Future Changes in Global Monsoon Precipitation and their Uncertainty: Results from High-Resolution MRI-AGCM Ensemble Simulation with Multi-SSTs and Multi-Physics

Akio KITOH\textsuperscript{1,2}, Hirokazu ENDO\textsuperscript{2}, Ryo Mizuta\textsuperscript{2}, Hideaki Kawai\textsuperscript{2} and Osamu Arakawa\textsuperscript{2}

\textsuperscript{1}Japan Meteorological Business Support Center, Tsukuba, Japan
\textsuperscript{2}Meteorological Research Institute, Tsukuba, Japan

From IPCC WGI AR5 Fig.14.24
Changes in the global monsoon by global warming

- Global monsoon precipitation is projected to increase due to increasing atmospheric moisture
Changes in the global monsoon by global warming

• Global monsoon precipitation is projected to increase due to increasing atmospheric moisture in spite of general weakening of the monsoon circulation.
Future change of the precipitation extremes

- Largest increases over the Asian monsoon domains
- Large increases in extremes over America and Africa

<table>
<thead>
<tr>
<th>Pav</th>
<th>SDII</th>
<th>R5d</th>
<th>CDD</th>
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<tbody>
<tr>
<td>EAS</td>
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<td>RCP4.5</td>
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<td>East Asia (EAS)</td>
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<tr>
<td>Pav</td>
<td>SDII</td>
<td>R5d</td>
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<td>N. America (NAM)</td>
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<td>N. Africa (NAF)</td>
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<td>S. Asia (SAS)</td>
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<td>S. America (SAM)</td>
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<td>S. Africa (SAF)</td>
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<td>Australia (AUS)</td>
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</table>

Kitoh et al. (2013 JGR)
Changes in the Asian monsoon by global warming

The Asian monsoon regions has larger increase in rainfall compared to other monsoon regions, due to less dynamical weakening (Endo and Kitoh 2014).

- South Asian westerlies weaken with strengthening in subtropical regions (Ogata et al. 2014).
- East Asian south-westerlies strengthen.

More, Endo and Kitoh (2017 submitted)
Toward high-resolution models

- Skill of CMIP models varies in reproducing the precipitation distribution
- High-resolution models better reproduce precipitation
- Weather extremes (e.g., tropical cyclones)

Dependence of model skill of MRI-AGCM3.2 models (color) and 24 CMIP5 atmospheric models (black). Skill measure is the spatial correlation coefficient between the GPCP 1DD and models over the globe for annual mean precipitation.

Kusunoki (2017 Atmosphere)
MRI-AGCM (60km, 20km) + NHRCM (5km, 2km)

Study of Future Change in Extreme Events
- Tropical Cyclones (e.g. Oouchi et al., Murakami et al.) → less number, more intense
- East Asia Monsoon (e.g. Kusunoki et al.) → seasonal migration delayed
- Extreme Rainfall (e.g. Kamiguchi et al.) → more frequent
- Blockings (e.g. Matsueda et al.) → less frequent
- Extratropical Cyclones (e.g. Mizuta et al.)

Impact Assessments
- Disasters
- Agriculture
- Water Resources

Regional Climate Change
- Outputs provided to researchers of each region
  (Korea, China, Taiwan, Philippines, Thailand, Indonesia, Viet Nam, Bangladesh, India, Israel, Saudi Arabia, Senegal, Spain, Netherlands, UK, Ireland, Denmark, Switzerland, Germany, USA, Mexico, Columbia, Barbados, Belize, Bolivia, Peru, Ecuador, Brazil, Argentina, Australia, Papua New Guinea)

Kitoh, Ose and Takayabu (2016 JMSJ)
Why we adopted this approach

- Current skill of CMIP model is not enough to downscale for adaptation studies
  - SST bias
  - circulation bias
- Trade-off between bias and on/off of air-sea interaction is an issue for climate change projection

Kitoh, Ose and Takayabu (2016 JMSJ)
MRI-AGCM3.2 experiment design

- 20km-mesh AGCM: 4 projections
  - 4 different ΔSST patterns

- 60km mesh AGCMs: 12 projections
  - 4 different ΔSST patterns
  - 3 different cumulus schemes

ΔSST: based on CMIP5-AOGCM projections (RCP8.5 scenario) (Mizuta et al. 2014)

<table>
<thead>
<tr>
<th>Duration</th>
<th>SST</th>
<th>Cumulus convection scheme</th>
<th>Yoshimura (YS)</th>
<th>Arakawa-Schubert (AS)</th>
<th>Kain-Fritsch (KF)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Present 1984-2003</td>
<td>Observation</td>
<td>SPA, SPA_m01, HPA, HPA_m02</td>
<td></td>
<td>HPA, HPA_m02, HPA_as, HPA_as_m02</td>
<td>HPA_kf, HPA_kf_m02</td>
</tr>
<tr>
<td>Future 2080-2099</td>
<td>All</td>
<td>SFA_rcp85, HFA_rcp85</td>
<td>HFA_rcp85</td>
<td>HFA_as_rcp85</td>
<td>HFA_kf_rcp85</td>
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<tr>
<td></td>
<td>Cluster 1</td>
<td>SFA_rcp85_c1, HFA_rcp85_c1</td>
<td>HFA_as_rcp85_c1</td>
<td>HFA_as_rcp85_c1</td>
<td>HFA_kf_rcp85_c1</td>
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<tr>
<td></td>
<td>Cluster 2</td>
<td>SFA_rcp85_c2, HFA_rcp85_c2</td>
<td>HFA_as_rcp85_c2</td>
<td>HFA_as_rcp85_c2</td>
<td>HFA_kf_rcp85_c2</td>
</tr>
<tr>
<td></td>
<td>Cluster 3</td>
<td>SFA_rcp85_c3, HFA_rcp85_c3</td>
<td>HFA_as_rcp85_c3</td>
<td>HFA_as_rcp85_c3</td>
<td>HFA_kf_rcp85_c3</td>
</tr>
</tbody>
</table>

20km 60km (use this data in this study)
Performance of global-scale monsoon precipitation

Monsoon metrics (B. Wang et al. 2011)
- **AM**: annual mean
- **AC1**: summer - winter
- **AC2**: spring - autumn
- **MPI**: seasonal difference divided by annual mean

Area: 45S-45N
Ref.: (GPCP+CMAP)/2
Performance of regional precipitation extremes

- **Pav**: all models reproduce well
- **Precipitation extremes** (Rx5d, Rx1d): YS and KF schemes reproduce well
Future changes in Pav and Rx5d

On a broad scale, the projection indicates the “wet-gets-wetter” pattern and “dry-gets-drier” pattern. The “warmer-gets-wetter” pattern is found over the tropical oceanic regions.

Rx5d similar to Pav, but with larger area in positive changes. A significant increase of Rx5d is found over the land monsoon regions.
Future percentage changes in precipitation indices over the land monsoon regions

- **Pav**: increase in almost all regions. Large increase rate in EAS. Large scatter in AUSMC
- **Rx5d/Rx1d**: increase in all regions. Larger increase rate than Pav.
Two-way ANOVA for summer season

- **SST** is responsible for the uncertainty of precipitation amount over the tropical Pacific.
- **Cumulus** is responsible for the uncertainty of precipitation amount and extremes over most monsoon regions.
MRI-AGCM vs CMIP5 AOGCM

- Global scale: 20/60km-AGCM agree well with CMIP5 MME
- Northwestern Pacific: Different sign between 20/60km-AGCM and CMIP5 MME

Pav (May-Sep)
- Normalized by global mean ΔSAT
- Hatch: same sign more than 80%

Pav (Nov-Mar)

Rx1d

[mm/d/K]
Large ensemble future climate simulation
Database for Policy Decision-making for Future climate change (d4PDF)

6000 years for present and 5400 years for future
60-km mesh MRI-AGCM3.2

- **present experiment**
  - 60 years (1951-2010) x 100 members
- **4K warmer experiment**
  - 60 years under a 4K warmer climate than pre-industrial climate
  - SST: observed SST (detrend) + CMIP5 AOGCMs ΔSST
  - GHG/Aerosol/Ozone: 2090 year level based on the RCP8.5 scenario
  - **90 member ensemble**
    - 6 types of ΔSST patterns
    - 15 different atmospheric initial condition / SST perturbation
      → $6 \times 15 = 90$ members

(Mizuta et al. 2017 BAMS)

Also Kusunoki’s talk this morning
Rx1d and tropical cyclone (TC)-associated Rx1d

- High-resolution MRI-AGCM reproduces tropical cyclones and associated precipitation

**OBS: TRMM 1998–2012**
**MRI–AGCM: 60km, 6000 yr**

OBS (TRMM)
- ALL: large over the NW Pacific and Bay of Bengal, then ITCZ and SPCZ
- TC: similar to TC distribution, maximum over the NW Pacific 10N-25N, then NE Pacific off Mexico

MRI-AGCM
- Reproduces observed spatial distribution and strength, although underestimation over North Atlantic and NE Pacific
- 20-km mesh model closer to the observation (Kitoh and Endo 2016 SOLA)

**TRMM**

**60-km mesh MRI-AGCM**

Precipitation

TC-associated precipitation
within 500km from TC center
Rx1d and tropical cyclone (TC)-associated Rx1d decrease in the western North Pacific due to TC frequency decrease.

ref. Kitoh and Endo (2016 SOLA)
Future changes of (top) Rx1d and (bottom) TC-associated Rx1d (left) 50%-ile, (middle) 90%-ile, (right) 99%-ile

Over the northwestern tropical Pacific, median value of TC-associated Rx1d decreases, but its 90/99%-ile value increases around Japan
Summary

- MRI-AGCM3.2 with 60-km grid shows high performance in simulating monsoon mean and extreme precipitation, with some dependency on the choice of convection scheme for extreme precipitation.

- In a warmer climate, extreme precipitation is projected to increase with higher rates than mean precipitation, except some regions around the western tropical Pacific. The latter is due to decreasing frequency of tropical cyclones (TC). However, interannual variability and extremes of R1d will increase.

- The ensemble projections with multi-SSTs and multi-physics show that the projected uncertainties mainly come from the choice of cumulus scheme in most monsoon regions, including the Asian monsoon region, with an exception of the Australian-Maritime Continent where the SST pattern is the major source.

- Role of TC is large in changes of precipitation extremes for some regions. Thus model’s ability in simulating TC is important.
High resolution (~100km) (Kusunoki and Arakawa, 2015, Table 1)
The SST spread in the experiment is similar to the spread of CMIP5 models.
Comparison between RCP8.5 SST and SRES A1B SST

With larger warming (RCP8.5 > SRES A1B), cumulus scheme effect becomes larger.