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Relationship between atmospheric blocking and cold day extremes in current and RCP8.5 future climate conditions over Japan and the surrounding area

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Abstract

Atmospheric blocking is one of the most impactful weather patterns in midlatitude regions, causing floods, droughts and unusually high or low temperatures. This study investigates the relationship between extremely cold days over Japan and its surroundings and North Pacific blocking in the European Centre for Medium-range Weather Forecasts (ECMWF) re-analysis (ERA-40), phase 5 of the Coupled Model Intercomparison Project (CMIP5) for historical weather and the representative concentration pathway 8.5 (RCP8.5) experiments based on nine climate model datasets in the boreal winter season. Under the climate change conditions based on the RCP8.5 future scenario, extreme cold days (i.e. the first percentile of cold days) over Japan and its surroundings will become weaker but occur more widely when blocking is generated over the northwestern Sea of Okhotsk and its surroundings, because the blocking frequency over this area will decrease and the intensity will weaken.

Keywords: atmospheric blocking; extreme cold days; Japan and its surrounding areas, climate change; CMIP5

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1. Introduction

Atmospheric blocking is one of the most impactful weather patterns in midlatitude regions, causing floods, droughts and unusually high or low temperatures. Blocked winters have been the subject of many recent studies. In boreal winter (December to February; DJF), blocking and the cold spell over North America in the 1983/1984 winter season were analyzed in association with the El Niño-Southern Oscillation (Quiroz, 1984). In January 2008, the 'icy weather', i.e. rainfall and snowfall during a cold spell over southern China, was mainly influenced by three conditions: (1) blocking over Siberia, (2) the inflow of moist air from the Bay of Bengal and (3) the inversion of the atmospheric boundary layer due to snow accumulation (Zhou *et al.*, 2009). Scaife and Knight (2008) analyzed the cold European winter of the period 2005–2006, which was influenced by blocking, and showed the importance of stratospheric circulation and sea-surface temperature (SST) in the Atlantic Ocean. Maidens *et al.* (2013) assessed record-breaking low temperatures over Europe and concluded that ocean heat content and SST in the Atlantic Ocean were responsible for the successful forecast. Most parts of Japan experienced a cold spell during the 2012/2013 DJF, associated with a blocking high over eastern Siberia with a negative Arctic Oscillation (AO) (Tokyo Climate Center, Japan Meteorological Agency, 2013). The blocking high enabled the polar front jet stream to meander

southward over Japan; upper-level cold air moved over northern Japan.

In terms of climatological discussion for extreme events associated with blocking, Carrera *et al.* (2004) investigated the downstream weather impacts over Alaska in North America in DJF. Lee and Jhun (2006) studied the direct relationship between blocking activity and the Asian winter monsoon with regard to its influence on temperature and precipitation variations over China and the surrounding area. Takaya and Nakamura (2005) studied the Siberian High, which is dominant in the Asian winter climate. They concluded that the intraseasonal amplification of the Siberian High was affected by blocking over the North Pacific region and west Siberia.

The frequency of blocking is generally explained using indices that were introduced in the 1980s (Barriopedro *et al.*, 2010) and that have been applied in statistical analyses and case studies. One of the most popular indices, which measures the inverse of the meridional distribution of geopotential height at the 500-hPa level, was developed by Lejenäs and Okland (1983) and modified by Tibaldi and Molteni (1990). Pelly and Hoskins (2003) proposed another index, which is more reliant on the meteorological and the dynamic characteristics of the upper tropospheric flow. Using this method, blocking is defined by a reversal of the meridional potential temperature at the 2 potential vorticity unit (2 PVU) level (Hoskins *et al.*, 1985). Matsueda *et al.* (2009) assessed the blocking frequency

in current global climate models (GCMs) and showed that a high model resolution reproduced more accurate Europe–northeastern Atlantic blocking. On the other hand, Scaife *et al.* (2010) and Vial and Osborn (2011) reported the importance of the mean state of the models for the reproducibility of blocking.

Recently, a blocking index that considers the characteristics of not only longitudinal but also meridional distribution was applied to examine a multimodel ensemble from phase 5 of the Coupled Model Intercomparison Project (CMIP5) datasets (Anstey *et al.*, 2013). CMIP5 is the current phase of the CMIP project, whose purpose is to provide climate scientists with a database of coupled GCM simulations under standardized boundary conditions. Masato *et al.* (2013) analyzed the change in blocking frequency from the 20th to 21st centuries and used the outputs in CMIP5. They concluded that a winter poleward shift of high-latitude blocking over the North Pacific and a clear eastward shift of blocking in boreal summer over eastern Europe and western Russia may occur in the 21st century. On the other hand, Dunn-Sigouin and Son (2013) indicated that there would be no noticeable change in the duration of individual blocking in future climate simulations.

The blocking frequency and its geographical distribution based on the latest climate change scenario have been considered in recent studies, which have revealed features such as the northeastward shift of the blocking frequency over the North Pacific region (Masato *et al.*, 2013). However, the relationship between extreme weather events and blocking frequency has not been fully discussed over Japan and the surrounding area, the area that is the focus of this study. Therefore, we investigated how the northeastward shift of blocking over the North Pacific in future climate configurations will influence extreme events over Japan and the surrounding area utilizing re-analysis data and a multimodel ensemble of coupled GCMs obtained from CMIP5. Section 2 describes the methodology. The results are introduced in Section 3, and we summarized this study in Section 4.

2. Methodology

We used model outputs from the CMIP5 dataset. Nine GCMs used in previous studies about blocking frequency were selected: BNUESM, GFDL-CM3, GFDL-ESM2M, IPSL-CM5A-LR, IPSL-CM5A-MR, MIROC5, MIROC-ESM-CHEM, MPI-ESM-MR and MRI-CGCM3 (Anstey *et al.*, 2013; Dunn-Sigouin and Son, 2013; Masato *et al.*, 2013). The horizontal and vertical resolutions of these GCMs are provided in Table S1, Supporting information. Historical (HISTORICALs; December 1959–February 1999) and representative concentration pathway 8.5 (RCP8.5s; December 2059–February 2099) experiments were considered. The former experiment simulated the 20th-century climate with all forcing, and the latter experiment simulated future greenhouse gas emissions and

concentrations, leading to radiative forcing of 8.5 W m^{-2} at the top of the atmosphere in 2100. RCP8.5s were selected to focus on the years in which global warming had progressed, and the results were compared with previous studies (Masato *et al.*, 2013). The 40-year European Centre for Medium-range Weather Forecasts (ECMWF) re-analysis (ERA-40; Uppala *et al.*, 2005) was adapted as well as HISTORICALs and RCP8.5s. The air temperature at 2 m and geopotential height at 500-hPa level were used in ERA-40, HISTORICALs and RCP8.5s, respectively, to identify blocking and extreme events. The horizontal resolution of the CMIP5 models and the re-analysis differed. All nine GCMs, for HISTORICALs, RCP8.5s and ERA-40 were interpolated to 1.5° (latitude) $\times$ 4.5° (longitude) for the analyses, following Masato *et al.* (2013).

Blocking was identified using a two-dimensional blocking index derived from the daily 500-hPa geopotential height by following Masato *et al.* (2013). Here, the details of this diagnosis are introduced. The blocking index at longitude λ_0 and latitude φ_0

$$B_i = \frac{2}{\Delta\varphi} \int_{\varphi_0}^{\varphi_0 + \Delta\varphi/2} Z_i(\lambda_0, \varphi) d\varphi - \frac{2}{\Delta\varphi} \int_{\varphi_0 - \Delta\varphi/2}^{\varphi_0} Z_i(\lambda_0, \varphi) d\varphi \quad (1)$$

was defined as the difference in the northern and southern geopotential height average. Z_i is the geopotential height at every grid cell in longitude λ_0 and latitude φ_0 and φ is the latitude with $\Delta\varphi = 30^\circ$. If $B_i > 0$, then a large-scale reversal of the meridional gradient of the geopotential height (symptomatic of wave breaking) occurs on average from north to south centered at the point (λ_0, φ_0) . φ_0 is limited to the latitude band 15° – 75° N. Because wave breaking alone is not sufficient to determine the existence of blocking (i.e. blocking must have long-term persistency), limitations of duration and spatial movement were introduced, as given below:

1. Identification of each wave breaking: blocking centers defined by local positive B_i maxima in the B_i fields were detected each day.
2. Limitation of spatial movements from the onset: a blocking event finished when the local positive B_i maxima disappeared in a 40.5° (latitude) $\times$ 54° (longitude) box centered at the blocking center of the onset day, when B_i first became positive in 40° – 70° N.
3. Limitation of spatial movements between adjacent days (day n and day $n + 1$): a B_i maximum detected at day $n + 1$ within a 27° (latitude) $\times$ 36° (longitude) box centered at the blocking center of day n was defined as consecutive maxima. If two or more maxima were detected, the closest one was chosen.
4. Limitation of duration: if B_i maxima were relatively well connected by conditions 2 and 3, and lasted >5 days, then the positive B_i related to the B_i maxima was labeled as ‘blocked’.

Using these algorithms, the blocked area on each grid and for each day was identified using not only the DJF period, but also all monthly data to count the blocking extending from November to March. The blocking frequency was defined as the percentage of blocked days out of the total (3600 days) in the DJF over the entire 40-year period. In reference to Tyrlis and Hoskins (2008) and Davini *et al.* (2012), we defined the blocking intensity by the averaged value of B_i when blocking was detected by the previous algorithm for the three datasets, such as ERA-40, HISTORICALs and RCP8.5s, respectively.

The target region for extremes was Japan and its surrounding area (29.5–50.5°N; 126.0–148.5°E), which consists of 90 grid cells, within a 1.5° (latitude) × 4.5° (longitude) grid for all of the datasets used in this study (see the green rectangle in Figure 1(a)). Unusual temperature days above the 99th percentile or below the 1st percentile were defined as high or low temperature days (HEAT99, COLD1), respectively.

COLD1 and HEAT99 were derived from the daily data for the 40 winters from December 1959 to February 1999 for both ERA-40 and HISTORICALs or from December 2059 to February 2099 for RCP8.5s. COLD1 tended to occur in the first decade within the 40 target years in the case of RCP8.5s and HEAT99 tended to occur in the last decade within the target 40 years. Therefore, COLD1 and HEAT99 were assessed for each decade because the extreme temperature was affected by the trend of global warming.

3. Results

Figure 1 shows the geographic distributions of the blocking frequency over the Northern Hemisphere in DJF from 1959/1960 to 1998/1999 for ERA-40 (Figure 1(a)), HISTORICALs (Figure 1(b)) and from 2059/2060 to 2098/2099 for RCP8.5s (Figure 1(c)) with solid black lines. The colors in Figure 1(b) and (c) show the differences in blocking frequency between the HISTORICALs and ERA-40 (HISTORICALs minus ERA-40) and the differences between RCP8.5s and HISTORICALs (RCP8.5s minus HISTORICALs), respectively. The consistency of the surplus or deficit tendency between HISTORICALs and RCP8.5s for all nine GCMs is plotted in Figure 1(d). In the figure, red colors indicate high consistency between the two datasets in the change of blocking frequency.

In Figure 1(a), peaks of blocking frequency are apparent over the Russian Far East (62.5°N; 153.0°E), Greenland (64.0°N; 49.5°W) and the Czech Republic (50.5°N; 13.5°W), reaching 43.3, 16.3 and 10.2%, respectively. This geographic distribution, especially over the North Pacific region, is similar to that in HISTORICALs (Figure 1(b)). Over eastern Russia and north China (52–65°N; 111.0–140.0°E), the blocking frequency in HISTORICALs was approximately 4–8% higher than in ERA-40. On the other hand, the blocking frequency over Europe and the eastern

Atlantic tended to be underestimated by approximately 1–6%. RCP8.5s also had peaks of blocking frequency over the North Pacific region, but the center was shifted to the northeast, compared with HISTORICALs, as shown in Figure 1(c). These characteristics are similar to those suggested by Masato *et al.* (2013). As indicated in Figure 1(c) and (d), almost all models showed a decrease in blocking frequency over the Sea of Okhotsk. On the other hand, the Bering Strait and Alaska in the United States were expected to experience an increase in the blocking frequency under this climate change condition.

In Figure 2, the geographical distribution of blocking intensity in winter for ERA-40 (Figure 2(a)), HISTORICALs (Figure 2(b)) and RCP8.5s (Figure 2(c)) is displayed. As in Figure 1, the color shading represents the differences in blocking intensity between HISTORICALs and ERA-40 (Figure 2(b)) and between RCP8.5s and HISTORICALs (Figure 2(c)). Figure 2(d) shows the consistency of the surplus or deficit tendency between HISTORICALs and RCP8.5s for all nine GCMs. As with the blocking frequency, there were peaks of blocking intensity over the Russian Far East and Greenland. In Figure 2(c) and (d), it can be seen that the blocking intensity over the Sea of Okhotsk consistently decreased in RCP8.5s for models 5–8.

Figure 3 shows the difference in the blocking frequency between COLD1 and HEAT99 days over Japan and its surroundings against the climatology of the blocking frequency. All of the panels in Figure 3 are for ERA-40 during DJF between 1959/1960 and 1998/1999. The contour lines indicate the climatology of the blocking frequency, which is shown in Figure 1(a). For the COLD1 days shown in Figure 3(a), the blocking frequency tended to be larger over the entire Pacific blocking region. This characteristic is particularly apparent (12–24%) over the northwestern Sea of Okhotsk and the adjoining Russian Far East (blue rectangle; 52.0–62.0°N; 126.0–148.5°E). On the other hand, the blocking frequency was <10% over the northern Pacific and the Russian Far East for HEAT99 days (Figure 3(b)). It is considered that the westerly jet meanders southward over Japan and its surroundings due to blocking over the sea of Okhotsk and that the unusual warm temperature does not occur due to cold air from high latitudes. In this study, the relationship between COLD1 over Japan and its surroundings and the blocking frequency over the Pacific region were considered in association with climate change conditions.

Next, with regard to the spatial scale, the number of COLD1 days was determined by calculating the area covered (%) that satisfied COLD1 over Japan and its surroundings on the same day. Figure 4(a) shows the relationship between the number of COLD1 days (%) in DJF over a 40-year period (vertical axis) and the area covered (horizontal axis) in which COLD1 occurred over Japan and its surroundings for ERA-40 (green color), HISTORICALs (blue color) and RCP8.5s (red color), respectively. The number of COLD1 days shown on the vertical axis for HISTORICALs and RCP8.5s

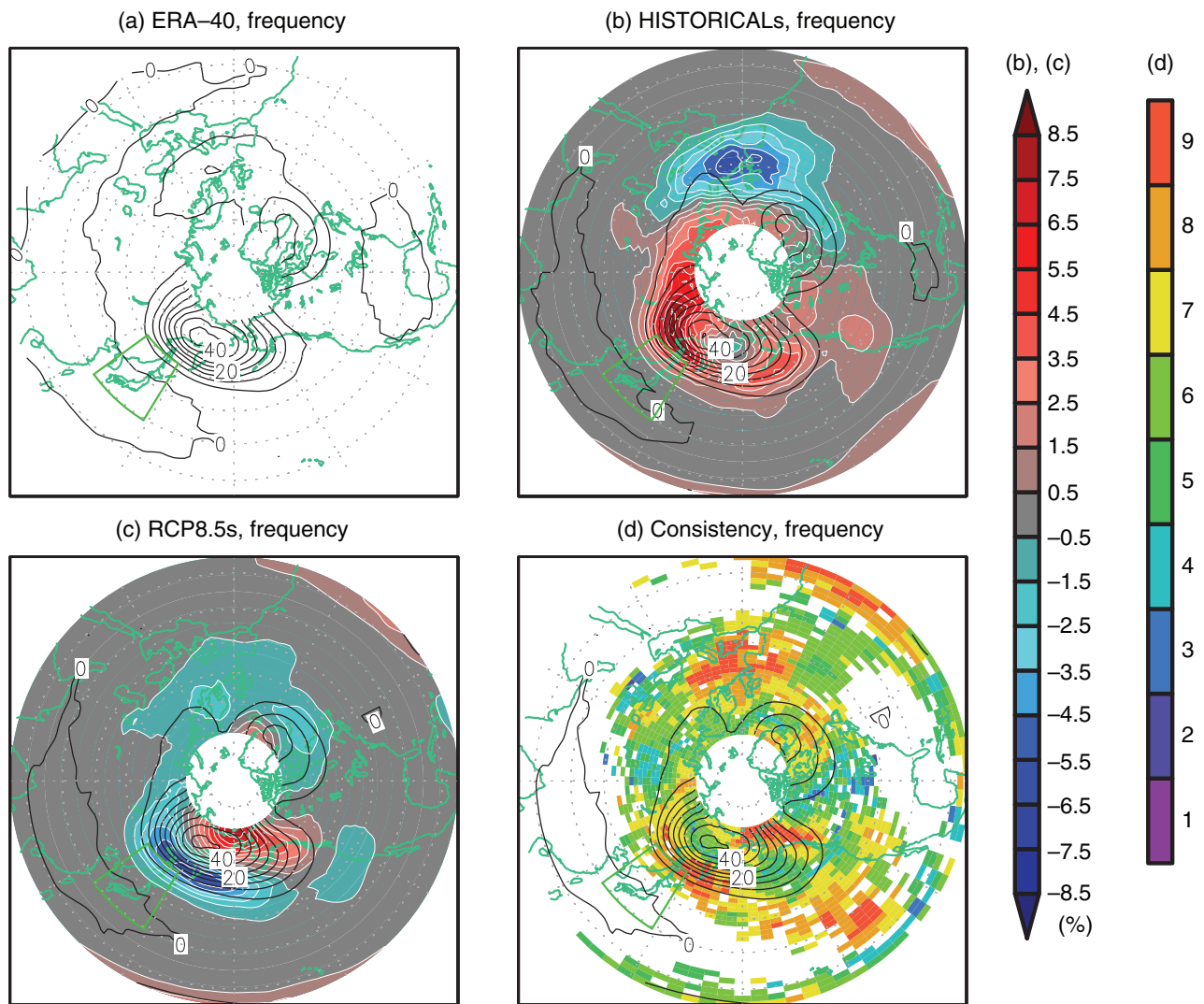


Figure 1. Blocking frequency during boreal winter (DJF) for (a) ERA-40 and nine sets of multimodel ensemble means of (b) HISTORICALs and (c) RCP8.5s. Solid black lines indicate the blocking frequency. Contours are 5% intervals. The colors represent the differences in the blocking frequency between (b) HISTORICALs and ERA-40, (c) RCP8.5s and HISTORICALs, respectively. Red (blue) color shows a surplus (deficit) tendency compared with ERA-40 in (b) and an increased (decreased) tendency compared with HISTORICALs in (c). Color shading (d) denotes the number of GCMs showing the same signed tendency in (c). Solid black lines in (d) denote the blocking frequency in RCP8.5s. The rectangular areas in all panels show Japan and its surroundings (29.5–50.5°N; 126–148.5°E).

is the multimodel ensemble average among the nine GCMs. To highlight the characteristics of these lines for a high area covered, the upper-right vertical axis is provided for the cases with >16% cover. The differences between HISTORICALs and RCP8.5s are plotted in Figure 4(b). As shown in Figure 4(a), all three lines indicate similar behavior. By comparing HISTORICALs and RCP8.5s in Figure 4(b), it can be seen that RCP8.5s had negative values up to approximately 16%. In contrast, many positive values were apparent for a higher area covered. Therefore, COLD1 will occur more widely at the same time over Japan and its surroundings under this climate change condition. The difference between climatological temperature and its first percentile, averaged in Japan and its surroundings, will be small, i.e. from 7.7° in HISTORICALs to 6.7° in RCP8.5s. A more detailed analysis of the tendency of the area covered to occur with blocking over the Sea

of Okhotsk and its surroundings is shown in Figure S1, Supporting information.

Here, details of the number of COLD1 days and their spatial scale between HISTORICALs and RCP8.5s in association with blocking over the northwestern Sea of Okhotsk and its surroundings (blue rectangle in Figure 3(a); 52.0–62.5°N; 126.0–148.5°E) are investigated. Figure 5 shows the number of COLD1 days (%) in the DJF periods over a 40-year period when blocking occurred over the northwestern Sea of Okhotsk and its surrounding area for both HISTORICALs and RCP8.5s. The colors indicate the area covered that satisfied the COLD1 condition. According to this figure, COLD1 days with spatially small scales (0–10% over Japan and its surroundings) that are associated with blocking over the northwestern Sea of Okhotsk and its surroundings will decrease under the climate change condition assessed here. On the other hand, COLD1

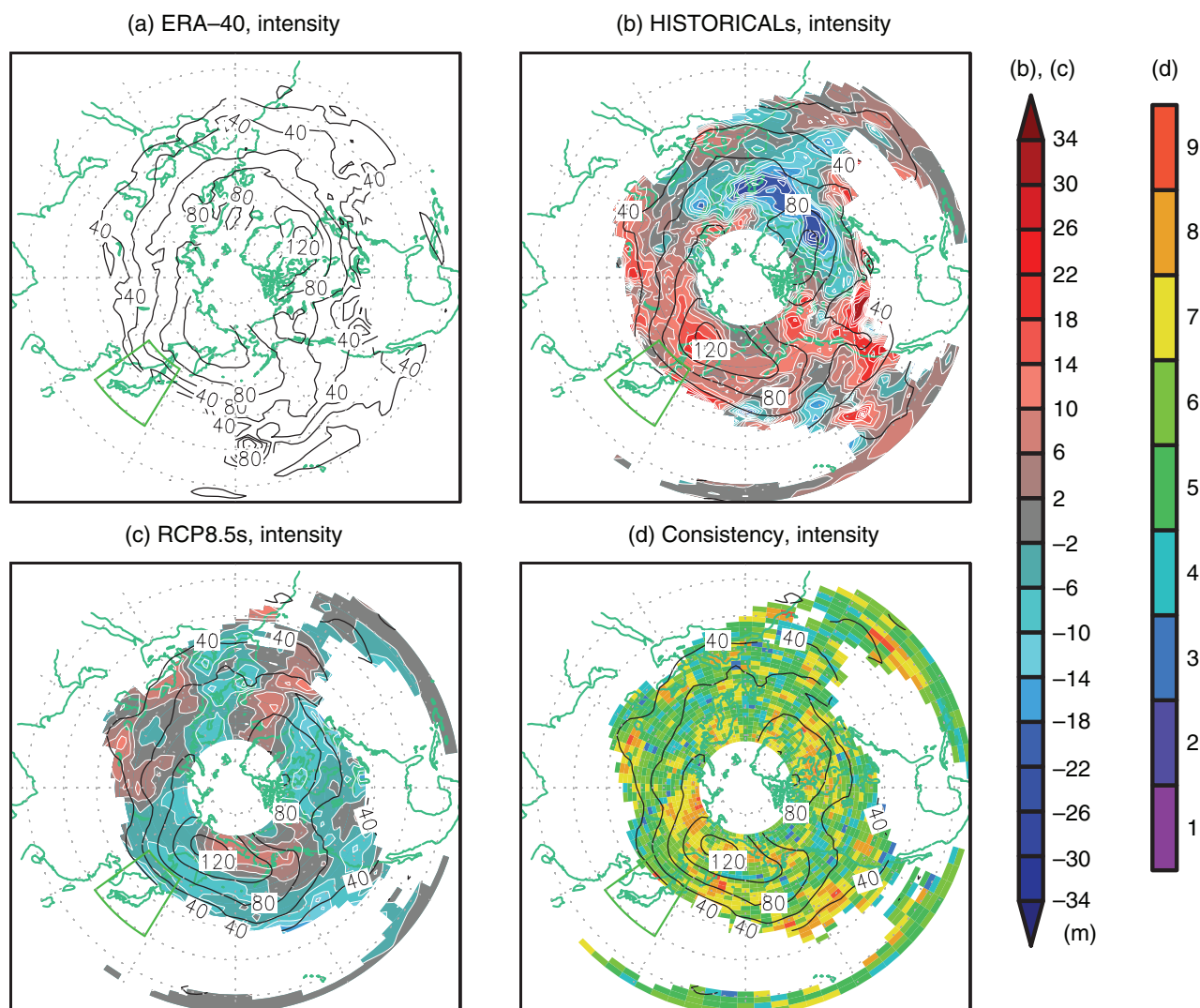


Figure 2. As in Figure 1, but for intensity. Contours are 20 m intervals.

days with a spatially wider range will increase under these climate conditions.

4. Summary

This study focused on the relationship between unusual temperature days over Japan and its surroundings and the frequency and intensity of atmospheric blocking over the North Pacific region by analyzing ERA-40 and nine GCM projections for current and future climate conditions. The results showed that a 1-in-100-day cold day (COLD1) tended to occur with a large blocking frequency over the North Pacific blocking region, particularly over northwestern Sea of Okhotsk and its surrounding area. This characteristic was confirmed for the future climate conditions investigated here, even though the North Pacific blocking will be shifted northeasterly compared with the current climate condition (Figure 1(c); Masato *et al.*, 2013). Furthermore, COLD1 days over Japan and its surroundings will become weaker and occur more widely, while the total number of COLD1 days will decrease. It is expected

that the severity of unusual cold days over Japan and its surroundings will become weaker due to the reduction of blocking intensity over the Sea of Okhotsk, and the decrease of blocking frequency over this area will lead to less frequent but more widespread unusual cold weather in the future climate.

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Supporting information

The following supporting information is available:

Table S1. The details of the nine GCMs used for HISTORICALs and RCP8.5s.

Figure S1. Differences in the blocking frequency between COLD1 days with a smaller (<16% area covered over Japan and

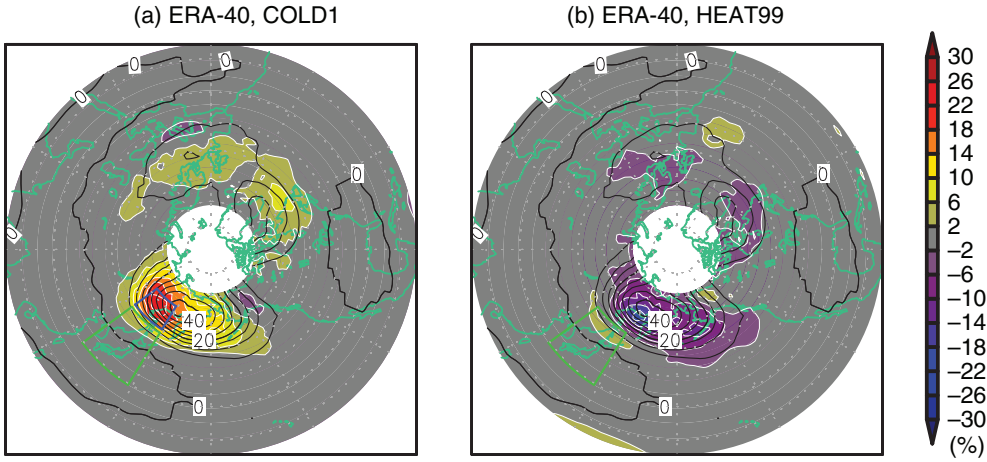


Figure 3. Differences in the composite blocking frequency for (a) COLD1 and (b) HEAT99 over Japan and its surroundings against the climatological mean blocking frequency for DJF in ERA-40. Contours are 5% intervals and indicate the climatological mean blocking frequency, as shown in Figure 1(a).

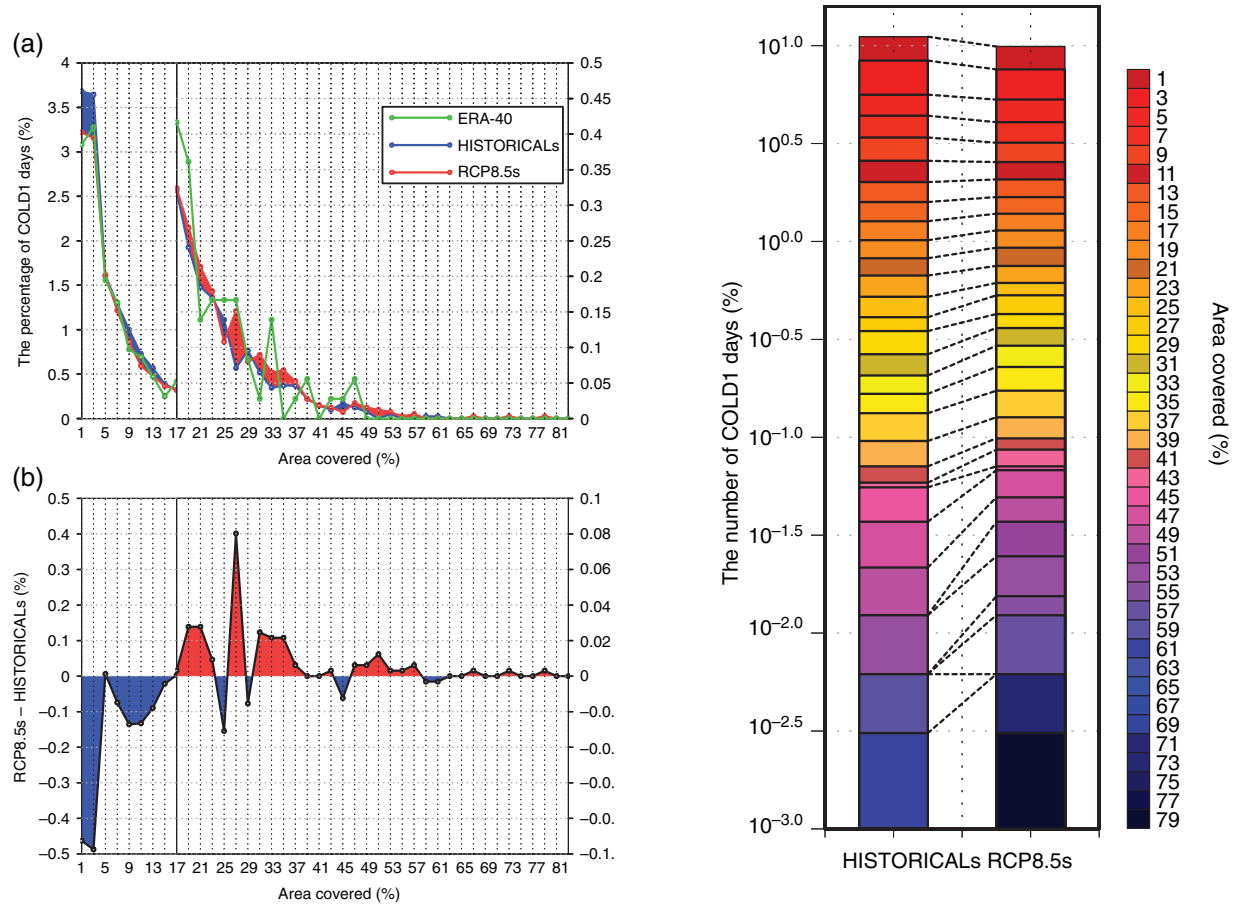


Figure 4. (a) The number of COLD1 days (%) in the DJF periods over a 40-year period (vertical axis) and the area covered (horizontal axis) at which COLD1 days occur over Japan and its surroundings for ERA-40 (solid green line), HISTORICALs (solid blue line) and RCP8.5s (solid red line). The shaded blue and red areas represent the differences between HISTORICALs and RCP8.5s. The right-hand side of this panel refers to the upper-right vertical axis and highlights the characteristics of all three lines for the spatially wider extent of COLD1 days. (b) Differences in the number of COLD1 days between HISTORICALs and RCP8.5s (RCP8.5s minus HISTORICALs). The right-hand side of this panel also refers to the upper-right vertical axis.

Figure 5. The number of COLD1 days (%) in the DJF periods over a 40-year period (3600 days) and the area covered (%) when atmospheric blocking occurs over the northwestern Sea of Okhotsk and its surroundings for HISTORICALs and RCP8.5s.

its surroundings) spatial range and climatological mean for (a) ERA-40, (b) HISTORICALs and (c) RCP8.5s. Similar panels for a wider spatial range ($>16\%$ over Japan and its surroundings) are shown for (d) ERA-40, (e) HISTORICALs and (f) RCP8.5s. The solid black lines indicate the climatological mean blocking frequency for each scenario and at 5% intervals. The blue rectangular areas ($52\text{--}62.5^\circ\text{N}$; $126\text{--}148.5^\circ\text{E}$) have a higher blocking

frequency than the climatology for (d)–(f) when COLD1 days occur with wide spatial area covered.

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