Future precipitation changes during summer in East Asia and model dependence in high-resolution MRI-AGCM experiments

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Abstract:

Global warming experiments using high-resolution climate models are important for studying the impact of global warming on human society from region to region. Three different cumulus schemes (YS: Yoshimura, KF: Kain-Fritsch and AS: Arakawa-Schubert) in the high-resolution Meteorological Research Institute AGCM have simulated slightly different future summer mean precipitation changes in East Asia, which are not negligible in the context of regional climate change. Specifically, 25-year mean June-July-August (JJA) average precipitation clearly decreases over eastern Japan, and tends to increase over northern Japan in YS. However, in KF and AS, decreases in precipitation are not significant over Japan, and an increase is clear from central China through southwestern Japan. Additionally, the increase is extended over the Pacific side of Japan in KF.

The above dependence of future changes in precipitation in East Asia on the scheme used is interpreted by comparing future changes in water and heat balances in the atmosphere. Among possible global warming effects, scheme dependence is attributed to different changes in mean vertical velocity associated with southward shift of the westerly jet over the northern Pacific and weakened Asian monsoon circulations over Eurasia.

KEYWORDS global warming; precipitation; East Asia; Asia monsoon; Meiyu-Baiu; MRI-AGCM

INTRODUCTION

Since warming of the climate system is unequivocal (IPCC, 2007), study of the impact of global warming on society (e.g., natural disasters, industries, life, and health) is becoming increasingly important. The impact of global warming differs from region to region, especially with respect to precipitation changes. To consider regional climate change, reliable high-resolution projection using a high-resolution climate model is necessary. Global warming experiments using the high-resolution Meteorological Research Institute atmospheric general circulation model (MRI-AGCM) combined with regional downscaling have contributed to the study of regional climate change (Kusunoki et al., 2006; Kitoh et al., 2016). However, the influence of global warming on precipitation is uncertain during summer in the Asian monsoon, especially in South Asia and Southeast Asia, and differs depending on the cumulus scheme used (Endo et al., 2012). In contrast, precipitation change during the summer in East Asia is relatively consistent, although slightly different changes are found regionally. These differences are not insignificant when assessing the impact of regional climate change on local people. In addition, it is important to understand the factors that are responsible for differences in precipitation change during summer in East Asia in order to reduce the uncertainty in future projections.

In this study, MRI-AGCM experiments for projections are analyzed from the viewpoint of water balance in the atmosphere, where projected precipitation change is divided into increased moisture effects due to global warming (e.g. Held and Soden, 2006) and contributions from vertical velocity change. The latter is further resolved into the effect of increased vertical stability due to global warming (Vecchi and Soden, 2007) and contributions from horizontal heat advection change (Sampe and Xie, 2010). The dependence of precipitation changes on the scheme used is discussed in relation to atmospheric circulation changes.

GLOBAL WARMING EXPERIMENTS FOR ANALYSIS

The global warming experiments analyzed in this study are the same as in the 60km resolution MRI-AGCM (MRI-AGCM3.2H) experiments described as MRI-AGCM3.2H (YS), MRI-AGCM3.2H (KF), and MRI-AGCM3.2H (AS) under the RCP8.5 scenario in Table 1d of Kitoh et al. (2016), except for prescribed future SSTs and experiment periods. The future SST increase relied on the CMIP5 multi-model ensemble (MME) for the RCP8.5 scenario in Table 1d of Kitoh et al. (2016). The experiment period was 25 years (1979 through 2004) for the present-day and 25 years (2075 through 2099) for the future. The model of MRI-AGCM3.2H (YS) uses the cumulus scheme of YS; MRI-AGCM3.2H (KF) uses that of KF, and MRI-AGCM3.2H (AS) uses that of AS. The YS or YoShimura scheme (Yoshimura et al., 2015) is a spectral scheme interpolating two Tiedtke-type updrafts (Tiedtke, 1989). The KF scheme is a scheme based on Kain and Fritsch (1990). The AS scheme is a scheme based on Arakawa and Schubert (1974) but modified to a large extent (Japan Meteorological...
Agency, 2007). Here, the corresponding experiment sets for the present-day and future are simply referred to as YS, KF, and AS. Analysis focuses on the 25-year mean June-July-August (JJA) averages.

**FUTURE CHANGE IN PRECIPITATION AND ATMOSPHERIC WATER BALANCE**

Figure 1b, 1c and 1d use contours to indicate present-day climatological precipitation in East Asia for YS, KF, and AS respectively, compared with the observations according to GPCP (Huffman et al., 1997) and CMAP (Xie and Arkin, 1997) in Figure 1a. They also use colors to indicate future precipitation changes. Future changes in precipitation in East Asia are relatively common compared with those in South Asia and the subtropical central Pacific in YS, KF, and AS (Endo et al., 2012): a tendency towards increased precipitation is seen in eastern China, especially in northeastern China, and to the south of Japan. Some decreases are commonly found in areas to the north of Japan. Some differences, however, can be detected between the schemes. For instance, precipitation decreases in eastern Japan and tends to increase in northern Japan in YS. In KF and AS, decreases in precipitation are not significant over Japan, while an increase is clear from central China through southwestern Japan. An increase also can be found over the Pacific side of Japan in KF, which is not clear in YS. These features were confirmed in another experiment set using the same MRI-AGCMs but with a CMIP3 SST increase and radiative forcing under the SRES A1B scenario (Figure S1).

To clarify future changes in long-term mean precipitation, water budget changes in the atmosphere were examined. The long-term mean water budget change is roughly approximated in Equations (1) and (2) (for details, see Text S1), where $q_s$ is surface specific humidity, $\omega$ is vertical velocity in the pressure coordinate, $P$ is surface precipitation, $E$ is surface evaporation, and $p$ and $g$ are pressure and gravity. The bars above the characters represent long-term mean variables, and the future change is denoted with a $\delta$ notation:

$$\delta (P - E) \approx - \delta \left\{ \frac{\partial q_s}{\partial p} \right\}$$

$$\approx - \delta \left\{ \frac{\partial q_s}{\partial p} \right\} \approx - \delta \left\{ \frac{\partial q_s}{\partial p} \right\} \approx - \delta q_s$$

Future change in precipitation minus evaporation ($dP - dE$) in 25-year mean JJA for YS is illustrated in Figure 2a. Comparison with precipitation change ($dP$) for YS in Figure 1b indicates that the spatial pattern is basically unchanged, except for shifts toward the negative because evaporation changes are positive and evenly distributed. The ($dP - dE$) in Figure 2a, which is also drawn using contours in Figure 2b, is comparable to the colored map of Figure 2b, calculated from Equation (2) using 25-year averaged JJA mean variables. In addition to the examination in Text S1, the above comparisons seem to justify the use of Equation (2) for this study.

The right-hand side of Equation (2) consists of two

![Figure 1](image-url)

Figure 1. (a) 1980 through 2004 JJA-averaged observed climatological precipitation of GPCP (colors) and CMAP (contours). (b) Future JJA precipitation change during 2075 through 2099 for YS (colors) relative to present-day JJA climatological precipitation during 1980 through 2004 (contours). (c) The same but for KF and (d) for AS. Units are mm/day
The first term, \((dq \cdot w_{500})\), is an increased moisture effect denoted by colors in Figure 2c, which leads to wetter conditions in the wet region and drier conditions in the dry region in the future (e.g. Held and Soden, 2006). The second term, \((q \cdot dw_{500})\), is the contribution from future change in vertical velocity, indicated by colors in Figure 2d. Compared to the features of \((dq \cdot w_{500})\) in Figure 2c, those of \((q \cdot dw_{500})\) in Figure 2d are more comparable to those of \((dP – dE)\) denoted by contours. The major characteristics of \((dP – dE)\) for YS come from the second term \((q \cdot dw_{500})\) in Equation (2). This is also the case for KF and AS (not shown).

The results above indicate that the future changes in the 25-year JJA mean vertical velocity is basically responsible for the differences in the characteristics of precipitation changes over East Asia among the three schemes.

FUTURE CHANGE IN VERTICAL VELOCITY AND ATMOSPHERIC HEAT BALANCE

Case for YS

An atmospheric heat balance is described in Equation (3) (e.g. Yanai et al., 1992), where \(\vec{v}\) is horizontal velocity vector, \(s\) is dry static energy, \(p\) is pressure, and \(\omega\) is its time-derivative. \(Q1\) includes radiative heating \((QR)\), condensation heating \((c)\), evaporation cooling \((e)\), and vertical turbulence mixing of \(s\) within model grids:

\[
\partial s/\partial t + \vec{v} \cdot \text{grad}(s) + \omega \cdot \text{grad}(s)/\partial p = Q1 = QR + L(c – e) - \omega \cdot (\partial \delta s/\partial p)
\]

The 25-year JJA mean change in vertical velocity is diagnosed, denoting future changes with a \(\delta\) notation:

\[
\delta \omega = \sum \left[ \delta \vec{v} \cdot \text{grad}(s) + \vec{v} \cdot \text{grad}(\delta s) - \omega \cdot (\partial \delta s/\partial p) - \partial (Q1) \right]/(\partial \delta s/\partial p)
\]

Following Sampe and Xie (2010), which explained the Meiyu-Baiu rainband from adiabatic induction of upward motion originating from the advection of warm air, we focus on vertical motion changes related to heat advection and vertical stability changes:

\[
\delta \omega_{\text{adv}} + \delta \omega_{\text{stab}} = \sum \left[ \delta \vec{v} \cdot \text{grad}(s) + \vec{v} \cdot \text{grad}(\delta s) - \omega \cdot (\partial \delta s/\partial p) \right]/(\partial \delta s/\partial p)
\]

The first and second terms on the right hand side of Equation (5) represent the change in vertical motions associated with that in horizontal heat advection \((dw_{\text{adv}})\). The third term is also the change in vertical motions, but that is caused by the change in vertical static stability due to global warming \((dw_{\text{stab}})\) (Vecchi and Soden, 2007).

Precipitation change resolved by Equations (2) and (5) is symbolically described:

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\[ dP - dE = (-dq \cdot w_{500}) + (-q \cdot dw_{500}) \] (6)

\[ \approx (-dq \cdot w_{500}) + (-q \cdot dw_{500\_adv}) + (-q \cdot dw_{500\_stab}) \] (7)

The summation of \((-q \cdot dw_{500\_adv})\) and \((-q \cdot dw_{500\_stab})\) is indicated with colors in Figure 3a, and reproduces the major characteristics of \((-q \cdot dw_{500})\) shown with contours, it is shifted toward the negative on average though. Change in vertical static stability itself has little geographical variability and tends to weaken vertical circulation (Vecchi and Soden, 2007) so that precipitation changes originating from changes in vertical static stability \((-q \cdot dw_{500\_stab})\) are distributed quite similarly to climatological vertical velocity but with reverse directions (not shown). Therefore, \((-q \cdot dw_{500\_stab})\) tends to be negative in wet region of the Asia monsoon including East Asia.

Figure 3b illustrates \((-q \cdot dw_{500\_adv})\), which is precipitation change related to change in horizontal heat advection, with contours for \((-q \cdot dw_{500})\). In East Asia, \((-q \cdot dw_{500\_adv})\) is qualitatively responsible for the feature of \((-q \cdot dw_{500})\), however, quantitatively, the variability of \((-q \cdot dw_{500\_adv})\) is about one quarter to one half of that of \((-q \cdot dw_{500})\). These are consistent with Sampe and Xie (2010), which mentions that “the ascending motion induces convection and is enhanced by the resultant condensational heating”.

For the analysis shown in Figure 3, the 25-year JJA mean variables were used in Equation (5) because the purpose of this study was not to accurately estimate dynamical contribution to precipitation changes but to understand the model dependence of precipitation changes in East Asia as simply as possible. For reference, Figure S5 is given for the same analysis except that monthly variables during the 25 years are applied in Equation (5). The same qualitative characteristics in Figure 3 can be found in Figure S5.

Comparison of YS, KF, and AS

Figures 3c and 3d are the same as Figure 3b, but for KF and AS. Precipitation changes related to \((-q \cdot dw_{500\_adv})\) for YS, KF, and AS are basically similar. However, some differences can be found. One difference is a relatively large decrease in precipitation over Japan in YS, compared with a weak decrease over Japan in KF and an eastward shift in the decrease in AS. Another difference is a relatively clear increase from southern and central China through southwestern Japan and its further expansion to the south of Japan in KF, and from central China to the southwestern Japan in AS. The corresponding change is relatively weak in YS.

If we adopt the causality for East Asian summer rainbands suggested by Sampe and Xie (2010), the above relative differences in \((-q \cdot dw_{500\_adv})\) among YS, KF, and AS (colors in Figures 3b, 3c, and 3d) lead to the relative differences in future precipitation changes (colors in Figures 1b, 1c, and 1d).

EXPLANATION BASED ON FUTURE CHANGE IN ATMOSPHERIC CIRCULATION

Figure 4a indicates climatological 500 hPa ‘temperature’...
(to put it accurately, dry static energy divided by specific heat at constant pressure $C_p$ relative to 273.1 K) denoted by colors and future change in the 500 hPa stream function denoted by contours for YS. Cyclonic changes in the stream function (C2) are located in the 50 to 52.5°C ‘temperature’ zone with northeasterly wind change over western and eastern Japan. Therefore, negative heat advection to the west of C2 induces downward vertical motion (Figure 3b and Figure S6b), and results in decreased precipitation (Figure 1b). Another cyclonic change (C1) creates southerly or southeasterly wind change over northeastern China, Korea, and close to northern Japan. Correspondingly, upward vertical motion (Figure 3b and Figure S6b) is induced by positive heat advection to the east of C1, and contributes to increased precipitation (Figure 1b).

The future change in the 500 hPa zonal wind depicted in Figure 4b clarifies what happens in 500 hPa atmospheric circulation for YS under global warming. The cyclonic change (C2) indicates that the mid-latitude westerly jet expanding eastward from Japan over the northwestern Pacific tends to shift southward. The cyclonic change (C1) is located at the northeastern edge of the Tibetan High, which weakens over northern Eurasia due to global warming (Figure S7a). On the other hand, in South Asia, anticyclonic changes (A1 and A2) are found from the Bay of Bengal through Southeast Asia. These changes indicate that global warming weakens low-level cyclonic Asia monsoon circulations at 850 hPa, influencing circulations at 500 hPa, in response to weakened upward motion in South Asia (Figure 5a and Figure 4a) due to increased vertical stability (Hirahara et al., 2012). In the tropics, changes in vertical motions due to stabilized vertical profiles ($-q \cdot \frac{dw}{dt}_{500\_stab}$) are generally more significant than those due to horizontal heat advection changes ($-q \cdot \frac{dw}{dt}_{500\_adv}$), contrasted with the mid-latitudes such as East Asia, because horizontal temperature gradients in the tropics are relatively weak and do not produce significant horizontal heat advections (not shown). These contrast between the tropics and the mid-latitudes is clearly seen, for example, by comparing the vertical velocity change induced by horizontal heat advection of Figure S6b and the total vertical velocity change of Figure 5a for YS.

Figures 4c and 4d are the same as Figure 4a but for KF and AS, respectively. Anticyclonic changes of A1 and A2 and cyclonic changes of C1 and C2 can be identified clearly in Figure 4c for KF and Figure 4d for AS, as well as Figure 4a for YS. Although all these are located in similar geophysical places among the three simulations, detailed locations and magnitudes of A1 and A2 and of C1 and C2 differ among YS, KF, and AS.

Adopting the cause-result relationships between dynamical environments and rain-bands in East Asian summer (Sampe and Xie, 2010), the differences in precipitation change among YS, KF and AS can be explained as follows. In the northeast of C1, northward heat advection and related upward changes commonly induce an increase in
precipitation in northeastern China (Figure 4, Figure 3 and Figure 1). Increased precipitation over northern Japan in YS may be attributed to the northeasterward extension of C1. C2 is located further south for YS than for KF and AS. C2 for YS forms northeasterly wind changes along the north-south gradient of the climatological ‘temperature’ over Japan and strong downward motion, resulting in dry climate change there (Figure 4a, Figure 3b and Figure 1b). C2 for KF shifts eastward around the dateline. Therefore, changes in associated vertical motion and precipitation are relatively weak over Japan (Figure 4c, Figure 3c and Figure 1c). C2 for AS is shifted eastward so that a tendency towards decreased precipitation appears in the eastern side of Japan (Figure 4d, Figure 3d and Figure 1d).

Relatively strong downward changes occur over South Asia, Southeast Asia, and the tropical northwestern Pacific for KF (Figure 5) compared with YS and AS. These changes produce strengthened A1 and A2 (Figure 5 and Figure 4), resulting in strong westerly change from south of the Tibetan Plateau through southern China to south of Japan. Those westerly wind changes occur along an east-west gradient of climatological ‘temperature’ and are accompanied by upward motion change. Then, precipitation is increased over southern and central China, and the south of Japan (Figure 4c, Figure 3c and Figure 1c). The A2 for AS expanding into central China forms southerly wind change, upward motion change and increased precipitation from central China through the East China Sea (Figure 4d, Figure 3d and Figure 1d).

SUMMARY AND DISCUSSION

In high-resolution MRI-AGCM global warming experiments, future precipitation changes over summer in East Asia have been examined, focusing on differences among YS, KF and AS through the analysis of water balance and heat advection in the atmosphere. Their qualitative differences can be attributed to differences in future changes in vertical motion accompanied by changes in long-term mean horizontal heat advection.

Two changes in atmospheric circulation are involved. One is tropical atmospheric responses (A1 and A2) to suppressed upward motion from South Asia to the tropical Pacific in the Asia monsoon (Hirahara et al., 2012). Differences in suppression of upward motion in South Asia among YS, KF and AS results in different changes in low-level circulation from southern Asia to the subtropical western Pacific in terms of strength and extension (Figure 5). These changes influence up to 500 hPa level circulations and appear as A1 and A2, which affect precipitation changes from southern and central China to the south of Japan.

The other atmospheric change occurs in the mid-latitudes (C1 and C2). The C1, probably related to the southward shrinking of the Tibetan High, is common among the three schemes and creates increased precipitation to the east of C1. The details of cyclonic circulation change of C2 or southward shift of the westerlies in the northern Pacific, is the key for precipitation changes over central areas of
Japan. The C2 changes seem to be formed downstream of the A2 changes, which are supposedly associated with changes in vertical motions in the subtropical and tropical Pacific, and therefore depend on cumulus schemes as well as the distribution of sea surface temperature.

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SUPPLEMENTS

Text S1. Approximations of vertically integrated water budget in the atmosphere
Figure S1. Future precipitation changes in the MRI-AGCM experiments with SRES A1B CMIP3 MME SST change and environment
Figure S2. Water budget changes based on 6-hourly output
Figure S3. Water budget changes based on monthly output
Figure S4. Water budget changes for 25 years
Figure S5. Precipitation changes due to heat advection changes
Figure S6. Future changes in the 500 hPa stream function and 500 hPa vertical velocity induced by horizontal heat advection
Figure S7. Future changes in the 200 hPa stream function and 500 hPa vertical velocity

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