# Cloud Feedbacks in the climate system:
A critical Review

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The radiative-convective equilibrium paradigm

REC: To first order, the atmosphere exists in a state of *quasi balance* between radiative cooling and the convective processes that give rise to latent and sensible heating.

RCE and cloud feedback
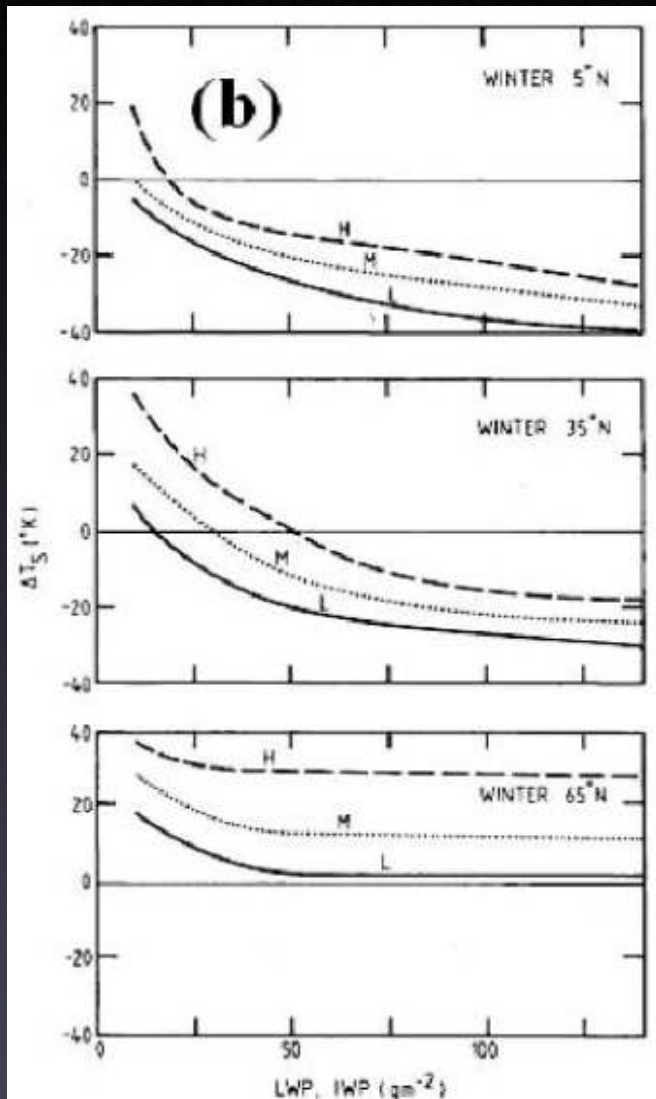

CRITICAL BLACKNESS

(a)

TEMPERATURE (°K)
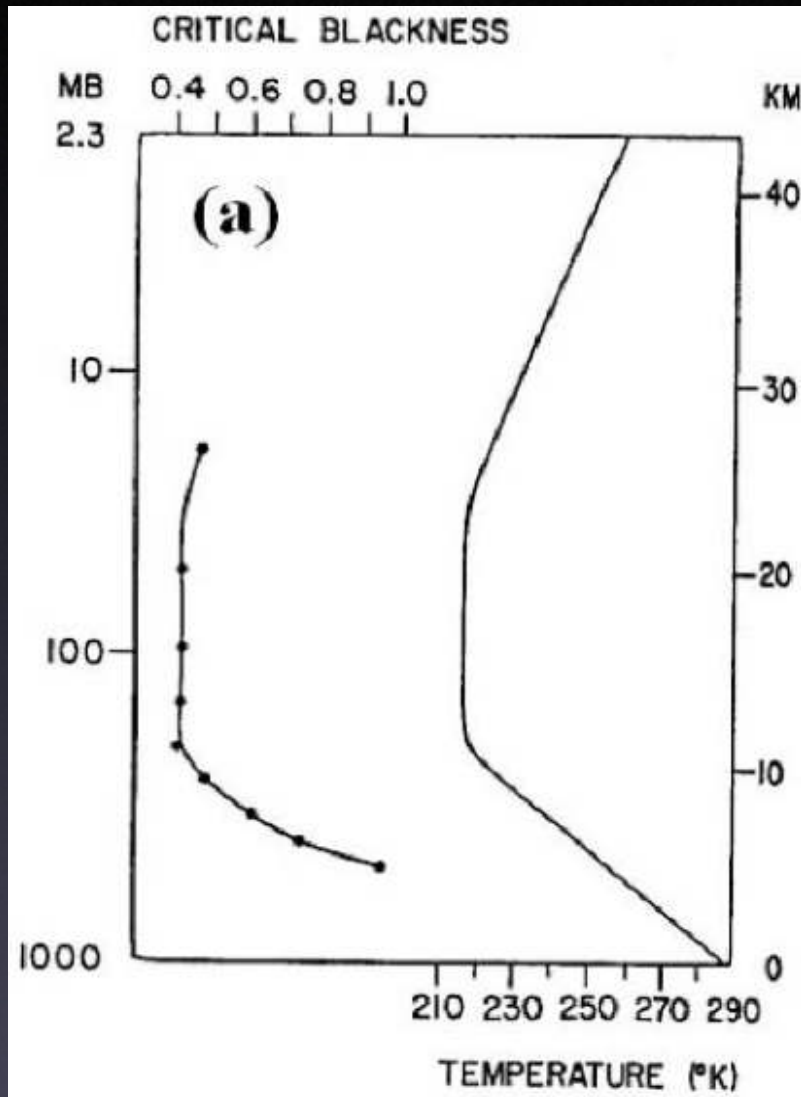
The critical-blackness cloud experiment of Manabe and Strickler.

- Manabe and Strickler (1964) using simple RCE model pointed out that high cirrus clouds heat the surface by an amount affected by their height and emissivity whereas low clouds cool the surface.

- They argued that this heating occurs when the emissivity exceeds about 0.5 (i.e., thicker cirrus).

- The profile to the left is the profile of emissivity above which clouds warm the surface relative to the given clear-sky temperature profile (right).

Cloud albedo and emission are related producing complicated balance at the TOA!

RCE and cloud feedback

The change in equilibrium surface temperature as a function of cloud LWP and IWP for low, middle and high clouds

- Stephens and Webster (1981): when treated in a physically consistent manner, linked via cloud water and ice paths and thus optical depth, then it is not the thicker cirrus that produces a surface heating but rather the thin cirrus.

These kinds of experiments had less to do with defining actual cloud feedback and climate sensitivity per se but more to do with demonstrating the potential relevance of cloud–radiation interactions to the climate system.

RCE and cloud-resolving models

- The early RCE studies were meant to represent, loosely, a quasi-global-mean state.

- These simple models have been replaced by more complex GCM climate models although many of the sensitivities derived from RCE models were broadly replicated in GCMs.

- More recently, however, the RCE paradigm has been revisited in a series of equilibrium experiments conducted using cloud-resolving models (CRMs).

- The use of CRMs in these experiments offers a more self-consistent treatment of convection and related cloud-radiation processes than is possible with the simple RCE models.

- To date, CRM–RCE experiments have been constructed as open systems of fixed SST.

RCE and the Earth's hydrological cycle

- RCE can also be defined in terms of the atmospheric energy budget. This budget, to first order, occurs as a balance between the radiative cooling of the atmosphere and latent heating associated with precipitation.

- *Thus RCE implies that the radiation balance of the atmosphere and the planetary hydrological cycle are connected.*

- If one accepts the simple hypothesis that the hydrological cycle adjusts to changes in the atmospheric radiative cooling, then we have a basis for interpreting how the hydrological cycle might change under global warming.

- Both column water vapor and clouds are principal factors that influence the gross radiative budget of the atmosphere. Consequently, changes to clouds and water vapor that induce a change to the column atmospheric cooling will, in turn, produce compensating changes to the hydrological cycle.
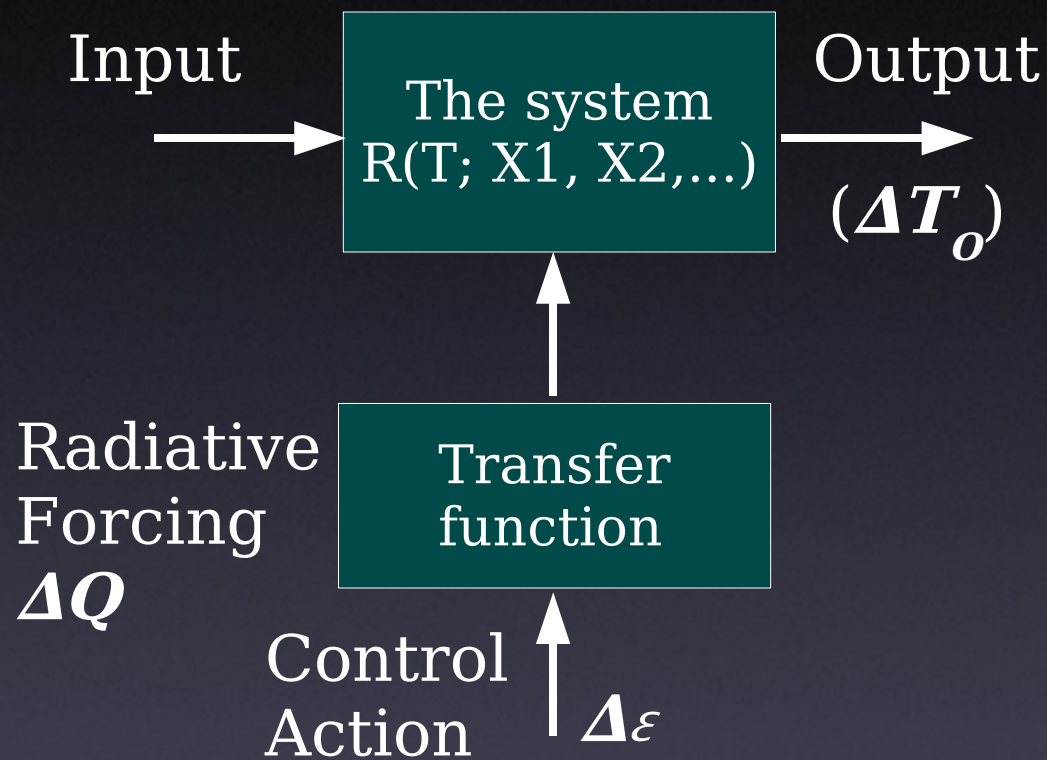
Regulation of tropical SSTs

Tropical SSTs come under the influence of a runaway water vapor greenhouse effect and that a negative feedback must operate to limit that the climatological SSTs to about 30C.

- A feedback induced by the coupling of meridional momentum transport, low level winds, and evaporation.

- Feedbacks that combine the radiation balance and large-scale dynamics: large-scale dynamics produces a communication between the atmosphere above the warmest waters and deepest convection and the atmosphere above the cooler waters as part of the Walker circulation.

- A cloud-radiation feedback involving the relationships between SST, deep convection, and detrained anvil cirrus and solar radiation.

- It is practically impossible to verify the simplifying assumptions of the hypotheses in part because we cannot isolate those processes in the real world and in part due to the ambiguous nature of the proxy data used to examine processes.

A systems perspective of cloud feedback

Input →

The system
R(T; X1, X2,...)

→ Output

(ΔT_o)

Radiative Forcing ΔQ

Transfer function

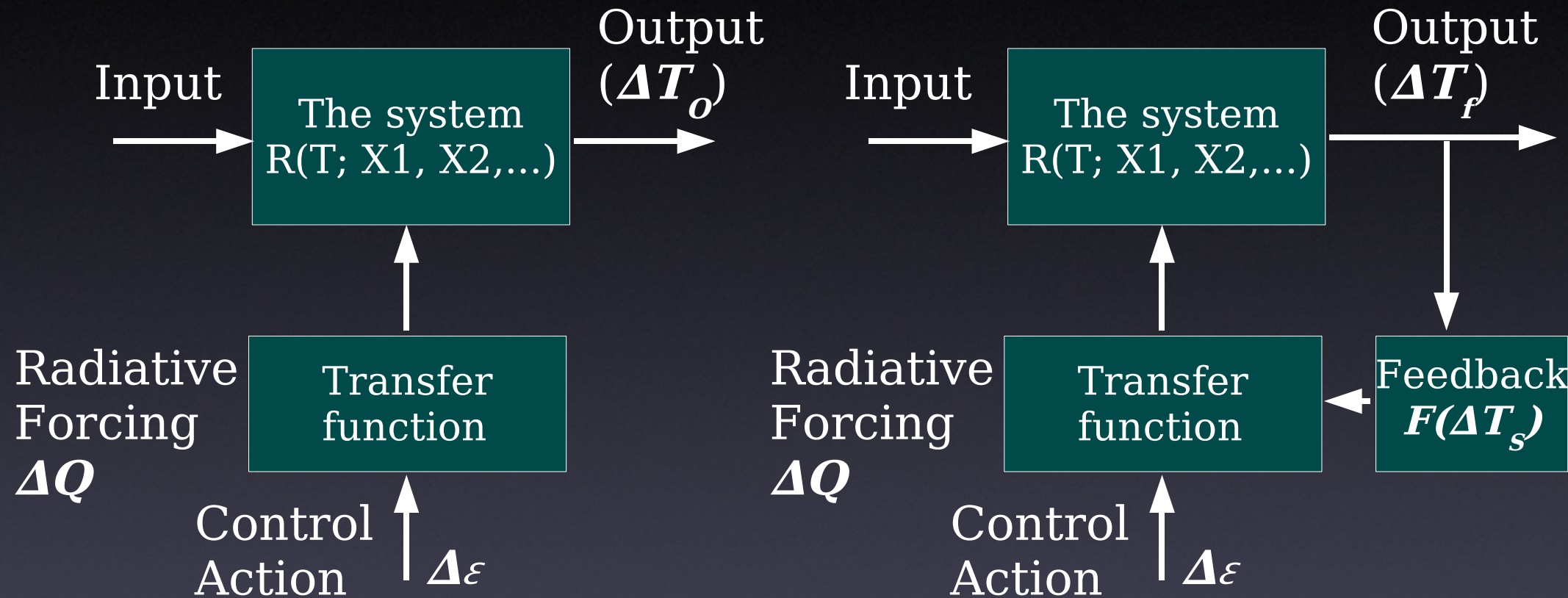Control Action $\Delta\varepsilon$

Control system here is defined as an arrangement of connected physical components that act as an entire self-regulating unit.

- *System* is the entire global climate system composed of subsystems with connecting inputs and outputs.

- *Input* is the solar energy received from the sun (can vary on many time scales - diurnal, seasonal, and longer).

- The *output* of the system may also be expressed in a number of ways, but usually this is taken to be the global temperature T_s

- *Control action* is responsible for activating the system to modulate the output now expressed as a change T_s

Open vs closed system

Input → **The system R(T; X1, X2,…)** → Output (ΔT_o)

Input → **The system R(T; X1, X2,…)** → Output (ΔT_f)

Radiative Forcing ΔQ

Transfer function

Transfer function

Feedback $F(\Delta T_s)$

Radiative Forcing ΔQ

Control Action $\Delta \varepsilon$

Control Action $\Delta \varepsilon$

Open (energy balance) system – the control action is independent of output and the sensitivity is that which occurs *without* feedbacks

Closed or feedback system - the action triggers a response that modulates the radiative forcing. Feedbacks can operate in a series, in parallel or as some combination if both.

System identification

- What is the system, its component processes and its "control action"?

- What is the system output? Feedbacks are only meaningful when defined with respect to a given output.

- How do we observe or otherwise quantify open and closed system responses in parallel?

A simple open system

- Suppose that the radiation budget at the TOA can be defined *uniquely* by *time-* and *space-averaged* quantities:

$$R_{TOA} = R_{TOA}(\epsilon, T; X_1, X_2, ...) = 0 \qquad \Delta R_{TOA} = \partial_\epsilon R_{TOA} \Delta\epsilon + \partial_T R_{TOA} \Delta T$$

$$\text{Equilibrium} \to \Delta R_{TOA} = 0 \qquad \Delta T_{eq,o} = -\left(\partial_T R_{TOA}\right)^{-1} \partial_\epsilon R_{TOA} \Delta\epsilon$$

$$\Delta T_{eq,o} = \Delta Q_o / \lambda_o$$

- Example:

$$R_{TOA} = \frac{Q_o}{4}(1 - \bar{\alpha}) - \sigma T_p^4 \qquad \lambda_o = 4\sigma T_p^3 = 3.7 \, W \, m^{-2} K^{-1} : T_p = 253 \, K$$

- The relevance of this simple analysis to more complex systems such as the real climate system or even of climate simulated by GCMs is unclear being a gross oversimplification of these systems. Consider a system defined by output $T_S = T_S(T_P)$.

Relevance?

- The relevance of this simple analysis to more complex systems such as the real climate system or even of climate simulated by GCMs is unclear being a gross oversimplification of these systems. Consider a system defined by output $T_S = T_S(T_P)$.

$$\lambda_o = 4\,\sigma\,T_p^3\,\frac{dT_p}{dT_s}$$

- The complex (unknown) functional dependence $T_S(T_P)$ represents the sequence of atmosphere processes and radiative transferthat establishes the connection between surface temperature T_S and T_P

- Alternatives: OLR ($\lambda_o = 2\ W\,m^{-2}\,K^{-1}$) ; implicitly λ_o to the he sensitivity derived using the clear-sky portions of the R_{TOA}

Quantifying strictly requires observations of the equivalent system without feedbacks, which requires a identification of the system itself and ability to isolate processes within it.

A simple closed feedback system

- Consider a system, the feedbacks are established by the processes $X_j(T)$, where T is the independent output:

$$R_{TOA} = R_{TOA}(\epsilon, T; X_j(T), j=1..n) = 0$$

$$\Delta R_{TOA} = \partial_\epsilon R_{TOA} \Delta \epsilon + \left(\partial_T R_{TOA} + \sum_{j=1}^{n} \partial_{X_j} R_{TOA} \frac{dX_j}{dT}\right) \Delta T$$

$$\text{Equilibrium} \rightarrow \Delta R_{TOA} = 0$$

$$\Delta T_{eq,o} = -\left(\partial_T R_{TOA} + \sum_{j=1}^{n} \partial_{X_j} R_{TOA} \frac{dX_j}{dT}\right)^{-1} \partial_\epsilon R_{TOA} \Delta \epsilon$$

$$\Delta T_{eq,f} = \Delta Q_o / \lambda_f$$

Feedback parameter

$$\frac{\Delta T_{eq,f}}{\Delta T_{eq,o}} = \frac{\lambda_o}{\lambda_f} \equiv 1 - f \qquad\qquad f = \frac{1}{\lambda_o} \sum_{j=1}^{n} \frac{\partial R_{TOA}}{\partial X_j} \frac{dX_j}{dT} = f_1 + f_2 + \dots f_n$$

- f_j emerges as a measure of the feedback arising from process $X_j(T)$

- For an open loop system $f = 0,$ and $\lambda_o = \lambda_F$

- A strategy typically employed to estimate f from model simulations is to determine each individual feedback contribution and sum these.

- Two model-based methods have been introduced for this purpose. One uses a simple one- or two-dimensional model and the second uses 3D GCM-derived fields as input into offline radiation calculation.

Problems: system identification, assumption that the feedbacks are independent and linear.

The cloud optical depth feedback example

- A number of studies indicate that cloud feedbacks couple to other feedback in the climate system.

- The principal process connecting cloud feedbacks to others, and water vapor feedbacks in particular, is the atmospheric circulation.

- **Question:** how does the influence of circulation alter otherwise simple ideas about cloud and water vapor feedbacks?

- **Answer:** examine a simple cloud liquid water-optical depth feedback

The cloud optical depth feedback example

- A simple cloud liquid water-optical depth feedback, might exist given the association between optical depth and liquid water path, and given that the relation between liquid water path and temperature was controlled in a manner predicted by simple thermodynamic relationships.

$$R_{TOA} = \frac{Q_0}{4}\left\{1 - \alpha[LWP(T_s)]\right\} - \sigma T_p(T_s)^4 \qquad X_1 = LWP(T_s)$$

$$\frac{\Delta T_{eq,f}}{\Delta T_{eq,o}} = \frac{1}{1 - f}$$

- **f = -1.3** implies a strong negative feedback

The cloud optical depth feedback example

- Analyzes that correlate global observations of cloud optical depth and cloud LWP data with cloud temperature show convincingly that the cloud liquid water path-temperature relationship is grossly affected by factors other than temperature (i.e. through cloud thickness) changes).
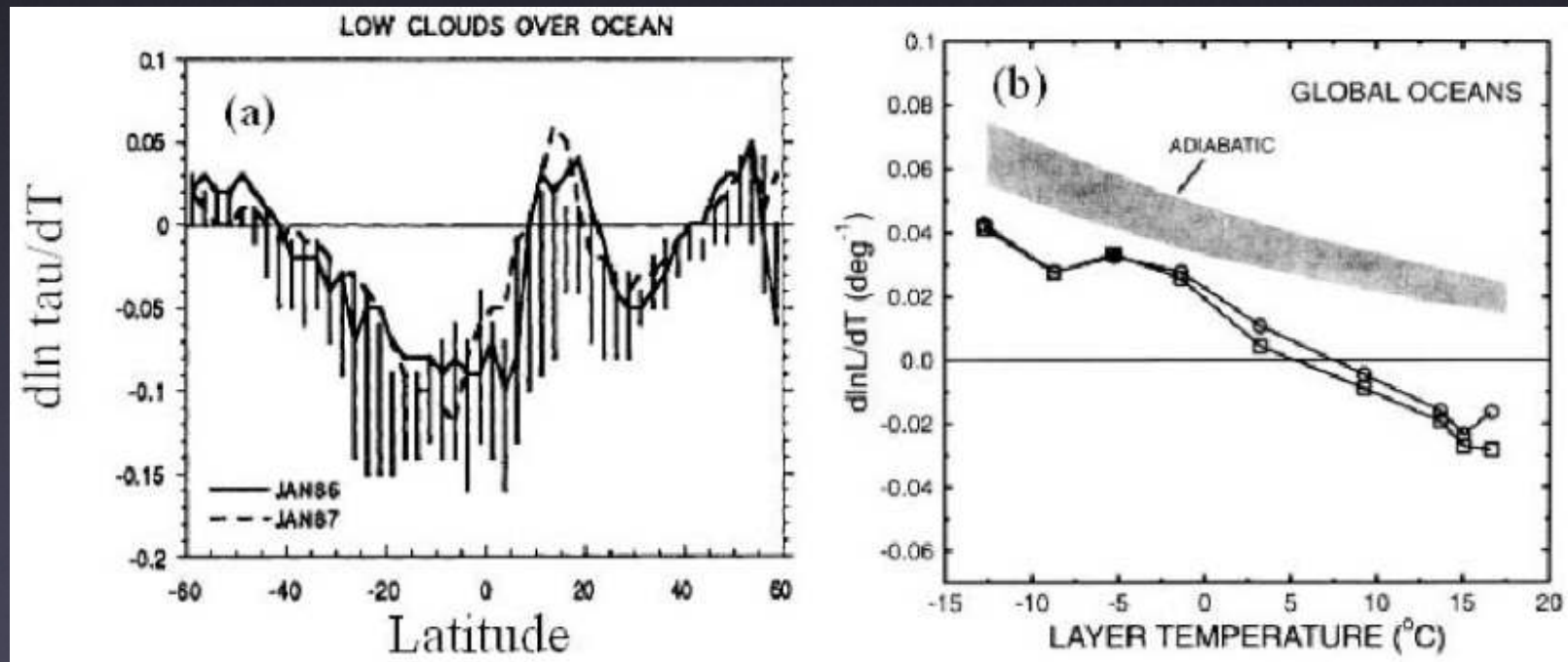
Cloud feedback and precipitation

- Cloud feedbacks that affect the radiative heating of the atmosphere will also influence the response of the hydrological cycle to any climate forcing.

- Consider the global-mean atmospheric energy budget:

$$R_{atm}[\epsilon, T, X(T), ...] = F_{SH} + F_{LH} \qquad\qquad F_{LH} = LP$$

- R_{atm} is the net radiation budget and $F_{SH, LH}$ are the fluxes at the atmospheric-surface interface.

- L is the latent heat of vaporization and P is the global-mean surface precipitation.

- Lets assume a single feedback established by the process $X(T)$ and *ignore* the perturbations to the sensible heat term cased by small climate forcing.

Cloud feedback and precipitation

$$\Delta R_{atm} \approx \Delta F_{LH} = L\Delta P$$

$$\Delta R_{atm} = \partial_\epsilon R_{atm} \Delta\epsilon + \left(\partial_T R_{atm} + \partial_X R_{atm} \frac{dX}{dT}\right)\Delta T \qquad \Delta Q_{atm} = \partial_\epsilon R_{atm}\Delta\epsilon$$

$$\Delta R_{atm} = \Delta Q_{atm} + \Delta R_T = L\Delta P$$

- where $\boldsymbol{\Delta Q_{atm}}$ is the radiative forcing of the atmosphere.

- For example, a doubling of CO2 leads to $\boldsymbol{\Delta Q_{atm}} \sim$2-3 Wm^{-2}

- $\boldsymbol{\Delta R_T}$ is the component of the perturbed budget that depends on $\boldsymbol{T}$ directly through the feedback process $\boldsymbol{X(T)}$

- It is convenient to separate the clear-sky contribution and the atmospheric cloud radiative forcing

$$\Delta R_T = \Delta R_{clr,T} - \Delta C_T \qquad \Delta R_{clr,T} \propto w \propto \exp^*(SST)$$

Cloud feedback and precipitation
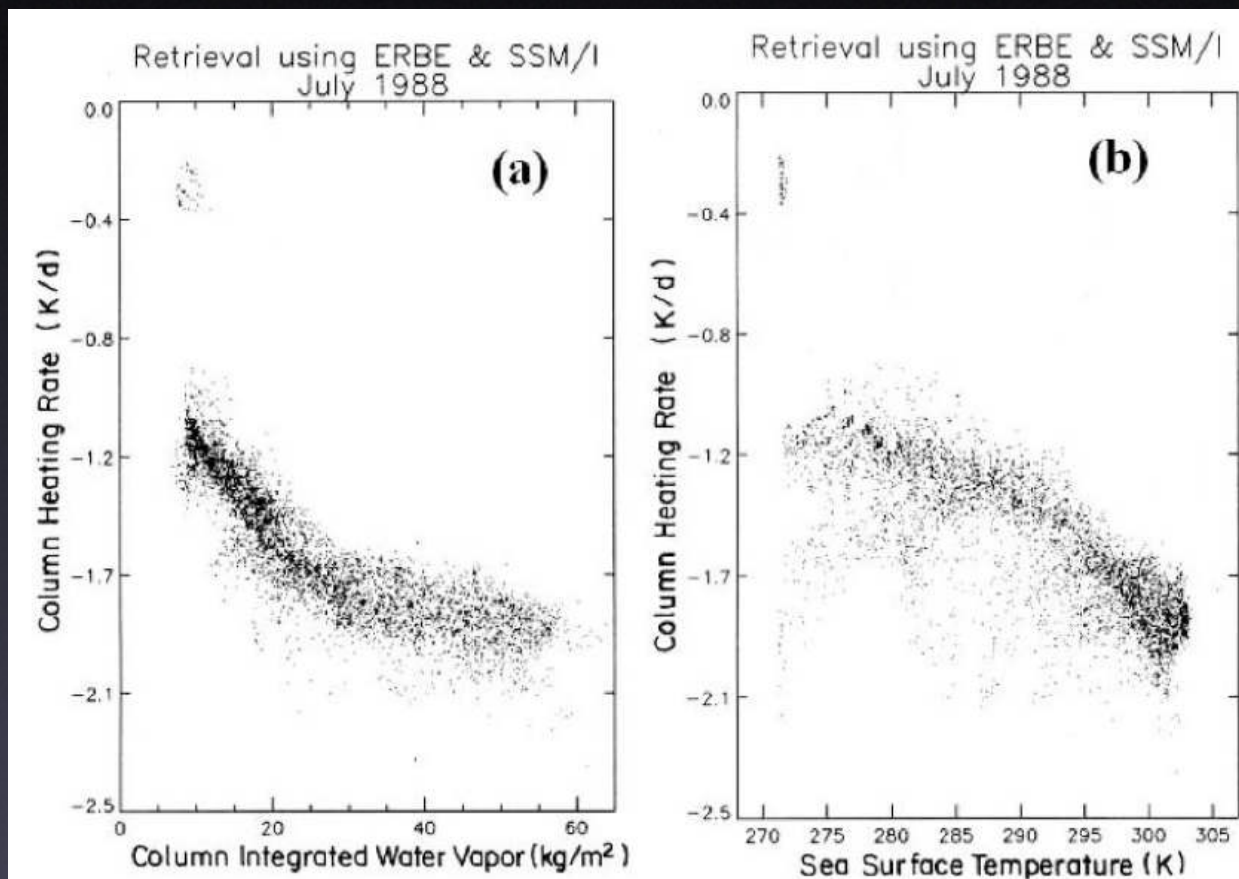
- From the observed relationship between clear-sky $R_{clr, T}$, w and SST, was suggested

$$\Delta R_{clr,T} = K_T \Delta SST$$

$$K_T = 1.88 \, W \, m^{-2} \, K^{-1}, SST < 290K$$
$$K_T = 6.6 \, W \, m^{-2} \, K^{-1}, SST > 290K$$

$$\Delta Q_{atm} - \Delta C_T + K_T \Delta T = L \Delta P$$

The sharp increase in column cooling above 290 K implied by K_T values reflects the effects of the supergreenhouse over the warmer, moist tropical atmosphere.