Patterns of temperature change and tropical precipitation/cyclones

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Summary

• Substantial progress has been made describing, understanding and attributing multi-decadal changes in global mean surface temperature.

• However, for regional tropical precipitation and tropical cyclones the “patterns” of temperature change may be more relevant:
  - Patterns in space: SST change relative to tropical-mean key to tropical precip and cyclone response
  - Patterns in height/depth (stability and stratification changes)
  - Patterns in time (multi-year to decadal changes)
Global temperatures have shown clear long-term increase (seen in other datasets, CRU, GISS, etc).

GCMs have exhibited skill in recovering these century-scale changes.
On monthly and regional scales, changes have been more nuanced.
Observed hurricane changes: uncertain, not monotonic & spatially heterogeneous

The rough pattern of changes in the spatial structure of hurricane activity (and the impact of a storm count adjustment on these changes) resembles that described in VK08 for tropical storms.

c. Relationships between indices

In this section, we explore relationships between various measures of Atlantic hurricane activity and between those measures and several SST indices. Figure 5 visually summarizes the relationships between global and tropical Atlantic SSTs and a series of tropical storm and hurricane frequency indices (unadjusted and adjusted basinwide and U.S. landfalling). All time series have been smoothed with a 5-yr running mean and then normalized to have unit standard deviation.

The SST indices we examine include SSTs averaged over the Atlantic main development region (MDR, 10°–20°N, 80°–20°W), which we refer to here as "absolute SST," which has been found to exhibit a correlation with measures of basinwide Atlantic tropical cyclone activity (e.g., Mann and Emanuel 2006; Emanuel 2007; Holland and Webster 2007; Mann et al. 2007; Vecchi et al. 2008).

In addition, we explore SSTs in the MDR minus the SSTs averaged over the global tropics (30°S–30°N), which we refer to as "relative SST." Relative SST appears to strongly influence large-scale climate conditions that impact hurricane activity (e.g., Latif et al. 2007; Vecchi and Soden 2007a). It also exhibits a statistical connection to measures of Atlantic basinwide tropical cyclone activity (e.g., Swanson 2008; Vecchi et al. 2008; Villarini et al. 2010). Furthermore, it has been found to describe the response of Atlantic hurricane frequency to anthropogenic warming in high-resolution dynamical model experiments (e.g., Knutson et al. 2008; Zhao et al. 2009, 2010; Vecchi et al. 2011).

The multiyear variability of the various storm frequency measures shown in Fig. 5 is similar, yet the century-scale trends differ. The unadjusted basinwide frequency indices (blue) show significant increases, and a relationship to absolute MDR SST (though the period of enhanced frequency in the late nineteenth century is apparently not accompanied by warm Atlantic SSTs). Meanwhile, the various adjusted storm frequency indices (red) do not show significant increases, and their behavior is more similar to the U.S. landfalling counts (yellow) and to relative SST (bottom time series). While neither the absolute nor the relative SST index shows a strong maximum like that in hurricane counts at the end of the nineteenth century.

Vecchi and Knutson (2011, J. Climate)
21st Century response of TC frequency in single 50km global atmospheric model forced by four projections: uncertain, heterogeneous.

Regional increase/decrease much larger than global-mean.

Pattern depends on details of ocean temperature change.

Sensitivity of response seen in many studies

e.g., Emanuel et al 2008, Knutson et al 2008, etc

Red/yellow = increase
Blue/green = decrease

Adapted from Zhao et al. (2009, J. Climate)
Long-term SST trends in Tropical Pacific Uncertain

Linear trends (1880-2005) in four SST estimates.

Overall warming seen in all. Structure dependent on reconstruction.

Adapted from Vecchi, Clement and Soden (2008, EOS)
Data infilling leads to differences in east Pacific SST trends

Deser et al. (2010, GRL)
GFDL GCM precipitation response to 2xCO2 and 2°C Uniform Warming

Shade: Precip response to 2xCO2
Contour: SST change minus tropical-mean

Xie et al. (2009, J. Clim.)
Free tropospheric temperature changes relatively uniform ("Weak Temperature Gradient" Hypothesis, Sobel et al 2001); changes in stability follow surface temperature changes relative to tropical-mean.

Fig. A1. Annual-mean change in CM2.1 A1B: (a) 300-hPa temperature (shading > 2.75 K) and (b) gross convective instability $I_M/c_p$ (shading > 2 K).

Xie et al. (2009, J. Clim.)
“Threshold” for strong precipitation seems to follow tropical-mean SST in obs. and models

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**Observed**
- Tropical mean SST
- SST threshold estimate ($P = 2$ mm d$^{-1}$)
- SST threshold estimate (linear $P$ fit)

**GCM Response**

<table>
<thead>
<tr>
<th>Rainfall rate (mm d$^{-1}$)</th>
<th>SST deviation from tropical mean (°C)</th>
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<tbody>
<tr>
<td>0</td>
<td>-8</td>
</tr>
<tr>
<td>5</td>
<td>-6</td>
</tr>
<tr>
<td>10</td>
<td>-4</td>
</tr>
<tr>
<td>0</td>
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<td>0</td>
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<tr>
<td>10</td>
<td>2</td>
</tr>
<tr>
<td>20</td>
<td>4</td>
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</tbody>
</table>

**Figure 3** | Twenty-first-century changes in rainfall rate and SST frequency distributions. **a, b**, Ensemble mean rainfall rate as a function of SST (**a**) and SST frequency distribution (**b**) for 2001–2020 (blue, solid) and 2081–2100 (red, dashed) for the ten CMIP3 models of Fig. 2. SST is expressed as the deviation from the 20-year tropical mean.

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*Johnson and Xie (2010, Nature Geosci.)*
Response to 2xCO2 of models of different resolution:
- CM2.1 (1°Ocn, 2.5°Atm)
- CM2.5 (0.25°Ocn, 0.5°Atm)

Surface Temperature

Precipitation

Delworth et al. (2011, J. Clim.)
Delworth et al. (2011, J. Clim.)
For related reasons tropical cyclone potential intensity tracks SST relative to tropical-mean, not local SST*

*global-mean PI changes still need to be explained.

Vecchi and Soden (2007, Nature)
Modeled “threshold” for hurricane genesis also depends on tropical-mean SST

Knutson et al. (2008, Nature Geosci.)
Dynamical Models Exhibit Consistent Relationship To Large-Scale Through Statistical Model - All consistent with observations

Villarini et al. (2011, J. Clim. in press)
Statistical Projections of 21st Century NA TS Trends

Sources of uncertainty for relative SST change different from those to regional or global SST change

Uncertainties arising from differences in model response to forcing other key source of uncertainty for coming decades (whole century for TS’s)

Because modeled hurricane counts depend on relative SST, trends sensitive to forcing used even over satellite SST era

Tropical storm frequency response to same AGCM but different estimates of observed SST

HadISST forced

NOAA-OI.v2 forced

AGCM is 100km version of Zhao et al (2009, J. Clim.)

Vecchi et al (2011, in prep.)

How do we confidently evaluate model skill in this context?
Vertical changes

Changes in atmospheric stability impact potential intensity. Uncertainty in past changes to upper tropospheric temperature limit confidence in past (and future) PI changes.

Ocean near-surface thermal stratification key control on intensity of strongest cyclones. How does it change?
PI Impact of swapping NCEP T-Trend with HiRAM T-Trend

- Mid-lower troposphere (p > 300 hPa)
- Upper troposphere (150 hPa, 300 hPa)
- Tropopause layer (70 hPa - 150 hPa)

No impact from 70 hPa and above
Do we know vertical structure of warming well enough?
Relatively small inter-model TA trend spread still gives large \(<\text{PT}\rangle\) spread (±2m/s)

For now: assume GCM lapse rate response “reasonable” estimate?

Intensity of most intense hurricanes impacted by ocean stratification

Ocean cooling following tropical cyclones has non-monotonic relationship to intensity, indicating ocean influence.

Strongest hurricanes tend to occur over water with light stratification (deep mixed layer).

Lloyd and Vecchi (2010, J. Climate)
MLD should decrease in mean from CO2, but what about regional patterns?

Changes in circulation can lead to local thermocline deepening

Vecchi and Soden (2007, J. Clim.)

Thermodynamically-driven shoaling of mean mixed-layer

Lloyd (2011, PhD Thesis)
Summary

• For regional tropical precipitation and tropical cyclones the “patterns” of temperature change may be more relevant:
  - Patterns in space: SST change relative to tropical-mean key to tropical precip and cyclone response
  - Patterns in height/depth (atmospheric stability and ocean stratification changes)
  - Patterns in time (multi-year to decadal changes)

• The past character of “patterns” of change is less well known.

• The potential mechanisms impacting “patterns” more varied (redistribution, non-uniform radiative forcing, non-uniform response to uniform forcing, etc.)
Regional changes important to global mean: Cloud Feedbacks

Soden and Vecchi (2011, GRL)
Differences in HiRAM/NCEP Tropical-mean lapse rate rate trends largely explain differences in 1982-2006 potential intensity trends.
On multi-decadal and shorter timescales internal variability can dominate Walker Circulation changes.

<table>
<thead>
<tr>
<th>Length of record over which $\Delta$SLP trend is computed (Years)</th>
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<tr>
<td>30</td>
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<td>3</td>
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LEGEND
- **CM2.1 5-member ensemble-mean (1861-2000)**
- **Observations**
  - Kaplan (1854-1992)
  - Hadley (1871-1998)
  - Kaplan/Hadley/NCEP Blend (1854-2003)

Linear trend value (Pa·year$^{-1}$)

$\Delta$SLP linear trend (two-sided)

$p$-value of $\Delta$SLP linear trend (two-sided)

Zoom area (lower panel)
Both absolute an relative SST consistent with recent hurricane changes, only relative SST consistent with dynamical models (e.g., Vecchi et al. 2008, Villarini et al. 2011) and homogenized century scale hurricane records (Villarini et al. 2010).