Importance of clouds and aerosols in assessing climate change

Olivier Boucher, Laboratoire de Météorologie Dynamique, Paris, France

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Acknowledgements

Lead Authors of IPCC WGI Fifth Assessment Report

... especially those from the “Clouds and Aerosols” chapter
Introduction & Forcing, feedbacks and climate response

Role of aerosols in a changing energy budget
   Aerosol-radiation interactions
   Aerosol-cloud interactions

Role of clouds in a changing energy budget

Concluding remarks
Introduction & Forcing, feedbacks and climate response

Role of aerosols in a changing energy budget
   Aerosol-radiation interactions
   Aerosol-cloud interactions

Role of clouds in a changing energy budget

Concluding remarks
“Clouds and aerosols continue to contribute the largest uncertainty to estimates and interpretations of the Earth’s changing energy budget.”
Changes in the Earth’s radiative budget

\[ Q = F + \left( \lambda_{\text{Planck}} + \lambda_{\text{WV/LS}} + \lambda_{\text{surface}} + \lambda_{\text{cloud}} \right) \Delta T \]

F is the effective radiative forcing \((Wm^{-2})\)
Climate forcings

<table>
<thead>
<tr>
<th>Emitted compound</th>
<th>Resulting atmospheric</th>
<th>Radiative forcing by emissions and drivers</th>
<th>Level of confidence</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO₂</td>
<td>CO₂</td>
<td>1.68 [1.33 to 2.00]</td>
<td>VH</td>
</tr>
<tr>
<td>CH₄</td>
<td>CO₂, H₂O, O₁, CH₆</td>
<td>0.97 [0.74 to 1.20]</td>
<td>H</td>
</tr>
<tr>
<td>Halocarbons</td>
<td>O₂, CFCs, HCFCs</td>
<td>0.18 [0.01 to 0.36]</td>
<td>H</td>
</tr>
<tr>
<td>N₂O</td>
<td>N₂O</td>
<td>0.17 [0.13 to 0.21]</td>
<td>VH</td>
</tr>
<tr>
<td>Sulfur gases</td>
<td>CO₂, CH₄, O₃</td>
<td>0.23 [0.16 to 0.30]</td>
<td>M</td>
</tr>
<tr>
<td>NOₓ</td>
<td>N₂O</td>
<td>0.10 [0.05 to 0.15]</td>
<td>M</td>
</tr>
<tr>
<td>Aerosols and precursors</td>
<td>Mineral dust, Sulfate, Nitrate, Organic carbon, Black carbon</td>
<td>-0.27 [-0.77 to 0.23]</td>
<td>H</td>
</tr>
<tr>
<td></td>
<td>Cloud adjustments due to aerosols</td>
<td>-0.55 [-1.33 to -0.06]</td>
<td>L</td>
</tr>
<tr>
<td></td>
<td>Albedo change due to land use</td>
<td>-0.15 [-0.25 to -0.06]</td>
<td>M</td>
</tr>
<tr>
<td>Natural</td>
<td>Changes in solar irradiance</td>
<td>0.05 [0.00 to 0.10]</td>
<td>M</td>
</tr>
</tbody>
</table>

Total anthropogenic RF relative to 1750

- 2011: 2.29 [1.13 to 3.33] (H)
- 1980: 1.25 [0.64 to 1.86] (M)
- 1950: 0.57 [0.29 to 0.86] (M)

IPCC AR5, SPM, 2013
IPCC AR5, Chapter 8, 2013
Changes in the Earth's radiative budget

\[ Q = F + (\lambda_{\text{Planck}} + \lambda_{\text{WV/LS}} + \lambda_{\text{surface}} + \lambda_{\text{cloud}}) \Delta T \]

- F is the effective radiative forcing (Wm\(^{-2}\))
- Feedback terms
  - Sum of \( \lambda \)s is negative (for climate to be stable)
\[ Q = F + (\lambda_{\text{Planck}} + \lambda_{\text{WV/LS}} + \lambda_{\text{surface}} + \lambda_{\text{cloud}}) \Delta T \]

- **\( Q \)** is the net feedback parameter \((\text{Wm}^{-2}\text{K}^{-1})\), alltogether negative.
- **\( \Delta T \)** is the surface temperature change (K).
- **\( F \)** is the effective radiative forcing \((\text{Wm}^{-2})\).
Q is the radiative imbalance at the top-of-atmosphere but given the small heat capacity of the atmosphere is estimated as the heat flux to the ocean (Wm^{-2})

F is the effective radiative forcing (Wm^{-2})

\( \lambda \) is the net feedback parameter (Wm^{-2}K^{-1}), altogether negative

\( \Delta T \) is the surface temperature change (K)
Changes in the Earth’s radiative budget

\[ Q = F + (\lambda_{\text{Planck}} + \lambda_{\text{WV/LS}} + \lambda_{\text{surface}} + \lambda_{\text{cloud}}) \Delta T \]

- **\( Q \)** is the radiative imbalance at the top-of-atmosphere but given the small heat capacity of the atmosphere is estimated as the heat flux to the ocean (Wm\(^{-2}\))

- **\( F \)** is the effective radiative forcing (Wm\(^{-2}\))

- **\( \lambda \)** is the net feedback parameter (Wm\(^{-2}\)K\(^{-1}\)), altogether negative

- **\( \Delta T \)** is the surface temperature change (K)
Total forcing vs. sensitivity

Climate sensitivity (°C per doubled CO$_2$ or better in °C per Wm$^{-2}$)
Rapid adjustments = do not act through a surface-temperature change
Feedbacks = act through a surface temperature change

IPCC AR5, Chapter 7, 2013
Outline

Introduction & Forcing, feedbacks and climate response

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Concluding remarks
Aerosol-radiation interactions

**Scattering aerosols**

(a) Aerosols scatter solar radiation. Less solar radiation reaches the surface, which leads to a localised cooling.

(b) The atmospheric circulation and mixing processes spread the cooling regionally and in the vertical.

**Absorbing aerosols**

(c) Aerosols absorb solar radiation. This heats the aerosol layer but the surface, which receives less solar radiation, can cool locally.

(d) At the larger scale there is a net warming of the surface and atmosphere because the atmospheric circulation and mixing processes redistribute the thermal energy.
Aerosol-cloud interactions

Aerosols serve as cloud condensation nuclei upon which liquid droplets can form.

More aerosols result in a larger concentration of smaller droplets, leading to a brighter cloud. However, there are many other possible aerosol-cloud-precipitation processes which may amplify or dampen this effect.

IPCC AR5, Chapter 7, 2013
Aerosol radiative forcings

Irradiance Changes from Aerosol-Radiation Interactions (ari)

Irradiance Changes from Aerosol-Cloud Interactions (aci)

Direct Effect
Semi-Direct Effects
Cloud Albedo Effect
Lifetime (including glaciation & thermodynamic) Effects

Radiative Forcing (RFari)
Adjustments
Radiative Forcing (RFaci)
Adjustments

Effective Radiative Forcing (ERFari)

IPCC AR5, Chapter 7, 2013
Aerosol radiative forcings
Aerosol day-to-day variability

MACC II aerosol monitoring and forecasting system = MODIS + IFS aerosol model + 4D-VAR

MACC II / Copernicus © S. Mantonavi (MEEO, Italy) & Angela Benedetti (ECMWF)
“Climate-relevant aerosol processes are better understood and, climate-relevant properties better observed, than at the time of the AR4.”
What can be said of aerosol trends?

"Overall, confidence in satellite based global average AOD trends is low."

IPCC, Chapter 2, 2013
Aerosol RFari assessment

\[
\text{RFari} = -0.35 \text{ (-0.85 to +0.15) Wm}^{-2}
\]

\[
\text{ERFari} = -0.45 \text{ (-0.95 to +0.05) Wm}^{-2}
\]

IPCC AR5, Chapter 7, 2013
RFari due to BC aerosols

AeroCom II models underestimate BC in many source regions, do well in some outflow region such as Japan but overestimate BC concentrations in some remote regions, especially at heights, which has an impact on the simulated normalized RF and RF.

Samset et al. (2013) & Boucher et al. (2014)
Need for higher resolution in aerosol models

R. Wang, Y. Balkanski & O. Boucher
Model-observation comparison for BC surface concentration

Wang et al. PNAS 2014
## Study of aerosol-cloud interactions

<table>
<thead>
<tr>
<th>Observations</th>
<th>Small-scale models</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Form the basis for studying aerosol-cloud interactions but...</td>
<td>• Can represent clouds better but…</td>
</tr>
<tr>
<td>• Aerosol observations can be contaminated by clouds (or vice versa)</td>
<td>• Overlook large-scale feedbacks</td>
</tr>
<tr>
<td>• Aerosols and cloud properties co-vary with the meteorology (humidity, winds, meteorological situation, ...)</td>
<td>• Are expensive to runs</td>
</tr>
<tr>
<td>=&gt; One can try to deconvolve this effect but statistics go down</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Large-scale models</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Can represent the variability in large-scale conditions and can be constrained by large-scale observations but ...</td>
</tr>
<tr>
<td>• Clouds are heavily parametrised</td>
</tr>
</tbody>
</table>
Aerosol-cloud interactions

Satellite approaches to aerosol-cloud interactions involve correlating cloud properties with aerosol properties (e.g. in log-log space) accounting for by weather regime and region.

Example: cloud droplet column concentration vs AOD

North America JJA

North America DJF

Asia MAM

Quaas, Boucher et al., PNAS, 2011
Aerosol ERF_{ari+aci} assessment

Latest GCM study from each group

More emphasis on studies that also included effects on convective clouds or mixed-phase clouds

Satellite studies corrected for LW effects

LES & CRM studies

Combined with expert judgement to estimate ERF_{ari+aci} as -0.9 (-1.9 to -0.1) Wm^{-2}

IPCC AR5, Chapter 7, 2013
“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 RF estimate.”
Major research gaps - Aerosols

• Aerosol absorption is not well observed. Black carbon is underestimated in source regions but possibly overestimated in remote regions in global models ⇒ better observations & models, need to know anthropogenic fraction, high resolution modelling.

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

• Trends in aerosols are not well understood at the global scale ⇒ better monitoring & satellite calibration, source inversion, sampling uncertainties in the historical period, focus on the last 40-50 years in Earth’s energy budget studies.

• Are there robust changes in circulation and weather extremes in response to the aerosol forcings?
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Cloud climatology

“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
Cloud climatology

IPCC AR5, Chapter 7, 2013
What can be said of cloud trends?

"An assessment of long-term variations in global-mean cloud amount from nine different satellite datasets by Stubenrauch et al. (2013) found differences between datasets were comparable in magnitude to the interannual variability. Such inconsistencies result from differences in sampling as well as changes in instrument calibration and 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
"Robust mechanisms are those simulated by most models and possessing some kind of independent support or understanding"

"No robust mechanisms contribute negative (cloud) feedback"

IPCC AR5, Chapter 7, 2013
Cloud climate feedbacks

"The sign of the net radiative feedback due to all cloud types is likely positive."

IPCC AR5, Chapter 7, 2013
“There is high confidence that, as climate warms, extreme precipitation rates [...] will increase faster than the time average.”

IPCC AR5, Chapter 7, 2013
Major research gaps - Clouds

- Aerosol-cloud interactions continue to be a stumbling block in climate models but ⇒ new approaches are now possible (large-domain CRM and LES, new parameterizations, systematic verification of weather models, data assimilation techniques, synergetic use of observations and models needed to disentangle aerosol-cloud interactions from the impact of meteorology, etc.)

- Trends in clouds are not well understood at the global scale ⇒ better monitoring & satellite calibration ⇒ look for circulation changes as a proxy for cloud feedbacks

- 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 climate sensitivity ⇒ WCRP grand challenge, some theoretical and multi-model approach, rapid adjustments and slow feedbacks decomposition
Concluding remarks

• Observing capability of clouds and aerosols have substantially improved. However monitoring of trends is imperfect.

• There has been substantial improvement in our understanding of aerosol and cloud processes, but not all of this new knowledge is yet "available" in global climate models.

• Aerosol forcing (ERFari+aci) and cloud feedbacks remain uncertain, prohibiting strong constraint on the climate sensitivity parameter ⇒ More focus on the energy budget

• Aerosols are thought to contribute to a RF that is less negative than in AR4. They continue to dominate the uncertainty in the total anthropogenic RF.

• The sign of the net radiative feedback due to all cloud types is likely positive. No robust mechanisms contribute a negative cloud feedback.

• Some cloudiness and humidity changes to global warming are now understood as responses to large-scale circulation changes

• High resolution modelling is needed ⇒ good news = satellite are already high resolution in model’s world