Potential Climate Surprises: Compound Extremes and Tipping Elements

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Climate Science Special Report

Fourth National Climate Assessment (NCA4), Volume I

This report is an authoritative assessment of the science of climate change, with a focus on the United States. It represents the first of two volumes of the Fourth National Climate Assessment, mandated by the Global Change Research Act of 1990.
The report can be summarized in one sentence:

It’s real
It’s us
It’s serious
.. and the window of time to prevent widespread dangerous impacts is closing fast.
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Plus several Appendices

Risk Management Framework

New York City Panel on Climate Change, 2009
Greenhouse Gas Concentrations

- **Greenhouse Gases**
  - Carbon dioxide (CO2), Methane (CH4), Nitrous Oxide (N2O)
- Transparent to sunlight, but trap thermal radiation
- Long residence times

- **Recent Measurements**
  - Mauna Loa, Hawaii
Shifting Statistics of Extreme Events

What can a few degrees warmer do?

A small average change can have large effect on extremes

Very Likely Increase:

Days with Extreme Heat
The frequency and intensity of extreme heat and heavy precipitation events are increasing in most continental regions of the world.
“Nuisance Flooding”—flooding associated with high tides—is Increasing Across the United States
Sea level rise of just 2 feet, without any changes in storms, would more than triple the frequency of dangerous coastal flooding along much of the U.S. coast.
Risk Management Framework

![Risk Management Framework Diagram](image)

- **RED**: Risks for which adaptation strategies should be developed.
- **ORANGE**: Risks for which adaptation strategies may need to be developed or for which further information is needed.
- **YELLOW**: Risks for which impacts should be monitored but which may not need actions at this time.

New York City Panel on Climate Change, 2009
Greenhouse Gas Concentrations

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- **Recent Measurements**
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While climate models incorporate important climate processes that can be well quantified, they do not include all of the processes that can contribute to feedbacks, compound extreme events, and abrupt and/or irreversible changes. Future changes outside the range projected by climate models cannot be ruled out.

Moreover, the systematic tendency of climate models to underestimate temperature change during warm paleoclimates suggests that climate models are more likely to underestimate than overestimate the amount of long-term future change.
Potential Surprises

- Positive feedbacks (self-reinforcing cycles) within the climate system have the potential to accelerate human-induced climate change. Some feedbacks are probably still unknown.

- The physical and socioeconomic impacts of compound extreme events can be greater than the sum of the parts (very high confidence). Few analyses consider the spatial or temporal correlation between extreme events.

- Future changes outside the range projected by climate models cannot be ruled out (very high confidence).
Tipping Elements

K. Harrison, 2013, adapted from D. Wasdell, 2013
### Tipping Element Examples

#### Table 15.1: Potential tipping elements (adapted from Kopp et al. 2016\textsuperscript{11}).

<table>
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<tr>
<th>Candidate Climatic Tipping Element</th>
<th>State Shift</th>
<th>Main Impact Pathways</th>
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<td><strong>Atmosphere–ocean circulation</strong></td>
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<td>Atlantic meridional overturning circulation</td>
<td>Major reduction in strength</td>
<td>Regional temperature and precipitation; global mean temperature; regional sea level</td>
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<tr>
<td>El Niño–Southern Oscillation</td>
<td>Increase in amplitude</td>
<td>Regional temperature and precipitation</td>
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<td>Equatorial atmospheric superrotation</td>
<td>Initiation</td>
<td>Cloud cover; climate sensitivity</td>
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<tr>
<td>Regional North Atlantic Ocean convection</td>
<td>Major reduction in strength</td>
<td>Regional temperature and precipitation</td>
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<td><strong>Cryosphere</strong></td>
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<td>Antarctic Ice Sheet</td>
<td>Major decrease in ice volume</td>
<td>Sea level; albedo; freshwater forcing on ocean circulation</td>
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<tr>
<td>Arctic sea ice</td>
<td>Major decrease in summertime and/or perennial area</td>
<td>Regional temperature and precipitation; albedo</td>
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<tr>
<td>Greenland Ice Sheet</td>
<td>Major decrease in ice volume</td>
<td>Sea level; albedo; freshwater forcing on ocean circulation</td>
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<td><strong>Carbon cycle</strong></td>
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<td>Methane hydrates</td>
<td>Massive release of carbon</td>
<td>Greenhouse gas emissions</td>
</tr>
<tr>
<td>Permafrost carbon</td>
<td>Massive release of carbon</td>
<td>Greenhouse gas emissions</td>
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<td><strong>Ecosystem</strong></td>
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<td>Amazon rainforest</td>
<td>Dieback, transition to grasslands</td>
<td>Greenhouse gas emissions; biodiversity</td>
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<tr>
<td>Boreal forest</td>
<td>Dieback, transition to grasslands</td>
<td>Greenhouse gas emissions; albedo; biodiversity</td>
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<tr>
<td>Coral reefs</td>
<td>Die-off</td>
<td>Biodiversity</td>
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\textsuperscript{11} Reference to Kopp et al. (2016) for more detailed information on tipping elements in the cryosphere, carbon cycle, and ecosystems.
Global mean sea level has risen by about 7–8 inches (about 16–21 cm) since 1900, about 3 of those inches since 1993.

Emerging science on Antarctic ice sheet stability suggests that, for high scenarios, global mean sea level rise exceeding 8 feet by 2100 is physically possible, although the probability of such an extreme outcome cannot currently be assessed.
Marine Ice Sheet Instability (MISI) on Antarctica

ICE STREAM/GLACIER GROUNDED ON BEDROCK RIDGE; 2) WARM CIRCUMPOLAR DEEP WATER FLOWS INTO CAVITY, THINS ICE SHELF, MELTS GLACIER BASE AT GROUNDING LINE; 3) GROUNDING LINE RETREATS DOWNSLOPE, THINS ICE SHELF MORE, CAUSING GLACIER TO ACCELERATE FORWARD.

MODIFIED FROM BETHAN DAVIES, ANTARCTICGLACIERS.ORG
Ice Cliff Failure – Antarctica

CREDIT: DAVID POLLARD; ROBERT DECONTO
Hydrofracturing on Ice Sheet
Arctic Sea Ice Extent
(Area of ocean with at least 15% sea ice)
Ocean Ecosystems

Ocean acidification
- Lowered pH will dissolve calcium-based shells and skeletons

Coral Reefs
- **Require a narrow range of ocean temperatures**
- Require sea level to be at a certain level
- Cannot migrate and grow as fast as temperatures and depths will change
Fire and drought in the western states …
Drought

California Mean Winter Precipitation

Seager et al., Journal of Climate, 2015

Lake Oroville, August 19, 2014

http://www.cbsnews.com/pictures/californias-drought/
CALIFORNIA 3-YR MEAN ANNUAL TEMPERATURE

http://media.nbcwashington.com/images/1200*675/heatWave_80404600.jpg

Williams et al., Geophysical Research Letters, 2015
FUTURE SOIL MOISTURE
HIGH EMISSIONS SCENARIO

Cook et al., Science Advances, 2015
Ten Indicators of a Warming World

- Air Temperature Near Surface (Troposphere)
- Glaciers and Ice Sheets
- Snow Cover
- Temperature Over Land
- Sea Level
- Ocean Heat Content
- Temperature Over Oceans
- Sea Surface Temperature
- Sea Ice
- Water Vapor
Compound Extremes
Categories of Compound Extremes

- Multivariate
- Correlated through space
- Correlated through time
Temperature + Humidity

• The lowest temperature that can result from evaporative cooling = wet bulb temperature

• Max in recent heatwaves: 31°C

• Theoretical max for human tolerance: 35°C (Sherwood, Huber, 2010)

Coffel, E., R.M. Horton, and A. De Sherbinin, Population exposure to heat stress in the 21st century (in preparation)
Eastern US: 1-2 days per year

India: highest global risk, 3+ days per year and high population density
ENSO and maize yield variability

Tropical SST anomalies

Crop yield anomalies

Weston Anderson, 2018
Are there examples from your region of how a unique sequence of extreme weather/climate events has produced impacts (including perhaps changes in behavior), that are distinct from what would be expected if weather/climate events were considered in isolation?

June 2012 Derecho and Heatwave in Washington, DC.
Impact Surprises

Tuvalu - The Guardian – 05/16/2008, photo by Matthieu Paley/Corbis
Kennedy Space Center
Carbon Countdown

How many years of current emissions would use up the IPCC's carbon budgets for different levels of warming?
**Key Points**

- The statistics of many types of extreme events have already shifted in recent decades.

- As long as greenhouse gas concentrations rise, we expect to see an acceleration of many of these changes in extreme event statistics.

- The further we push the climate system, the greater the potential for surprises.

- Innovations in greenhouse gas mitigation, and adaptation, could also lead to surprises.
Solutions can be a tipping point as well.
Non-linear impact and adaptation relationships: heat and human health

Cumulative Relative Risk

Temperature °C

Petkova et al., 2014
Planned Berm and Park, Lower East Side, Manhattan, NY