Idealized climate models as tools for the understanding of some basic concepts of climate dynamics

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Dr. Qiang Fu of U. Washington for radiative-transfer model;

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Large-scale topography such as Tibetan Palteau (TP) induces not only mechanic forcing, but also thermal forcing, on general circulation. TP acts as heat source during summer for monsoon over East Asia (Yeh T.C. et al., 1954, Tellus) .

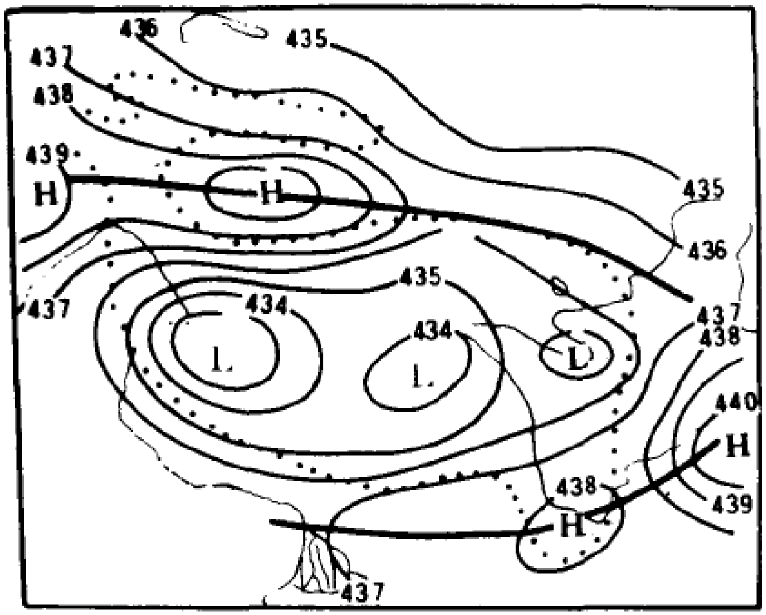


FIG. 1. Mean July 600 mb contours (decameters for 1200 GMT). Dotted line provides outline of Qinghai-Xizang (Tibet) Plateau.

Bulletin American Meteorological Society

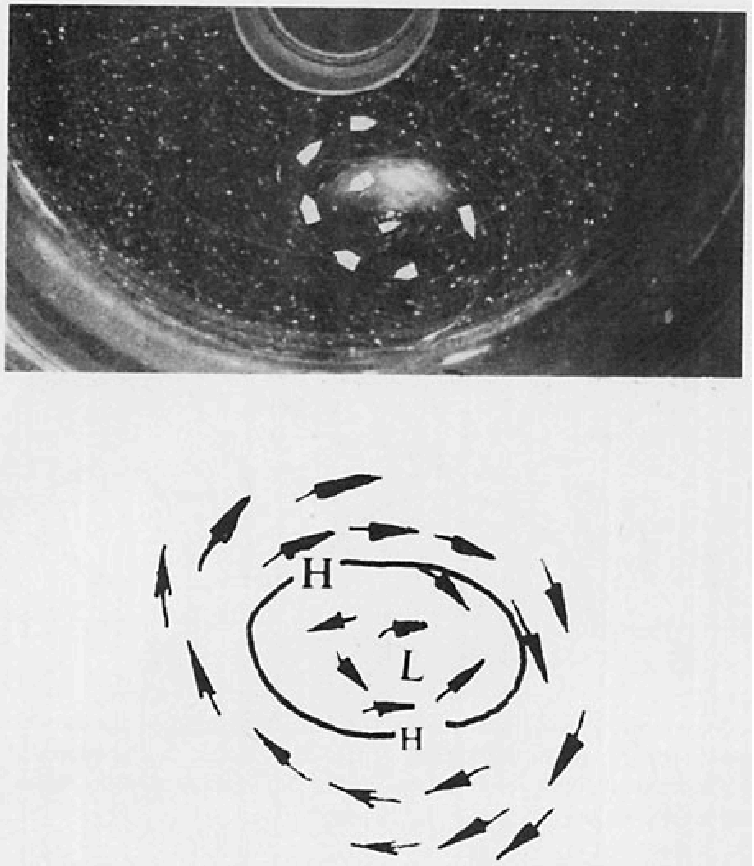


FIG. 5. (a) Photograph of the horizontal circulation on a level near the top of a heated model plateau in a fluid initially motionless relative to the rotating annulus. Experimental conditions: Radius of inner cylinder, 9.2 cm; radius of outer cylinder, 38.2 cm; depth of the working substance (mixture of water and glycerine, specific weight 1.043), 6 cm; major axis of the model plateau, 7.0 cm, minor axis, 4.0 cm, height, 3.0 cm; rate of rotation of the annulus, 0.177 s^{-1}; intensity of heating of the model plateau, 0.026 watt/cm^2. (b) Sketch of the circulation shown in (a).

(Yeh T.C. 1981, B.A.M.S. 62:14-18)

Ye D.Z. (Yeh T.C.), Some Characteristics of the Summer Circulation Over the Qinghai-Xizang (Tibet) Plateau and Its Neighborhood 1981, B.A.M.S. 62:14-18

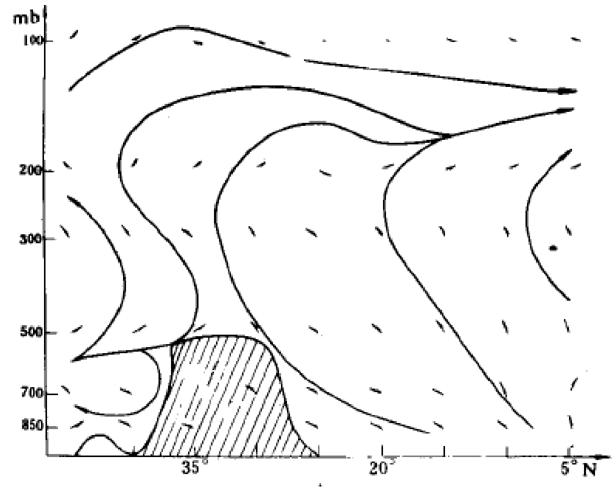


FIG. 2. The mean July meridional and vertical circulation of the sector 75°E–110°E.

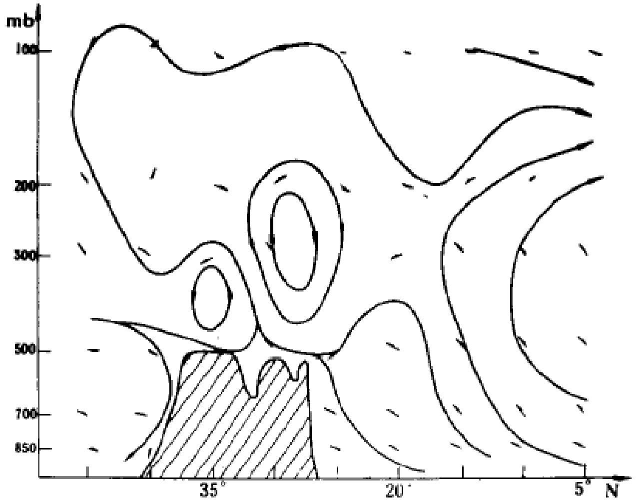


FIG. 3. The mean July meridional and vertical circulation along 90°E.

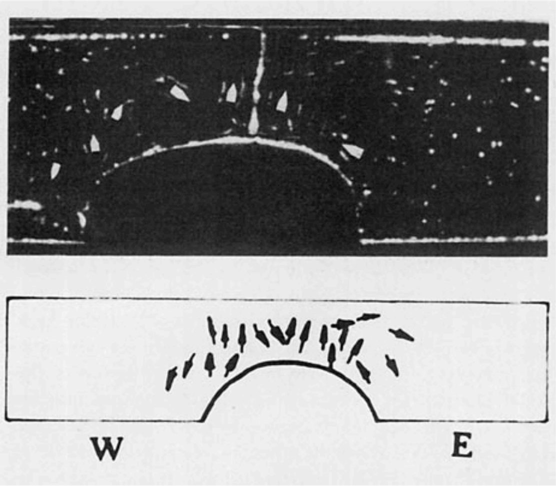


FIG. 6. (a) Photograph of the vertical circulation in a west-east vertical plane across the center of a heated model plateau. Experimental conditions: same as in Fig. 5a. (b) Sketch of the circulation shown in (a).

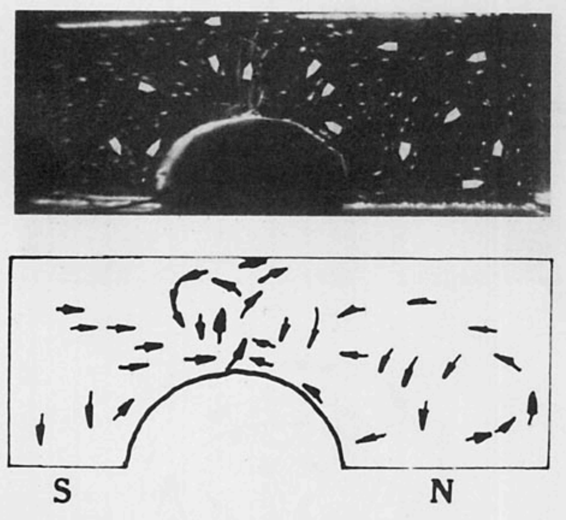


FIG.7. (a) Photograph of the vertical circulation in the north-south vertical plane across the center of a heated model plateau. Experimental conditions: same as in Fig. 5a. (b) Sketch of the circulation shown in (a).

The interactions between the dynamical and thermodynamical processes, between the physical and chemical or even biological processes may make the study of climate very interesting to young students because of the richness in climate phenomena. They may also cause puzzle to the students because of the complexity of the climate system: Where can we start to understand such a complex system?

This talk is mainly based on our recent research on using the idealized models as tools to understand some basic concepts of climate dynamics. Meanwhile, the idealized models are, to me (J. Lu), wonderful self-teaching tools to understand the synergesitc nature of climate processes.

Outline

- **Build an idealized climate model**
- **Use idealized model to understand the climate forcing and climate feedbacks**
- **Use idealized experiments to study the polar warming amplification and the role of dynamics in climate change**
- **Summary**

Part I

Build an idealized climate model

- Dynamical Core + Raleigh friction at boundary layer (as Held-Suarez (1994))
- Radiative-transfer model (Fu and Liou 1993);

DIY Part:

- Slab-ocean model (5 m depth);
- Dry convective adjustment scheme: the critical lapse rate for convection decreases from 6.5 K /km in tropics to 9.8 K/km in higher latitudes;

Some features:

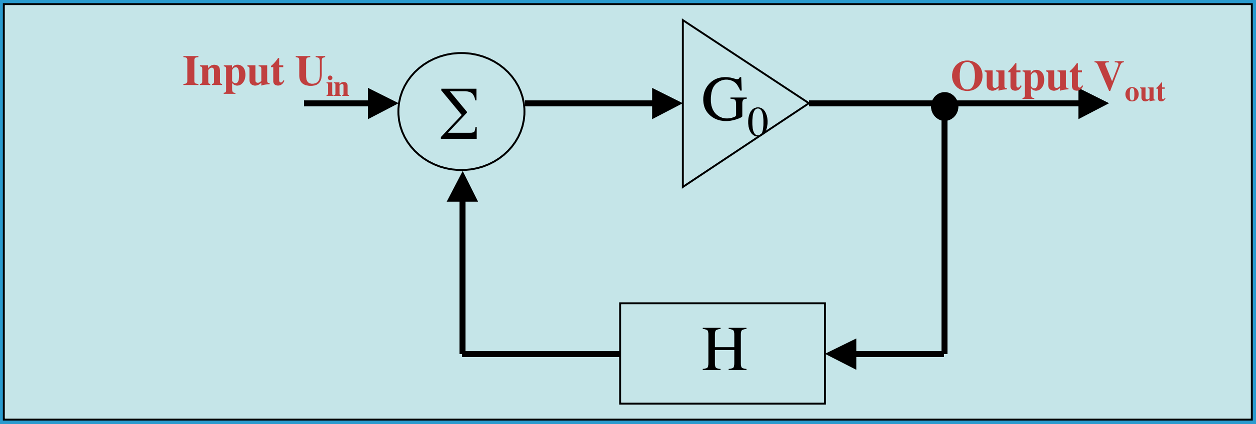
- Fixed relative humidity (The spatial pattern is from the GFDL output for CMIP3), so the water vapor feedback is included in a heuristic way;
- 1xCO2 (330 ppmv) and 2xCO2 (660 ppmv) experiments,integrating the model (with fixed annual solar radiation) for about 12000 days; Use the output of last 10000 days;
- No hydrological cycle (cloud and precipitation); No parameterization of sub-grid processes; No ice-albedo feedback;
- Could be reduced to one-dimensional coupled convective-radiative-surface model (similar with the Manabe and Wetherald (1967) model).

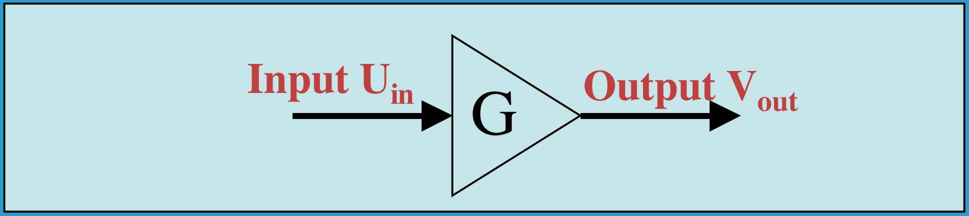
We would not expect the "prediction" from such a simple model as the projection of the future climate change because of its simplicity.

But its simplicity makes it an ideal tool for the understanding of basic physics and dynamics of climate system.

Part II

Use idealized model to understand the climate forcing and climate feedbacks





$$V_{out} = G\bullet U_{in} = G_0 f\bullet U_{in}$$

$$= \frac{G_0}{1-\sum_i g_i}\bullet U_{in}$$

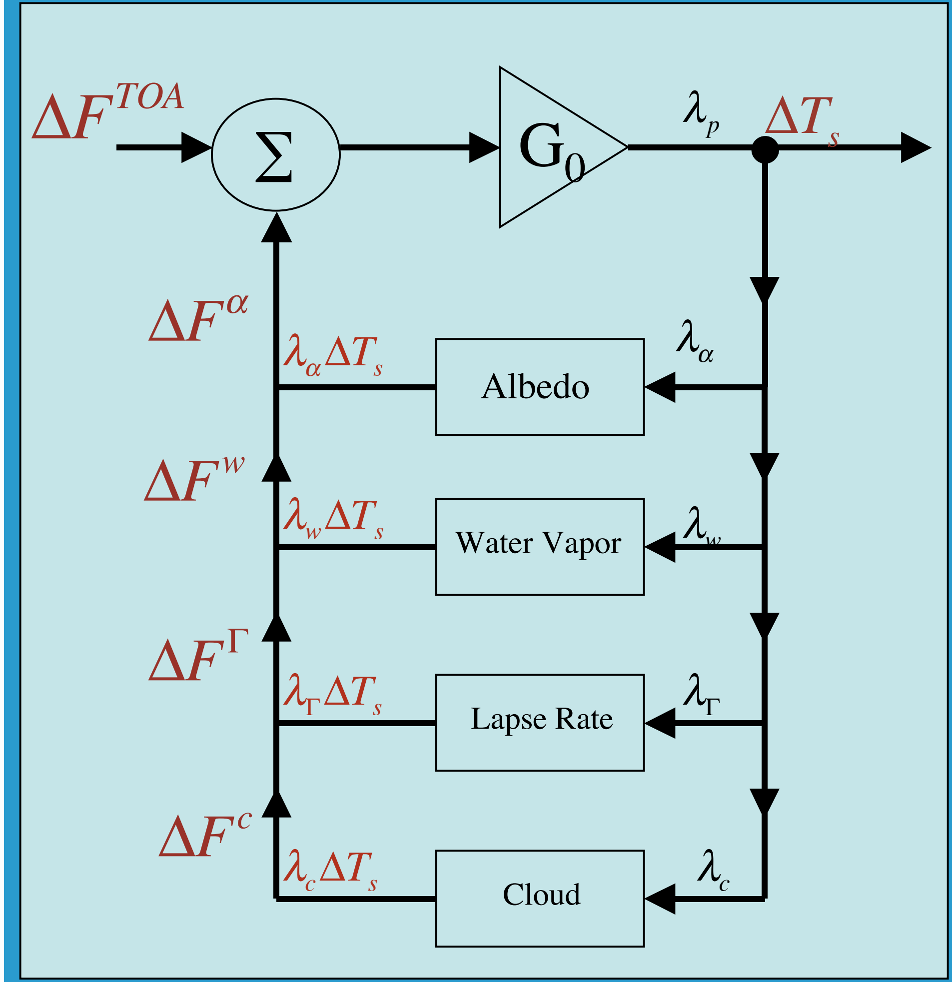
$$U_{in} = -\lambda\bullet V_{out} = -(\lambda_0+\lambda_1+\cdots)\bullet V_{out}$$

$$G_0 = -\frac{1}{\lambda_0}$$

$$g_i = -\frac{\lambda_i}{\lambda_0}$$

(Peixoto and Oort(1992): Physics of Climate)

Feedbacks in the climate system



In equilibrium state:

$$\Delta F^{TOA} + \Delta F^{\alpha} + \Delta F^{w} + \Delta F^{\Gamma} + \Delta F^{c} + \lambda_p \Delta T_s = \Delta R_n^{TOA} = 0$$

$$\Delta F^{TOA} + (\lambda_p + \lambda_\alpha + \lambda_w + \lambda_\Gamma + \lambda_c)\Delta T_s = 0$$

$$\Delta T_s = \frac{\Delta F^{TOA} / (-\lambda_p)}{1 - \frac{\lambda_\alpha}{-\lambda_p} - \frac{\lambda_w}{-\lambda_p} - \frac{\lambda_\Gamma}{-\lambda_p} - \frac{\lambda_c}{-\lambda_p}}$$

Peixoto and Oort (1994); Bony et al. (2006); among others

Some questions on the electrics - climate analogy

1. Why is ΔT_s chosen as the output? Why not the temperature at 500hPa?

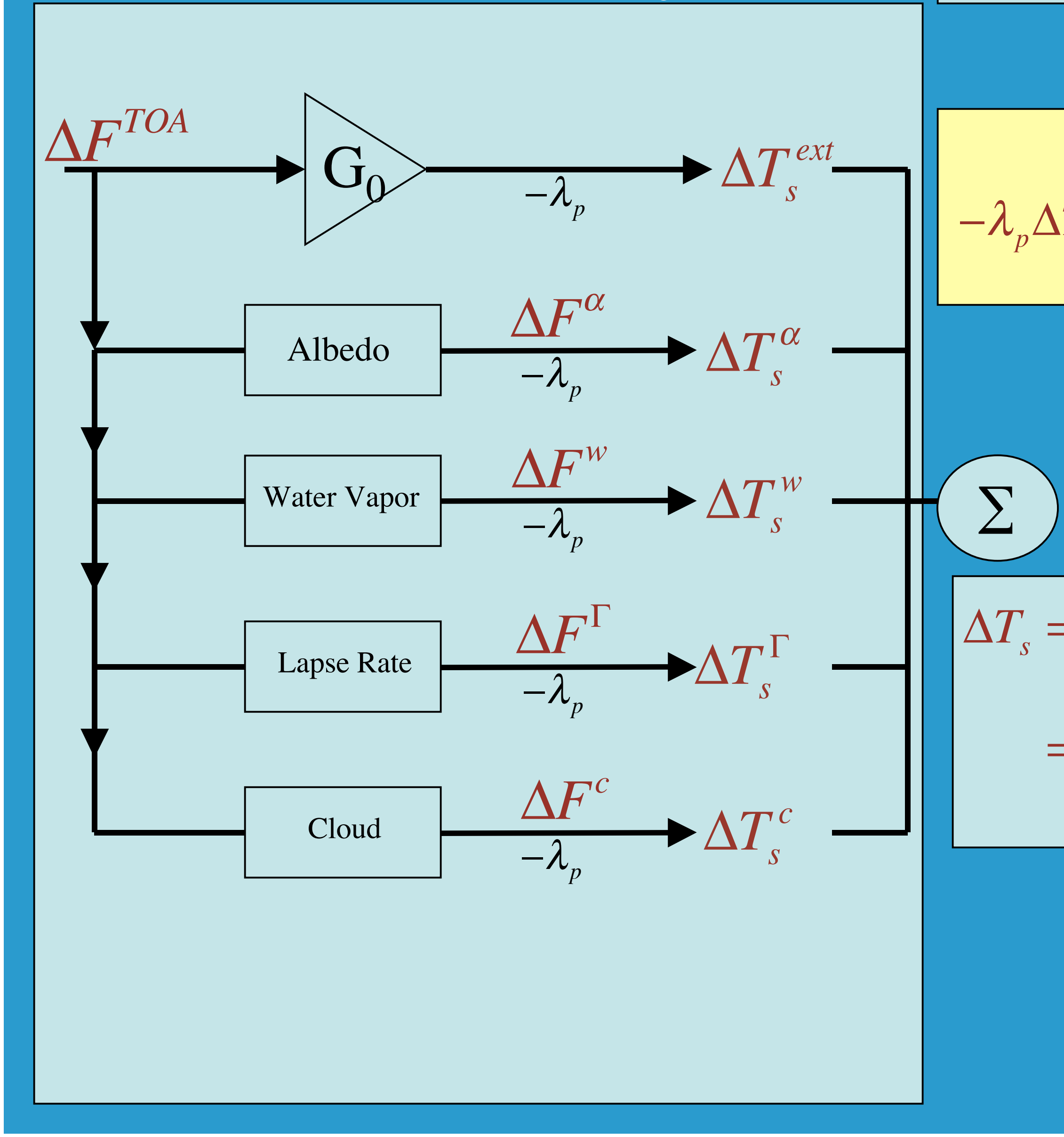
Is the surface temperature physically more important than other variables? or just because we live at the land surafce?

2. Why are the changes in water vapor, in lapse rate, in cloud considered "induced by ΔT_s" as shown in the feedback parameters?

3. Why does the radiative forcing ΔF^{TOA} has to be at TOA?

4. How could we diagnose the "dynamical" feedback mechanisms, such as the changes in evaporation, in convection, in large-scale atmospheric (and oceanic) transport of the energy?

Another way to analyze the feedbacks in climate system



$$\Delta F^{TOA} + \Delta F^{\alpha} + \Delta F^{w} + \Delta F^{\Gamma} + \Delta F^{c} + \lambda_p \Delta T_s = \Delta R_n^{TOA} = 0$$

$$-\lambda_p \Delta T_s = \Delta F^{TOA} + \Delta F^{\alpha} + \Delta F^{w} + \Delta F^{\Gamma} + \Delta F^{c}$$

$$\Delta T_s = \Delta T_s^{ext} + \Delta T_s^{\alpha} + \Delta T_s^{w} + \Delta T_s^{\Gamma} + \Delta T_s^{c} = \frac{\Delta F^{TOA}}{-\lambda_p} + \frac{\Delta F^{\alpha}}{-\lambda_p} + \frac{\Delta F^{w}}{-\lambda_p} + \frac{\Delta F^{\Gamma}}{-\lambda_p} + \frac{\Delta F^{c}}{-\lambda_p}$$

Mathematically, the difference between the two methods is just about the arrangement of the terms in radiation balance equation at the top of at the atmosphere

$$\Delta F^{TOA} + \Delta F^{\alpha} + \Delta F^{w} + \Delta F^{\Gamma} + \Delta F^{c} + \lambda_p \Delta T_s$$
$$= \Delta R_n^{TOA} = 0$$

$$\Delta F^{TOA} + (\lambda_p + \lambda_\alpha + \lambda_w + \lambda_\Gamma + \lambda_c)\Delta T_s = 0$$

$$\Delta T_s = \frac{\Delta F^{TOA} / (-\lambda_p)}{1 - \frac{\lambda_\alpha}{-\lambda_p} - \frac{\lambda_w}{-\lambda_p} - \frac{\lambda_\Gamma}{-\lambda_p} - \frac{\lambda_c}{-\lambda_p}}$$

$$-\lambda_p \Delta T_s = \Delta F^{TOA} + \Delta F^{\alpha} + \Delta F^{w} + \Delta F^{\Gamma} + \Delta F^{c}$$

$$\Delta T_s = \Delta T_s^{ext} + \Delta T_s^{\alpha} + \Delta T_s^{w} + \Delta T_s^{\Gamma} + \Delta T_s^{c}$$
$$= \frac{\Delta F^{TOA}}{-\lambda_p} + \frac{\Delta F^{\alpha}}{-\lambda_p} + \frac{\Delta F^{w}}{-\lambda_p} + \frac{\Delta F^{\Gamma}}{-\lambda_p} + \frac{\Delta F^{c}}{-\lambda_p}$$

Physically speaking, the second method represents a different thinking on the nature of feedbacks in climate system:

(1) The changes in albedo, cloud, water vapor, and lapse rate, as well as the change in surface temperature, are synergetic responses of climate system to the external forcing.

(2) The radiative perturbations (feedbacks) are not considered as the "induced inputs" from one single output (say, ΔT_s), but as the "induced inputs" from the systemic outputs. ΔT_s ***is only one part of the "systematic outputs" in response to the external forcing.***

---Possible implication for the reduction of the uncertainty in climate projection.

Why does the radiative forcing ΔF^{TOA} have to be at TOA?

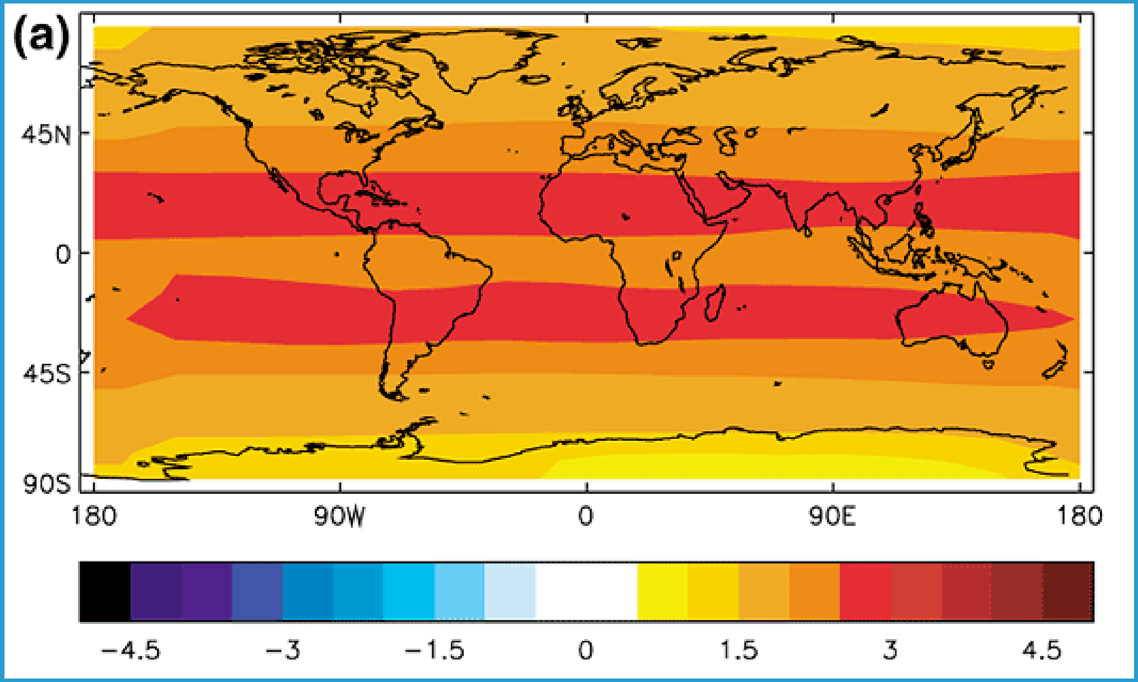
Two aspects of radiative forcing:

(1) Amount

The radiative perturbation at TOA is the vertical integration of radiative heating from the surface to the TOA.

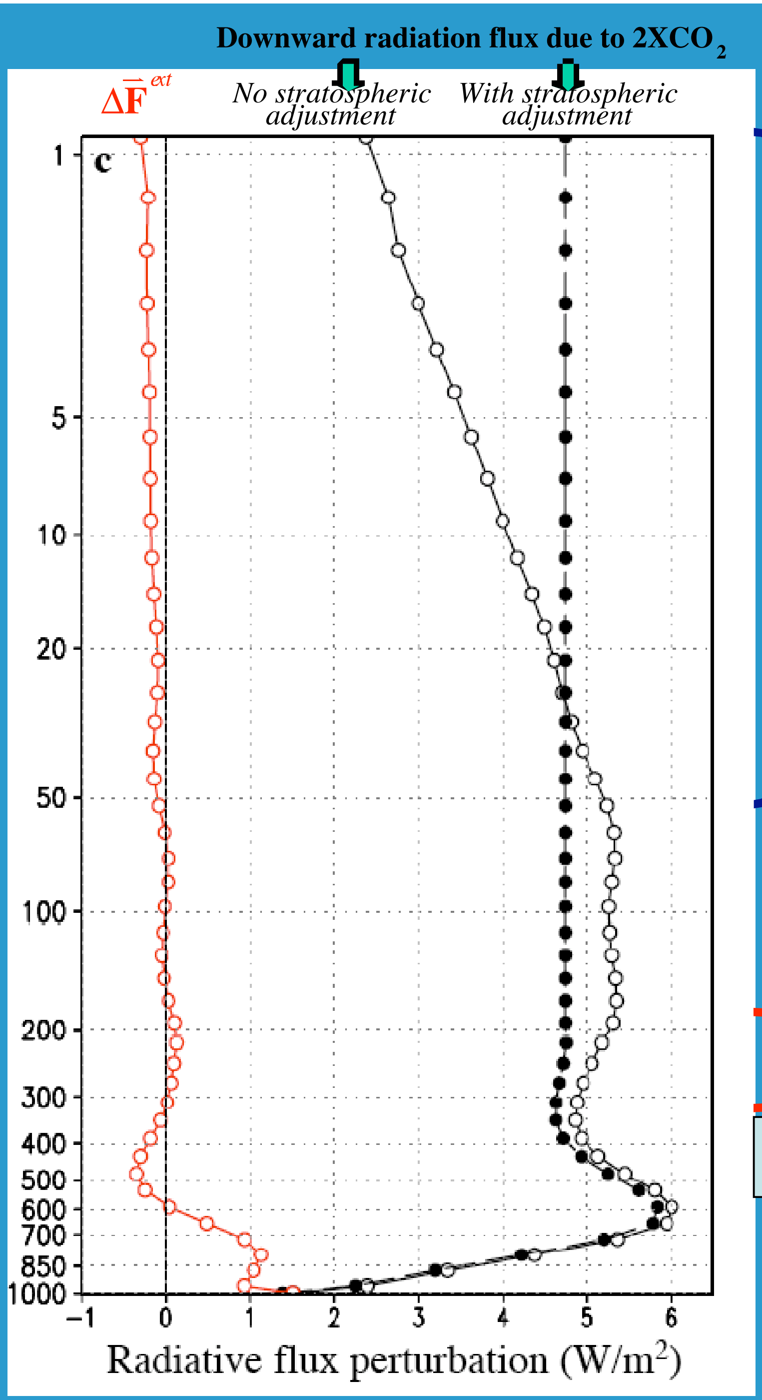
(2) Vertical structure.

Radiative forcing at TOA



IPCC 2001 *the geographical distribution of present-day annual-average radiative forcing (1750 to 2000) due to well-mixed greenhouse gases including CO2 ,CH4 ,N2O, CFC-11 and CFC-12 (Shine and Forster, 1999)*

Vertical Structure of radiative forcing due to doubling CO_2



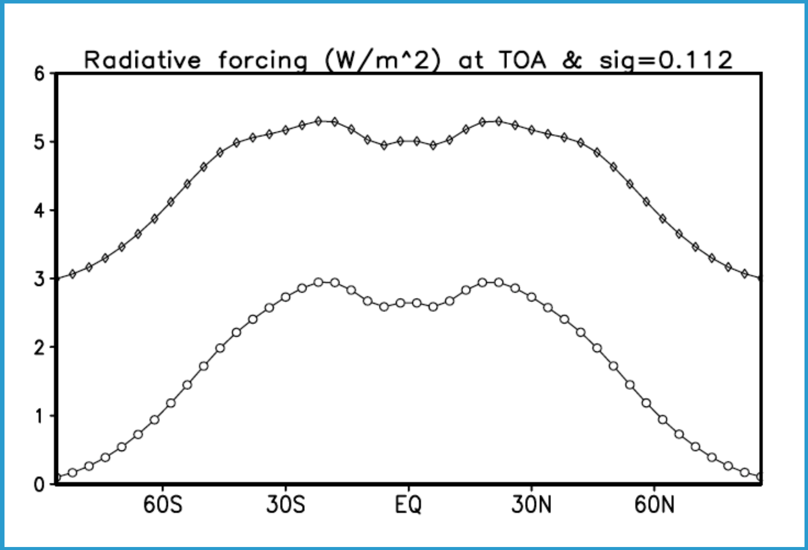
Stratospheric cooling

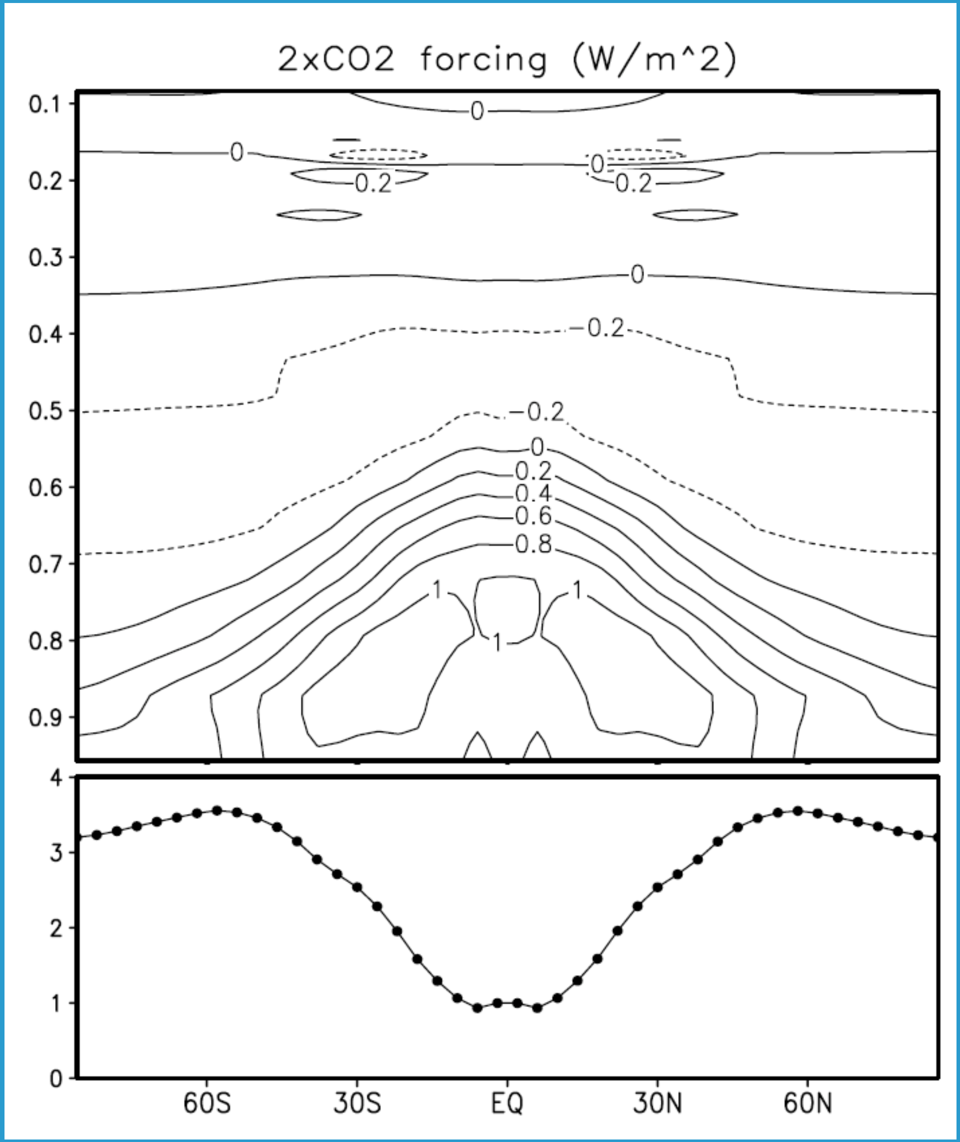
Upper tropospheric and surface heating

Mid-tropospheric Cooling

Lower tropospheric and surface heating

Vertical and horizontal structure of radiative forcing





Climate feedback and the dynamics of Atmosphere and Ocean

In a TOA-based climate feedback analysis framework, all of the local-dynamic feedbacks (from convection, large-scale vertical transport of energy, surface sensible and latent heat fluxes), and part of the non-local dynamic feedbacks (from large-scale horizontal energy transport in atmosphere and ocean) are lumped into one single feedback agent: lapse rate feedback.

(Lu and Cai (2008); Cai and Lu (2008) Climate Dynamics)

Can the dynamic feedbacks explicitly represented in climate feedback analysis?

Coupled Atmosphere-surface
Climate Feedback-response Analysis Method (CFRAM)

(Lu and Cai (2008); Cai and Lu (2008) Climate Dynamics)

Energy balance equation in the atmosphere (Peixoto and Oort, 1994)

Vertically integrated energy balance equation in the ocean (Wunsch and Ferrari (2004), Annual Reviews of Fluid Mechanics)

$$\boxed{\frac{\partial}{\partial t} \simeq 0}$$

$$\vec{\mathbf{R}} = \vec{\mathbf{S}} + \vec{\mathbf{Q}}^{conv} + \vec{\mathbf{Q}}^{turb} - \vec{\mathbf{D}}^{h} - \vec{\mathbf{D}}^{v} + \vec{\mathbf{W}}^{fric}$$

$$\underbrace{\begin{pmatrix} R_1 \\ \vdots \\ R_M \\ R_{M+1} \end{pmatrix}}_{\text{Infrared Radiative energy out-flux}} = \underbrace{\begin{pmatrix} S_1 \\ \vdots \\ S_M \\ S_{M+1} \end{pmatrix}}_{\text{Solar Radiative energy in-flux}} + \underbrace{\begin{pmatrix} Q_1^{turb} \\ \vdots \\ Q_M^{turb} + LE + H \\ -LE - H \end{pmatrix}}_{\text{engergy in-flux due to turbulent transport}} + \underbrace{\begin{pmatrix} Q_1^{conv} \\ \vdots \\ Q_M^{conv} \\ 0 \end{pmatrix}}_{\text{convective engergy in-flux}} \underbrace{- \begin{pmatrix} D_1^{v} \\ \vdots \\ D_M^{v} \\ 0 \end{pmatrix} - \begin{pmatrix} D_1^{h} \\ \vdots \\ D_M^{h} \\ D_{M+1}^{h} \end{pmatrix}}_{\text{energy in-flux due to large-scale vertical and horizontal transport}} + \underbrace{\begin{pmatrix} W_1^{fric} \\ \vdots \\ W_M^{fric} \\ W_{M+1}^{fric} \end{pmatrix}}_{\text{Work due to friction}} \begin{matrix} \left.\vphantom{\begin{matrix}a\\b\\c\end{matrix}}\right\} \text{atmosphere} \\ - \quad \text{surface} \end{matrix}$$

The perturbation of energy-balance by climate forcing ($\Delta\vec{\mathbf{F}}^{ext} = (F_1^{ext}, \cdots, F_M^{ext}, F_{M+1}^{ext})^T$) is

$$\boxed{\Delta\vec{\mathbf{R}} = \Delta\vec{\mathbf{F}}^{ext} + \Delta\vec{\mathbf{S}} + \Delta\vec{\mathbf{Q}}^{conv} + \Delta\vec{\mathbf{Q}}^{turb} - \Delta\vec{\mathbf{D}}^{v} - \Delta\vec{\mathbf{D}}^{h} + \Delta\vec{\mathbf{W}}^{fric}}$$

where,

$$\Delta\vec{\mathbf{R}} = \left(\frac{\partial\vec{\mathbf{R}}}{\partial\vec{\mathbf{T}}}\right)\Delta\vec{\mathbf{T}} + \Delta^{(w)}\vec{\mathbf{R}} + \Delta^{(c)}\vec{\mathbf{R}}$$

$$\Delta\vec{\mathbf{S}} = \Delta^{(c)}\vec{\mathbf{S}} + \Delta^{(\alpha)}\vec{\mathbf{S}} + \Delta^{(w)}\vec{\mathbf{S}}$$

$$\left(\frac{\partial\vec{\mathbf{R}}}{\partial\vec{\mathbf{T}}}\right) = \underbrace{\begin{pmatrix} \dfrac{\partial R_1}{\partial T_1} & \cdots & \dfrac{\partial R_1}{\partial T_{M+1}} \\ \vdots & \ddots & \vdots \\ \dfrac{\partial R_{M+1}}{\partial T_1} & \cdots & \dfrac{\partial R_{M+1}}{\partial T_{M+1}} \end{pmatrix}}_{\textbf{Planck Feedback Matrix}}$$

$$\Delta\vec{\mathbf{T}} = \begin{pmatrix} \Delta T_1 \\ \Delta T_2 \\ \vdots \\ \Delta T_M \\ \Delta T_{M+1} \end{pmatrix}$$

(w) : Water vapor feedback

(c) : cloud feedback

(a) : surface albedo feedback

The responses of atmosphere-surface temperatures to climate forcing and feedbacks can be determined by

$$\left(\frac{\partial\vec{\overline{\mathbf{R}}}}{\partial\vec{\overline{\mathbf{T}}}}\right)\Delta\vec{\overline{\mathbf{T}}} = \underbrace{\Delta\vec{\overline{\mathbf{F}}}^{ext}}_{\text{Forcing}} + \underbrace{\Delta^{(\alpha)}\vec{\mathbf{S}} + \Delta^{(c)}(\vec{\mathbf{S}} - \vec{\overline{\mathbf{R}}}) + \Delta^{(w)}(\vec{\mathbf{S}} - \vec{\overline{\mathbf{R}}})}_{\text{Thermodynamic feedbacks}}$$

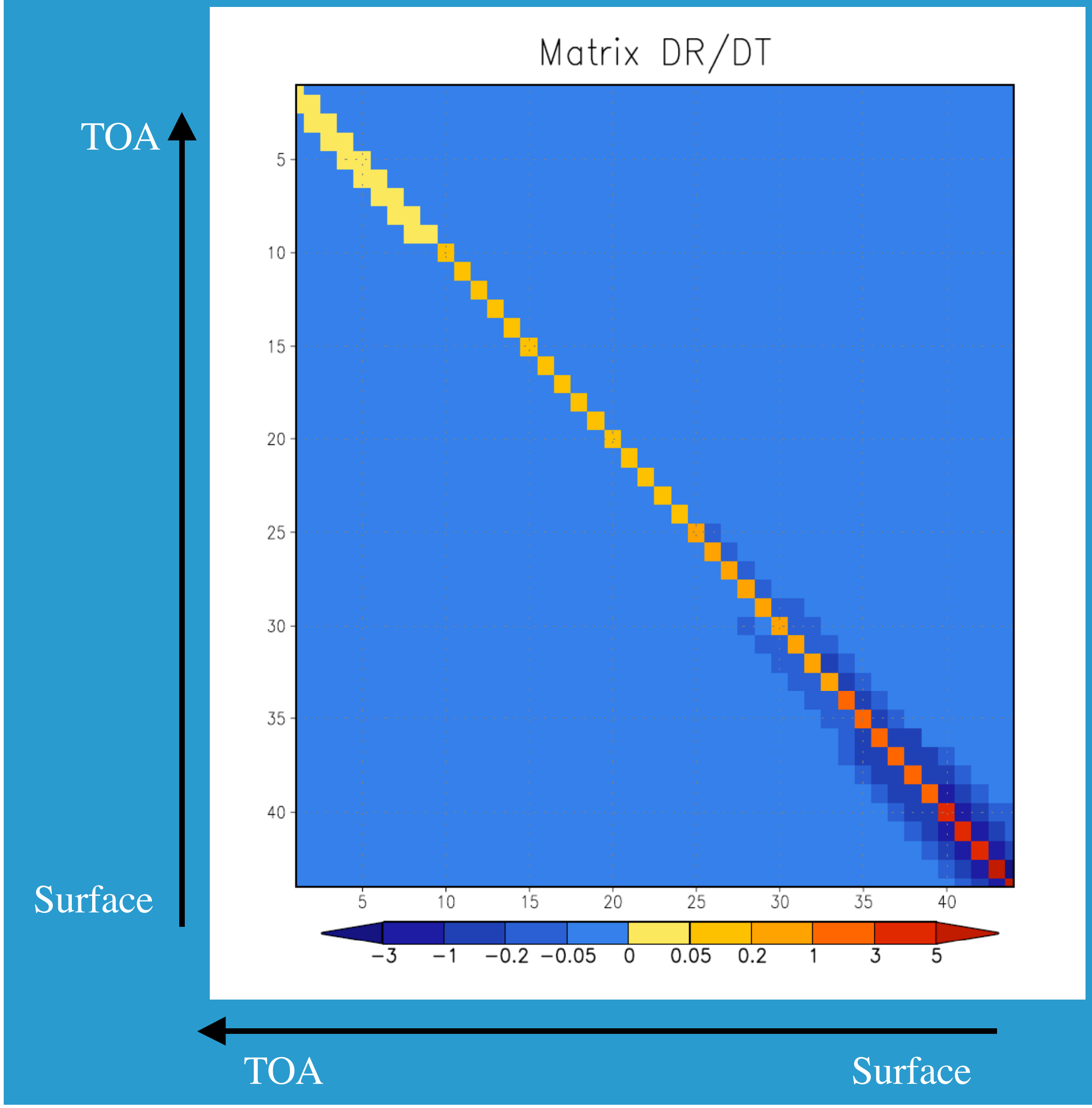
$$+\underbrace{\Delta\vec{\overline{\mathbf{Q}}}^{conv} + \Delta\vec{\overline{\mathbf{Q}}}^{turb} - \Delta\vec{\overline{\mathbf{D}}}^{v} - \Delta\vec{\overline{\mathbf{D}}}^{h} + \Delta\vec{\overline{\mathbf{W}}}^{fric}}_{\text{Dynamic feedbacks}}$$

$$\Delta\vec{\overline{\mathbf{T}}} = \left(\frac{\partial\vec{\overline{\mathbf{R}}}}{\partial\vec{\overline{\mathbf{T}}}}\right)^{-1} \{\Delta\vec{\overline{\mathbf{F}}}^{ext} + \Delta^{(\alpha)}\vec{\mathbf{S}} + \Delta^{(c)}(\vec{\mathbf{S}} - \vec{\overline{\mathbf{R}}}) + \Delta^{(w)}(\vec{\mathbf{S}} - \vec{\overline{\mathbf{R}}})$$

$$+\Delta\vec{\overline{\mathbf{Q}}}^{conv} + \Delta\vec{\overline{\mathbf{Q}}}^{turb} - \Delta\vec{\overline{\mathbf{D}}}^{v} - \Delta\vec{\overline{\mathbf{D}}}^{h} + \Delta\vec{\overline{\mathbf{W}}}^{fric}\}$$

$$= \left(\frac{\partial\vec{\overline{\mathbf{R}}}}{\partial\vec{\overline{\mathbf{T}}}}\right)^{-1} \sum_{n=0}^{8} \Delta\vec{\overline{\mathbf{F}}}^{(n)}$$

Planck Feedback Matrix $\left(\frac{\partial \vec{R}}{\partial \vec{T}}\right)$



Planck feedback matrix (unit: $Wm^{-2}K^{-1}$)

The abscissa is the column index (j) and the ordinate the row index (i) of the matrix. The j^{th} column of the matrix is the mass-weighted cooling rate change from the top layer (i = 1) to the surface layer (i = 44) due to 1 K temperature increase at the j^{th} layer from an equilibrium temperature profile of a radiative-convective model.

What I've learned from the research are:

(1) climate change is not only the change in (radiative) energy exchange between the climate system and outer space, or the changes in temperature, precipitation, atmospheric or oceanic circulation etc, but also the changes in 3-D energy cycle in the climate system;

(2) climate forcing is the changes in vertical (and horizontal) structure of "energy cycle" of the climate system directly due to external factors; Climate feedbacks are the adjustment in vertical (and horizontal) structure of "energy cycle" of the climate system to the forcing; TOA-based forcing and feedbacks are only vertically-integrated version of the general definition;

(3) Based on these generalized definition of climate forcing and feedbacks, we can develop new tools for climate feedback analysis which could reveal how the dynamic feedbacks and thermodynamic feedbacks work synergistically in response to external forcing.

Part III

Use idealized CGCM to study the polar warming amplification and diagnose the role of dynamics in climate change

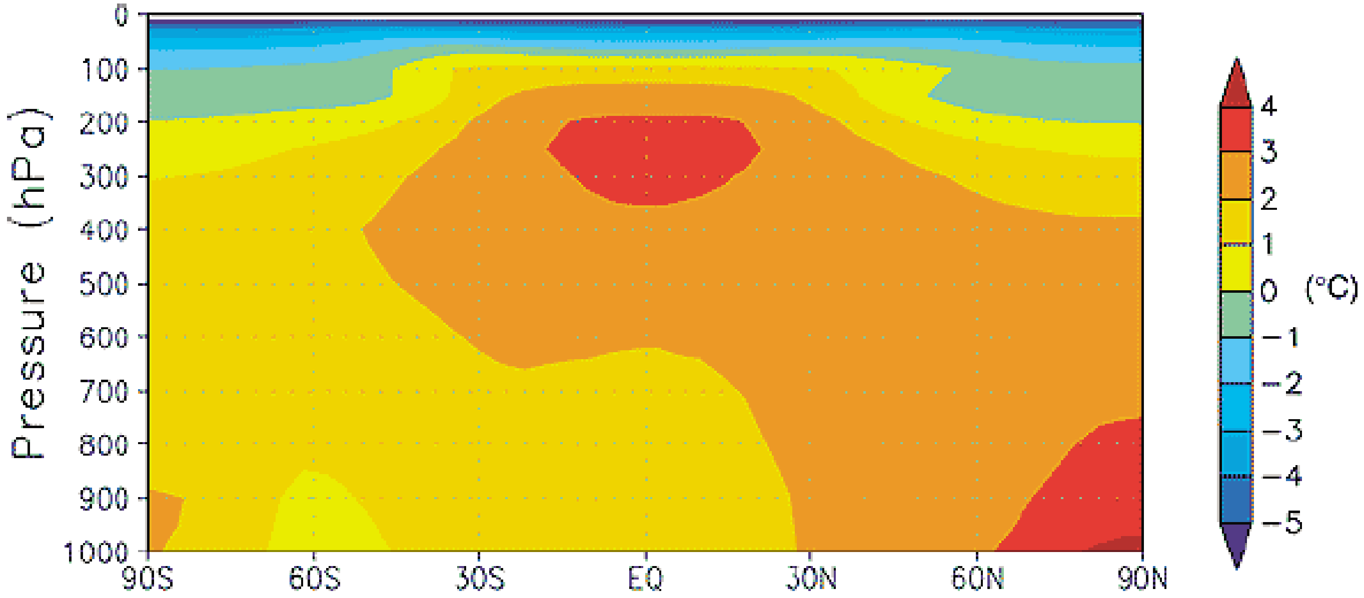


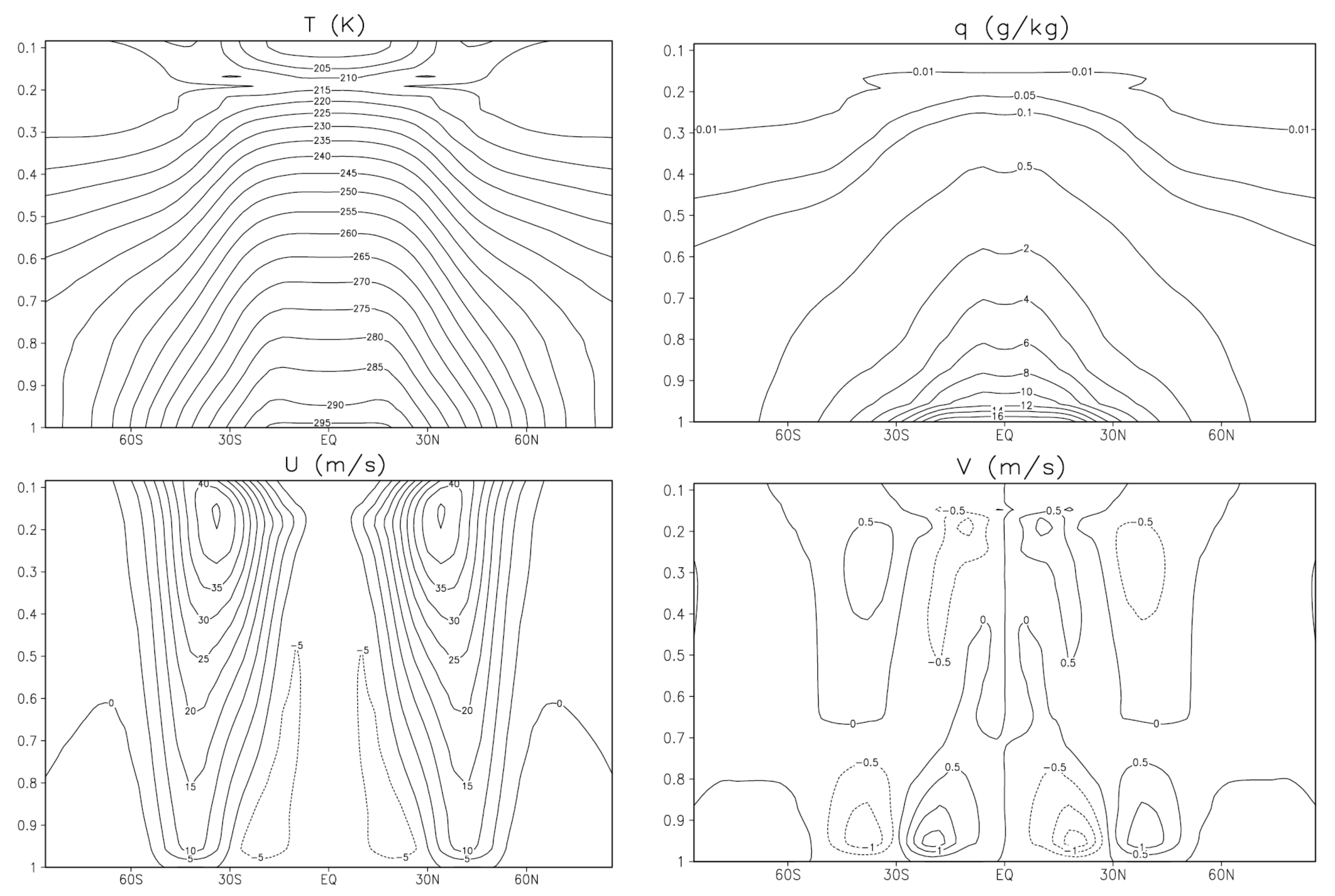
Figure 9.8 of IPCC (2001)

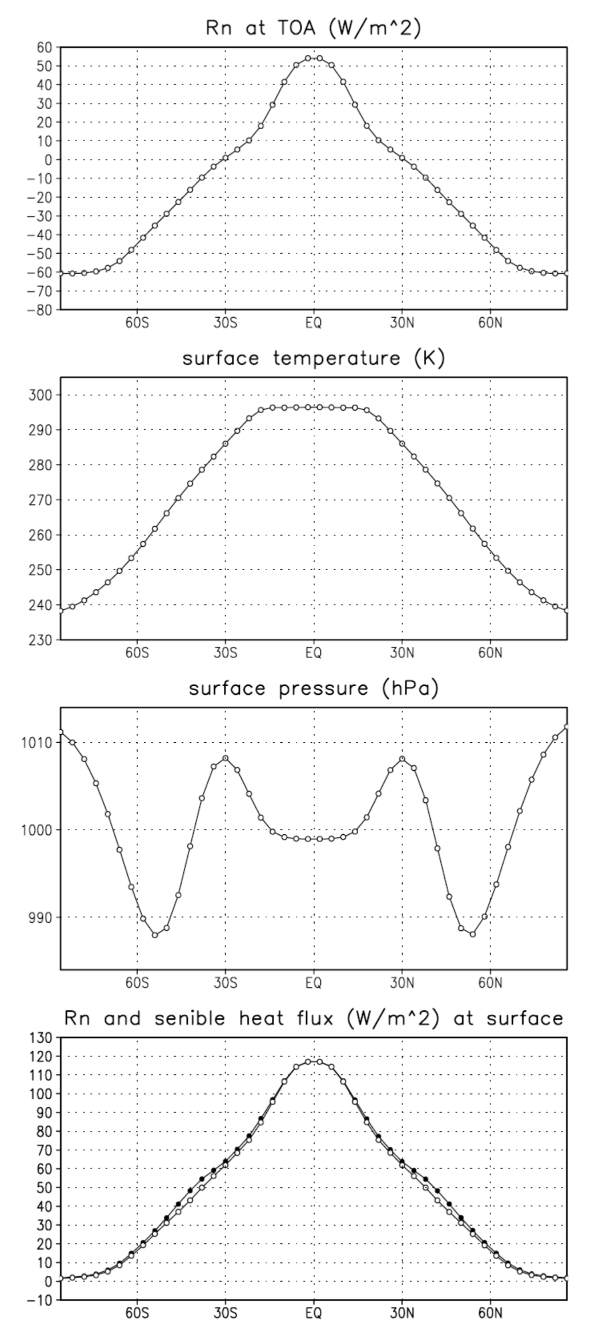
How to understand the global warming pattern with idealized CGCM?

Dynamic amplification of polar warming (even without ice-albedo feedback) in an idealized CGCM

(Based on manuscript in preparing of Lu and Cai)

Mean Climate of the idealized CGCM



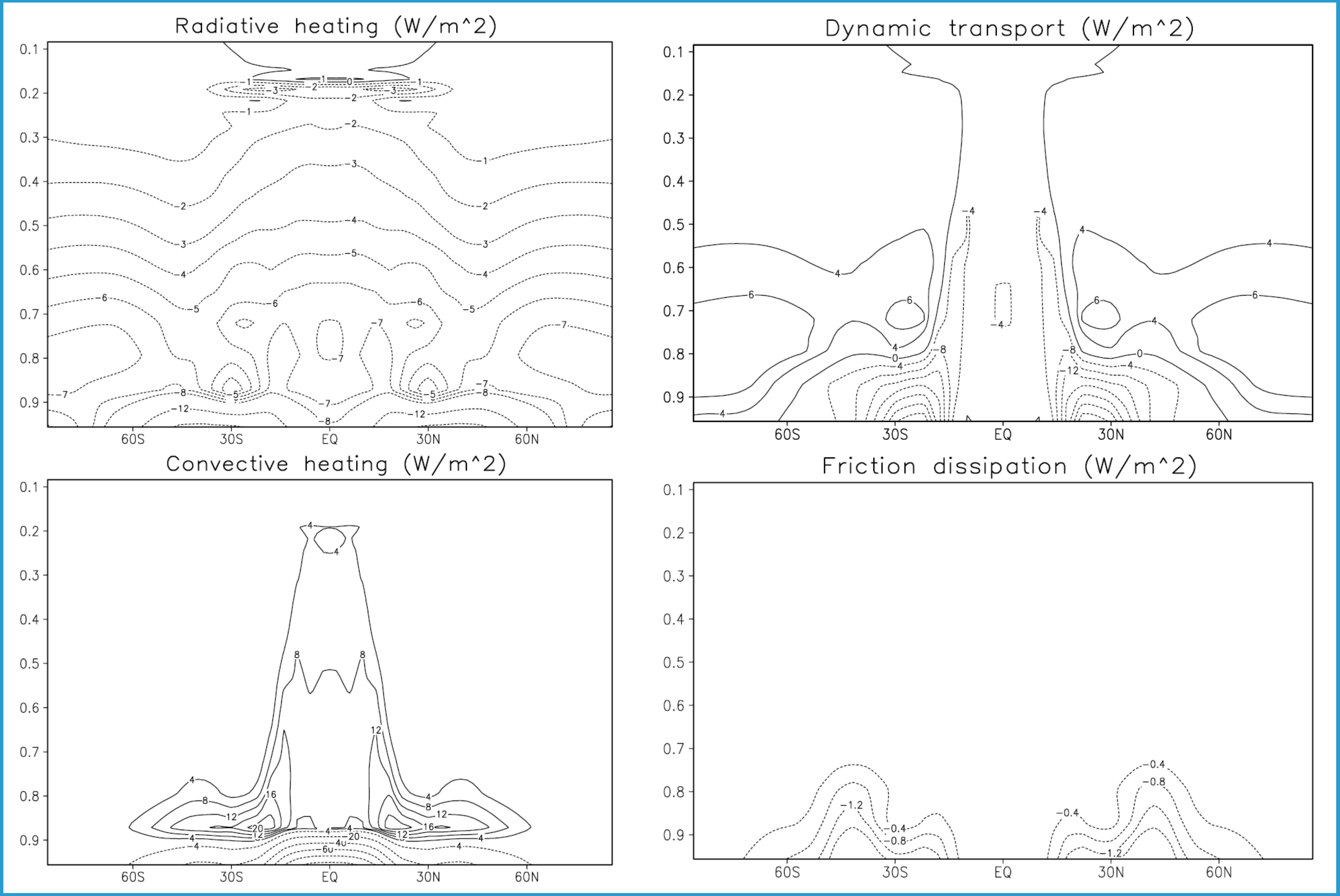

Rn at TOA (W/m^2)

surface temperature (K)

surface pressure (hPa)

Rn and senible heat flux (W/m^2) at surface

The mean condition of energy balance (cycle) in the atmosphere



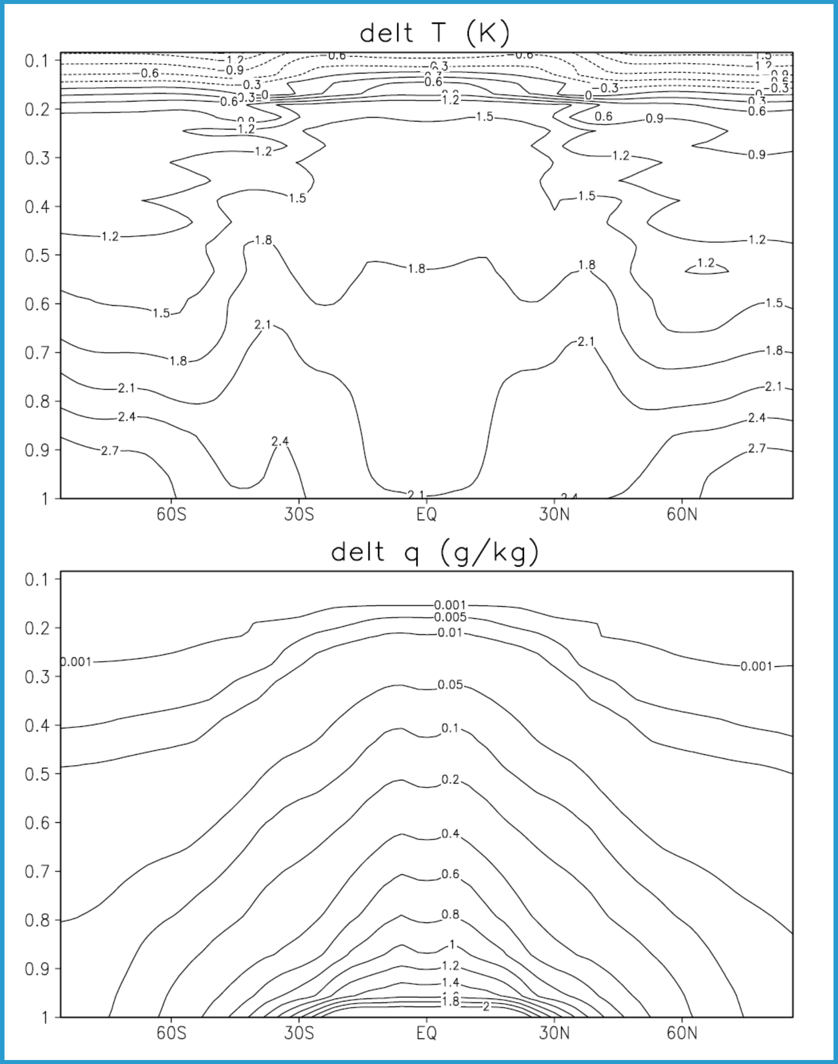
Radiative heating (W/m^2)

Dynamic transport (W/m^2)

Convective heating (W/m^2)

Friction dissipation (W/m^2)

Changes in Temperature and specific humidity (2xCO2 - 1xCO2)



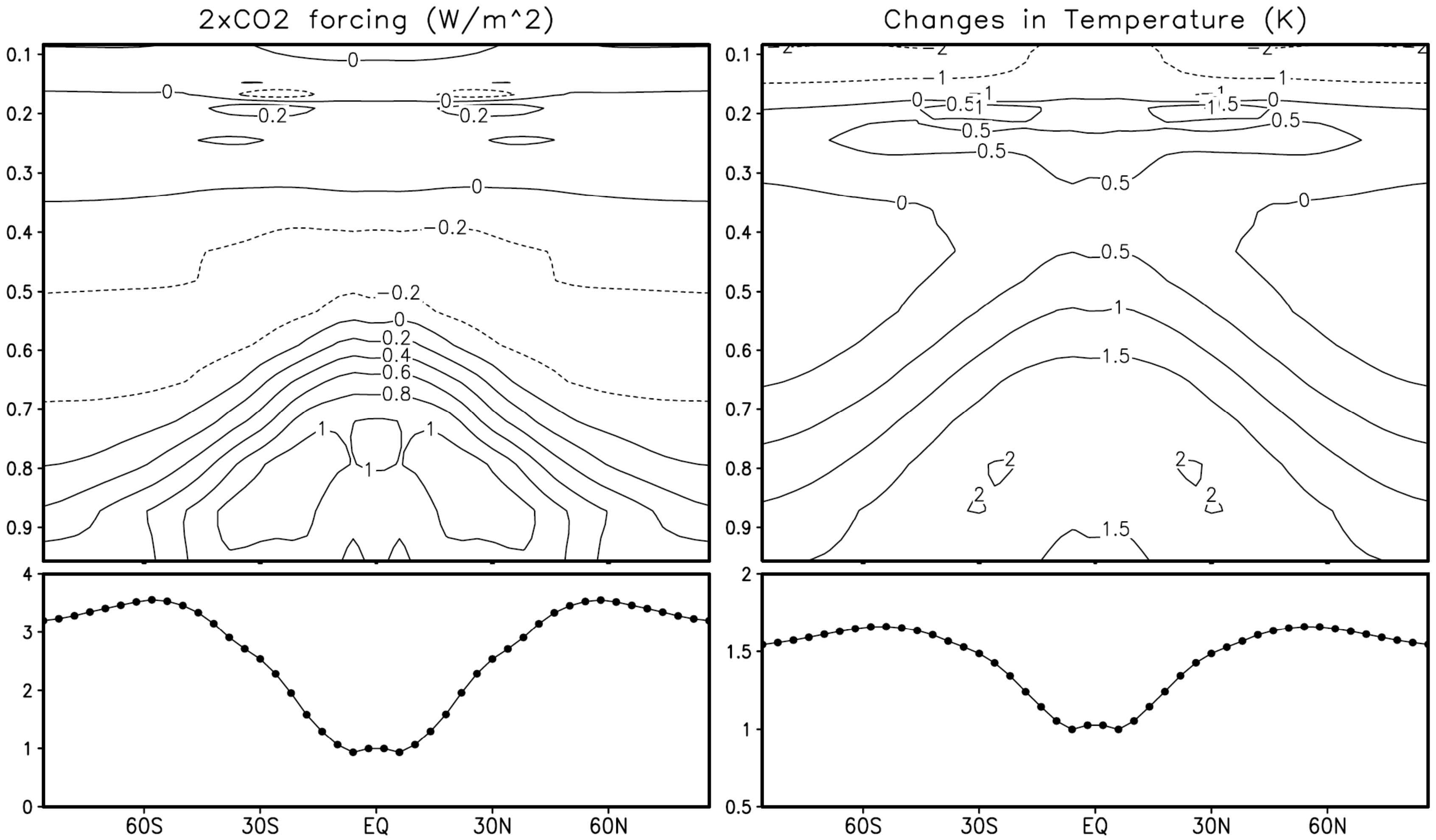
1. Polar surface warming > Tropical warming

2. Tropical warming in upper troposphere > polar tropospheric warming

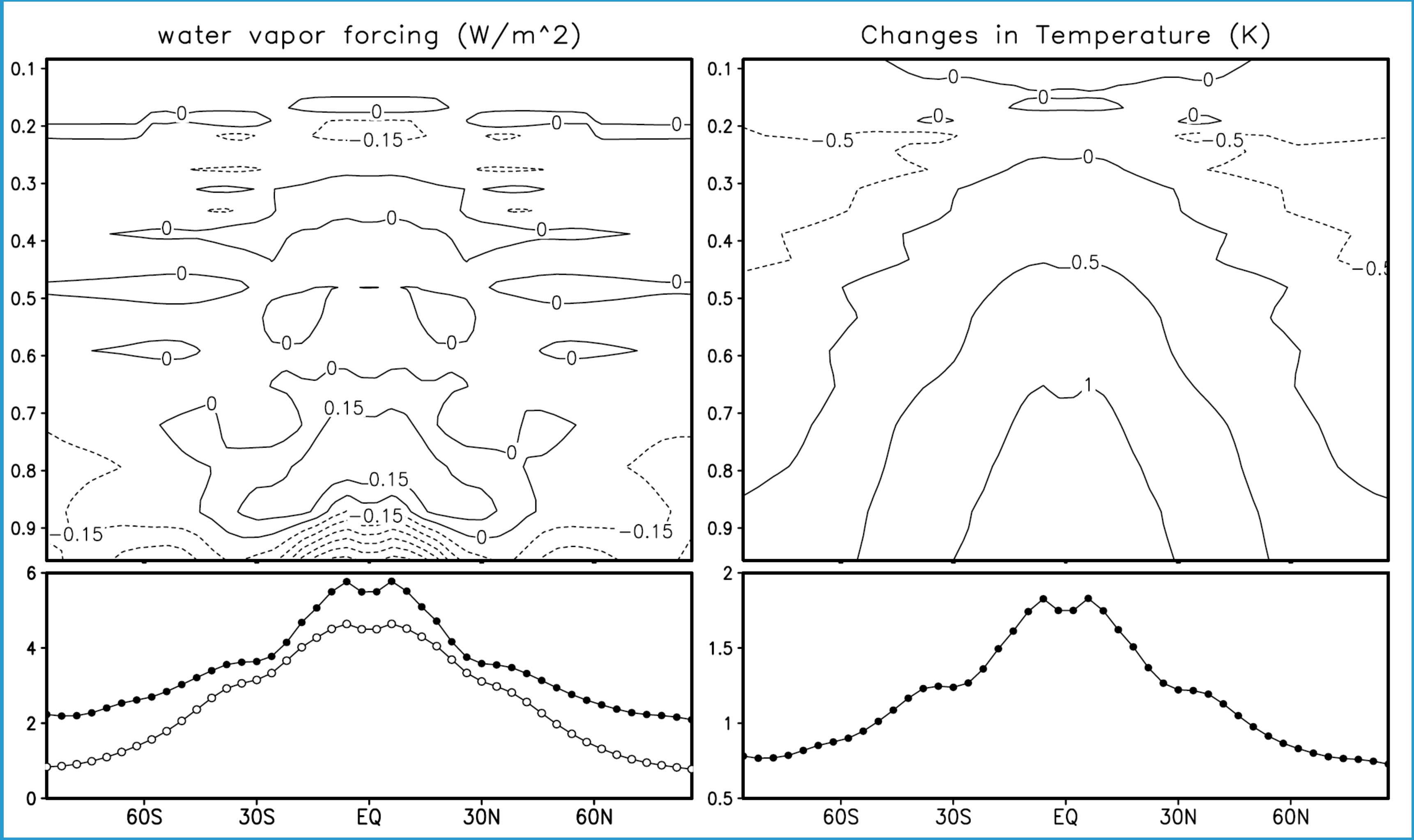
3. Stratospheric cooling

Decomposing the temperature change due to doubling CO2 with the CFRAM

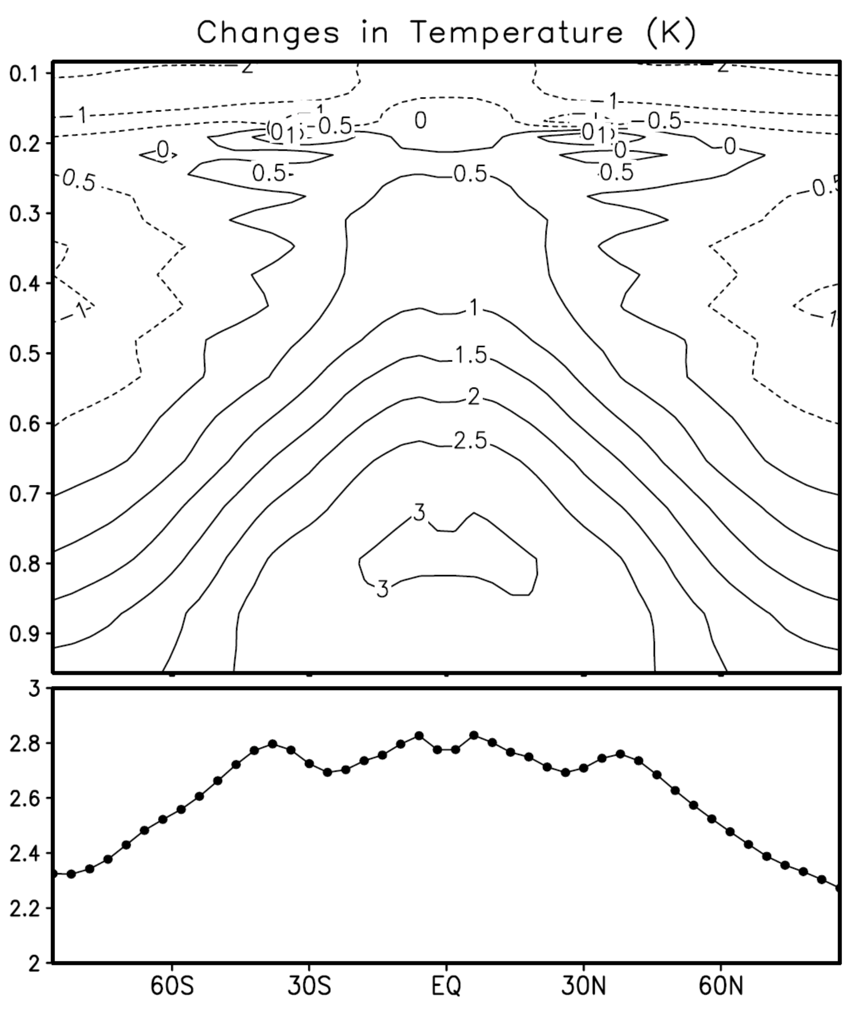
Response to direct effect of external forcing



Response to the water vapor feedback

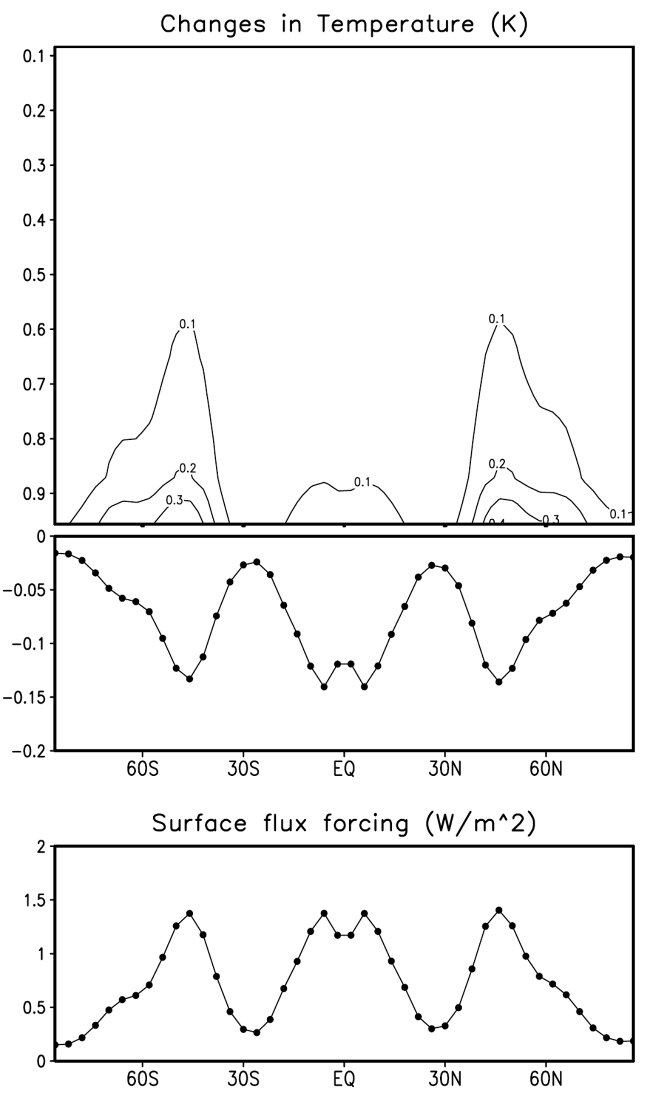


Sum of the Responses to forcing + water vapor feedback



1. **Tropical (surface and atmosphere) warming > warming in high latitudes;**
2. **Cooling in polar mid-upper troposphere.**

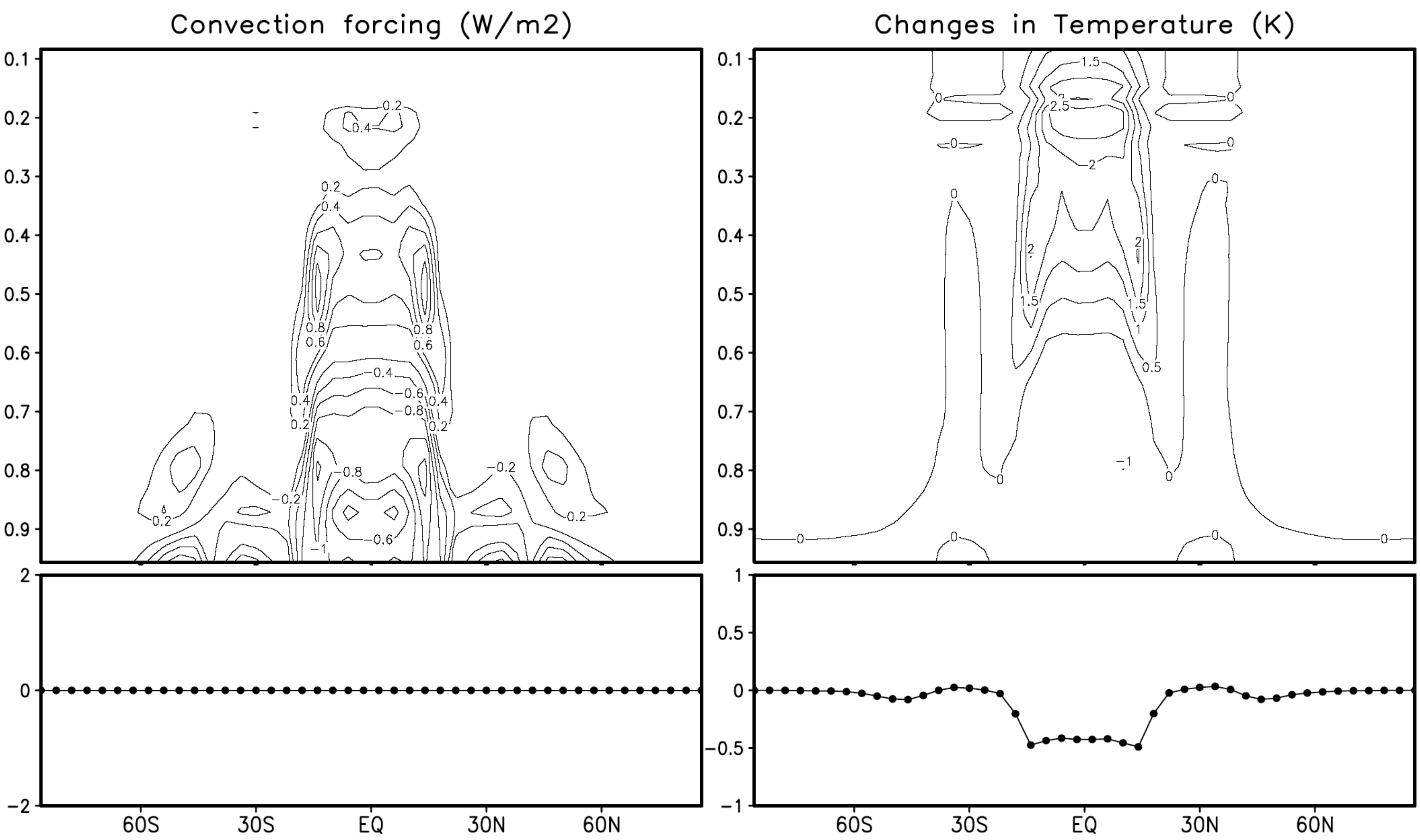
Response to surface sensible heat flux feedback



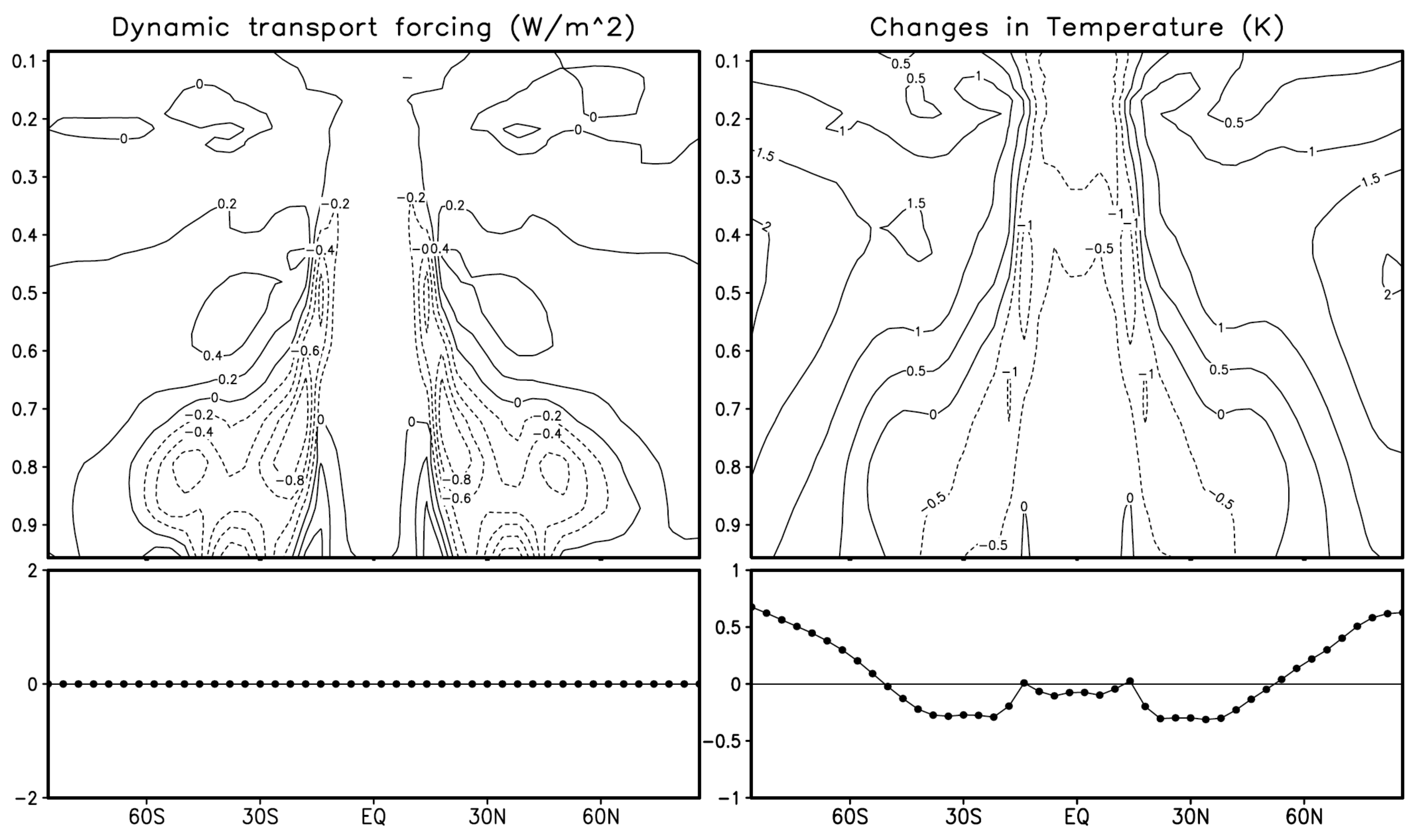
Changes in Temperature (K)

Surface flux forcing (W/m^2)

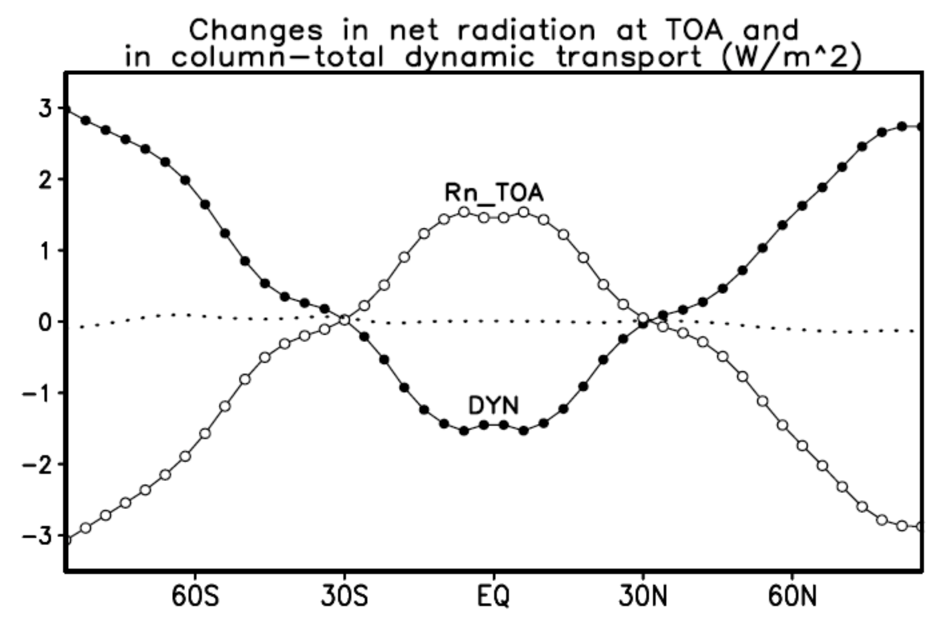
Response to dry convection feedback



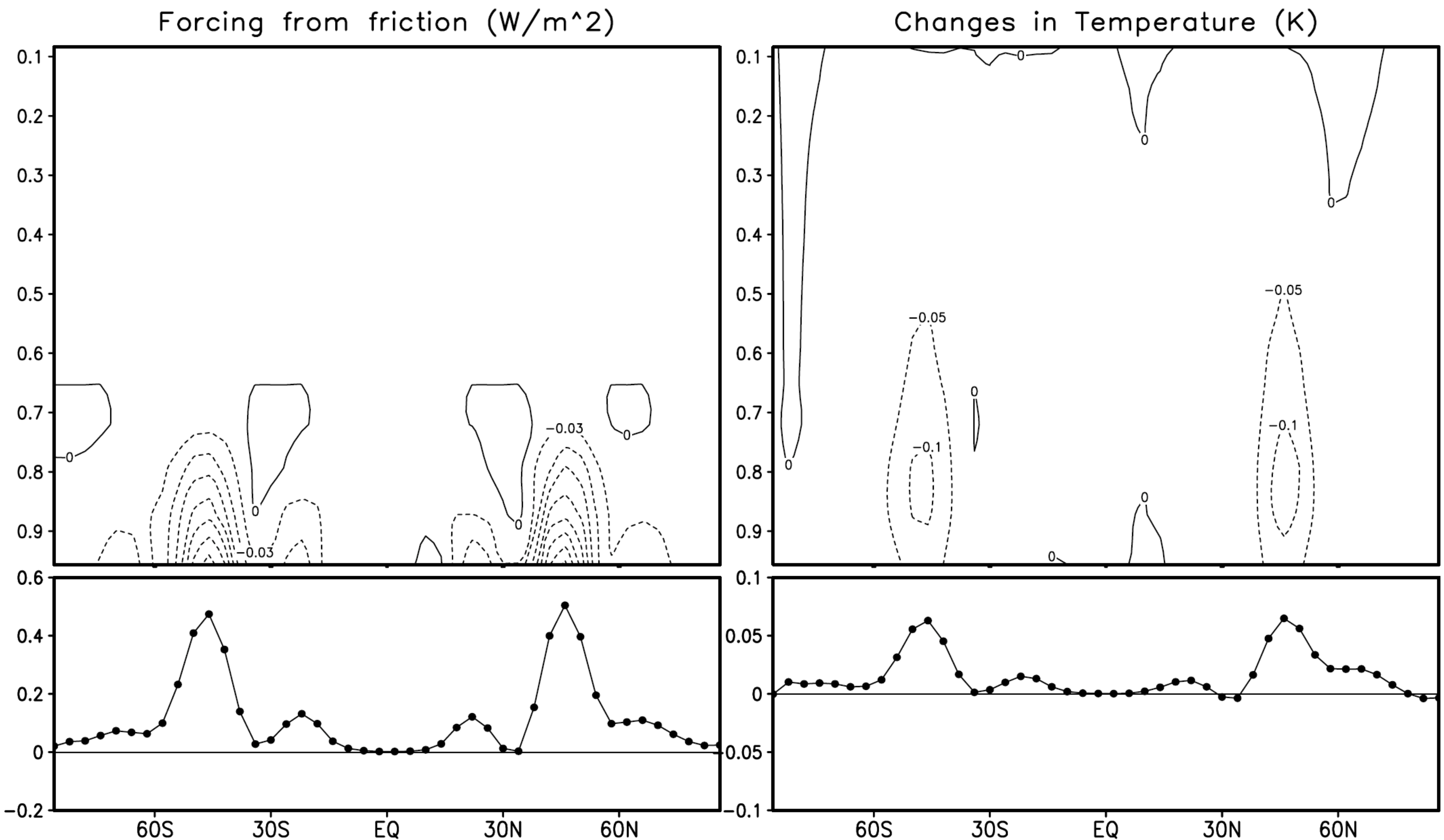
Response to dynamic transport feedback



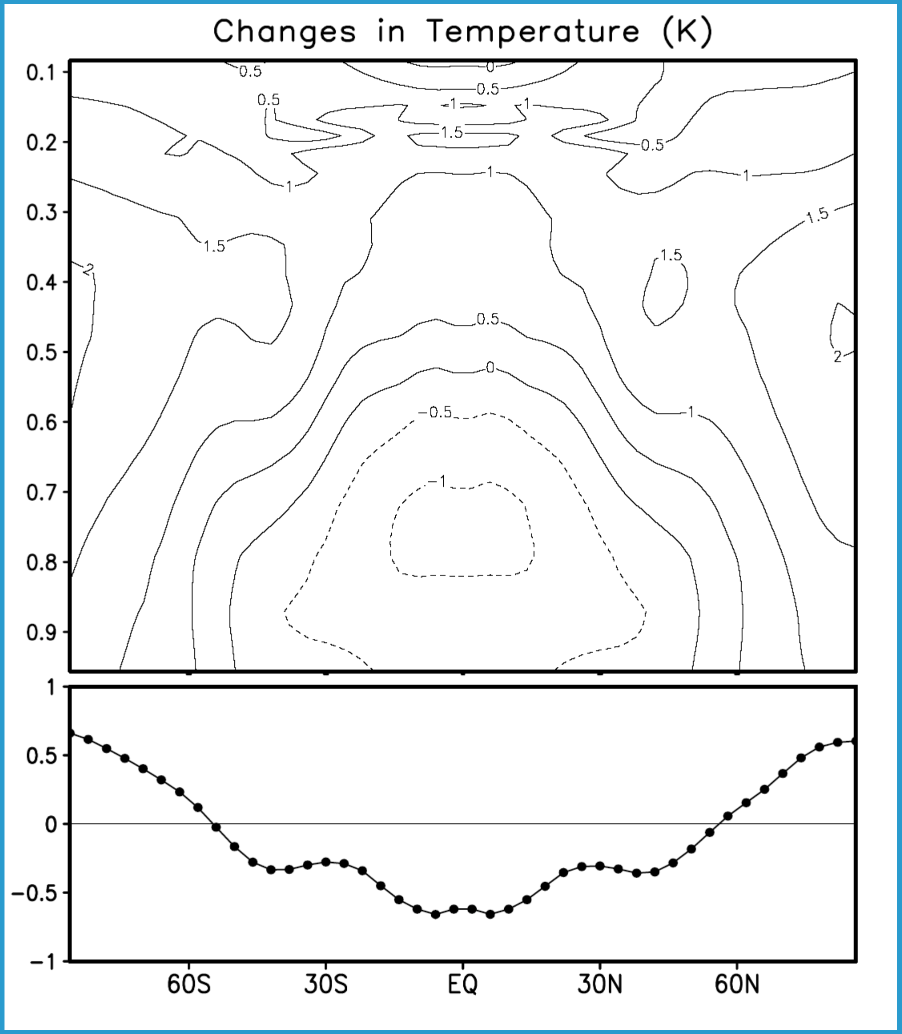
Changes in net radiation at TOA and the vertically integrated dynamic transport



Response to friction feedback

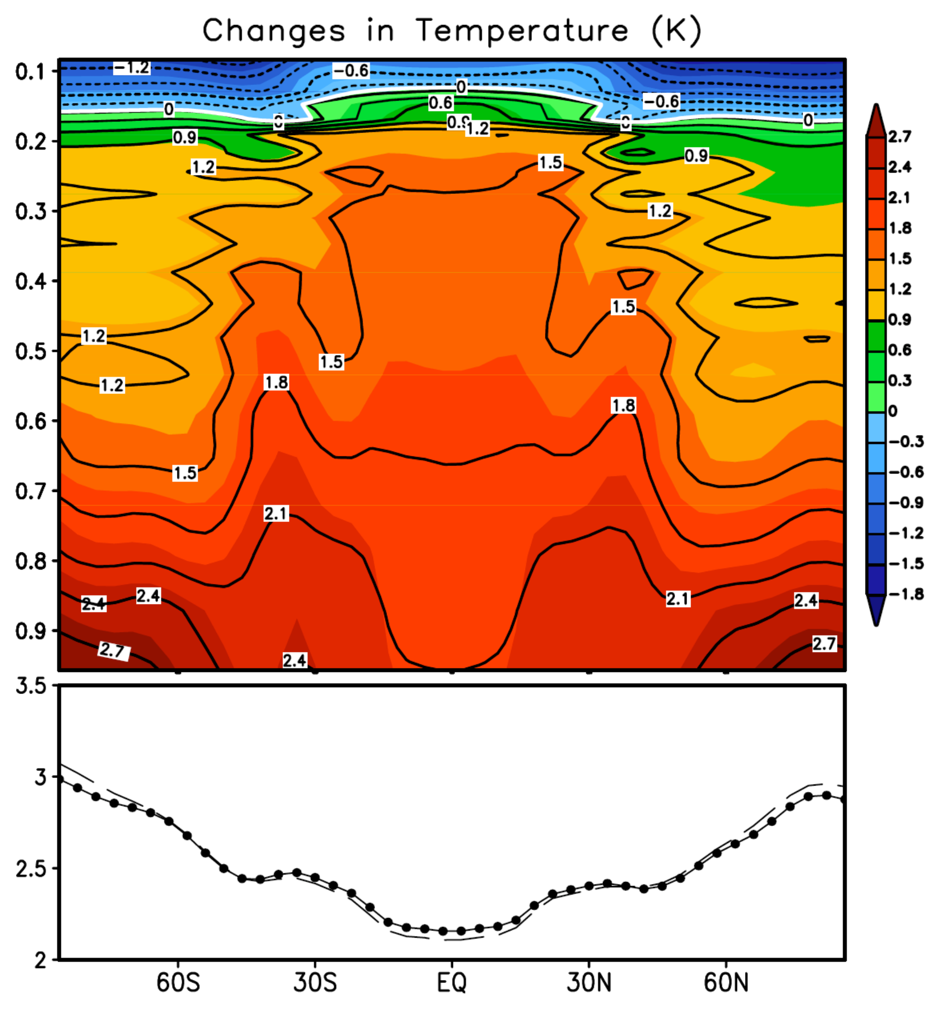


The total response to the dynamic-related feedbacks



Dynamics-induced polar amplification of surface and tropospheric warming

Is the CFRAM decomposition reliable ?



Summary

1. We use idealized climate models to explore the climate forcing and feedbacks: climate forcing is the changes in vertical (and horizontal) structure of "energy cycle" of the climate system directly due to external factors; Climate feedbacks are the adjustment in vertical (and horizontal) structure of "energy cycle" of the climate system to the forcing; TOA-based forcing and feedbacks are only vertically-integrated version of the general definition;

2. We also use the idealized climate model to illustrate the dynamical feedbacks as possible mechanisms responsible for polar amplification of global warming.

Interesting Issues:

Is it possible that some kind of interactions in the climate system could be included in the GFD experiments, as suggested in Peter Rhines' lecture?

How to compare the idealized models ('approximate GFD experiments ') with the GFD experiments ('precise numerical simulations', Peter Rhines)?