than the global reanalyses for 9 out of 10 cases. Some SLP developments were represented by the RCM analogously to the JMA values, but some showed a time lag like e.g. typhoon Songda. In 7 out of 10 cases the highest resolution simulation was closest to the best track SLP. For near-surface wind speed CLM was closer to the best track wind speed in 8 out of 10 cases compared to NCEP. Still, for all analysed typhoons the RCM underestimated the low pressure values and the strength of the maximum winds. The great circle difference between the modelled typhoon tracks and the JMA best track data was for all cases smaller for the reanalyses than for the RCMs, even though the SLP and near-surface wind speed showed larger deviations the location of the track was better represented.
Precipitation patterns showed pronounced differences between both applied RCM resolutions. The rainbands were simulated more realistically with the 0.165° grid distance and so were the rainfall rates. The values were about twice as high as for the 0.5° resolution simulation, reaching values of about the same order satellite data showed. Also the precipitation patterns seem to be more realistically simulated with the higher resolution.
It is concluded that typhoons can be dynamically downscaled using a state-of-the art RCM and global reanalyses as surface and boundary forcing data. The location of the typhoon tracks is already well represented in the reanalyses, but SLP and near-surface wind speed in the vicinity of the typhoon cores show large differences compared to observations. An improvement by

dynamical downscaling is expected not for the track, but for pressure and wind speed developments as well as for precipitation patterns and amounts. It was shown that the regional model is able to simulate a typhoon development inside the RCM model without introducing an artificial vortex. The next step will be to show that not only single typhoon events can be simulated, but also the statistics. This will imply to set objective options for the tracking algorithm so that the number of typhoons simulated for a certain time period can be analysed. If this can be performed successfully a long-term, high-resolution atmospheric hindcast can be computed to serve as input for wave, storm surge and water level models.

7. Acknowledgments

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