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2 **Decrease of Rossby Wave Breaking Frequency over the**

3 **Middle North Pacific in Boreal Summer**

4 **under Global Warming in Large-Ensemble Climate**

5 **Simulations**

6

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Abstract

Future change of Rossby wave breaking (RWB) frequency over the middle North Pacific (MNP) in August and the related features of large-scale atmospheric circulation are examined using large-ensemble simulations of current and future climates with a global circulation model. Correlation analysis indicates that the RWB frequency over the MNP in the current climate can show a relationship to El-Niño Southern Oscillation as reanalysis. The RWB frequency in the future climate shows significant decreases over the MNP, compared to that in the current climate. The large-scale atmospheric circulation in the upper troposphere in the future climate indicates a significant weakening of the Asian summer monsoon circulation and the consequent southward shifted Asian jet. The decreased RWB frequency over the MNP is associated with the modulated Asian jet, through reduced diffuence and deceleration of the jet in the basic-state over the region. Rossby wave propagation over Eurasia and the North Pacific in mid-latitudes is also clearly reduced in the future climate, consistent with the decreased RWB frequency over the MNP. Correlation and histogram analyses of the current and future experiments indicate that the significantly decreased RWB frequency over the MNP is associated with significantly suppressed convective activities east of the Philippines in the future climate. The diagnosis using ω -equation further shows the dynamical impact of the decreased RWB frequency on the suppressed convective activities, through the weakened extension of the Mid-Pacific trough and the consequent weakening of dynamically induced ascent east of the

45 Philippines.

46

47 **Keywords** future change; Rossby wave; wave breaking; Asian monsoon

48

49 **1. Introduction**

50 Rossby wave propagation along the Asian jet ([Lu et al. 2002](#), [Enomoto et al. 2003](#))
51 frequently causes Rossby wave breaking (RWB) east of Japan (e.g., [Postel and Hitchman](#)
52 [1999, 2001](#), [Abatzoglou and Magnusdottir 2006](#)), where the Asian jet exit is located, in
53 boreal summer. The RWB near Japan is accompanied by an equivalent barotropic structure
54 of anticyclone, which is referred to as the Bonin high ([Enomoto 2004](#)), and causes
55 abnormally hot summer climate over the region. Most of the RWBs east of Japan in boreal
56 summer are categorized as anticyclonic type ([Bowley et al. 2019](#), [Takemura et al. 2020](#))
57 associated with the RWB occurrence to the south of the subtropical jet core in the basic
58 state. The anticyclonic RWB east of Japan has impacts on enhanced convective activities
59 to the south over the subtropical western North Pacific (WNP), through the southwestward
60 intrusion of high potential vorticity (PV) air mass and the consequent dynamically induced
61 ascent ([Takemura et al. 2017](#), [Takemura and Mukougawa 2020](#)). [Takemura and](#)
62 [Mukougawa \(2020\)](#) further indicated that enhanced convection over the subtropical WNP
63 due to the RWB east of Japan can promote the Pacific-Japan (PJ) pattern ([Nitta 1987](#),
64 [Kosaka and Nakamura 2006](#)) accompanied by anticyclonic circulation anomalies near
65 Japan. This polarity of the PJ pattern also corresponds to the enhanced Bonin high
66 associated with the extended North Pacific subtropical high toward Japan, and contributes
67 to abnormally hot summer climate over the region ([Wakabayashi and Kawamura 2004](#)).

68 Future changes of the RWB frequency east of Japan due to long-term trend thus will be

one of essential debates to reveal the detailed process in the long-term trend of surface temperature over Japan in summer (e.g. [Imada et al. 2017](#)). [Vries et al. \(2013\)](#) examined seasonal frequency of atmospheric blocking from the North Atlantic to Europe in the future climate, indicating a significant decrease of the frequency over the North Atlantic in summer due to a northward shift of jet. Although the blocking includes not only the RWB but also “ Ω ”-shaped amplified ridge ([Pelly and Hoskins 2003](#)), the blocking frequency is expected to approximately correspond to the RWB frequency. For the North Pacific, [Matsueda and Endo \(2017\)](#) showed unique and uncertain changes of summertime blocking frequency in the future climate, with a slight increase for the duration between 15 and 29 days and a decrease for that between 5 and 9 days. [Takemura et al. \(2020\)](#), on the other hand, suggested a long-term decreasing trend of the RWB frequency, which is derived from reversal of potential temperature fields at the dynamical tropopause ([Pelly and Hoskins 2003](#)), from Japan to the east in August using a dataset of the Japanese 55-year reanalysis (JRA-55; [Kobayashi et al. 2015](#)). Their suggestion motivates us to examine the future change of the RWB frequency east of Japan in more detail. The Silk Road pattern ([Enomoto et al. 2003](#), [Kosaka et al. 2009](#)), which is a wave train associated with Rossby wave propagation along the Asian jet, frequently causes the RWB near the jet exit region ([Enomoto 2004](#)). [Uchida and Kosaka \(2019, 2020\)](#) indicated decreased amplitude of the Silk Road pattern in the future climate, based on a principal component analysis of 200-hPa relative vorticity in summer derived from large-ensemble climate simulations. Considering

89 the contribution of the strong Rossby wave propagation to the RWB near the Asian jet exit
90 region (e.g., [Enomoto 2004](#), [Postel and Hitchman 1999, 2001](#)), the result of [Uchida and](#)
91 [Kosaka \(2019, 2020\)](#) implies a possibility of a decrease in RWB frequency east of Japan in
92 the future climate. The future change of the RWB frequency east of Japan, on the other
93 hand, has not been examined yet.

94 Meanwhile, the future change of atmospheric circulation in the tropical WNP has been
95 ongoing debate in previous studies. [Kosaka and Nakamura \(2011\)](#) showed a reduced
96 occurrence of the PJ pattern with cyclonic (anticyclonic) circulation anomalies around the
97 Philippines (Japan) under the climatologically suppressed convective activity over the
98 tropical WNP in the future climate, from multi-model ensemble simulations. [Yoshida et al.](#)
99 [\(2017\)](#) and [Sugi et al. \(2020\)](#) indicated a decreased number of tropical cyclones and their
100 seeds over the tropical WNP in a future climate, which is consistent with the suppressed
101 convective activities over the tropical WNP.

102 Based on the aforementioned results, this study assesses the future change of the RWB
103 frequency east of Japan and the related large-scale atmospheric circulation from low- to
104 mid-latitudes in boreal summer, using results of high-resolution experiments with
105 large-ensemble historical and future climate simulations. This line of investigation is
106 expected to contribute to risk management of increased heatwave episode in boreal
107 summer resulting from ongoing global warming ([Imada et al. 2019](#)), and the associated
108 socio-economic decision-making.

109

110 **2. Dataset and methods**

111 To examine the future change of the RWB frequency east of Japan and the associated
112 features of atmospheric circulation, results of the large-ensemble climate simulation in
113 August, which are referred to as “Database for Policy Decision-Making for Future Climate
114 Change” (d4PDF; [Mizuta et al. 2017](#)), for historical and future global climates are
115 diagnosed. The daily dataset used has a grid interval of 2.5° and 24 pressure levels (top at
116 0.5 hPa). The numerical simulations are performed using the atmospheric general
117 circulation model (MRI-AGCM3.2) developed by the Meteorological Research Institute
118 ([Mizuta et al. 2012](#)). The model has horizontal resolution of a triangular truncation of 319
119 with a linear Gaussian grid (T_L319), which corresponds to a grid interval of approximately
120 55 km, and 64 vertical levels with the top at 0.01 hPa. The historical climate simulations
121 (hereafter referred to as “current experiment”) were forced by the monthly averaged
122 historical sea surface temperature (SST) and sea ice based on COBE-SST2 ([Hirahara et al.](#)
123 [2014](#)) with historical anthropogenic forcing such as greenhouse gases and natural forcing.
124 The current experiment has 100 ensemble members with different atmospheric initial
125 perturbations and perturbed SSTs as the boundary condition, which was integrated for the
126 60-yr period from 1951 to 2010. The future climate simulations (hereafter referred to as
127 “future experiment”) were forced by six warming patterns of SST in the future climate, which
128 are projected by multiple models based on phase 5 of the Coupled Model Inter-comparison

129 Project (CMIP5). The future experiment simulates 4-K warmer global-mean surface air
130 temperature than the preindustrial climate, which corresponds to a warming level at 2090
131 according to the representative concentration pathway 8.5 (RCP8.5) scenario of the CMIP5.
132 The future experiment has total 90 ensemble members with the same initial perturbations
133 as the current experiment, which was integrated for the 60-yr period from 2051 to 2110.
134 Here the boundary condition of SSTs in the future experiment is those in the current one
135 after detrended and the climatological SST warming pattern is added, showing the same
136 interannual variability of the SSTs between the current and future experiments. Further
137 detail for each type of the climate simulations is described in [Mizuta et al. \(2017\)](#). A
138 difference in the 60-yr climatology of the ensemble means between the future experiment
139 and the current experiment is referred to as “future change” in this study. The future change
140 thus represents a shift of the climatological mean without modulations in the interannual
141 variability of SST such as El-Niño Southern Oscillation (ENSO).

142 Vertical motion including convective activities in tropics is estimated using vertical
143 p-velocity (ω) at 500 hPa. To verify this estimation, we also used the monthly mean dataset
144 of interpolated outgoing longwave radiation (OLR) ([Liebmann and Smith 1996](#)) in August,
145 which was provided by the U.S. National Oceanic and Atmospheric Administration (NOAA).
146 The climatology of OLR is defined as the 30-yr monthly averages from 1981 to 2010.

147 To assess reproducibility for interannual variability of the RWB frequency east of Japan in
148 the climate simulations, we used daily datasets of the JRA-55 ([Kobayashi et al. 2015](#)) in

149 August during the 61-yr period from 1958 to 2018. The JRA-55 system has a horizontal
 150 resolution of T_L319 , and we used the data interpolated to 1.25° horizontal resolution and 37
 151 pressure levels (top at 1 hPa). To assess a reproducibility of relationships between the
 152 RWB frequency in the climate simulations and the ENSO, the 5-month running mean SST
 153 deviation for Niño-3 index (Tokyo Climate Center 2020), which is defined as areal-averaged
 154 SST over the area of $[5^\circ\text{S}–5^\circ\text{N}, 150^\circ–90^\circ\text{W}]$, is used. Here the SST deviation is defined as
 155 a deviation from the latest sliding 30-yr average.

156 To examine the diffluence and deceleration of basic flow near the Asian jet exit region,
 157 which is a preconditioning of the RWB (Colucci 2001), stretching deformation (d_B) of the
 158 basic-state was calculated from the horizontal wind as follows:

$$159 \quad d_B \equiv \frac{\partial u_B}{\partial x} - \frac{\partial v_B}{\partial y}, \quad (1)$$

160 which is defined according to Mak and Cai (1989) and Bluestein (1992). Here, the subscript
 161 B denotes the basic-state defined by zonal wavenumbers $k \leq 3$, to exclude flows due to
 162 the Rossby waves. The diffluent and decelerated basic flow thus corresponds to negative
 163 d_B , and is generally seen over the region near or upstream of the RWB (e.g., Colucci and
 164 Alberta 1996, Colucci 2001), contributing to trigger the RWB occurrence.

165 To calculate the RWB frequency, we used a daily dynamical blocking index (Pelly and
 166 Hoskins 2003) based on meridional distributions of potential temperature θ on the
 167 dynamical tropopause defined by 2 potential vorticity units (PVU; $1 \text{ PVU} = 10^{-6} \text{ K kg}^{-1} \text{ m}^2$
 168 s^{-1}), which is conserved without diabatic processes. The blocking index B (unit: K) is

expressed as follows:

$$B = \frac{1}{\Delta\lambda} \int_{-\Delta\lambda/2}^{\Delta\lambda/2} \left\{ \frac{2}{\Delta\phi} \left(\int_{\phi_0}^{\phi_0+\Delta\phi/2} \theta d\phi - \int_{\phi_0-\Delta\phi/2}^{\phi_0} \theta d\phi \right) \right\} d\lambda \quad (2)$$

where λ is the longitude, $\Delta\lambda$ is the width of zonal average, ϕ is the latitude, $\Delta\phi$ is the typical meridional scale of the wave breaking, and ϕ_0 is the central latitude. We defined $\Delta\lambda$ as 5° and $\Delta\phi$ as 30° , respectively, according to [Pelly and Hoskins \(2003\)](#). A daily RWB is detected when B has a positive value: there is high θ to the north and low θ to the south. We defined monthly RWB frequency as the fraction of days for which the RWB is detected in the month, as in [Takemura et al. \(2020\)](#).

The propagation of quasi-stationary Rossby wave packets is analyzed using the wave activity flux (WAF) defined by Takaya and Nakamura (2001). The horizontal WAF is defined as follows:

$$\mathbf{W} = \frac{1}{2|\mathbf{U}|} \begin{pmatrix} \bar{u}(\psi_x'^2 - \psi' \psi_{xx}') + \bar{v}(\psi_x' \psi_y' - \psi' \psi_{xy}') \\ \bar{u}(\psi_x' \psi_y' - \psi' \psi_{xy}') + \bar{v}(\psi_y'^2 - \psi' \psi_{yy}') \end{pmatrix}, \quad (3)$$

where u is the zonal wind, v is the meridional wind, $\mathbf{U}$ is the climatological horizontal wind vector, and ψ is the stream function. The overbars (primes) denote the basic states (perturbations), defined as the 60-yr climatology (anomaly from the 60-yr climatology). The subscripts x and y denote the partial derivatives with respect to longitude and latitude, respectively. The WAF is derived from the five-day running mean anomalies and climatology.

3. Reproducibility of interannual variability of RWB frequency

189 In this section, we describe a reproducibility of the RWB frequency, focusing on the
190 interannual variability and its relationship with the ENSO. Figure 1 firstly shows the RWB
191 frequency in August during the 53-yr period from 1958 to 2010, for the reanalysis (JRA-55)
192 and the current experiment. Although the RWB frequency in both the reanalysis (Fig. 1a)
193 and the current experiment (Fig. 1b) attains their maxima over the North Pacific, the center
194 of the maximum in the current experiment slightly shifts eastward compared with that in the
195 reanalysis. The smaller RWB frequency in the current experiment will be described later in
196 Fig. 1c. There is another maximum of the RWB frequency from North America to the North
197 Atlantic, also showing a clear eastward shift of the maximum in the current experiment
198 compared with the reanalysis. The large RWB frequency from the eastern part of North
199 Africa to South Asia south of 25°N (Figs. 1a and 1b) corresponds to the meridional
200 overturning of the potential temperature on the 2-PVU surface, where the climatological
201 Tibetan high is located to the north. The large climatological RWB frequency in the
202 low-latitudes are out of scope in this study.

203 To highlight the RWB frequency in mid-latitudes, the RWB frequency averaged over the
204 latitudinal band of 25°–45°N is shown in Fig. 1c. Here the RWB frequency in the current
205 experiment (black line in Fig. 1c) represents the ensemble mean. Although the RWB
206 frequency in the current experiment attains its local maximum over the North Pacific as in
207 the reanalysis (green line in Fig. 1c), the simulated RWB frequency is about half of the
208 reanalysis counterpart over the region. The underestimated RWB frequency is also seen

209 over North America. The eastward shifted RWB frequency in the current experiment is also
210 clear by comparing Figs. 1a and 1b. [Scaife et al. \(2010, 2011\)](#) indicated from their sensitive
211 experiments that the underestimated frequency of the atmospheric blocking in the
212 numerical models, compared to a reanalysis, is primarily due to large-scale climatological
213 mean bias of atmospheric fields and SSTs in the models, rather than the horizontal
214 resolution. [Vries et al. \(2013\)](#), who indicated the significant future decrease of the RWB
215 frequency over the North Atlantic, also notes the underestimation of the blocking frequency
216 over the region.

217 To examine environmental atmospheric circulations in the upper troposphere associated
218 with the underestimated and eastward shifted RWB frequency over the North Pacific,
219 stretching deformation and zonal wind at 200 hPa of the basic-state (zonal wavenumbers
220 $k \leq 3$) for the current experiment and the reanalysis are shown in Figs. 2a and 2b.
221 Distributions of the upper-level zonal wind fields and stretching deformation from Eurasia to
222 the North Pacific in the reanalysis are generally reproduced in the current experiment (Figs.
223 2a and 2b). The detailed structure of the upper-level stretching deformation in the current
224 experiment over the region (shading in Fig. 2b), by contrast, is different from that in the
225 reanalysis (shading in Fig. 2a) associated with slight differences of the horizontal wind
226 fields: the upper-level stretching deformation in the current experiment is weaker from
227 Japan to the east and extends eastward over the mid-latitude North Pacific. The
228 upper-level stretching deformation for the current experiment and the reanalysis also

229 clearly shows the positive and negative differences over the western and central to eastern
230 parts of the mid-latitude North Pacific (Fig. 2c), respectively, corresponding to the
231 underestimated and eastward shifted RWB frequency in the current experiment (Fig. 1c).
232 Although these results suggest that the underestimated and eastward shifted RWB
233 frequency is expected to be primarily due to the climatological mean bias of the
234 atmospheric fields, further investigation for the associated detailed factors will be required.
235 Although the bias of the RWB frequency will have some quantitative impacts on its future
236 change as noted by [Vries et al. \(2013\)](#), its relative change from the current climate to the
237 future climate in a single climate model, which will be presented in this study, has validity to
238 be investigated.

239 [Bowley et al. \(2019\)](#) indicated a statistically close relationship between the anticyclonic
240 RWB frequency over the North Pacific and the ENSO. [Takemura et al. \(2020\)](#) also
241 statistically indicated that the anticyclonic RWB is dominant from Japan to the east in
242 August, and showed a significant increase of the RWB frequency over the region during La
243 Niña years. They further showed the related process that an enhanced Walker circulation
244 and the consequent northward shift of the Asian jet associated with the La Niña condition
245 can contribute to the frequent RWB from Japan to the east. According to their results, a
246 reproducibility of relationships between the RWB frequency averaged over the middle North
247 Pacific (25°–45°N, 150°E–150°W; hereafter referred to as “MNP”) and the ENSO is
248 assessed. Figure 3 shows scatter diagrams between the Niño-3 indices and the RWB

frequency averaged over the MNP. The RWB frequencies in both all ensemble members of the current experiment (dots in Fig. 3a) and the reanalysis (opened circles in Fig. 3b) show relationships with the Niño-3 indices with negative correlation coefficients of -0.31 and -0.51, respectively. The RWB frequency of the ensemble mean in the current experiment and the Niño-3 indices (opened circles in Fig. 3a) have a stronger relationship with a negative correlation coefficient of -0.57. The ensemble mean extracts variability externally forced by SST and sea ice, indicating that atmospheric internal variability represented by all ensemble members can obscure the relationship to the ENSO. These negative correlations indicate the relationship between the RWB frequency over the MNP and the ENSO, consistent with the results of [Bowley et al. \(2019\)](#) and [Takemura et al. \(2020\)](#). It shows that responses of the RWB frequency to the ENSO, which is one of the most dominant interannual climate variabilities, is seen in the current experiment (Fig. 3a), suggesting the reproducibility for the component of interannual variation. The aforementioned results also imply that the responses of the RWB frequency to the future change can be investigated.

263

264 **4. Future change of RWB frequency and large-scale atmospheric circulation**

265 This section describes the future change of the RWB frequency over the MNP and the
266 associated modulation of large-scale atmospheric circulation. Figure 4 shows the RWB
267 frequencies averaged over 25°–45°N in August for the current and future experiments. The
268 decrease in RWB frequency over the MNP is significant in the future climate (red line in Fig.

4), compared to the current one (black line in Fig. 4). The areal average of RWB frequency over the MNP decreases by more than 20 % in the future climate. The RWB frequency also shows decreasing tendencies over a wide area in the latitudinal band of 25°–45°N, and the decreased frequency over the North Atlantic is consistent with the result of [Vries et al. \(2013\)](#). The RWB frequency in the mid-latitudes shows increasing tendency west of the MNP near 120°–140°E only, although the change of the RWB frequency is not large. The following subsections show noteworthy features of the modulated large-scale atmospheric circulations in the future climate, in association with the decreased RWB frequency over the MNP.

278

4.1. Large-scale tropical divergence in the upper troposphere and the Asian jet

Figure 5a shows the future change of 200-hPa velocity potential in August. In the upper troposphere, a large-scale divergence from South to Southeast Asia is significantly weakened, indicating suppressed Asian monsoon circulation in the future climate, consistent with the results of [Sugi et al. \(2002\)](#), [Hirahara et al. \(2012\)](#). The future change of velocity potential with zonal wavenumber 1 (shading in Fig. 5a) also indicates a weakened Walker circulation, compared to the current climate (contour in Fig. 5a), showing an El Niño-like atmospheric response in the tropics.

To examine an influence of the tropical circulation on the Asian jet in the future climate, the future change of 200-hPa zonal wind is shown in Fig. 5b. The future change of the

289 upper-level zonal wind shows a significant meridional dipole pattern with westerly and
290 easterly changes to the south and north of the jet core over Eurasia, indicating southward
291 shift of the Asian jet in the future climate. To further assess features of the Asian jet of the
292 basic-state (zonal wavenumbers $k \leq 3$), the future changes of 200-hPa zonal wind of the
293 basic-state from central Eurasia to the North Pacific in August are also shown in Figs. 5c.
294 The southward shifted Asian jet core is seen in the future climate (red contour in Fig. 5c),
295 compared to the current climate (black contour in Fig. 5c), associated with the suppressed
296 Asian monsoon circulation.

297 To further investigate a vertical structure of the Asian jet, latitude-pressure cross-section
298 of the future change of zonal wind of the basic-state averaged over 60°–120°E is shown in
299 Fig. 6. The center of the Asian jet in the future climate (red contour in Fig. 6) clearly shifts
300 not only southward but also upward compared with that in the current climate (black
301 contour in Fig. 6). The future change of the zonally averaged zonal wind (shading in Fig. 6)
302 also indicates the significantly upward-shifted Asian jet. The upward displacement of the
303 Asian jet core is consistent with [Lorenz and DeWeaver \(2007\)](#), who indicated the elevated
304 tropopause height and zonal-mean zonal wind response to the warmer climate. It is
305 noteworthy that the southward shifted Asian jet (Figs. 5b and 5c) is inconsistent with the
306 northward shift of zonal-mean zonal wind in the warmer climate described by [Lorenz and](#)
307 [DeWeaver \(2007\)](#).

308 To focus on an influence of the suppressed Asian monsoon circulation on the southward

309 shifted Asian jet in the future climate, the future change of absolute vorticity at 200 hPa is
 310 shown in Fig. 7a. The upper-level absolute vorticity clearly indicates positive (cyclonic)
 311 changes along a zonally elongated strong gradient of absolute vorticity, corresponding to
 312 the southward shifted Asian jet (Figs. 5b and 5c). To assess a contribution of the
 313 suppressed upper-level divergence from South to Southeast Asia to the southward shifted
 314 Asian jet, the future change of the absolute vorticity advection by horizontal divergent wind
 315 at 200 hPa is shown in Fig. 7b. Here the absolute vorticity advection due to the divergent
 316 wind (S_χ) is defined as follows:

$$317 \quad S_\chi = -\overline{\mathbf{v}_\chi} \cdot \nabla(\bar{\zeta} + f), \quad (4)$$

318 where $\mathbf{v}_\chi = (u_\chi, v_\chi)$ is the horizontal divergent wind vector, ζ and f are the relative and
 319 planetary vorticity, respectively. The overbars denote the 60-yr monthly climatology in each
 320 climate simulation. The shading of Fig. 7b clearly shows positive vorticity tendencies along
 321 the Asian jet, particularly over the eastern part, corresponding to the positive change of the
 322 upper-level absolute vorticity (Fig. 7a). The positive vorticity tendencies are associated with
 323 the weakened northward divergent wind (vectors in Fig. 7b) resulting from the suppressed
 324 upper-level divergence from South to Southeast Asia (Fig. 5a), indicating their contributions
 325 to the southward shifted Asian jet in the future climate. The southward shifted Asian jet
 326 shown in Figs. 5b and 5c further corresponds to the weakened extension of the Tibetan
 327 high, which is also closely associated with the suppressed Asian monsoon circulation (e.g.,
 328 [Sooraj et al. 2015](#)). The southward shifted Asian jet is consistent with the result of [Hirahara](#)

et al. (2012) and Horinouchi et al. (2019), who suggested that the Asian jet core would shift southward in the future climate in summer, from results of climate simulations based on CMIP3 and CMIP5, respectively.

The upper-level absolute vorticity advection by the divergent wind (Fig. 7b) also shows positive changes from Japan to the east, which have opposite signs to the change of the upper-level absolute vorticity (Fig. 7a). The absolute vorticity advection by rotational wind in the upper troposphere, which includes the horizontal vorticity advection and β effect, shows clear negative vorticity tendencies from Japan to the east (not shown), cancelling and inverting the positive change of absolute vorticity advection by the divergent wind (Fig. 7b), and corresponding to the change of the upper-level absolute vorticity (Fig. 7a).

4.2. Modulated Asian jet, Rossby wave activity, and decreased RWB frequency

To assess an influence of the modulated Asian jet on the decreased RWB frequency in the future climate, the future change of 200-hPa stretching deformation of the basic-state described in Eq. (1) is shown as shading in Fig. 5c. A negative change of the stretching deformation is significantly seen over East Asia. The increased jet diffuence and deceleration over East Asia are associated with a slight westward shift of the Asian jet exit region at 200 hPa level in the future climate, compared with the current one (see contour lines of 25 m s^{-1} in Fig. 5c). The negative change of the stretching deformation further corresponds to the region with the increasing tendency of the RWB frequency near 120° –

140°E (Fig. 4), indicating a relationship between the modulated Asian jet and the increased
RWB frequency over East Asia in the future experiment. By contrast, a positive change of
the stretching deformation is significantly seen near the MNP, indicating a contribution of
reduced diffuence and deceleration to the decrease in the RWB frequency over the MNP.
The reduced diffuence and deceleration may be associated with the above-mentioned
westward shift of the Asian jet exit region. Longitudinal profile for the future change of the
stretching deformation along 42.5°N (Fig. 5d), which corresponds to a latitude near the
Asian jet core, also represents the positive change near or upstream of the MNP, indicating
the relationship with the decrease in the RWB frequency over MNP. To further examine the
relationship of the RWB frequency over the MNP and the variability of the jet diffuence and
deceleration fields, the 200-hPa stretching deformation of the basic-state regressed onto
the RWB frequency over the MNP for the current experiment is shown in Fig. 8a. The
regressed anomalies, which are scaled to the magnitude of future change in the RWB
frequency over the MNP, indicate that a significantly positive stretching deformation east of
Japan is related to the decreased RWB frequency over the MNP. The amplitude of the
regressed stretching deformation is comparable to that of the future change (Fig. 5c).
Longitudinal profile for the regressed stretching deformation along 42.5°N (Fig. 8b) also
shows the relationship between the positive change of the stretching deformation near or
upstream of the MNP and the decrease in the RWB frequency over the MNP. It is
noteworthy that the amplitude of the regressed profile is almost the same amplitude as the

369 future change (Fig. 5d) with their opposite sign, suggesting that the decrease in RWB
370 frequency can be explained by the reduced diffuence and deceleration. These results
371 indicate that the modulated Asian jet is closely associated with the decreased RWB near
372 the jet exit region in the future climate.

373 [Uchida and Kosaka \(2019\)](#) indicated a reduced amplitude of the Silk Road pattern in the
374 future climate using the large-ensemble climate simulations, as described in Section 1.

375 [Uchida and Kosaka \(2020\)](#) further suggested contributions of the reduced wave energy
376 from the upstream, which is due to the southward shifted Asian jet and a decreased
377 blocking frequency over Europe, to the decreased amplitude of the Silk Road pattern. To
378 examine the future change of the Rossby wave propagation from Eurasia to east of Japan,
379 the 60-yr climatology of horizontal component of daily WAF at 200 hPa in August is shown
380 in Fig. 9. Here, the daily WAFs are derived from the five-day running mean fields of all
381 ensemble members. From a comparison in the zonal component of WAF between the
382 current and future climate (shadings in Figs. 9a and 9b), weakened eastward propagations
383 of the Rossby wave packets are seen over Eurasia and the North Pacific. To more clearly
384 describe their difference, the future change of the climatological WAFs is shown in Fig. 9c.
385 The future change clearly indicates the weakened Rossby wave propagation from Eurasia
386 to the North Pacific, except near 120°E. The weakened Rossby wave propagations over
387 Eurasia and the North Pacific are consistent with the decreased amplitude of the Silk Road
388 pattern ([Uchida and Kosaka 2019, 2020](#)) and the decreased RWB frequency over the MNP

389 (Fig. 4) in the future climate, respectively. The future change of the WAF also shows an
390 enhanced northward wave emanation near 120°E, contributing to an enhancement of
391 Rossby wave propagation north of 50°N to the east, contrary to the weakened propagation
392 over the mid-latitude North Pacific. The enhanced northward wave emanation near 120°E
393 further corresponds to the region where the increased jet diffluence and deceleration at 200
394 hPa over East Asia (Fig. 5c) and the associated increase of the RWB frequency near 120°–
395 140°E (Fig. 4) are seen.

396 These results suggest that the modulated Asian jet can contribute to the reduced Rossby
397 wave activity over the mid-latitude North Pacific and the consequent decrease of the RWB
398 frequency over the MNP, through the northward shifted wave propagation over the North
399 Pacific (Figs. 9b and 9c). The dynamical relationship between the upper-level enhanced
400 stretching deformation (Fig. 5c) and the enhanced northward wave emanation (Fig. 9c)
401 over East Asia will need to be further examined. The other detailed factors of the reduced
402 wave activity, which are suggested by [Uchida and Kosaka \(2020\)](#), are out of scope in this
403 study.

404

405 *4.3. Convective activities east of the Philippines*

406 [Takemura et al. \(2017\)](#) and [Takemura and Mukougawa \(2020\)](#) showed that the
407 upper-level equatorward vorticity advection (i.e., high PV intrusion) associated with the
408 RWB east of Japan can contribute to dynamically induced ascent over the subtropical WNP

409 and promotes enhanced convection over the region. Their results suggest that the
 410 decreased RWB frequency over the MNP may cause the suppressed convection over the
 411 subtropical WNP in the future climate. To assess the abovementioned hypothesis, the
 412 future change of large-scale atmospheric circulations over the subtropical WNP in August
 413 are shown in Fig. 10. The 500-hPa ω in August in the current experiment shown in Fig.
 414 10a indicates large-scale upward motion from the Philippines to the east, associated with
 415 the enhanced Asian summer monsoon. The region of upward motion shown in the negative
 416 ω at 500 hPa corresponds to the low OLR in the climatology denoted as contours in Fig.
 417 10a, indicating the validity to assess convective activities over the tropical WNP using ω .
 418 The future change of 500-hPa ω shown in Fig. 10b clearly shows positive change east of
 419 the Philippines, indicating the significantly suppressed convective activities over the region
 420 in the future climate.

421 Figure 10c shows absolute vorticity advection by horizontal wind at 200 hPa in the
 422 current experiment. Here the absolute vorticity advection S is defined as follows:

$$423 \quad S = -\bar{\mathbf{v}} \cdot \nabla(\bar{\zeta} + f), \quad (5)$$

424 where $\mathbf{v} = (u, v)$ is the horizontal wind vector. The overbars, $\bar{\zeta}$ and $\bar{f}$ are defined in Eq.
 425 (4). The upper-level positive vorticity advection in the current experiment is seen over and
 426 south of 20°N east of the Philippines, corresponding to the southwestward extended
 427 Mid-Pacific trough from east of the dateline (contours in Fig. 10c). The meridional
 428 overturning of the absolute vorticity over the North Pacific (Figs. 7a and 10c) also describes

the frequent occurring of RWB over the region. The S at 200 hPa shown as shading in Fig. 10d clearly indicates negative future changes over and south of 20°N east of the Philippines, where the positive S is seen in the current experiment (Fig. 10c). The weakened positive vorticity advection is associated with the weakened extension of the Mid-Pacific trough in the future climate (contours in Fig. 10d), which is resulting from the decreased RWB frequency over the MNP (Fig. 4). The absolute vorticity advection and its future change derived from daily fields in August (not shown) show the similar patterns but weaker amplitude than those from monthly averages (Figs. 10c and 10d). This result indicates that the weakened extension of the Mid-Pacific trough, not only with the daily time-scale but also the monthly timescale, is associated with the decreased RWB frequency over the MNP in the future climate. To examine the relationship between the RWB frequency and the extended Mid-Pacific trough, the absolute vorticity advection by 200-hPa horizontal wind regressed onto the areal average of RWB frequency over the MNP for all ensemble members in the current experiment is further shown in Fig. 11. Here, the absolute vorticity advection is derived from monthly average. The regression of the upper-level absolute vorticity advection, which is scaled to the magnitude of future change in the RWB frequency over the MNP, shows significant positive anomalies (blue shading) from east of the Philippines to south of the MNP. The amplitude of the regressed absolute vorticity advection is comparable to that of the future change (Fig. 10d). These results indicate a contribution of the decreased RWB frequency to the weakened extension of the

449 Mid-Pacific trough through the weakened positive vorticity advection in the future climate.

450 To assess a dynamical influence of the weakened upper-level vorticity advection (Fig.
451 10d) on the suppressed large-scale upward motion east of the Philippines (Fig. 10b),
452 vertical motion induced under the quasi-geostrophic balance is diagnosed using
453 ω -equation (e.g., Hoskins et al. 1978, Holton 1992) expressed as follows:

$$454 \quad \left(\nabla^2 + \frac{f_0^2}{\sigma} \frac{\partial^2}{\partial p^2} \right) \omega_{dyn} \cong \frac{f_0}{\sigma} \frac{\partial}{\partial p} \left[\mathbf{v}_g \cdot \nabla \left(\frac{1}{f_0} \nabla^2 \Phi + f \right) \right] + \frac{1}{\sigma} \nabla^2 \left[\mathbf{v}_g \cdot \nabla \left(-\frac{\partial \Phi}{\partial p} \right) \right] \quad (6a-1)$$

$$455 \quad \cong -\frac{2}{\sigma} \nabla \cdot \mathbf{Q} + \frac{f_0}{\sigma} \beta \frac{\partial \mathbf{v}_g}{\partial p}, \quad (6a-2)$$

$$456 \quad \mathbf{Q} \equiv \left(-\frac{R}{p} \frac{\partial \mathbf{v}_g}{\partial x} \cdot \nabla T, -\frac{R}{p} \frac{\partial \mathbf{v}_g}{\partial y} \cdot \nabla T \right), \quad (6b)$$

457 where ω_{dyn} is the dynamically induced vertical p-velocity, f_0 is the reference Coriolis
458 parameter at the latitude of 30°N, f is the Coriolis parameter, $\mathbf{Q}$ is the $\mathbf{Q}$ -vector, $\mathbf{v}_g =$
459 (u_g, v_g) is the geostrophic horizontal wind vector, Φ is the geopotential, and T is the
460 temperature, respectively. $\sigma = RT_0 p^{-1} d \ln \theta_0 / dp$ is the static stability, with the gas
461 constant R and the reference potential temperature θ_0 , derived from the area-averaged
462 temperature T_0 over the Northern Hemisphere north of 20°N. Equation (6a-1) shows that
463 the ω_{dyn} is balanced with the vertical derivatives of vorticity advection (the first term of the
464 RHS) and thermal advection (the second term of the RHS). The first term of the RHS thus
465 indicates that the upper-level positive vorticity advection as described in Fig. 10c is
466 associated with the negative ω_{dyn} (i.e., ascent). Here the $\mathbf{Q}$ -vector and the RHS in Eq.
467 (7a-2) are derived from monthly averages, as in the absolute vorticity advection S (Eq. 5).
468 The ω_{dyn} is calculated, applying a relaxation method to solve the Poisson's equation in Eq.

469 (6a), with meridional boundary conditions at 5°N and the North Pole and vertical ones at
470 pressure levels of bottom (1000 hPa) and top (0.5 hPa) given by $\omega_{dyn} = 0$. The ω_{dyn} at
471 500 hPa in the current experiment shown in Fig. 10e indicates the dynamically induced
472 ascent east of the Philippines, where the northeastern part of the large-scale climatological
473 upward motion is located (dashed contours in Fig. 10e), suggesting the contribution to the
474 enhanced convection over the region.

475 Dynamical influence of the RWB over the mid-latitude western North Pacific on the
476 upward motion east of the Philippines was elucidated by [Takemura and Mukougawa \(2020\)](#),
477 based on a lag composite analysis using the **Q**-vector diagnosis. They indicated that a
478 primary contribution of the upper-level positive vorticity advection associated with the
479 southward intruded high PV accompanied by the RWB to dynamically induced ascent east
480 of the Philippines. Their results support the relationship between the RWB over the MNP
481 and the convective activity east of the Philippines described in this study. The
482 quasi-geostrophic diagnostics in the subtropics, which are the region between the tropics
483 and the mid-latitudes, is conducted by [Tam and Li \(2006\)](#) and [Funatsu and Waugh \(2008\)](#),
484 and its validity is also mentioned by [Funatsu and Waugh \(2008\)](#).

485 The ω_{dyn} at 500 hPa shown as shading in Fig. 10f indicates positive future changes in a
486 wide area east of the Philippines, where the dynamically induced ascent is seen in the
487 current experiment (Fig. 10e). The positive change of the ω_{dyn} thus shows the weakening
488 of dynamically induced ascent associated with the weakened positive vorticity advection as

described in Fig. 10d, indicating a partial contribution of the weakened ω_{dyn} to the suppressed convective activities (i.e., the weakened ω) over the region. The contribution rate of the weakened ω_{dyn} will be estimated later in Fig. 12b. The residual component of the suppressed convective activities east of the Philippines, which cannot be explained by the weakened ω_{dyn} , is presumed to be closely associated with the weakened Walker circulation (Fig. 5a) due to increased static stability in tropics in the future climate.

To more quantitatively indicate the aforementioned relationship between the decreased RWB frequency over the MNP and the suppressed dynamically-induced vertical motion, and the relationship with the convective activities east of the Philippines, their scatter diagrams and histograms for all ensemble members in the current and future experiments are shown in Fig. 12. Here the 500-hPa ω_{dyn} and ω shown in the scatter diagrams are averaged over the area east of the Philippines (12.5°–22.5°N, 140°E–180°; red dashed rectangles in Fig. 10). The scatter diagram shown in Fig. 12a indicates a close relationship of the RWB frequency over the MNP with the 500-hPa ω_{dyn} with a negative correlation coefficient of $R=-0.60$ at a confidence level of 99 %, which is derived from all ensemble members of both the current and future experiments. Their relationships for the current and future experiments are also seen with negative correlation coefficients of $R_C=-0.58$ and $R_F=-0.53$. The scatter diagram shown in Fig. 12b further indicates a close relationship between the ω_{dyn} and ω at 500 hPa with a positive correlation coefficient of $R=+0.61$ at a confidence level of 99 % for all ensemble members of both the current and future

509 experiments. Their relationships for the current and future experiments are also seen with
510 positive correlation coefficients of $R_C=+0.62$ and $R_F=+0.49$. The histograms shown in the
511 upper and right of Figs. 12a and 12b further show clear decreasing shift of the RWB
512 frequency, weakening shift of dynamically induced ascent, and weakening shift of
513 large-scale upward motion in the future climate, compared to the current one, respectively.
514 Either difference in the averaged RWB frequency, ω_{dyn} and ω at 500 hPa between the
515 future experiment and the current experiment shown in the histograms of Figs. 12a and 12b
516 is significant at a confidence level of 99 %.

517 A ratio of a variability in the dynamically-induced ascent (ω_{dyn}) to that in the large-scale
518 upward motion (ω) at 500 hPa can be calculated from slope of their regression line derived
519 from all ensemble members in the current and future experiments (green dashed line in Fig.
520 12b). The ratio derived from the areal averages over the area east of the Philippines (red
521 dashed rectangles in Fig. 10) is statistically estimated as approximately 36 %, indicating a
522 non-negligible relationship of the weakened dynamically-induced ascent with the
523 suppressed convective activities east of the Philippines.

524 The results of diagnosis using the ω -equation and correlation analysis described in this
525 subsection indicate the contribution of the decreased RWB frequency over the MNP to the
526 suppressed convective activities east of the Philippines. The significantly suppressed
527 convection near the Philippines (Fig. 10b) is consistent with the reduced frequency of the
528 PJ pattern with cyclonic (anticyclonic) circulation anomalies around the Philippines (Japan),

529 which is indicated by [Kosaka and Nakamura \(2011\)](#).

530

531 **5. Concluding remarks**

532 The future change of RWB frequency over the MNP in August and the related features of
533 the large-scale atmospheric circulation were examined using the d4PDF dataset, which is
534 the large-ensemble simulations with a global circulation model. The correlation with the
535 reanalysis indicated that the RWB frequency over the MNP in the current experiment could
536 show the relationship to the ENSO as JRA-55. The RWB frequency over the MNP in the
537 future climate showed the significant decrease compared to that in the current climate. The
538 upper-level atmospheric circulation in the future climate indicated the significant weakening
539 of large-scale divergence from South to Southeast Asia and the consequent southward
540 shifted Asian jet. The decreased RWB frequency over the MNP is associated with the
541 modulated Asian jet, through the reduced diffuence and deceleration of the jet in the
542 basic-state over the region. The reduced Rossby wave propagation over Eurasia and the
543 North Pacific in mid-latitudes was also clear in the future climate, also consistent with the
544 decreased RWB frequency over the MNP. The results of correlation analysis in the current
545 and future experiments indicated that the decreased RWB frequency over the MNP is
546 related to the suppressed convective activities east of the Philippines. The diagnosis using
547 ω -equation further showed the process in the impact of the decreased RWB frequency on
548 the suppressed convective activities in the future climate, through the weakened extension

549 of the Mid-Pacific trough and the consequent weakening of dynamically induced ascent
550 east of the Philippines. The suppressed large-scale upward motion shown in this study
551 suggests a consistent condition with the decreased number of tropical cyclones and its
552 seeds (e.g., [Yoshida et al. 2017](#), [Sugi et al. 2020](#)), although these future changes cannot be
553 fully explained from those of ω at 500 hPa.

554 As noted in Section 3, the underestimated and eastward shifted RWB frequency
555 reproduced in the current experiment compared to the reanalysis may have an impact on
556 the quantitative assessment for the future change of the frequency. [Scaife et al. \(2010\)](#)
557 showed a largely improved reproducibility of the blocking frequency, resulting from the
558 corrected climatological mean bias of geopotential height in their model. According to the
559 result of [Scaife et al. \(2010\)](#), physical understanding for the reproducibility of the RWB in
560 the climate models will provide us further confidences in the future changes of the RWB
561 frequency. Although the future changes shown in this study was estimated from a
562 large-ensemble simulation with 100 members using a single climate model, the statistical
563 relationship with the vertical p-velocity shown in Figs. 7b–d may be somewhat affected by
564 cumulus parameterization scheme in the model.

565 Although the interannual variability of SSTs in the future experiment is the same as in the
566 current one as described in Section 2, modulation of ENSO associated with a warmer
567 climate was indicated by [Cai et al. \(2018\)](#). According to the close relationship between the
568 RWB frequency over the MNP and the ENSO (Fig. 3), the RWB frequency may also be

569 influenced by the modulated ENSO under the warmer climate, which is not included in the
570 results of the future experiment.

571 Based on the aforementioned discussions, further diagnosis of the large-ensemble
572 simulation using the other schemes or climate models with the other boundary conditions
573 will be desired to perform more rigorous and quantitative assessment for the future
574 changes of the RWB frequency.

575

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585

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Fig. 1. RWB frequency (%) in (a) JRA-55 and (b) current experiment (ensemble mean), and (c) that averaged over 25°–45°N in August during the 53-yr period from 1958 to 2010. Black and green lines in (c) indicate the RWB frequency in current experiment (ensemble mean) and JRA-55, respectively. Gray and light green bars denote the standard deviations for interannual variability of each RWB frequency for the current experiment (all ensemble members) and the JRA-55 during the 53-yr period, respectively. Red dashed rectangle in (c) denotes area of MNP defined as longitudinal area from 150°E to 150°W.

Fig. 3. Scatter diagrams between 5-month running mean Niño-3 indices (unit: K; horizontal axis) and RWB frequency (unit: %) averaged over the MNP (25°–45°N, 150°E–150°W) (vertical axis) in August. The diagrams in (a) and (b) indicate current experiment (all ensemble members; dots) and JRA-55 (opened circles), respectively. The opened circles in (a) denote the ensemble mean. Statistical period in (a) and (b) is during the 60-yr period from 1951 to 2010 and the 61-yr period from 1958 to 2018, respectively. The correlation coefficients (R) between the 5-month running mean Niño-3 indices and the RWB frequency of (a) all the ensemble members, (b) the JRA-55 are shown at the bottom left. Red dashed lines denote their regression lines. Red and blue shadings denote the 5-month running mean Niño-3 indices higher than +0.5 K and lower than -0.5 K, which are one of the criteria of El Niño and La Niña, respectively.

Fig. 4. RWB frequencies (%) averaged over 25°–45°N in August for current and future experiments during the 60-yr period from 1951 to 2010 and from 2051 to 2110, respectively. Black and red lines indicate the ensemble mean RWB frequencies in the current and future experiments, respectively. Gray and light red bars denote the standard deviations for interannual variability of each RWB frequency for all ensemble members in the current and future experiments during the 60-yr period, respectively. Green shadings denote longitudinal area where future changes of the RWB frequency are significant with a confidence level of 95 %.

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748 Fig. 5. Future changes of (a) velocity potential (unit: $10^6 \text{ m}^2 \text{ s}^{-1}$), (b) zonal wind (unit: m s^{-1}),
749 (c) stretching deformation of the basic-state (zonal wavenumbers $k \leq 3$) (unit: 10^{-7} s^{-1}) at
750 200 hPa (shading) and (d) its longitudinal profile along 42.5°N (blue line) in August.
751 Contours indicate (a) the 200-hPa velocity potential with the interval of $2 \times 10^6 \text{ m}^2 \text{ s}^{-1}$,
752 (b) 200-hPa zonal wind with the interval of 10 m s^{-1} in the current experiment, and (c)
753 200-hPa zonal wind of the basic-state exceeding 20 m s^{-1} in the current (black) and future
754 (red) experiments with the contour interval of 5 m s^{-1} . Dots denote the significant change
755 of (a) the velocity potential, (b) the zonal wind, and (c) the planetary-scale stretching
756 deformation at 200 hPa for all ensemble members of each experiment, with a confidence
757 level of 95 % based on Welch's t-test. Gray shading in (d) shows longitudinal area of the
758 MNP ($150^\circ\text{E} - 150^\circ\text{W}$).

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Fig. 6. Latitude-pressure cross-section of future change of zonal wind of the basic-state (zonal wavenumbers $k \leq 3$) averaged over 60°-120°E in the upper troposphere (shading). Contours indicate the zonally-averaged zonal wind exceeding 20 m s⁻¹ in the current (black) and future (red) experiments with the contour intervals of 5 m s⁻¹. Color shading denotes the future change of the zonal wind, which is significant with a confidence level of 95 %.

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769 Fig. 7. Same as Fig. 5, but for (a) absolute vorticity (unit: 10^{-6} s^{-1}), and (b) horizontal

770 advection of the absolute vorticity (unit: 10^{-11} s^{-2}) by divergent wind, at 200 hPa. Contours

771 indicate absolute vorticity in the current experiment with the intervals of $10 \times 10^{-6} \text{ s}^{-1}$.

772 Vectors in (b) denote the future change of 200-hPa divergent wind (unit: m s^{-1}).

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Fig. 8. (a) Stretching deformation (shading; unit: 10^{-7} s^{-1}) of the basic-state (zonal wavenumbers $k \leq 3$) at 200 hPa regressed onto areal average of RWB frequency over the MNP (red dashed rectangle) and (b) its longitudinal profile along 42.5°N (blue line). The regressed pattern is derived from the interannual variability of all ensemble members in the current experiment, and is normalized by future change of the RWB frequency over the MNP. To highlight the features of stretching deformation associated with the decreased RWB frequency, the order of colors for the shading is reversed from those in Fig. 5c. Dots in (a) denote the statistical significance of the regression with a confidence level of 95 % based on t-test. Gray shading in (b) shows longitudinal area of the MNP. Contour denotes 200-hPa zonal wind of the basic-state exceeding 20 m s^{-1} in the current experiment with the interval of 5 m s^{-1} .

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788 Fig. 9. Climatology of horizontal component of WAF (vector; unit: $\text{m}^2 \text{s}^{-2}$) and the zonal
789 component (shading) at 200 hPa in August for the (a) current, (b) future experiments and
790 (c) the future change (i.e., (b) minus (a)). The climatology in (a) and (b) is defined as
791 60-yr mean of the monthly-averaged daily WAFs, and the daily WAFs are derived from
792 the five-day running mean fields of all ensemble members.

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Fig. 10. (a, b) 500-hPa vertical p-velocity (unit: $10^{-2} \text{ Pa s}^{-1}$), (c, d) absolute vorticity advection by 200-hPa horizontal wind (unit: 10^{-11} s^{-2}), and (e, f) dynamically induced vertical motion (ω_{dyn}) north of 5°N at 500 hPa (unit: $10^{-2} \text{ Pa s}^{-1}$) in (left) 60-yr climatology of the current experiment and (right) future changes. Contours in (a, b) denote the climatological OLR smaller than 240 W m^{-2} with the intervals of 10 W m^{-2} . Contours in (c)

and (d) denote 200-hPa absolute vorticity (unit: 10^{-6} s^{-1}) in the 60-yr climatology of the current experiment and the future change with the intervals of $10 \times 10^{-6} \text{ s}^{-1}$ and $2 \times 10^{-6} \text{ s}^{-1}$, respectively. Contours and vectors in (e, f) indicate vertical p-velocity and **Q**-vector (unit: $\text{m}^2 \text{ kg}^{-1} \text{ s}^{-1}$) at 500 hPa in (e) the 60-yr climatology of the current experiment and (f) the future change, respectively. Dots in (b) denote the significant change of 500-hPa vertical p-velocity for all ensemble members of each experiment, with a confidence level of 95 % based on Welch's t-test. Red dashed rectangles denote area between $[12.5^{\circ}\text{--}22.5^{\circ}\text{N}, 140^{\circ}\text{E}\text{--}180^{\circ}]$ to calculate areal-averaged 500-hPa vertical p-velocity shown in Fig. 12.

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814 Fig. 11. Same as Fig. 8, but for absolute vorticity advection by 200-hPa horizontal wind
 815 (shading; unit: 10^{-11} s^{-2}) regressed onto areal-average of RWB frequency over the MNP
 816 (red dashed rectangle). The absolute vorticity advection is derived from monthly average.
 817 The regressed pattern is normalized by future change of the RWB frequency over the
 818 MNP. To highlight the features of absolute vorticity advection associated with the
 819 decreased RWB frequency, the order of colors for the shading is reversed from those in
 820 Fig. 10c.

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Fig. 12. Scatter diagrams between (a) the RWB frequency (X-axis) and dynamically induced vertical motion (ω_{dyn}) at 500 hPa (unit: $10^{-2} \text{ Pa s}^{-1}$) averaged over the area east of the Philippines (EOP; 12.5° – 22.5°N , 140°E – 180°) and (b) the ω_{dyn} and 500-hPa vertical p-velocity (ω) (unit: $10^{-2} \text{ Pa s}^{-1}$) averaged over the EOP. Gray and light red dots denote all ensemble members in the current and future experiments, respectively. Black squares and red triangles denote the ensemble mean in the current and future experiments, respectively. The correlation coefficients between the X- and Y-components in all ensemble member of the current (R_C) and future (R_F) experiments and their combination (R) are shown at the bottom right. Green dashed line in (b) denotes a regression line derived from all ensemble members of the current and future experiments. The upper and right of each scatter diagram show histograms of the X- and Y-components, respectively. Black boxes and red bars indicate the histograms of all ensemble members in the current and future experiments. The histograms are

836 normalized by each sample number.

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