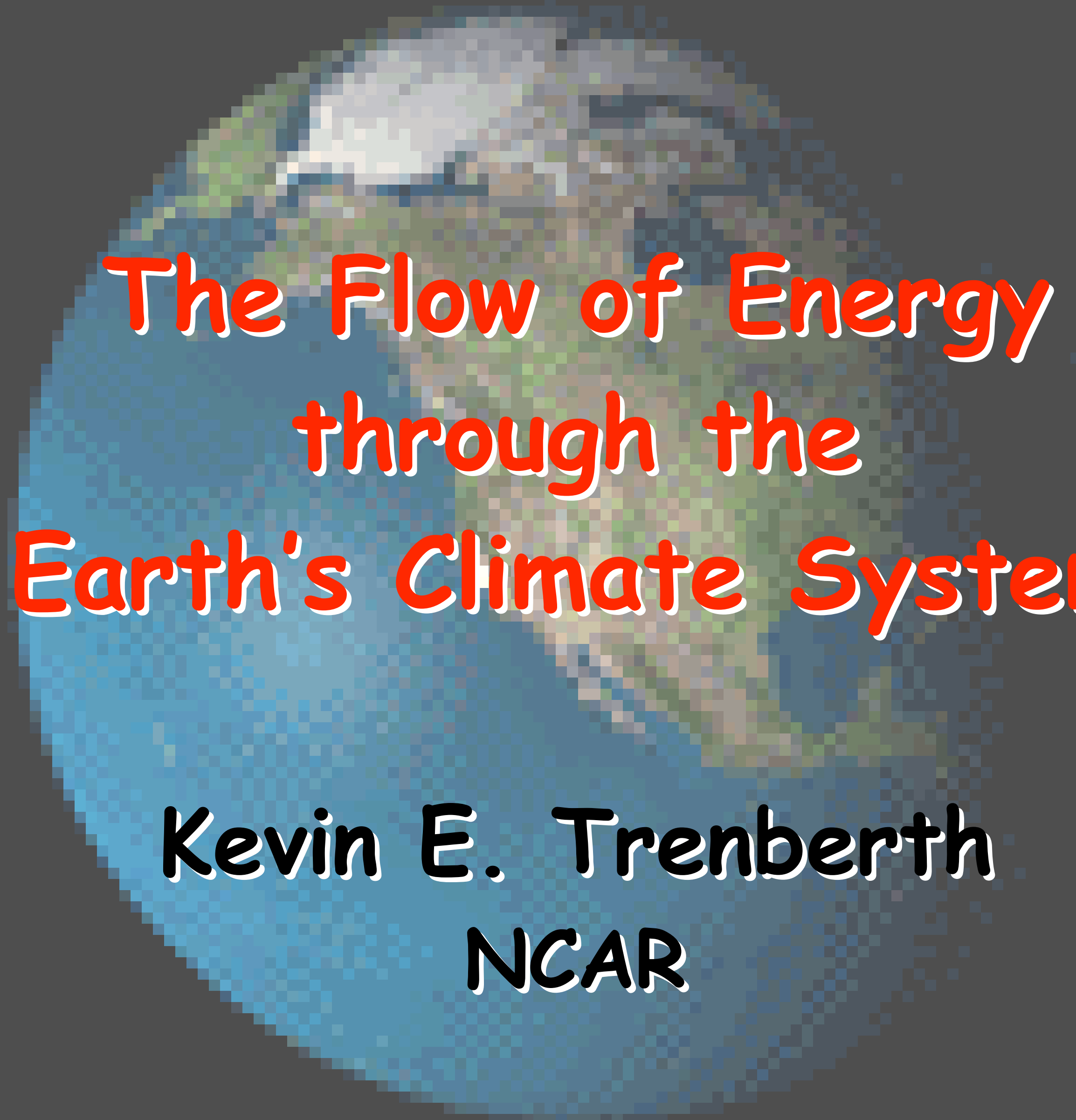
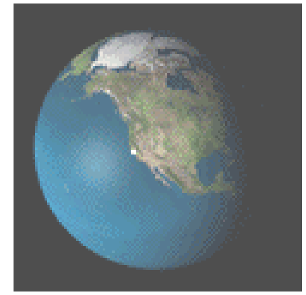


The Flow of Energy through the Earth's Climate System

Kevin E. Trenberth
NCAR

Energy on Earth



The main external influence on planet Earth is from radiation.

Incoming solar shortwave radiation is unevenly distributed owing to the geometry of the Earth-sun system, and the rotation of the Earth.

Outgoing longwave radiation is more uniform.

What is the net radiation?

Where does the energy go?

How does it get from where it comes in to where it goes out?

How much is stored, where?

: annual cycle, longer term?

How does it get out?

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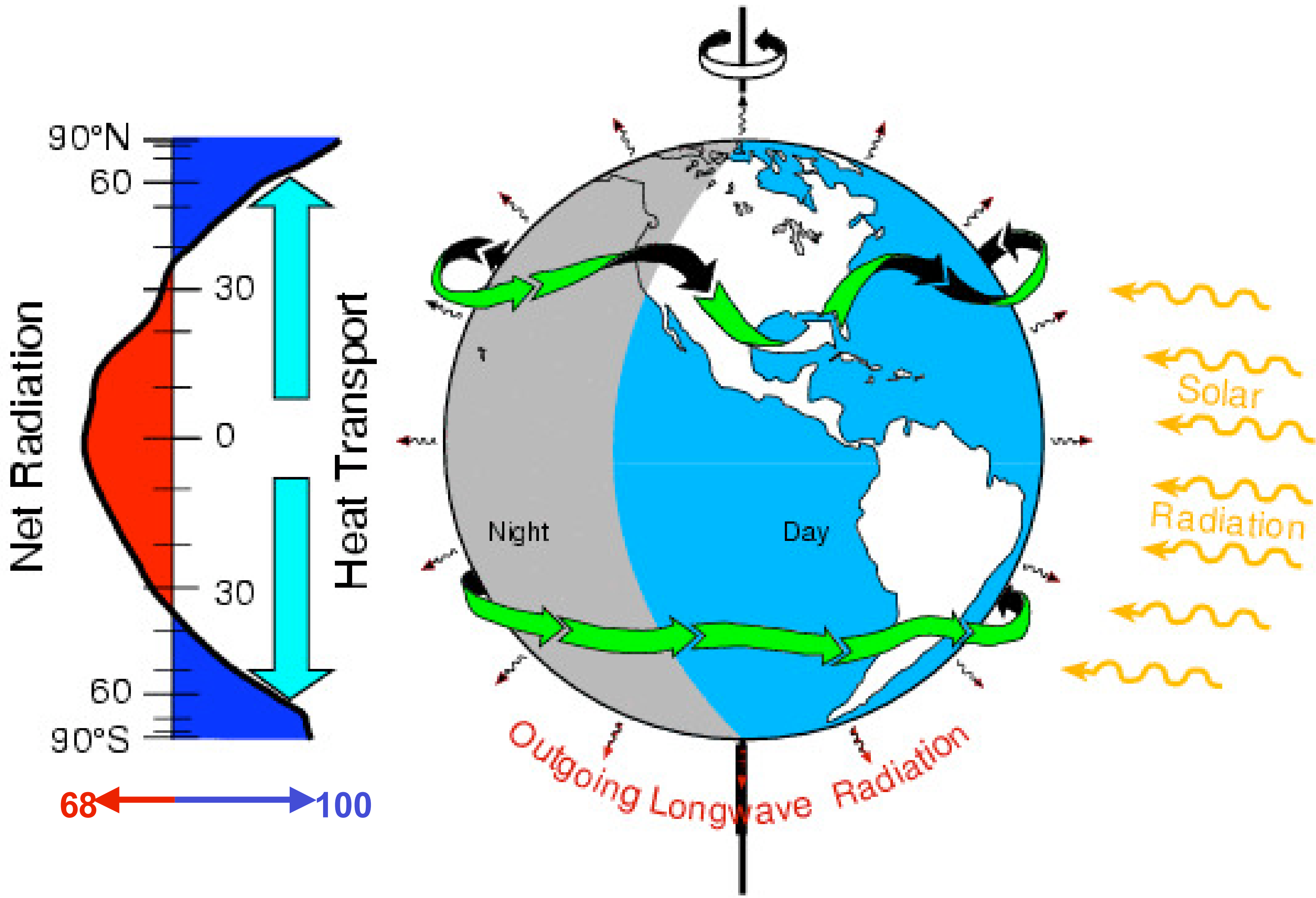

90°N
60
30
0
30
60
90°S
Net Radiation
Heat Transport
68
100
Night
Day
Solar
Radiation
Outgoing Longwave Radiation

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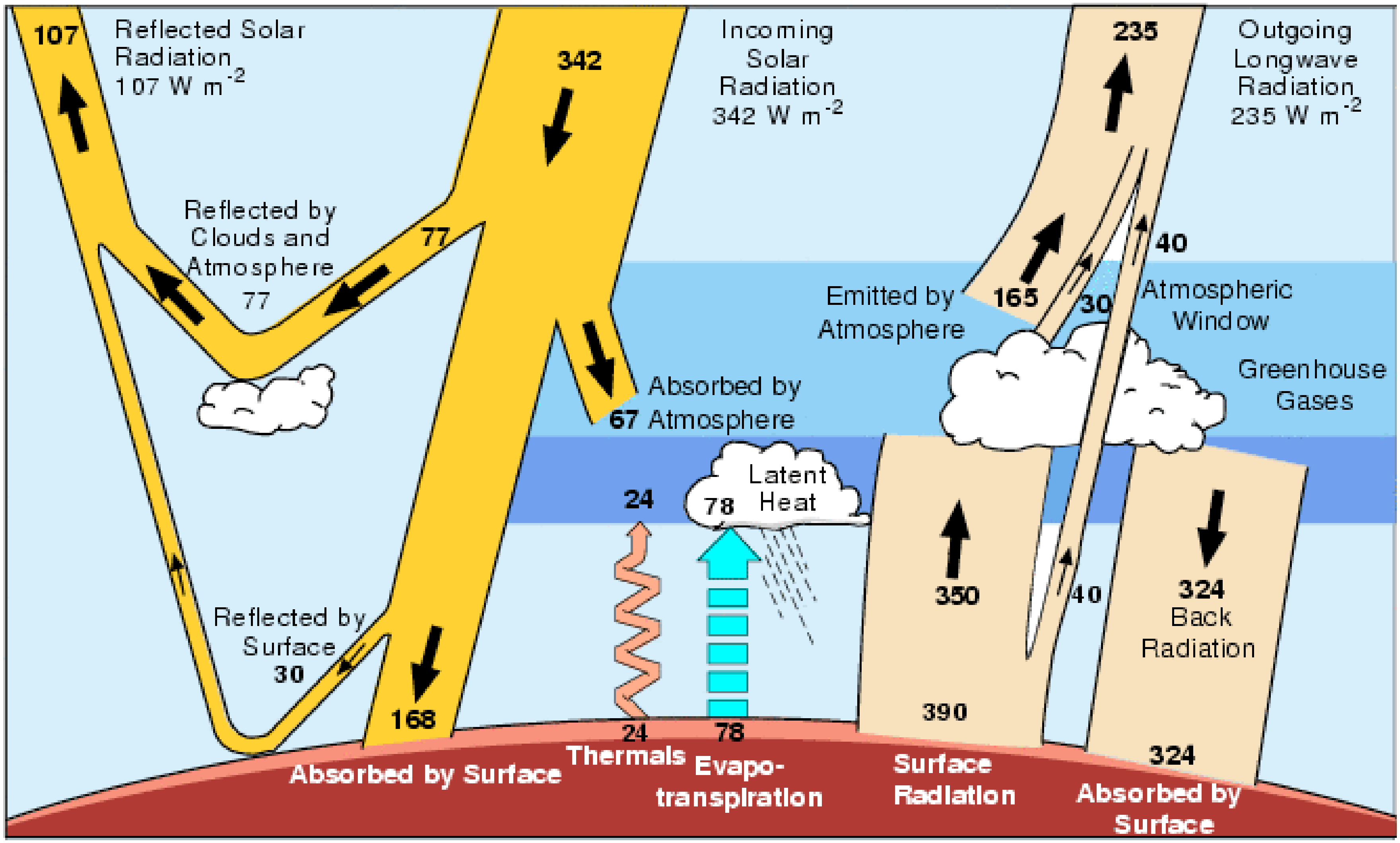
Global Heat Flows



Kiehl and Trenberth 1997

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Energy on Earth

The incoming radiant energy is transformed into various forms (internal heat, potential energy, latent energy, and kinetic energy) moved around in various ways primarily by the atmosphere and oceans, stored and sequestered in the ocean, land, and ice components of the climate system, and ultimately radiated back to space as infrared radiation.

An equilibrium climate mandates a balance between the incoming and outgoing radiation and that the flows of energy are systematic. These drive the weather systems in the atmosphere, currents in the ocean, and fundamentally determine the climate. And they can be perturbed, with climate change.

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The role of the climate system

Atmosphere: Volatile turbulent fluid, strong winds,
Chaotic weather, clouds, water vapor feedback Transports heat, moisture, materials etc. Heat capacity tiny, equivalent to 3.2 m of ocean

Ocean: 70% of Earth, wet, fluid, huge heat capacity

Stores, moves heat, fresh water, gases, chemicals

Adds delay of 10 to 100 years to response time

Land: Small heat capacity, small mass involved (conduction)

Water storage varies: affects sensible vs latent fluxes

Wide variety of features, slopes, vegetation, soils

Mixture of natural and managed

Vital in carbon and water cycles, ecosystems

Ice: Large heat capacity only on long time scales (conduction)

High albedo: ice-albedo feedback

Melts ⇒ fresh water, changes sea level

Antarctica 65 m (WAIS 4-6m), Greenland 7m, other glaciers 0.35m

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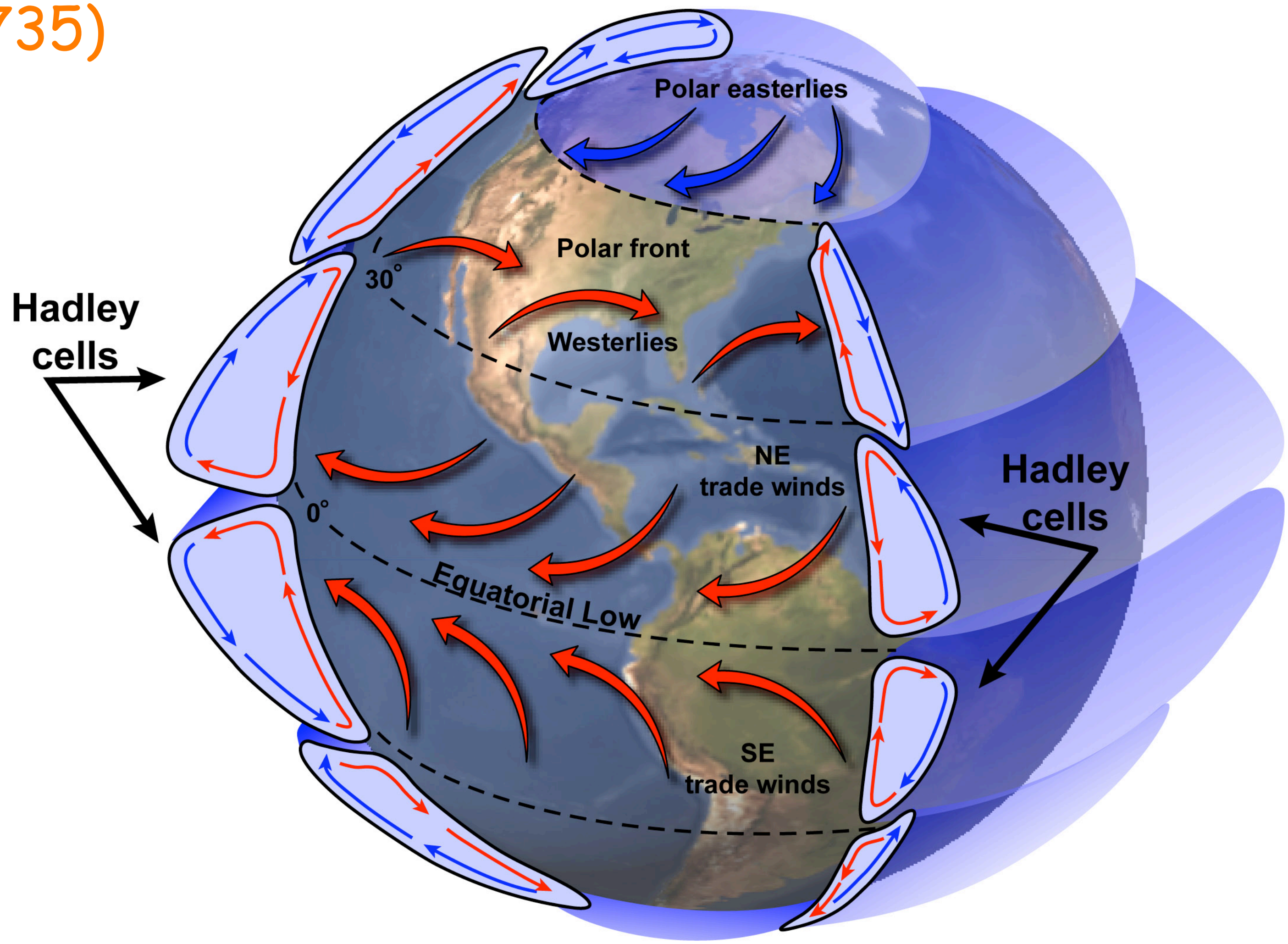
George Hadley (1685-1768), English lawyer and scientist.

"I think the cause of the general Trade-winds have not been explained by any of those who have wrote on that subject" (1735)

The overturning Hadley cells are the main way the atmosphere transports energy polewards in



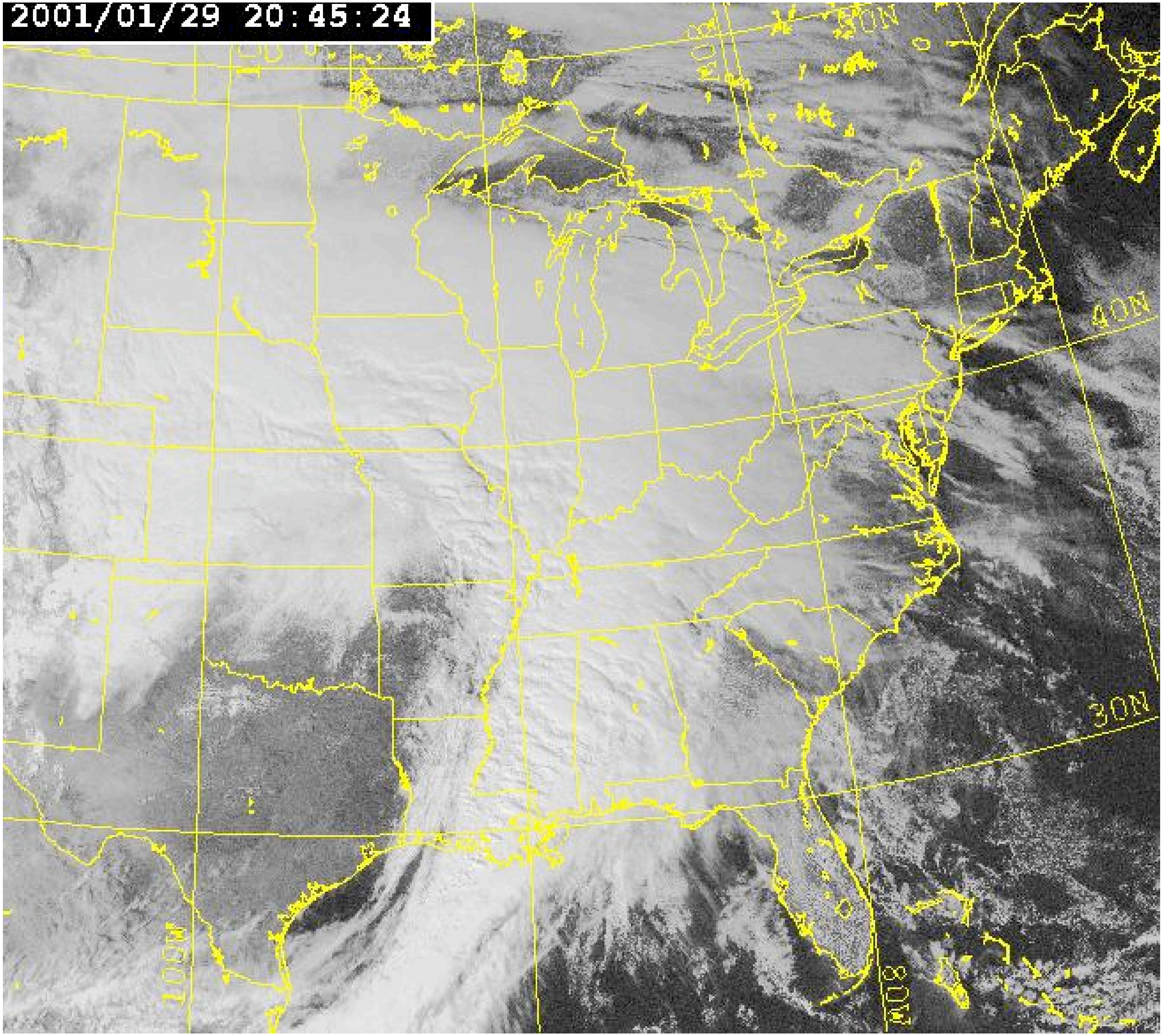
"Extratropical Storms"

Cyclones and anticyclones are the main way of transporting energy polewards in extratropics.

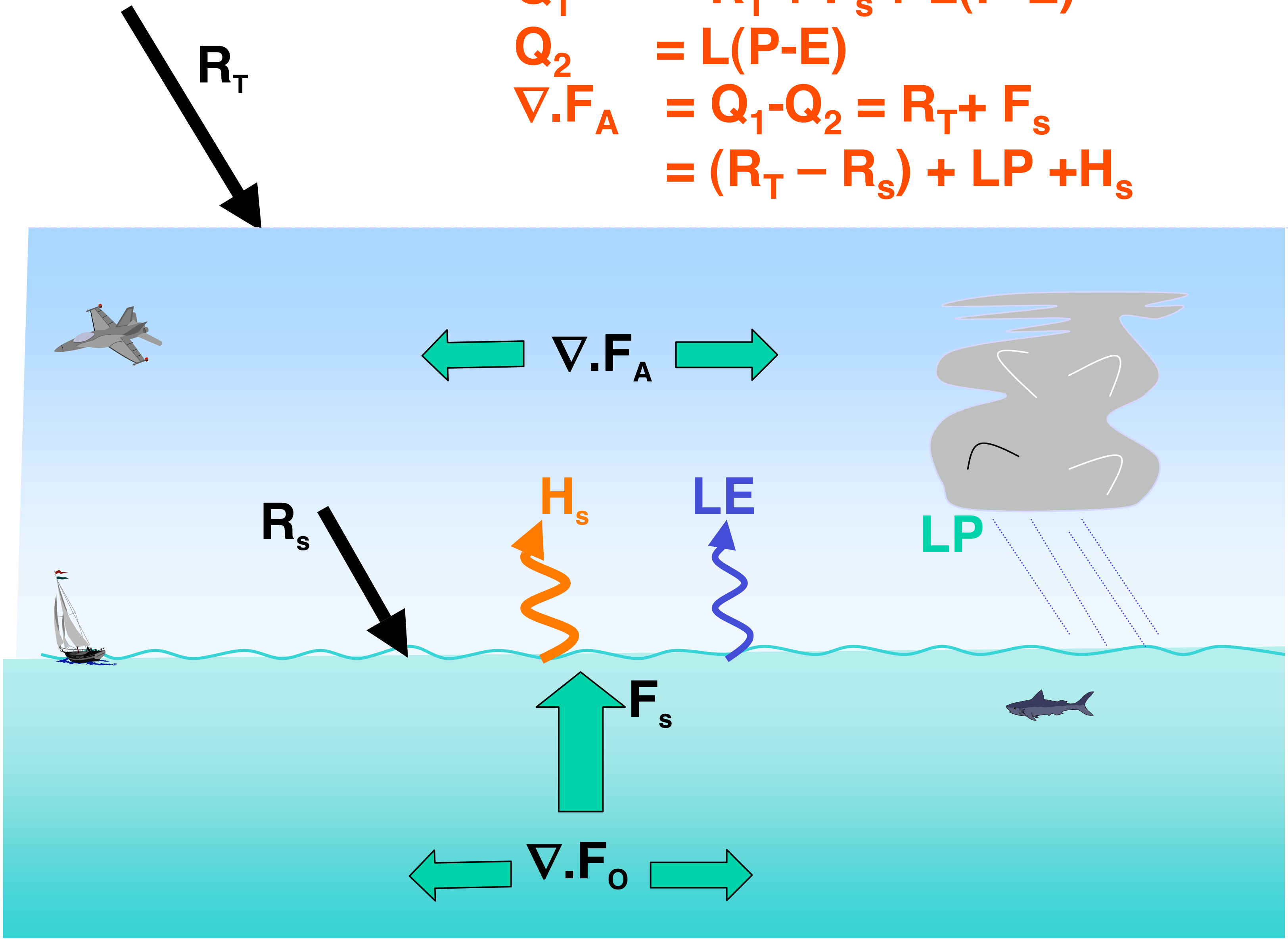
Winds converging into the low, pull cold air from the poles toward the equator, and warm air from the equator to the poles.

Where they meet is where we find fronts, bringing widespread precipitation and significant weather, like

Source: USA TODAY research by Chad Palmer, Graphic by Chuck Rose


2001/01/29 20:45:24
40N
30N
100W
80W

$$F_s = H_s + LE - R_s$$
$$Q_1 = R_T + F_s + L(P-E)$$
$$Q_2 = L(P-E)$$
$$\nabla . F_A = Q_1 - Q_2 = R_T + F_s$$
$$= (R_T - R_s) + LP + H_s$$



Atmospheric transports

TE = PE + IE + LE + KE

total energy = potential + internal + latent + kinetic

can not be expressed in terms of DSE or MSE

Transport of energy also involves work done:

We partition Total Energy transports into Dry Static Energy (**DSE**), Latent Energy (**LE**), and Kinetic Energy (KE), but the latter is small.

Dry static energy	**DSE = SH + PE**	sensible heat+geopotential
Moist static energy	**MSE = DSE + LE**	DSE+latent
Total energy F_A	**TE = MSE + KE**	Kinetic energy (small)

Divergence of transports balanced by diabatic forcings, ignoring tendencies and friction heating (small)

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We deal with the **vertically-integrated** atmosphere.

We define "**transient**" contribution to be that from within-month eddies.

$$\overline{vT} = \bar{v}\bar{T} + \overline{v'T'}$$

"**Quasi-stationary**" : long-term mean plus the interannual and inter-monthly variability.

Hence it includes the **Hadley** and **Walker** circulations in the tropics: part of "**global monsoon**".
And it includes **quasi-stationary planetary waves** (mainly a factor in NH extratropics in winter)

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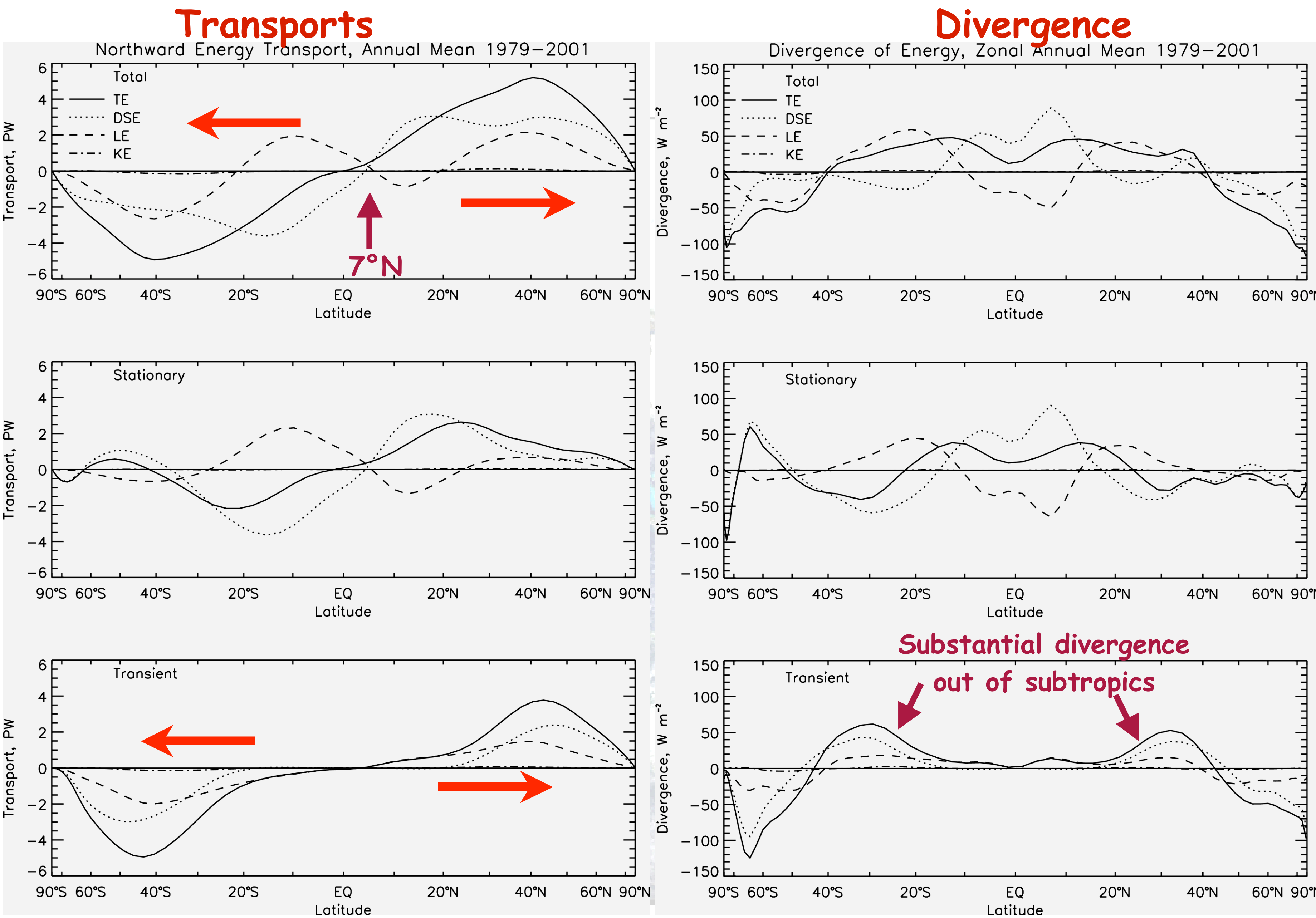

Seamless total northward transports and divergence, but structure in components. DSE and LE opposite for stationary but additive for transients.

Trenberth & Stepaniak, 2003

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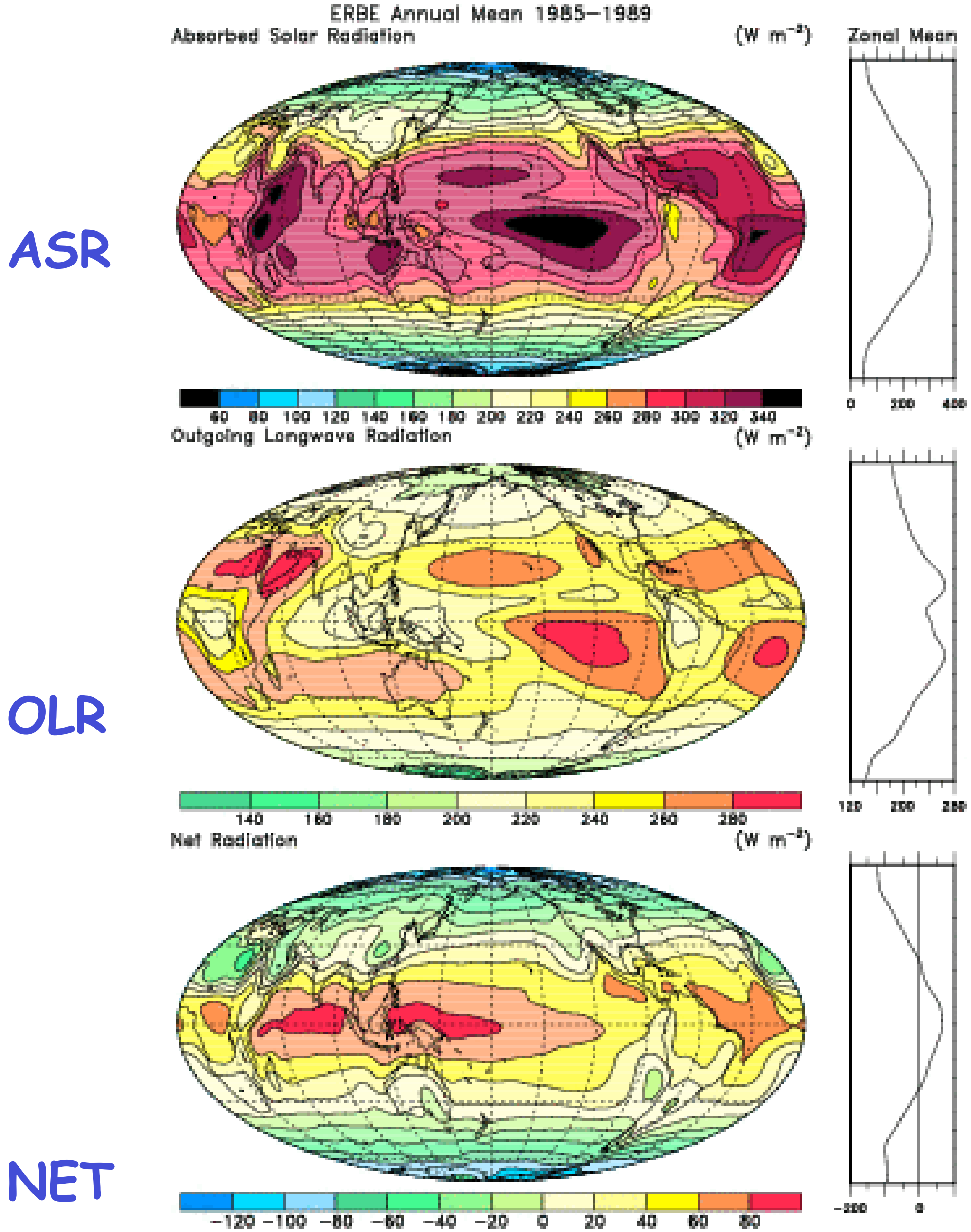
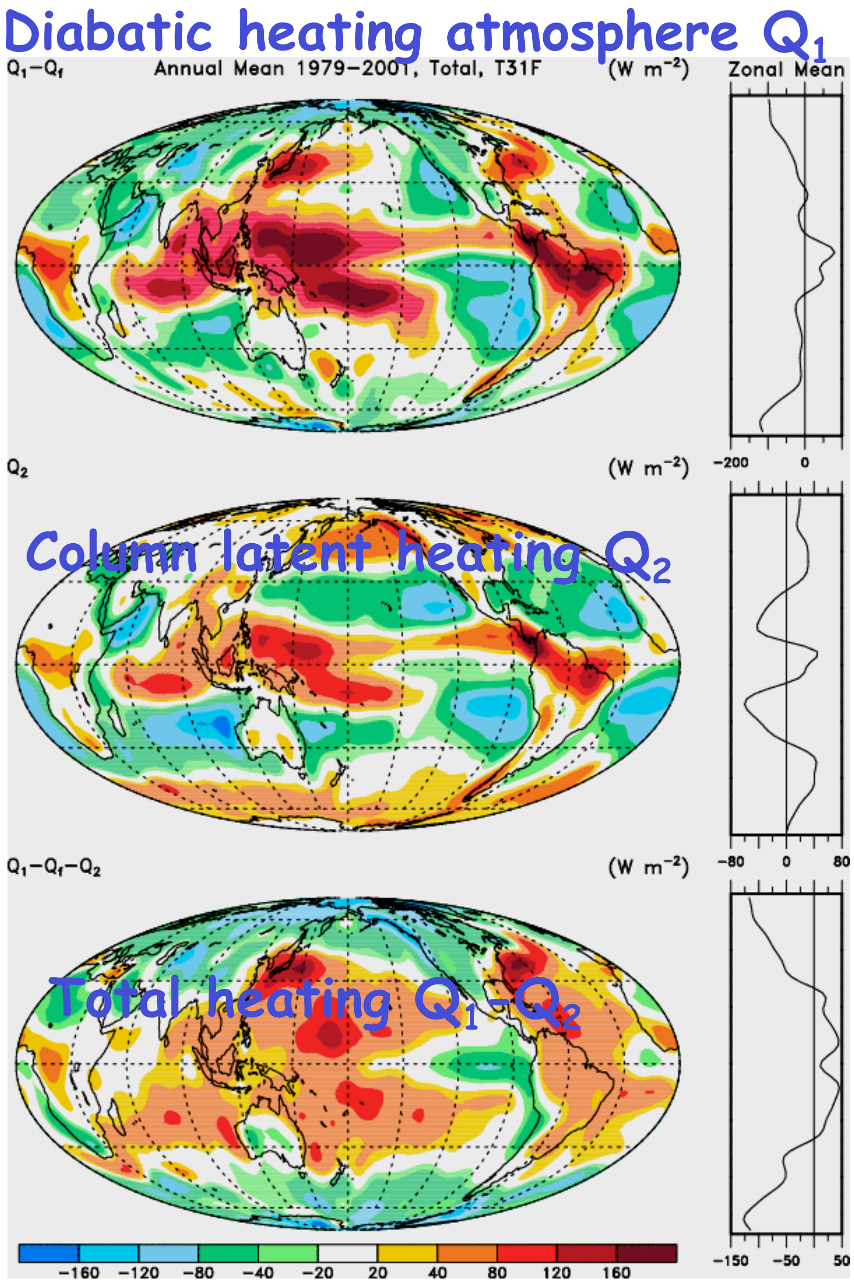


Radiation TOA

Quite strong structure due to clouds in ASR and OLR that mostly cancels in the net; some other albedo effects (e.g., Sahara) and land-sea differences, but sun-Earth geometry explains most of pattern.

Trenberth and Stepaniak, J. Clim. 2003

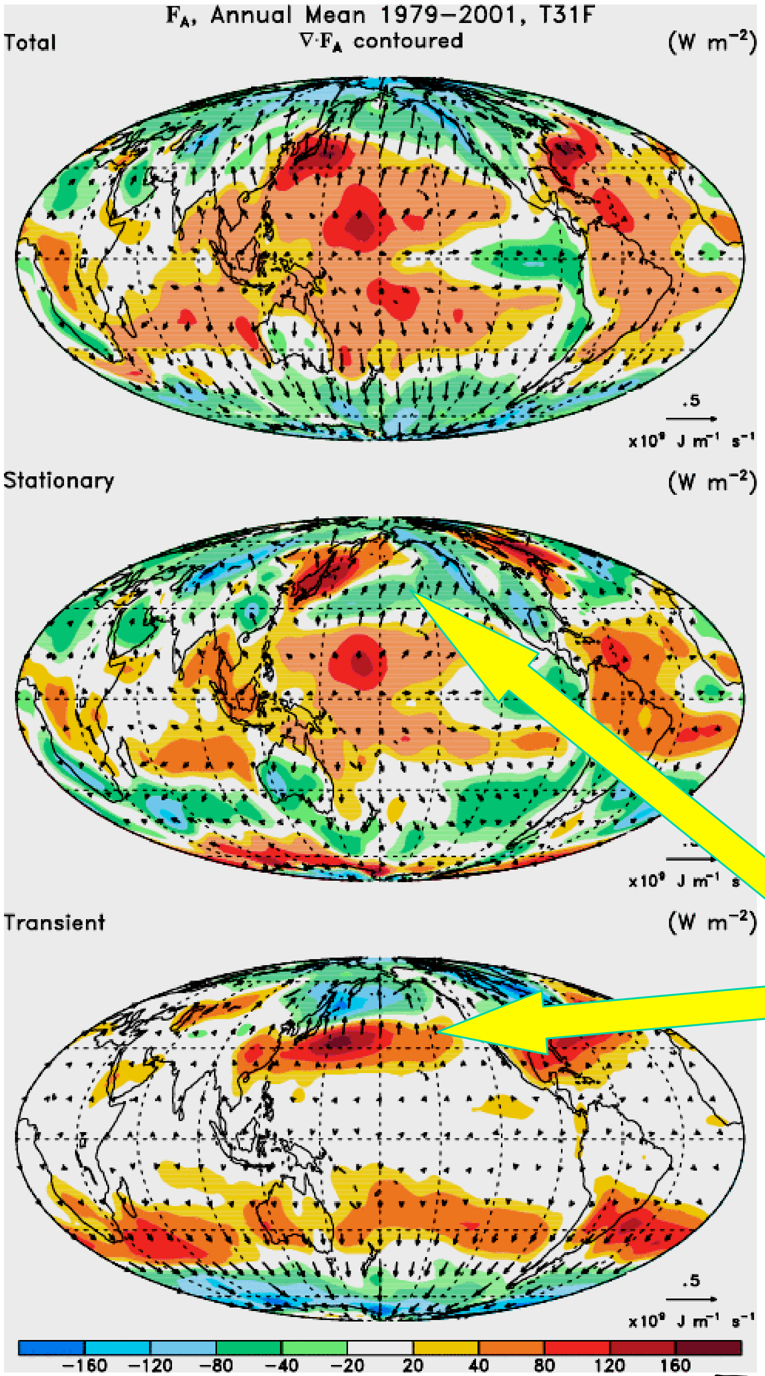


Includes LP term

Includes L(P-E) term

Removes LP term but includes LE term as moistening or latent heat.

Trenberth & Stepaniak, 2003



<u>**Divergence of total atmospheric energy**</u>

Note how transient and stationary components almost exactly compensate in extratropics:

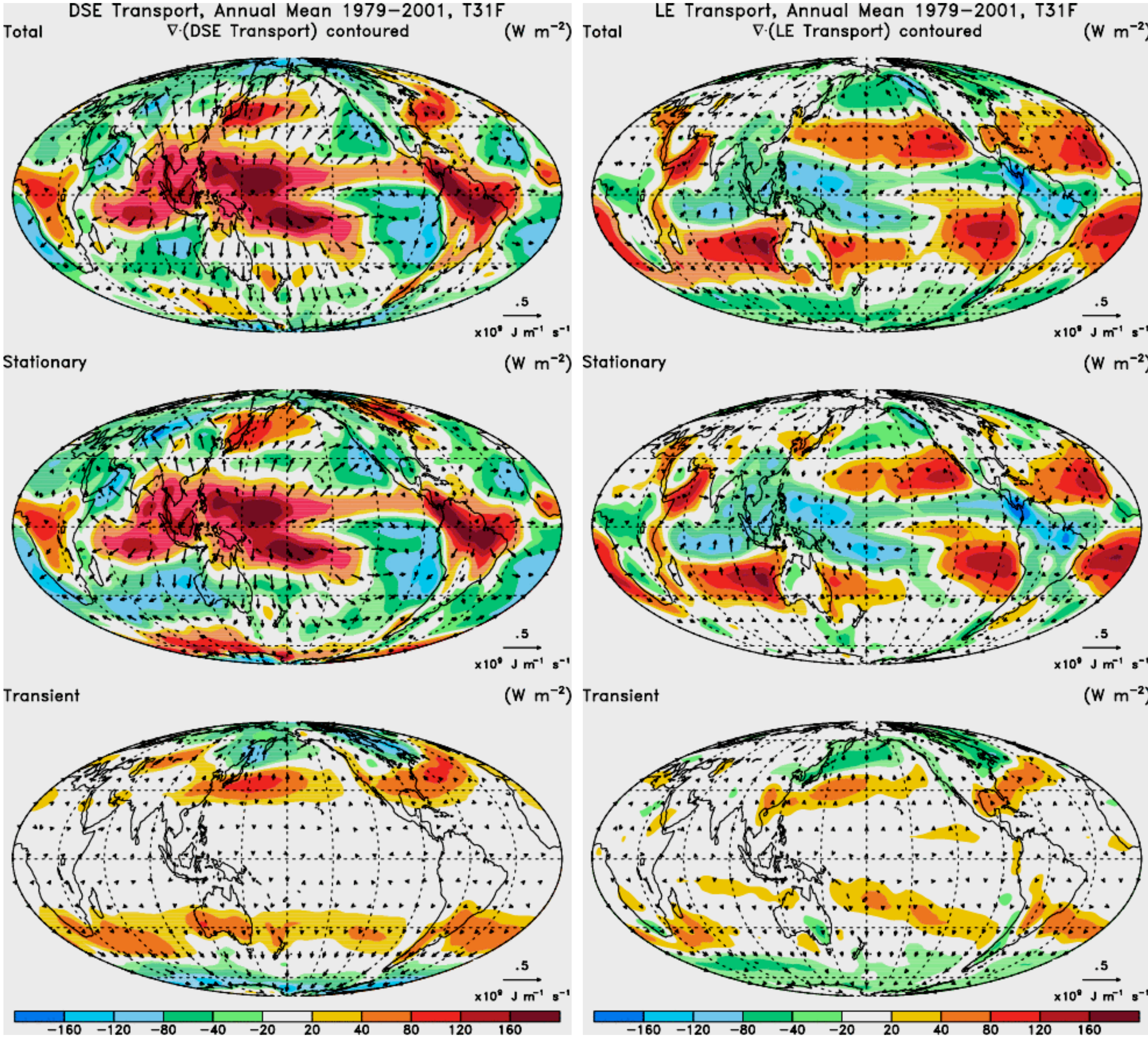
Divergence by transients in subtropics is compensated by **subsidence** and hence convergence by stationary component and, at same time, values of opposite sign to north and south.

Trenberth and Stepaniak, J. Clim. 2003

Divergence of:

DSE

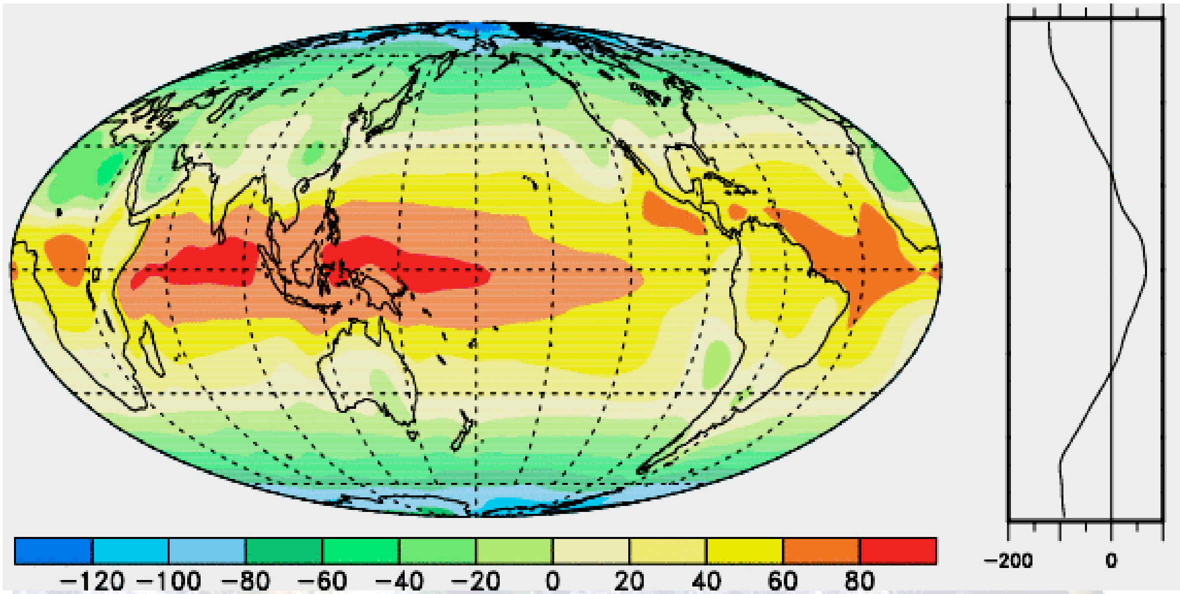
LE



Note strong compensation locally in stationary component. Closer relation with DSE and LE transients.

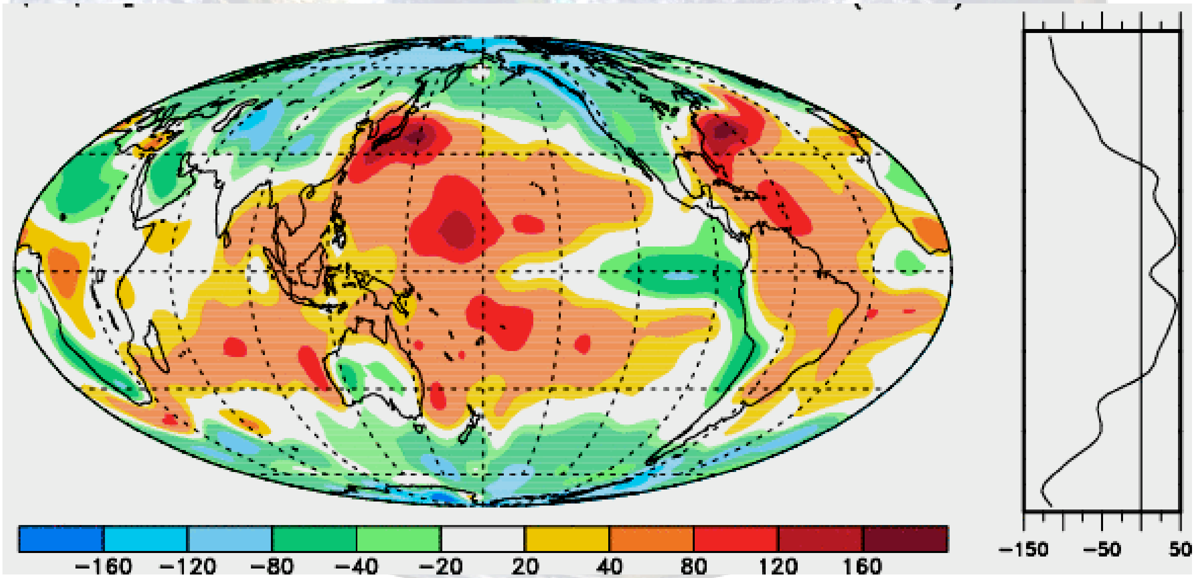
Trenberth and Stepaniak, 2003

Net Radiation TOA



Difference due to ocean transports

Total heating Q_1-Q_2



Trenberth & Stepaniak, 2003

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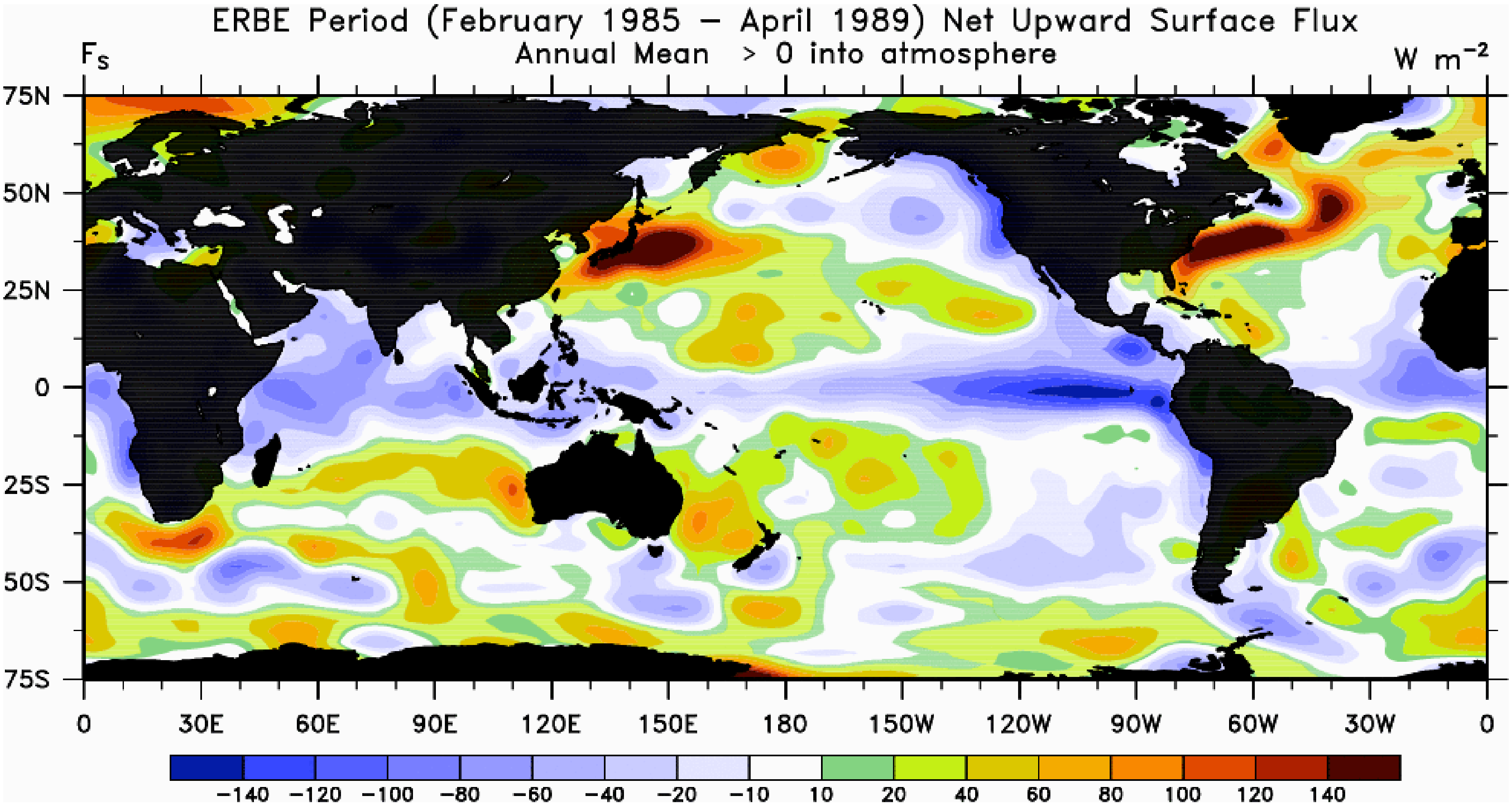
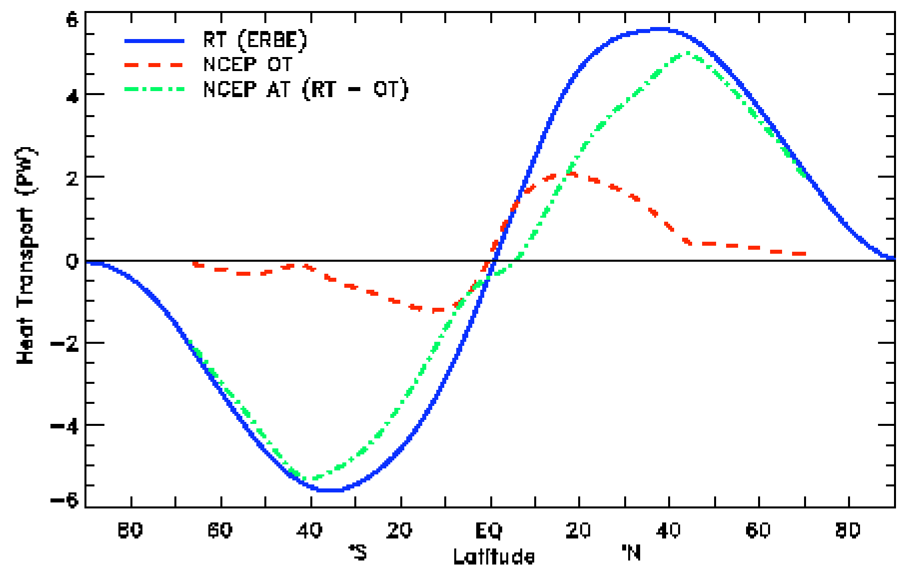
Annual mean net surface flux



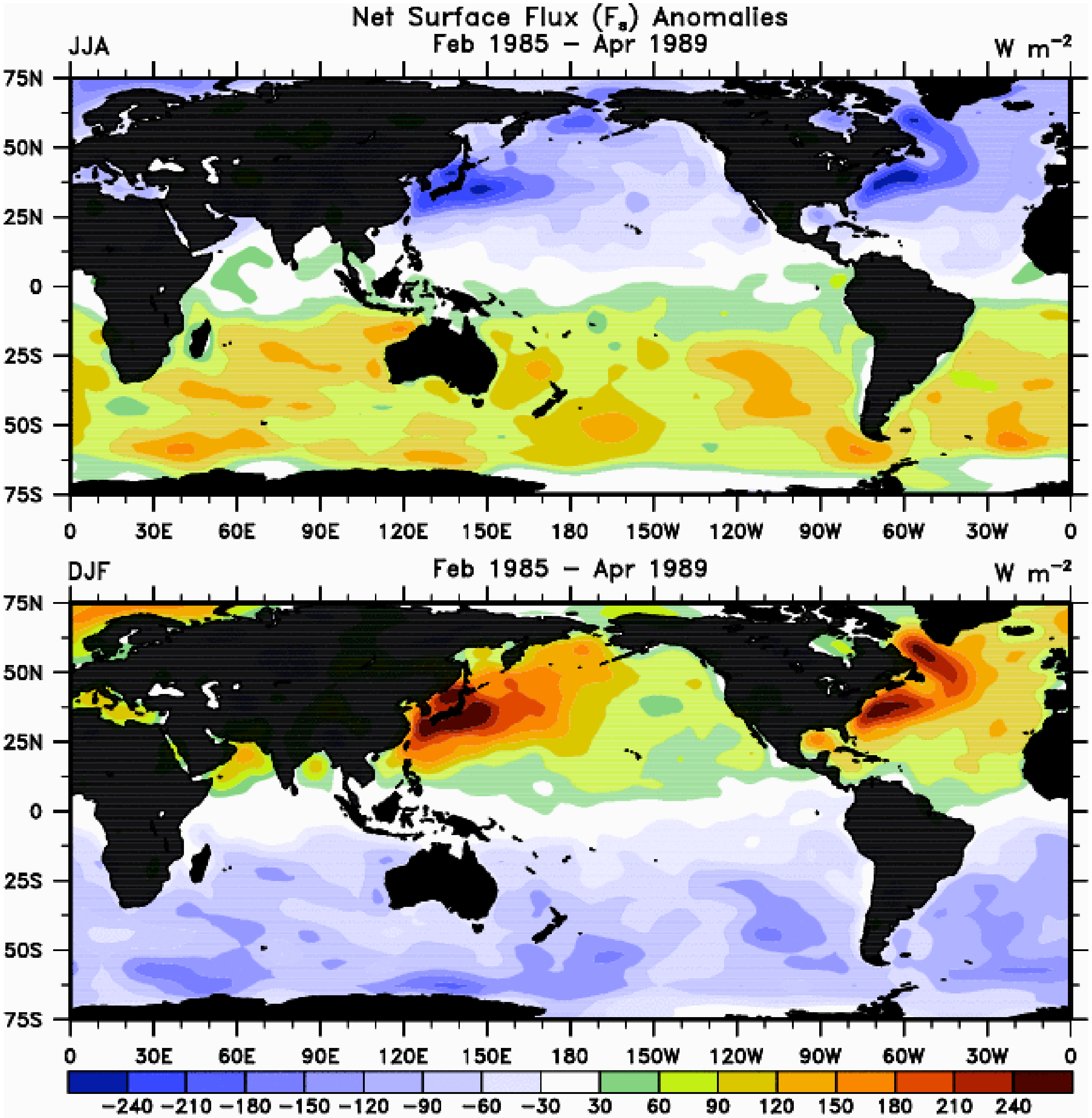
OCEAN-ATMOSPHERE TRANSPORTS

The latest best estimate of the partitioning of meridional transports by the atmosphere and ocean.



Trenberth and Caron, J. Clim. 2001

At 35° latitude, where the peak polewards transport occurs the atmosphere accounts for 78% (NH) and 92% (SH) of the total. Values estimated from atmospheric analyses agree with direct ocean estimates and those from the best coupled climate models (including CCSM).

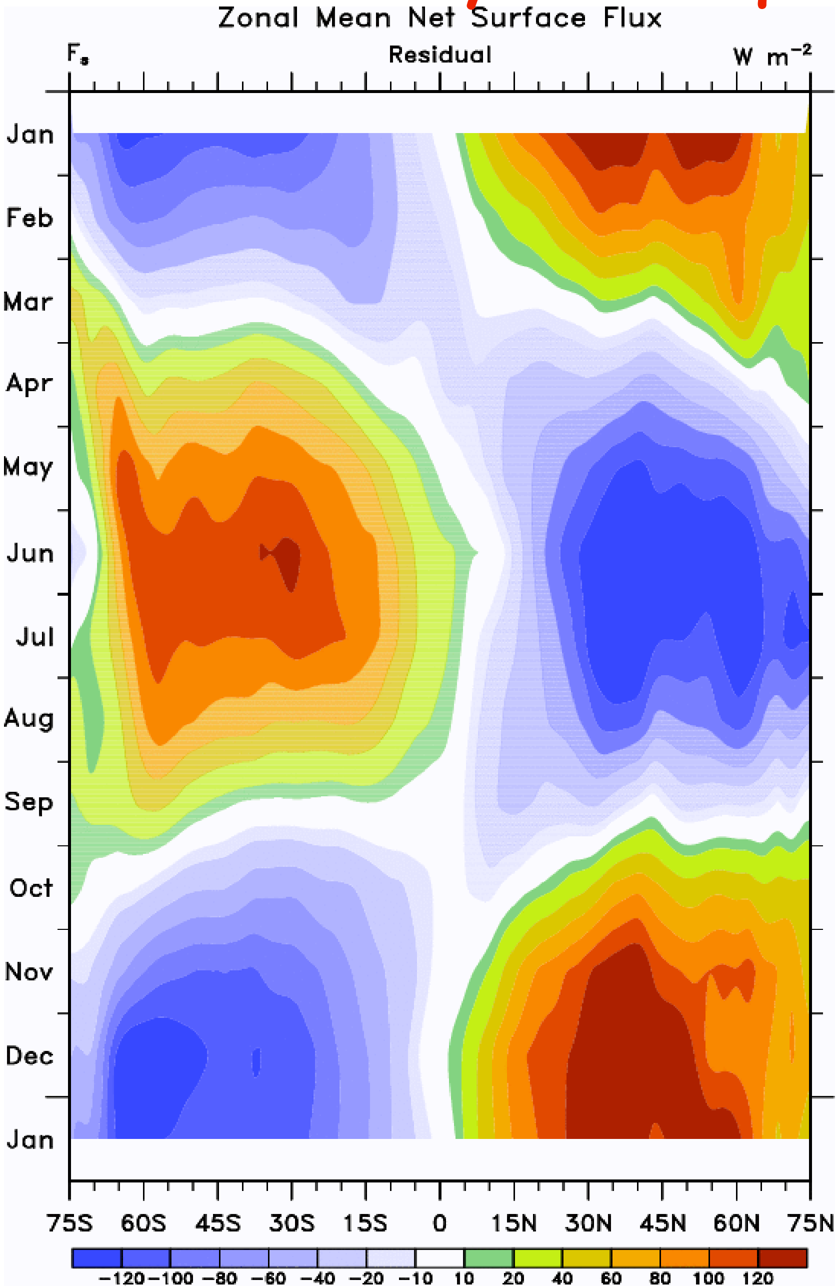


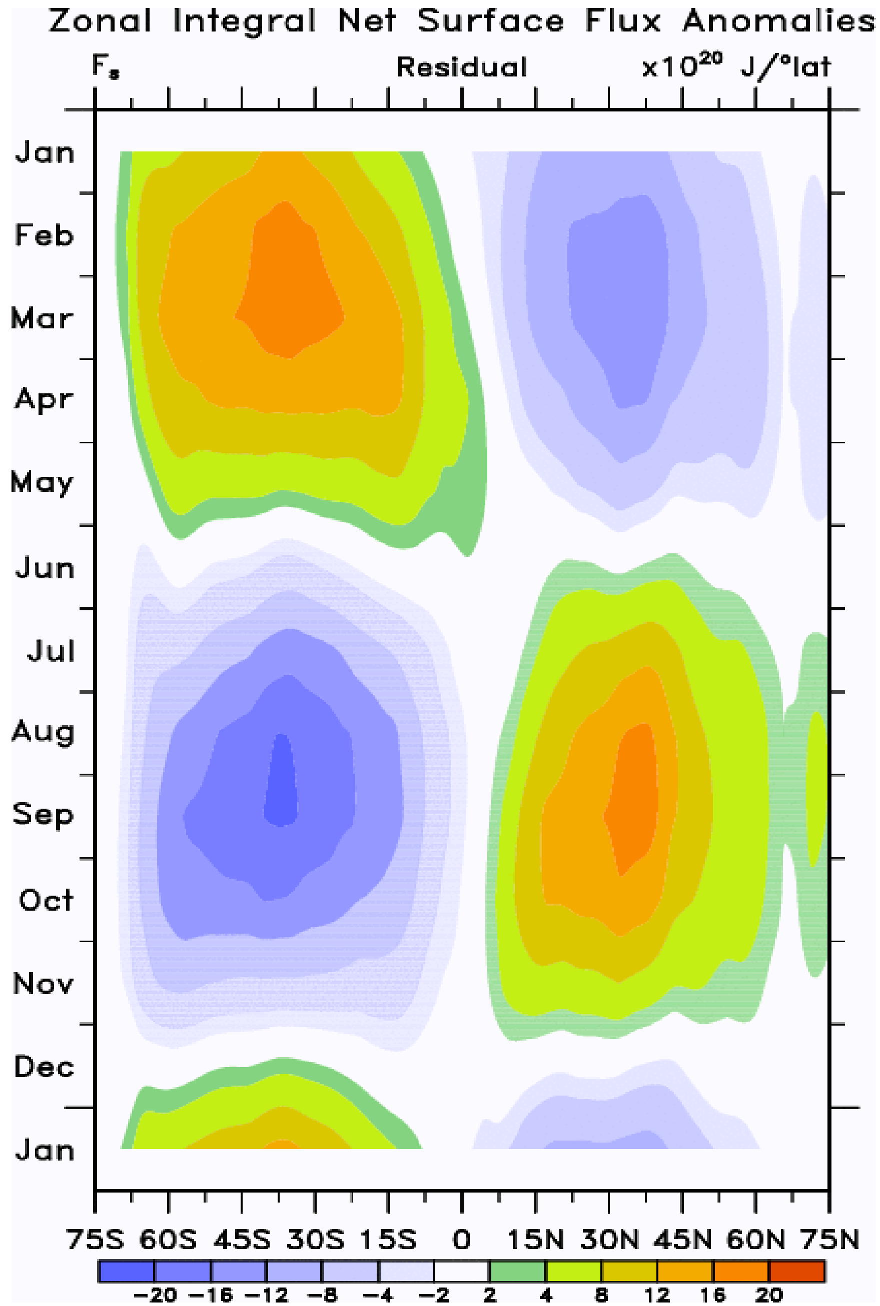
Departures from annual mean:

Equivalent ocean heat content

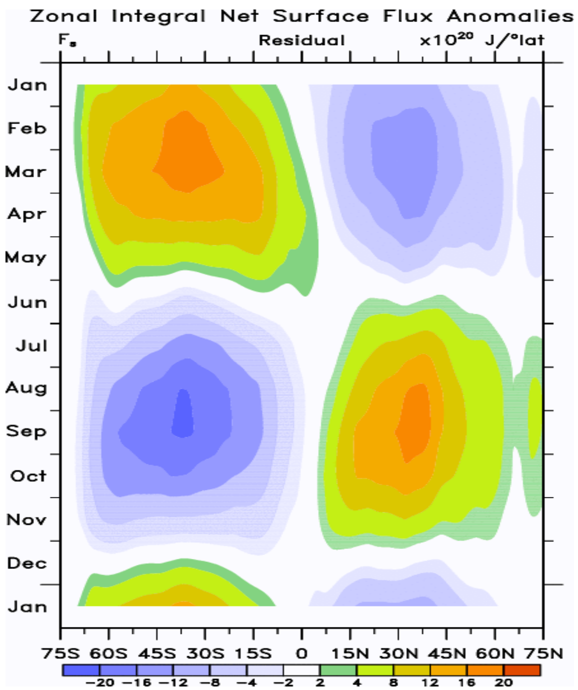
(Includes annual cycle in ocean heat transports)

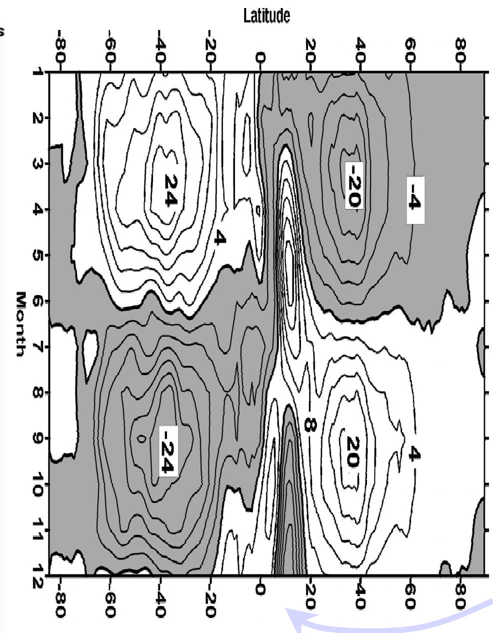
Annual cycle of equivalent ocean heat content





Annual cycle of inferred equivalent ocean heat content





Antonov et al. 2004 GRL

The rates of change are converted into equivalent ocean heat content and compared with Antonov, Levitus and Boyer, 2004.
Note: Antonov et al. use incorrect values for density and specific heat (4.4% too large for heat content).

Main differences from actual ocean heat content occur in Tropics, especially ~10°N with

There is good evidence for an annual cycle of heat transports by the ocean (cf. WOCE assumptions) in the Tropics. In extratropics heat transports amplify annual cycle in heat content somewhat owing to larger poleward heat transport in summer than winter (mainly Ekman): Zhang et al. (JGR 2002).

WOA results exhibit small spotty

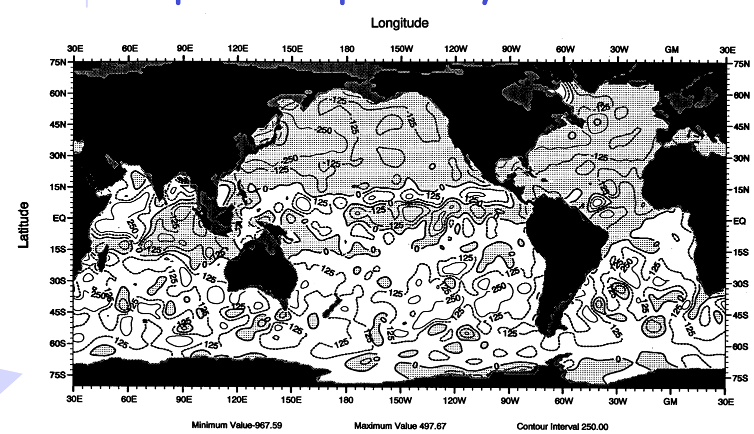
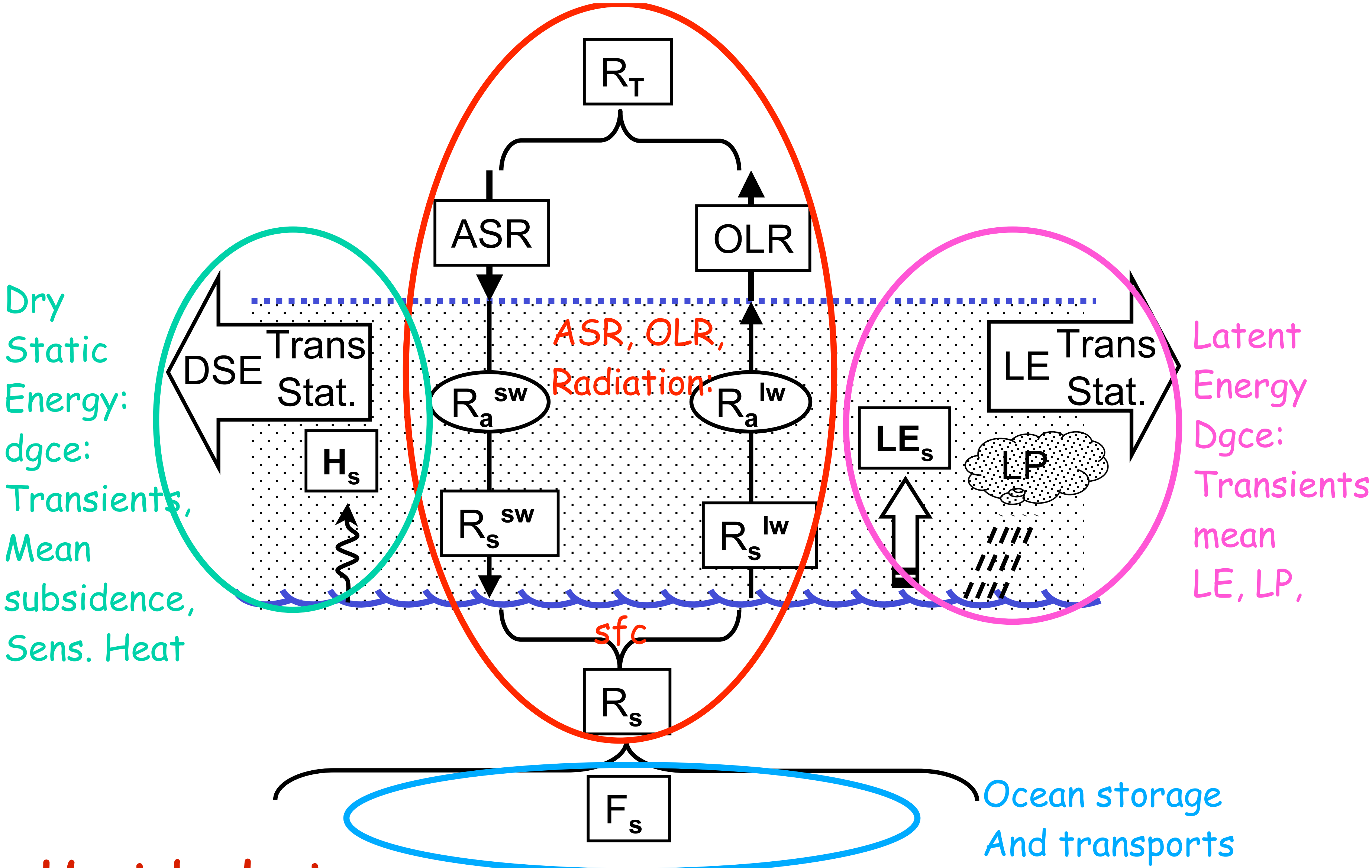


Fig. E1 Rate of heat storage (W/M^2) integrated through 275 m depth for January

Levitus and Antonov 1997

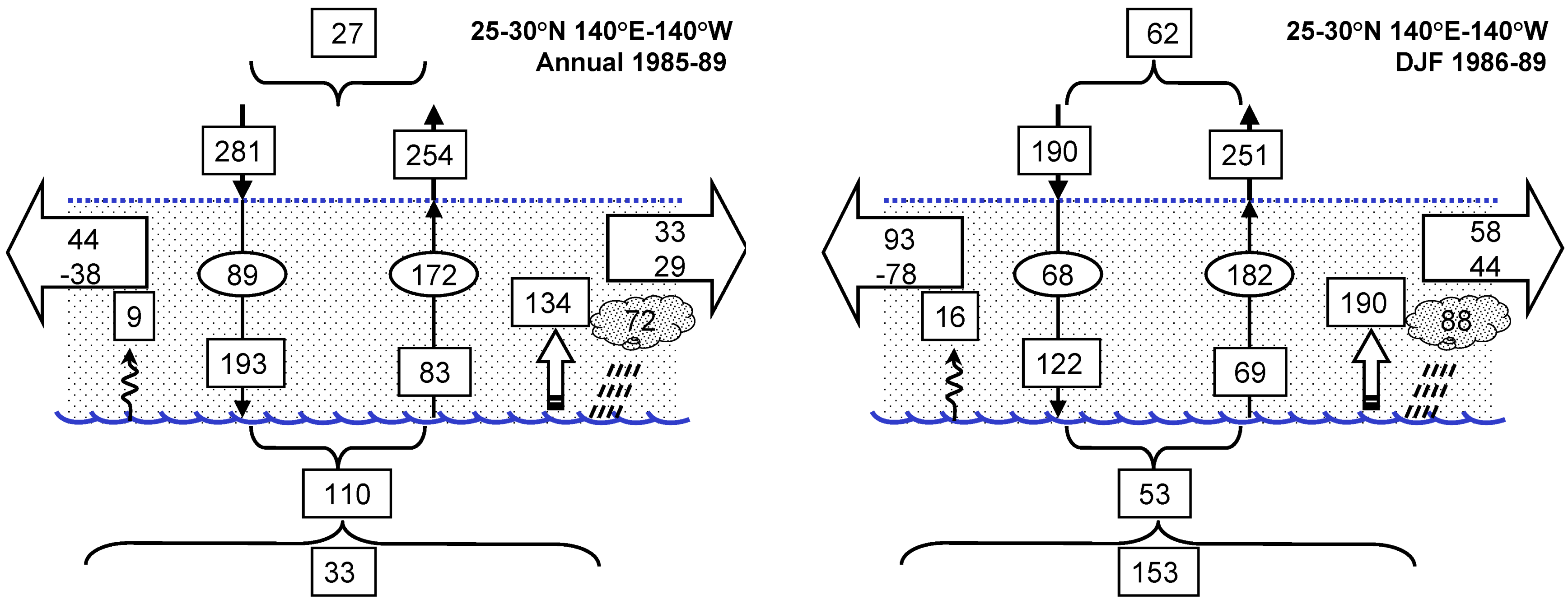


Heat budgets:

Top-of-atmosphere, surface and within atmosphere.

Using SOC atlas, NCEP reanal, ERBE

Heat budgets Northern Hemisphere Pacific subtropics
ERBE period (Feb. 1985- Apr. 1989) W m^{-2}

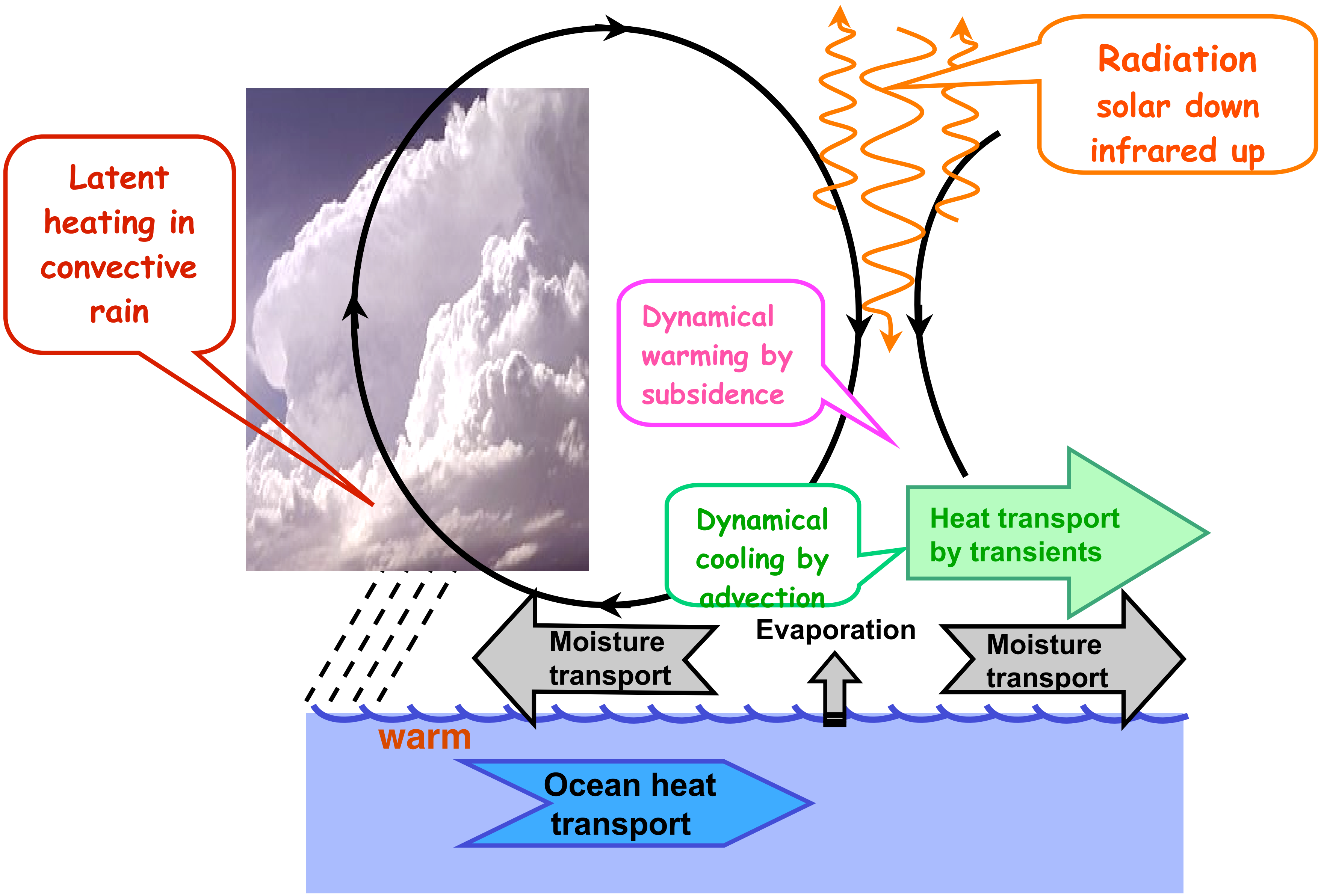


W m^{-2}

Main seasonal changes are:

- solar radiation, absorbed at surface in summer, released in winter
- increased divergence of energy by eddies in winter
- increased evaporation and precipitation in winter
- stronger Hadley circulation in winter

Hadley circulation and heat budget in subtropics



Trenberth and Stepaniak, J. Clim. 2003

1. **In Tropics: Global monsoon**

TE transport is small residual of DSE and LE.

Solar radiation in clear skies heats ocean, cooled by evaporation: moisture transported into upward branch, feeds DSE.

Circulation that provides transport, supplies LE.

2. **In extratropics: transient baroclinic waves** LE and DSE additive, moisture more prominent in low-mid-lats.

3. **Quasi-stationary waves** in NH in winter relate to shift in storm tracks: complementary heat transports.

4. ENSO: **heat from ocean goes into atmosphere mainly through evaporation, location of convection controlled by SSTs.** **Teleconnections alter stationary waves <u>and</u> hence storm tracks.**

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What about variability and change?

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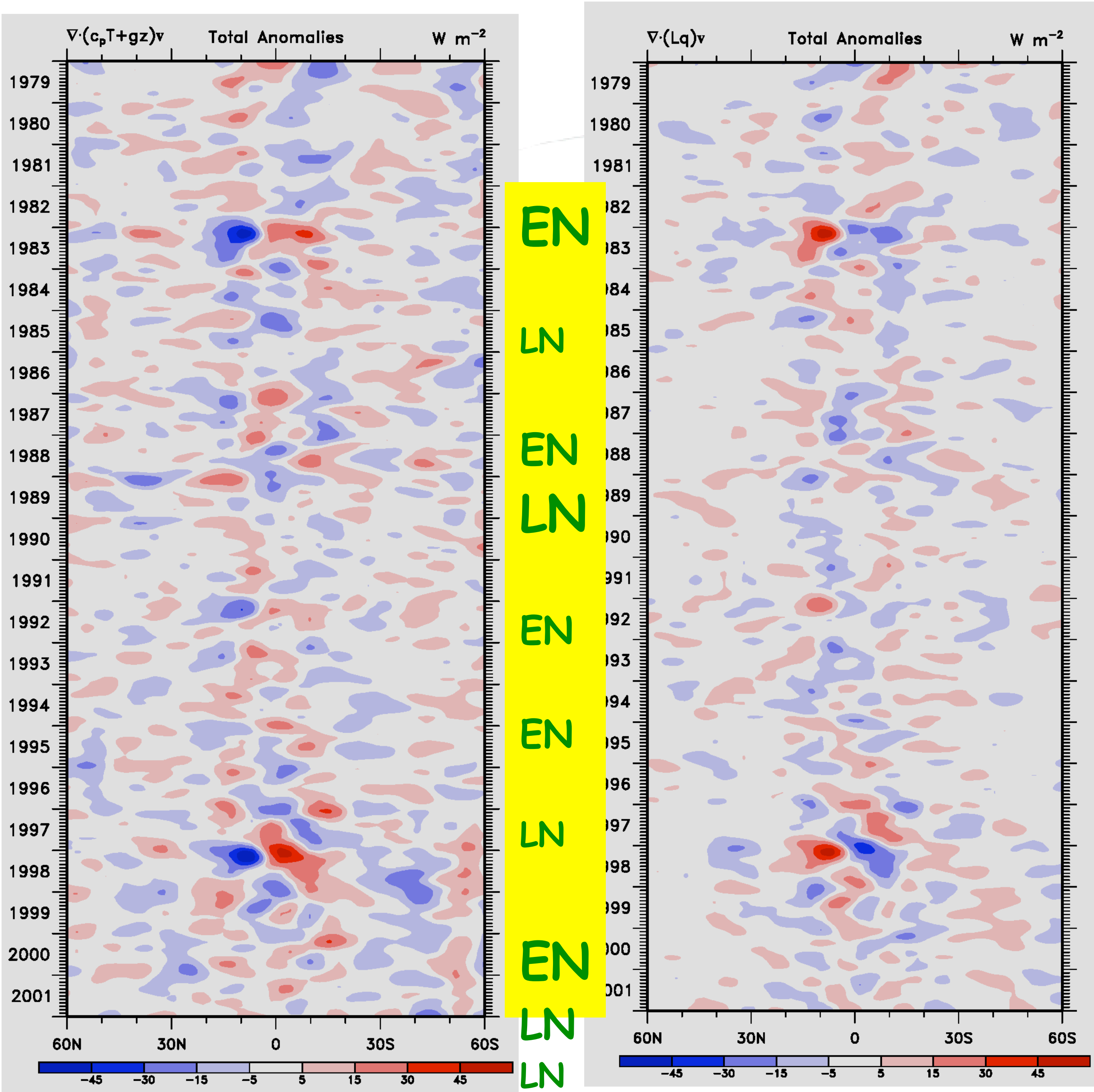

Dominant signal from ENSO:

Large opposite anomalies in DSE and LE

Trenberth and Stepaniak, 2003

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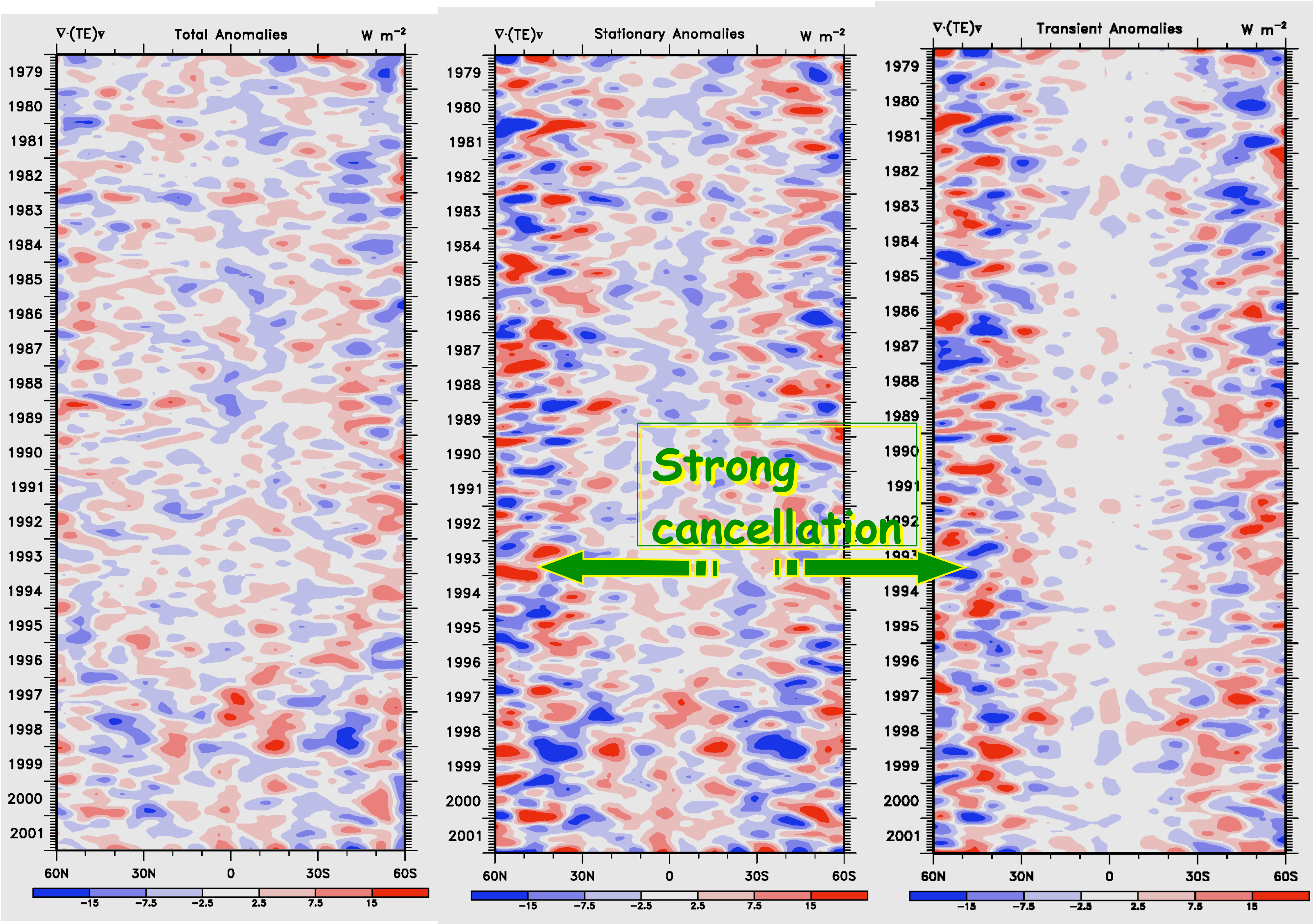

Trenberth and Stepaniak, J. Clim. 2003

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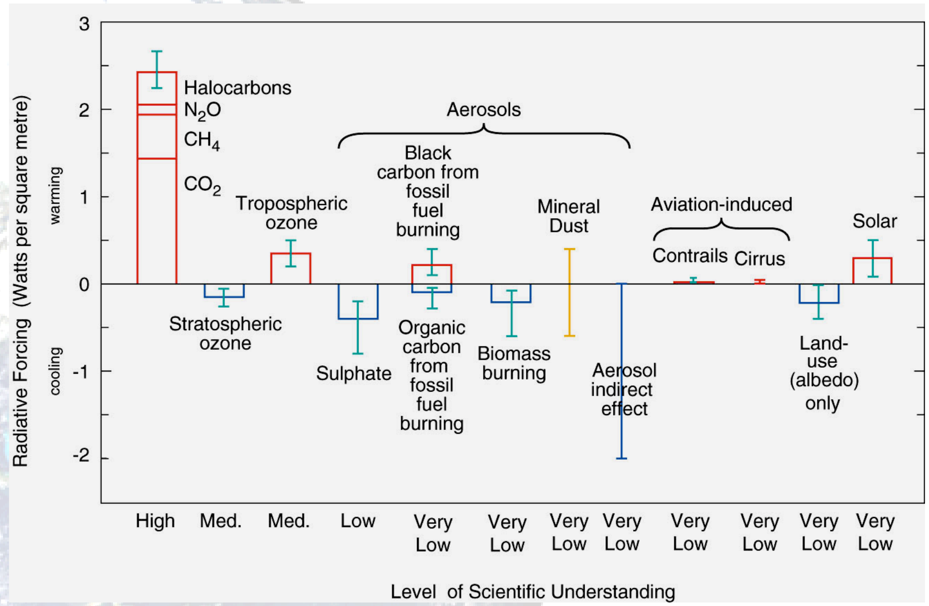
Climate Change:

Net TOA radiative forcing, estimated ~1.4 Wm^{-2}

CO_2 1.4 Wm^{-2}
Other GHG 1.4 Wm^{-2}
Aerosols -1.4 $W\ m^{-2}$



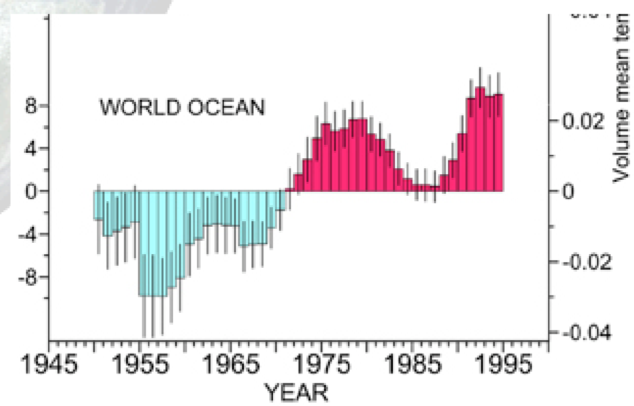
Partly compensated for by climate change

Net

Radiative imbalance 2000 TOA 0.7 $W\ m^{-2}$
Radiative imbalance 1950 TOA 0.1 $W\ m^{-2}$

Mean heating since 1950 0.4 $W\ m^{-2}$

Warming of oceans since 1950 0.3 $W\ m^{-2}$



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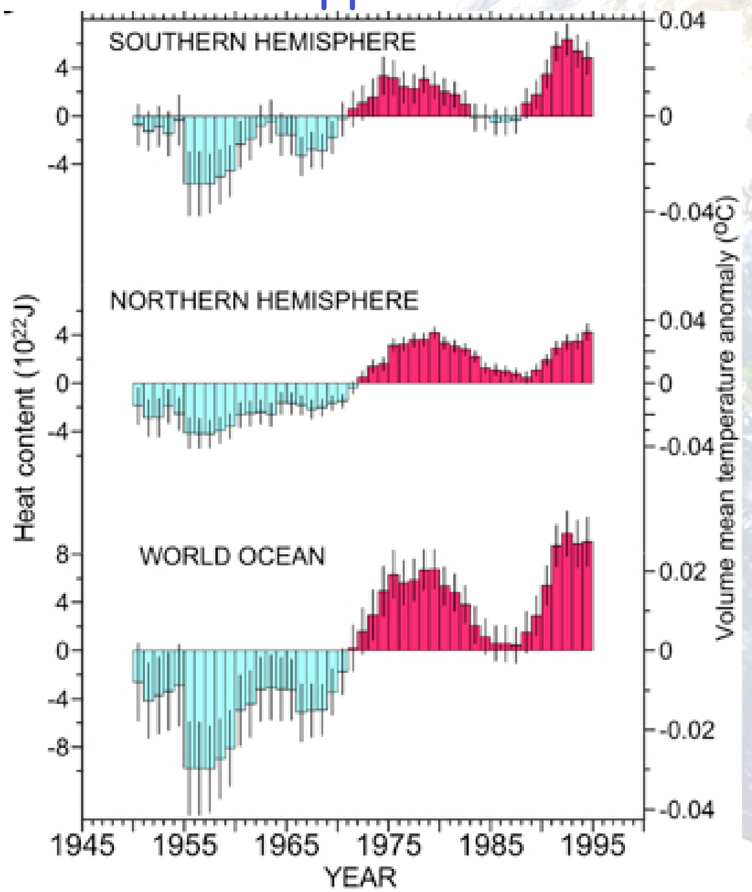
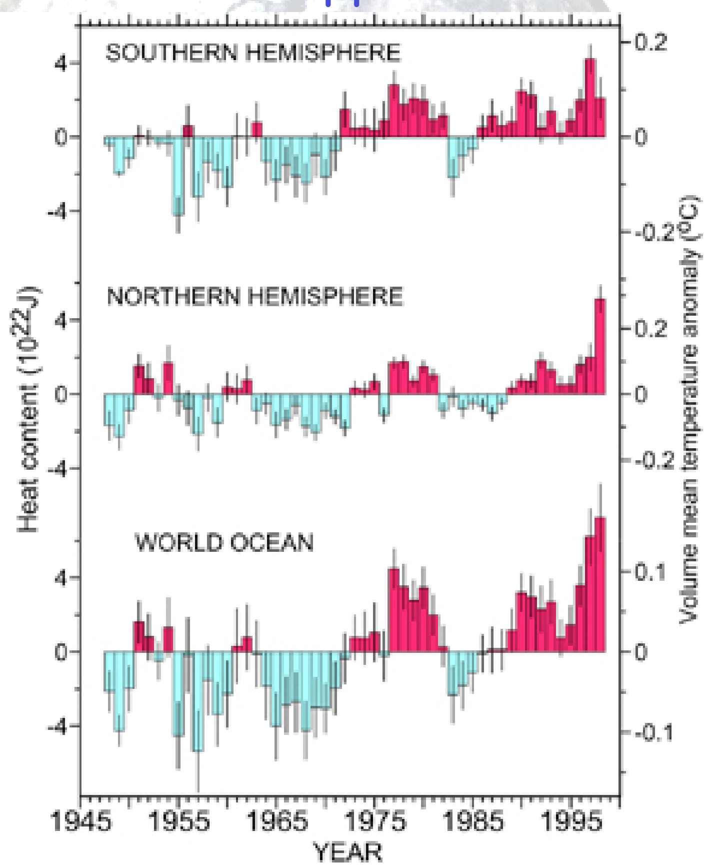
What about changes in the ocean heat content?

Changes in Ocean heat content in upper 3000 m



Changes in Ocean heat content in upper 300 m



Contributes to eustatic rise in sea level.

Levitus et al. 2000

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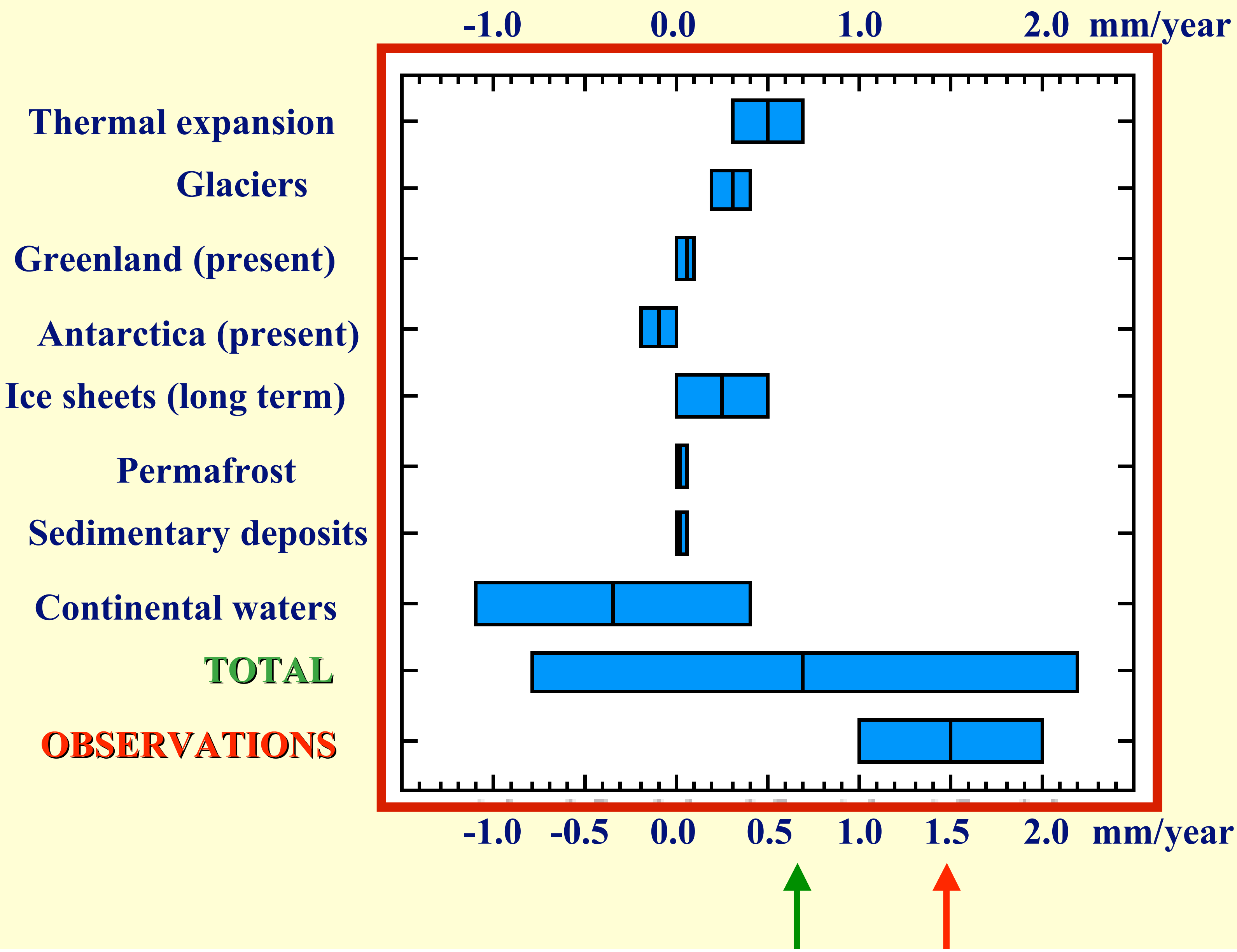
20th Century Sea Level Rise - IPCC, 2001-



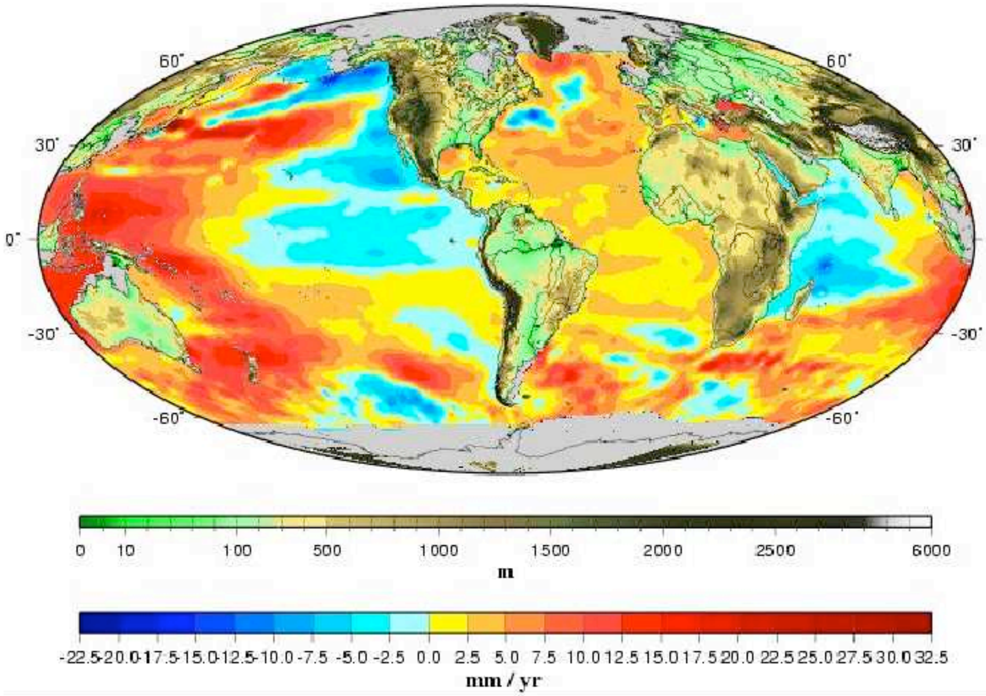


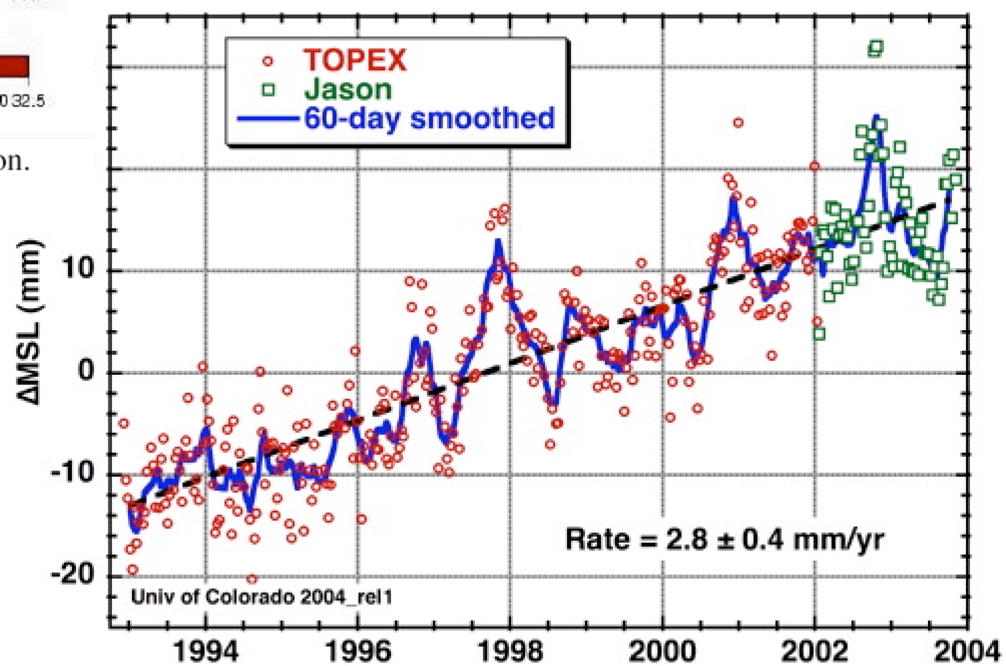
Figure 7. Sea level trends over 1993-2003 from the T/P mission.

Oceans and sea level

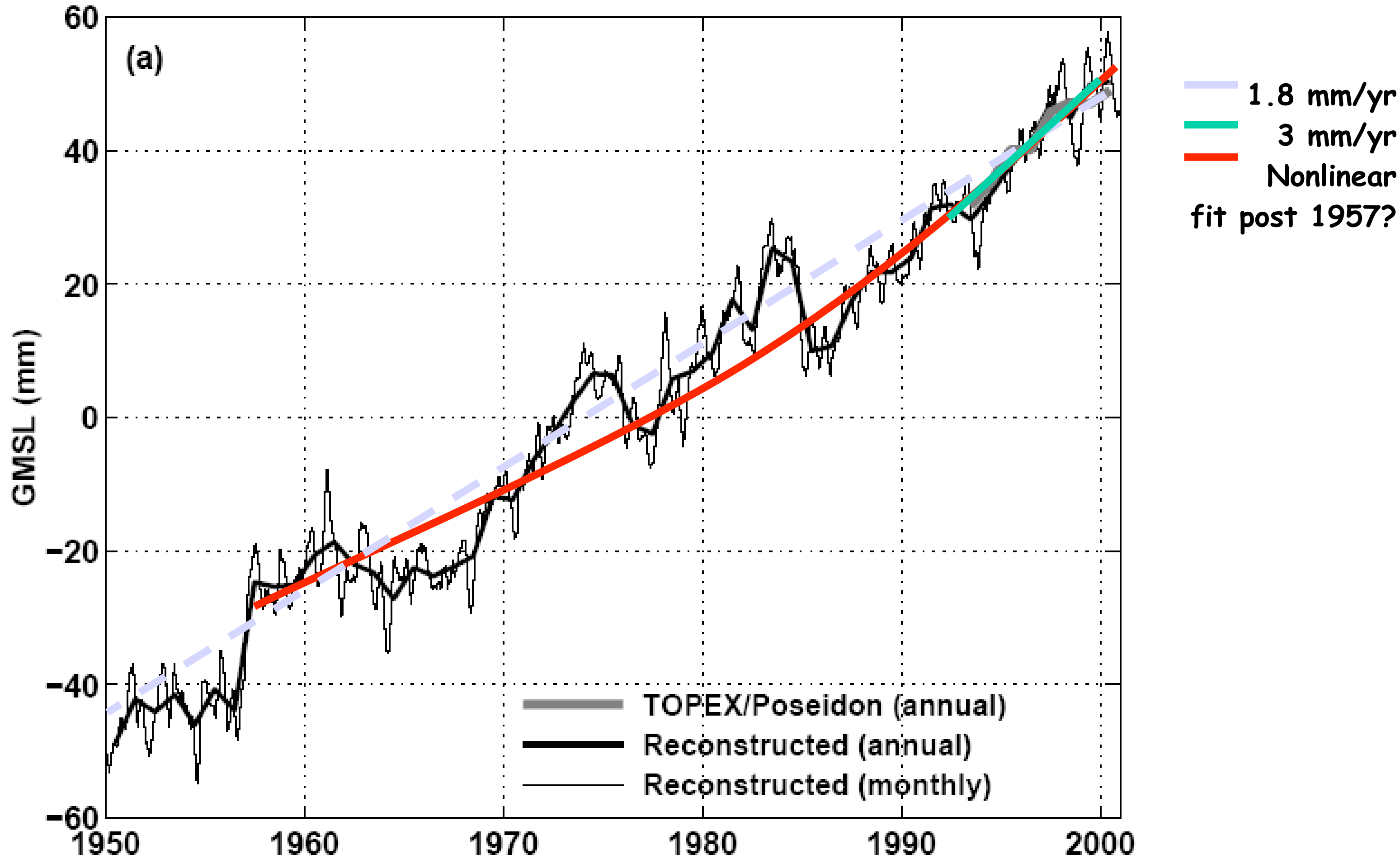
New global observations by satellite: TOPEX-Poseiden, Jason

1993-2003

Observed sea level rise reported from satellite: about 3mm/yr. Thermal expansion can account for almost all in 1990s, but steric sea level rise from melting glaciers etc is about 1 mm/yr. Increased use (irrigation) and storage (reservoirs) on land –1 mm/yr



[Figures from Cazenave and Nerem, 2004]



Global sea level reconstructed using sea level station data and EOF patterns based on TOPEX period, with Metrovic glacial isostatic adjustment applied.   The mean rate is 1.8 mm/yr.

Note **absence of decadal variability** cf Levitus heat content.

From Church et al. 2004

Thermal expansion and surface heat flux

If heat deposited at depth, where it is colder, expansion is a lot less. α 0.5 (0°C) to 3 (26°C) x10^{-4}

IPCC 2001: Levitus et al. 0.5 mm/yr is 0.3 W m^{-2}

Willis, Roemmich and Cornelle (JGR 2004 in press?)
For T/P 1993-2002 period, estimate thermal expansion as 1.8 mm/yr and heat flux of 0.95 W m^{-2}.

The Church et al (2004, J Clim in press?) 1.8 mm/yr includes 0.3 mm/yr isostatic rebound and order 0.2-0.5 mm/yr from melting glaciers presumably.

Cazanave and Nerem (2004, Rev. Geophys. in press?)
For T/P 1993-2003 3.1 mm/yr is 2.8 mm/yr without isostatic rebound and could be order 1.5 W m^{-2}.

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The **challenge** is to better determine the **heat budget** at the **surface of the Earth** on a continuing basis:
Provides for changes in **heat storage of oceans**, glacier and ice sheet melt, changes in SSTs and associated changes in atmospheric circulation, some aspects of which should be **predictable** on decadal time scales.

Several models now can simulate major changes like the Sub-Sahara African drought beginning in the 1960s, the "Dust Bowl" era in North America in the 1930s, given the global SSTs.

Can coupled models predict these evolutions?
(Not so far). But there is hope that they will improve.
In any case models should show some skill simply based on the current state, when it becomes well known and properly

We urgently need:

an ocean observing system!

(coming with ARGO floats)

And ongoing

top-of-atmosphere radiation fluxes

(in jeopardy).

2 specific papers on this topic,

J Climate, 15 Nov 2003 issue:

Trenberth, K. E., and D. P. Stepaniak, 2003: Co-variability of components of poleward atmospheric energy transports on seasonal and interannual timescales. *J. Climate*, **16**, 3690–3704

Trenberth, K. E., and D. P. Stepaniak, 2003: Seamless poleward atmospheric energy transports and implications for the Hadley circulation. *J. Climate*, **16**, 3705–3721.

All of our recent papers (including these) are available from our web site: www.cgd.ucar.edu/cas

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