Estimation of **Climate Sensitivity** at Surface from **CESM1, CCSM4** and Observation

AMWG Meeting. NCAR. Boulder.
Feb. 15. 2011

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20th Century Simulation

Why does the simulation differ from the observation?

FORCING
Natural: Solar Radiation, Volcanic Eruption
Anthropogenic: CO₂, CH₄, N₂O, O₃, Aerosols

FEEDBACK or PARAMETERIZATION
$2 \times CO_2$ CESM1 SOM Experiment

SOM : Slab Ocean Model

\[ LHF \approx -C_D \cdot WS \cdot \left[ q_s(T_s) - q_{v,\text{air}} \right] \]

\[ SHF \approx -C_D \cdot WS \cdot \left[ T_s - T_{\text{air}} \right] \]

$\psi \equiv \frac{T'}{F'_{AN}} = 0.8 \text{ [K/W m}^{-2}\text{]}$
MOTIVATIONS

• *Conventional* climate sensitivity defined as the response of global surface temperature to global radiative forcing at TOA is a convenient quantity because it is a single-valued and easy to compare between the models.

• However, global surface temperature is controlled by LHFLX, SHFLX and surface radiative flux, each of which is not slaved to radiative forcing at TOA even though the sum is.

• Once initial surface temperature anomaly is developed by external radiative forcing, subsequent evolution of surface temperature is controlled by the way how each LHFLX, SHFLX and surface radiative flux responds to underlying surface temperature anomalies, i.e., *surface heat flux feedback, λ*.

• Thus, detailed analysis of surface heat flux feedback for each surface heat flux component may provide useful information for understanding global climate sensitivity.

• This analysis can be useful in tracing the source of discrepancy between the observed and simulated climate sensitivities down into the process levels (e.g., PBL, convection, macro-micro, aerosol, radiation, dynamic processes).
Linkage between **Climate Sensitivity** and $\lambda$

- Imagine a static ocean mixed layer with a depth of $H$.
- Any natural surface flux $Q'$ can be represented as a linear function of underlying SST, $T'$ using a Taylor expansion as $Q' = -\lambda \cdot T' + f'_{NA}$ where $f'_{NA}$ is a fast (e.g., stochastic) atmospheric forcing.
- Anthropogenic forcing, $F'_{AN}$ is additionally added.
- Then, we can write the following budget equation for a static ocean mixed layer:

$$c \cdot \frac{dT'}{dt} = -\lambda \cdot T' + f'_{NA} + F'_{AN}$$

$$c \equiv \rho \cdot C_p \cdot H$$

$$T'(t) = \exp\left( -\frac{\lambda}{c} \cdot t \right) \cdot \left[ T'(0) + \frac{1}{c} \int_0^t f'_{NA}(t') \cdot \exp\left( -\frac{\lambda}{c} \cdot t' \right) \cdot dt' \right] + \frac{F'_{AN}}{\lambda} \cdot \left[ 1 - \exp\left( -\frac{\lambda}{c} \cdot t \right) \right]$$

- Regardless of the types of external forcing, climate sensitivity at surface, $\psi \left[ \frac{K}{W m^{-2}} \right]$ is controlled by the strength of **surface heat flux feedback**, $\lambda \left[ \frac{W m^{-2}}{K} \right]$.

$$\psi \equiv \left| \frac{T'}{F'_{AN}} \right| = \frac{1}{\lambda} > 0$$
Surface Heat Flux Feedback Parameter $\lambda$ \((\text{W m}^{-2} \text{K}^{-1})\):

The change of upward surface flux when underlying surface temperature increases by 1K.

$$\lambda = \lambda_{\text{LHF}} + \lambda_{\text{SHF}} + \lambda_{\text{SW}} + \lambda_{\text{LW}}$$

$$\lambda_{\text{LHF}} = \lambda_{\text{LHF,qv(sfc)}} + \lambda_{\text{LHF,qv(air)}} + \lambda_{\text{LHF,ws(air)}} + \lambda_{\text{LHF,SS}}$$

$$\lambda_{\text{SHF}} = \lambda_{\text{SHF,T(sfc)}} + \lambda_{\text{SHF,T(air)}} + \lambda_{\text{SHF,ws(air)}} + \lambda_{\text{SHF,SS}}$$

$$\lambda_{\text{SW}} = \lambda_{\text{SW,CLR}} + \lambda_{\text{SW,CLD}}$$

$$\lambda_{\text{LW}} = \lambda_{\text{LW,CLR}} + \lambda_{\text{LW,CLD}}$$

$$\lambda_{\text{SW,CLR}} = \lambda_{\text{SW,CLR,A}}$$

$$\lambda_{\text{SW,CLD}} = \lambda_{\text{SW,CLD,Sc}} + \lambda_{\text{SW,CLD,Ci}}$$

$$\lambda_{\text{LW,CLR}} = \lambda_{\text{LW,CLR,P}} + \lambda_{\text{LW,CLR,W}}$$

$$\lambda_{\text{LW,CLD}} = \lambda_{\text{LW,CLD,Sc}} + \lambda_{\text{LW,CLD,Ci}}$$
<table>
<thead>
<tr>
<th>Turbulent Fluxes</th>
<th>Clear-Sky Radiation</th>
<th>Cloudy-Sky Radiation</th>
</tr>
</thead>
</table>
| \[
\lambda_{\text{LHF, } qv(sfc)} + \lambda_{\text{SHF, } T(sfc)}
\] | \[
\lambda_{\text{LW, CLR, P}}
\] | \[
\lambda_{\text{SW, CLD, Sc}}
\] |
| \[
\lambda_{\text{LHF, } qv(\text{air})} + \lambda_{\text{SHF, } T(\text{air})}
\] | \[
\lambda_{\text{SW, CLR, A}}
\] | \[
\lambda_{\text{SW, CLD, Ci}}
\] |
| \[
\lambda_{\text{LHF, } ws(\text{air})} + \lambda_{\text{SHF, } ws(\text{air})}
\] | \[
\lambda_{\text{LW, CLR, W}}
\] | \[
\lambda_{\text{LW, CLR, W}}
\] |
| \[
\lambda_{\text{LHF, SS}} + \lambda_{\text{SHF, SS}}
\] | \[
\lambda_{\text{SW, CLR, Sc}}
\] | \[
\lambda_{\text{LW, CLD, Sc}}
\] |
| \[
\lambda_{\text{LW, CLD, Ci}}
\] | \[
\lambda_{\text{SW, CLD, Ci}}
\] | \[
\lambda_{\text{LW, CLD, Ci}}
\] |

- Apparent Turbulent Damping
- Atmospheric Thermal Adjustment
- Surface Wind Speed Feedback
- Surface Stability Feedback
- Apparent Planck Radiative Feedback
- Surface Albedo Feedback
- Water Vapor Feedback
- SW Stratocumulus Feedback
- SW Cirrus Feedback
- LW Stratocumulus Feedback
- LW Cirrus Feedback

\[
\mathcal{Q}' \approx q' - \lambda \cdot T'
\]

\[
\lambda(t) = \left[ \frac{\text{Cov}(T'(t - \Delta t) \cdot q'(t)) - \text{Cov}(T'(t - \Delta t) \cdot Q'(t))}{\text{Cov}(T'(t - \Delta t) \cdot T'(t))} \right]
\]

\[
\tau_q << \Delta t << \tau_T, \quad \Rightarrow \quad \text{Cov}(T'(t - \Delta t) \cdot q'(t)) \approx 0
\]

\[
\lambda(t) = -\left[ \frac{\text{Cov}(T'(t - \Delta t) \cdot Q'(t))}{\text{Cov}(T'(t - \Delta t) \cdot T'(t))} \right] \quad \Delta t = 1, 2, 3 \text{ [ Month ]}
\]

**Data:**
- Monthly surface radiative flux from ISCCP-satellite (1984-2007)
- Ship-observed monthly SST and latent & sensible heat fluxes (1956-2008)
- Monthly SST & surface heat fluxes from 160/200-years coupled CCSM4/CESM1
- *Linear ENSO signals were pre-filtered before performing this analysis.*
Latent Heat Flux Feedback, $\lambda_{\text{LHF}}$

Yellow Color: No Observation Or Not-Valid Analysis

Solid line: Ship-observed Stratocumulus AMT

OBS. JJA.

Positive Feedback: Amplifies $T_s'$

Negative Feedback: Dampens $T_s'$

CCSM4. JJA.

CESM1. JJA.
Sensible Heat Flux Feedback, $\lambda_{\text{SHF}}$

Solid line: Ship-observed Stratocumulus AMT

OBS. JJA.

CCSM4. JJA.

CESM1. JJA.
Apparent Planck Radiative Feedback, $\lambda_{\text{LW,CLR,P}}$  
( Use Clear-Sky Upward LW Flux at Surface )

OBS. JJA.

Solid line: Ship-observed Deep Cumulus FQ

CCSM4. JJA.

CESM1. JJA.
Water Vapor Feedback, $\lambda_{LW, CLR, W}$
( Use Clear-Sky Downward LW Flux at Surface )

Note that ISCCP LW radiation retrieval at surface is questionable.
Surface Albedo Feedback, $\lambda_{SW,CLD,A}$

(Use Clear-Sky Net Downward SW Flux at Surface)
**SW Cloud Feedback, $\lambda_{SW,CLD}$**

(Use Cloudy-Sky Net Downward SW Flux at Surface)

- **Negative SW radiative feedback** associated with Tropical Cirrus
- **Positive SW radiative feedback** associated with Stratocumulus

- **Solid line**: Ship-observed Stratocumulus AMT

- **Stronger Positive SW feedback** over the Arctic in CESM1
LW Cloud Feedback, $\lambda_{\text{LW,CLD}}$
(Use Cloudy-Sky Net Downward LW Radiative Flux at Surface)

Note that ISCCP LW radiation retrieval at surface is questionable.

No Infrared Iris of Tropical Cirrus

Infrared Iris of Stratocumulus
Mean Surface Heat Flux Feedback over the North Pacific
30°N-55°N, 140°E-240°E
Mean Surface Heat Flux Feedback over the Arctic
70°N-90°N, 0°E-360°E
Response of Atmospheric Profile to Surface Temperature Change

GLOBAL. ANNUAL.
Response of Physical Tendencies

GLOBAL. ANNUAL.

\[ \left( \frac{\partial T}{\partial t} \right) \]
Response of Atmospheric Profile to Surface Temperature Change

North Pacific. August.
**Why does simulation differ from observation?**

20th Century Coupled Simulation vs Obs.

‘Forcing’ (CO₂, Aerosol) or ‘Feedback’?

**Computation of Global Climate Sensitivity ψ**

2 x CO₂ Coupled [ SOM ] Experiment

- Remove uncertainty associated with ‘Forcing’
- A single ψ: easy to compare between models
- Cannot be compared with the observation
- Hard to dig-up physical insight on ψ

**Analysis of Surface Heat Feedback λ**

1850 Long-Term Coupled Simulation vs Obs.

- Directly comparable with the observation
- Provide physical and local insight on ψ

λ (θ, qᵥ, qᵢᵣ, u, v, ω, RH, CLDAMT; Tendency)

1850 Long-Term Coupled Simulation vs Obs.

• Provide physical insight on ψ at the process level

ψ ≡ \[ \frac{T'}{F''_{AN}} \]

T'

\[ \lambda(t) = \frac{\text{Cov}(T'(t - \Delta t) \cdot Q'(t))}{\text{Cov}(T'(t - \Delta t) \cdot T'(t))} \]

\[ \left[ \begin{array}{c} \lambda_{\text{LHF}} \\ \lambda_{\text{SHF}} \\ \lambda_{\text{LW,CLR,Planck}} \\ \lambda_{\text{LW,CLR,Water-Vapor}} \\ \lambda_{\text{LW,CLR,Sfc-Albedo-Ice}} \\ \lambda_{\text{SW,CLR,Stratocumulus}} \\ \lambda_{\text{SW,CLR,Cirrus}} \\ \lambda_{\text{LW,CLR,Cirrus}} \end{array} \right] \]
\[
\rho \cdot C_p \cdot H \cdot \frac{dT'}{dt} = -\lambda \cdot T' + f'_{NA} + F'_{AN}
\]

\[
\rho = 1025.\text{[kg/m}^3\text{]} \quad C_p = 4000.\text{[J/kg/K]} \quad H = 1000.\text{[m]}
\]

\[
|f'_{NA}| = 200.\text{[W/m}^2\text{]} \quad \text{Gaussian white noise}
\]

\[
\psi \equiv \left| \frac{T'}{F'_{AN}} \right| = \frac{1}{\lambda} > 0
\]