The Importance of Cloud Thermodynamic Phase Partitioning for Equilibrium Climate Sensitivity Estimates

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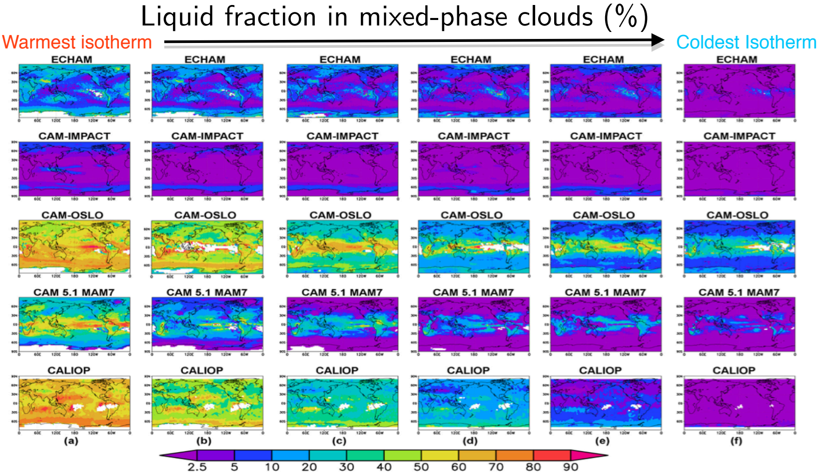
Motivation



From Fig. 3, Komurcu *et al* (2014)

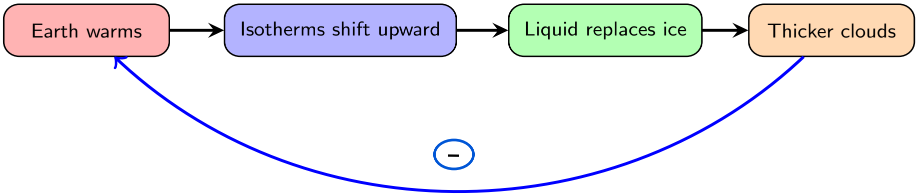
Motivation

Cloud thermodynamic phase partitioning in mixed-phase clouds:

- is poorly constrained in models owing to lack of observations
- can influence equilibrium climate sensitivity (ECS) through ramifications of the cloud phase feedback

Cloud Phase Feedback

A negative feedback, where as the atmosphere warms, the isotherm at which liquid in mixed-phase clouds freezes into ice moves upward in altitude, thereby leaving behind liquid at the altitude at which ice was previously present. The resulting optically thicker liquid clouds with longer lifetimes act to lower surface temperatures.



Objectives

1. Use observations of cloud phase to constrain it by repeatedly adjusting cloud microphysical tuning parameters related to mixed-phase cloud processes in a model
2. Apply a sensitivity analysis to quantify the relative importance of the mixed-phase cloud processes
3. Isolate how cloud phase partitioning impacts ECS estimates based on these constrained simulations

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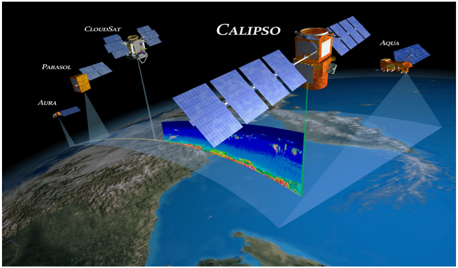
Tools

- **GCM:** NCAR's CESM
- **Satellite observations:** NASA's CALIOP

Method

CALIOP



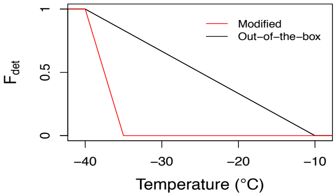
- Level 2, VFM
- Nighttime, medium and high confidence CAD scores only
- Nov 2006 - Dec 2013
- NCEP-DOE Reanalysis II Data to obtain data on isotherms

$$SCF = \frac{f_{liquid}}{f_{ROIC} + f_{HOIC} + f_{liquid}}$$

Method

CESM

- CAM5.1 microphysics with MAM3 & CESM1.0.5
- Standalone: $4^{\circ} \times 5^{\circ}$ horizontal, 30 vertical levels, 15 months
- Coupled resolution: $1.9^{\circ} \times 2.5^{\circ}$ horizontal, 30 vertical levels
- Meyers *et al.* (1992) with DeMott *et al.* (2015) parameterization of IN concentrations (uses prognostically modelled dust aerosol concentrations $>0.5\ \mu$m in diameter)
- Adjustments to the original convective detrainment scheme



$$SCF = \frac{r_{liquid}}{r_{ice} + r_{liquid}}$$

Method

Quasi-Monte Carlo sampling of a 6-D cloud microphysical parameter space

Process Investigated	Parameter	Default Value	Investigated Range
Fraction of dust aerosols active as IN	*fin*	1	[0,0.5]
WBF timescale exponent for ice	*epsi*	0	[-6, 0]
WBF timescale exponent for snow	*epss*	0	[-6, 0]
Fraction of aerosols scavenged in stratiform clouds	*sol_facti*	1	[0.5,1]
Fraction of aerosols scavenged in convective clouds	*sol_factic*	0.4	[0.2,0.8]
Ice crystal fall speed	*ai*	700 s^{-1}	[350,1400] s^{-1}

- Adopted QMC sampling to select 256 parameter combinations
- Assuming uniform probability distributions for the parameters following Zhao *et al.* (2013), QMC sampling spans full parameter space, guarantees good dispersion of the parameters

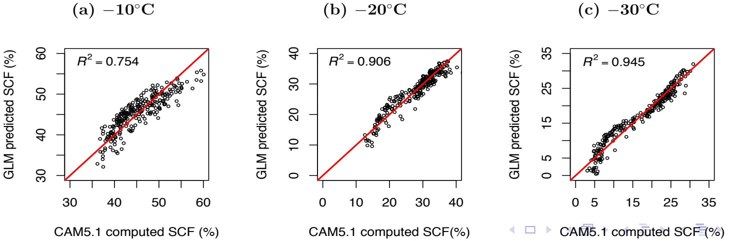
Method

Variance-Based Sensitivity Analysis: Generalized Linear Model

- The contribution of individual parameters and two-way interactions between them on variance in SCF through null hypothesis testing

$$Y^i = \beta_0 + \sum_{j=1}^{n} \beta_j \cdot p_i^j + \sum_{j=1}^{n}\sum_{k=1}^{n} \beta_{j,k} \cdot p_j^i \cdot p_k^i + \varepsilon_i, \varepsilon_i \overset{iid}{\sim} N(0, \sigma^2),$$

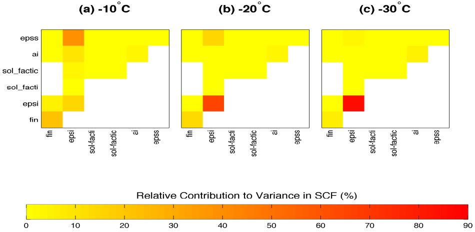
Globally-averaged SCFs:



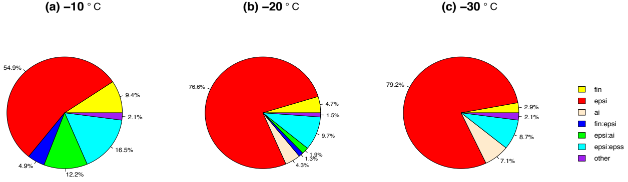
Results

Sensitivity Analysis

Globally-averaged SCFs:



Southern Ocean SCFs:



R^2=0.89 R^2=0.95 R^2=0.97

Method

Selecting the "best" matches to CALIOP observations

- Selection criteria: want to select the simulations that perform best overall (in all 9 latitude bands and 3 isotherms)

$$score = \sum_{j=1}^{n} \sum_{i=1}^{m} \left(\overline{SCFM_{i,j}} - \overline{SCFO_{i,j}} \right)$$

- Parameters yielding "best" matches will be used in CALIOP-constrained simulations that will be run to equilibrium

Results

Global SCFs – CALIOP & CALIOP-Constrained

CALIOP

Best match #1: CESM-7

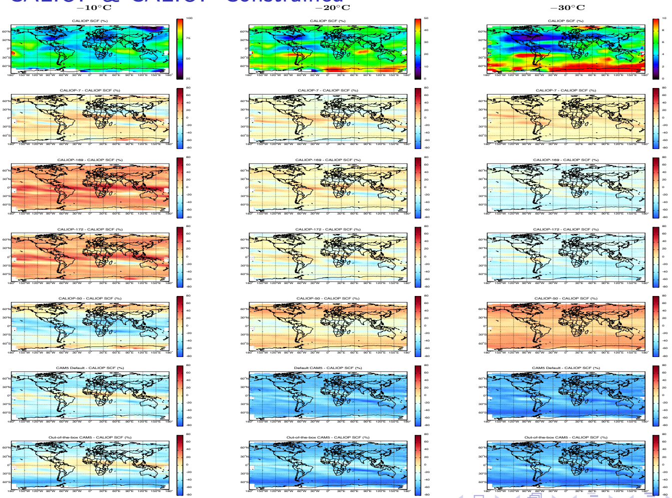
Best match #2 CESM-169

Best match #3: CESM-172

Worst match: CESM-50

Default CAM5

Out-of-the-box CAM5



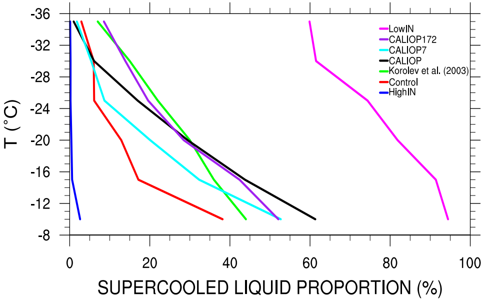
CESM Simulations

Model: CAM5.1/CESM1.0.5 at 1.9° × 2.5°, 30-level resolution

- SCF in extreme simulations, LowIN & HighIN mainly controlled through ice nuclei (IN) concentrations

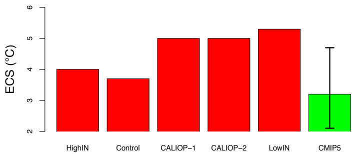
Simulation	Description
LowIN†	ice-nuclei-free
Control	out-of-the-box CESM
CALIOP-7†	CALIOP-constrained
CALIOP-172†	CALIOP-constrained
HighIN†	ice nuclei × 75

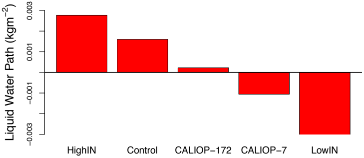
† Includes modified detrainment scheme and DeMott *et al.* [2015] ice nucleation scheme



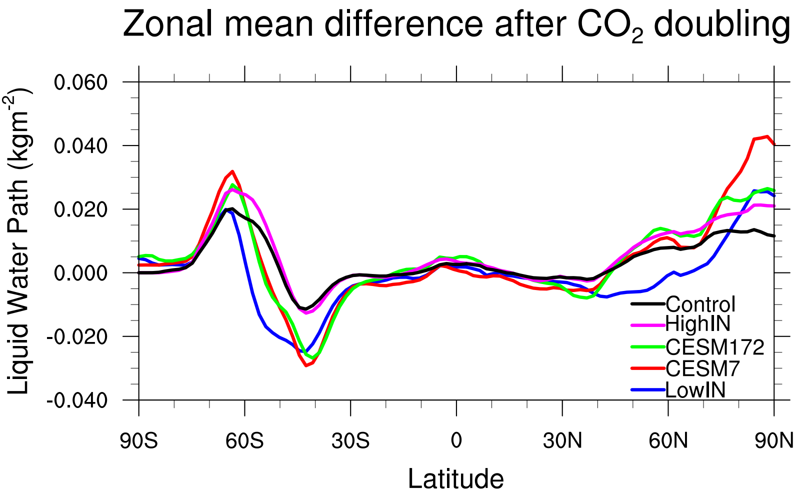
Total: 10 simulations (PD & 2xCO2)

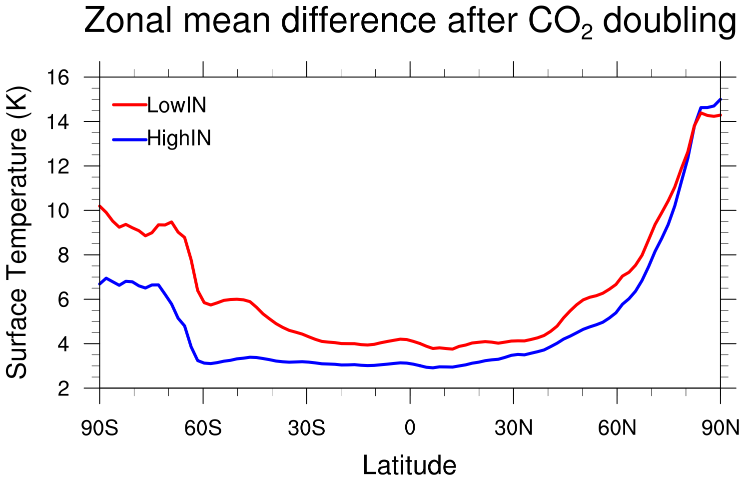
Preliminary Equilibrium Climate Sensitivities





- The CALIOP-constrained simulations are closer to the upper bound of the CMIP5 ECS estimates
- ECS of CESM are $\sim$2°C above the CMIP5 mean when SCFs are higher in the model


Zonal mean difference after CO_2 doubling
Liquid Water Path (kgm^{-2})
0.060
0.040
0.020
0.000
-0.020
-0.040
90S
60S
30S
0
30N
60N
90N
Latitude
Control
HighIN
CESM172
CESM7
LowIN



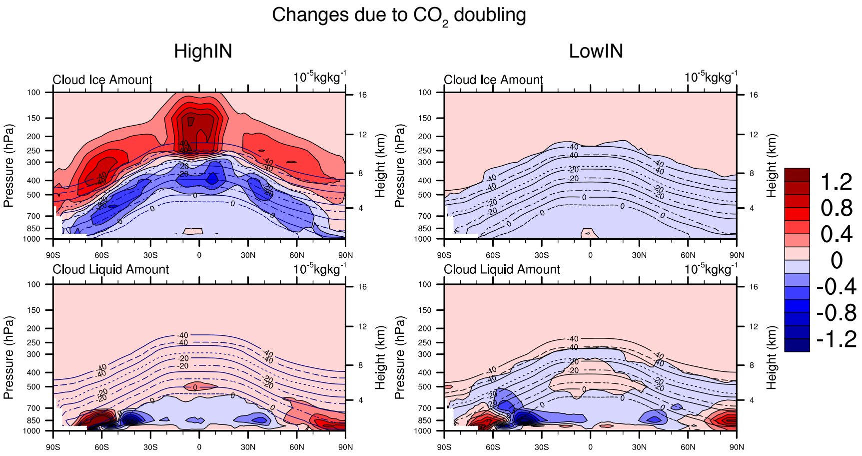
Zonal mean difference after CO_2 doubling
Surface Temperature (K)
16
14
12
10
8
6
4
2
LowIN
HighIN
90S
60S
30S
0
30N
60N
90N
Latitude

Cloud Radiative Forcings

Decease in SWCF in LowIN after CO_2 doubling dominates

Simulation	SWCF (Wm^{-2})	LWCF (Wm^{-2})
HighIN	-67.3	38.7
HighIN_2xCO_2	-67.2	39.1
HighIN_2xCO_2 – HighIN	0.094	0.45
	very small warming	**small warming**
LowIN	-62.0	31.1
LowIN_2xCO_2	-57.3	29.0
LowIN_2xCO_2 – LowIN	4.7	-2.1
	strong warming	**moderate cooling**

Cloud phase feedback at work



Conclusions

- Cloud liquid is greatly underestimated in CESM compared to observations by CALIOP outside the tropics and extratropics
- WBF process timescale for growth of ice single-handedly accounts for most of the variance in SCF in CAM5
- The CALIOP-constrained simulations generally have much higher SCFs and ECS near the upper bound of the CMIP5 models, exceeding the CMIP5 mean by $\sim 2^{\circ}$C
- ECS increase when SCFs are tuned to match observations. The cloud phase feedback likely accounts for this effect and potentially much of the spread in ECS among the CMIP5 models
- The fact that liquid replaces ice higher in the atmosphere in LowIN in the cloud phase feedback can explain the larger decrease in shortwave cloud forcing, which leads to a greater warming effect