Uncertainties in future changes in tropical cyclone activity projected by multi-physics and multi-SST ensemble experiments

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Murakami et al. (2012, Clim. Dyn.)
Outline

- Motivation
- Methodology for multi-physics and multi-SST ensemble experiments
- Results
- Summary
Motivation

Uncertainty due to prescribed SSTs

Emanuel et al. (2008, *BAMS*)
Different future SST causes different sign of projected changes in TC genesis number in a specific basin.

Uncertainty due to model physics

Murakami et al. (2012, *J. Climate*)
Different cumulus convection scheme causes different sign of projected changes in TC frequency of occurrence in a specific basin.

Which of SST or cumulus convection scheme causes uncertainty largely?
A key factor is to derive robust signals across different exp. settings.
Multi-model & Multi-SST Ensemble Projections using 60-km-mesh model

- Using 60-km-mesh MRI-AGCM, 12 ensemble future (2075-2099) experiments were conducted.

\[3 \text{ (cumulus)} \times 4 \text{ (SST)} = 12 \text{ ensemble experiments}\]

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Cumulus Convection Scheme</th>
<th>Prescribed Future SST</th>
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<tr>
<td>Y0</td>
<td>Yoshimura Scheme (YS)</td>
<td>18 CMIP3 Models Ensemble Mean</td>
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<tr>
<td>Y1</td>
<td>Yoshimura Scheme (YS)</td>
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<tr>
<td>YG</td>
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<td>1.83K uniform warming</td>
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### Three types of physics used for multi-physics exp.

<table>
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<tr>
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<th>MRI-AGCM 3.2 AS</th>
<th>MRI-AGCM 3.2 KF</th>
<th>MRI-AGCM 3.2 YS</th>
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<tr>
<td><strong>Horizontal resolution</strong></td>
<td></td>
<td></td>
<td><strong>$T_L 319$ (60km)</strong></td>
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<td><strong>Vertical resolution</strong></td>
<td></td>
<td></td>
<td><strong>64 levels (top at 0.01hPa)</strong></td>
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<tr>
<td><strong>Time integration</strong></td>
<td></td>
<td>Semi–Lagrangian</td>
<td></td>
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<tr>
<td><strong>Time step</strong></td>
<td></td>
<td></td>
<td><strong>20 minutes</strong></td>
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<td><strong>Cumulus convection</strong></td>
<td><strong>Prognostic Arakara–Schubert</strong></td>
<td><strong>Kain–Fritsch</strong></td>
<td><strong>Yoshimura (Tiedtke–based)</strong></td>
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<tr>
<td><strong>Cloud</strong></td>
<td></td>
<td></td>
<td><strong>Tiedtke (1993)</strong></td>
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<td><strong>Radiation</strong></td>
<td></td>
<td><strong>JMA (2007)</strong></td>
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<td><strong>GWD</strong></td>
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<td></td>
<td><strong>Iwasaki et al. (1989)</strong></td>
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<td><strong>Land surface</strong></td>
<td><strong>SiB ver0109 (Hirai et al.2007)</strong></td>
<td><strong>MellorYamada Level2</strong></td>
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<td><strong>Aerosol (direct)</strong></td>
<td></td>
<td></td>
<td><strong>5 species</strong></td>
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<tr>
<td><strong>Aerosol (indirect)</strong></td>
<td></td>
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</table>
Multiple convective updrafts with different heights depending on entrainment rates explicitly calculated.

Only a single convective updraft but represented as a more derailed entraining and detraining plume.

Two Tiedtke-type updrafts are calculated. Updrafts between min. and max. rates are assumed to be continuously present.

Temperature, water vapor mixing ratio, entrainment rate etc. are obtained by linear interpolation between the two. Multiple updrafts with different heights are represented.
Time Slice Experiments

CMIP3 CGCMs

60km AGCM

Observed SST (AMIP-type)

Obs + Projected SST change (A1B)
Multi-SST Ensemble Projections

Fractional SST change relative to tropical mean change in CMIP3 models under A1B scenario.
Cluster 1 shows small spatial variance in tropics, while Cluster 3 SST shows large spatial variance in tropics.
Performance of control simulations

The YS and KF simulates reasonable TC global distribution, whereas AS has pronounced biases.
Future changes in TC number [%]

Y: Yoshimura, K: Kain-Fritsch, A: Arakawa Shubert
0: CMIP3 mean SST, 1: Cluster 1, 2: Cluster 2, 3: Cluster 3, G: Global uniform

Statistically significant decreases in global and hemispheric scales (by about 3-35%).

Generally, statistically significant decreases in the WNP, SIC, and SPO.

Difference in SST causes larger variances rather than model physics.
Future changes in TC frequency of occurrence and TC genesis frequency

Cross mark indicates that the difference is statistically significant at the 90% confidence level or above and more than 10 experiments show the same sign of mean change.

Consistent decrease in the WNP

Consistent decrease in the SIO and SPO.

Consistent increase in the central Pacific.
Future changes in TC genesis frequency and SST anom.

Ensemble mean of future changes in tropical cyclone genesis frequency (TGF, shading) and sea surface temperature anomaly ($S_a$, contours) [K] relative to tropical (30°S-30°N) mean. Locations where $S_a$ increases substantially show large increases in TC genesis frequency as well.
Future changes in TC genesis frequency and SST anom.

Ensemble mean of future changes in tropical cyclone genesis frequency (TGF, shading) [number/25-year] and sea surface temperature anomaly ($S_a$, contours) [K] relative to tropical (30°S-30°N) mean.

Projected future changes in TC genesis frequency are relatively independent of the chosen cumulus convection scheme.
A two-way analysis of variance (ANOVA)

\[ \sum_{i=1}^{a} \sum_{j=1}^{b} (X_{ij} - \overline{X}_.)^2 = b \sum_{i=1}^{a} (\overline{X}_i - \overline{X}_.)^2 + a \sum_{j=1}^{b} (\overline{X}_j - \overline{X}_.)^2 + \sum_{i=1}^{a} \sum_{j=1}^{b} (X_{ij} - \overline{X}_i - \overline{X}_j + \overline{X}_.)^2 \]

All variance = Variance by diff. in SST + Variance by diff. in convection schemes + Residual

- Difference in SSTs causes substantial inter-experimental variance in projected changes in TC genesis number.
- North Indian Ocean, North Atlantic, and South Pacific show substantial variance caused by difference in the cumulus convection schemes.
In order to evaluate uncertainties, we conducted multi-SST and multi-model ensemble projections.

(a) Every ensemble simulation commonly shows decrease in global and hemispheric TC genesis numbers by about 5-35% under the global warming environment regardless of the difference in model cumulus convection schemes and prescribed SSTs.

(b) All experiments tend to project future decreases in the number of TCs in the western North Pacific (WNP), South Indian Ocean (SIO), and South Pacific Ocean (SPO), whereas they commonly project increase in the central Pacific.

(c) Future changes in spatial distribution of SST are major source of uncertainty in terms of future changes in TC genesis. Further SST ensemble experiments may be necessary for minimizing uncertainty.
Thank you
Spatial variation in SST is a source of uncertainty in projecting future changes in TC genesis frequency through responses of dynamical factors. Further SST ensemble experiments are necessary to minimize those uncertainties.
Reference

Murakami, H., and co-authors, 2011: Future changes in tropical cyclone activity projected by the new high-resolution MRI-AGCM. *J. Climate, revised.*


Future changes in TC frequency and genesis frequency

Dynamic factors have high correlations, indicating these dynamic parameters are of primary importance for the future changes in TC genesis global distribution.
\[ MPI^2 = \frac{C_k}{C_D} \frac{T_s}{T_0} \left( CAPE^* - CAPE^b \right) \]

where \( C_k \) is the exchange coefficient for enthalpy, \( C_D \) is the drag coefficient, \( T_s \) is the SST (K), and \( T_0 \) is the mean outflow temperature (K). The quantity \( CAPE^* \) is the value of convective available potential energy (CAPE) of air lifted from saturation at sea level, with reference to the environmental sounding, and \( CAPE^b \) is that of the boundary layer air. Both quantities are evaluated near the radius of maximum wind which is theoretically determined.
In recent years, TCs become more active.

- Hurricane activity in the North Atlantic (NA) showed an increase over the past 30 years.
  - Hurricane Katrina (2005): the most damaging storm in USA
  - Hurricane Rita (2005): the most intense (895 hPa) TC observed in the Gulf of Mexico
  - Hurricane Wilma (2005): the most intense (882 hPa) TC in NA

- Abnormal TC number in the western North Pacific in 2004.

- Typhoon Morakot in 2009 caused catastrophic damage in Kaohsiung in Taiwan.
Previous studies have proposed that these recent changes are due to global warming.

Emanuel, 2005; Anthes et al., 2006; Hoyos et al., 2006; Mann and Emanuel, 2006; Trenberth and Shea, 2006; Holland and Webster, 2007; Mann et al., 2007a; Mann et al., 2007b

However, this view has been challenged by the following points:

a) The observation before satellite era (before 1979) is not reliable.

Landsea et al., 2006; Landsea, 2007

b) Recent increases in the frequency of NA TCs are within the range of multi-decadal variability.

Pielke et al., 2006; Bell and Chelliah, 2006

c) Projectons by climate models are not reliable because the models are too coarse to resolve TC structures.

Goldenberg et al. 2001.

TC scale is 100–1000 km, while typical horizontal resolution of climate models is 100–300 km or coarser.
Asian summer monsoon (JJA mean)

Colors: Precipitation
Arrows: 850hPa wind
Contours: Thickness(200-500hPa)

Prev Model
20km25years

OBS (JRA + CMAP)

New Model
20km25years

Prev Model
20km25years

diff from OBS
Skill score of 25-year climatology

Skill Score by Taylor (2001)

σ: standard deviation (model/obs), R: correlation coefficient

<table>
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<th>Region</th>
<th>Variable</th>
<th>Region</th>
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<td>CMAP Global</td>
<td>Precip</td>
<td>GPCP Global</td>
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<td>Z500</td>
<td>JRA25 Global</td>
<td>SLP</td>
<td>JRA25 Global</td>
</tr>
<tr>
<td>T850</td>
<td>JRA25 Global</td>
<td>U850</td>
<td>JRA25 Global</td>
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<td>U200</td>
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<td>V200</td>
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<td>T850</td>
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</table>

Better at New Model
Better at Prev Model
**How to prescribe SST**

**Present SST**
- **Observed SST 1979~2003**
- **AR4_20thCentury Exp. SST -2001**

**Future SST**
- **CMIP3 SST change**
  - **CMIP3 SST Trend 2075-2099**

**Inter-annual variability of Observed SST**
- **1979-2003**

**Mizuta et.al (2008)**

**CMIP3 ensemble mean SST under the A1B Scenario Experiment**

\[ \Delta SST = \text{Present SST} + \text{Future SST} \]

\[ \Delta SST = \text{Mean SST(2075-2099)} - \text{Mean SST(1979-2003)} \]
How to prescribe SST

Present SST

Observed SST 1979~2003

AR4_20thCentury Exp. SST -2001

Future SST

CMIP3 SST change

CMIP3 SST Trend 2075-2099

Inter-annual variability of Observed SST 1979-2003

\[ \Delta SST = \text{Mean SST}(2075-2099) - \text{Mean SST}(1979-2003) \]

ΔSST

Also applies for 2015-2039

Mizuta et al. (2008)
1) For each CMIP3 model, a mean future change in SST is computed by subtracting the 1979-2003 mean SST from the 2075-2099 mean SST.

2) The computed mean future change in SST is normalised by dividing by the tropical mean (30°S-30°N) future change in SST.

3) The normalised value for each model is subtracted from the multi-model ensemble mean of the normalised value.

4) The inter-model pattern correlation $r$ of the normalised values is computed between each pair of models.

5) Norms (or distances) are defined as $2 \times (1 - r)$ for each model, and the cluster analysis is performed using these norms.

6) When the final three groups are bounded, the clustering procedure is terminated.
Factors responsible for Inter-experiment differences

Difference in dynamical parameters are highly correlated with TGF difference among the experiments in the WNP, ENP, and SIO, indicating the difference in future changes in dynamical parameters are primary source of uncertainty.

The experiments with identical prescribed SSTs are eccentrically located in the panels, indicating that the dynamical parameters are more heavily influenced by differences in the SST spatial patterns.
Factors responsible for Inter-experiment differences

Y: YS, K: KF, A: AS, black: CMIP3 mean, blue:C1, green:C2, red:C3
Factors responsible for Inter-experiment differences

<table>
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<tr>
<th></th>
<th>$\delta S_a$</th>
<th>$\delta RH$</th>
<th>$\delta V_{pot}$</th>
<th>$-\delta \chi$</th>
<th>$-\delta \Gamma_d$</th>
<th>$\delta \eta_{850}$</th>
<th>$-\delta V_s$</th>
<th>$-\delta V_{zs}$</th>
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<td>0.15</td>
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<td>-0.66</td>
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<td>0.64</td>
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<td>-0.42</td>
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Dynamic factors have high correlations, indicating these dynamic parameters are of primary importance for the inter-experimental differences.