The Tropical Atmosphere and Climate Change

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Tropical Energy Balance:

On the next page is a block diagram of the tropical energy balance, where the tropics are defined as the region from 30S-30N. About 50 Wm^{-2} are taken in as the net radiation flux at the top of the atmosphere. The same amount is exported to the extratropics, in about equal measures from atmospheric and oceanic transport. About two-thirds of the absorbed solar radiation is absorbed by the ocean, another 100 Watts is absorbed in the atmosphere. The largest term moving heat out of the ocean is evaporation at about 115W, followed by longwave at 50W, and sensible cooling of the surface of about 10W. Since the surface is mostly wet and warm, sensible cooling is small in comparison to latent cooling of the surface. So if we want to investigate the sensitivity of the tropical SST, for example, we should look at the sensitivity of the larger terms in the surface energy balance.

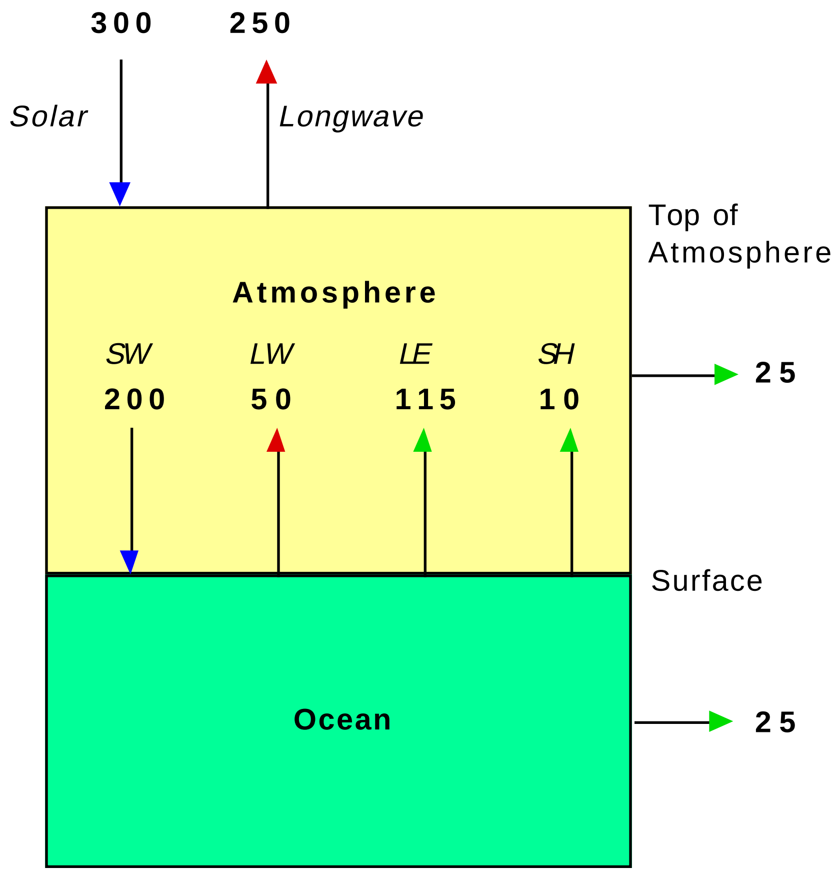


Figure. Block diagram of tropical energy fluxes. Units are Watts per square meter of surface area.

Surface: Longwave Radiation -50 Wm^{-2}

Longwave cooling of surface decreases with surface temperature in the tropics because of the water vapor greenhouse feedback. In figure 9.8 in Global Physical Climatology we see that the actual longwave cooling of the surface decreases with increasing surface temperature quite rapidly at tropical temperatures of around 300K. This is because of the rapid closing of the water vapor window between 8 and 12 microns by continuum absorption by water vapor. Although the upward emission from the surface increases at about 6 Wm^{-2} per degree K of surface temperature increase, the downward longwave emission from the atmosphere INCREASES at a faster rate of about 9 Wm^{-2} . So the surface loses its capacity to remove heat by infrared emission.

This is a positive feedback at the surface!

$$-\frac{\partial LW}{\partial T_s} \approx +3\,\mathrm{Wm^{-2}K^{-1}}$$

when

$$-\left.\frac{\partial(\sigma T_s^4)}{\partial T_s}\right|_{300K} \approx -6\,\mathrm{Wm^{-2}K^{-1}}$$

We have the makings of a runaway greenhouse effect, but something stops the train. One thing that is working in the opposite direction is evaporation.

Surface: Evaporative Cooling -115 Wm^{-2}

Begin by considering the aerodynamic formula for evaporative cooling of the surface, which depends on the wind speed U and the contrast in specific humidity between the surface and the air.

$$LE \cong \rho_a\, L\, C_D\, U\left(q_s - q_a\right)$$

$$LE \approx \rho_a\, L\, C_D\, U\, q_s^* \left((1-RH) + RH\left(\frac{L}{R_v T_s^2}\right)\left(T_s - T_a\right)\right)$$

To produce a 20% increase in LE:

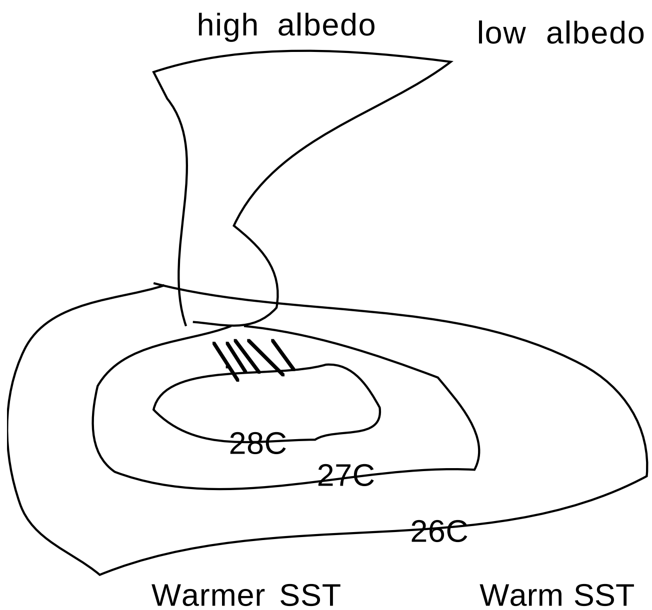
U = 5 ms^{-1} to 6 ms^{-1} :	1 ms^{-1}	20%
RH = 80% to 76% :	4%	5%
T_s = 300K to 303K :	3K	1%

Fix RH and U, get large negative feedback

$$-\left.\frac{\partial LE}{\partial T_s}\right|_{300K} \approx -7\ \mathrm{Wm^{-2}K^{-1}}$$

Surface: Solar +200 Wm^{-2}

Clouds can greatly decrease the solar energy reaching the surface. If we contrast the cloudy regions, which tend to occur over the warmest SST, with the adjacent clear regions, we can get a gigantic value for the estimate of the sensitivity of surface insolation to SST. This is basically what Ramanathan and Collins(1991) did to emphasize the potential importance of blocking of solar radiation by clouds in the tropics.



$$\frac{Q_{sol_{warm}} - Q_{sol_{cool}}}{T_{s_{warm}} - T_{s_{cool}}} \approx -25 \text{ Wm}^{-2}\text{K}^{-1}$$

This surely represents a gross overestimate of the magnitude of the role of the radiative effect of convective cloud on tropical SST, and the sign may be wrong. To get a good estimate of climate sensitivity, one needs to average over the area of the large-scale circulation that connects the most active convection to regions of subsidence (Hartmann and Michelsen 1993).

Top of Atmosphere: Clouds

Shortwave Cloud Forcing (SWCF) = Clouds reduce solar energy absorbed by planet.

Thermostat Hypothesis: Ramanathan and Collins '91

Convective cloud albedos increase rapidly with SST in the tropics and this limits SST.

Problems:

1. Strong SWCF by convective clouds is more dependent on large-scale circulation than on local SST. Cloud optical properties respond much more strongly to large-scale forcing than to absolute value of SST. Cloud-resolving model experiments show this.

2. SWCF is negated by LWCF in convective regions of the tropics, so that the main effect is a vertical redistribution of energy in a region where vertical redistribution by convection is very efficient. Strong compensation between solar heating and evaporation affects hydrological cycle, but SST not sensitive to this in two-box model.

Top of Atmosphere: Water Vapor

Water vapor is #1 Greenhouse Gas

CW & Null Hypthesis: Relative humidity will remain about constant, and this positive feedback through saturation vapor pressure dependence on temperature gives a doubling of climate sensitivity.

$$\text{Greenhouse Effect} = \sigma T_s^4 - \text{OLR}$$

• Water vapor is injected into troposphere by convection and removed by subsidence.

• Subsidence is driven by radiative cooling, in clear air largely from water vapor.

Energy and Moisture Budget Consideration:
In convective region:

Precipitation	~ 3 m/yr	~ 240 Wm^{-2}
Evaporation	~ 1.4 m/yr	~ 115 Wm^{-2}
P - E = L.S. Transport	~ 1.6 m/yr	~ 125 Wm^{-2}

A Very Interesting Question:

Why is ΔR_{net}~ zero for tropical convective clouds?? Why is the net radiation in regions of intense tropical convection the same as the net radiation in adjoining regions?

Kiehl (1994) suggested that this is a fortuitous effect of tropopause height, given that forcing comes from high, thick clouds.

Too facile an explanation:

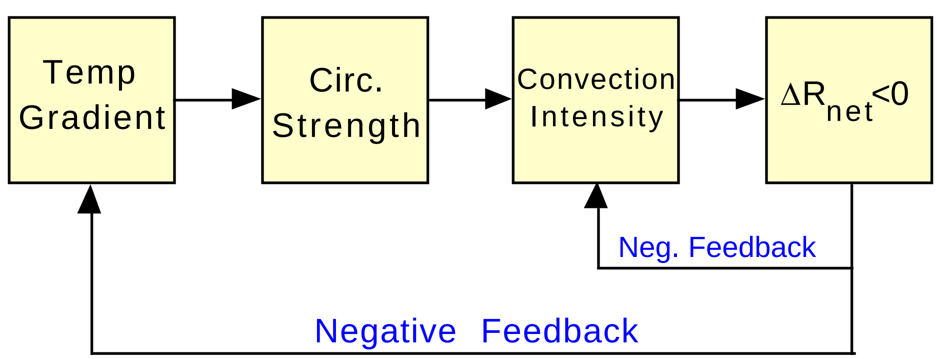
1. ΔR_{net} varies from day to day.

2. ΔR_{net} varies with cloud type. ΔR_{net}~ 0 results from cloud distribution (Hartmann, et al. 1992).

Alternate Hypothesis:

Active feedback control for ΔR_{net}~ 0 Convective Clouds must produce approximately same R_{net} as adjacent tropical regions, or a circulation anomaly will result that will adjust cloud optical properties to ΔR_{net}~ 0 condition.

Feedback to Maintain ΔR_{net} ~0
that Invokes Large-Scale Dynamics



Some Conclusions:

The convective/subsiding dichotomy paradigm of tropical climate reveals a number of interesting feedbacks in the tropics that may be important in climate change. e.g.:

1. Water vapor in the free troposphere of the subsiding region interacts strongly with the large-scale circulation and the atmospheric mixed layer to produce a feedback that reduces climate response to upper tropospheric humidity in the subsiding zone. Increased humidity above the mixed layer increases subsidence, and thins and dries the mixed layer

2. The tendency of convective clouds to produce the same top of atmosphere net radiation as adjacent subsiding regions may be a result of an active feedback between large-scale circulations and convective cloud optical properties.

References:

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