The Certainty about the Certainties and Uncertainties in the Forcing of Climate Change

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V. Ramaswamy

Co-authors: M. Bollasina, P. Ginoux, L. Horowitz, Y. Ming, I. Ocko, G. Persad, M. D. Schwarzkopf

Geophysical Fluid Dynamics Laboratory
Observed global-mean surface temperature (GMST) since 1850 shows a long-term warming trend, overlaid by fluctuations.

Each of the last three decades has been successively warmer at the Earth’s surface than any preceding decade since 1850.

In the Northern Hemisphere, 1983–2012 was likely the warmest 30-year period of the last 1400 years (medium confidence).
Projected Climate Changes and Challenges

Ten Indicators of a Warming World

Warming is unequivocal (IPCC, 2007)

Seven of these observed indicators would be expected to increase in a warming world and observations show that they are, in fact, increasing. Three would be expected to decrease and they are, in fact, decreasing.
Multiple Independent Lines of Evidence for Global Warming
CO$_2$, CH$_4$ and N$_2$O increase in the Industrial Era

Ice core records

Atmospheric monitoring
CO₂ provides largest RF

**Climate Drivers**

<table>
<thead>
<tr>
<th>Long-lived Gases</th>
<th>Short-lived Gases</th>
<th>Short-lived Aerosols</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO₂</td>
<td>CH₄</td>
<td>O₃</td>
</tr>
<tr>
<td>N₂O</td>
<td></td>
<td></td>
</tr>
<tr>
<td>CO</td>
<td>CH₄, O₃</td>
<td></td>
</tr>
<tr>
<td>NMVOC</td>
<td>CO₂, CH₄, O₃</td>
<td></td>
</tr>
<tr>
<td>NOₓ</td>
<td>Nitrate, CH₄, O₃</td>
<td></td>
</tr>
<tr>
<td>Aerosols and precursors (Mineral dust, SO₂, NH₃, Organic carbon and Black carbon)</td>
<td></td>
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<tr>
<td>Cloud adjustments due to aerosols</td>
<td></td>
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<tr>
<td>Albedo change due to land use</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Natural</td>
<td>Changes in solar irradiance</td>
<td></td>
</tr>
</tbody>
</table>

Total anthropogenic RF relative to 1750

<table>
<thead>
<tr>
<th>Year</th>
<th>RF Relative to 1750 (W m⁻²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2011</td>
<td>2.29 [1.13 to 3.33]</td>
</tr>
<tr>
<td>1980</td>
<td>1.25 [0.64 to 1.86]</td>
</tr>
<tr>
<td>1950</td>
<td>0.57 [0.29 to 0.85]</td>
</tr>
</tbody>
</table>

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Human influence on the climate system is clear.
The Short-Lived Climate Drivers: Aerosols

Major Uncertainty in 20th C “Climate Drive”
Aerosol Optical Depth in CMIP5 Models

⇒ 3-fold range ⇒ a large uncertainty
Aerosol-Climate Interactions

Clear Sky
- Reflection
- Wet Particles
- Hygroscopic Growth

Cloudy Sky
- SW Radiation
- Reflection
- Absorption

Interstitial Aerosols
- Droplets
- Activation

Advection
- Emission

Land
Ocean

Credit: Y. Ming
Validating aerosol vertical distribution with CALIPSO

CALIOP (Cloud-Aerosol Lidar with Orthogonal Polarization)

Credit: P. Ginoux
Surface shortwave radiative (SSR) flux trend

The GFDL AM3/CM3 model has the best representation of the dimming trends among all CMIP5 model (Allen et al., 2012).

Global Energy Balance Archive (GEBA) stations used in Norris and Wild (2009)

Courtesy: G. Persad and Y. Ming
Surface Air Temperature change

[WMGGO3 (warming) and Aerosol (cooling) effects dominant]

Credit: L. Horowitz
Greenhouse Gases vs. Aerosols [Bollasina et al., 2011]

**GLOBAL surface temperature time series**

- HadCRUT3
- AERO
- ALL_F
- WMGGO3

WMGGO3 Temp. effect reduced by Aerosols

**Precipitation time series and trend (Summer: NORTH-CENTRAL INDIA)**

- CRU
- AERO
- NAT
- ALL_F
- WMGGO3

Summer monsoon reduction dominated by Aerosols
Present-Day Annual Burdens

Black Carbon (ng/m²)

Sulfate
Black Carbon

Latitude

90S  60S  30S  EQ  30N  60N  90N
\[ \Delta \text{Surface Air Temperature} \]

- Sulfate DRF
- Black Carbon DRF
- Aerosol IRF
- LLGHG

Ocko et al., J. Clim., in press
Forcing sign, NH/SH asymmetry, Circulation, Precipitation

Ocko et al., J. Clim., in press
The 21\textsuperscript{st} C
Representative Concentration Pathways (RCP)

Box TS.6 for further details
Projections

Fig. SPM.7
Under all RCPs the rate of GMSLR will very likely exceed that observed during 1971–2010.

Stabilising global mean surface temperature does not stabilise global mean sea level.

Earlier CO₂ emissions cause greater GMSLR.
Near term projections

Fig. TS.14
Warming caused by cumulative carbon emissions to 2010

Cumulative emissions of CO$_2$ largely determine global mean surface warming by the late 21st century and beyond.
Warming caused by cumulative carbon emissions to 2100
Current state-of-the-science

- Multiple lines of observational evidence ➔ WARMING.
- Human influence on the climate system is clear.

Uncertainty in Forcing due to AEROSOLS

- AEROSOLS have reduced the LLGHGs’ warming effect.
- AEROSOL species themselves have an offsetting effect.
- Aerosols introduce a NH-SH perturbation asymmetry that is absent for LLGHGs ➔ Affects equatorial precipitation.
Factors affecting decadal warming rate estimates

- Incomplete knowledge of the *internal variability* of the system
- Incomplete knowledge of the temporal evolution and spatial structure of the *Short Lived Climate Forcers (SLCFs)*, in particular aerosols
- Gaps in the understanding of the *climate feedbacks to the natural and anthropogenic forcings*
The longer-term perspective for the 21st C

...........A certainty under the scenarios!

Long-Lived Greenhouse Gases the dominant human-influenced climate forcer over the 21st C
The END

Thank you for your attention!
Regional trends in ocean salinity provide indirect evidence that evaporation and precipitation over the oceans have changed (medium confidence).
Aerosol radiative forcings

“There is high confidence that aerosols … have offset a substantial portion of global mean forcing from well-mixed greenhouse gases. They continue to contribute the largest uncertainty to the total radiative forcing estimate.”

- Aerosol absorption is not well observed and not well modelled ⇒ *Maybe the last issue in the quantification aerosol-radiation interactions*

- Aerosol-cloud interactions continue to be a stumbling block in climate models ⇒ *New approaches are now possible (large-domain CRM and LES, new parameterizations, systematic verification of weather models, data assimilation techniques, etc.)*

- Are there robust circulation trends in response to the aerosol forcings?
"Climate-relevant aerosol processes are better understood and, climate-relevant properties better observed, than at the time of the AR4."

"New satellite sensors and new analysis of previous data sets have given us a clearer picture of the Earth's clouds since AR4."

IPCC AR5, Chapter 7, 2013
"Overall, confidence in satellite based global average AOD trends is low."

"An assessment of long-term variations in global-mean cloud amount … found differences between datasets were comparable in magnitude to the interannual variability. Inconsistencies in sampling and instrument calibration inhibit an accurate assessment of global-scale cloud cover trends."

"It is likely that circulation features have moved poleward since the 1970s, involving a widening of the tropical belt, a poleward shift of storm tracks and jet streams, and a contraction of the northern polar vortex."

IPCC AR5, Chapter 2, 2013
We need to improve our understanding of feedbacks associated with low-level clouds (the "joker" of cloud feedbacks)

The new frontier is to understand links between clouds, atmospheric circulation and how this relates to climate sensitivity ⇒ WCRP grand challenge, some theoretical and multi-model approach, rapid adjustments and slow feedbacks decomposition
Physical feedbacks (Planck, Water Vapour, Albedo)
Sensitivity to modeling of aerosol-cloud interactions

Models

CM3: GFDL CMIP5 model.

CM3w,c: configurations with alternate but plausible parameter choices.

Net warming

<table>
<thead>
<tr>
<th>Observations</th>
<th>Models</th>
</tr>
</thead>
<tbody>
<tr>
<td>NOAA NCDC</td>
<td>0.59 °C</td>
</tr>
<tr>
<td>NASA GISS</td>
<td>0.53 °C</td>
</tr>
<tr>
<td>HadCRUT3</td>
<td>0.56 °C</td>
</tr>
<tr>
<td>GFDL CM3w</td>
<td>0.57 °C</td>
</tr>
<tr>
<td>GFDL CM3</td>
<td>0.22 °C</td>
</tr>
<tr>
<td>GFDL CM3c</td>
<td>-0.01 °C</td>
</tr>
</tbody>
</table>

Golaz et al. (2013, GRL)

Credit: C. Golaz
Projections

Fig. SPM.8
How large is the projected change compared to internal variability?

**Hatching:** changes are “small” compared with internal variability.

**Stippling:** changes are “large” compared with internal variability, and at least 90% of models agree on sign of change.

**Precipitation change (%)**

![Map showing precipitation change with hatching and stippling for RCP8.5 scenario.](image)

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**IPCC AR5 Working Group I**
**Climate Change 2013: The Physical Science Basis**
Observed GMSLR 1993-2010 is consistent with the sum of observed contributions (*high confidence*)

Data from Table 13.1

*High confidence* in an anthropogenic influence on these largest contributions

Likely anthropogenic influence

Low confidence in attributing the causes

- Thermal expansion
- Glaciers
- Greenland ice sheet
- Antarctic ice sheet
- Land water storage
- Total of contributions

Observed GMSLR

Data from Table 13.1
Confidence in projections of GMSLR has increased

Data from Table 13.5 for RCP4.5 for 2081-2100 relative to 1986-2005
AR4 and AR5 projections are very similar but uncertainties are not decreasing

Knutti and Sedlacek, 2013
Warming will persist for centuries

- Zero CO$_2$ emissions lead to near constant surface temperature.
- A large fraction of climate change persists for many centuries.
- Depending on the scenario, about 15-40% of the emitted carbon remains in the atmosphere for 1000 yrs.
Cumulative carbon determines warming

- Peak warming is approximately proportional to cumulative (total) emissions.
- Transient climate response to cumulative carbon emissions TCRE = Warming per 1000 PgC
NOAA/ GFDL Modeling and Research
Probing the Frontiers

12.5 km

HiRAM

Resolution

Earth System Complexity

Sea-Level Rise (1860-2100)

20th C

Strat cooling

Surface-Tropos warming
Back Scattering (Cooling)

Absorption (Atmospheric Warming)

Forward Scattering

Dimming of Surface
Surface Cooling

Absorption (Column Warming)

Cloud Evaporation (Warming)

Cloud Seeding (Cooling)

Suppression of Rain; increase of life time .... Cooling
Large additional warming projected from aerosols over 21st century
Aerosol, LLGHGs, and Poleward heat transport
Evidence for a reduced forcing trend from 1998 compared to from 1951

- The reduced trend in radiative forcing is primarily due to volcanic eruptions and the downward phase of the solar cycle.

Fig 8.19
Aerosols in the Stratosphere from Volcanic Eruptions