Projection of Changes in Future Surface Wind around Japan Using a Non-hydrostatic Regional Climate Model

Mizuki Hanafusa, Hidetaka Sasaki, Akihiko Murata, and Kazuo Kurihara
Meteorological Research Institute, Tsukuba, Japan

Abstract

Changes of a surface wind under the future climate condition in and around Japan were investigated by using a 5-km-mesh non-hydrostatic regional climate model (NHRCM05). In the present climate, monthly mean surface wind speeds are well reproduced by NHRCM05. Additionally, the NHRCM05 reproduces the seasonal change of mean surface wind speeds fairly well: the wind during the cold season is calculated to be stronger than that in the warm season.

Under the future climate, monthly mean surface wind speeds show little change. In the warm season, according to a 20-km-mesh atmospheric general circulation model (AGCM20), the Pacific anticyclone is projected to weaken near Japan, and the sea level pressure over the seas around the Philippine Islands is projected to rise, so the frequency of the westerly wind is projected to increase across Japan by NHRCM05.

During the cold season, according to NHRCM05, the wind speeds around Hokkaido are projected to increase a little value due to the decrease of the sea ice in the Sea of Okhotsk. Further, the frequency of southeasterly wind is projected to increase significantly. In the future, the Monsoon Index is projected to be lower than in the present climate by AGCM20, resulting in southeasterly wind inflow to Japan.

(Citation: Hanafusa, M., H. Sasaki, A. Murata, and K. Kurihara, 2013: Projection of changes in future surface wind around Japan using a non-hydrostatic regional climate model. SOLA, 9, 23–26, doi:10.2151/sola.2013-006.)

1. Introduction

How climate change due to global warming impacts social life is one of the biggest issues climatologists face. In order to project the temperature and precipitation changes that will occur, many climate change projection experiments have been conducted using general circulation models (GCM) or regional climate models (RCM). For instance, Kusunoki and Mizuta (2008) investigated the behavior of the future Baiu rain band around Japan by using a 5-km-mesh global atmospheric model. Kanada et al. (2012) investigated future changes of the precipitation amount around Japan using a non-hydrostatic regional climate model. AGCM20, the 5th-generation atmospheric general circulation model (ECHAM5) and the Hadley Center RCM (HadCM3). Pryor et al. (2005) investigated the future wind change in the United Kingdom by using climate models, including the 5th-generation atmospheric general circulation model (ECHAM5) and the Hadley Center RCM (HadCM3).

In contrast, there had been no studies focused on how the wind in Japan will change in the future due to global warming. In Japan, tropical cyclones or strong extratropical cyclones cause disasters every year. Additionally, focus has been recently turned toward wind-powered generators as renewable energy sources. The potential to project dangerous storms and to develop renewable energy sources shows the importance of understanding how wind characteristics will change in the future across Japan. In this study, we investigated wind changes across Japan by using output data from a 5-km-mesh non-hydrostatic regional climate model (hereafter NHRCM05).

We explain the experimental design in Section 2, the reproducibility of the present climate in Section 3, the future changes in the warm and cold seasons in Section 4, and we summarize our findings and offer some concluding remarks in Section 5.

2. Experimental design

We used NHRCM05, which adopts a multiple nesting method into a 20-km-mesh atmospheric general circulation model (hereafter AGCM20). AGCM20 has performed time integration from 1979 to 2003 for the present climate and from 2075 to 2099 for the future one under the Special Report on Emission Scenario (SRES) A1B emission scenario reported by the Intergovernmental Panel on Climate Change (IPCC). Details of AGCM20 are described in Kitoh et al. (2009). First, a 15-km-mesh non-hydrostatic regional climate model (hereafter NHRCM15) was nested within AGCM20 in order to generate information of cloud water, cloud ice and other cloud substances into boundary conditions for NHRCM05. Moreover, NHRCM05 is nested within the NHRCM15. NHRCM15 has 211 × 661 grids horizontally and 40 vertical layers. The calculation domain of NHRCM05 is skewed from northeast to southwest, which reduces the computer resource needed while still covering almost all of the Japanese Archipelago. NHRCM05 is equipped with the improved Mellor-Yamada level 3 planetary boundary layer scheme (Nakanishi and Niino 2004) for vertical turbulent diffusion, and MRI/JMA Simple Biosphere scheme (MJ-SiB) for a land surface model (Hirai et al. 2007).

For surface winds, wind speeds at a 10-m height were derived at NHRCM05 and AGCM20. Integrations were conducted from 1980 to 2000 to represent the present and from 2076 to 2096 to represent the future. Details for this model are described in Sasaki et al. (2011, 2012).

3. Reproducibility of the present climate

We verified the reproducibility of the present surface wind by the data from NHRCM05 by comparing the model output to the observed data from the Japan Meteorological Agency (JMA) meteorological observatories (155 points). The value of the nearest model grid point over land to each observation point was used for comparison. To show the importance of downscaling, results from AGCM20 are also indicated. A monthly mean surface wind speed, averaged over all observation points, was rather well reproduced by NHRCM05 for the warm season from July to September (Fig. 1). The seasonal change in wind speed around Japan was fairly well reproduced by NHRCM05: the wind during the cold season from December to February was calculated to be stronger than that in the warm season. This characteristic was also reproduced by AGCM20, but the AGCM20-derived wind speed had a bigger bias for the actually observed wind than the NHRCM05-derived...
wind all year round with a confidence level of more than 95% by Welch’s t-test. Here, NHRCM05-derived wind speed was averaged in 20km-grid, and we verified the reproducibility of 20km-averaged NHRCM05-derived wind speeds was also superior to that of AGCM20.

The wind direction was also quite sensitive to small topographic structures, so it is very difficult for a model to exactly reproduce the most frequently observed wind direction. To show the reproducibility of wind direction by NHRCM05, the first and second probable wind directions with respect to the 16 points of the compass were determined. In this study, the reproducibility measure of wind direction \( S \) is defined as follows,

\[
S = \frac{100}{n} \sum (S_1 + S_2),
\]

where \( d_1 \) and \( d_2 \) are wind directions of the first and second maximum frequencies determined by the model, and \( d_1 \) and \( d_2 \) are the observed maximum frequencies. The number of observation points is \( n \), and \( S_1 \) and \( S_2 \) are calculated for all observation points. \( S = 100 \) represents perfect reproducibility. The reproducibility of wind direction for NHRCM05 was superior to that for AGCM20 all year round (Fig. 2). Reproducibility was better during the cold season than the warm season for both AGCM20 and NHRCM05, and the differences of \( S \) between the models were smaller during the cold season. A frequency distribution of \( S \) was not a normal distribution, so we adopted Wilcoxon signed-rank test to conduct significant test of \( S \). The result showed that it was significant at the 95% confidence level for \( S \) value of NHRCM05 and AGCM20 except for January, March and December. Generally, a northwesterly monsoon wind is blowing and the pattern tended to persist for long periods around Japan during the cold season, so reproducibility of the synoptic pattern was relatively good. In contrast, the synoptic pattern is changeable and does not last long during the warm season. In addition, small structures, such as land and sea breezes or mountain and valley winds, are apt to develop during the warm season, so reproducing the climate features was difficult, especially in AGCM20.

As stated above, the reproducibility of land surface wind speed and direction in NHRCM05 were superior to those in AGCM20, which indicates that the dynamical downscaling was successful. While, it is very difficult to verify the reproducibility of sea surface winds, as there is little observation of wind at sea. Iizuka et al. (2012) assessed ocean surface wind in three 20-km-mesh RCMs and indicated that RCMs showed a smaller bias in the mean satellite-measured ocean surface winds than the reanalysis data which had resolution of 1.125° × 1.125° and were used as boundary conditions for RCMs. So, we also suggest that the reproducibility of sea surface wind speed for NHRCM05 was better than that for AGCM20 by conducting dynamical downscaling. In this study, annual mean sea surface wind speeds of NHRCM05 were about 0.4 m s⁻¹ greater than AGCM20.

### 4. Future wind changes

Compared to the results from the present simulation by NHRCM05, the difference between the present and the future seasonal wind speeds was small in each month (Fig. 1), and it was insignificant at the 90% confidence level by Welch’s t-test except for March, April, October and November. Details of the characteristics of future wind changes in the warm and cold seasons are described in the following sub sections.

#### 4.1 Changes to the future warm season

Although wind speeds averaged over all observation points did not change much, changes varied among the areas (Fig. 3). Wind speed increased mainly over the Japan Sea and north of 42°N over the Pacific Ocean, including land areas north of Tohoku and Hokkaido. In particular, wind speed around the Sea of Okhotsk during the warm season was projected to increase about 0.5 m s⁻¹, and it was significant at the 90% confidence level (Fig. 3a). Around the Nansei Islands, the surface wind speed was projected to decrease by more than 0.5 m s⁻¹, but it was insignificant at the 90% confidence level. According to Knutson et al. (2010), tropical cyclones will tend to strengthen in the future, but the globally averaged frequency of tropical cyclones is projected to decrease. To examine how much typhoons affect mean surface wind speed in the warm season around the Nansei Islands, we compared the sum of hourly wind speeds with that for cases where typhoons were in the area. In this study, based on the definition of JMA, typhoons were defined as cyclones whose maximum wind speeds are over 17 m s⁻¹. In the result, typhoons contributed about 21% and 17% to mean surface wind speed in the present and future climate, re-
respectively, and the number of typhoons around the Nansei islands was 76% in the future climate compared with the present climate. Then, the monthly mean wind speed is expected to decrease due to the reduced number of typhoons. As the number of typhoons varies greatly from year to year, wind speed also fluctuates widely. Thus, the change in wind speed in the future around the Nansei Islands is not significant at the 90% confidence level.

Wind direction is also projected to change in the future. In this study, the westerly wind was defined as wind blowing from 210° to 330° from the north. In the warm season, the frequency of westerly wind is projected to increase around Japan (Fig. 4a). In present warm seasons, the frequency of the westerly winds accounts for approximately between 30% and 50% over the land, and between 15% and 30% over the sea around Japan (Fig. S1a, Supplement 1). South of latitude 40°N the future frequency of the westerly wind is projected to be 20% higher than the present frequency. This change will be induced by a large scale situation. In future warm seasons, the Pacific anticyclone is projected to be weaker around Japan (Fig. 5a). In contrast, the sea level pressure over the seas around the Philippine Islands is projected to increase, which would result in more frequent westerly winds around Japan due to a change in the pressure gradient. Endo (2012) also showed that the sea level pressure is projected to increase in tropical regions and decrease in regions between latitudes 30°N and 40°N through analyzing eighteen SRES A1B scenario simulations in the Phase 3 of the Coupled Model Intercomparison Project (CMIP3) datasets.

4.2 Changes to the future cold season

For the future cold season, wind speed was projected to increase to the north of 38°N and decrease to the south. Near the Nansei Islands, areas of increasing wind speed were also apparent (Fig. 3b). Over land, the wind speed in the eastern part of Japan was projected to mainly increase, while the wind speed in the western part of Japan was projected to decrease. Around Hokkaido, the surface wind speed was projected to increase more than 0.5 m s$^{-1}$ (Fig. 3b). The amount of change was determined to be large especially over the Sea of Okhotsk: the wind speed was projected to increase more than 0.75 m s$^{-1}$ with a confidence level of more than 90%. We attribute that the increase of wind speed in the future is related to decreased sea ice in the Sea of Okhotsk, where in the present winter climate, sea ice frequently covers a large portion of the sea (Fig. 6); focusing on the local field of atmospheric circulation, the air mass is easily cooled over the sea ice as compared to over the sea, so anticyclones tend to develop over the sea ice. Easterly wind blows from the anticyclone, weakening northwesterlies. In the future, we expect that the anticyclones will not develop due to the decrease of sea ice over the Sea of Okhotsk. There will be no obstacles to prevent or lessen cold season monsoons near Hokkaido, and the wind speed is projected to increase in the future. Reduction of sea ice also causes an increase of wind speed due to the lower roughness over the sea than over sea ice (Okubo and Mannoji 1994). Furthermore, extratropical cyclones affect the change of wind speed around Hokkaido. In future cold seasons, sea level pressure over the Pacific north of 45°N is projected to decrease (Fig. 5b). Mizuta et al. (2011) suggested that the central pressures of extratropical cyclones will strengthen in the future on the poleward and downstream sides of the Atlantic and Pacific storm tracks. Due to these changes, a pressure gradient force will be strengthened around Hokkaido.

At present, northwesterly winds generally dominate in the cold season around Japan, and southeasterly winds do not appear often (Fig. S1b, Supplement 1). To investigate how this tendency changes in the future, we focused on the frequency of southeasterly winds. In this study, southeasterly winds were defined as those blowing from angles between 110° and 160°. We found that the future frequency of southeasterly wind in the area between 25°N and 40°N in the cold season is predicted to be 30% higher than the present frequency (Fig. 4b) with the confidence

![Fig. 4. The changes in frequency of (a) westerly wind during the warm season and (b) southeasterly wind during the cold season in the future relative to the present climate. The ‘+’ symbol indicates areas where the confidence level is more than 90% by Welch’s t-test.](image)

![Fig. 5. The difference of sea level pressure between the present and future climate (shaded) in (a) August and (b) February derived by AGCM20. Solid and dash contours are sea level pressure in the present and future climate respectively (every 4 hPa).](image)

![Fig. 6. Monthly mean surface temperature in present climate (a) January and (c) February, and in future climate (b) January and (d) February. On the sea, the areas of lower than 0 degrees Celsius are covered with sea ice.](image)
level of more than 90%. Hanawa et al. (1988) introduced a Monsoon Index which indicates the intensity of the typical cold season atmospheric pressure pattern around Japan and is calculated as the pressure difference between Nemuro and Irkutsk in Russia. A large Monsoon Index means that the Siberian high pressure is distinct and northwesterly wind blows strongly around Japan. The changes to the Monsoon Index (Table 1) suggest that monsoons in the cold season will weaken in the future; the confidence level for the Monsoon Index decrease for February is more than 97%. In the future, the frequency of southeasterly winds is projected to increase in February but not in January (data not shown), which further supports the projection that monsoons will be weaker in the future cold season and suggests that the cold season will end earlier compared with the present climate.

5. Summary and concluding remarks

We examined the reproducibility of surface winds around Japan simulated by NHRCM05. The monthly mean surface wind speed is somewhat overestimated in NHRCM05 compared to what is observed every month, but the bias is small in the warm season. NHRCM05 also reproduces the seasonal pattern: the wind is strong in the cold season and weak in the warm season. A score $S$ was proposed in this paper as the reproducibility measure of wind direction. The reproducibility for NHRCM05 is better than that for AGCM20 all year round; in particular, the reproducibility for NHRCM05 for the warm season is much better than that for AGCM20. As stated above, dynamical downscaling using NHRCM05 is successful.

In the future, the monthly mean surface wind speed projected by NHRCM05 does not change much when averaged across the Japan land area. Although the changes in future monthly mean surface winds in the warm season are very small, the frequency of westerly winds is projected to increase. In the future climate, the Pacific Anticyclone will weaken around Japan and the sea level pressure over the seas around the Philippine Islands will rise; as a result, the westerly wind will tend to blow around Japan due to the change in the pressure gradient pattern.

In future cold seasons, wind speed is projected to increase to the north of $38^\circ$N and decrease to the south. Around Hokkaido, the change in the pressure gradient pattern. Anticyclone will weaken around Japan and the sea level pressure winds is projected to increase. In the future climate, the Pacific

### Table 1. Monsoon Index December, January, February and March in present and future climates and confidence level of these differences conducted by Welch’s t-test.

<table>
<thead>
<tr>
<th>Month</th>
<th>Present [hPa]</th>
<th>Future [hPa]</th>
<th>Confidence level [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>December</td>
<td>16.62</td>
<td>15.45</td>
<td>68.08</td>
</tr>
<tr>
<td>January</td>
<td>18.22</td>
<td>19.79</td>
<td>60.98</td>
</tr>
<tr>
<td>February</td>
<td>17.26</td>
<td>14.22</td>
<td>97.84</td>
</tr>
<tr>
<td>March</td>
<td>10.97</td>
<td>10.79</td>
<td>10.24</td>
</tr>
</tbody>
</table>

### Acknowledgements

The boundary conditions data for NHRCM05 was provided by the Kakushin Program, which is supported by the Ministry of Education, Culture, Sports, Science and Technology of Japan. The authors thank the members of the Kakushin Program.

### Supplement

Supplement 1 shows that the frequency of (a) westerly wind during the warm season and (b) southeasterly wind during the cold season in the present climate.

### Reference


Manuscript received 18 October 2012, accepted 30 January 2013

SOLA: http://www.jstage.jst.go.jp/browse/sola