Exchanges at the interface between terrestrial ecosystems, the water cycle and climate

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Overview

- A global context for the biosphere
- Impact on the global energy balance
- Local controls
- Optimality and regulation
- Motivation for CO_2 and water (exchanges)
- Water and carbon exchange
- Regulation of CO_2 exchange by humidity

- Before this talk: Vegetation controlled by atmosphere (i.e., 1-way interaction)
- After this talk: Biosphere and atmosphere co-evolve (i.e., 2-way coupling)

Thought experiment: Warmer world with higher CO_2, with same, high, or lower relative humidity. How would terrestrial productivity change?

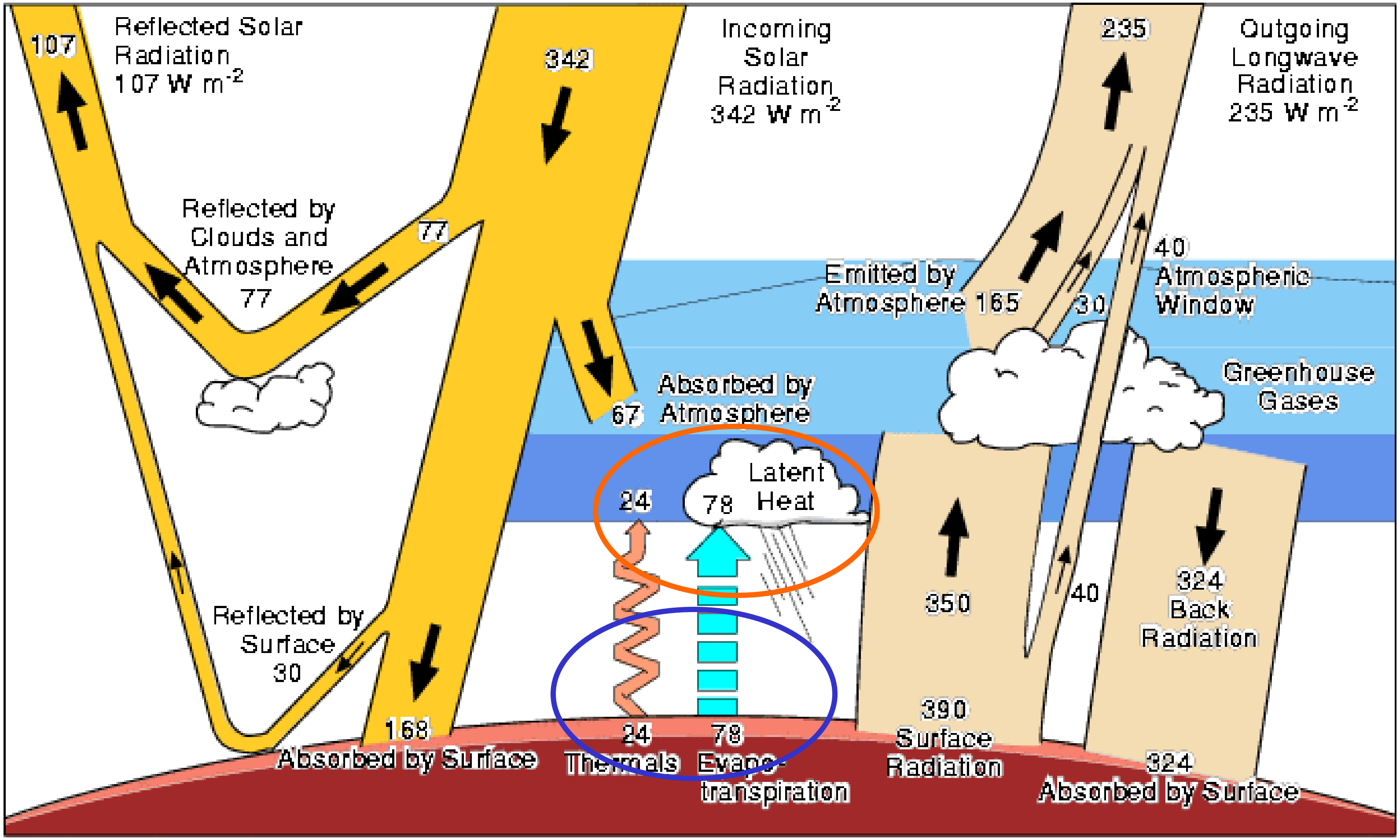
Guiding question

- To what degree does the terrestrial biosphere regulate/amplify/control the local climate variations?
- Mostly via hydrologic cycle
- (Also by carbon cycle, longer time scales)

The answer is one that is constrained by:

- Energy
- Mass (of carbon and water)
- Momentum (the land is a momentum source/sink for the atmosphere)
- Entropy…?

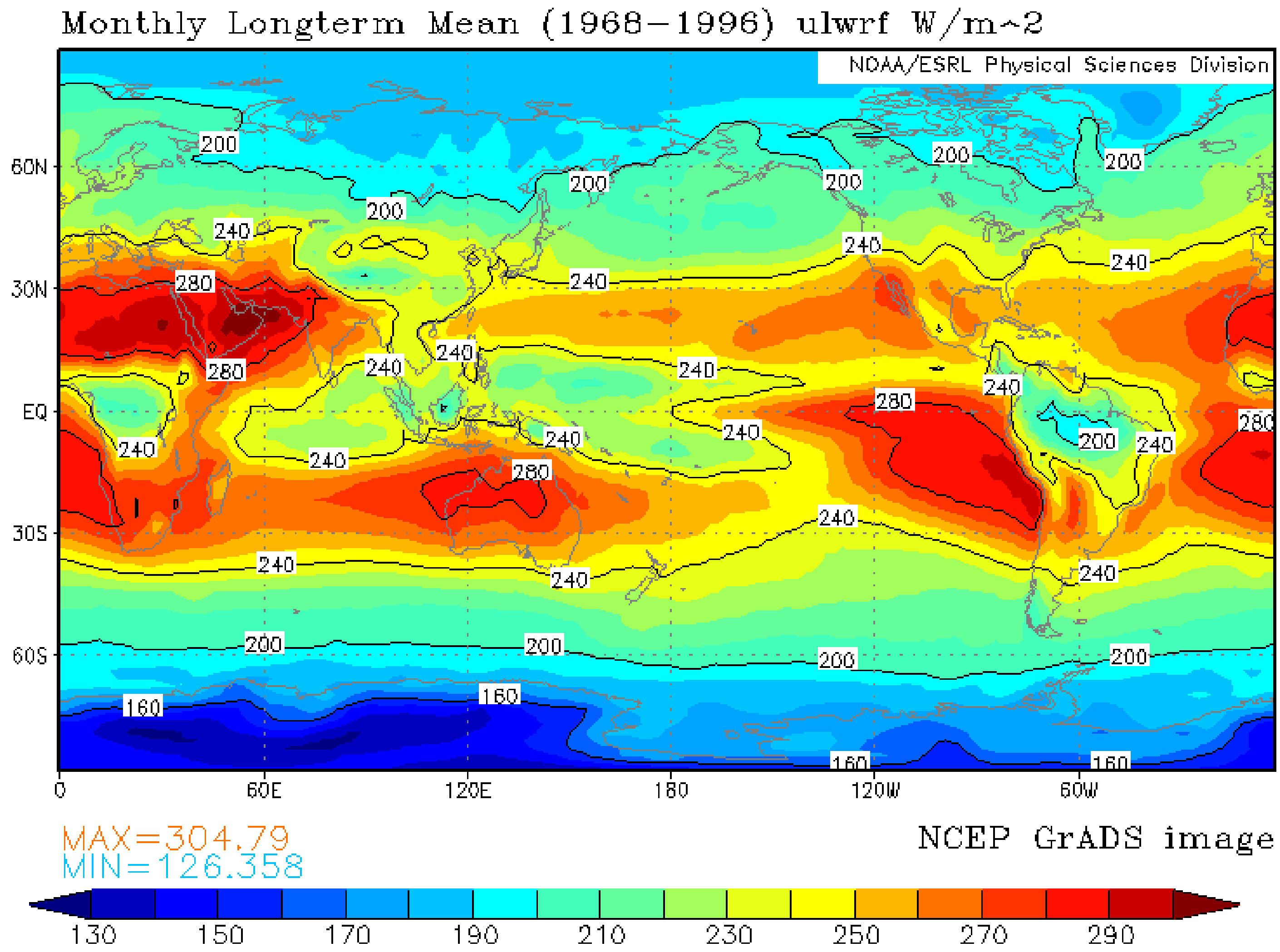
Global Heat Flows



Kiehl and Trenberth 1997

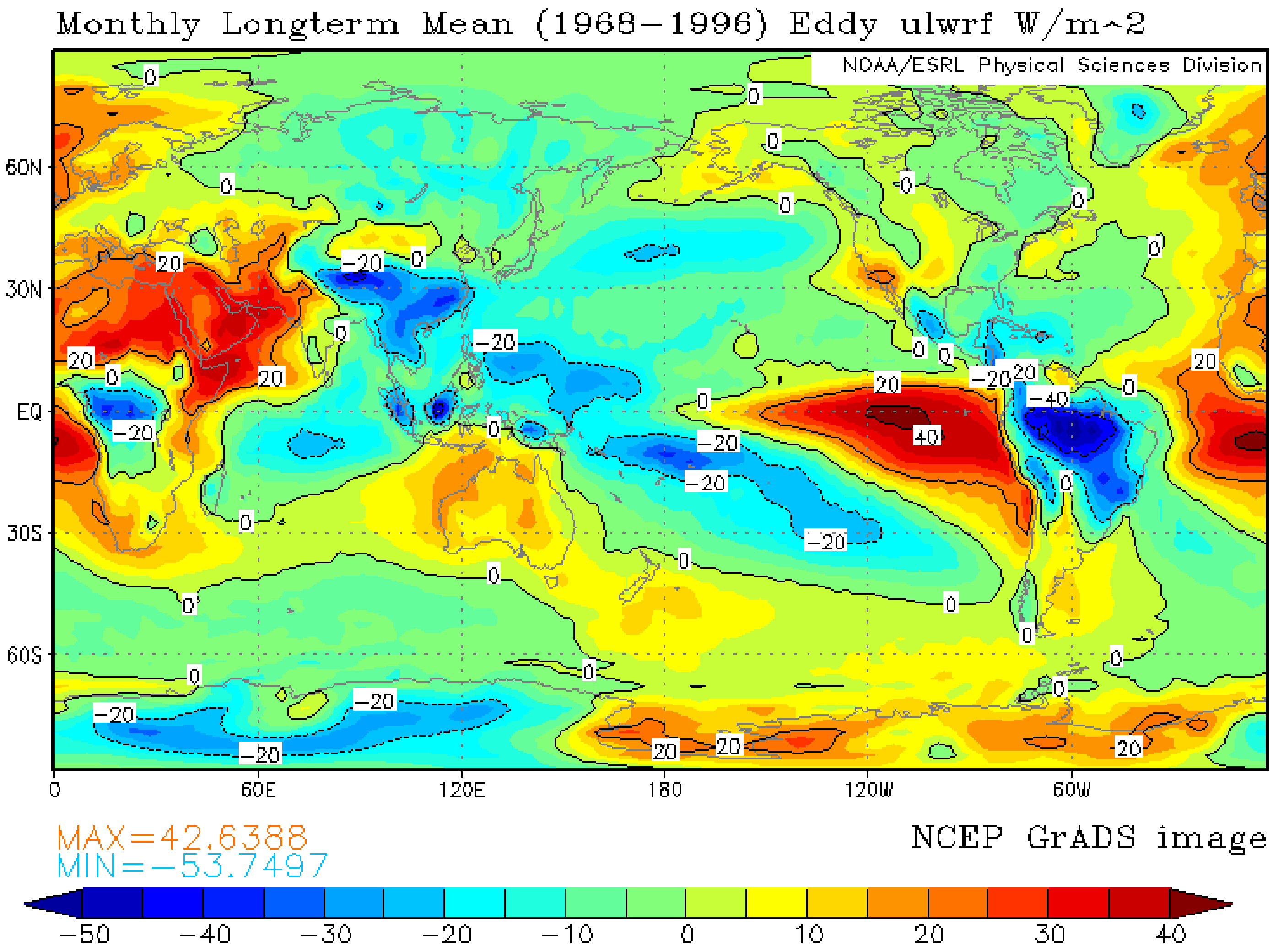
Atmospheric heating: 26 W/m^2 by longwave radiation
24 W/m^2 by sensible heating (dry mixing)
78 W/m^2 by latent heating (cloud processes)

Longwave up at top of atmosphere

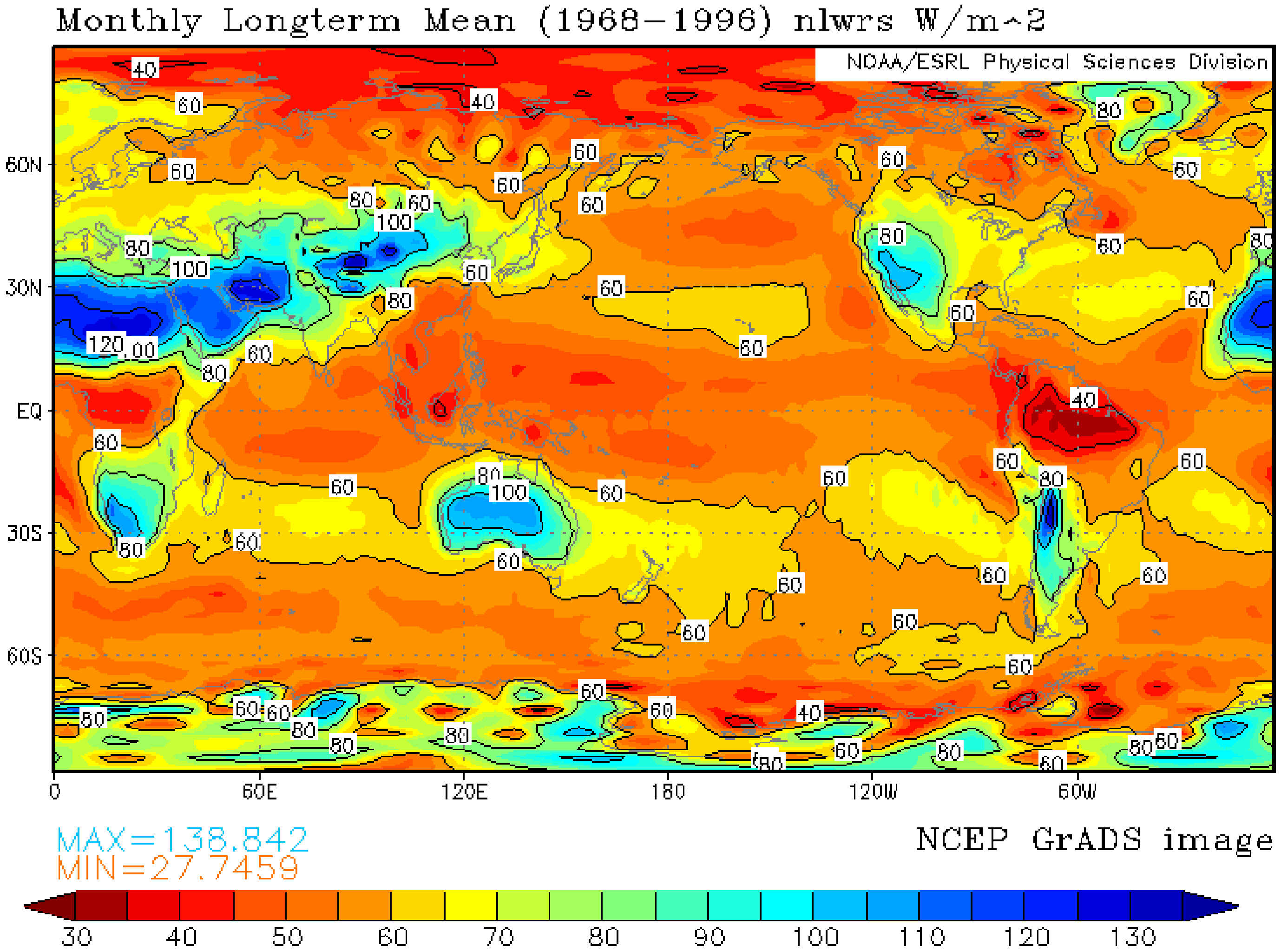


Annual mean, NCEP Reanalysis, CIRES/NOAA-PSD

TOA longwave – zonal mean



Surface (upwards) longwave flux



- Arid/semi-arid environments surface energy balance dominated by sensible heat flux
- Climatologically moist areas stronger local greenhouse term (downwelling longwave radiation)
- Trapping, by moisture and clouds

Surface energy balance

$$C\frac{dT}{dt} = \lambda c_w\left(e_a - e_s(T)\right) + c_h(T_a - T) + L_\downarrow - L_\uparrow + (\alpha - 1)S$$

"ET"

Constraint on water balance

$$\frac{dW}{dt} = P - ET - (R + D)$$

Changes in vegetation controls:

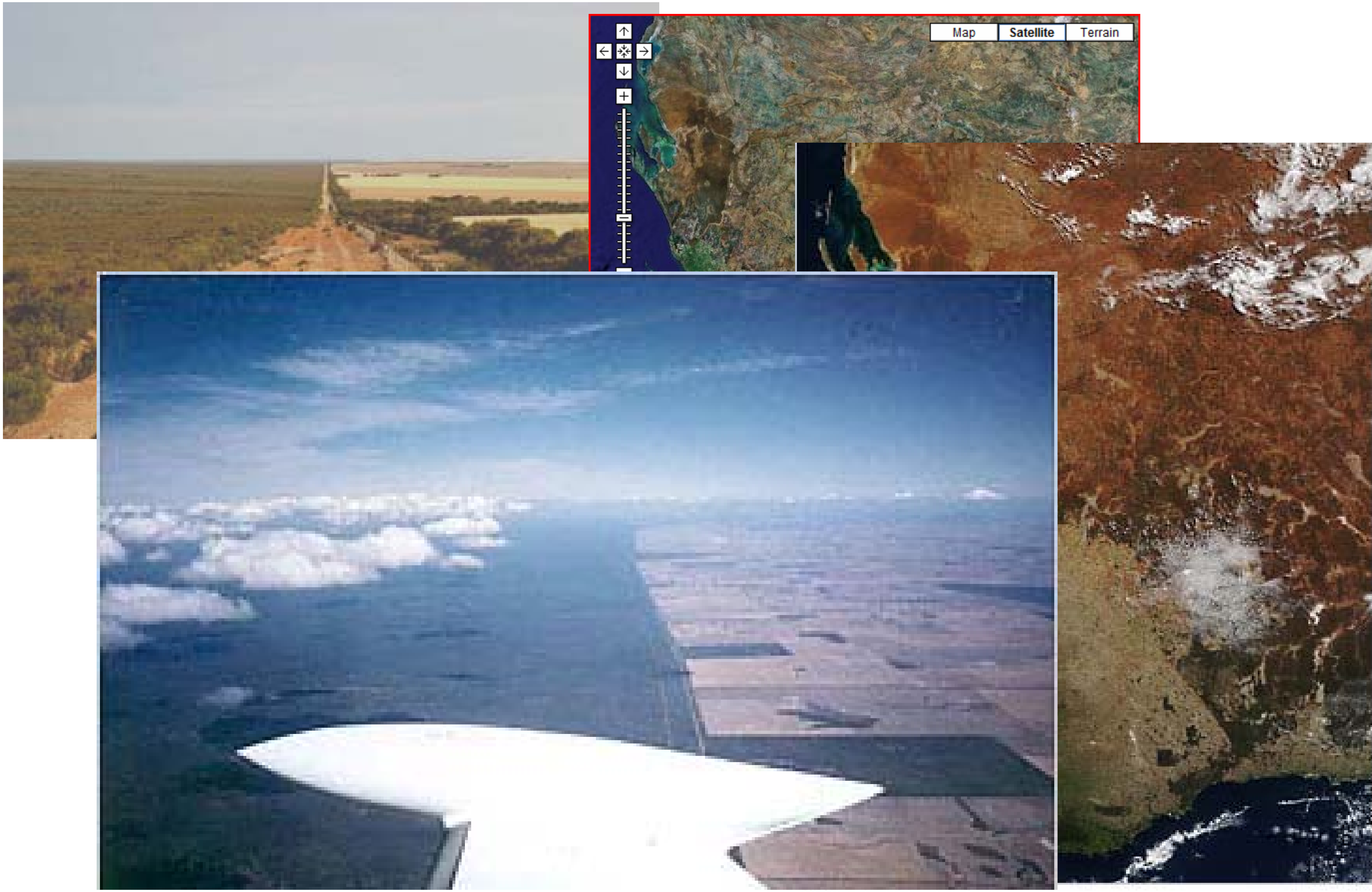
- Albedo and surface emissivity
- Roughness – turbulent, molecular conductance (C_w and C_h)
- Also, water availability via roots, runoff, …
- CO_2 uptake "consumes" radiation

Classic coupled problem: T and W depend on T_a and e_a, and vice-versa

Which way is north?

(Hint Northern Hemisphere)

Bunny proof fence



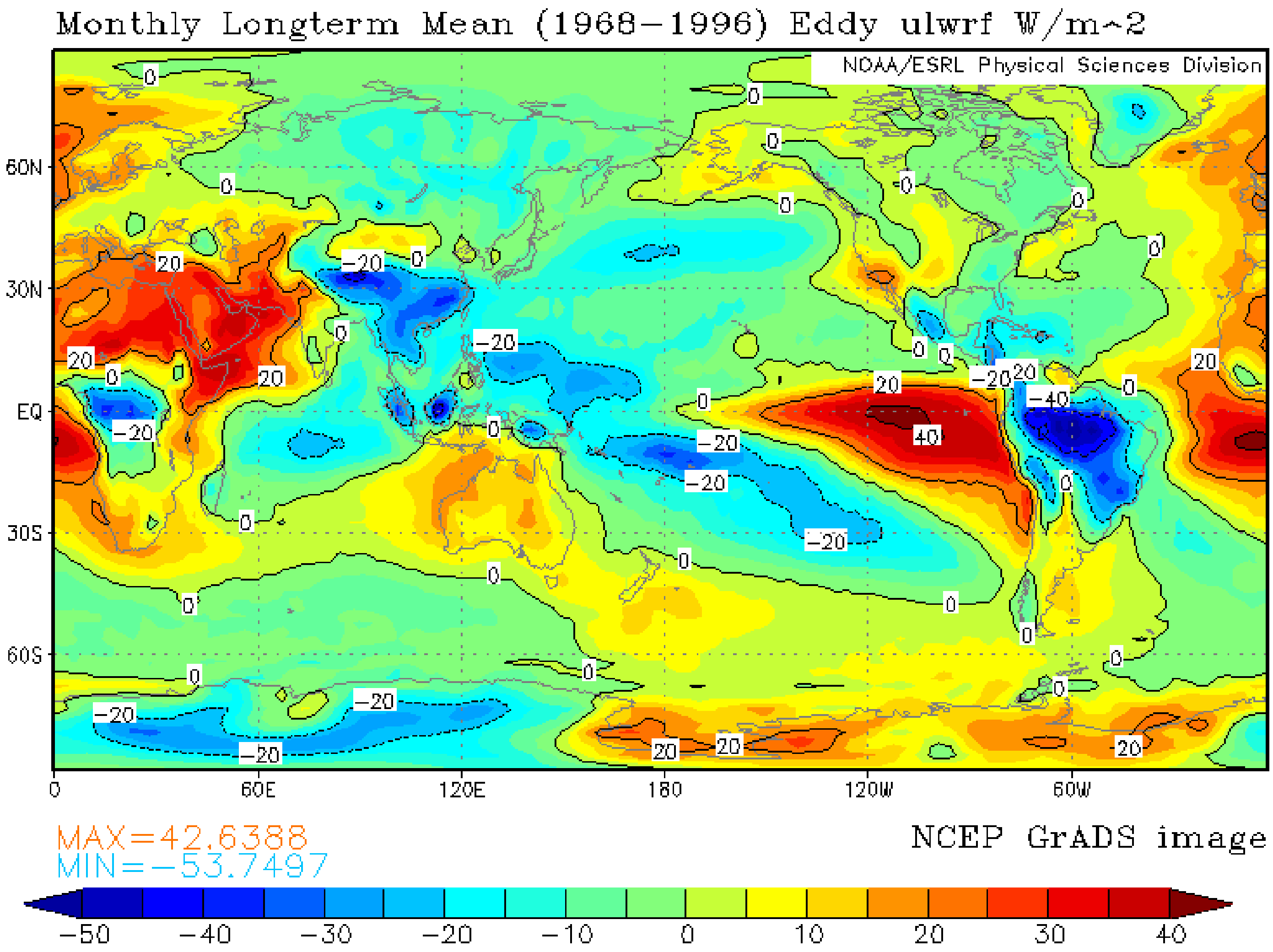
Influences at regional scales

- Vegetation controls albedo, thus local energy balance.
- Vegetation controls cloudiness
  (or, lack of vegetation associated with aridity)

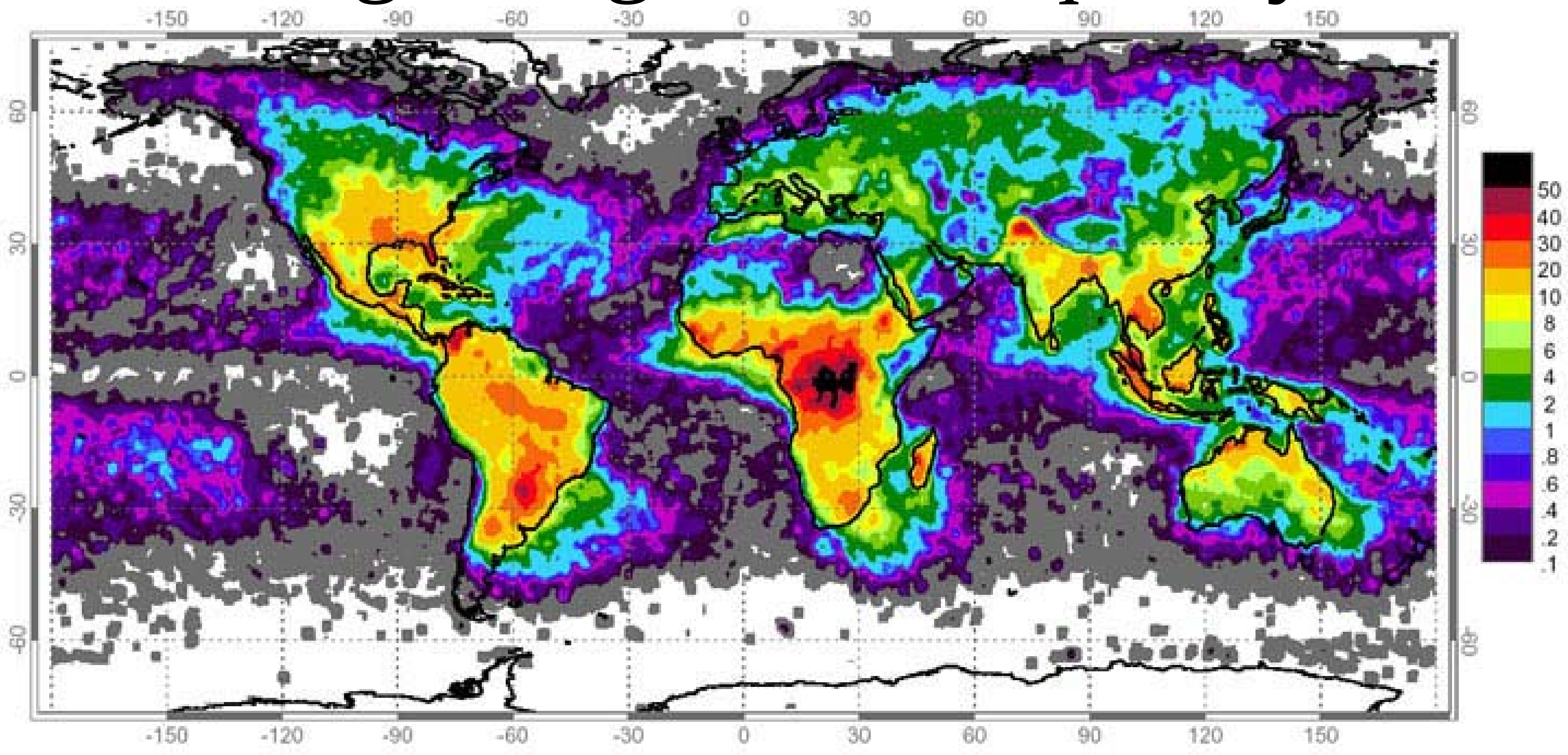
Goes both ways

- no clouds → no rain → dry, so no vegetation
- Also, no vegetation → less latent heat flux (lack of access to soil water) → less cloud, less moisture convergence → …

TOA longwave – zonal mean



Lightning strike frequency

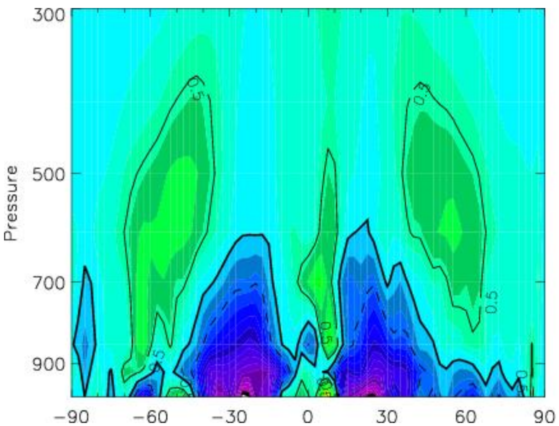


Location of deep storms – strong latent heating of the atmosphere.

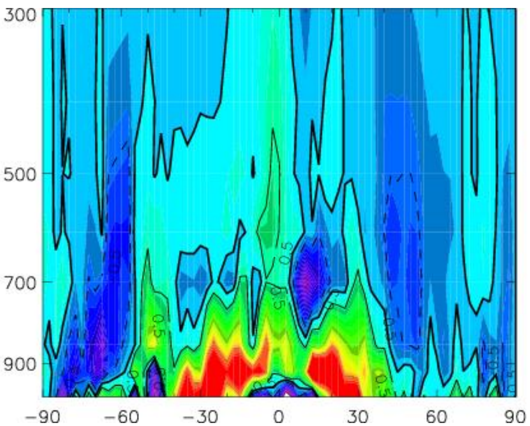
Associated with heat source that will move poleward, and dissipated to space by longwave radiation

LIS, NASA, 2005

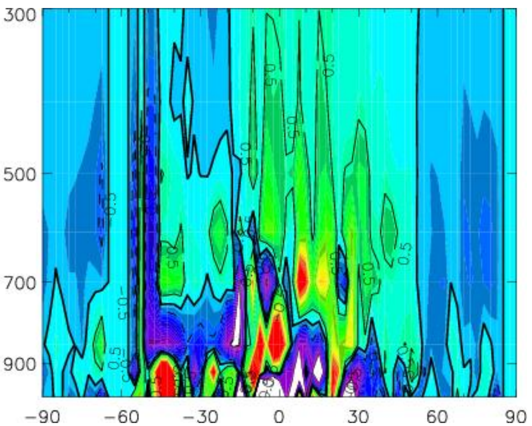
Latent heating by cloud proceses



All longitudes



Land - ocean



High – low veg. (NDVI)

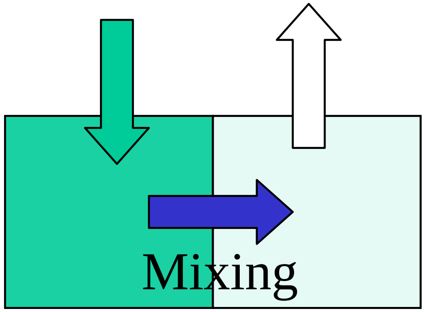
NCAR Community Atmosphere Model – annual mean

- **Less cooling due to evaporation over land**
- **Stronger heating in mid troposphere**
- **Particularly over highly vegetation areas in the tropics**
- **Associated with large source of convective potential since exchange of water and heat over vegetation is constrained (c.f. ocean)**

Optimality

Optimality in turbulence

- Mixing flux optimal with respect to some metric (entropy production for instance)
- Forcing versus rapid dissipation (supercriticality, self organized criticality: sand piles, perhaps, atmospheric mactoturbulence)



(e.g., gas into a vacuum)

•Demand for mixing turbulence due to concentration gradient

•Amount of mixing due to “environmental” conditions

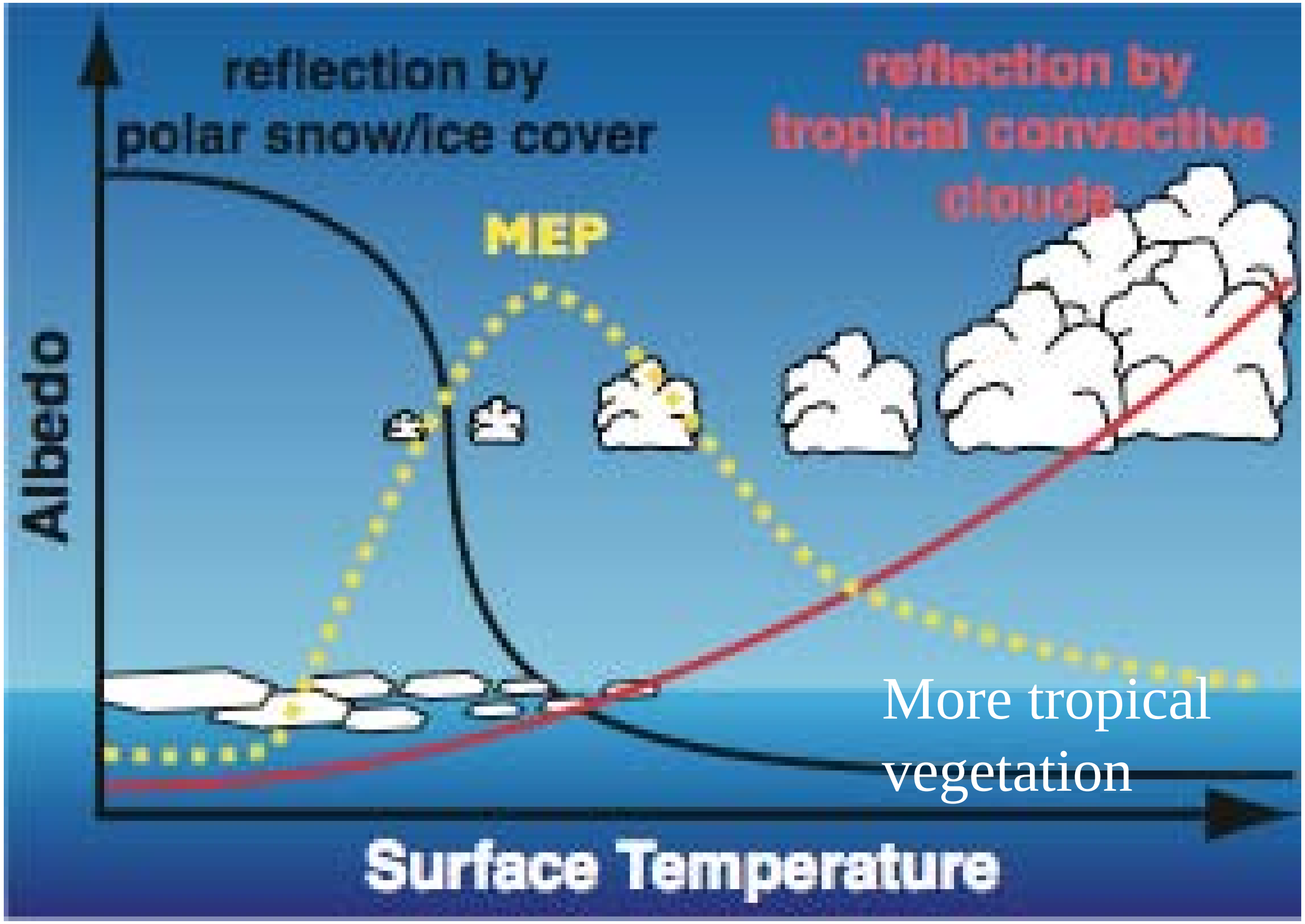
Atmosphere-biosphere

•Controls on (energy) fluxes via albedo

•Balance of water and heat exchange

•Demend set by gradients, amount regulated by state

Impact of water on the carbon cycle



Compensation by albedo at high latitudes versus tropical clouds

Optimal state based on entropy production

Kleidon et al, 2006

Biosphere exchange

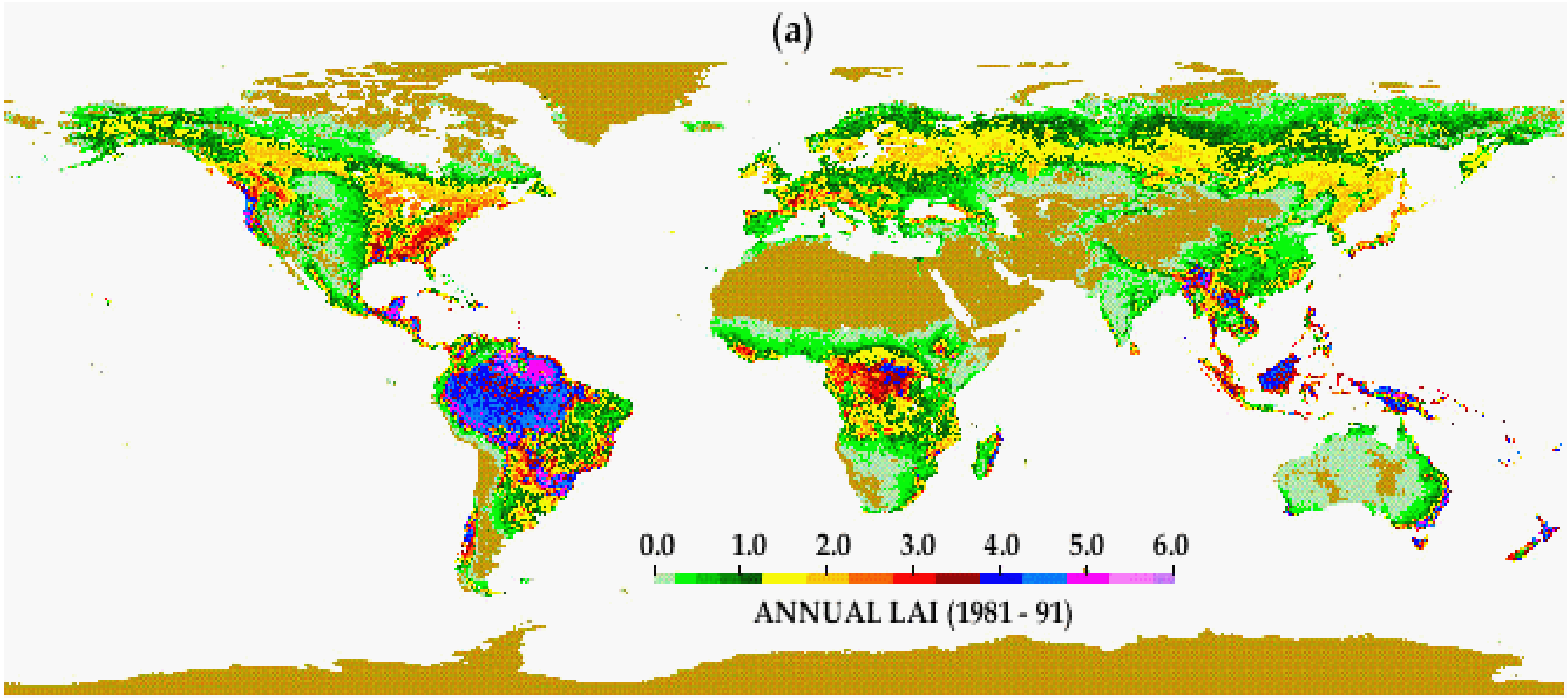
- Energy – albedo, latent/sensible heating
- Water – latent heating (vegetation composition)
- (Carbon)

Plants grow (photosynthesize) when:

- Warm (not frozen, photosynthesis rate)
- Wet (soil water available, not stressed by low humidity)
- Sunny (photons available for photosynthsis)

- In tropics not limited by water

Location of the biosphere

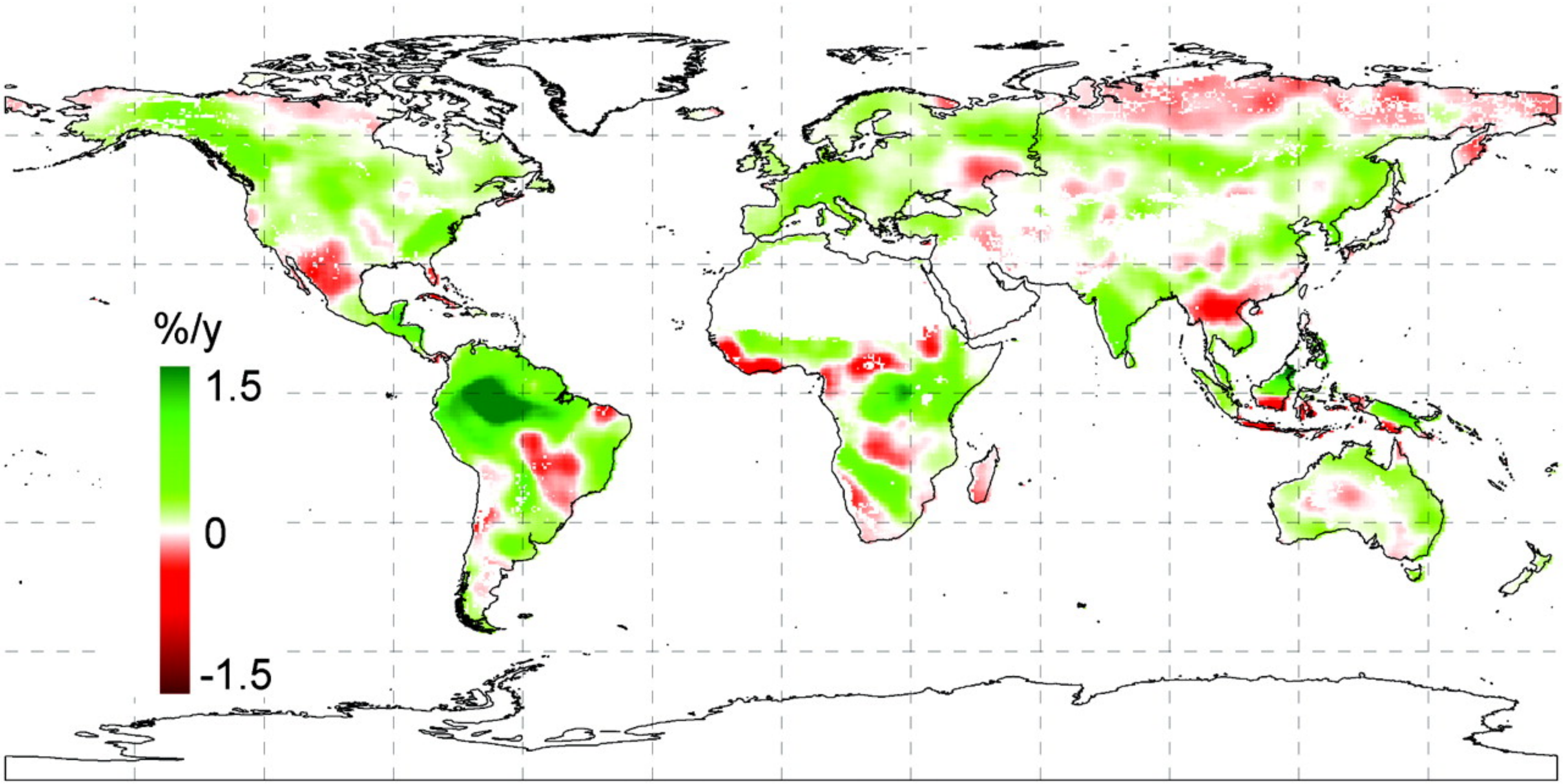


Leaf Area Index – area of leaves per units are of ground

Most productive regions low energy flux at TOA, and largest downwelling longwave.

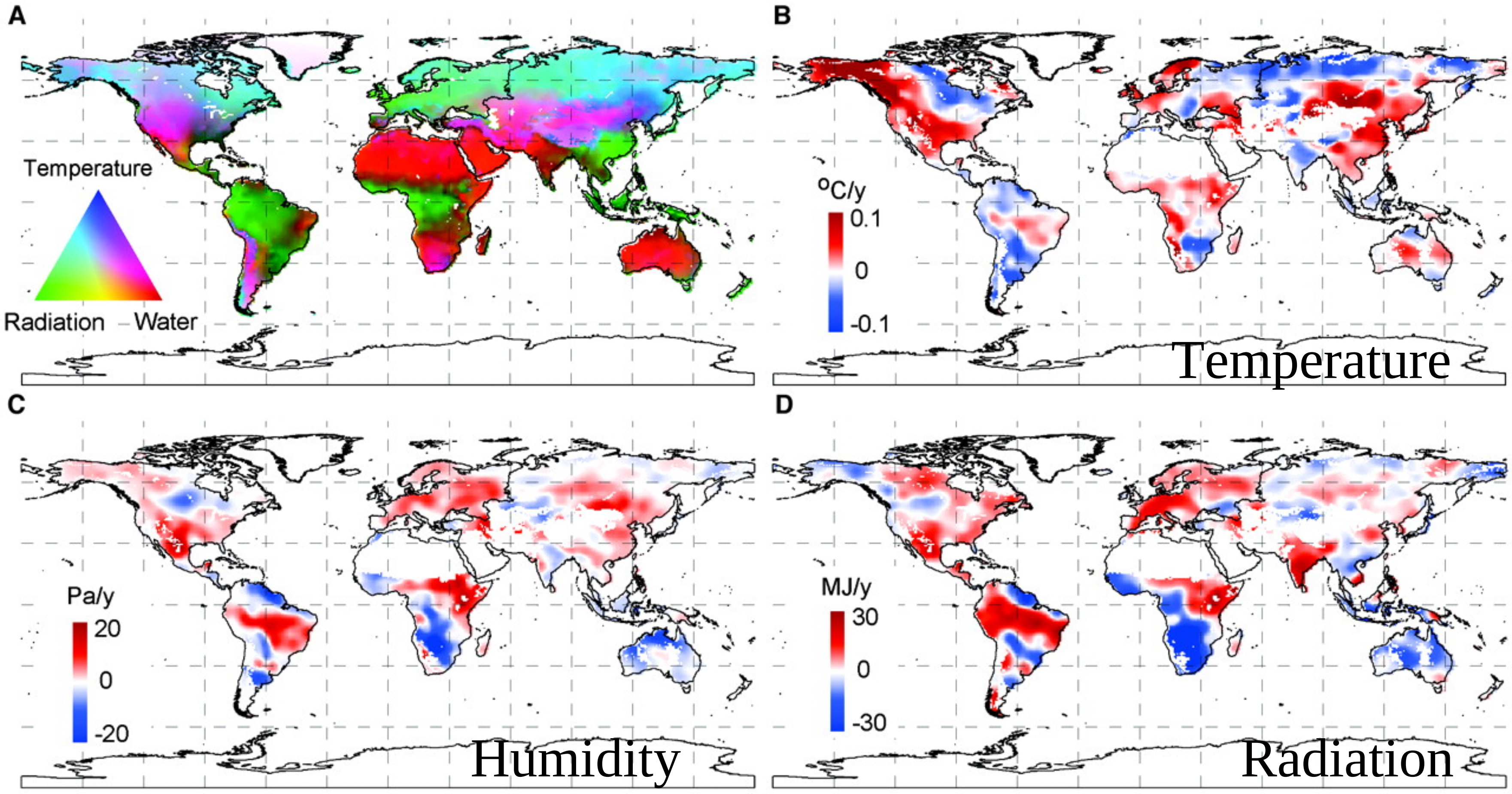
LAI, MODIS, NASA

Change in NPP 1983-1999



Nemani et al., 2003

Limitations on biospheric production



Nemani et al., 2003

Clouds-vegetation regimes

Very dry surface (desert)

- Supply of sensible heat, not latent heat
- Give rise to dry turbulence

Very moist surface (ocean)

- Supply of both latent and sensible heat
- Water source un constrained
- With trigger, cooling provides condensation

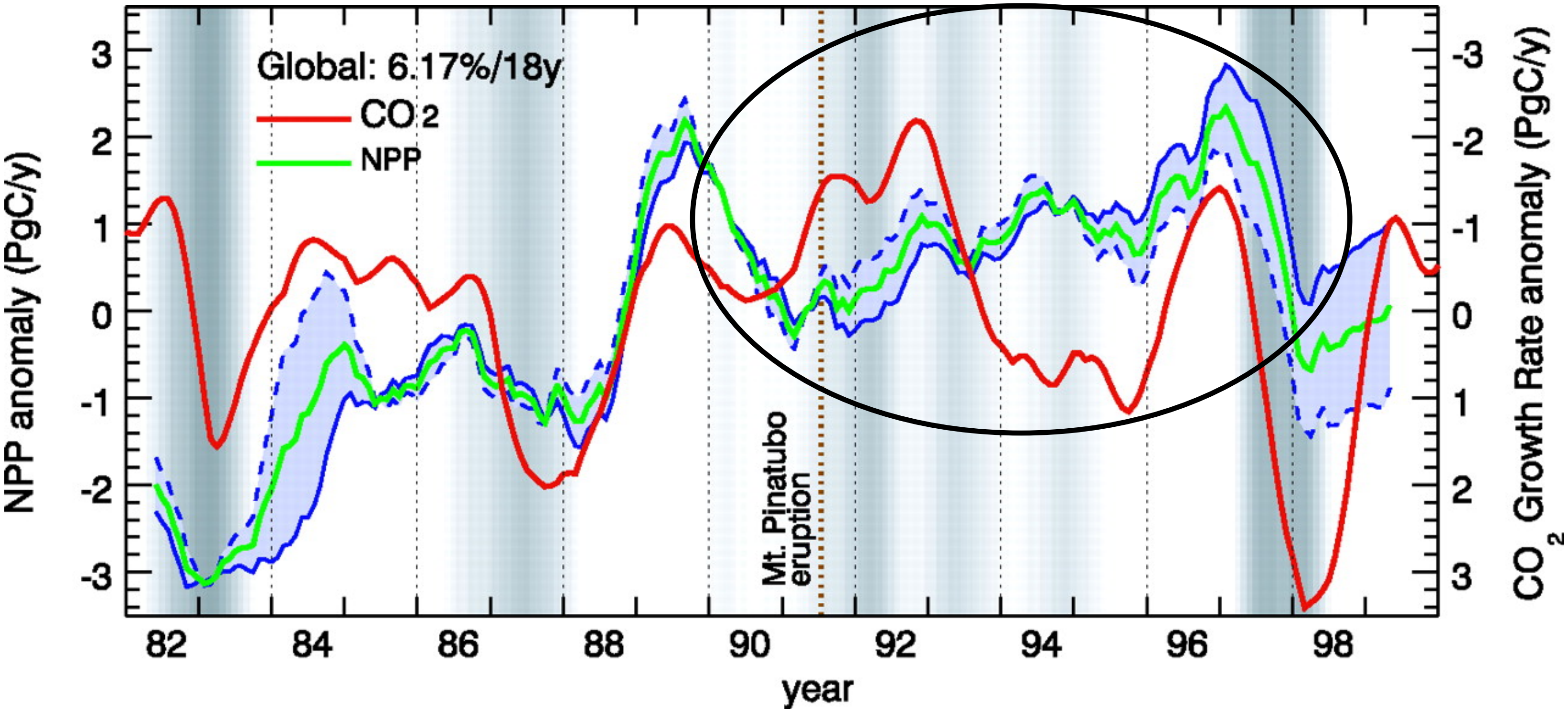
Vegetation (in between)

- Latent heating and sensible heating
- Generation of buoyancy
- Build up more convection potential without saturation
- Some trigger now release energy more catastrophically, allowing deeper clouds, and higher optical depth

Is this an MEP state? For the biosphere, for the atmosphere, for the coupled system?

More clouds, less frequently allows more radiation at the surface, so more production on average…?

Trend in global NPP



Nemani et al., 2003

Pose a question

- Seek evidence for hydrologic driver
(link clouds/rain with humidity and production)
- What is the linkage between the water cycle and the carbon cycle?
- Control by stomatal conductance

$$E = \frac{1}{r_b + r_s}(e_s - e) \qquad F = \frac{1}{r_b + r_s}(c_s - c_a)$$

One can (can one?) assume plants maximize their production (“growth”) given available resources (water and light)?

[If not, someone else will and they will be out competed]

* Assumption that plants choose to maximize their photosynthesis given a minimal loss of water by regulating their stomatal aperture.

Conclusions

- Misnomer that “climate” controls vegetation and ecosystems
- Strong evidence that vegetation modifies local climate, some evidence that vegetation changes large-scale (regional? Global)
- One can invoke ideas of the Gaia hypothesis, perhaps Daisy World. Better, organization to optomize.
- Ideas of self regulation have sound analogs in turbulence theory (supercriticality, and self organized criticality, for instance)
- Does biosphere regulate though radiation? Water? CO2?
- Is there, should there be, regulation, or is there a transient response where optimization provides a local (in time) positive feedback?
- Isotopes are particularly enlightening because the reflect the details of the exchange process

Questions arising…

- Does "local" optimality imply optimal global states?
- Does a local tendency toward local optimality lead to globally optimal states?
- To what degree does vegetation control local hydrologic cycle.
  i.e., Existence of vegetation $\rightarrow$ clouds $\rightarrow$ local divergent flow balanced and energy transport
- Greater optimality associated with interaction
- Can understanding the requirements of optimal states, given constraints, lead to prediction of sign and strength of feedbacks which result?
- Optimality (perhaps based on entropy) is a convenient construct, but presently lacks rigor