The “warming hiatus”: A teachable moment

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American Meteorological Society Short Course, “Weather and Climate in Times of Change”

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Structure

- Introduction to the “warming hiatus”

- Possible causes of differences between modeled and observed temperature changes during the “warming hiatus” period:
  - Observational uncertainties
  - Natural internal variability
  - Model response errors
  - Model forcing errors

- Conclusions
“Global warming stopped in 1998”… True or false?

Source: Summary for Policymakers, IPCC Fifth Assessment Report (2013)
“…models have a strong tendency to over-warm the atmosphere relative to actual observations”. True or false?

Testimony of Prof. John R. Christy, House Committee on Natural Resources (May 13, 2015)
Claims that “models over-warm” have received high-level attention (I)

“Further confusing the policy debate, the models that scientists have come to rely on to make climate predictions have greatly overestimated warming. Contrary to model predictions, data released in October from the University of East Anglia’s Climate Research Unit show that global temperatures have held steady over the past 15 years, despite rising greenhouse gas emissions”

(Lamar Smith, Chairman of the House Committee on Science, Space, and Technology)

Claims that “models over-warm” have received high-level attention (II)

“My view actually is simple. Debates on this should follow science, and should follow data. And many of the alarmists on global warming, they’ve got a problem because the science doesn’t back them up”

“Satellite data demonstrate for the last 17 years there’s been zero warming — none whatsoever”

“…it wasn’t warming, but the computer models still say it is, except the satellites show it’s not”

Source: Senator Ted Cruz, “Late Night with Seth Meyers”, March 17, 2015
Claims that “models over-warm” have received high-level attention (II)

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Why is this issue important?

- In formal Congressional testimony, some scientists are claiming that:
  - Computer models have large errors in climate sensitivity
  - Observational temperature data “falsify” climate models

- If such claims were correct, they would undermine confidence in:
  - The reliability of computer model projections of 21st century climate change
  - The value of model projections for making public policy decisions
Why are temperature trends since 1998 larger in models than observations?

1. Errors in observations
   - In surface thermometer measurements
   - In satellite and radiosonde estimates of tropospheric temperature change

2. Natural internal variability (ENSO, PDO, AMO, IPO)

3. Climate model response errors
   - Overestimate of climate sensitivity ($\Delta T_{2\times CO_2}$)

4. Model errors in “negative forcings” (external cooling influences)
   - Volcanic aerosols
   - Solar irradiance
   - Particulate pollution (sulfate aerosols)
   - Stratospheric ozone depletion
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1a. Errors in surface temperature observations

Possible artifacts of data biases in the recent global surface warming hiatus

Thomas R. Karl,1* Anthony Arguez,1 Boyin Huang,1 Jay H. Lawrimore,1 James R. McMahon,2 Matthew J. Menne,1 Thomas C. Peterson,1 Russell S. Vose,1 Huai-Min Zhang1

1National Oceanographic and Atmospheric Administration (NOAA), National Centers for Environmental Information (NCEI), Asheville, NC 28801, USA. 2LMI, McLean, VA, USA.
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- “...central estimate for the rate of warming during the first 15 years of the 21st century is at least as great as the last half of the 20th century”

- “...results do not support the notion of a “slowdown” in the increase of global surface temperature”

Karl et al., Science (2015)
1a. Errors in surface temperature observations

Karl et al., Science (2015)
1a. Errors in surface temperature observations

![Graph showing temperature anomaly with and without corrections from 1880 to 2010.](image-url)

*Karl et al., Science (2015)*
1b. Errors in surface temperature observations

Coverage bias in the HadCRUT4 temperature series and its impact on recent temperature trends

Kevin Cowtan\textsuperscript{a*} and Robert G. Way\textsuperscript{b}
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\textsuperscript{b}Department of Geography, University of Ottawa, Canada

*Correspondence to: K. Cowtan, Department of Chemistry, University of York, York YO10 5DD, UK.
E-mail: kevin.cowtan@york.ac.uk

- “Incomplete global coverage is a potential source of bias in global temperature reconstructions…”
- “Coverage bias causes a cool bias in recent temperatures relative to the late 1990s”

1b. Errors in surface temperature observations

Temperature trends over January 1997 to December 2012 (°C/decade)
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1b. Errors in satellite-based temperature estimates

Measuring atmospheric temperature with Microwave Sounding Units

- Higher temperatures = more microwave emissions from O₂ molecules
- By choosing different microwave frequencies, temperatures of different atmospheric layers can be measured
1b. Errors in satellite-based temperature estimates

- TLS: Temperature of Lower Stratosphere
- TMT: Temperature of Mid- to Upper Troposphere
- TLT: Temperature of Lower Troposphere

Figure and text courtesy of Carl Mears
Remote Sensing Systems
1b. Errors in satellite-based temperature estimates

- Satellite-based estimates of tropospheric temperature change are not direct temperature measurements
- They are complex geophysical retrievals
- There are large uncertainties in these retrievals
1b. Errors in satellite-based temperature estimates

Effects of orbital decay on satellite-derived lower-tropospheric temperature trends

Frank J. Wentz & Matthias Schabel

Remote Sensing Systems, 438 First Street, Suite 200, Santa Rosa, California 95401, USA

- “...we identify an artificial cooling trend in the satellite-derived temperature series caused by previously neglected orbital-decay effects”

1b. Errors in satellite-based temperature estimates

The Effect of Diurnal Correction on Satellite-Derived Lower Tropospheric Temperature

Carl A. Mears and Frank J. Wentz

- “We have derived a diurnal correction that, in the tropics, is of the opposite sign from that previously applied”

- “…we find tropical warming consistent with that found at the surface and in our satellite-derived version of middle/upper tropospheric temperature”
“Large differences in tropical TMT trends between this work and that of the University of Alabama in Huntsville (UAH) are attributed to differences in the treatment of the NOAA-9 target factor and the diurnal cycle correction”
“As the satellite drifts over time, changes in the satellite-measured brightness temperature due to changes in the local sampling time can be much larger than the temperature change associated with the long-term climate change” (Po-Chedley et al., Journal of Climate, 2014)
1b. Errors in satellite-based temperature estimates

Mid- to upper tropospheric temperature trend in °C/decade over 1979 to 2012 (Po-Chedley et al., Journal of Climate, 2014)
1b. Errors in satellite-based temperature estimates

**Fig. 8.** Tropical (20°S–20°N) land (red), ocean (blue), and combined land–ocean (black) difference time series for NOAA, RSS, and UAH minus UW. A time series of $UW_{GCM}$ is also shown to understand the differences caused by diurnal cycle corrections (all other processing decisions are held constant between UW and $UW_{GCM}$). The time series are smoothed using a 5-month moving average.

Po-Chedley et al., Journal of Climate (2014)
1b. Errors in satellite-based temperature estimates

**Table 4.** T24 trends (K decade$^{-1}$) over 1979–2012 in the tropics (20°S–20°N) over land, ocean, and the entire tropical region, as derived from various MSU/AMSU datasets. The values in parentheses are the amplification ratio, which is defined here as the T24 trend divided by the HadCRUT4 surface trend. We compute T24 using T24 = 1.1TMT − 0.1TLS. The UW and UW$_{GCM}$ T24 trends are calculated using TMT from the present study and TLS from NOAA STAR v3.0 data.

<table>
<thead>
<tr>
<th>Group</th>
<th>Both</th>
<th>Ocean</th>
<th>Land</th>
</tr>
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<tbody>
<tr>
<td>UW</td>
<td>0.160</td>
<td>0.163</td>
<td>0.150</td>
</tr>
<tr>
<td>UW$_{GCM}$</td>
<td>0.170</td>
<td>0.179</td>
<td>0.141</td>
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<tr>
<td>NOAA</td>
<td>0.149</td>
<td>0.163</td>
<td>0.106</td>
</tr>
<tr>
<td>RSS</td>
<td>0.125</td>
<td>0.123</td>
<td>0.133</td>
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<tr>
<td>UAH</td>
<td>0.064</td>
<td>0.044</td>
<td>0.129</td>
</tr>
<tr>
<td>HadCRUT4</td>
<td>0.114</td>
<td>0.101</td>
<td>0.175</td>
</tr>
</tbody>
</table>

Po-Chedley et al., Journal of Climate (2014)
1b. Errors in satellite-based temperature estimates

Moist air rises as ocean surface warms

Moist air condenses and releases latent heat

Tropical ocean

Amplification of surface temperature change vs. Height above Earth’s surface (kilometers)
1b. Errors in satellite-based temperature estimates

**Table 4.** T24 trends (K decade⁻¹) over 1979–2012 in the tropics (20°S–20°N) over land, ocean, and the entire tropical region, as derived from various MSU/AMSU datasets. The values in parentheses are the **amplification ratio**, which is defined here as the T24 trend divided by the HadCRUT4 surface trend. We compute T24 using $T24 = 1.1TMT - 0.1TLS$. The UW and $UW_{GCM}$ T24 trends are calculated using TMT from the present study and TLS from NOAA STAR v3.0 data.

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<tr>
<td>UW</td>
<td>(1.41)</td>
<td>(1.62)</td>
<td>(0.86)</td>
</tr>
<tr>
<td>$UW_{GCM}$</td>
<td>(1.50)</td>
<td>(1.78)</td>
<td>(0.81)</td>
</tr>
<tr>
<td>NOAA</td>
<td>(1.32)</td>
<td>(1.62)</td>
<td>(0.61)</td>
</tr>
<tr>
<td>RSS</td>
<td>(1.10)</td>
<td>(1.22)</td>
<td>(0.76)</td>
</tr>
<tr>
<td>UAH</td>
<td>(0.56)</td>
<td>(0.44)</td>
<td>(0.73)</td>
</tr>
<tr>
<td>HadCRUT4</td>
<td></td>
<td></td>
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</tr>
</tbody>
</table>
1c. Errors in radiosonde-based temperature estimates

- Radiosonde-based estimates of tropospheric temperature change also have large uncertainties

- Radiosonde atmospheric temperature measurements are not an unambiguous “gold standard” for evaluating the quality of different satellite temperature estimates

Sherwood et al., Science (2005)
1c. Errors in radiosonde-based temperature estimates

Atmospheric changes through 2012 as shown by iteratively homogenized radiosonde temperature and wind data (IUKv2)

Steven C Sherwood and Nidhi Nishant

- “...tropical warming is equally strong over both the 1959–2012 and 1979–2012 periods, increasing smoothly and almost moist-adiabatically from the surface (where it is roughly 0.14 K/decade) to 300 hPa (where it is about 0.25 K/decade over both periods), a pattern very close to that in climate model predictions”

- “...contradicts suggestions that atmospheric warming has slowed in recent decades or that it has not kept up with that at the surface”
Figure 3. Time evolution of temperature in three latitude bands. (Symbols) troposphere (simple mean of mandatory levels from 850 to 300 hPa inclusive) averaged over ‘good’ stations in three latitude bands, separated by 30S and 30N latitude boundaries. (Line) mean surface temperature from the HadCRUT4 (Moricc et al 2012) dataset. ‘Good’ stations are defined as those whose temperature trend (1958–2012) is no more than two standard deviations away from the median for stations in that latitude band.
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   - Stratospheric ozone depletion
2. Natural internal variability: General issues

Is the climate warming or cooling?
David R. Easterling\(^1\) and Michael F. Wehner\(^2\)

- “We show that the climate over the 21\(^{st}\) century can and likely will produce periods of a decade or two where the globally averaged surface air temperature shows no trend or even slight cooling in the presence of longer-term warming”

Easterling and Wehner, Geophysical Research Letters (2009)
2. Natural internal variability: General issues

Figure 2. One realization of the globally averaged surface air temperature from the ECHAM5 coupled climate model forced with the SRES A2 greenhouse gas increase scenario for the 21st century.

Easterling and Wehner, Geophysical Research Letters (2009)
Because of the pronounced effect of interannual noise on decadal trends, a multi-model ensemble of anthropogenically-forced simulations displays many 10-year periods with little warming. A single decade of observational TLT data is therefore inadequate for identifying a slowly evolving anthropogenic warming signal.”
Signal-to-noise ratios: Comparing the size of observed changes in tropospheric temperature relative to internal variability

Santer et al., Journal of Geophysical Research (2011)
Recent global-warming hiatus tied to equatorial Pacific surface cooling

Yu Kosaka¹ & Shang-Ping Xie¹,²,³

“Our results show that the current hiatus is part of natural climate variability, tied specifically to a La Niña-like decadal cooling”

Kosaka and Xie, Nature (2013)
“In addition to the shallow La Niña–like patterns in the Pacific that were the previous focus, we found that the slowdown is mainly caused by heat transported to deeper layers in the Atlantic and the Southern oceans, initiated by a recurrent salinity anomaly in the subpolar North Atlantic”
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3. Model response errors

“On average, models warm the global atmosphere at a rate three times that of the real world”
Testimony of Prof. John R. Christy, House Committee on Natural Resources (May 13, 2015)
Prof. Christy has made similar “model response error” claims in previous testimony

- “This evidence strongly suggests that climate model simulations on average are simply too sensitive to increasing greenhouse gases and thus overstate the warming of the climate system…”

- “This is an example of a model simulation (i.e., hypothesis) which can provide a prediction to test: that prediction being the rate at which the Earth’s atmosphere should be warming in the current era.”

- “In this case, the model-average rate of warming fails the test.”
What might be the consequences of a fundamental model error in climate sensitivity?

We would expect to see errors in the temperature response to large volcanic eruptions (Santer et al., Nature Geoscience 2014)
What might be the consequences of a fundamental model error in climate sensitivity?

In the tropics, we would expect to see errors in tropospheric amplification of surface warming that were consistent across multiple timescales (Santer et al., Science, 2005)
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4. Model forcing errors

The Persistently Variable “Background” Stratospheric Aerosol Layer and Global Climate Change


- “…the ‘background’ stratospheric aerosol layer is persistently variable rather than constant, even in the absence of major volcanic eruptions”
- “…independent data sets show that stratospheric aerosols have increased in abundance since 2000”
- “Near-global satellite aerosol data imply a negative radiative forcing due to stratospheric aerosol changes over this period of about –0.1 watt per square meter, reducing the recent global warming that would otherwise have occurred”
4. Model forcing errors

Volcanic contribution to decadal changes in tropospheric temperature

Benjamin D. Santer\(^1\)*, Céline Bonfils\(^1\), Jeffrey F. Painter\(^1\), Mark D. Zelinka\(^1\), Carl Mears\(^2\), Susan Solomon\(^3\), Gavin A. Schmidt\(^4\), John C. Fyfe\(^5\), Jason N. S. Cole\(^5\), Larissa Nazarenko\(^4\), Karl E. Taylor\(^1\) and Frank J. Wentz\(^2\)

- “Even a hypothetical ‘perfect’ climate model, with perfect representation of all the important physics operating in the real-world climate system, will fail to capture the observed evolution of climate change if key anthropogenic and natural forcings are neglected or inaccurately represented”

- “It is not scientifically justifiable to claim that model climate sensitivity errors are the only explanation for differences between model and observed temperature trends”

4. Model forcing errors

[Graph showing estimated optical depth from 1985 to 2010, with labels for different events and lines indicating aerosol optical depth from Vernier et al. and Sato et al. updated.]

Vernier et al. aerosol optical depth
Sato et al. aerosol optical depth (updated)

Early 21st century volcanic eruptions have signatures across the electromagnetic spectrum

Source: Santer et al., Nature Geoscience (2014)
Early 21\textsuperscript{st} century volcanic eruptions have signatures across the electromagnetic spectrum

**VISIBLE:** Stratospheric Aerosol Optical Depth (Vernier et al., 2011)

**SHORT-WAVE:** CERES net clear-sky SW radiation

Source: Santer et al., *Nature Geoscience* (2014)
Early 21st century volcanic eruptions have signatures across the electromagnetic spectrum.

**Microwave:** MSU lower tropospheric temperature (with ENSO removed)

**Visible:** Stratospheric Aerosol Optical Depth (Vernier et al., 2011)

**Short-Wave:** CERES net clear-sky SW radiation

**Rowave:** MSU lower tropospheric temperature (ENSO removed)

Source: Santer et al., Nature Geoscience (2014)
A non-negligible percentage of the temporal variance of climate data is explained by volcanic activity.

The “swarm” of early 21st century volcanic eruptions continues
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The “swarm” of early 21st century volcanic eruptions continues
Conclusions (I)

- A ≠ B
- B is highly reliable
- Therefore A is wrong

It is scientifically incorrect to provide only a single explanation of “A ≠ B”
Conclusions (II)

- Understanding the causes of differences between modeled and observed warming rates is a fascinating detective story – a “they-dunnit” rather than a “who-dunnit”

- Differences between modeled and observed warming rates in the last 17 years are due to multiple factors:
  - Errors/uncertainties in observations
  - Natural internal climate variability
  - Model response errors
  - Model forcing errors
  - They are not due to a single factor only – there is no “one explanation to rule them all”

- The scientific challenge is to reliably quantify the contributions of different factors

- The recent “warming hiatus” does not pose a fundamental challenge to our understanding of the sensitivity of the climate system to human influences