Understanding climate processes through a hierarchy of models

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How to Assess our Confidence in Model Projections?

- Long-standing characteristics of long-term projections from climate models:
  - Some aspects robust amongst models
  - Others associated with large inter-model differences

How to assess our confidence in climate projections?
- Are consensual results reliable?
- Reasons for inter-model differences? Are some results more credible than others?

Key questions for long-term climate change assessments

[IPCC, 2007]
Unlike in weather prediction, the reliability of model predictive capabilities for long-term climate change can not be established in a straightforward way... but only through indirect routes. Few observational tests are fully discriminating of long-term projections. Do we apply relevant observational tests? Confidence in climate projections thus remains disproportionately dependent on the development of understanding.
Spatial and temporal scales

Spatial scale (m)
- 10,000 km
- 1,000 km
- 100 km
- 10 km
- 1 km
- 100 m
- 10 m
- 1 m
- 100 mm
- 10 mm
- 1 mm

Temporal scale (s)

- GCM: Climate models
  - Climate phenomena
  - Climate changes

- Physical local laws (conservation laws)

- Conservation laws

- Deep convection
- Low Clouds
- Clouds microphysics (cloud droplet size, precipitation, ice/water...)

- Physical local laws (conservation laws)
Our physical understanding of the climate system relies on a spectrum of models and theories. Our confidence in modelling results depends on our ability:

- to connect robust behavior across a spectrum of relevant models
- to connect this behavior both to basic physical principles and to observations

[Model simplicity](relative to system)
How to Assess our Confidence in Model Projections?

Questions:
- What is the added value of the ongoing increase of complexity?
- Are consensual results reliable?
- Why model estimates differ?
- Are some results more credible than others?

Outline:
- Origin of the spread of current estimate of climate sensitivity
- Origin of the spread of the cloud feedbacks
- Understanding the response of low-level clouds through a spectrum of models
Climate sensitivity estimates from CMIP3 GCMs (IPCC-AR4)

Transient Climate Response: (1% CO2/yr, transient warming at 2xCO2)

Equilibrium Climate Sensitivity: (warming for sustained 2xCO2)

Climate sensitivity and TCR estimates depend on:
- radiative forcing
- climate feedbacks
- ocean heat uptake (transient only)

How do these different components contribute to inter-model differences in climate sensitivity?

[IPCC, 2007]
Contribution of individuals feedbacks to the temperature increase in response to a CO2 doubling

Surface temperature increase

*Multi-model mean*

**Transient experiment**

- total
- clouds
- albedo
- water vapour
- if only temperature were changing
- Ocean heat uptake

**Change at equilibrium**

\[ \Delta T_{\text{ref}} \]

[Dufresne & Bony, 2008]
Contribution of individuals feedbacks to the temperature increase in response to a CO2 doubling

Surface temperature increase

*Inter-model spread*

**Transient experiment**

**Change at equilibrium**

[Dufresne & Bony, 2008]
What explains the spread of GCM’s cloud feedbacks?

- Deep convective activity
- Baroclinic activity & frontal clouds
- Boundary-layer turbulence and clouds
What explains the spread of GCM's cloud feedbacks?

15 CMIP3/AR4 Coupled Ocean-Atmosphere GCMs; +1% CO2/year experiments

Sensitivity of the tropical NET CRF to surface temperature change (W/m²/K)

ΔSST = 1.2 ± 0.2 K (low-sensitivity models)

ΔSST = 1.7 ± 0.3 K (high-sensitivity models)

Reduced cooling effect of clouds

Enhanced cooling effect of clouds

Dominant effect of tropical clouds on the climate sensitivity

(Bony and Dufresne, GRL, 2005)
What explains the spread of GCM’s cloud feedbacks?

Low level tropical clouds are the primary source of spread of the climate sensitivity

(Bony and Dufresne, GRL, 2005)
Cloud feedbacks have been confirmed as the primary source of climate sensitivity uncertainty. The spread of the response of cloud is dominated by the response of the low-level clouds in the tropics. The SW response of clouds is the most uncertain. Understanding the response of low-level clouds in the tropics through a spectrum of models.
Analysis of the IPSL-CM5A model

IPSL-CM5A Ocean-Atmosphere Coupled GCM
CO2 increases by 1%/year

Global mean surface temperature

Cloud radiative forcing

Tropical mean cloudiness

IPSL-CM5A:
- high-sensitivity model, large positive feedback
- global cloud feedback dominated by the tropical cloud response
- Tropical cloud response associated with a strong decrease of low-level clouds

NB: “CRF” = Cloud Radiative Forcing (or effect of clouds on radiation, W/m2)
What controls the low-cloud response in the IPSL-CM5A GCM? How robust is this response?

Understanding the response of low-level clouds through a spectrum of models
Cloud radiative changes:

→ Dominated by regimes of weak subsidence (w ~ 20 hPa/day)

→ What controls the response of clouds to climate change in these regimes?
Vertical distribution of clouds in weak subsidence regimes: $\omega_{500} = 20 \text{ hPa/day}$

- Maximum of low-level clouds around 950 hPa (1.5 km)
- Decrease of this cloud layer in climate change
Cloud fraction in the subsident regions \((\omega_{500} = 20 \text{ hPa/day})\)

Ocean-Atmosphere coupled model

Atmospheric model & Aqua-Planet

Cloud fraction changes

+1\%CO2/yr pre-ind
(\sim +2.3K)

+2K-CTRL
Single-Column Model forced by CGILS forcing + stochastic forcing:

Aqua-planet GCM
Vertically-integrated energy budget analysis of the single column

\[ \Delta CRF = - (\Delta CSRadCooling + \Delta (LH + SH) + \Delta (-\omega \frac{\partial MSE}{\partial P}) + \Delta (\vec{V} \cdot \vec{\nabla} MSE)_{LS}) \]

Boundary-layer vertical advection term

\[ \Delta CF = 1.68 \times \Delta BVA \]

R^2 = 0.82

[Brient & Bony, 2012]
Vertically-integrated energy budget analysis of the single column

\[
\Delta CRF = -(\Delta CSRadCooling + \Delta (LH + SH) \\
+ \Delta (-\omega \frac{\partial MSE}{\partial P}) + \Delta (\vec{V} \cdot \vec{\nabla} MSE)_{LS})
\]

Boundary-layer vertical advection term

[Brient & Bony, 2012]
Positive low-cloud feedback analyzed through a range of CMIP5 experiments and configurations (OAGCM, AGCM, aqua-planet, 1D).

Primary physical mechanisms controlling the feedback identified (e.g. vertical gradient of MSE at the top of the PBL).
In a Large-Eddy Simulation (LES) model

Idealized experiment assuming a nearly unchanged relative humidity atmosphere

(Rieck, Nuijens and Stevens, 2012)
Mechanism controlling low level clouds

Clouds (or CRF) response to global warming (W/m²/K or %/K)

1D model

Clouds (or CRF) in the current climate (W/m² or %)

- Perturbation of multiple model parameters (precipitation efficiency, cloud effective radius, statistical cloud scheme, etc)
- Mechanism at work in all model versions (less low-level clouds in a warmer climate)
- Correlation between present-day low clouds and the low-clouds response to global warming.

[Brient & Bony, 2012]
Mechanism controlling low level clouds

- Clouds (or CRF) response to global warming (W/m²/K or %/K)
- Clouds (or CRF) in the current climate (W/m² or %)
- Perturbation of multiple model parameters (precipitation efficiency, cloud effective radius, statistical cloud scheme, etc)
- Correlation between present-day low clouds and the low-clouds response to global warming.
- Correlation found also in the 3D GCM

[Brient & Bony, 2012]
Interpretation of the correlation

Low-level clouds contribute to their own maintenance through their radiative effects (local cooling)

Less low-level clouds → less ACRF → less low-level clouds

Local positive feedback between ACRF and low-cloud fraction, both in the current climate and in climate change (“β feedback”)

[Brient & Bony, 2012]
The simulation of cloud-radiative effects in the present-day climate is likely to affect the amplitude of the cloud response to global warming.

Importance of evaluating cloud-radiative effects in models [Brient & Bony, 2012]
Conclusions

Our ability to anticipate long-term climate changes primarily relies on our physical understanding of how the climate system works.

Therefore, to better assess predictive capabilities of models and improve our assessment of future climate changes:

- Developing more realistic climate models (more comprehensive, complex, higher-resolution) and better quantifying uncertainty in projections
- Need to physically interpret model results in terms of processes or basic principles, and to connect them to simpler models, concepts, theories and observations.
- Conflict between realism/complexity and understanding/simplification
- The hierarchy of model is a useful methodology to link these two aspects

A key for:
- Assessing our relative confidence in different aspects of the projections
- Determining how available observations might help to assess projections
- Communicating with the public and society
CFMIP (Cloud Feedback Model Intercomparison Project) an example of international project based on this methodology

GCM analysis through a spectrum of models

Process studies (in-situ obs, LES/CRMs)

Satellite observations & simulators (COSP)

Understanding

Evaluation

Assessment of cloud-climate feedbacks

CFMIP (Cloud Feedback Model Intercomparison Project)
Thank you for our attention