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

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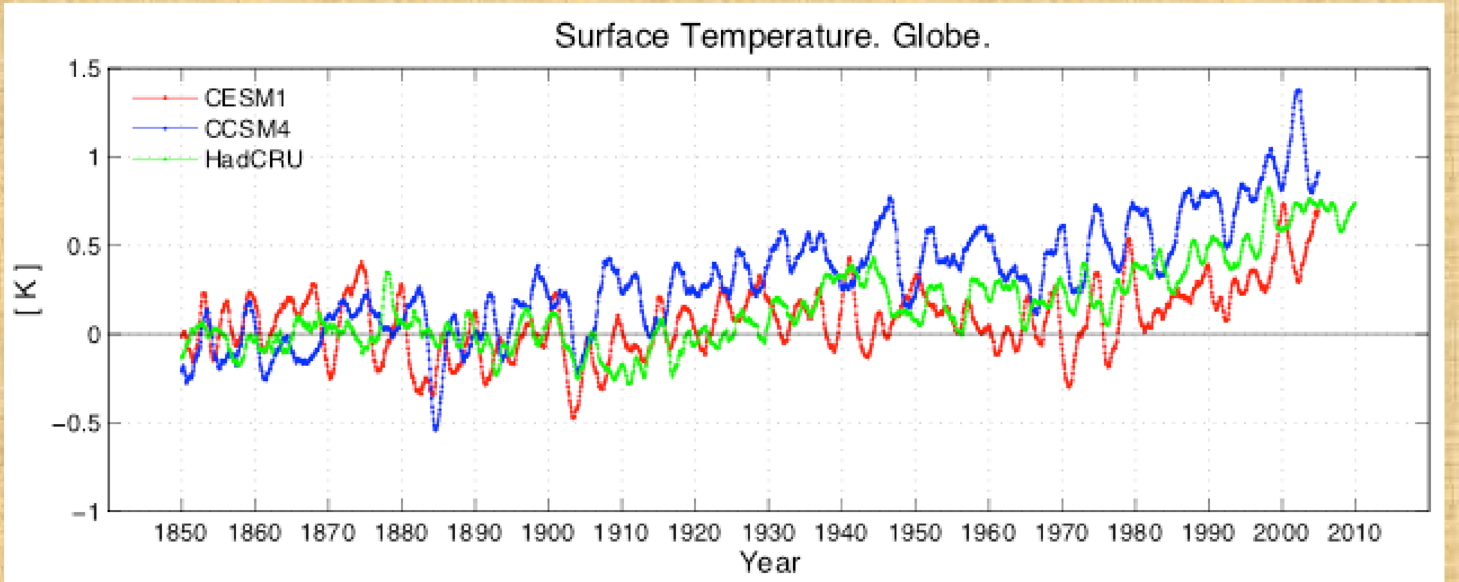
20th Century Simulation



Why does the simulation differ from the observation ?

FORCING

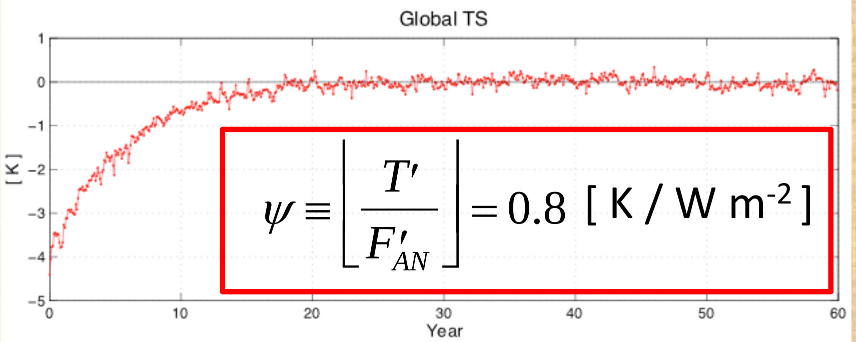
Natural : *Solar Radiation*, *Volcanic Eruption*
Anthropogenic : *CO_2*, *CH_4*, *N_2O*, *O_3*, *Aerosols*

FEEDBACK
or
PARAMETERIZATION

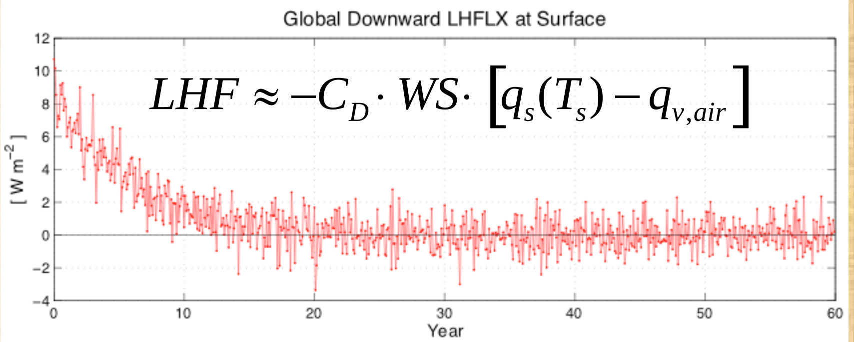
2 x CO_2 CESM1 SOM Experiment

SOM : Slab Ocean Model

T'

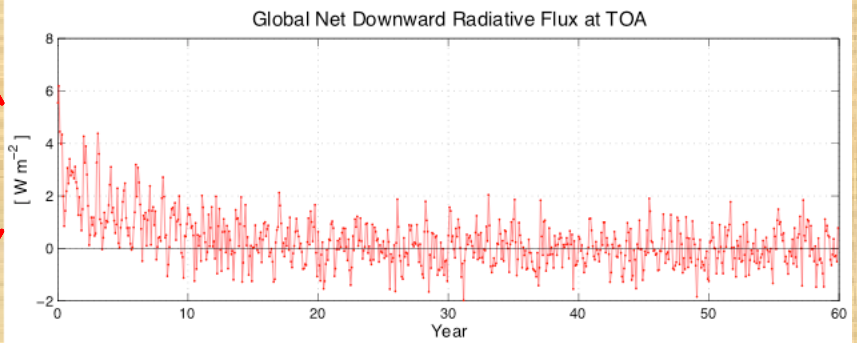

Global TS

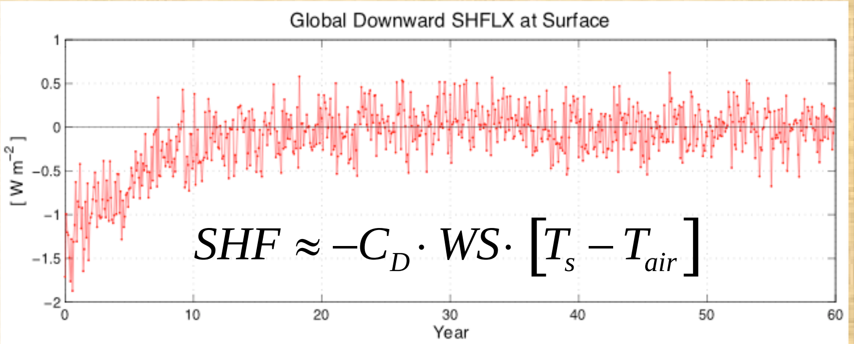
$$\psi \equiv \left\lfloor \frac{T'}{F'_{AN}} \right\rfloor = 0.8 \ [\ \mathrm{K / W\ m^{-2}}\ ]$$


Global Downward LHFLX at Surface

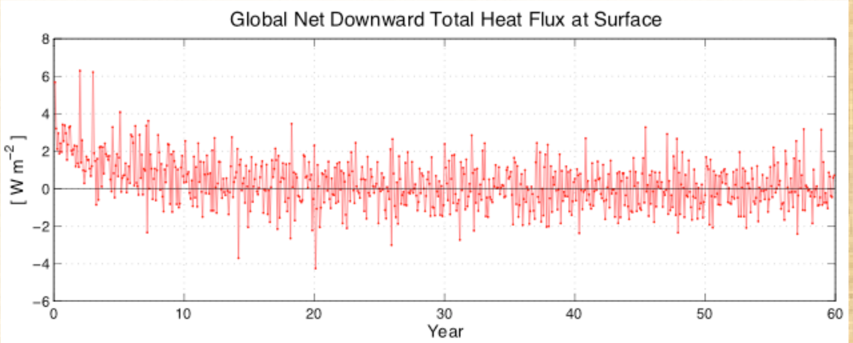
$$LHF \approx -C_D \cdot WS \cdot \left[q_s(T_s) - q_{v,air} \right]$$

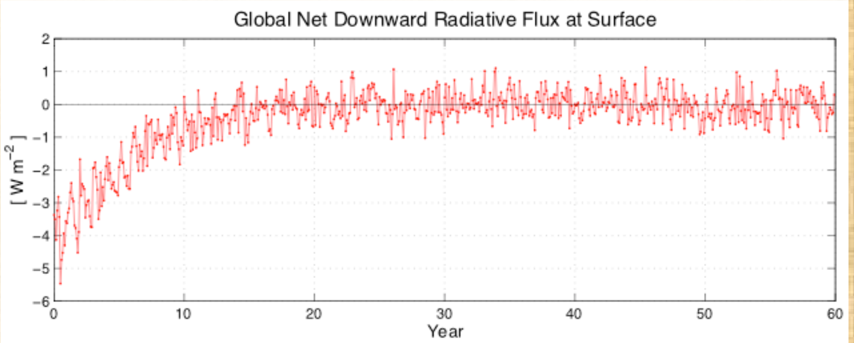
F'_{AN}


Global Net Downward Radiative Flux at TOA


Global Downward SHFLX at Surface

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


Global Net Downward Total Heat Flux at Surface


Global Net Downward Radiative Flux at Surface

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 λ

- 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 $Q' = -\lambda \bullet T' + f'_{NA}$ 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 :

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

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

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

- Regardless of the types of external forcing, climate sensitivity at surface, ψ [K / (W m^{-2})] is controlled by the strength of *surface heat flux feedback*, λ [(W m^{-2}) / K].

$$\psi \equiv \left\lfloor \frac{T'}{F'_{AN}} \right\rfloor = \frac{1}{\lambda} > 0$$

Surface Heat Flux Feedback Parameter λ [($W\ m^{-2}$) / K] :

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

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

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

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

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

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

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

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

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

$$\lambda_{LW,CLD} = \lambda_{LW,CLD,Sc} + \lambda_{LW,CLD,Ci}$$

Turbulent Fluxes	$[\lambda_{\mathrm{LHF,qv(sfc)}} + \lambda_{\mathrm{SHF,T(sfc)}}]$	Apparent Turbulent Damping
	$[\lambda_{\mathrm{LHF,qv(air)}} + \lambda_{\mathrm{SHF,T(air)}}]$	Atmospheric Thermal Adjustment
	$[\lambda_{\mathrm{LHF,ws(air)}} + \lambda_{\mathrm{SHF,ws(air)}}]$	Surface Wind Speed Feedback
	$[\lambda_{\mathrm{LHF,SS}} + \lambda_{\mathrm{SHF,SS}}]$	Surface Stability Feedback
Clear-Sky Radiation	$[\lambda_{\mathrm{LW,CLR,P}}]$	Apparent Planck Radiative Feedback
	$[\lambda_{\mathrm{SW,CLR,A}}]$	Surface Albedo Feedback
	$[\lambda_{\mathrm{LW,CLR,W}}]$	Water Vapor Feedback
Cloudy-Sky Radiation	$[\lambda_{\mathrm{SW,CLD,Sc}}]$	SW Stratocumulus Feedback
	$[\lambda_{\mathrm{SW,CLD,Ci}}]$	SW Cirrus Feedback
	$[\lambda_{\mathrm{LW,CLD,Sc}}]$	LW Stratocumulus Feedback
	$[\lambda_{\mathrm{LW,CLD,Ci}}]$	LW Cirrus Feedback

Estimation of λ using monthly SST and heat flux data based on the *time-scale splitting* of atmospheric and oceanic fluctuations (FK2002, Park-Deser-Alexander.2005, 2006, Park2011)

$$Q' \approx q' - \lambda \cdot T'$$

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

$$\tau_{q'} << \Delta t << \tau_{T'} \rightarrow \quad Cov\big(T'(t-\Delta t) \cdot q'(t)\big) \approx 0$$

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

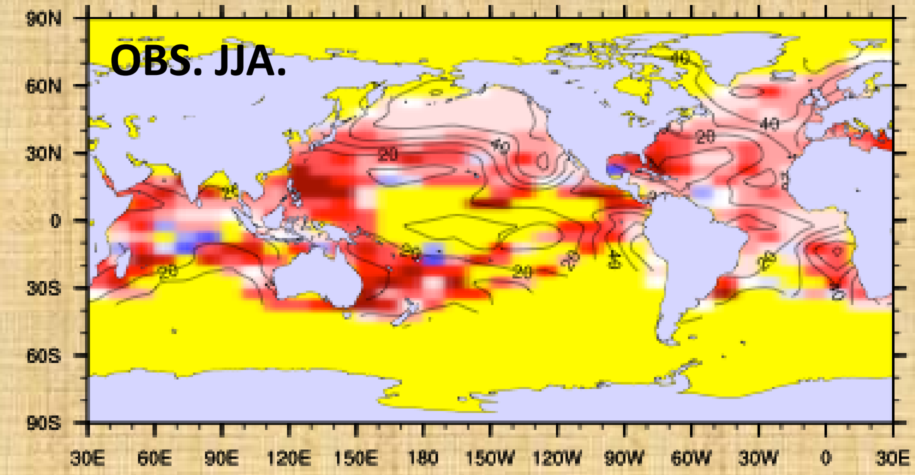
$\Delta t = 1, 2, 3$ [Month]

Data :

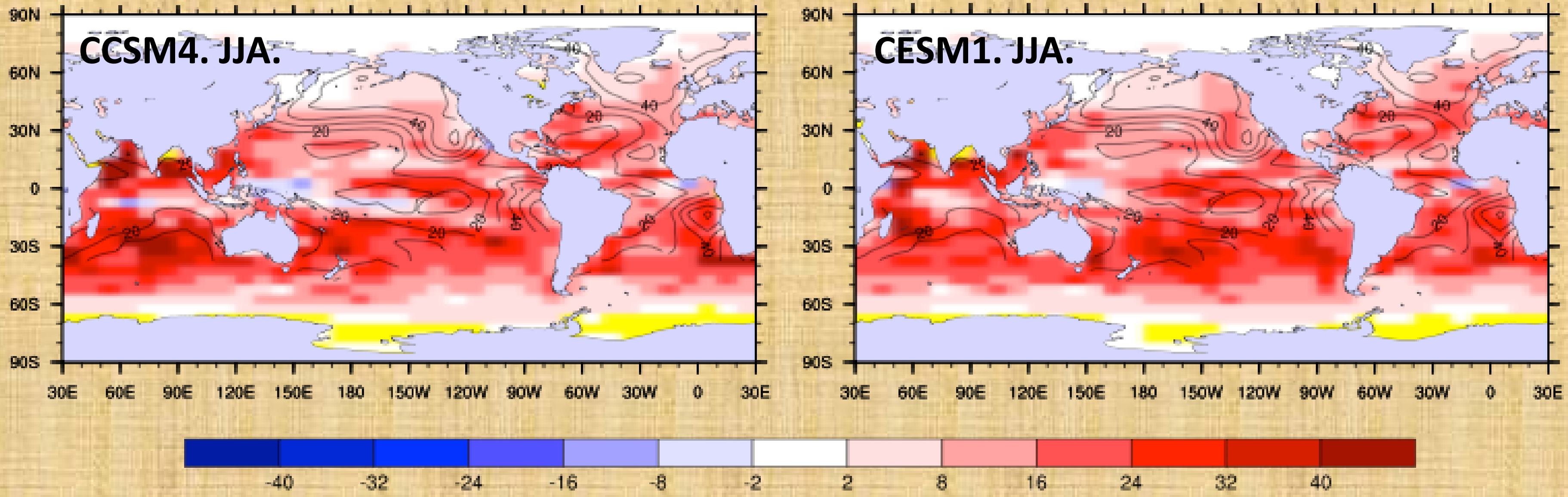
- Monthly surface radiative flux from ISCCP-satellite (1984-2007)
- Ship-observed monthly SST and latent & sensible heat fluxes (1956-2008)
- Monthly SST & surface heat fluxes from 160/200-years coupled CCSM4/CESM1
- *Linear ENSO signals were pre-filtered before performing this analysis.*

Latent Heat Flux Feedback, λ_{LHF}

Yellow Color : No Observation Or Not-Valid Analysis



Solid line : Ship-observed Stratocumulus AMT

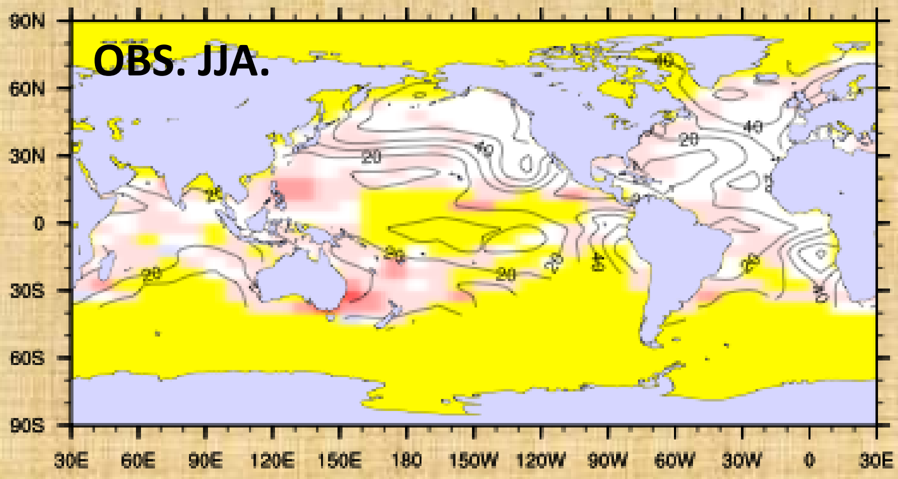


Positive Feedback : Amplifies Ts’

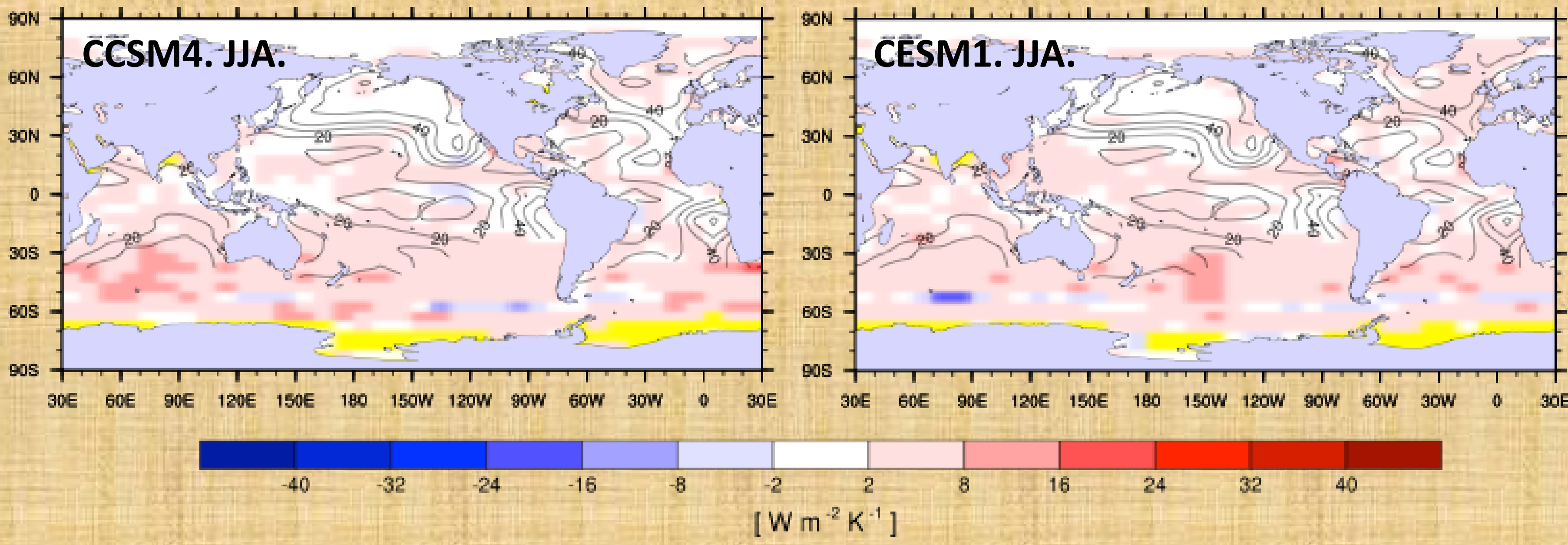
[W m^{-2} K^{-1}]

Negative Feedback : Dampens Ts’

Sensible Heat Flux Feedback, λ_{SHF}

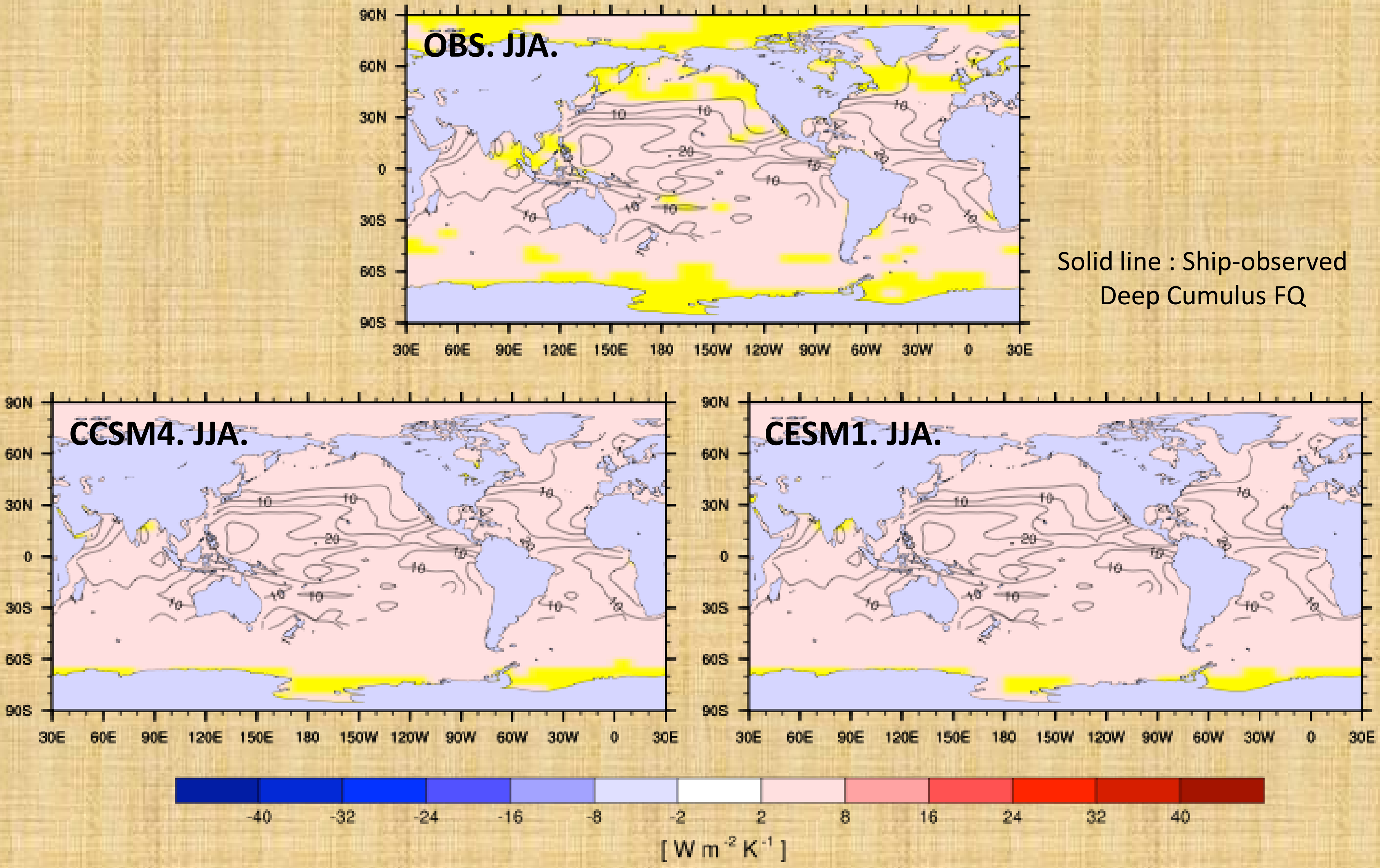


Solid line : Ship-observed Stratocumulus AMT



Apparent Planck Radiative Feedback, , $\lambda_{LW,CLR,P}$

(Use Clear-Sky Upward LW Flux at Surface)

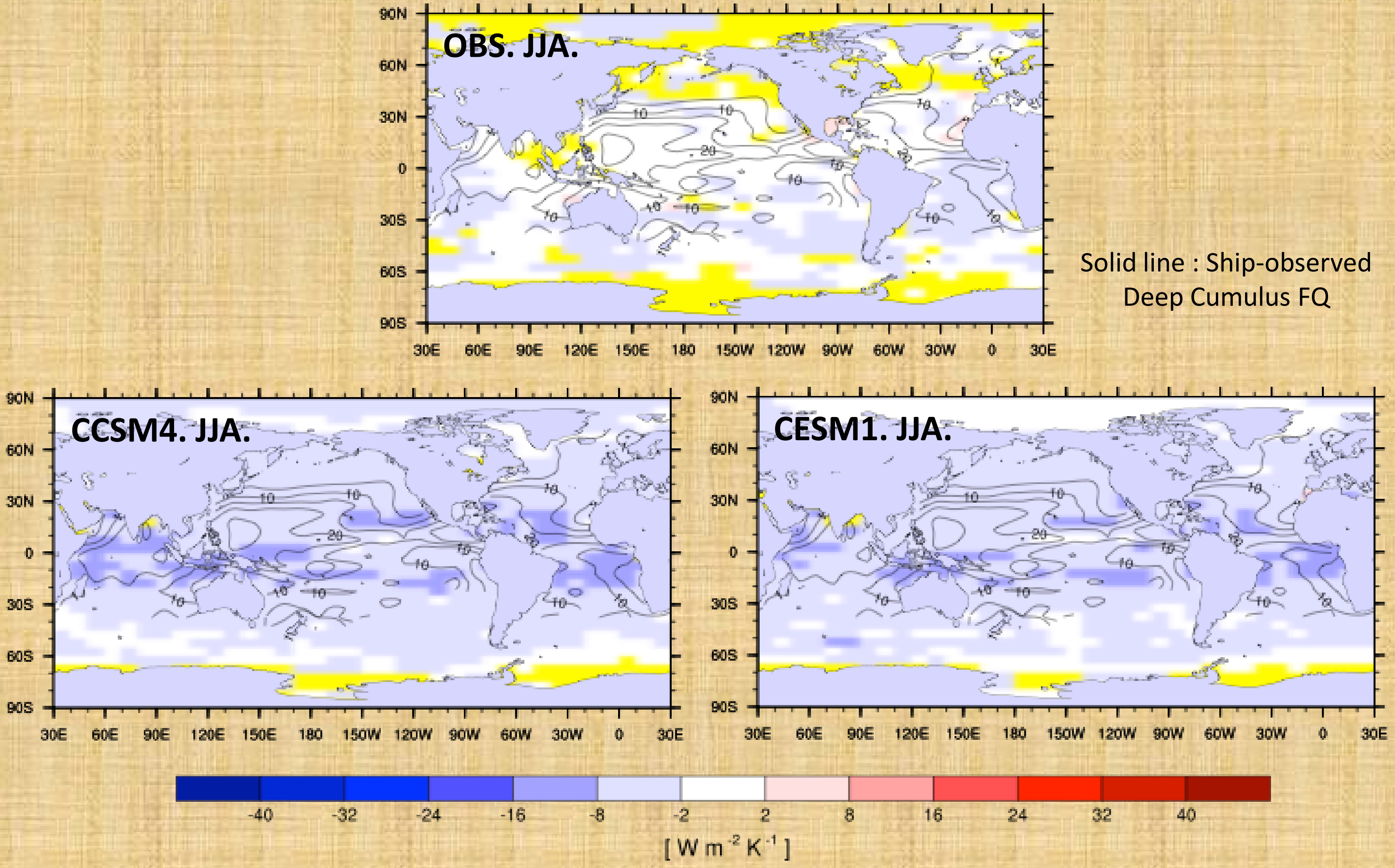


Solid line : Ship-observed
Deep Cumulus FQ

Water Vapor Feedback, $\lambda_{LW,CLR,W}$

(Use Clear-Sky Downward LW Flux at Surface)

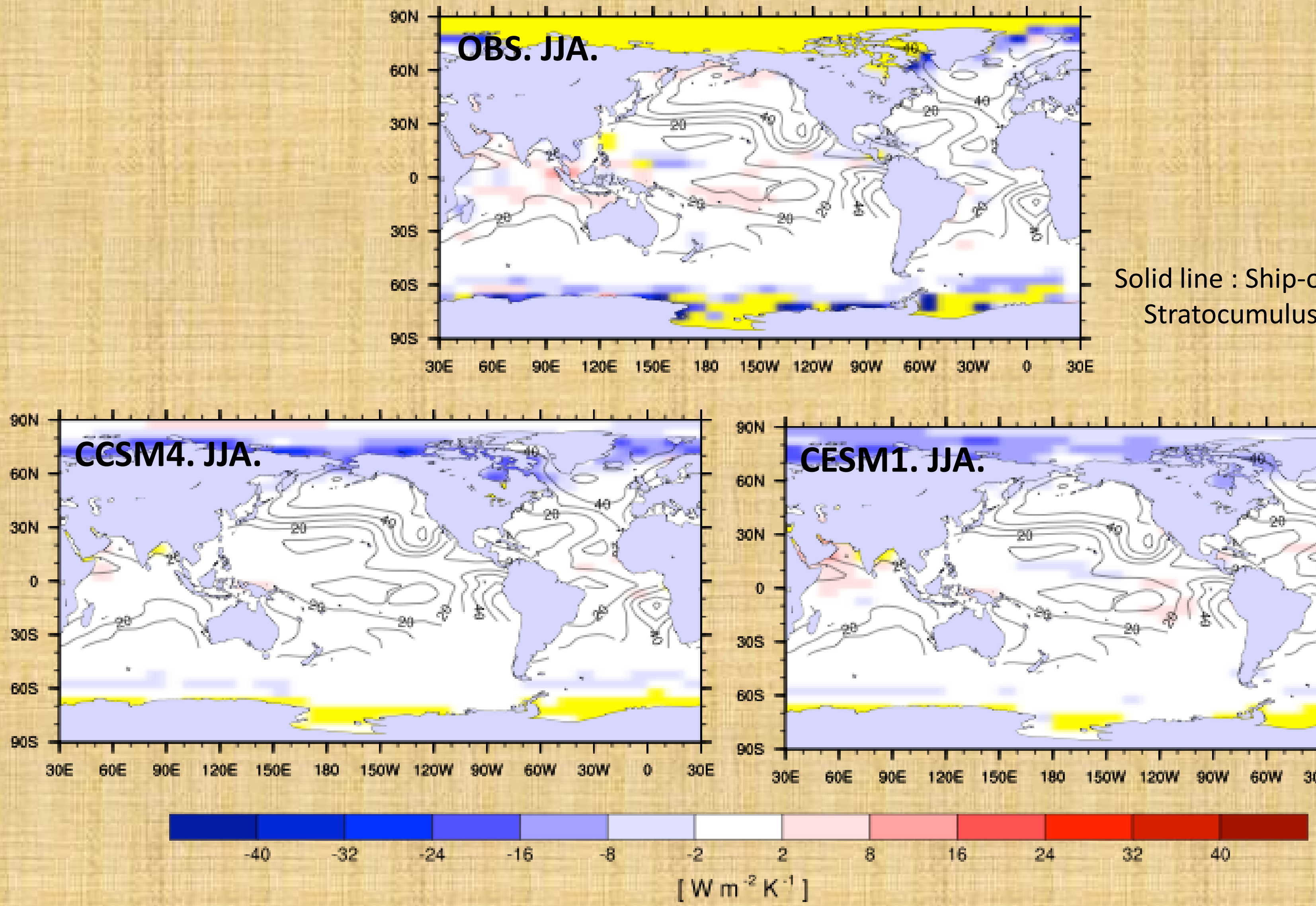
Note that ISCCP LW radiation retrieval at surface is questionable.



Solid line : Ship-observed Deep Cumulus FQ

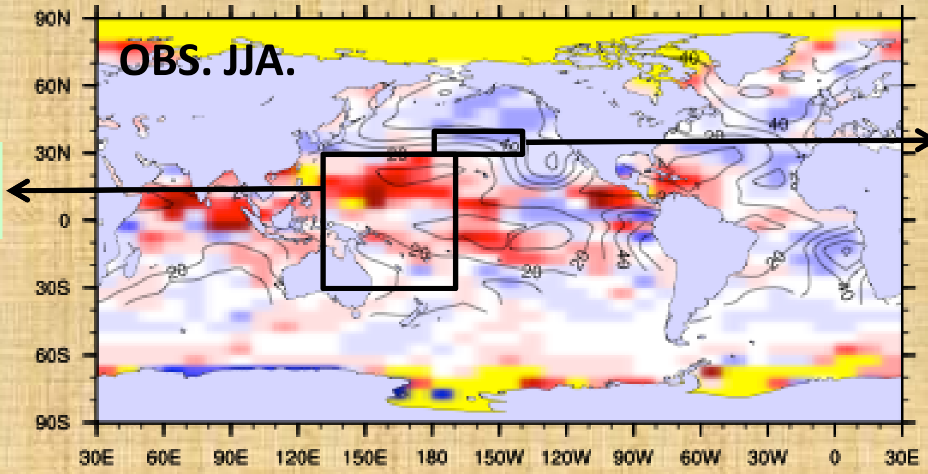
Surface Albedo Feedback, $\lambda_{SW,CLD,A}$

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



Solid line : Ship-observed Stratocumulus AMT

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

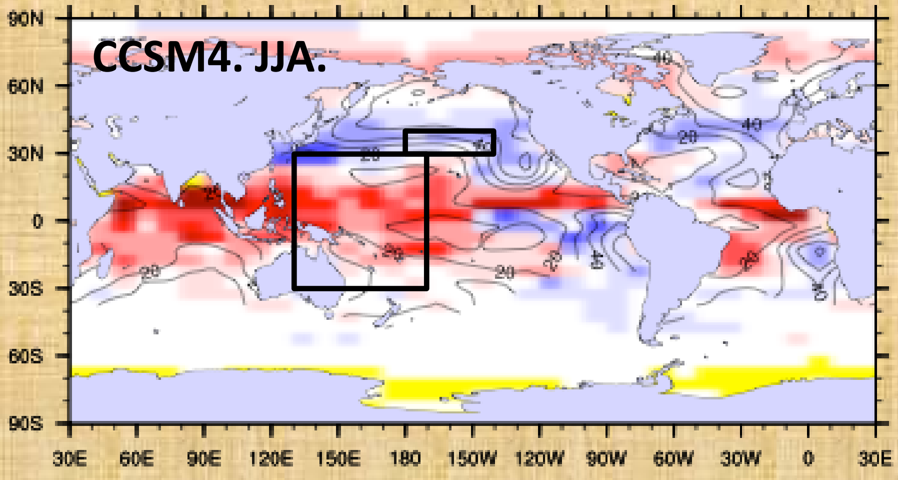


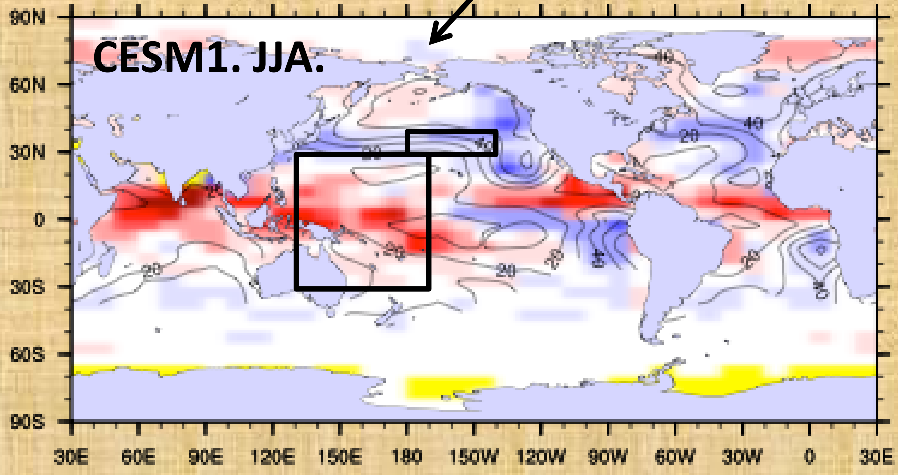
Negative SW radiative feedback associated with Tropical Cirrus

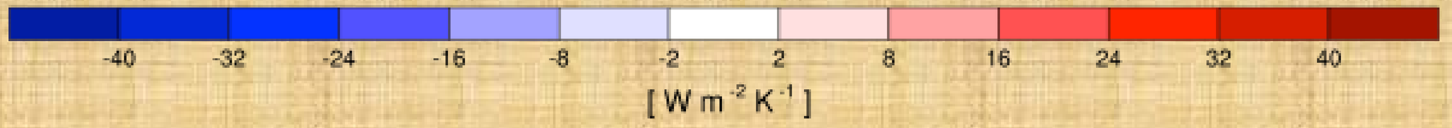
Positive SW radiative feedback associated with Stratocumulus

Solid line : Ship-observed Stratocumulus AMT

Stronger Positive SW feedback over the Arctic in CESM1



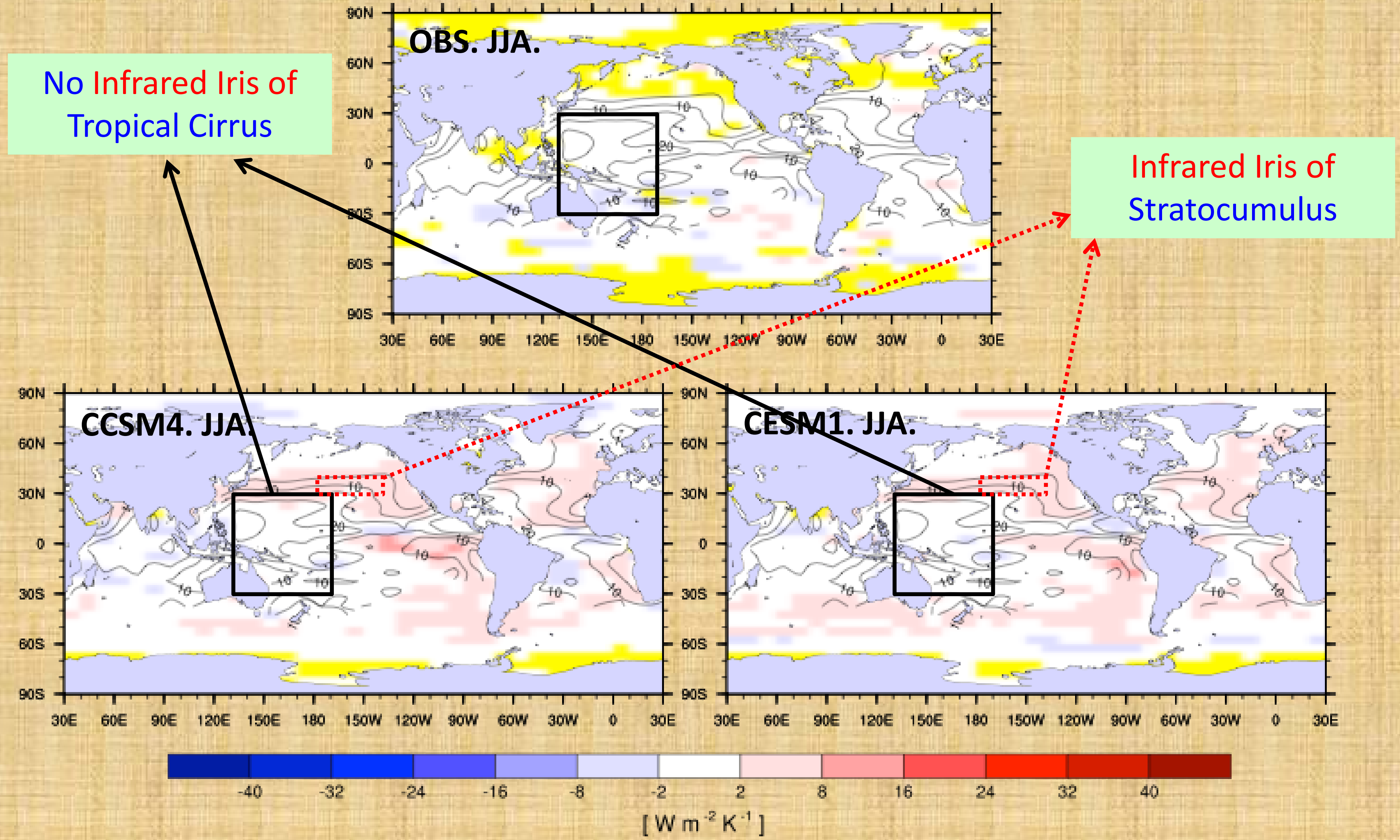




LW Cloud Feedback, $\lambda_{LW,CLD}$

(Use Cloudy-Sky Net Downward LW Radiative Flux at Surface)

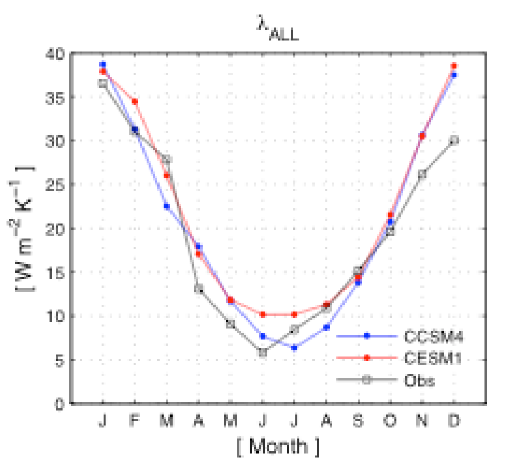
Note that ISCCP LW radiation retrieval at surface is questionable.

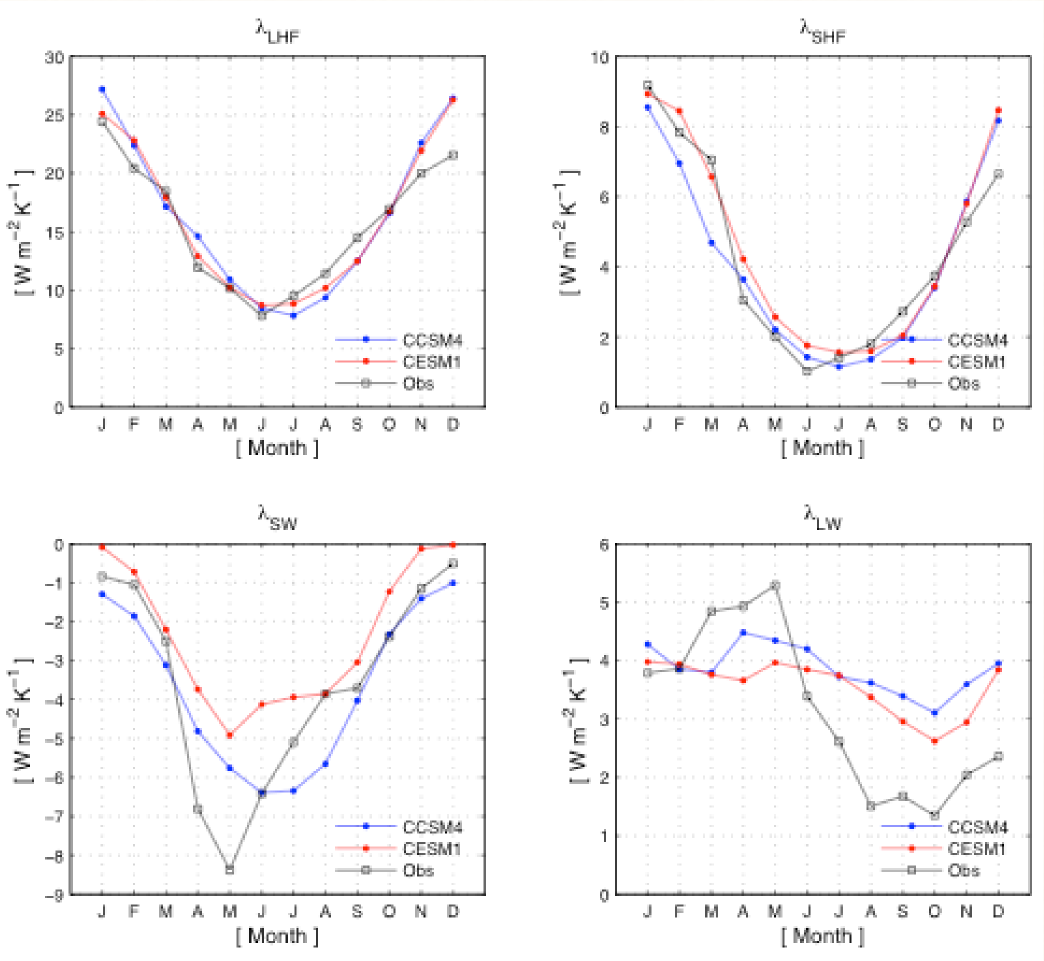


No Infrared Iris of Tropical Cirrus

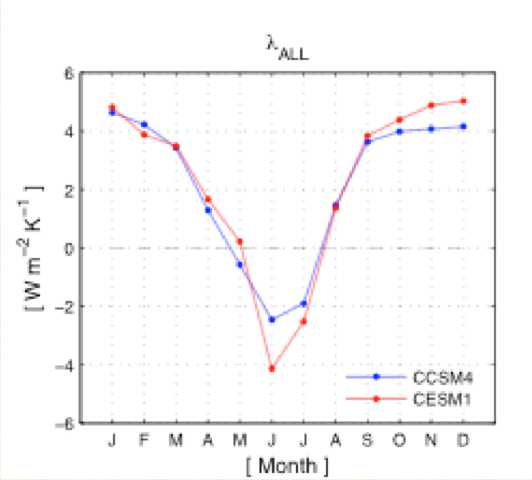
Infrared Iris of Stratocumulus

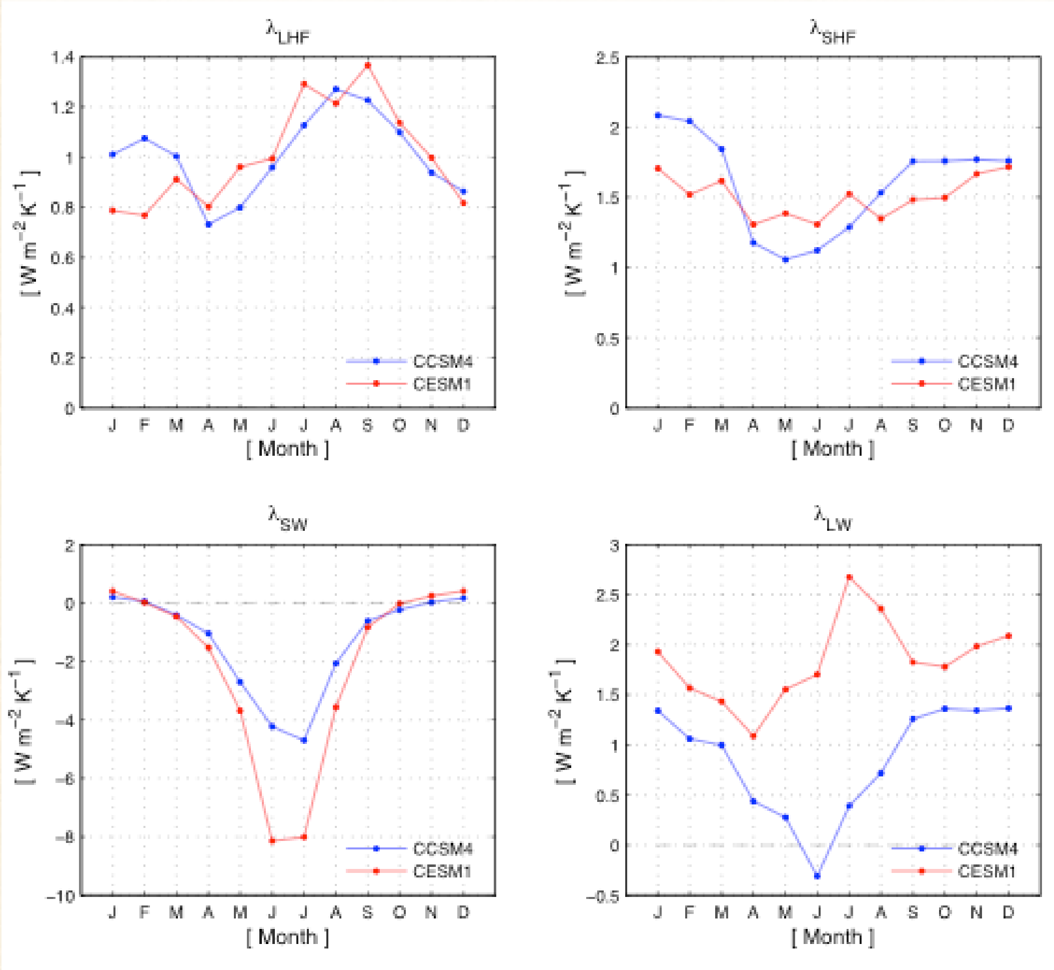
Mean Surface Heat Flux Feedback over the North Pacific
30°N-55°N, 140°E-240°E

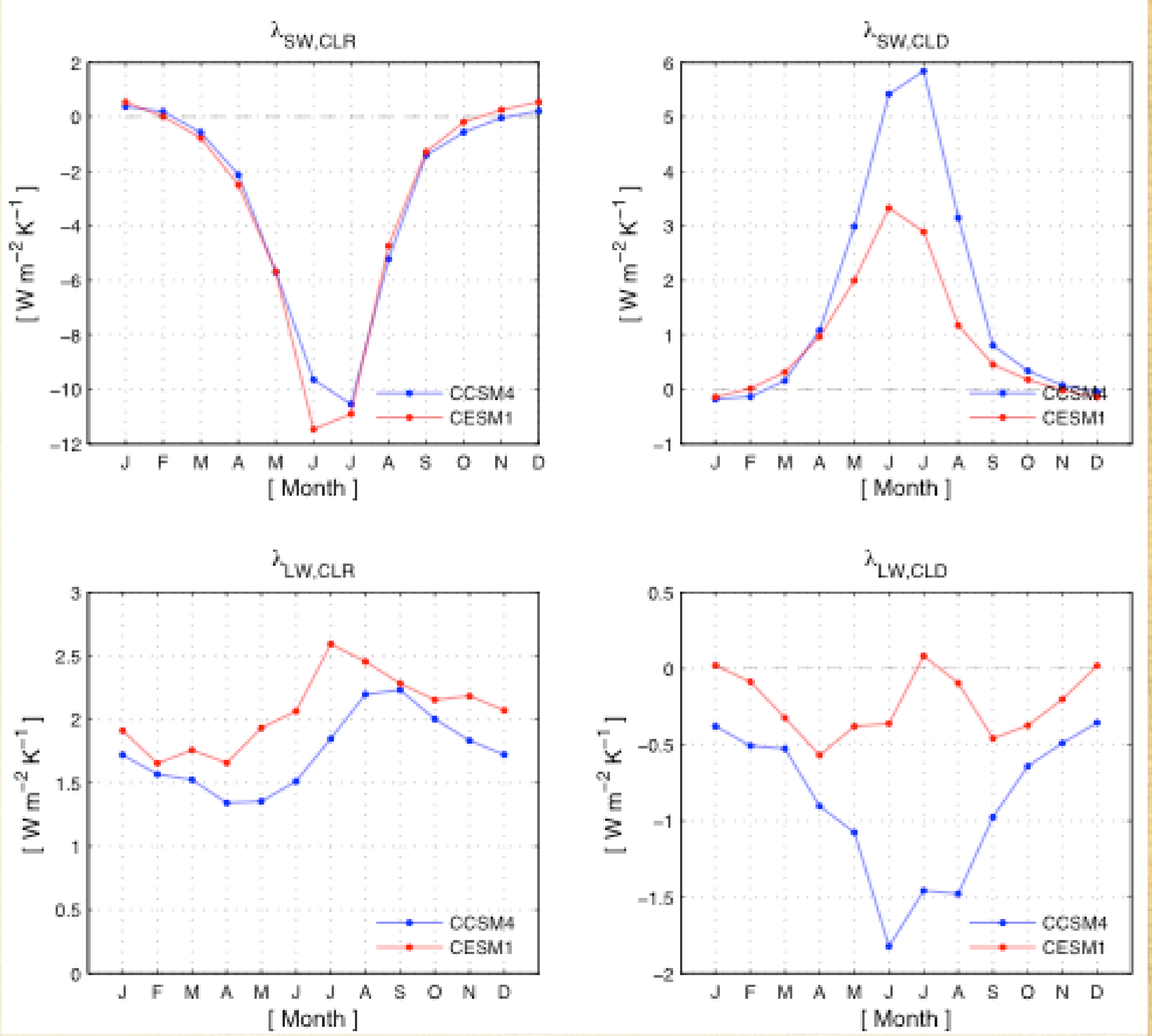




Mean Surface Heat Flux Feedback over the Arctic
70°N-90°N, 0°E-360°E

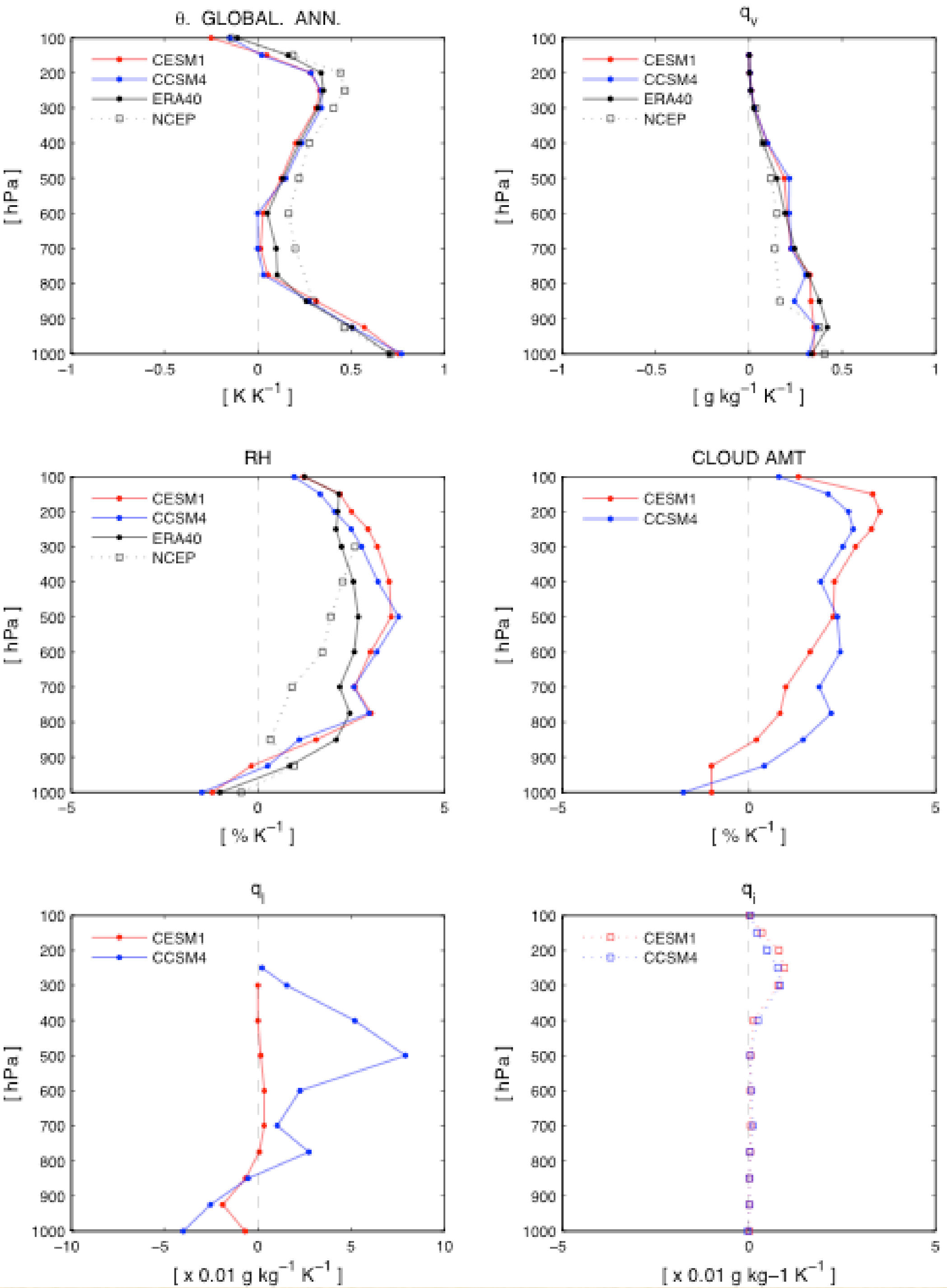





λSW,CLR
λSW,CLD
λLW,CLR
λLW,CLD
[W m−2 K−1]
[Month]
J F M A M J J A S O N D
2 0 −2 −4 −6 −8 −10 −12
6 5 4 3 2 1 0 −1
3 2.5 2 1.5 1 0.5 0
0.5 0 −0.5 −1 −1.5 −2
CCSM4
CESM1

Response of Atmospheric Profile to Surface Temperature Change

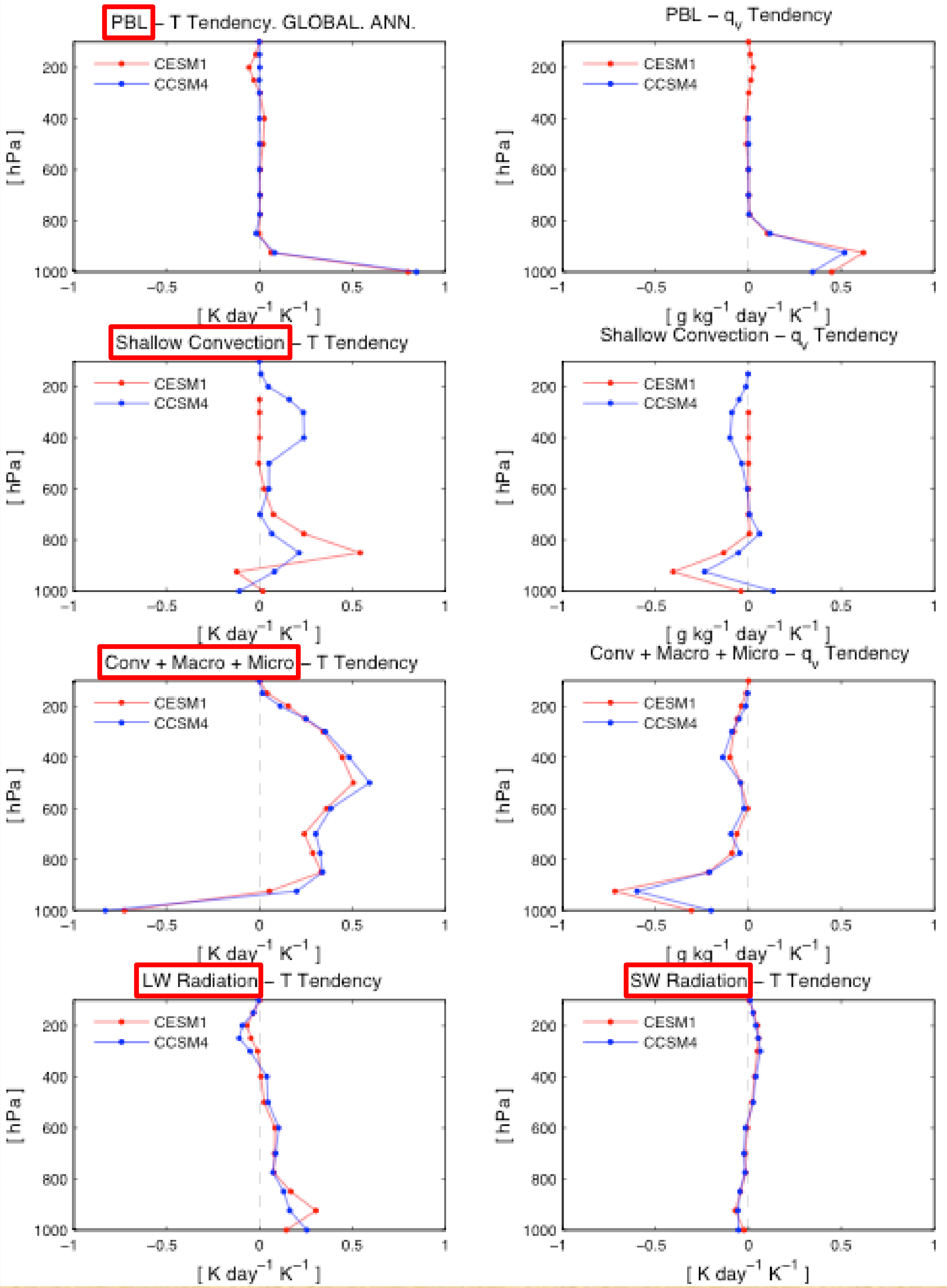
GLOBAL. ANNUAL.



Response of
Physical Tendencies

GLOBAL. ANNUAL.

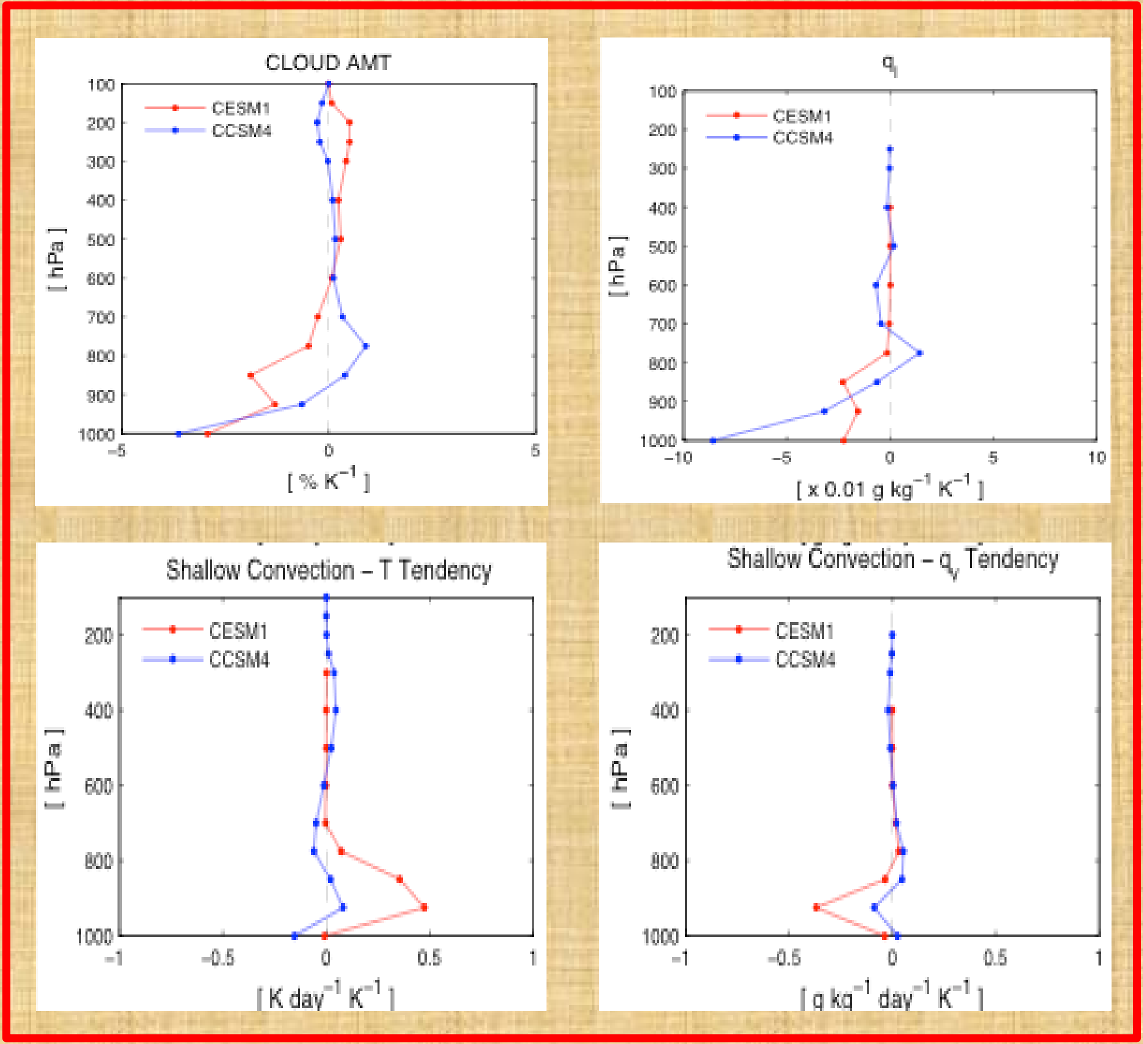
$$\left(\frac{\partial T}{\partial t}\right)$$



$$\left(\frac{\partial q_v}{\partial t}\right)$$

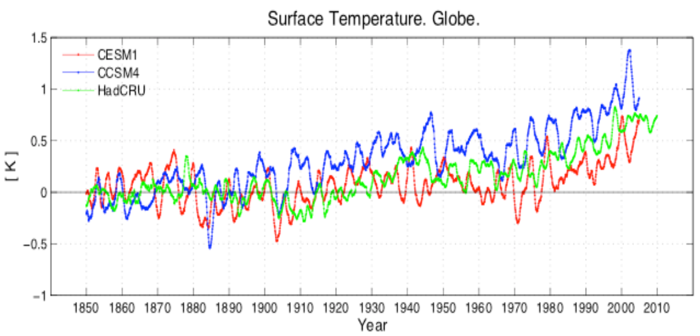
Response of
Atmospheric Profile
to Surface Temperature Change

North Pacific. August.



Why does simulation differ from observation ?

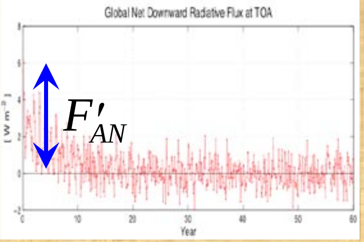
20th Century Coupled Simulation vs Obs.

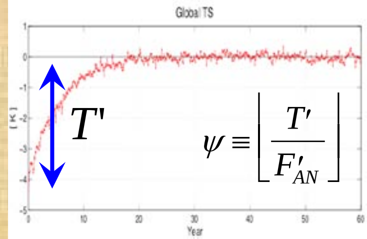


‘**Forcing**’ (CO_2, Aerosol) or ‘**Feedback**’ ?

Computation of **Global Climate Sensitivity ψ**

2 x CO_2 Coupled [SOM] Experiment





$$\psi \equiv \left\lfloor \frac{T'}{F'_{AN}} \right\rfloor$$

- 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.

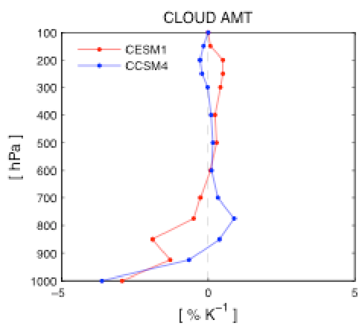
$$\psi \equiv \left\lfloor \frac{T'}{F'_{AN}} \right\rfloor = \frac{1}{\lambda} \qquad \lambda(t) = -\left\lfloor \frac{Cov\left(T'(t-\Delta t)\cdot Q'(t)\right)}{Cov\left(T'(t-\Delta t)\cdot T'(t)\right)} \right\rfloor$$

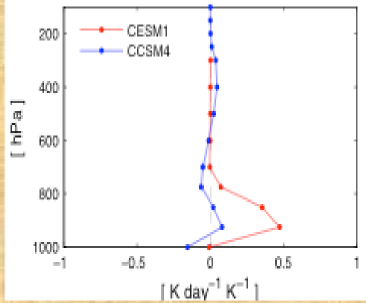
[λ_{LHF}] , [λ_{SHF}]
[$\lambda_{LW,CLR,Planck}$] , [$\lambda_{LW,CLR,Water-Vapor}$]
[$\lambda_{SW,CLR,Sfc-Albedo-Ice}$]
[$\lambda_{SW,CLD,Stratocumulus}$] , [$\lambda_{LW,CLD,Stratocumulus}$]
[$\lambda_{SW,CLD,Cirrus}$] , [$\lambda_{LW,CLD,Cirrus}$]

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

λ (θ, q_v, q_l, q_i, u, v, ω, RH, CLDAMT; Tendency)

1850 Long-Term Coupled Simulation vs Obs.



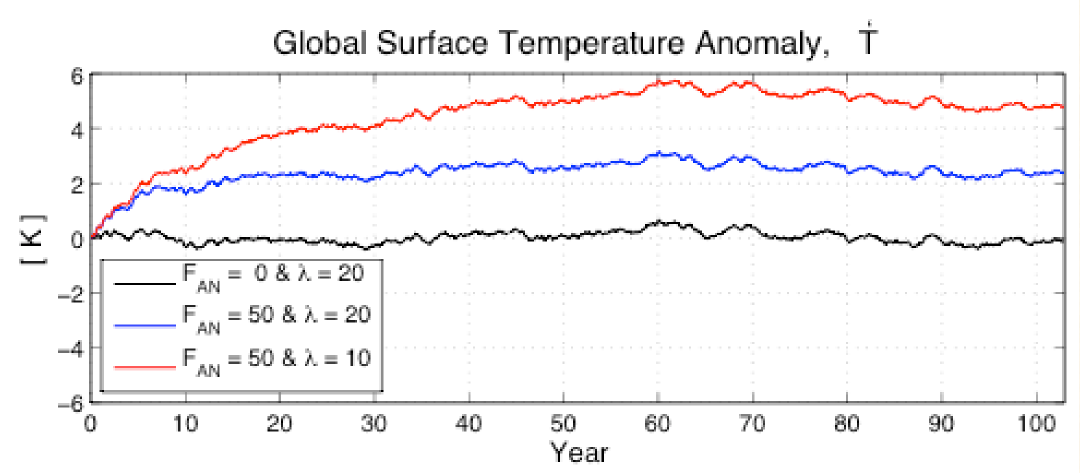


- Provide physical insight on ψ at the process level

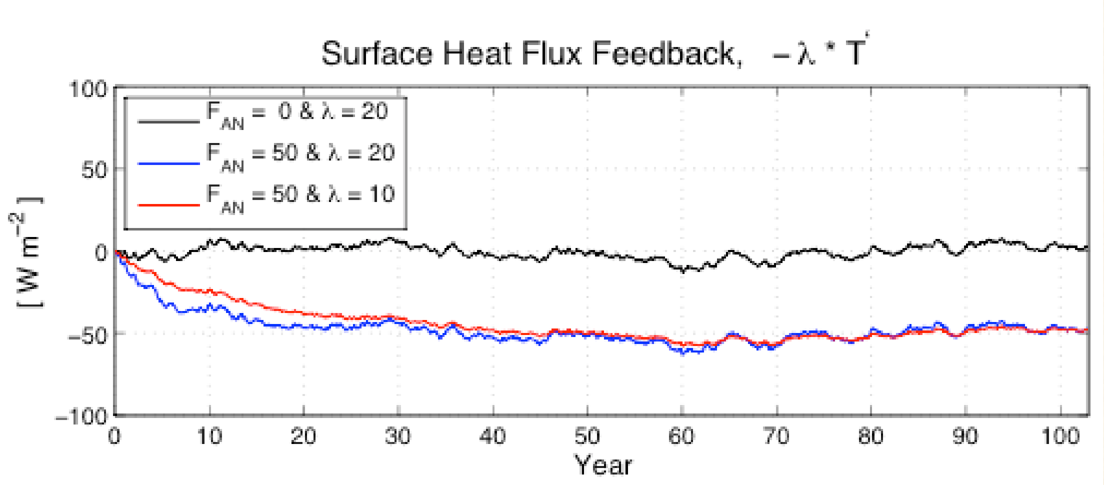
$$\boxed{\rho \cdot C_p \cdot H \cdot \frac{dT'}{dt} = -\lambda \cdot T' + f'_{NA} + F'_{AN}}$$

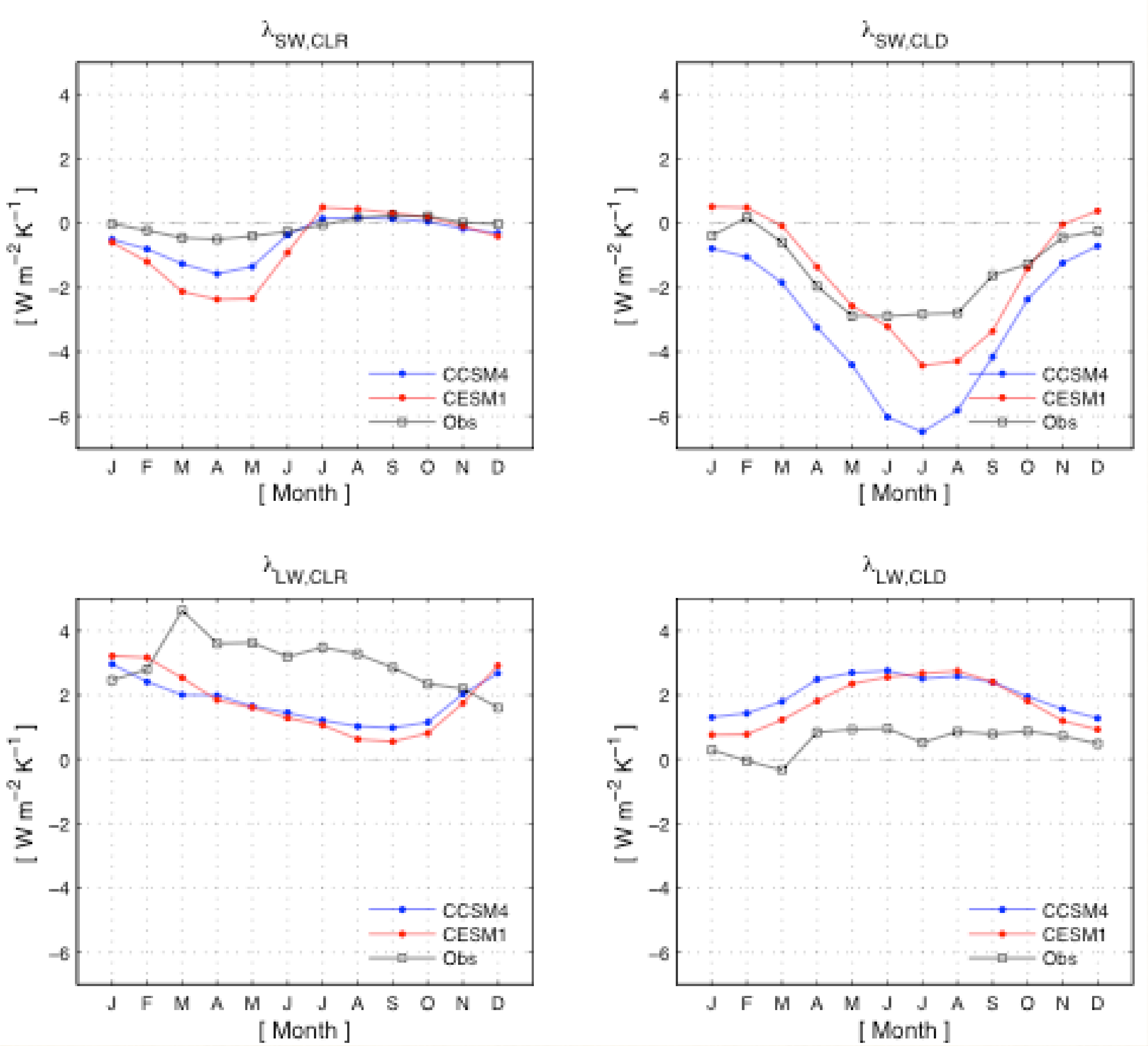
$$\rho = 1025.[kg/m^3] \quad C_p = 4000.[J/kg/K] \quad H = 1000.[m]$$

$\left| f'_{NA} \right| = 200.[W/m^2]$, Gaussian white noise



$$\psi \equiv \left\lfloor \frac{T'}{F'_{AN}} \right\rfloor = \frac{1}{\lambda} > 0$$




$\lambda_{SW,CLR}$
$\lambda_{SW,CLD}$
$\lambda_{LW,CLR}$
$\lambda_{LW,CLD}$
[W m^{-2} K^{-1}]
4
2
0
−2
−4
−6
J F M A M J J A S O N D
[Month]
CCSM4
CESM1
Obs