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Reproduction of climate for the mid-Holocene over the Korean Peninsula using a high-resolution numerical model

Seong-Joong Kim*, Ji-Won Kim

Korea Polar Research Institute, KIOST, PO Box 32, Incheon 406-840, Republic of Korea

A R T I C L E I N F O

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A B S T R A C T

The climate response over Korea to the change in orbital parameters for the mid-Holocene at 6000 BP is reproduced using a relatively high-resolution (about 75 km) climate model of National Center for Atmosphere Research (NCAR) Community Climate Model version 3 (CCM3). In response to the mid-Holocene orbital conditions, the surface temperature over Korea increased over the northern part and decreased over the southern part by up to about ±0.5 °C. The increase in surface temperature is mainly due to the increase in summer surface temperature as the earth receives more energy. Despite the reduced insolation in winter, surface temperature increased in North Korea, associated with the increase in downward long wave and turbulent heat fluxes. The cooler climate in the southern part is due to the reduced surface temperature in winter, spring, and autumn. In the mid-Holocene, precipitation decreased overall in most of Korea, except for the southern part, where it slightly increased. Associated with the reduced precipitation, the climate was overall drier in most of Korea, especially the northern part, though climate was slightly wetter in southernmost Korea, including Jeju Island. In comparison to some proxy records, the increase in surface temperature in the mid-Holocene is overall consistent. In terms of precipitation and hydrological budget, the southern part agrees with proxy evidence, but in central Korea there exists a disagreement. However, there are only limited numbers of proxy records throughout Korea. A greater number and lines of proxy evidence are required before we draw any clear conclusions regarding climate change for the mid-Holocene over Korea.

1. Introduction

The Korean Peninsula is located between Eurasia and the North Pacific Ocean. The Eurasia continent is very sensitive to the change in diurnal heating or cooling, whereas the North Pacific Ocean is relatively stable to a change in external heating because the ocean has much larger heat capacity than the land. Moreover, the Tsushima Current flowing towards the Korean peninsula is a branch of the warm Kuroshio Current from the tropics (Lie and Cho, 2002), and provides abundant heat to nearby land areas. Associated with this special geographic setting, the Korean peninsula is under the strong influence of seasonal climate contrast from the Asian monsoon, which has a strong influence on agriculture, socio-economy, and culture (Webster et al., 1998; Ding and Chan, 2005).

Towards summer, the increasing short wave radiation heats the Asian continent and leads to the low pressure relative to the North Pacific, where relatively high pressure develops. With time, the front between low pressure over the continent and high pressure over the ocean moves northward and brings moisture to East Asian countries. Over Korea, this heavy rainfall, called Changma, starts around late June and accounts for more than half of the annual precipitation over Korea (Choi et al., 2012). Towards winter, on the other hand, with the reduction of radiative heating and accumulation of snow, the Asian continent experiences extreme surface cooling, especially over Mongolia and southern Siberia, and high pressure develops. The Siberian high in relation to the Aleutian Low strongly influences the winter weather over Korea and Japan (Jhun and Lee, 2004). With this seasonally contrasting climate sensitivity, the Korean peninsula has very distinct seasons.

According to the Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report (AR4), warming over the past 100 years (1906–2005) is 0.74 C° (±0.18 °C) (IPCC, 2007), while the warming trend is larger towards present from the updated IPCC Fifth Assessment Report (IPCC, 2013) with 0.85 C° (±0.2) from 1880

* Corresponding author. Korea Polar Research Institute, Polar Climate Change, 26 Songdomiraero, Yeonsu-gu, Incheon 406-840, Republic of Korea.
E-mail address: seongjkim@kopri.re.kr (S.-J. Kim).

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to 2012. Compared to the degree of global warming, the warming trend over Korea is about twice as large, 1.7 C° over the past 100 years (KMA, 2009). Precipitation over Korea is also substantially increasing, by about 19% during recent years in comparison to the early 20th century (KMA, 2009). The weather has been more extreme and the summer season is longer, while winter is shorter. According to the future climate projection using ECHO-G numerical model simulation, the temperature over Korea is expected to warm by 4 C° by the end of 21st century, especially in winter. Precipitation will increase by 17%, especially in August and September, with larger spatial variability of more extreme drought and heavy rainfall. By the end of 21st century, most of South Korea is expected to have a subtropical climate, changing from the temperate climate at present. However, this climate projection has a large uncertainty. For example, in the recent decade since 2000, cold surges have occurred more frequently with longer duration and lower surface temperature than in the previous decade in 1990s (Woo et al., 2012). Unfortunately, this hemispheric anomalous extreme climate event is not well captured by the current numerical models. To assess the degree of mean and variability of future climate change, especially in regional scale, numerical model's predictability must be substantially improved through an understanding of how the climate operated.

The numerical simulation of past climates can help understand climate change in the future as an alternative source through a comparison with proxy data. Moreover, the performance of numerical models could be tested against known past climate fluctuations to have confidence in their future predictive skill. The mid-Holocene climate events provide the optimal opportunity to examine the Earth's climate change mechanisms as a future analogy, because the mid-Holocene climate is generally warmer than present and paleoclimate proxy data are relatively abundant. During the mid-Holocene, the summer insolation was about 7% (30 W m^{-2}) higher than present at 65°N, whereas the summer insolation was less by −3.5% (15 W m^{-2}) at 65°S. This solar insolation change is due to the variation in orbital parameters.

Mid-Holocene and late Holocene change in vegetation and climate over Korea was deduced from pollen records (Yi et al., 2008). By analyzing stalagmite records from Daeya Cave in Korea, Jo et al. (2011) detected the mid-Holocene climatic optimum between 8500 and 5900 years before present. By combining isotopic composition and pollen records, Lim et al. (2012) obtained millennial-scale fluctuations in five stages during Holocene time. Nahm et al. (2006, 2011) studied the Holocene environment using river wetland samples, and interpreted that the increased abundance of coarse-grained sediment was due to increased precipitation during the mid-Holocene. These proxy reconstructions provide useful information for the climate in the mid-Holocene. A comparison of numerically reproduced results with these proxy reconstructions will be useful in understanding the change mechanism. In this study, a relatively fine-resolution numerical model is used to investigate the change in temperature and hydrological budget for the mid-Holocene. This study compares the reproduced results from the second phase of Paleoclimate Modelling Intercomparison Project (PMIP2) with proxy reconstructions.

2. Model description and experiments

The numerical model used to simulate the mid-Holocene over Korea is the third version of the Community Climate Model (CCM3) developed in the National Center for Atmosphere Research (NCAR) (Bonan, 1998; Kiehl et al., 1998). Horizontal resolution of the model used in this study is 512 × 256 cells, which is about 75 km (Duffy et al., 2003). This is relatively high resolution compared to other existing models. The model has 18 vertical layers and includes land surface processes. A more detailed illustration of the model is found in Kim et al. (2008).

The modern climate simulation, called MOD, is forced by prescribed, climatologically averaged, monthly climatology of sea-surface temperatures (SSTs) and sea ice distributions provided by NCAR, a contemporary atmospheric CO_2 concentration of 355 ppm, and the present land mask and topography. In the mid-Holocene simulation, we applied orbital parameters for 6000 BP. They are composed of eccentricity as a measure of ellipticity of the earth's revolution orbit around the sun with periods of 100,000 and 400,000 y, obliquity as a measure of earth's tilt angle from 22.1° to 24.5° with a period of 41,000 y, and precession of the earth with periods of 19,000 and 23,000 y. Because, at 6000 BP, the obliquity was larger (24.1°) than present (23.44°) and the longitude of perihelion was about 90° out of phase from the present, the earth received more energy in summer in the Northern Hemisphere, and less in the Southern Hemisphere. In this experiment, the same sea surface temperature (SST) condition as in the MOD is used because mid-Holocene SST reconstructions are limited and their change is relatively small. According to the second phase of the Paleoclimate Modelling Intercomparison Project (PMIP2) results, the SST change between the mid-Holocene and preindustrial period is less than 0.5 °C in most ocean basins (Joussaume and Taylor, 2000). We presume that the effect of the SST on the climate of Korea is relatively small compared to the effect of the change in the radiation budget associated with the change in orbital parameters. This experiment is named HOL.

3. Results

The experiments were integrated for 6 years, and the last 4 years were averaged and analyzed. The model performance of the CCM3 used in this study and large-scale features are described in detail in Kim et al. (2008) and Unterman et al. (2011). In this study, we focus on the description of the seasonal climate change over Korea for the mid-Holocene using simulated results from the high-resolution model. As proxy evidence for past temperature and aridity is abundant over Korea, we present these variables. For convenience, winter is averaged values for December–January–February (DJF), spring for March–April–May (MAM), summer for June–July–August (JJA), and autumn for September–October–November (SON).

3.1. Model response

Table 1 lists the annual and seasonal mean quantities averaged over Korea from the MOD and HOL simulations. In summer, surface air temperature (SAT) increases by 0.82 °C, which is associated with the increase in insolation by 27.41 W m^{-2} (~6%) over Korea, because the perihelion, the time when the earth is closest to the sun, occurs during summer in the northern hemisphere. Short wave heat fluxes increase by 29.11 W m^{-2} (~13%) at the surface. In spring and autumn, SAT decreases by about 0.3 °C, consistent with the reduction in insolation. In winter, on the other hand, despite the reduction in insolation by 13.72 W m^{-2} (~7%) and short wave heat fluxes at the surface, SAT increases over Korea. This anomalous increase in winter SAT is associated with the increase in downward long wave heat fluxes and turbulent heat fluxes. In the mid-Holocene, precipitation decreases overall, and the largest reduction occurs in summer, by about 18%.

Table 1
Annual and seasonal mean quantities from MOD and HOL simulations and their differences averaged over Korea (123°–132°E; 33°–43°N).

	MOD	HOL	HOL–MOD
Surface temperature (K)			
Ann	284.49	284.50	0.01
DJF	274.65	274.84	0.19
MAM	281.72	281.43	−0.29
JJA	294.01	294.83	0.82
SON	287.15	286.89	−0.26
Insolation (W m^{-2})			
Ann	337.60	337.17	−0.43
DJF	204.92	191.20	−13.72
MAM	397.94	395.10	−2.84
JJA	461.28	488.69	27.41
SON	286.22	273.74	−12.48
Short wave (W m^{-2})			
Ann	168.25	173.51	5.26
DJF	97.29	93.05	−4.24
MAM	213.53	215.37	1.84
JJA	217.44	246.52	29.11
SON	144.81	138.69	−6.12
Precipitation (mm/day)			
Ann	1.91	1.56	−0.35
DJF	2.79	2.48	−0.31
MAM	3.74	3.55	−0.19
JJA	3.52	2.87	−0.65
SON	2.16	1.92	−0.24

Fig. 1 displays the geographic distribution of the difference in seasonal-mean and annual-mean surface air temperature (SAT) over Korea between HOL and MOD. In the mid-Holocene, insolation and short wave heat fluxes increase during summer over Korea and this leads to the increase in SAT over the entire Korean Peninsula. The summer surface warming is especially more pronounced along the eastern flank of Korea towards the north by more than 1 °C (Fig. 1c). In autumn, associated with the reduction in insolation, SAT decreases almost everywhere in Korea, especially in the southernmost and northern parts. In spring, there is overall surface cooling over Korea and the surface cooling is larger in the northern part, by more than 1.5 °C. In winter, surface temperature reduction is expected because the earth receives less insolation. However, SAT increases over most of Korea, except for the southern part, where a slight cooling of about 0.4 C° occurs (Fig. 1a). The SAT increase is larger in the northern part.

In order to investigate the cause of the anomalous winter SAT increase over northern most of Korea, we analyzed the change in radiative and turbulent heat fluxes (Fig. 2). In winter, short wave heat fluxes at the surface overall decrease, especially in the northern part (Fig. 2e). This is consistent with the reduction in insolation at the mid-Holocene. However, the net long wave radiative heat flux increases slightly in the northern and north-eastern part of Korea, though it decreases in the southern and south-western parts (Fig. 2a). The increase in net long wave heat fluxes in the northern part of Korea is mainly due to the increase in downward long wave heat fluxes, as shown in Fig. 2b. The change in the turbulent (latent and sensible) heat fluxes shows that in the mid-Holocene turbulent heat flux, especially the sensible heat flux, acts to warm the surface over Korea (Fig. 2c and d). This result indicates that the anomalous increase in SAT in winter over most of Korea is due to the increase in long wave and turbulent heat fluxes in spite of the decrease in insolation and short wave heat fluxes.

Overall, in the mid-Holocene, the annual-mean surface temperature increases slightly and relatively large annual-mean warming occurs along the eastern flank of Korea by more than about 0.3 °C (Fig. 1e). The largest warming is found over the north-eastern tip of Korea, more than 0.5 °C. On the other hand, in the southern part of Korea, especially in the south-western part, surface cooling by more than 0.3 °C is indicated. Jeju Island appears to be slightly colder in the mid-Holocene.

In addition to surface temperature change, hydrological budget change is an important indicator for climate change. As indicated in the area-averaged value in Table 1, in the mid-Holocene, precipitation appears to be overall reduced over Korea, though spatial variabilities are shown (Fig. 3). In the boreal winter, precipitation appears to decrease in most of Korea, especially in central South Korea (Fig. 3a). In spring, a substantial reduction of precipitation occurs in the northern part of Korea, whereas precipitation increases over most of South Korea, and the largest increase of more than 1 mm/day occurs along the southern part and Jeju Island. In summer, the reduction of precipitation is large overall of North Korea and the eastern part of South Korea (Fig. 3c). On the other hand, an increase in summer precipitation occurs in the southern part of Korea. In autumn, the precipitation change pattern is opposite to that of summer, i.e. increase over the northern part of Korea and decrease in the western flank and southern part of Korea.

Overall, the annual-mean precipitation appears to decrease over most of Korea, except for the southern part of South Korea where a slight increase in precipitation of more than 0.4 mm/day occurs (Fig. 3e). The decreased summer precipitation in the mid-Holocene over Korea is at odds with the increase in the summer monsoon precipitation over East Asia obtained in many previous model studies (e.g., de Noblet et al., 1996; Texier et al., 2000; Turner and Annamalai, 2012; Jiang et al., 2013). We examined the precipitation over East and South Asia, and precipitation increases, consistent with these previous model results, but not in the Korean Peninsula. Thus, the reduced precipitation over Korea in mid-Holocene summer is a local feature, driven by local circulation change.

Even though precipitation increases in one area, if there is more evaporation, the climate could be drier. The net water budget between precipitation and evaporation is, thus, important in determining the climate zone. Fig. 4 shows the geographic distribution of the change in precipitation minus evaporation between HOL and MOD experiments. In winter, over South Korea, evaporation exceeds precipitation and climate was slightly drier (Fig. 4a). The drier winter climate is especially more pronounced in central South Korea near Seoul. In spring, while North Korea was drier in the mid-Holocene, South Korea was wetter (Fig. 4b). In summer, most of the Korean Peninsula was drier, which is mainly related to the reduction in precipitation as shown in Fig. 3c. In autumn, there is little change in hydrological budget over Korea, though slightly wetter climate is simulated in the northern part of peninsula.

The annual-mean hydrological budget change between present and mid-Holocene reproduced in the model indicates that, in the northern part of Korea, the climate was overall drier than at present, while, in the southern part, the climate was slightly wetter in the mid-Holocene (Fig. 4e). The drier climate over the northern part of Korea in the mid-Holocene is mainly due to the reduction in precipitation, especially along the eastern flank of the Korean peninsula.

The change in low level winds plays a critical role in determining moisture transport as an indicator of the Asian monsoon. Fig. 5 shows the difference in low-level (850 hPa) winds between HOL and MOD. Under the strong influence of the East Asian Monsoon, seasonally contrasting winds occur over Korea. In winter, associated with the strengthening of the Siberian High, north-westerly or northerly winds prevail over Korea, while in summer, with the strengthening of the North Pacific high in response to the weakening of the Siberian High due to the heating leads to the south-easterly or southerly winds. In the mid-Holocene winter, low level winds appear to be weaker than at present with an easterly wind anomaly. A similar result occurs in spring, when an easterly wind anomaly develops in central Korea. In summer, on the other hand, low level winds increase over Korea with a strong southerly

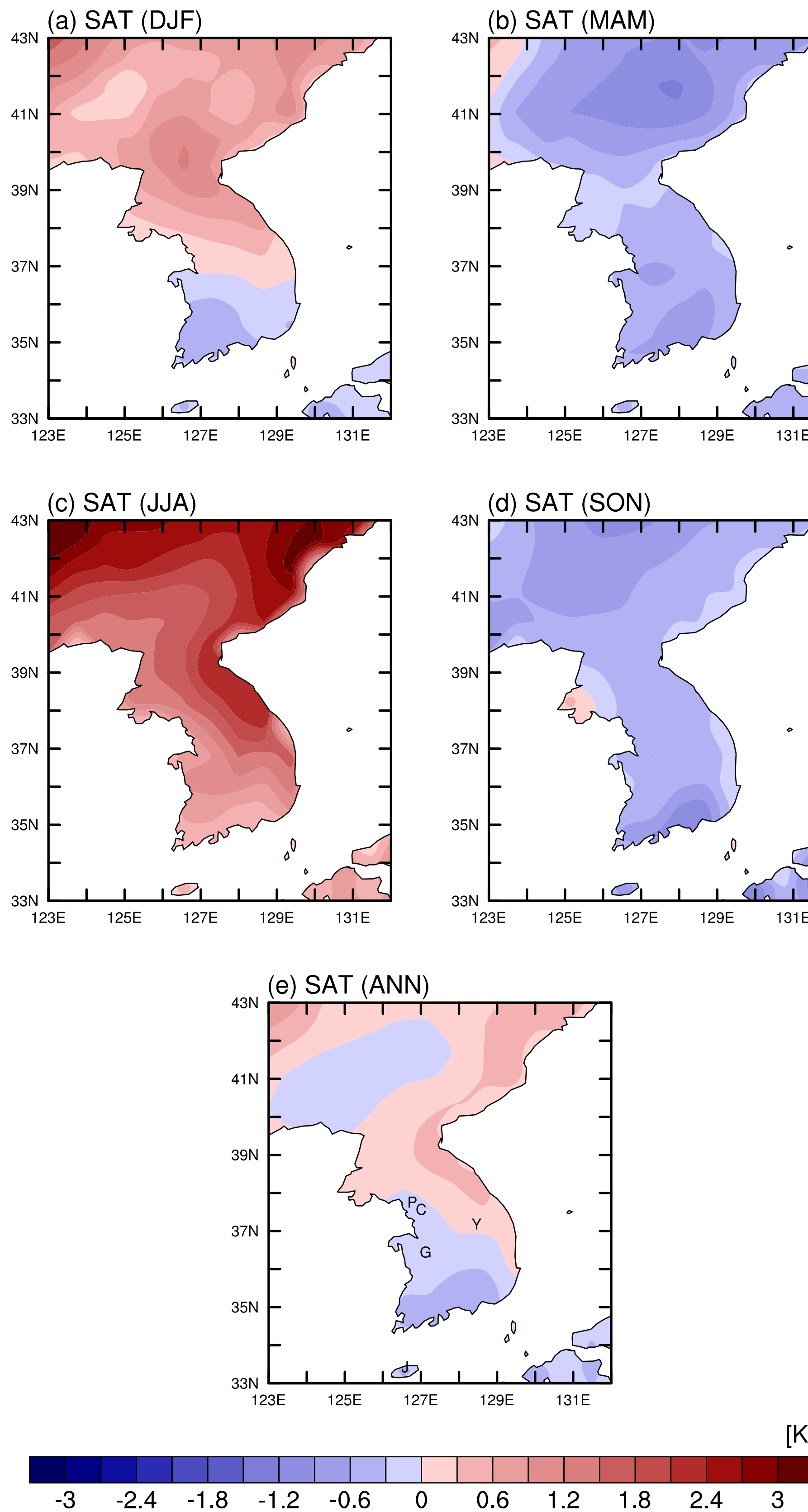

Fig. 1. Geographic distribution of the change in reproduced surface air temperature (SAT) between modern (MOD) and mid-Holocene (HOL) averaged for (a) winter (December–January–February), (b) spring (March–April–May), (c) summer (June–July–August), (d) autumn (September–October–November), and (e) annual-mean.

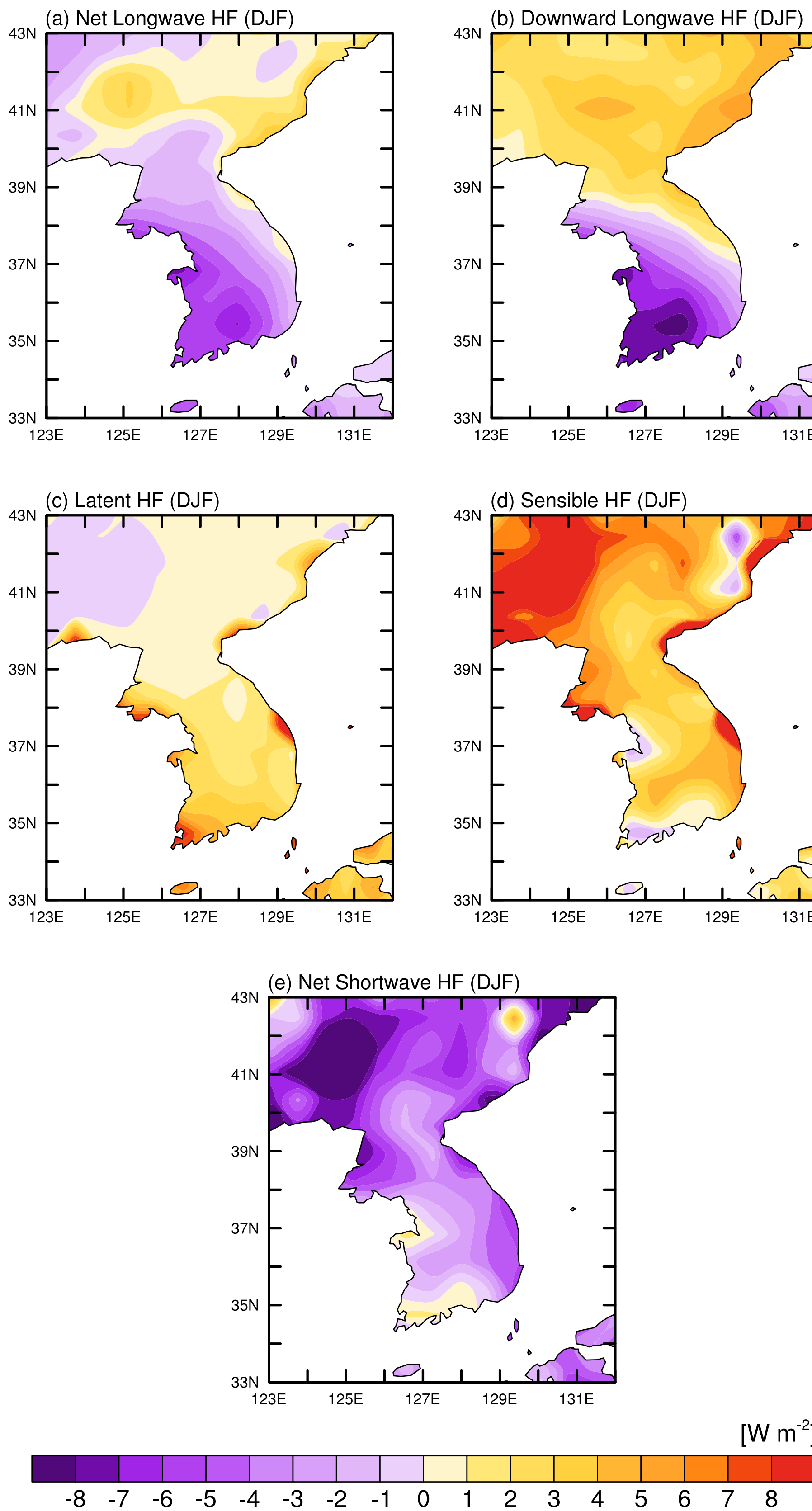

Fig. 2. Geographic distribution of the change in winter heat fluxes between MOD and HOL at the surface for (a) net long wave, (b) downward long wave, (c) latent, (d) sensible, and (e) net short wave. Units are in W m^{-2}.

wind anomaly (Fig. 5c). In autumn, low level winds are enhanced in the mid-Holocene with westerly wind anomalies. Overall, in the mid-Holocene, annual-mean low level winds are weaker than at present in most of Korea, with easterly and north easterly wind anomalies.

3.2. Comparison to PMIP2 data

In order to simulate the climate change for the mid-Holocene, one needs to consider the effect of ocean and vegetation change in addition to the effect of orbital parameters. The Paleoclimate Modelling Intercomparison Project (PMIP) has exerted a huge effort in reproducing the mid-Holocene climate using atmosphere-ocean-vegetation coupled models. We compared the high-resolution model results with the second phase of PMIP (PMIP2) data.

Fig. 6 shows the SAT and precipitation change between HOL and MOD experiments averaged over Korea from different climate models. In winter and spring, all models reproduce the reduction in SAT by about 0.5–1 °C. The spring cooling is consistent with the high-resolution model result, but winter cooling is different from the high-resolution model, which produced anomalous warming over Korea. In summer and autumn, all PMIP2 models show warming to various degrees. In terms of precipitation, model to model variabilities are large. In winter, a slight reduction of precipitation occurs in all models, except for FGOALS and MIROC, which leads to the slight increase in precipitation. In spring, all models show a slight decrease in precipitation. In summer, FGOALS shows a slight reduction in precipitation, while GISS and IPSL models show substantial increase over Korea. In autumn, almost all models show an increase in precipitation, although the degree of increase is less than 1 mm/day. The change in SAT and precipitation derived from PMIP2 results is consistent with those over China (Jiang et al., 2012). Overall, a very little change in annual-mean precipitation is reproduced in the PMIP2 models over Korea in the mid-Holocene.

In comparison to the response of those of the high-resolution model, the SAT reduction in winter and spring is overall larger. Note that the high-resolution model reproduced the anomalous warming over Korea in the mid-Holocene. This difference may be related to the ocean feedback, which is not included in the high-resolution model. Previous studies showed that in the mid-Holocene surface ocean was slightly colder in the low and mid latitudes due to the delayed response to orbital forcing (Marzin and Braconnot, 2009). The colder ocean in the mid-Holocene may give some negative feedback to Asian summer monsoons (Marzin and Braconnot, 2009). Wang and Wang (2013) analyzed PMIP2 Ocean and Atmosphere General Circulation Models (OAGCMs) and applied Institute of Atmospheric Physics (IAP) coupled models to test the role of ocean on the Indian and East Asian Monsoon and suggested that in the mid-Holocene, the cold ocean acted to reduce the warming driven by orbital parameters over east Asia, while it partly enhanced the east Asia monsoon. On the other hand, using Community Climate System Model version 4 (CCSM4) coupled model and Community Atmosphere Model version 4 (CAM4), Tian and Jinag (2013) found that the annual-mean temperature increased by 0.2–0.5 °C over East Asia and annual precipitation decreased over China.

Overall, the role of ocean feedback to Asian summer monsoon appears to play a significant role in enhancing the land-sea contrast, which drives a stronger atmospheric circulation over East Asia. However, the effect of ocean on the climate over East Asia remains controversial. Moreover, in Korea, local effects are also important because of the special geographic setting, and thus overall reduction in summer precipitation and anomalous winter warming, that are in general different from PMIP2 model results, occur.

3.3. Comparison to proxy data

There have been active studies to reconstruct Holocene climate over Korea using various proxies such as pollen records in wetland sediment cores and cave records. Locations of the proxy records are shown as initial letters in the annual-mean SAT and precipitation (Figs. 1e and 3e). In central eastern Korea, 'Y' represents Yeongwol, in the western South Korea 'P' represents Paju, 'C' represents Cheonggye-cheon, 'G' represents "Gongju', and in southern Korea, 'J' represents Jeju Island.

By analyzing stalagmite records obtained in the Daeya Cave, which is located in Yeongwol, central-eastern South Korea, Jo et al. (2011) found lighter carbon isotopic components, well-developed fibrous calcite crystals, and faster growth rates of the stalagmite sample, and they interpreted these as representing the warmest and wettest climate conditions during the Holocene. Even though the signal is weak in this region in the numerical model result, there is a qualitative agreement between model and proxy reconstruction in surface temperature change, but a disagreement occurs in the hydrological budget, which was slightly drier in the model.

By analyzing a sediment core sampled from a wetland on Jeju Island, Lim and Fujiki (2011) found that the period between 6500 BP and 4000 BP is dominated by non-arboreal pollen type such as Artemisia, dry-tolerant. Towards the present, temperate broadleaved trees become more dominant. This pollen analysis indicates that in the mid-Holocene, the climate over Jeju Island was colder and drier, which is in part consistent with the model results. From a buried soil sampled in Yugu floodplain, Gongju, central South Korea, Lim et al. (2012) investigated millennial-scale vegetation changes during Holocene using stable isotopic composition ($\delta^{13}C$) and pollen and found that from 8900 to 6100 BP, C4 plants were abundant, and high percentages of arboreal pollen and low percentages of spores were found. This result indicates more arid environment during early- to mid-Holocene than present, consistent with the model results.

From multi-proxy data from sedimentary cores sampled in river valley of the Paju area, located northeast of Seoul, Korea, Nahm et al. (2011) found coarse sands containing pebbles in 7100 BP–5000 BP sediments and interpreted these to represent intensified rainfall during the mid-Holocene. From pollen analysis from the same area, Yi and Kim (2012) found dense woodlands in the mid-Holocene, indicating an increase in summer monsoon precipitation. These results are at odds with model results, which show reduced precipitation in summer in the Paju area (see Fig. 3). Yi et al. (2008) examined the change in vegetation types during the mid- to Late-Holocene using the samples of Cheonggye-cheon, a tributary of the Han River, in Seoul, and found evergreen and deciduous broadleaved trees, indicating warmer climate. These proxy records are consistent with model response, especially in summer (Fig. 1), even though the model response is weak.

Overall, proxy evidence suggests warmer climate in central Korea and slightly colder climate in southern Korea, Jeju Island, and this reconstruction is overall consistent with model results (Fig. 1). In terms of precipitation change, on the other hand, proxy records indicate the increase in the summer monsoon and associated precipitation in the mid-Holocene over central Korea, different from model results (Fig. 3). Regarding the hydrological budget change, however, some proxy evidence suggests more arid climate, while others suggest wetter in central Korea during the mid-Holocene. The model response is more arid in central and northern Korea, but shows little change in the southern part, making a conclusion difficult. We need more lines of proxy evidence in different locations over Korea.

4. Summary and conclusions

This study explores the response of the Asian summer monsoon to the imposition of mid-Holocene orbital conditions. The

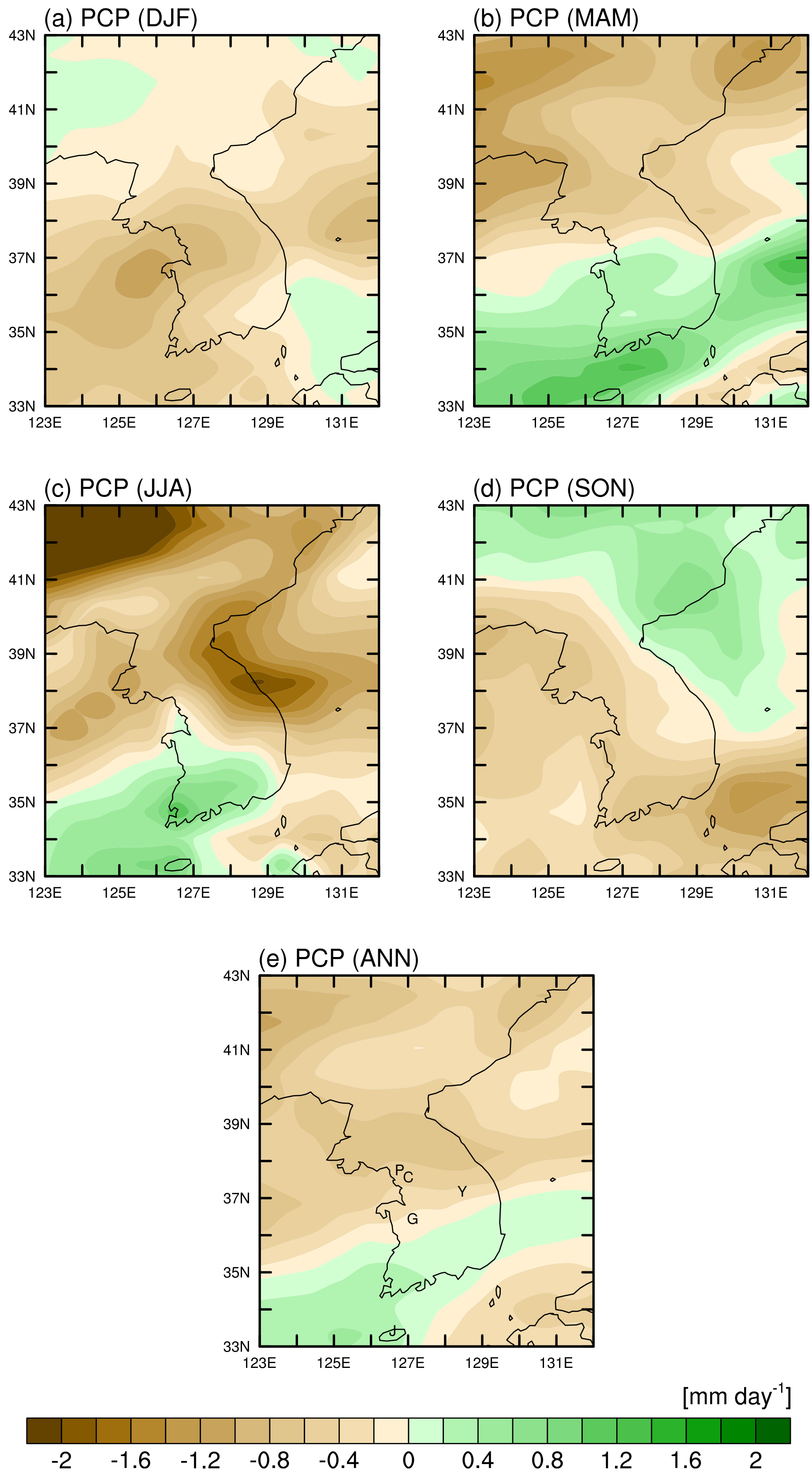

Fig. 3. Geographic distribution of the change in reproduced precipitation (PCP) between MOD and HOL averaged for (a) winter, (b) spring, (c) summer, (d) autumn, and (e) annual-mean. Units are in mm/day.

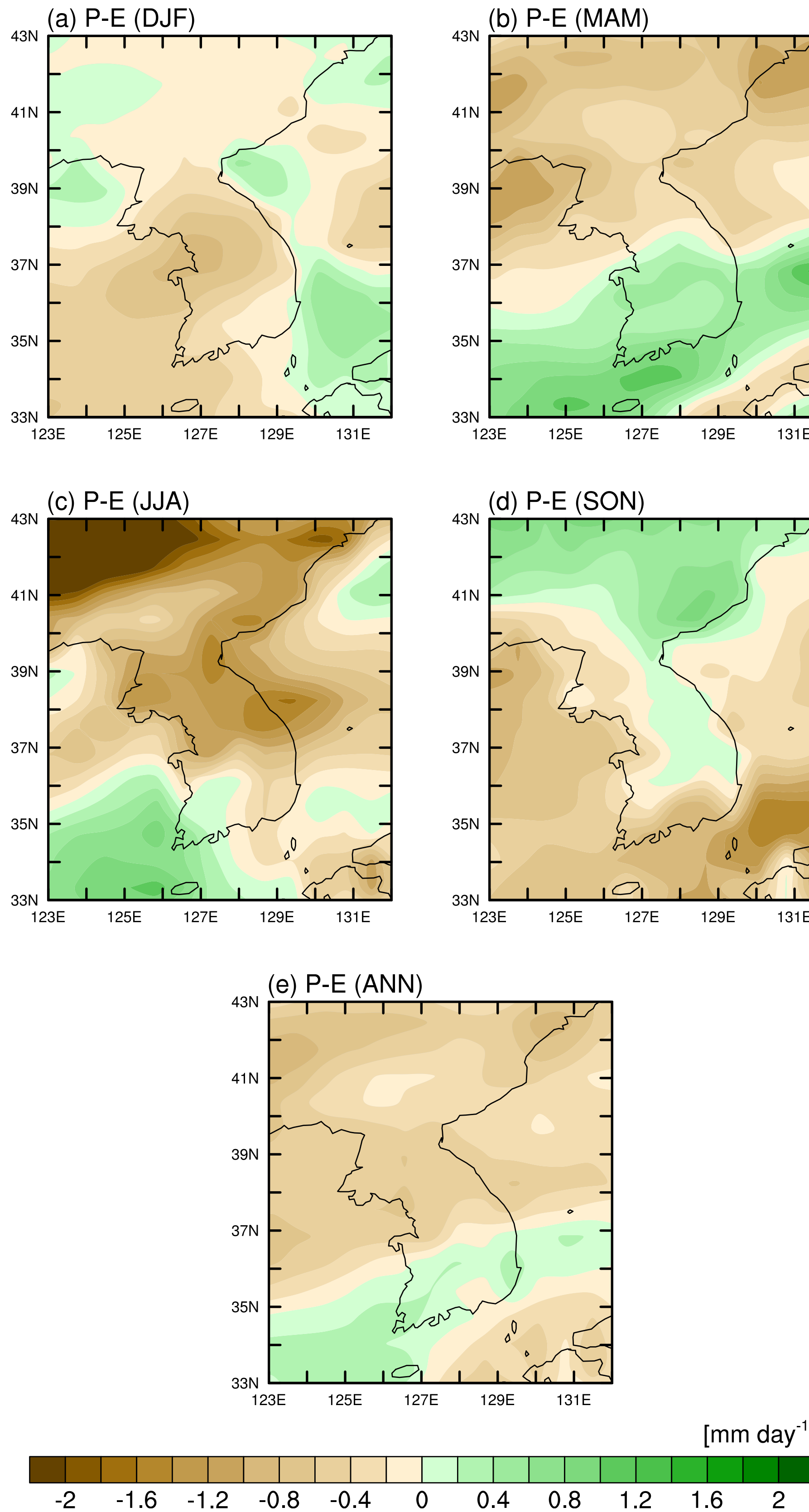

Fig. 4. Geographic distribution of the change in reproduced precipitation (P) minus evaporation (E) between MOD and HOL averaged for (a) winter, (b) spring, (c) summer, (d) autumn, and (e) annual-mean. Units are in mm/day.

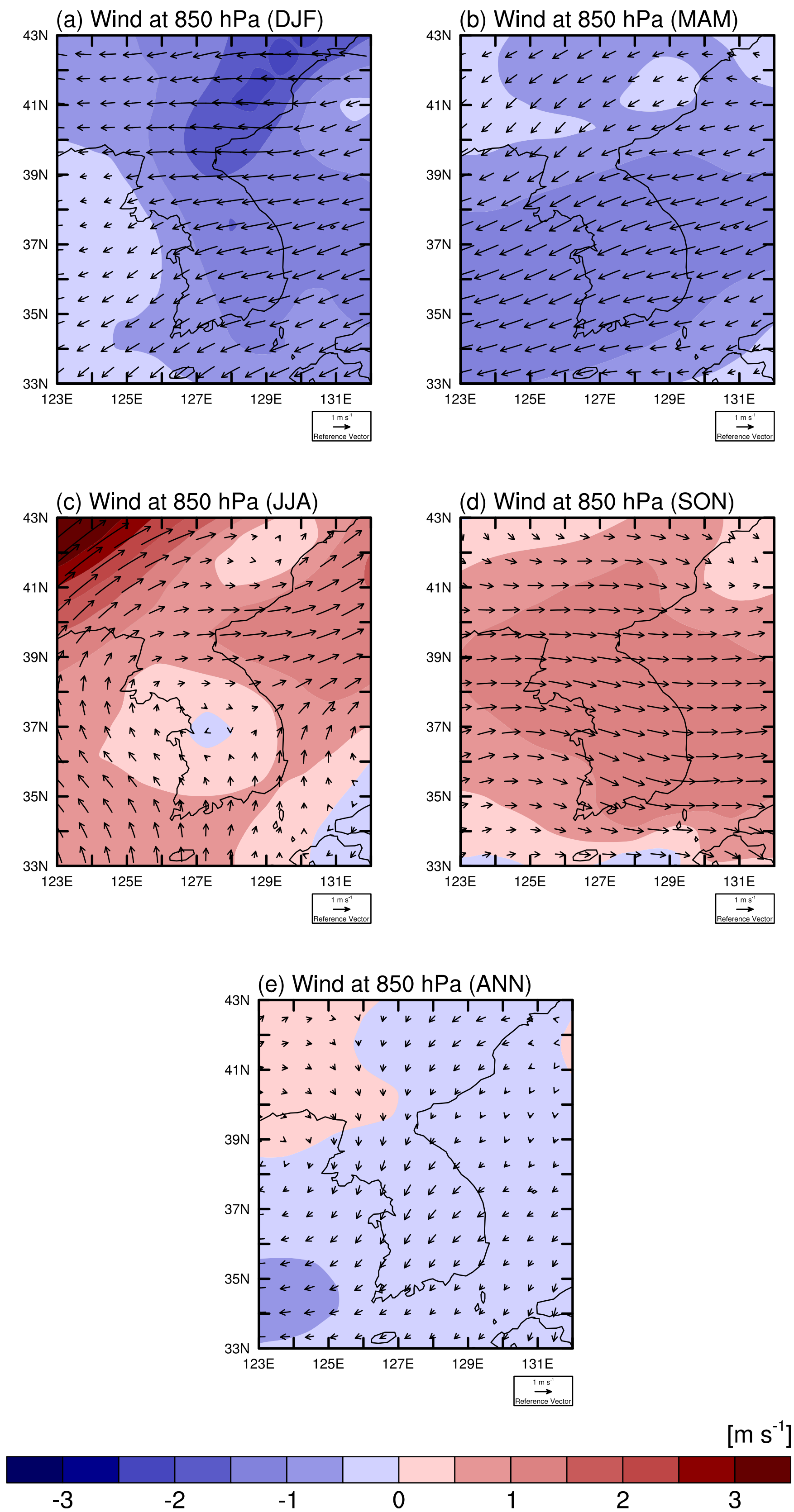

Fig. 5. Geographic distribution of the change in reproduced winds at 850 hPa between MOD and HOL averaged for (a) winter, (b) spring, (c) summer, (d) autumn, and (e) annual-mean. Units are in m s^{-1}.

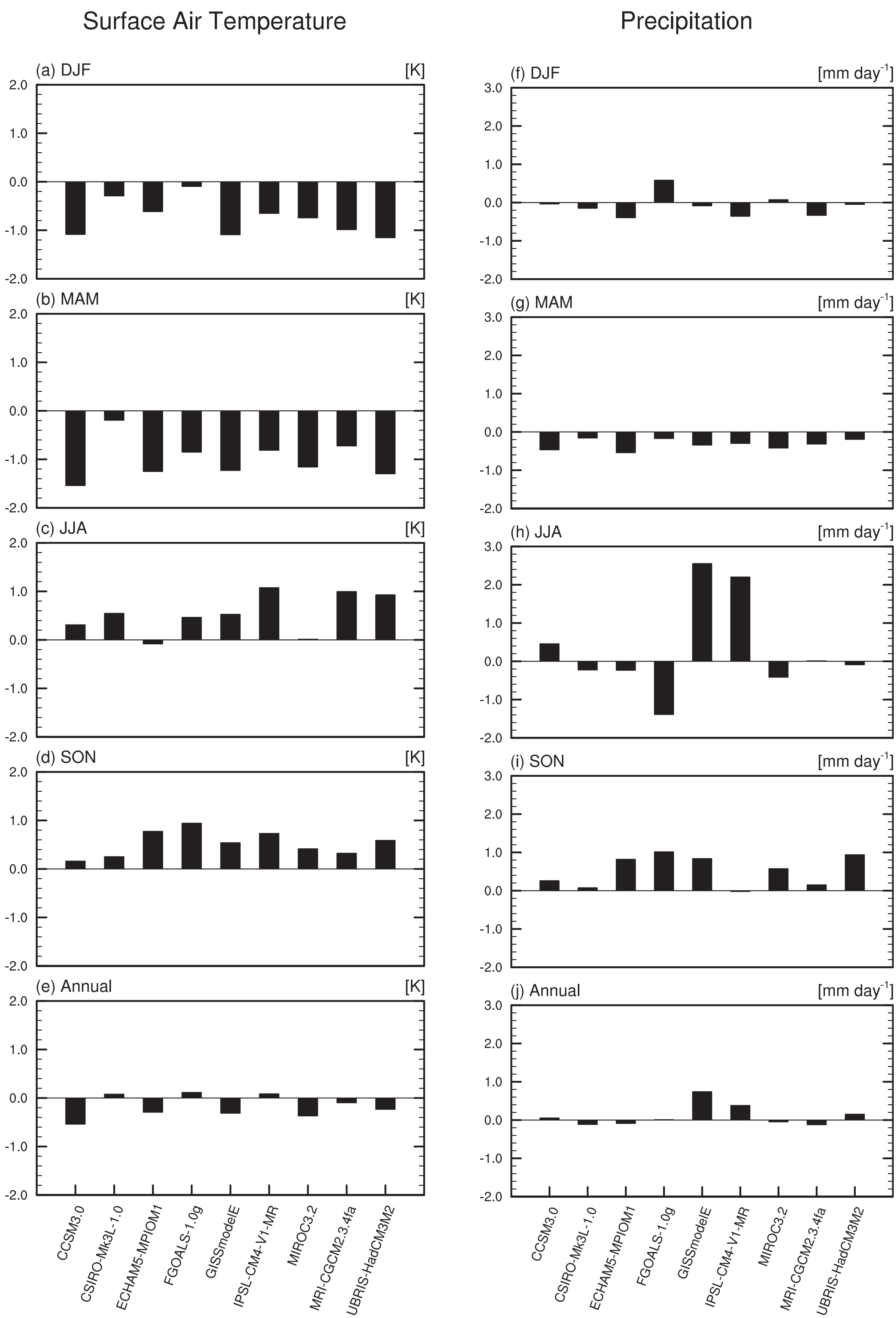

Fig. 6. Regionally averaged SAT over Korea for (a) winter, (b) spring, (c) summer, d) autumn, and (e) annual-mean and precipitation for (f) winter, (g) spring, (h) summer, (i) autumn, and (j) annual-mean. Units are in K for SAT and mm/day for precipitation.

simulations were performed with the NCAR CCM3 atmospheric general circulation model at a spectral truncation of T170, corresponding to a horizontal resolution of about 75 km. The model has 18 vertical layers and includes comprehensive land surface processes. The control simulation was forced by present sea surface temperature provided from NCAR. For the mid-Holocene experiment, we used orbital parameters for 6000 years before present. In terms of sea surface temperature, we used the same values for the mid-Holocene experiment, because the SST change for the mid-Holocene is known to be relatively small.

In response to the change in orbital parameters, summer surface temperature increases throughout Korea, as would be expected because the northern hemisphere received more energy in summer. The summer surface warming is especially larger in the northern part of Korea. In spring and autumn, the surface temperature decreases slightly, especially in the northern part in spring and the southern part in autumn. In winter, surface temperature increases in the northern part of Korea in spite of reduced insolation and short wave radiation at the surface. Analysis indicates that the winter anomalous warming in North Korea is due to the increase in downward long wave heat fluxes and turbulent, especially sensible, heat fluxes. Overall, in the mid-Holocene the surface is warmer in the northern part of Korea, whereas it is cooler in the southern part. This contrasting temperature response in the south and north agrees with some proxy evidence sampled in Jeju Island and the Gongju area, but disagrees with that from other locations. We need more proxy data to draw any clear conclusion on the surface temperature change in the mid-Holocene over Korea.

In term of hydrological budget change, precipitation increases in the southern part of Korea, especially in spring and summer. This seems to be due to the increase in the Asian summer monsoon during the mid-Holocene. Precipitation decreases in central Korea overall. The increase in summer precipitation is also found in proxy records, indicating heavy rainfall in South Korea. Even though precipitation increases overall, the precipitation minus evaporation budget response is negative in most of Korea, indicating a slightly drier climate in the northern part. The drier climate over central Korea is coincident with proxy records sampled in the Yugu floodplain and Daeya Cave data.

In conclusion, the climate is overall cooler and slightly wetter in the southern part and warmer and drier in the northern part of Korea in the mid-Holocene. This result is somewhat consistent with proxy evidence, but there are only limited records for the mid-Holocene. This result indicates that caution is needed when we look at the climate change over Korea for the mid-Holocene because regional factors are sometimes more important in modulating climate. With given limited proxy data from only a few locations, it is hard to reach any clear conclusion at the moment. We need wider coverage of proxy data to draw any clear conclusion for the mid-Holocene climate over Korea.

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