Global Change and Natural Variability

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On average, temperatures have been rising world-wide for the last century:
In 2006, the U.S. Congress was obsessing over a figure in the 2001 IPCC\(^1\) report.

In 2007, the U.S. Congress is tightening car fuel consumption standards (among other climate-related actions).

\(^1\)Intergovernmental Panel on Climate Change, a UNEP-WMO panel.
...And so is the Political Climate

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...But Not Everyone is on the Same Page
The consensus among climate scientists is that human activities have caused a change, which we expect to continue.

But part of the change could also be natural variability, which might reverse itself.

How much of each?
Outline

1. Background
2. The Instrumental Record
3. Statistical Modeling
4. Longer Temperature Records
5. Using Longer Records: Simulations
6. Summary and Conclusions
The instrumental temperature record is based on measurements from thermometers at thousands of meteorological stations worldwide.
IPCC historic temperature data based on work\textsuperscript{2} at the U.K. Met Office Hadley Centre and the Climatic Research Unit at the University of East Anglia:

\begin{figure}
\centering
\includegraphics[width=\textwidth]{temp_chart.png}
\caption{IPCC historic temperature data.}
\end{figure}

\textsuperscript{2}Brohan, P., J.J. Kennedy, I. Harris, S.F.B. Tett and P.D. Jones, 2006: Uncertainty estimates in regional and global observed temperature changes: a new dataset from 1850. J. Geophysical Research 111
Annual CO\textsubscript{2} emissions\textsuperscript{3} from the Carbon Dioxide Information Analysis Center:

\begin{itemize}
\end{itemize}
Putting them together

Temperatures and cumulative CO₂ emissions:

![Graph showing temperatures and cumulative CO₂ emissions over time.](image-url)
...And a Fit

Using cumulative CO₂ emissions to measure human impacts:
20th Century Change

- The fitted curve increases 0.67°C from AD 1900 to 2000.
- Part of that change could be natural variability:
  \[ \text{observed change} = \text{human caused} + \text{natural variability} \]
- We need bounds on the part due to natural variability.
Residuals $= \text{observed} - \text{fitted}$:

Is this what natural variability would have looked like?

![Graph showing temperature trends over time with residual calculations.](chart.png)
A simple time series model is

\[ \text{temperature} = \theta \times \text{cumulative CO}_2 + \text{noise}. \]

\( \theta \) measures the human impact.

The noise, representing natural variability, is assumed to be “autoregressive-integrated-moving-average” (\( ARIMA(p, d, q) \)).

Both the human-impact signal and the noise could be modeled more elaborately.
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Various Results

Results for various choices of \((p, d, q)\):

<table>
<thead>
<tr>
<th>(p)</th>
<th>(d)</th>
<th>(q)</th>
<th>(\hat{\theta})</th>
<th>(\text{SE}(\hat{\theta}))</th>
<th>(\text{AIC})</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>0</td>
<td>4</td>
<td>0.7615</td>
<td>0.0232</td>
<td>-266.15*</td>
</tr>
<tr>
<td>2</td>
<td>0</td>
<td>3</td>
<td>0.6880</td>
<td>0.0804**</td>
<td>-259.82</td>
</tr>
<tr>
<td>2</td>
<td>1</td>
<td>4</td>
<td>0.7479</td>
<td>0.2265</td>
<td>-258.62*</td>
</tr>
<tr>
<td>2</td>
<td>1</td>
<td>0</td>
<td>0.7726</td>
<td>0.5061</td>
<td>-240.38</td>
</tr>
<tr>
<td>0</td>
<td>1</td>
<td>0</td>
<td>0.7542</td>
<td>0.8431**</td>
<td>-223.00</td>
</tr>
</tbody>
</table>

Notes:

- *: minimum AIC for \(0 \leq p \leq 4, 0 \leq q \leq 4\).
- **: maximum SE for \(0 \leq p \leq 4, 0 \leq q \leq 4\).
The estimates of $\theta$ are quite similar: all suggest that the best estimate of 20th century human-caused warming is 0.7 to 0.8°C.

But $\pm 2SE$ intervals vary from an apparently precise 0.72 to 0.81°C to a very wide $-0.93$ to $+2.44$°C.

In the former case, we appear to have measured the change quite precisely, but in the latter case we’re not even sure the change has been upward!
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Notes:

- The models with $d = 0$ are *stationary*; natural variations fluctuate but consistently return to a long-term average level;

- The models with $d = 1$ are *non-stationary*; natural variations build on each other, and show *no* tendency to return to any long-term level.

- The Augmented Dickey-Fuller test fails to reject the null hypothesis $d = 1$, but the Phillips-Perron does reject it ($P < 0.01$).

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More Comments

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  - The instrumental record is too short to allow us to characterize the statistical nature of natural variability.

- **The solution:**
  - Use longer temperature records, derived from *proxy* data.
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- Use longer temperature records, derived from proxy data.
Prior to AD 1850, regional temperatures must be inferred from *proxy data*:

- tree ring widths and densities;
- ocean sediments;
- isotopic concentrations in ice cores;
- glacier lengths and borehole temperatures (not strictly proxies);
- other proxies.

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Rings from several trees can be linked into a single chronology:
A Southern Ocean (Antarctic) core sample:

Core sample taken from 15.5 to 16.6 meters beneath the ocean floor

(2 halves shown side by side)

notice the distinctly different layers at different depths in the core sample
Collecting ice cores in Greenland, 2005:
A Glacier retreats

The Qori Kalis Glacier, Quelccaya Ice Cap, Peru, in 1978 and 2002:
What Do We Know About Earlier Times?

The 1990 IPCC report included a proxy-based schematic representation of how temperature has changed over the past 1,000 years:
The 2001 IPCC report included a more detailed view, based on multi-proxy work by Michael Mann and co-workers (the “Hockey Stick”):
Comparing the Views

A Wikipedia entry compares the views:

[Graph showing temperature variations over time from 1000 to 2000 AD]
The Hockey Stick was controversial:
- No “Medieval Warm Period” or “Little Ice Age”;
- Instead, shows a steady cooling from AD 1000 to around 1900, followed by an abrupt warming;
- Iconically emphasizes recent warming.

But:
- neither view has the same detail as the instrumental record;
- neither can be used to extend the instrumental record in a homogeneous way.
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Other recent reconstructions have been made; seven were identified by a 2006 NRC Panel:

- Borehole temperatures (Huang et al. 2000)
- Glacier lengths (Oerlemans et al. 2005)
- Multiproxy (Mann and Jones 2003)
- Multiproxy (Hegerl et al. 2006)
- Multiproxy (Moberg et al. 2005)
- Tree rings (Esper et al. 2002)
- Instrumental record (HadCRUT2v)
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Other properties of the models, such as “backcast” standard errors, could also be used for comparison.
Simulating the Past

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The stationary model \( p = 3, d = 0, q = 4 \) (minimizes AIC for \( d = 0 \)):
Simulating the Past

The stationary model $p = 2, d = 0, q = 3$ (maximizes SE for $d = 0$):

![Graph showing temperature changes over time from 1000 to 2000 AD]
The non-stationary model $p = 2, d = 1, q = 4$ (minimizes AIC for $d = 1$):
Simulating the Past

The non-stationary model $p = 2, d = 1, q = 0$ (maximizes SE for $d = 1, p + q \geq 2$):
The non-stationary model $p = 0, d = 1, q = 0$ (maximizes SE for $d = 1$):
The two stationary models \((d = 0)\) are qualitatively similar to the **Hockey Stick**, but without the slow cooling, which they cannot be expected to reproduce.

These models would not be excluded, if we believed that the Hockey Stick shows a realistic level of natural variability; most climate scientists don’t.

Two of the non-stationary models \((p = 2, d = 1, q = 0\text{ and } p = 0, d = 1, q = 0)\) show variations of \(2.5 – 4\,^\circ\text{C}\), which are larger than any of the expert reconstructions show.

These models should probably be excluded.

The other non-stationary model \((p = 2, d = 1, q = 4)\) shows variations only a little larger than the most variable reconstruction, and seems the most plausible.
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Reconstructions of temperatures from AD 1000 to the present can be used to narrow down the choice of models.

The resulting estimate of the human contribution to 20$^{th}$ century warming is 0.75°C, ±0.45°C (2σ), or from 0.29°C to 1.20°C.
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