Cloud feedback

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What is cloud feedback?

The effect on an externally-forced climate perturbation of the response in cloud properties, especially:

– cloud fraction
– liquid/ice water path
– and their vertical distribution

Main practical interest is GHG-induced global warming:

feedback on global temperature $T_s$ via $\Delta$(TOA radiation)
[surface temperature and rainfall patterns]

Combination of

- fast ‘semidirect’ cloud response to GHG radiative changes
- ‘temperature-mediated’ cloud response to warming $T_s$
Outline

• GCM cloud feedback is positive, though $\Delta$CRF isn’t. Why?
• Subtropical low cloud feedback: compensating processes make models diverge and assessment difficult.
• Observing cloud feedbacks relevant to global warming - as unsolved problem.
Cloud feedback in GCMs is positive but uncertain

Clouds
0.16±0.05

Albedo
0.06±0.02

Water vapor/lapse rate
0.25±0.02

Feedback factor $f$

Total
0.48±0.05

IPCC 2007

Bony et al. 2008
Clouds are hard to simulate with climate models

Clouds challenge both the grid resolution and physical parameterizations of climate models

- Often thin, short-lived
- Often produced by small-scale turbulence (e.g. cumuli)
- Complex interactions of water and ice particles
- Cloud radiative effects can have either sign
  - High, thin clouds warm (greenhouse effect dominates)
  - Low clouds cool (shading effect dominates)

Hence the spread in GCM-simulated cloud feedbacks is not surprising. Identifying physical mechanisms can help organize model analysis and observational strategies.

Low clouds are particularly difficult due to their strong radiative feedbacks with turbulence.
Current cloud feedback methodologies

- **Analysis of GCM spread (coupled,+2K, step 4xCO₂)**
- Process models and mechanisms.
- Observed cloud and radiation trends and variability.
AR4-mean $\Delta$CRF $\approx 0$ for CO$_2$ doubling.

CRF = TOA cloud radiative forcing = net downward $F_{\text{rad}} - F_{\text{rad}}^{\text{clr}}$

- Tropical $\Delta$SWCRF drives spread but $> 0$ in most models (less low cld)
- Tropical $\Delta$LWCRF $< 0$ in most models (less high cld).
- How can cloud feedback be positive even if $\Delta$CRF $\approx 0$?

Bony et al. 2006
Partitioning of AR4 tropical $\Delta CRF/\Delta T_s$ vs. dynamical regime

- Median model shows little shortwave or longwave $\Delta CRF/\Delta T_s$ in deep convective regimes ($\omega_{500} < 0$)
- Model spread comes from subsiding regimes (boundary-layer clouds)
Soden et al (2004): $\Delta$CRF $\neq$ cloud feedback
... though they are well correlated.

Tropical mechanism: In a warmer, moister climate, the same cloud at the same level has less additional greenhouse effect. Hence, with no cloud feedback, $\Delta$CRF $\approx$ $\Delta$LWC$\text{CRF} < 0$. 

Shell et al. 2008
FAT and positive high cloud feedback

• Fixed Anvil Temperature (FAT) hypothesis (Hartmann and Larson 2002): Tropical ice clouds move upward in a warmer climate following isotherms, at least in models.

• This is a major contributor to positive cloud feedback.
Fixed Anvil Temperature (FAT) hypothesis

- Substantial clear-sky radiative cooling requires water vapor
- Upper tropospheric water vapor is temperature-limited.
- Clear-sky radiative cooling is weak for $T < 200$ K.

$\Rightarrow$ Convective anvil tops will occur near $T = 200$ K, regardless of surface temperature.

AR4 models, A1B scenario (Zelinka and Hartmann 2009)

Hartmann and Larson 2002
Vertical cloud profile changes with $\Delta T_s$

Kuang and Hartmann 2007: Radiative-convective equilibrium over fixed SST in a cloud-resolving model (CRM).

- Entire cloud profile above the freezing level collapses when plotted vs. $T$, while it rises 350 m/K$_{SST}$ when plotted vs. $z$. GCMs do similarly.
- FAT control anchors anvil tops, freezing level anchors bases, $T$-dependence of ice microphysics may help.
Summary of GCM cloud feedbacks

• Upward migration of tropical ice cloud and RH profiles produce strong high cloud feedback despite $\Delta LW_{CF} \approx 0$.

\[
\Delta LW_{FAT} = -\sigma \left[ T_A^4 - (T_A + \Delta T(z_A))^4 \right] f_{hi} \\
= - \frac{4 \sigma T_A^3}{2.5 \text{Wm}^{-2}\text{K}^{-1}} \frac{(\Delta T(z_A) / \Delta T_s)}{2} \frac{f_{hi}}{0.2} \\
\approx 1 \text{Wm}^{-2}\text{K}^{-1}
\]

• Enhanced in many models by positive subtropical low cloud feedback.

• In midlatitudes, rising freezing level induces a deeper layer of optically thick water cloud below (negative SW feedback) ; Senior and Mitchell (1993)
Clouds are turbulently maintained by radiative cooling and surface moistening/heating. Turbulence drives entrainment through capping inversion, which counteracts mean subsidence. Shallow PBL is well mixed with Sc, deep PBL is ‘Cu-coupled’
Subtropical low cloud feedback mechanisms

Due mainly to changes in stratification and free-trop emissivity

$\Delta \theta$  Warmer $\Rightarrow$ stronger inversion $\Rightarrow$ more cloud  $\quad$ (-)

$\Delta CO_2$  More CO$_2$ $\Rightarrow$ Less PBL rad cooling $\Rightarrow$ less cloud  $\quad$ (+)

$\Delta w$  Warmer $\Rightarrow$ less subsidence $\Rightarrow$

deeper, more cumuliform PBL $\Rightarrow$ less cloud  $\quad$ (+)
[but $w$ is driven by radiative + eddy cooling]

$\Delta RH$  Drier free-trop $\Rightarrow$ More PBL rad cool $\Rightarrow$ more cloud  (-)
Lower tropospheric stability \( \text{LTS} = \theta_{700} - \theta_{1000} \)

Correlated with subtropical marine low cloud cover in current climate (Klein & Hartmann)

\[ +1 \text{K} \Delta \text{LTS} \leftrightarrow +6\% \Delta \text{low cld} \leftrightarrow -6 \text{W m}^{-2} \Delta \text{CRF} \]

Less skillful in mid-latitudes. (EIS better)
LTS-predicted cloud feedback

- In a warmer climate, the low-latitude free troposphere has larger $d\theta/dz$.
- For spatially uniform SST increase, $\Delta \text{LTS} \approx 0.5 \Delta \text{SST}$
- Klein-Hartmann regression predicts 3%/K SST increase (Miller 1997), creating a strong negative low cloud feedback on climate change.
- However, ‘Klein line’ not predictive of GCM 2xCO$_2$ low cloud change (Meideros et al. 2008) - may not be climate-invariant.
Estimated Inversion Strength

Wood and Bretherton (2006)

- In the free-troposphere, \( d\theta/dz = \Gamma_{FT} \) follows a moist adiabat from 700 hPa to the MBL top.

- Well mixed surface layer below the LCL, i.e. \( d\theta/dz = 0 \)

- In the cloud layer, \( d\theta/dz = \Gamma_{CL} \) follows a moist adiabat from the top of the LCL to the MBL top.
EIS much better correlated than LTS with low cloud over the midlatitude oceans (where the summertime free troposphere is also close to moist-adiabatic but not as warm as in tropics)

EIS more climate-invariant?
Cloud amount vs EIS (SST+2K)

Wood and Bretherton

- SP-CAM
- CAM3
- AM2
- ISCCP/ERA40
- Obs fit
Low cloud change in an ensemble of 2xCO$_2$-control GCM simulations is poorly estimated using $\Delta$LTS.

Much better agreement with change in saturated stability (related to $\Delta$EIS).

Models with $\Delta$EIS >0 over subtropics tend to have $\Delta$lowcld>0.

$L\delta q/c_p \delta \theta$ also relevant? (Lock 2009)
A new path forward: Cloud-resolving models

- CRMs can simulate PBL clouds more realistically, given adequate grid resolution and ‘large-scale advective forcings’ of temperature, humidity.
- To apply CRMs to cloud feedback problem, must either:
  - run on a global scale (computationally intense)
  - run in limited domain, specify large-scale context

Focus: subtropical trades - important, well represented by CRMs with $\Delta z < 100$ m, $\Delta x < 250$ m.
Cloud feedbacks in a superparameterized GCM

- Superparameterization - a climate model with a small CRM running in place of the normal physical parameterizations in every grid column.
- Computationally expensive, but may simulate turbulent clouds (especially deep convection) more realistically.

- SP-CAM (Khairoutdinov and Randall 2005) uses 2D CRMs with 32x30 gridpoints, $\Delta x = 4$ km and $\Delta z \sim 200$ m in PBL - underresolves boundary-layer Cu and Sc.
- Has strong negative subtropical +2K low cloud feedbacks with $\Delta EIS > 0$ and increased boundary-layer radiative cooling (Wyant et al. 2009)
- Investigate low cloud response to instantaneous 4x CO$_2$ increase with fixed SST.
4xCO₂ experiment with SP-CAM

• Increase CO₂ while keeping SST constant (Gregory and Webb 2008).
• Complements +2K SST experiment by focusing on direct effects of CO₂-induced radiative changes on clouds.
• 2½ year integrations are used with the first ½ year discarded...short, but results hold in each of the 2 years.

Concept: More CO₂ ⇒ More downwelling LW ⇒ Less PBL radiative cooling

\[ \Delta 4xCO_2 \]

Radiative Heating

Cloud

\[ \Delta SWCF = 0.7 \text{ W m}^{-2} \]
MBL depth for control and perturbed runs

SST+2K

N×CO₂

MBL depth decreases despite reduced subsidence from CO₂ FT warming ⇒ MBL turbulence weakens

Rob Wood
A phase space for subtropical low cloud change

- EIS, stability-driven changes
- free trop. rad. heating/LW down changes
- $N \times CO_2$ fixed SST
- $N \times CO_2$ with SST
- SST+2K
- low cloud cover increasing

Rob Wood
Trends in surface and satellite cloud observations

- Surface ship observations show implausible low cloud cover increase since 1950 (sampling/reporting changes?)
- Satellite observations show low cloud decrease since 1983 (orbital and sensor drift)

⇒ Observations inadequately constrain global cloud feedbacks.
NE Pacific cloud variability: a cloud feedback analogue? (Clement et al. 2009 Science)

- NE Pacific interannual low cloud variability responds to Pacific Decadal Oscillation, increasing when regional SST decreases (noted earlier by Klein&Hartmann, Norris, etc.)
- Clement et al. treat this as evidence of positive cloud response to a warmer climate (warmer SST ⇒ less clouds).
- This ignores crucial role of free troposphere:
  Global warming: free trop warms more than subtropical SST, increasing LTS.
  NE Pac variability: free trop changes much less than subtropical SST, decreasing LTS.
- One MUST look for observational analogues with vertical stratification changes similar to global warming and/or
  convincingly test individual cloud feedback mechanisms (Clement et al. present a flawed approach to this, too)
Conclusions

• GCMs produce positive cloud feedback due to isothermal rise of high clouds and (in most models) subtropical cloud decreases.

• SP-CAM LES-based GCM suggests direct radiative response to more CO₂ is decreased low cloud.

• T-mediated cloud response is a tradeoff between a stronger inversion (more cloud) and deeper, decoupled boundary layer (less cloud) in a warmer climate. Models uncertain due to compensating feedbacks.

• Observations have not yet usefully constrained cloud feedbacks. A major breakthrough in cloud feedbacks would be to convincingly bring observations and models together.
Column analogue to SP-CAM

Hypothesis
Low cloud change can be idealized as a steady-state response to large-scale changes in subtropical free-trop temperature, RH, and GHG profiles and horizontal T/q advection.

Method (Blossey et al. 2009 JAMES):
1. For some cloud regime, make composite forcings/profiles for ctrl and SST+2K runs:
   - SST and surface wind speed
   - profiles and advective tendencies of T,q
   - Vertical p-velocity $\omega$
   We defined a Sc-to-Cu transitional regime using 80-90 percentiles of LTS over low-lat ocean column-months, and calculated the forcings from SP-CAM.
   CGILS is using regimes defined along NE Pacific transect.
2. Run CRM to steady-state with both forcings. 500 day integrations are used to calculate +2K cloud differences.
   Compare ‘CRM4km’ configured as in SP-CAM (dx=4km, L30) and high resolution CRM (dx=100m, dz=40m) to SP-CAM composites.
LTS80-90 forcings and profiles (from SP-CAM)

θ,q profiles; SST

advection

winds

ctrl +2K

hor tot

−u · ∇θ

+ ω′ + q nudging

averaging period

E-W and N-S winds, m s⁻¹
SP-CAM

CRM4km (similar to SP-CAM)

CRM100

Less cld and Δcld than 4km