Reproducibility and future projection of the midwinter storm-track activity over the Far East in the CMIP3 climate models in relation to the occurrence of the first spring storm (*Haru-Ichiban*) over Japan

Kazuaki Nishii

*Department of Earth and Planetary Science, University of Tokyo, Tokyo, Japan*

Takafumi Miyasaka

*Department of Earth and Planetary Science, University of Tokyo, Tokyo, Japan*

Yu Kosaka

*Department of Earth and Planetary Science, University of Tokyo, Tokyo, Japan*

Hisashi Nakamura

*Department of Earth and Planetary Science, University of Tokyo, Tokyo, Japan*

*Frontier Research Center for Global Change, JAMSTEC, Yokohama, Japan*

Corresponding author: Kazuaki Nishii, Department of Earth and Planetary Science, Graduate School of Science, University of Tokyo, 7-3-1 Hongo, Bunkyo-ku, Tokyo, 113-0033.

E-mail: nishii@eps.s.u-tokyo.ac.jp

(i)
Abstract

A reanalysis dataset is used to establish the relationship between the year-to-year fluctuations in the midwinter storm-track activity over the Far East measured by poleward heat flux associated with subweekly disturbances and the occurrence of the first spring storm with strong southerly wind over Japan (Haru-Ichiban). Our analysis reveals that its early (delayed) occurrence tends to follow the enhanced (suppressed) winter storm-track activity with less (more) apparent minimum in midwinter in the course of the seasonal march. A metric is defined on the basis of the eddy heat flux to measure the reproducibility of the particular seasonal march of the storm-track activity over the Far East simulated by each of the Coupled Model Intercomparison Project Phase 3 (CMIP3) climate models under the present climate. Under a particular global warming scenario, ensemble projection based on several models that show the highest reproducibility of the storm-track activity based on the particular metric indicates that the future enhancement is likely in the midwinter storm-track activity associated with the weakening of the winter monsoon, implying that the earlier occurrence of Haru-Ichiban is likely in the late 21st century.
1. Introduction

In late winter through early spring, events of strong southerlies occur over Japan associated
with synoptic cyclones developing to the north. The first of such events is called “Haru-Ichiban”,
the first storm of the spring. It is typically marked with a sharp temperature rise and thus
regarded as the event of seasonal transition marking the end of the winter. Therefore,
the Japan Meteorological Agency (JMA) has been officially recording the dates of the
Haru-Ichiban events for individual years separately for domestic regions. Hagimoto (2007)
suggested that the timing of the Haru-Ichiban event has been fluctuating with the mean-flow
anomalies associated with the Western Pacific (WP) teleconnection pattern (Wallace and
Gutzler 1981). Nakamura et al. (2002) found that long-term variability of the East Asian
winter monsoon tends to be linked to a monthly circulation anomaly pattern similar to a
combination of the WP pattern and the Pacific/North American (PNA) teleconnection
pattern (Wallace and Gutzler 1981). They also found that the midwinter storm-track
activity tends to be more active when the East Asian monsoon is weaker than normal
and vice versa.

It has been known that the Northwestern (NW) Pacific storm-track activity climatologically
undergoes unique seasonal cycle with dual maxima in late autumn and early spring and
a well-defined minimum in midwinter (Nakamura 1992). As opposed to linear theories
of baroclinic instability, the suppression of the storm-track activity occurs despite the
upper-tropospheric westerly wind speed is maximized in midwinter. Chang (2001) argued

\[1\text{The JMA officially defines the Haru-Ichiban as the first event of strong southerlies that occurs between 4 February and the spring equinox day in association with a cyclone developing over the Sea of Japan. No event was recorded in some of the years. The Haru-Ichiban dates for the Kantou region around Tokyo are available on the JMA website http://www.tokyo-jma.go.jp/sub_index/kiroku/kiroku/data/31.htm} \]
that convective precipitation enhanced due to cold air outbreaks behind individual cyclones acts to reduce eddy available potential energy and thereby retards their baroclinic growth. Nakamura and Sampe (2002) showed that the midwinter intensification of the North Pacific subtropical jet (STJ) leads to the trapping of upper-level eddies into its core located south of a surface baroclinic zone at around 40°N, which is anchored by an oceanic frontal zone. The trapping thus weakens the coupling of the upper-level eddies with the baroclinic zone, resulting in the retardation of their baroclinic growth.

These studies lead us to the conjecture that the early occurrence of Haru-Ichiban may be likely to follow the above-normal activity of the NW Pacific storm track in midwinter and vice versa. One aim of this study is to confirm the conjecture by comparing the midwinter storm-track activity based on a reanalysis dataset between early and late occurrences of Haru-Ichiban observed in association with natural climate variability. Owing to the regional nature of Haru-Ichiban, their relationship can be useful at least practically for inferring the occurrence of a Haru-Ichiban event based on gridded output data of a general circulation model (GCM). Meanwhile, the storm-track activity is estimated, for example, by using poleward eddy heat flux associated with subweekly fluctuations (e.g., Nakamura et al. 2002). This method, what may be called Eulerian method (Nakamura et al. 2004), based on time filtered quantities is suited for daily-gridded data. It has been used in study of future changes in extratropical cyclone activity on the basis of multiple climate model projections (e.g., Yin et al. 2005; Ulbrich et al. 2008).

The recent tendency for the midwinter storm-track activity over the NW Pacific to increase observed in association with the weakening trend in the East Asian winter monsoon (Nakamura et al. 2002) lead us to the conjecture that the particular tendency is likely to be augmented further in the future climate. In fact, under the projection of future climate
by using GCMs, the winter monsoon is very likely to weaken (Kimoto 2005; Hori and Ueda 2006), and the increased activity of the wintertime storm track over the NW Pacific is simulated in a high-resolution GCM (e.g., Inatsu and Kimoto 2005).

In this study, we attempt to examine future changes in the midwinter storm-track activity over the Far East in relation to the occurrence of a Haru-Ichiban event on the projections of Coupled Model Intercomparison Project Phase 3 (CMIP3). As mentioned earlier, the storm-track activity over the Far East is characterized by its unique seasonal march. Thus assessing the reproducibility of the unique feature in the storm-track activity in the climate models can offer a good benchmark test for a particular aspect of the model performance. The reproducibility is measured by constructing a metric based on the storm-track seasonal march simulated for the 20th Century Climate in Coupled Models (20C3M) experiments in the CMIP3 climate models. Several of the models that show the highest reproducibility of the storm-track activity over the Far East based on the metric are then selected for assessing the future projection of storm-track activity simulated under the global warming scenario (SRES-A1B).

2. Data and methodology

In the present study, we use daily-mean fields of wind and temperature based on the reanalysis data (ERA-40; Uppala et al. 2005) produced by the European Centre for Medium-Range Weather Forecasts (ECMWF), for defining observed westerly jet intensity and storm-track activity. We also use the corresponding daily-mean fields simulated in the 19 CMIP3 models for the 20C3M and SRES-A1B experiments available at the web site of the Program for Climate Model Diagnosis and Intercomparison (PCMDI) (http://www-pcmdi.llnl.gov).

As in Nakamura et al. (2002), 850-hPa poleward eddy heat flux is evaluated as a local
measure of storm-track activity based on the daily-mean time series of temperature and meridional wind velocity after 8-day high-pass filtering. The daily climatology of the heat flux and jet intensity has been defined for the 30-year period from 1969 to 1998 based on the ERA-40 and 20C3M data. The corresponding 18-year climatology for the SRES-A1B simulations has been defined for the period from 2082 to 2098. To obtain the smooth seasonal march of the flux, the pentad-mean climatology constructed from the daily climatology was exposed to moving average over 5 pentads. Since our primary focus is on the storm-track activity over Japan, the eddy heat flux has been averaged zonally from 130°E to 145°E. A latitude-time section of the climatological eddy heat flux at the 850-hPa level based on the ERA-40 data (Fig. 1a) clearly indicates its midwinter minimum associated with southward displacement of the storm-track axis, as observed by Nakamura (1992). The minimum occurs despite the westerly jet intensity maximized. To illustrate the seasonal evolution of the storm-track activity, the heat flux maximum between 20°N and 60°N for the climatological pentad mean is sampled for both the reanalysis dataset and the CMIP3 models (Fig. 2).

3. Interannual variability of the midwinter storm-track activity and the occurrence of Haru-Ichiban

According to the JMA record, the timing of a Haru-Ichiban event fluctuates considerably from one year to another. As shown in Fig. 1b, interannual variability of the storm-track activity is particularly large in the cold season including February and March, when a Haru-Ichiban event usually occurs. To identify covariability between the timing of Haru-Ichiban and the storm-track activity, composite analysis was performed for the eddy heat flux

The composite analysis reveals that the wintertime storm-track activity over the Far East in the years of the earlier occurrence of *Haru-Ichiban* tends to be stronger than in the years of its delayed occurrence (Fig. 3a). In the former winter, a *Haru-Ichiban* event occurs in early or mid-February. This timing is right after the marked minimum of the storm-track activity in the latter winter. In this type of winter, *Haru-Ichiban* event tends to occur in the course of the rapid enhancement of the storm-track activity in early or mid March (Fig. 3a). The corresponding composite analysis applied to midwinter westerly wind speed at the 300-hPa level over the Far East reveals its tendency to be weaker in the year of the earlier occurrence of *Haru-Ichiban* than in the year of its delayed occurrence (Fig. 3b), which implies the tendency of the weaker East Asian winter monsoon in the former winters. Actually, the Aleutian Low and Siberian High both tend to be weaker in the former winters (not shown). This relationship of the midwinter storm-track activity with winter monsoon and jet intensities is consistent with the finding by Nakamura et al. (2002). In addition, most of the years selected for the enhanced midwinter storm-track activity in their study are included in the years of the earlier occurrence of *Haru-Ichiban*, but none of them is among the years of its delayed occurrence. We thus confirm the tendency for the early occurrence of *Haru-Ichiban* to follow the enhanced storm-track activity over the Far East in midwinter and the weaker East Asian winter monsoon. This tendency arises from the close link of the occurrence of *Haru-Ichiban* with early spring recovery of the NW Pacific storm-track activity from its midwinter minimum as a unique characteristic of its seasonal evolution.
4. Reproducibility and future projection of Far East wintertime storm-track activity in climate models

Climatological seasonal evolution of storm-track activity over the Far East simulated for the 20C3M experiment by each of the CMIP3 climate models is presented in Fig. 2. The figure indicates 17 out of the 19 models can reproduce the midwinter suppression of the NW Pacific storm-track activity with no well-defined peak in midwinter. Several of them can even reproduce its well-defined midwinter minimum as actually observed. The model-simulated strength of the autumn maximum of the activity is clustered around the observed strength, whereas the model-simulated spring maximum is more scattered above its observed intensity.

A metric has been defined as a measure of reproductivity of the wintertime NW Pacific storm-track activity simulated in the CMIP3 models, for the purpose of selecting models adequate for assessing the future projection. We presume that those models that can realistically reproduce the storm-track activity in the 20C3M experiment should yield better projection of future changes of the storm track over the Far East. For the definition, the root mean square error (RMSE) was first evaluated between a pair of eddy heat flux time series sampled at the storm-track axis from October to March as shown in Fig. 2; one based on the ERA-40 data and the other on the 20C3M output of a particular CMIP3 model. We then defined the metric as the ratio of the standard deviation of the observed interannual variability of the eddy heat flux to the RMSE (Table 1). The interannual variability is based on the intensity of the 850-hPa poleward heat flux averaged from 130°E to 145°E at its latitudinal maximum (i.e., storm-track axis) for each pentad of a particular cold season. Its squared deviations from the climatological mean (c.f., Fig. 2) for individual pentads
were summed over the 30-years before averaged over the entire cold season from October to March. It should be stressed that the particular metric is merely a measure of the particular seasonal phenomenon over the Far East but not a global measure of the model performance. Eight out of the 19 models are found to have the highest skill scores based on particular metric that exceeds 2. As marked by bold lines in Fig. 2, they can reproduce the seasonal evolution of the storm-track activity as observed.

Since the availability of daily-mean output data for the SRES-A1B experiment is limited to only a single realization for each model and the output is available only from the early 2080s to the end of the 2090s, projected changes in the storm-track activity of individual models are likely to be contaminated by fluctuations due to the natural variability in the climate system. To reduce the contamination by the model’s internal variability, we have constructed the ensemble average of the projection of the climatological storm-track activity based on the 8 models with the highest reproducibility of the activity in the present climate based on the particular metric (Fig. 4a). For the constitution of the ensemble mean, the climatologies for the 20C3M and SRES-A1B experiments have been taken for 1982-1998 and 2082-2098, respectively.

Figure 4a indicates that the projected future activity of the NW Pacific storm track in January and February is likely stronger than the current activity. As a result, the midwinter activity minimum will become less clear in the future climate, consistent with the recent observational tendency (Nakamura et al. 2002) and the GCM experiment by Inatsu and Kimoto (2005) for the future climate. The latitude of the storm-track axis in midwinter will shift slightly northward (not shown), which is consistent with the result of Geng and Sugi (2003). The result implies the earlier occurrence of Haru-Ichiban is very likely in the future associated with the further weakening of the East Asia winter monsoon and associated
upper-tropospheric jet (Fig. 4b). Though less significant, the enhancement of the midwinter storm-track activity in the SRES-A1B projection can also be found in the corresponding comparison based on all the 19 available models (not shown).

5. Conclusions

In the present study, we have established a linkage between the seasonal march of objectively-defined storm-track activity over the Far East and the occurrence of a Haru-Ichiban event, which is a rather regional phenomenon of Japan. The analysis of the ERA-40 data has revealed that the occurrence tends to be earlier than normal following the above-normal storm-track activity in midwinter and vice versa. Having established this link, we have also found that as ensemble, several of the CMIP3 models with the highest reproducibility of the seasonal cycle of the storm-track activity over the Far East in the present climate (based on the 20C3M simulation) predicts increasing storm-track activity in midwinter under the projection of SRES-A1B scenario, which leads to the implication that the occurrence of Haru-Ichiban is likely to be earlier than today. As actually observed recently (Nakamura et al. 2002), the future enhancement in the storm-track activity is likely to be associated with the weakening of the winter monsoon and upper-tropospheric jet stream.

In assessing the model reproducibility of the storm-track activity, we defined a metric based on the RMSE of the simulated seasonal march in the lower-tropospheric eddy heat flux. We have to admit that the particular metric is based only on the climatological storm-track activity in the lower troposphere. A more complete metric should be defined by including the upper-tropospheric storm-track activity and interannual variability. Furthermore, we did not attempt to identify a Haru-Ichiban event based directly on the gridded data of the ERA-40 and CMIP3 model outputs, which is not necessarily straightforward though
because of its regional nature. A more straightforward future projection of a Haru-Ichiban event may be possible through by using, for example, a regional climate model nested on a GCM.

Acknowledgments

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References


Captions of Figures

Fig. 1. (a) Latitude-time (month) section showing the climatological seasonal evolution (1968-1998) of storm-track activity over the Far East (130°-145°) estimated by 850-hPa meridional eddy heat flux associated with subweekly eddies. Details are referred to section 2. Contour interval is 1 K m s⁻¹. Shading denotes the 300-hPa westerly wind speed between 30 and 40 m s⁻¹ and 50 and 60 m s⁻¹. (b) Interannual variability of the storm-track activity measured as the standard deviation of the 850-hPa eddy heat flux (every 1 K m s⁻¹). Shading is applied where the standard deviation exceeds 3 K m s⁻¹.

Fig. 2. Climatological seasonal evolution of 850-hPa eddy heat flux (K m s⁻¹) associated with subweekly disturbances based on the ERA-40 data (a thick line with crosses). The sampling was performed along the storm-track axis marked as the latitudinal maximum of the climatological-mean (1969-1998) heat flux averaged between 130°E and 145°E. The corresponding seasonal evolution in the climatological eddy heat flux simulated in each of the CMIP3 models for 20C3M experiment is superimposed. Eight of the 19 models that show high skill score of reproducibility (Table 1) are marked with bold lines. The other models are indicated with dashed lines. The definition of the metric as a measure of the reproducibility is discussed in section 4.

Fig. 3. (a) The same as in Fig. 2, but composite for the 10 winters of the earliest (solid line) and latest (dashed line) occurrence of Haru-Ichiban. Circles (earlier occurrence) and squares (delayed occurrence) denote the pentads of Haru-Ichiban events for those 20 winters. Note that the scale (K m s⁻¹) of the ordinate has been changed. (b) The same as in (a) but for 300-hPa westerly.

Fig. 4. (a) The same as in Fig. 2, but based on the ensemble averages for the 8
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