Projected changes in summer water vapor transport over East Asia under the 1.5°C and 2.0°C global warming targets

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ABSTRACT
This study investigates changes in summer water vapor transport (WVT) over East Asia under 1.5°C and 2.0°C global warming (GW) for the +4.5 and +8.5 W m\textsuperscript{-2} Representative Concentration Pathway (RCP) scenarios (RCP4.5 and RCP8.5, respectively). Of the 27 models used, 18 show better skill in simulating the climatological summer WVT over East Asia of the present day. Of those 18, 13 reach 1.5°C and 2.0°C GW for the two RCPs. Based on these 13 models, results show that — relative to the present day — the summer WVT is enhanced over East Asia under 1.5°C and 2.0°C GW for RCP4.5 and RCP8.5. The inter-model consistency is higher under 2.0°C GW. Increased water vapor content favors the enhanced WVT over both southern and northern East Asia, while lower-level circulation contributes to the enhanced WVT over southern East Asia. Compared to 1.5°C GW, the summer WVT under 2.0°C GW is further enhanced over most of East Asia for RCP4.5. For RCP8.5, the summer WVT is also further enhanced over southern East Asia, while this is not the case over northern East Asia. Under the additional 0.5°C GW, the changes in summer WVT, with low inter-model consistency, are closely related to anomalous lower-level circulation. Precipitation increases over the East China Sea to southern Japan, the Korean Peninsula, and Northeast China; for both RCP4.5 and RCP8.5. However, the changes in precipitation over the South China Sea and Northeast China are different for the two RCPs. This is connected to the changes in the WVT divergence.

1. Introduction
The Intergovernmental Panel on Climate Change (IPCC) Fifth Assessment Report shows that the global mean temperature increased remarkably during the last 100 years, which can be mainly attributed to anthropogenic greenhouse gas emissions. The global warming (GW) has caused climate changes in many areas (e.g. Chen and Sun 2017). Therefore, a key issue of concern is what the climate will be like if GW continues. Previous studies have projected future climate changes under a warmer world based on climate models. Results show that, the greater the level of GW, the greater the risk that the world will experience dramatic climate changes (e.g. Wang, Jiang, and Lang 2017; Xu et al. 2017; Chevuturi et al. 2018; Zhou et al. 2018).

In 2015, parties of the United Nations Framework Convention of Climate Change (UNFCCC) reached an agreement to hold GW below 2.0°C and pursue efforts to limit it to 1.5°C above pre-industrial levels (UNFCCC 2015). Recently, a 1.5°C special report has been released by the IPCC to assess the knowledge base for such GW. Based on the outputs of Phase 5 of the Coupled Model Intercomparison Project (CMIP5), studies have been carried out to detect the difference in climate changes over East Asia under the 1.5°C and 2.0°C GW targets. The average annual surface air temperature over China increases by 1.7°C–2.0°C (2.4°C–2.7°C) under the 1.5°C (2.0°C) GW target for various Representative Concentration Pathway (RCP) scenarios (Fu, Lu, and Guo 2017). The spatial pattern of increase in temperature over China, with more (less) of an increase in the

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northwest (southeast), is similar for the two GW targets (Fu, Lu, and Guo 2017). The summer lower-level monsoon circulation and precipitation over continental East Asia increase relative to the present day under the 1.5°C GW target for the +4.5 W m⁻² RCP scenario (RCP4.5), and the intensities of their interannual variability are also enhanced (Wang et al. 2017; Ren et al. 2017). Compared to 1.5°C GW, an additional 0.5°C GW would result in significant increases in temperature extremes (e.g. the hottest day, the frequency of heat events) and precipitation extremes over China (Chen and Sun 2018; Li et al. 2018; Sui, Lang, and Jiang 2018). Although several aspects of summer climate changes over East Asia are compared between 1.5°C and 2.0°C GW by previous studies, changes in water vapor transport (WVT) and its contribution to precipitation changes, which the present study tries to deal with, remain unknown.

The rest of the paper is organized as follows: section 2 describes the data and methods used; projected changes in summer WVT and its role in precipitation changes are presented in section 3; and a summary is provided in section 4.

2. Data and methods

The monthly outputs of 27 CMIP5 models are employed in this study (Taylor, Stouffer, and Meehl 2012). The historical and 21st century projected runs under the RCP4.5 and RCP8.5 scenarios are analyzed. Table 1 lists some key information about the models. To carry out a multimodel ensemble and comparison among the models, the horizontal resolutions of the runs are interpolated onto a 2.5° × 2.5° resolution. In addition, ERA-Interim data (Dee et al. 2011), with a horizontal resolution of 2.5° × 2.5°, are employed to assess the models.

The vector field evaluation diagram, proposed by Xu et al. (2016), is used to assess the WVT. Three statistical variables are involved in the diagram (Figure 1). The root-mean-square vector difference is used to measure the overall difference between two vector fields. The vector similarity coefficient and root-mean-square length are adopted to identify the pattern similarity and systematic difference of vector magnitude between two vector fields, respectively.

3. Results

Figure 1 presents the vector field evaluation diagram of the climatological summer (June–July–August) WVT integrated from the surface to 100 hPa over East Asia (5°–55°N, 105°–150°E) at the present day (1979–2005) for the 27 CMIP5 models. As marked by the blue rectangle, 18 of the 27 CMIP5 models show relatively smaller normalized root-mean-square vector differences, indicating better skill in reproducing the magnitude and direction of the climatological summer WVT over East Asia.

For each of the 18 models, the timings of 1.5°C and 2.0°C GW are obtained by calculating the 11-year running average of the annual global mean temperature with the baseline of 1861–90. Among them, 13 reach both 1.5°C and 2.0°C GW under RCP4.5 and RCP8.5. Therefore, the outputs of these 13 models are selected to carry out the following analysis. The timings of 1.5°C and 2.0°C GW for the selected 13 models are also listed in Table 1. The timings are basically earlier under RCP8.5 than RCP4.5.

The changes in summer WVT over East Asia, relative to the present day, during 1.5°C and 2.0°C GW periods are firstly addressed. The role of the dynamic and thermodynamic components in the changes is also shown. Compared with the present day, enhanced summer WVT can be found over East Asia under 1.5°C and 2.0°C GW for RCP4.5 (Figure 2a,c). In this study, enhanced (weakened) WVT refers to the magnitude of WVT in GW periods being greater (less) than the present day. Therefore, enhanced (weakened) WVT in a region does not mean a local convergence (divergence) of WVT. The spatial patterns of the enhanced WVT are similar to those

### Table 1. Details of 27 CMIP5 models and the periods when the selected models reach 1.5°C and 2.0°C GW.

| Model name          | Horizontal resolution (lat × lon) | 1.5°C GW period for RCP4.5/RCP8.5 | 2.0°C GW period for RCP4.5/RCP8.5 |
|---------------------|-----------------------------------|-----------------------------------|-----------------------------------|
| BCC-CSM1.1          | ~2.8° × 2.8°                      | 2017–2016                          | 2039–2042                          |
| BCC-CSM             | ~1.1° × 1.1°                      | 2017–2016                          | 2039–2042                          |
| 1.1-m               |                                    |                                   |                                   |
| BNU-ESM             | ~2.8° × 2.8°                      | 2017–2016                          | 2039–2042                          |
| CanESM2             | ~2.8° × 2.8°                      | 2017–2016                          | 2039–2042                          |
| CCSM4               | ~1.25° × 0.9°                     | 2013–2011                          | 2034–2044                          |
| CESM1-CAM5          | ~1.25° × 0.9°                     | 2024–2033                          | 2042–2053                          |
| CNRM-CM5            | ~1.4° × 1.4°                      | 2032–2026                          | 2053–2060                          |
| CSIRO-MK            | ~1.9° × 1.9°                      | 2017–2016                          | 2039–2042                          |
| 3.6.0               |                                    |                                   |                                   |
| FG0A5S-g2           | ~2.8° × 3.0°                      | 2017–2016                          | 2039–2042                          |
| FIO-ESM             | ~2.8° × 2.8°                      | 2017–2016                          | 2039–2042                          |
| GFDL-CM3            | 2.5° × 2.0°                       | 2017–2016                          | 2039–2042                          |
| GFDL-ESM2G          | 2.5° × 2.0°                       | 2017–2016                          | 2039–2042                          |
| GFDL-ESM2M          | 2.5° × 2.0°                       | 2017–2016                          | 2039–2042                          |
| GISS-E2-H           | 2.5° × 2.0°                       | 2017–2016                          | 2039–2042                          |
| GISS-E2-R           | 2.5° × 2.0°                       | 2017–2016                          | 2039–2042                          |
| HadGEM2-AO          | ~1.9° × 1.25°                     | 2017–2016                          | 2044–2043                          |
| HadGEM2-ES          | ~1.9° × 1.25°                     | 2017–2016                          | 2044–2043                          |
| IPSL-CMSA-LR        | ~3.75° × 1.9°                     | 2009–2016                          | 2025–2032                          |
| IPSL-CMSA-MR        | ~2.5° × 1.25°                     | 2013–2011                          | 2027–2037                          |
| MIROCS              | ~1.4° × 1.4°                      |                                   | 2013–2013                          |
| MIROC-ESM           | ~2.8° × 2.8°                      |                                   |                                   |
| MIROC-ESM-CHEM      | ~2.8° × 2.8°                      |                                   |                                   |
| MPI-ESM-LR          | ~1.9° × 1.9°                      | 2019–2011                          | 2036–2042                          |
| MPI-ESM-MR          | ~1.9° × 1.9°                      | 2018–2013                          | 2040–2043                          |
| MPI-ESM-MR-CGCM3    | ~1.1° × 1.1°                      |                                   |                                   |
| NorESM1-M           | ~2.5° × 1.9°                      | 2034–2027                          | 2069–2074                          |
| NorESM1-ME          | ~2.5° × 1.9°                      | 2036–2028                          | 2062–2042                          |
of climatological summer WVT and lower-level circulation of the present day. Clearly, enhanced anticyclonic (cycloic) WVT dominates over the western North Pacific (South China Sea) (Figure 2(a,c)). Therefore, enhanced southerly or southwesterly WVT prevails over southern East Asia (South China Sea to southern Japan). In addition, enhanced westerly WVT prevails over northern East Asia (eastern Mongolia to northern Japan). Under 1.5°C GW, the inter-model consistency of changes in WVT is low over East Asia, except the South China Sea and most of Northeast China where at least nine models show the same quadrants with the multi-model ensemble (Figure 2(a)). Relative to 1.5°C GW, the inter-model consistency improves under 2.0°C GW, especially over the East China Sea, Korean Peninsula, southern Japan, and eastern Mongolia (cf. Figure 2(a,c)).

Changes in WVT are caused by changes of atmospheric circulation and water vapor content. Due to increased tropospheric air temperature, atmospheric water vapor content increases over East Asia. This favors the enhanced WVT over both southern and northern East Asia. The water vapor is mainly located at the lower level. Therefore, changes in wind at the 850-hPa level over East Asia are analyzed to reveal their contribution to the enhanced WVT. Wind anomalies at the 850-hPa level are also similar under 1.5°C and 2.0°C GW for RCP4.5 (figure not shown). Due to an enhanced South China Sea summer monsoon trough and western North Pacific subtropical high, enhanced southerly or southwesterly flow dominates over southern East Asia, which favors the enhanced WVT. Anomalous southerly or southeasterly flow prevails over northern East Asia, which is in contrast with the enhanced westerly WVT over the region. Therefore, changes in lower-level circulation have less or negative contribution to the enhanced westerly WVT over the region. In short, both increased water vapor content and enhanced lower-level monsoon circulation favor the enhanced WVT over southern East Asia, while increased water vapor content plays a more important role than the changes of lower-level circulation in the enhanced WVT over northern East Asia.

The features of enhanced summer WVT and inter-model consistency over East Asia under 1.5°C and 2.0°C GW for RCP8.5 are similar to those for RCP4.5 (cf. Figure 2(a–d)). The South China Sea summer monsoon trough is enhanced under 1.5°C and 2.0°C GW (figure not shown). As a result, the lower-level monsoon circulation is enhanced over southern East Asia. Therefore, both enhanced lower-level monsoon circulation and increased water vapor content contribute to the enhanced summer WVT over the region. Over northern East Asia, anomalous westerly flow prevails under 1.5°C GW, but anomalous meridional winds dominate under 2.0°C GW (figure not shown). Therefore, enhanced westerly WVT is caused by both enhanced lower-level westerly and increased water vapor content under 1.5°C GW, but mainly caused by increased water vapor content under 2.0°C GW.
Although the spatial patterns of the changes in lower-level circulation show some differences over East Asia between RCP4.5 and RCP8.5, those of enhanced summer WVT are similar. Furthermore, they resemble the spatial patterns of the climatological summer WVT and lower-level circulation of the present day. Therefore, the increased water vapor content plays an important role in the enhanced summer WVT over East Asia under 1.5°C and 2.0°C GW for RCP4.5 and RCP8.5.

Next, the difference in changes of summer WVT over East Asia between 1.5°C and 2.0°C GW for RCP4.5 and RCP8.5 is demonstrated to show the implication of an additional 0.5°C GW on summer WVT. For RCP4.5, although the inter-model consistency is low, the
summer WVT is enhanced over East Asia, except in Southwest China and the middle reaches of the Yangtze River valley, under the additional 0.5°C GW (Figure 2(e)). Its spatial pattern is similar to that of the 850-hPa wind anomalies, with an enhanced South China Sea summer monsoon trough and western North Pacific subtropical high and an anomalous cyclone over northern East Asia (figure not shown).

For RCP8.5, the summer WVT is enhanced over southern East Asia, due to anomalous anticyclonic WVT over the South China Sea to western North Pacific (Figure 2(f)), under the additional 0.5°C GW. However, it is not uniformly enhanced over northern East Asia. Anomalous anticyclonic (cyclonic) WVT dominates over Northeast China (Japan) (Figure 2(f)). The inter-model consistency is also low. Wind anomalies at the 850-hPa level show a similar spatial pattern, with anomalous anticyclones over the South China Sea to western North Pacific and Northeast China, and an anomalous cyclone over Japan.

Under an additional 0.5°C GW, the summer WVT is further enhanced over southern East Asia for both RCP4.5 and RCP8.5. Over northern East Asia, it is also further enhanced for RCP4.5. However, this is not the case for RCP8.5. Anomalous anticyclonic (cyclonic) WVT dominates over Northeast China (Japan) for RCP8.5. Changes in summer WVT over East Asia are closely related to lower-level circulation anomalies under the additional 0.5°C GW for RCP4.5 and RCP8.5.

Finally, the relationship between changes in divergence of summer WVT and precipitation under an additional 0.5°C GW for RCP4.5 and RCP8.5 is explored. As shown by Figures 3 and 4, the spatial patterns of anomalous divergence of summer WVT are basically similar to those of anomalous precipitation. Their magnitudes are also comparable. The precipitation increases over the East Asia.

Figure 3. Multi-model ensemble changes in summer water vapor transport divergence (units: mm d$^{-1}$) over East Asia between 2.0°C and 1.5°C GW for (a) RCP4.5 and (b) RCP8.5. The different fill patterns (dots, forward slashes, backslashes) indicate the number of models showing the same sign as the multi-model ensemble, as indicated by the key on the right-hand side of the figure.

Figure 4. Multi-model ensemble changes in summer precipitation (units: mm d$^{-1}$) over East Asia between 2.0°C and 1.5°C GW for (a) RCP4.5 and (b) RCP8.5. The different fill patterns (dots, forward slashes, backslashes) indicate the number of models showing the same sign as the multi-model ensemble, as indicated by the key on the right-hand side of the figure.
4. Summary

Projected changes in summer WVT over East Asia under 1.5°C and 2.0°C GW is demonstrated for the RCP4.5 and RCP8.5 scenarios of CMIP5. To carry out the projections, the vector field evaluation diagram is firstly employed to assess the skills of models in reproducing the climatological summer WVT over East Asia at the present day. Of the 27 models used, 18 show relatively better skill. Furthermore, 13 of those 18 models reach 1.5°C and 2.0°C GW for RCP4.5 and RCP8.5. Therefore, the projections are based on the outputs of these 13 models. For these models, the timings of 1.5°C and 2.0°C GW are basically earlier for RCP8.5 than RCP4.5.

Compared to the present day, summer WVT is enhanced over East Asia under 1.5°C and 2.0°C GW for RCP8.5 and RCP4.5. That is, there is enhanced southerly or southwesterly WVT over southern East Asia and westerly WVT over northern East Asia. The inter-model consistency is low over East Asia, except over the South China Sea and Northeast China, under 1.5°C GW. Under 2.0°C GW, the inter-model consistency improves, especially over the East China Sea, Korean Peninsula, southern Japan, and eastern Mongolia. The increased water vapor content favors the enhanced WVT over both southern and northern East Asia. The lower-level circulation mainly contributes to the enhanced WVT over southern East Asia, but it also contributes to the enhanced WVT over northern East Asia under 1.5°C GW for RCP8.5.

Under an additional 0.5°C GW, summer WVT is further enhanced over most of East Asia for RCP4.5. For RCP8.5, it is also further enhanced over southern East Asia, while this is not the case over northern East Asia, where an anomalous anticyclonic (cyclonic) WVT dominates over Northeast China (Japan). The inter-model consistency is low. Changes in summer WVT are closely connected to lower-level anomalies over both southern and northern East Asia. There is consistently increased precipitation over the East China Sea to southern Japan, the Korean Peninsula, and North China for both RCP4.5 and RCP8.5. However, the changes in precipitation over the South China Sea and Northeast Asia are different between RCP4.5 and RCP8.5. This is related to the changes in WVT divergence. Increased precipitation and anomalous convergence dominate over the two regions for RCP4.5, but decreased precipitation and anomalous divergence dominate over most of the two regions for RCP8.5.

As shown above, changes in summer WVT, especially over northern East Asia, under an additional 0.5°C GW, are different between RCP4.5 and RCP8.5. Further study is needed in the future to explore such inconsistency.

Disclosure statement

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