Projection of the summer northern East Asian low under global warming in CMIP5 models

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ABSTRACT

The East Asian summer climate is modulated by a low-pressure system over northern East Asia (NEAL) and a subtropical high over the western North Pacific. Many studies have focused on the subtropical high, but little is known about NEAL, especially its change in the future under global warming scenarios. This study investigates the projected change in NEAL in the late twenty-first century, using the outputs of 20 models from Phase 5 of the Coupled Model Intercomparison Project — specifically, their historical climate simulations (HIST) and future climate projections under the Representative Concentration Pathway 4.5 (RCP4.5) and 8.5 (RCP8.5) scenarios. The results show that the models capture the NEAL well in HIST. The NEAL is weakened in the late twenty-first century under the two RCP scenarios, with a stronger weakening under RCP8.5 than under RCP4.5. The weakened NEAL increases the geopotential height zonal gradient in the west and causes a southerly anomaly, which may bring more moisture and rainfall to northern East Asia.

1. Introduction

The East Asian summer monsoon is modulated by a meridional land–sea thermal contrast between northern East Asia (NEA) and the western North Pacific (Han and Wang 2007; Lin 2014; Du, Lin, and Lu 2017), in addition to a planetary-scale thermal contrast between the Asian continent and North Pacific in the zonal direction (Guo 1983; Shi and Zhu 1996; Zhao and Zhou 2005; Zhu et al. 2005). The meridional thermal contrast is depicted by a low over continental northern East Asia (NEAL) and a subtropical high over the western North Pacific (Du, Lin, and Lu 2016; Lin and Wang 2016). Therefore, understanding the variability of the NEAL and the western North Pacific subtropical high is vital for predicting change in the East Asian summer climate. Many studies have investigated the variability of the subtropical high and its impact on East Asian summer climate (e.g. Chang, Zhang, and Li 2000; Lu 2001; Sui, Chung, and Li 2007; Lu and Fu 2010; Yeo, Jhun, and Kim 2012; He et al. 2015); however, little attention has been paid to the NEAL, especially its change under global warming.

Kamae et al. (2014a) investigated the summertime land–sea thermal contrast over East Asia under global warming. Their results showed an enhanced thermal contrast over East Asia, characterized by a warmer tropospheric temperature over continental East Asia compared to over ocean areas. The enhanced land–sea thermal contrast leads to a weakening of orthogonal winds and an eastward retreat of the western North Pacific subtropical high (He et al. 2015). Meanwhile, the enhanced land–sea thermal contrast, especially the warming in continental East Asia induced by the increase in greenhouse gases (Zhu et al. 2012; Kamae et al. 2014b), may also change the intensity of NEAL (Du, Lin, and Lu 2016). Therefore, the projected change in NEAL under global warming is investigated in this study.
2. Data

We use the results of 20 models from Phase 5 of the Coupled Model Intercomparison Project (CMIP5) – specifically, their historical climate simulations (HIST) and their future climate change simulations under the Representative Concentration Pathway 4.5 (RCP4.5) and 8.5 (RCP8.5) scenarios. Table 1 lists the resolutions of these models, and further details are documented online (https://cmipmd.ornl.gov/cmip5/index.html?submenuheader50). The 1981–2000 climatology in HIST is used as the baseline. The simulations for the period 2081–2100 under the RCP4.5 and RCP8.5 scenarios are used for the future projections under global warming. All the data are interpolated linearly onto a grid with a spatial resolution of 2.5° × 2.5°. The multi-model ensemble (MME) is obtained by simply averaging over the 20 models with equivalent weight.

Also used are the reanalysis data derived from the National Centers for Environmental Prediction/National Center for Atmospheric Research (NCEP/NCAR) for the period 1948–2015 (Kalnay et al. 1996). The NCEP/NCAR data are used to evaluate the models’ abilities in representing the observations. Summer refers to the mean of June, July, and August.

3. Results

3.1. Evaluation of the NEAL in HIST

Figure 1(a) and (b) show the averaged summer geopotential height at 850 hPa ($H_{850}$) during 1981–2000 in the NCEP/NCAR reanalysis data and the HIST MME. Vectors in (a) depict the summer-mean horizontal winds at 850 hPa during 1981–2000 based on the NCEP/NCAR reanalysis data. (c, d) As in (b), but during 2081–2100 under (c) RCP4.5 and (d) RCP8.5. The box depicts the NEAL core region.
NCAR reanalysis data and MME in HIST, respectively. The NEAL, associated with cyclone circulation, is identified in the observation (Figure 1(a)), similar to that found in Lin and Wang (2016) and Du, Lin, and Lu (2016). The NEAL is also captured well in HIST, with a low-pressure trough centered over (45°–60°N, 110°–130°E), which is referred to as the NEAL core region. The intensity is a little stronger than that observed, with an averaged $H_{850}$ over the NEAL core region of 1425 and 1436 gpm for the HIST MME and observations, respectively. Similar results are also obtained in HIST for each individual model, with low $H_{850}$ over northern East Asia (Figure 2), indicating the existence of NEAL in the models.

Figure 2. Summer mean $H_{850}$ (units: gpm) during 1981–2000 based on 20 individual models in HIST.
3.2. Projected NEAL in the late twenty-first century under RCP4.5 and RCP8.5

The NEAL is also identified in the late twenty-first century (2081–2100) under both RCP4.5 (Figure 1(c)) and RCP8.5 (Figure 1(d)). A low trough is clear over northern East Asia, similar to that during the late twentieth century in HIST (Figure 1(b)) and observations (Figure 1(a)). The averaged $H_{850}$ over the NEAL core region is 1436 gpm under RCP4.5 and 1447 gpm under RCP8.5, which is an increase of 11 and 22 gpm, respectively, compared with the value of 1425 gpm in HIST. The projected changes in NEAL can also be found in the meridional average of $H_{850}$ between 45°N and 60°N under the two scenarios (Figure 3(a)), which shows the projected increase in $H_{850}$ under the two RCP scenarios in comparison with that in HIST. However, the increased geopotential height over the northern East Asian region is probably attributable to a systematic global geopotential height increase due to global warming, according to the hydrostatic equation (Yang and Sun 2003; He et al. 2015; Wu and Wang 2015), and may not represent the changes in NEAL under global warming. Several studies have proposed using an eddy component, in which the zonal mean is subtracted, to represent the western North Pacific high at 500 hPa (Zhou et al. 2009; He et al. 2015; Huang et al. 2015; Wu and Wang 2015). However, this approach is incapable of depicting the lower-tropospheric NEAL (Du, Lin, and Lu 2016) due to missing values below 700 hPa within the Mongolian highlands and the Rocky Mountains in the midlatitudes of the Northern Hemisphere.

In this study, to remove the systematic $H_{850}$ increase, we use a slope of the NEAL trough to measure the NEAL intensity. As shown in Figures 1 and 3, NEAL is centered at 120°E in HIST and under both future scenarios. Therefore, the slope of the NEAL trough can be simply calculated as the difference between the $H_{850}$ averaged over 45°–60°N along the trough at 120°E and those 10° away in the east and west directions, respectively, i.e. along 110°E and 130°E:

$$\text{Slope} = H_{850}(120°E, 45°–60°N) - 0.5 \times [H_{850}(110°E, 45°–60°N) + H_{850}(130°E, 45°–60°N)].$$

The systematic increase in $H_{850}$ at 120°E is then offset by those at 110°E and 130°E. A larger negative slope represents a stronger NEAL trough. The slope is −5.5 gpm per 10° in HIST, and −5.0 and −4.7 gpm per 10° under RCP4.5 and RCP8.5 (Table 2). The slope increases by 0.5 gpm per 10° under RCP4.5 and by 0.8 gpm per 10° under RCP8.5, relative to that in HIST. That is, the projected NEAL intensity decreases in the future, with a stronger weakening under RCP8.5 than that under RCP4.5. We further examine the individual changes in the NEAL trough in the 20 models under the two RCP scenarios from that in HIST. There are 12 models under RCP4.5 and 14 models under RCP8.5 in which the NEAL trough is weakened, suggesting a more consistent weakening of NEAL under RCP8.5 than under RCP4.5. Similarly, the NEAL slope depicted by the difference between the averaged $H_{850}$ over 45°–60°N along 120°E and those along 105°E and 135°E is also calculated. The results are similar, with MME slopes of $-14.8, -13.4,$ and $-12.9$ gpm per 15° in HIST, RCP4.5, and RCP8.5, respectively (Table 2), indicating a weakened NEAL in the future, with a stronger weakening under RCP8.5 than under RCP4.5.

3.3. Possible impact of the change in NEAL on the East Asian summer monsoon

Previous studies have reported the importance of NEAL in affecting the summer monsoon and rainfall in East Asia (Lin and Wang 2016; Du, Lin, and Lu 2017). But how will the East Asian summer monsoon change as the NEAL weakens under global warming? Figure 4(a) shows the projected changes in winds at 850 hPa under the RCP4.5 scenario. A significant southerly anomaly is seen over northern East Asia, especially in the west around 110°E. Meanwhile, a similar but stronger southerly anomaly is also identified under the RCP8.5 scenario (Figure 4(b)).

The southerly anomaly is attributable to the weakening of NEAL. As the NEAL weakens, the zonal gradient of $H_{850}$ increases in the west under the RCP4.5 scenario.
a retreat of the climatological northerly in northern East Asia. Accordingly, the East Asian summer southwesterly may extend northwards and bring more moisture and rainfall to northern East Asia (figure not shown). The increase in rainfall over northern East Asia under global warming has also been reported in previous studies (Hsu et al. 2012; Qu, Huang, and Zhou 2014). We therefore conclude that a weakened NEAL, to a certain extent, is responsible for the increased rainfall over northern East Asia under global warming.

4. Summary and discussion

The projected change in NEAL is investigated in this study by analyzing the HIST, RCP4.5 and RCP8.5 outputs of 20 CMIP5 models. The results show that the models can capture NEAL well in HIST, with a low $H_{850}$ trough over northern East Asia during 1981–2000. The NEAL intensity is weakened in the late twenty-first century under both RCP4.5 and RCP8.5, with a stronger weakening under the latter. The weakened NEAL increases the $H_{850}$ zonal gradient in the west, causes a southerly anomaly, and suppresses the climatological northerly. Accordingly, the East Asian summer southwesterly may extend more northwards and bring more moisture and rainfall to northern East Asia.

This study shows that the NEAL weakens under global warming. The weakened NEAL is probably induced by surface warming over northern East Asia, especially around the Lake Baikal region (Xu, Zhu, and He 2011; Du, Lin, and Lu 2016). Based on simulation results with a prescribed surface warming around Lake Baikal in a linear baroclinic model, Du, Lin, and Lu (2016) presented an increased $H_{850}$ over northern East Asia in summer, which suppressed the NEAL intensity. The reported surface warming over northern East Asia under global warming (Zhu et al. 2012; Kamae et al. 2014a), therefore, may explain the weakening of the NEAL presented in this study.

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