UNIVERSITÄT LEIPZIG

Climate Dynamics (Summer Semester 2017)

J. Mülmenstädt

Today’s Lecture (Lecture 13): Uncertainties due to clouds and aerosols

Reference

IPCC AR5, Chs. 7 and 9

5.3 – Clouds and aerosols

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

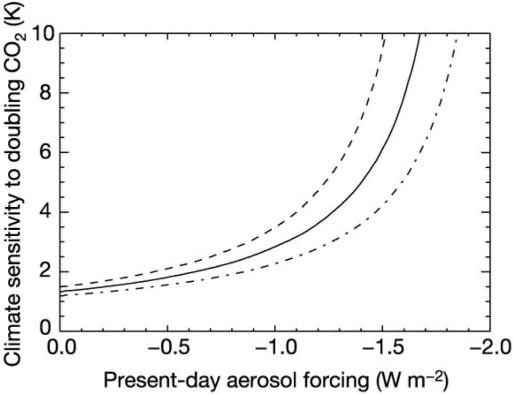
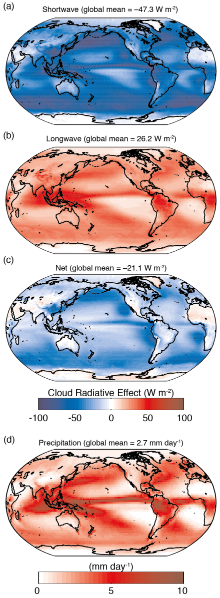


Figure: Andreae et al. (2005)

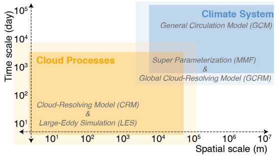
Challenges related to clouds



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



Figures: IPCC AR5 unless noted

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

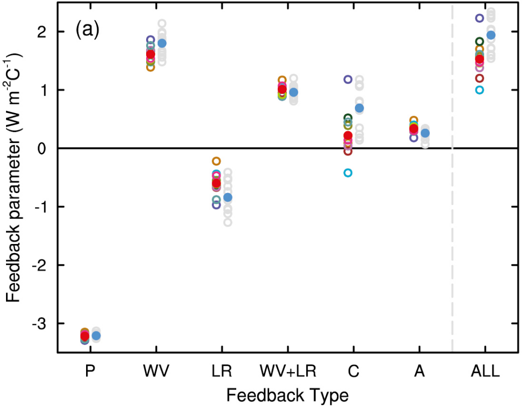
CRE is large compared to feedbacks (and forcings)

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

Need for models to evaluate feedbacks

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

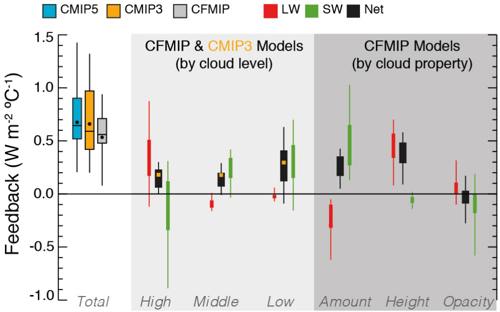
Feedbacks: water vapor + lapse rate



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

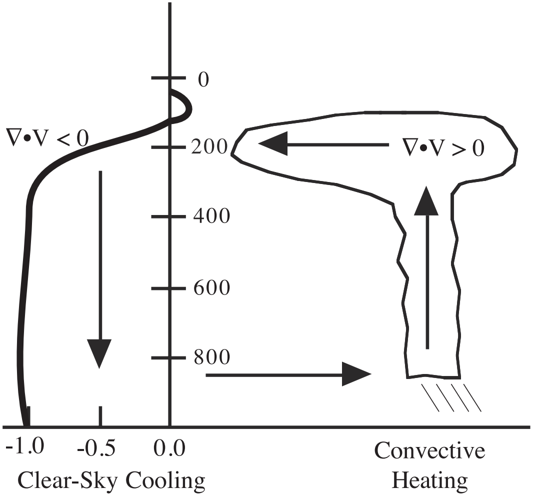


Cloud feedbacks:

- Changes in high-level cloud altitude and amount
- 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

Some changes occur at the GCM resolved scale, but most involve subgrid-scale processes that need to be parameterized

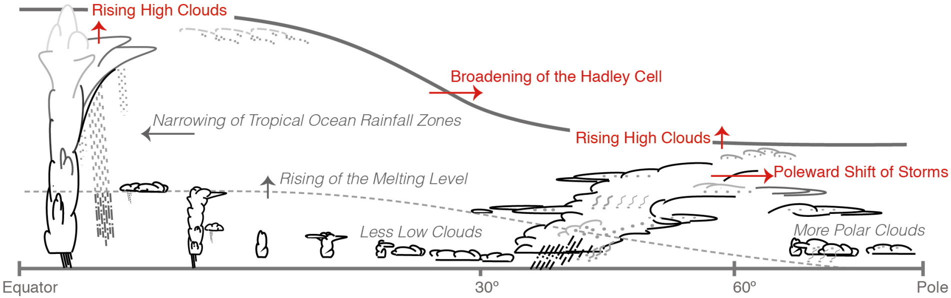
Cloud feedbacks: high-cloud altitude



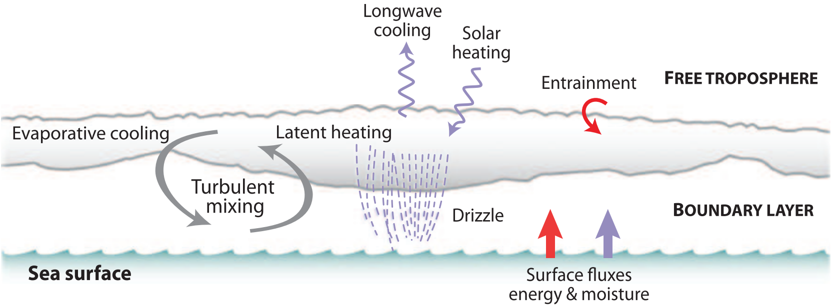
- Ascent in tropical deep convection is mass-balanced by compensating subsidence
- Compensating subsidence is due to equilibrium between radiative cooling and adiabatic compression
- The subsidence top occurs at the altitude where the water vapor mixing ratio decreases rapidly ($\approx$ 220 K); the 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



Boundary layer – the cloud-process view



Vertical structure

Boundary layer	is well mixed and capped by a . . .
Cloud layer	which maintains a temperature inversion by cloud-top cooling and is weakly coupled to the . . .
Free troposphere	by an entrainment layer

Processes

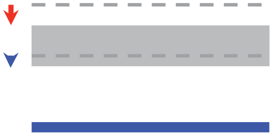
Sensible and latent heat flux	at the surface and . . .
Radiative cooling	at cloud top destabilize the airmass; this results in . . .
Convection	which mixes the layer vertically and horizontally

Figure: Wood 2012

Cloud feedbacks: low cloud

radiative

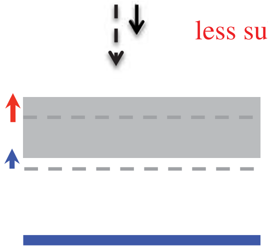
more emissive FT
(more CO_2 or H_2O)



less turbulence production by top longwave cooling. Less entrainment. Sc lowers, thins

dynamic

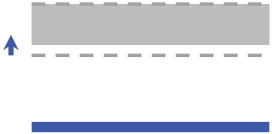
less subsidence



Sc top rises. More entrainment lifts cloud base. Sc thickens

thermodynamic

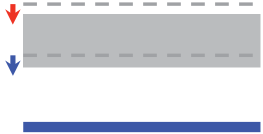
warmer SST
or drier RH



larger surface – FT moisture difference allows thinner cloud to sustain same entrainment. Sc thins

inversion strength

FT warms more than SST



stronger inversion reduces entrainment. Sc top and base lower. Sc thickens

Figure: Bretherton (2015)

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

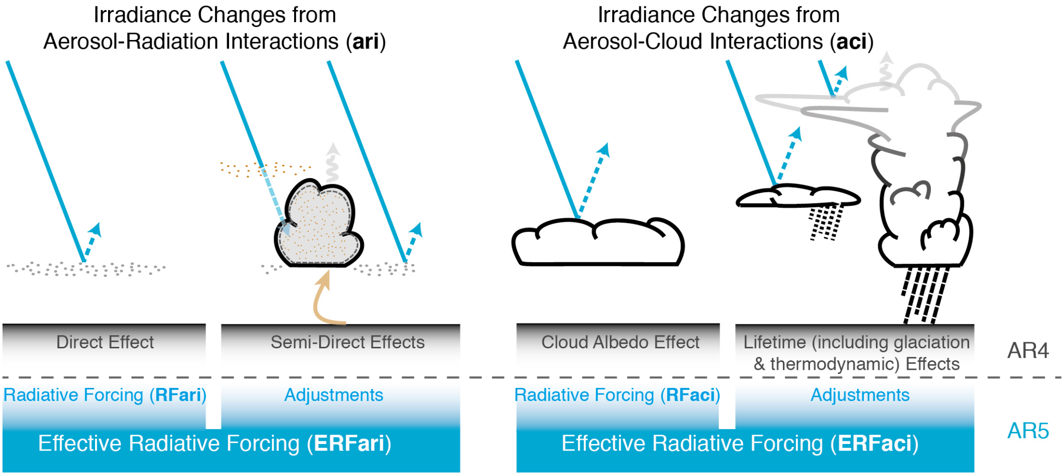
- horizontally more extensive, because changes in the lapse rate also modify the lower-tropospheric stability
- optically thicker, because adiabatic ascent condenses more liquid
- vertically more extensive in response to weakening of the tropical overturning circulation

Positive feedback mechanisms

- Warming-induced increase in moisture inversion strength reduces 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 GCMs, the low-cloud feedback ranges from -0.09 to $+0.63$ W m^{-2} K^{-1} (with approximately 80% probability of positive feedback); high-resolution modeling supports the mechanisms above

Radiative forcing: aerosol–radiation and aerosol–cloud interactions



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

AR4

Radiative Forcing (**RFari**)

Adjustments

Radiative Forcing (**RFaci**)

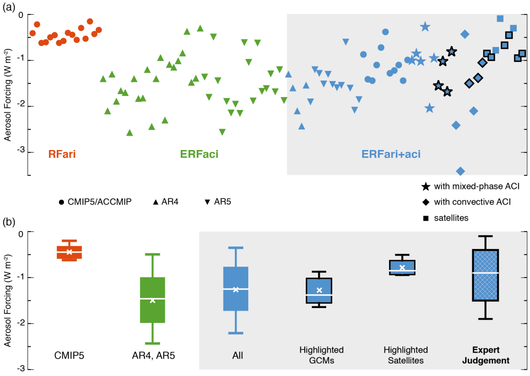
Adjustments

Effective Radiative Forcing (**ERFari**)

Effective Radiative Forcing (**ERFaci**)

AR5

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