Today's Lecture (Lecture 12): Uncertainties due to clouds and aerosols

Reference

IPCC AR5, Chs. 7 and 9

Why discuss clouds aerosols and clouds together?

- Anthropogenic activity affects clouds through aerosols and GHG (both through the surface temperature and through rapid adjustments)
- Past: strong aerosol forcing (relative to GHG); inter-model spread dominated by differences in aerosol
- Future: weak aerosol forcing (relative to GHG); inter-model spread dominated by feedbacks, mainly cloud
- Inability to constrain climate sensitivity from historical observations if the aerosol ERF is poorly constrained
- Clouds and aerosols each pose two distinct challenges:
  1. Fundamental understanding of processes
  2. Their representation in large-scale models

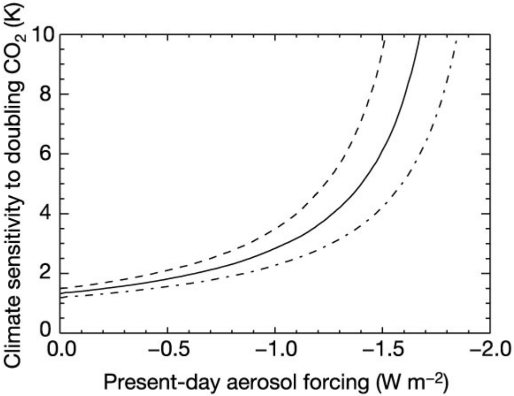
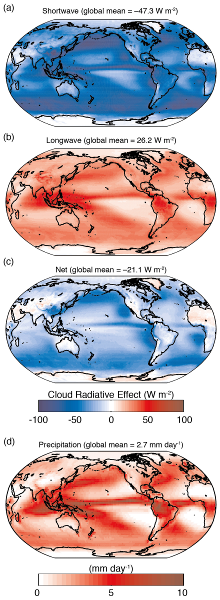


Figure: Andreae et al. (2005)

Challenges related to clouds

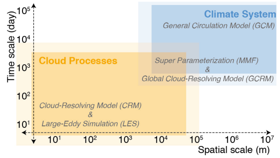


Representation of clouds in climate models

Parameterized subgridscale processes:

- Turbulence
- Cumulus convection
- Microphysical processes
- Radiative transfer
- Cloud amount (including the vertical overlap between different grid levels)
- Subgridscale transport of aerosol and chemical species

Many cloud processes are unrealistic in current GCMs → cloud response to climate change remains uncertain



Figures: IPCC AR5 unless noted

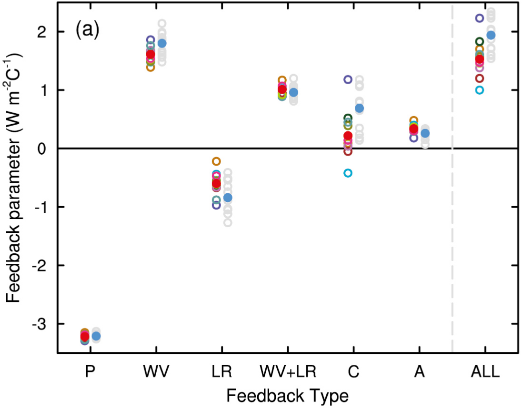
CRE is large compared to feedbacks (and forcings)

- LW and SW CRE: $\mathcal{O}(10)$ W m^{-2}
- Forcings: $\mathcal{O}(1)$ W m^{-2}
- Feedbacks: $\mathcal{O}(1)$ W m^{-2} K^{-1}

Need for models to evaluate feedbacks

- Observable climate variations are not good analogs for GHG climate change
- Change in TOA flux due to clouds is difficult to isolate

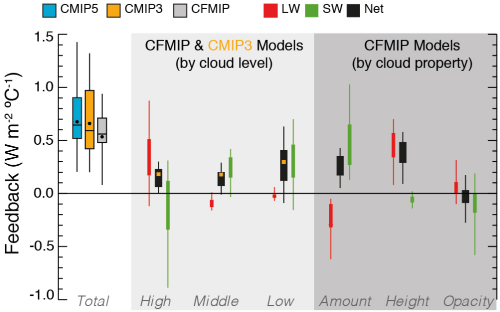
Feedbacks: water vapor + lapse rate



Compensation in intermodel spread of water vapor and lapse rate feedback

- Saturation water vapor pressure as a function of *surface* temperature: 7% K^{-1} near the surface, up to 17% K^{-1} in the upper troposphere
- Increase with height because of the lapse rate feedback
- Models with strong lapse rate feedbacks will have high increase in upper tropospheric water vapor, and therefore a strong water vapor feedback
- Combined lapse rate + water vapor feedback is well constrained; $+0.96$ to $+1.22$ W m^{-2} K^{-1}

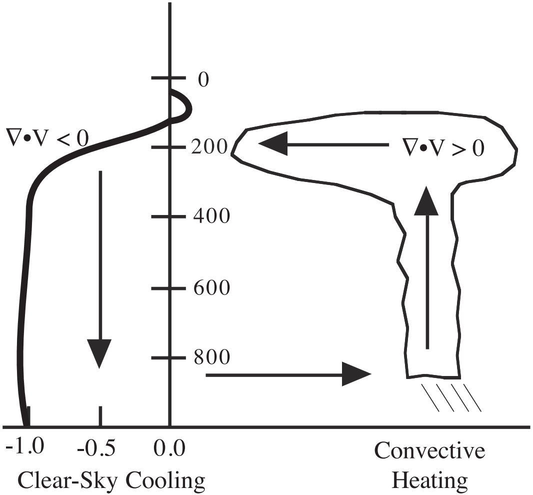
Feedbacks: clouds



Cloud feedbacks:

- Changes in high-level cloud altitude
- Effects of hydrological cycle and storm track changes on cloud systems
- Changes in low-level cloud amount
- Microphysically induced opacity (optical depth) changes
- Changes in high-latitude clouds

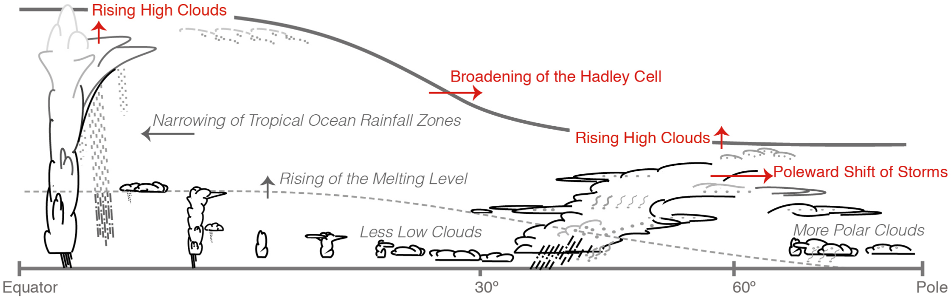
Cloud feedbacks: high-cloud altitude



- Ascent in tropical deep convection is mass-balanced by compensating subsidence
- Compensating subsidence is due to equilibrium between radiative cooling and adiabatic compression
- The subsidence top occurs at the altitude where the water vapor mixing ratio decreases rapidly ($\approx$ 220 K); the convection top will occur at the same altitude
- In a warming climate, the water vapor mixing ratio still has the same temperature dependence, so that the radiative cooling still become inefficient at $\approx$ 220 K
- The clear-sky emission temperature will increase due to atmospheric warming, but the cloud emission temperature will not, so that the LW CRE becomes stronger
- Expect $+0.5$ W m^{-2} K^{-1} (in the tropics); model range is $+0.09$ to $+0.58$ W m^{-2} K^{-1}

Figure: Hartmann and Larson (2002); argument: Zelinka and Hartmann (2010)

Cloud feedbacks: circulation changes



Cloud feedbacks: low cloud

Low clouds, especially in the tropics and subtropics, are the largest contributors to the intermodel spread in cloud feedback

Negative feedback mechanisms

In a warmer climate, low clouds might be

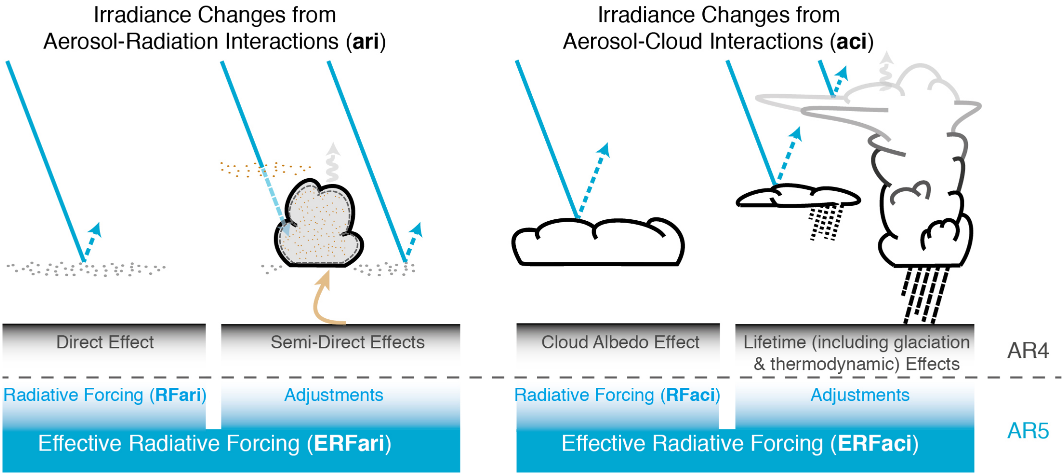
- horizontally more extensive, because changes in the lapse rate also modify the lower-tropospheric stability
- optically thicker, because adiabatic ascent releases more latent heat
- vertically more extensive in response to weakening of the tropical overturning circulation

Positive feedback mechanisms

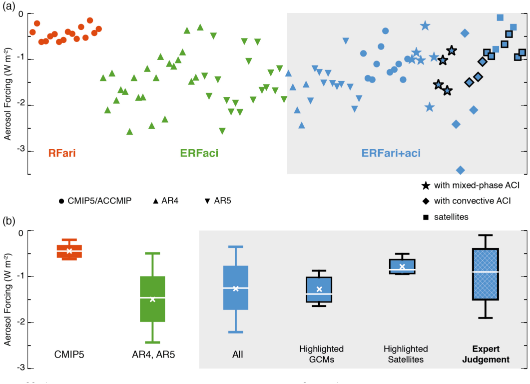
- Warming-induced changes in water vapor mixing ratio lapse rate require a reduction in cloud amount or thickness
- Energetic constraints prevent the surface evaporation from increasing with warming at a rate sufficient to balance expected changes in dry air entrainment, thereby reducing the supply of moisture to form clouds
- Increased concentrations of GHGs reduce the radiative cooling that drives stratiform cloud layers and thereby the cloud amount

It appears that the positive feedbacks, though less intuitive, are more important; in models, the low-cloud feedback ranges from -0.09 to $+0.63$ W m^{-2} K^{-1} (with approximately 80% probability of positive feedback)

Radiative forcing: aerosol–radiation and aerosol–cloud interactions



Aerosol–cloud and aerosol–radiation interactions: large uncertainties



Category	Best Estimate	Climate Model and/or Satellite Instrument	Reference
with mixed-phase clouds	–1.55	CAM Oslo	Hoose et al. (2010b)
with mixed-phase clouds	–1.02	ECHAM	Lohmann and Ferrachat (2010)
with mixed-phase clouds	–1.68	GFDL	Salzmann et al. (2010)
with mixed-phase clouds	–0.81	CAM Oslo	Storelvmo et al. (2008b; 2010)
with convective clouds	–1.50	ECHAM	Lohmann (2008)
with convective clouds	–1.38	GISS	Koch et al. (2009a)
with convective clouds	–1.05	PNNL-MMF	Wang et al. (2011b)
Satellite-based	–0.85	ECHAM + POLDER	Lohmann and Lesins (2002)
Satellite-based	–0.93	AVHRR	Sekiguchi et al. (2003)
Satellite-based	–0.67	CERES / MODIS	Lebsock et al. (2008)
Satellite-based	–0.45	CERES / MODIS	Quaas et al. (2008)
Satellite-based	–0.95	Model mean + MODIS	Quaas et al. (2009)
Satellite-based	–0.85	MACC + MODIS	Bellouin et al. (2013)

AVHRR = Advanced Very High Resolution Radiometer. MACC = Monitoring Atmospheric Composition and Climate. POLDER = Polarization and Directionality of the Earth's Reflectances.
CERES = Clouds and the Earth's Radiant Energy System. MODIS = Moderate Resolution Imaging Spectrometer.

Confounding by meteorology

Aerosol depends on airmass history (origin, precipitation, humidity, . . .), but so do clouds

Non-monotonic behavior of the adjustments

Magnitude and even sign of the adjustments depends on details of small-scale processes

Uncertain preindustrial state

Unlike for WMGHG, we have no reliable estimates of preindustrial aerosol; biomass burning contributed anthropogenic aerosol even before the Industrial Revolution