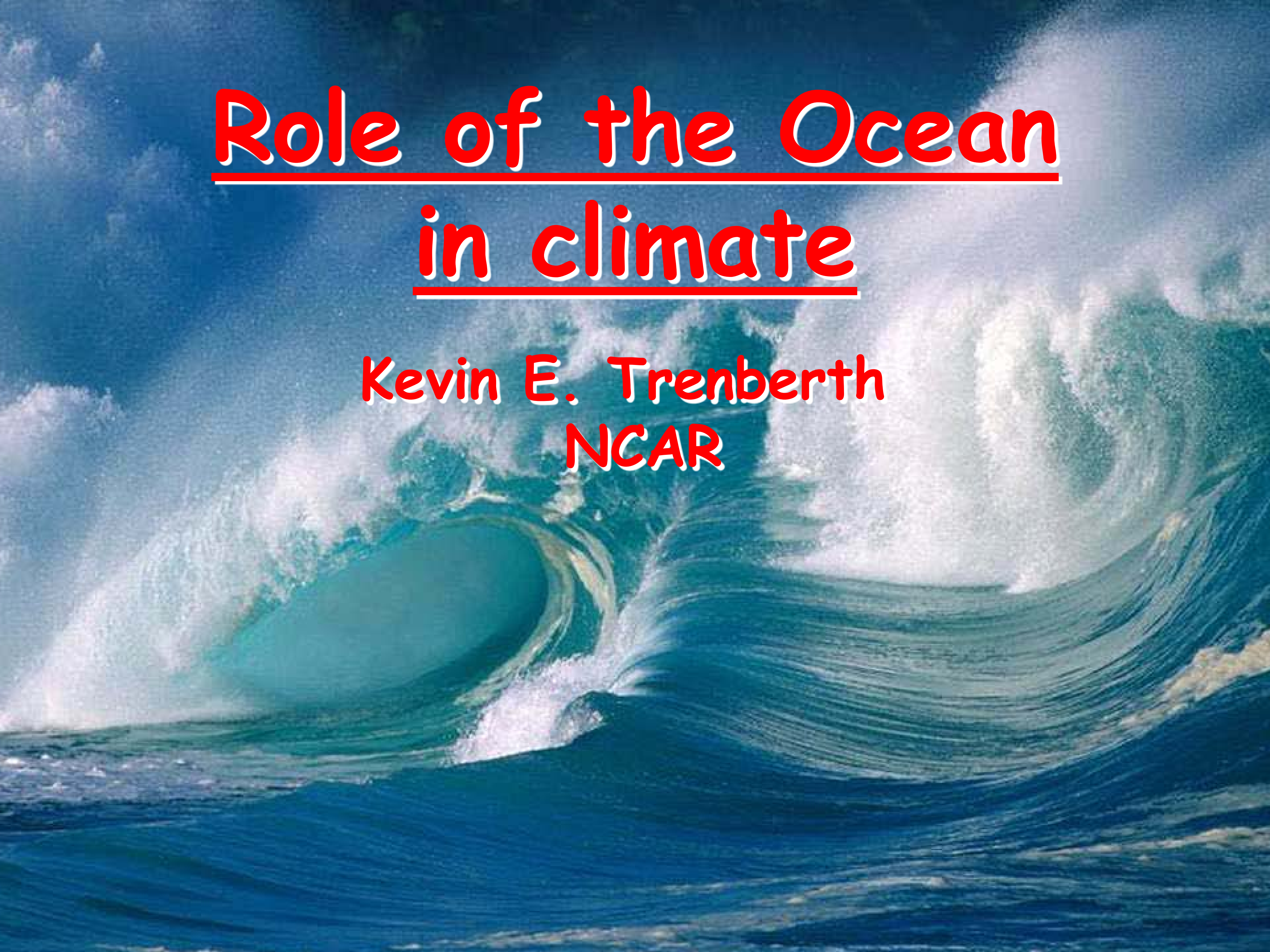
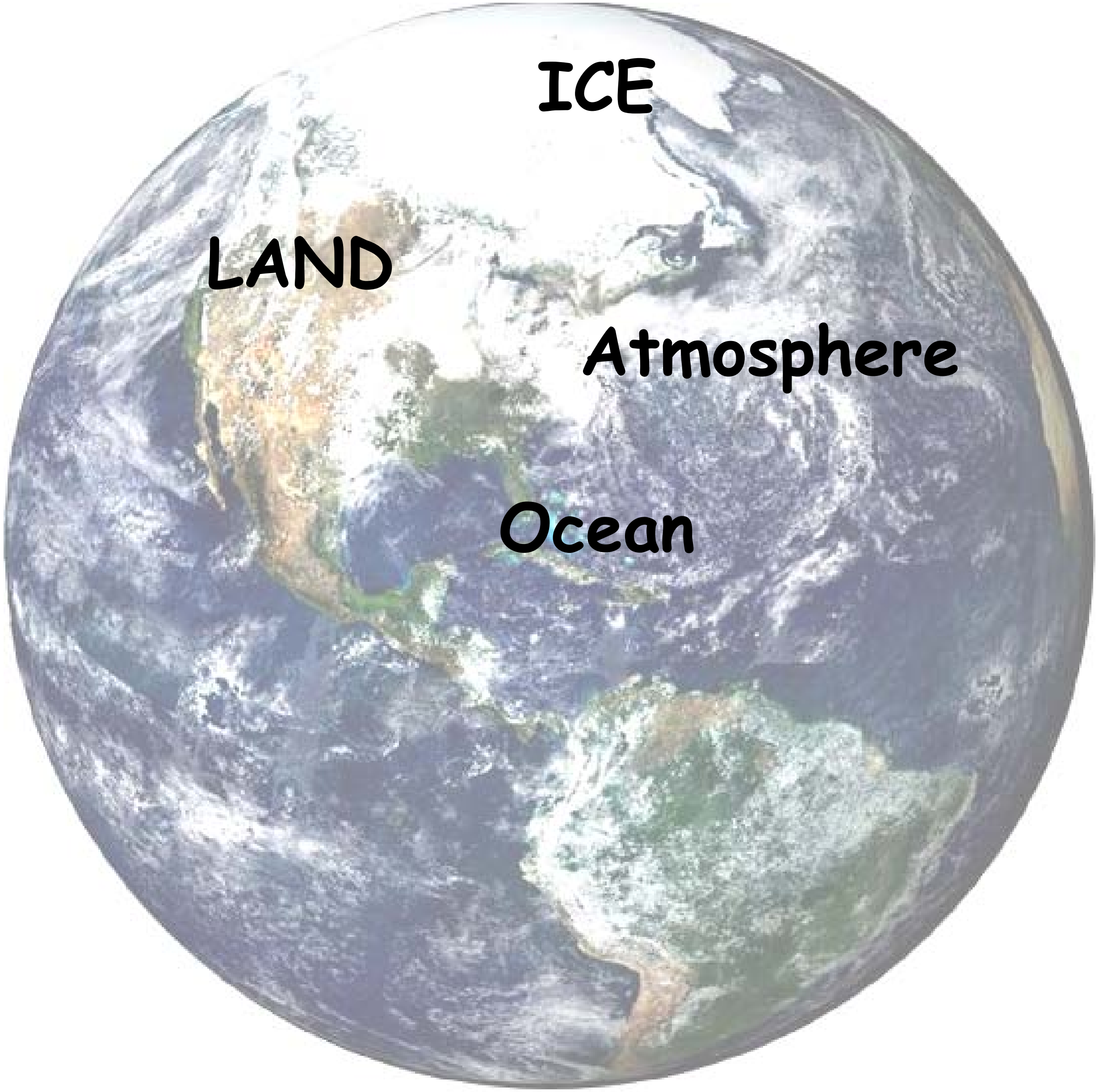


# Role of the Ocean in climate

Kevin E. Trenberth
NCAR

# The role of the climate system

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# The role of the atmosphere

- The atmosphere is the most volatile component of climate system
- Winds in jet streams exceed 100 mph or even 200 mph; winds move energy around.
- Thin envelope around planet 90% within 10 miles of surface 1/400$^{th}$ of the radius of Earth; clouds appear to hug the surface from space.
- The atmosphere does not have much heat capacity

- "Weather" occurs in troposphere (lowest part)
- Weather systems: cyclones, anticyclones, cold and warm fronts tropical storms/hurricanes move heat around: mostly **upwards** and **polewards**

# Role of Oceans

- The oceans cover 70.8% of the Earth's surface.
- The oceans are wet: water vapor from the surface provides source for rainfall and thus latent heat energy to the atmosphere.
- The heat capacity of the atmosphere is equivalent to that of 3.5 m of ocean. The oceans slowly adjust to climate changes and can sequester heat for years.
- The ocean is well mixed to about 20 m depth in summer and over 100 m in winter. An overall average of 90 m would delay climate response by 6 years.
- Total ocean: mean depth 3800 m.
- Would add delay of 230 years if rapidly mixed. In reality, the response depends on rate of ventilation of water through the thermocline (vertical mixing).
- Estimate of delay overall is 10 to 100 years.
- The ocean currents redistribute heat, fresh water, and dissolved chemicals around the globe.

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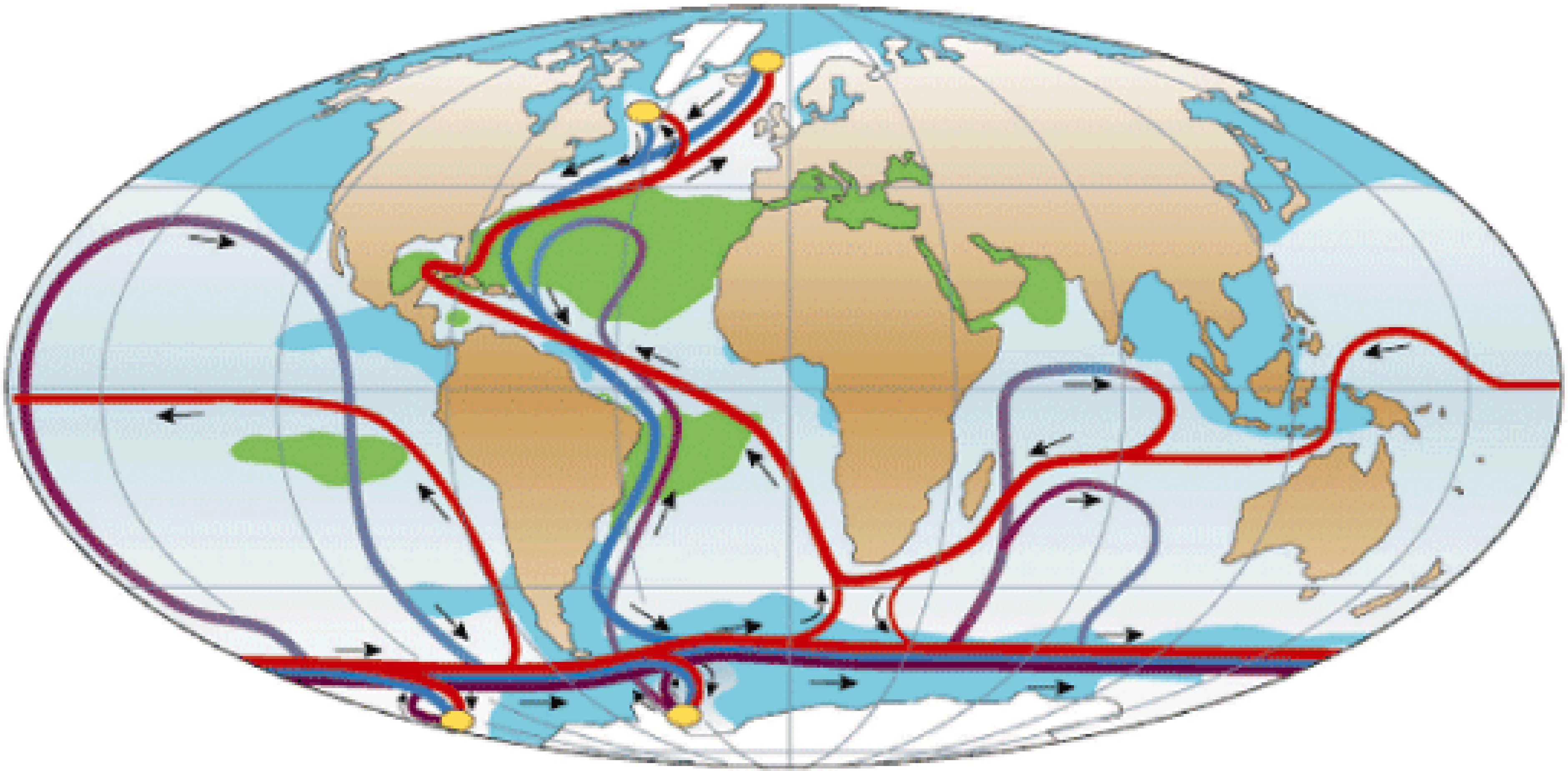
# The great ocean conveyer:
## of heat, freshwater and salts



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# Role of Land

- Heat penetration into land with annual cycle is ~2 m.
- Heat capacity of land is much less than water:
  - Specific heat of land 4½ less than sea water
  - For moist soil maybe factor of 2
- Land plays lesser role than oceans in storing heat.

**Consequently:**

- Surface air temperature changes over land are large and occur much faster than over the oceans.
- Land has enormous variety of features: topography, soils, vegetation, slopes, water capacity.
- Land systems are highly heterogeneous and on small spatial scales.
- Changes in soil moisture affect disposition of heat: rise in temperature versus evaporation.
- Changes in land and vegetation affect climate through albedo, roughness and evapotranspiration.

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# Role of Ice

Major ice sheets, e.g., Antarctica and Greenland. Penetration of heat occurs primarily through conduction.

⇒ The mass involved in changes from year to year is small but important on century time scales.

Unlike land, ice melts ⇒ changes in sea level on longer time-scales.

Ice volumes: 28,000,000 km$^3$ water is in ice sheets, ice caps and glaciers.

Most is in the Antarctic ice sheet which, if melted, would increase sea level by ~65 m, vs Greenland 7 m and the other glaciers and ice caps 0.35 m.

In Arctic: sea ice ~ 3-4 m thick

Around Antarctic: ~ 1-2 m thick

Ice is bright: reflects the solar radiat

Ice ↑ ⇒ radiation reflected ⇒ cooler

The West Antarctic Ice Sheet (WAIS

⇒ Warming could alter grounding of th
vulnerable to rapid (i.e. centuries) disin

⇒ rise in sea level of 4-6 m.

May be irreversible if collapse begins.

## Role of Coupling

# El Niño-Southern Oscillation ENSO

Some phenomena would not otherwise occur:

ENSO is a natural mode of the coupled ocean-atmosphere system

ENSO: EN (ocean) and SO (atmosphere) together:

Refers to whole cycle of warming and cooling.

ENSO events have been going on for centuries (records in corals, and in glacial ice in S. America)

ENSO arises from air-sea interactions in the tropical Pacific

El Niño: warm phase, La Niña: cold phase

EN events occur about every 3-7 years

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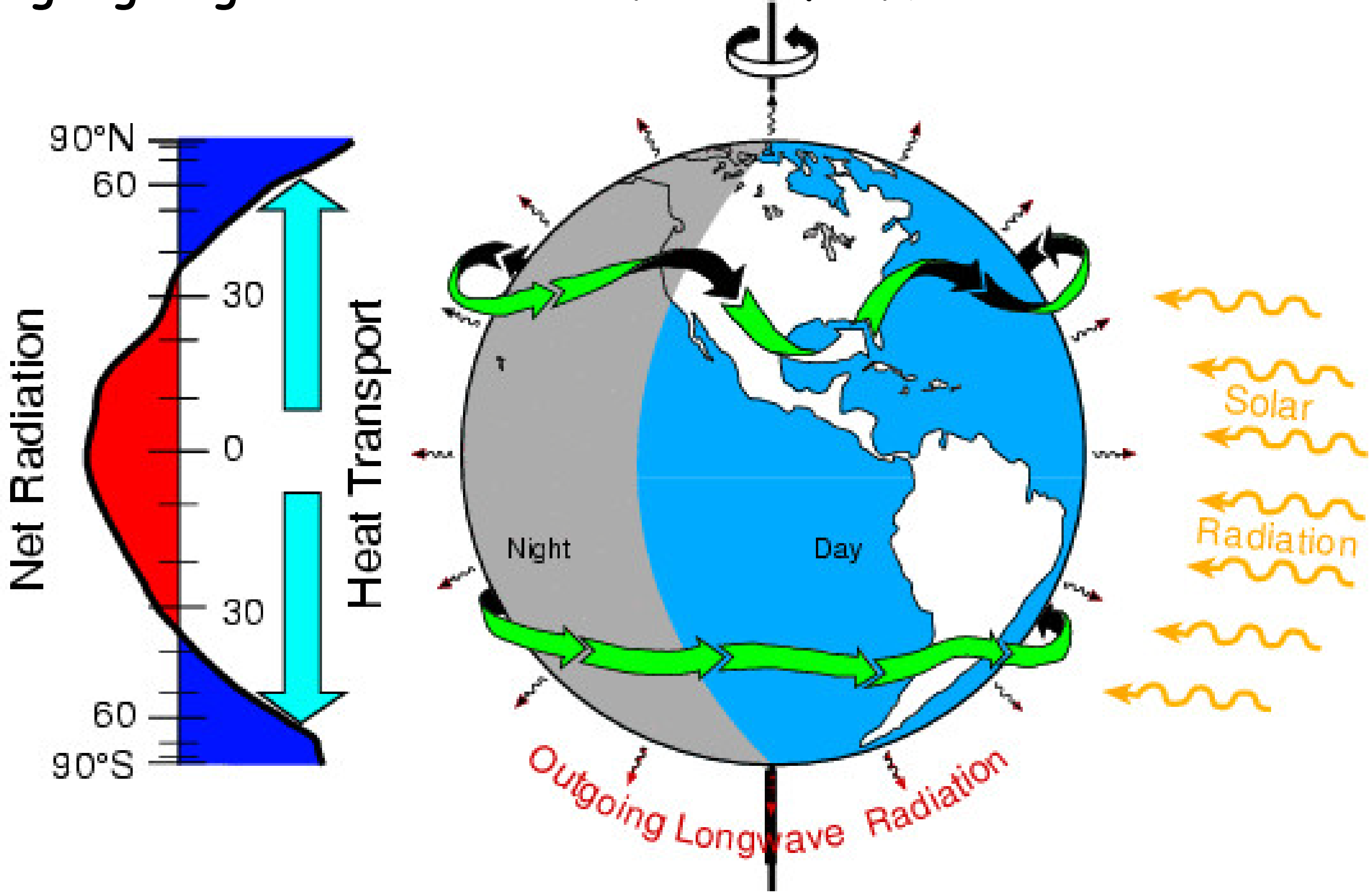
# Energy on Earth

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.



# 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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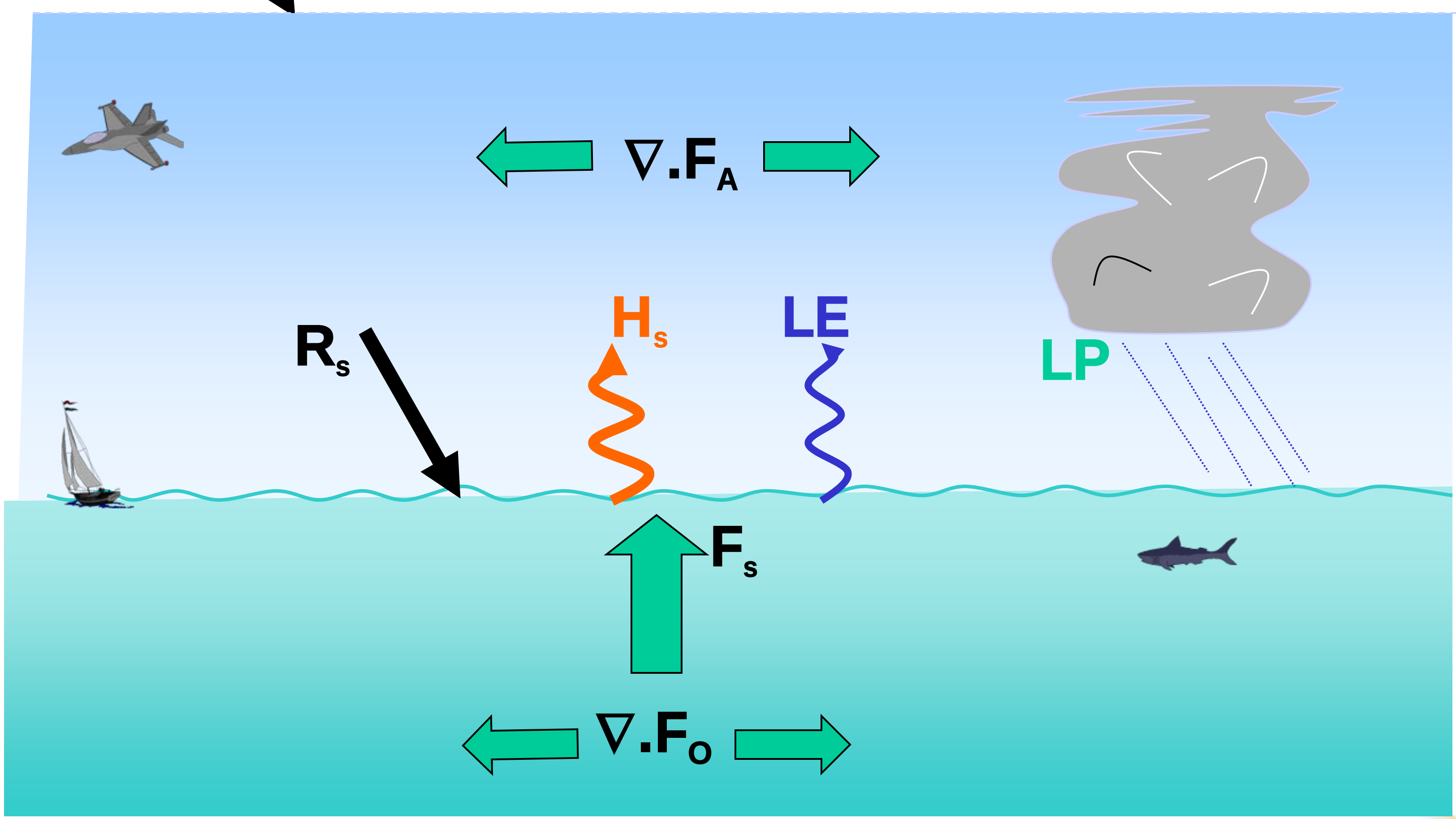
$$F_s = H_s + LE - R_s$$

$$Q_1 = R_T + F_s + L(P-E)$$

$$Q_2 = L(P-E)$$

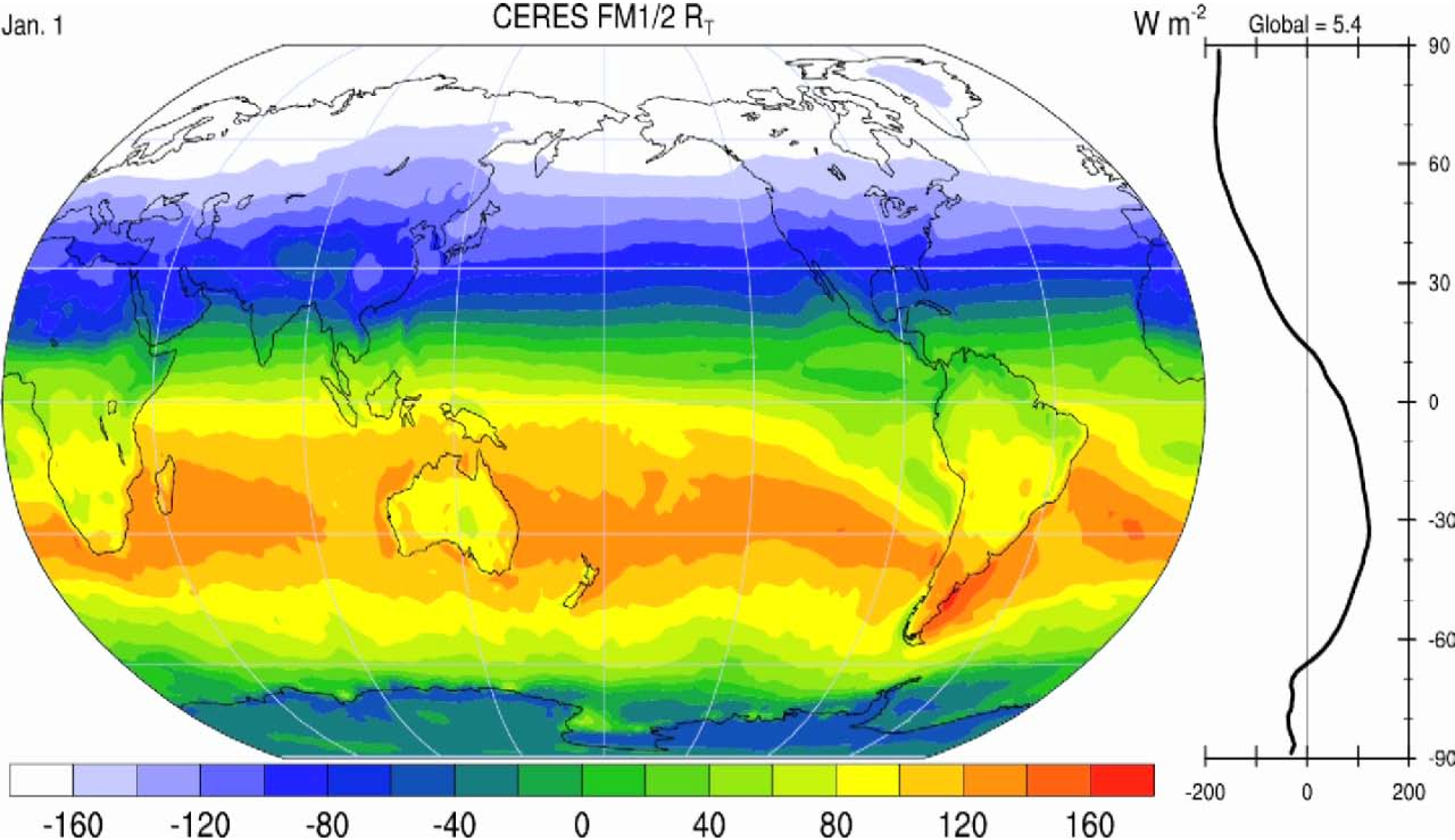
$$\nabla.F_A = Q_1 - Q_2 = R_T + F_s$$

$$= (R_T - R_s) + LE + H_s$$

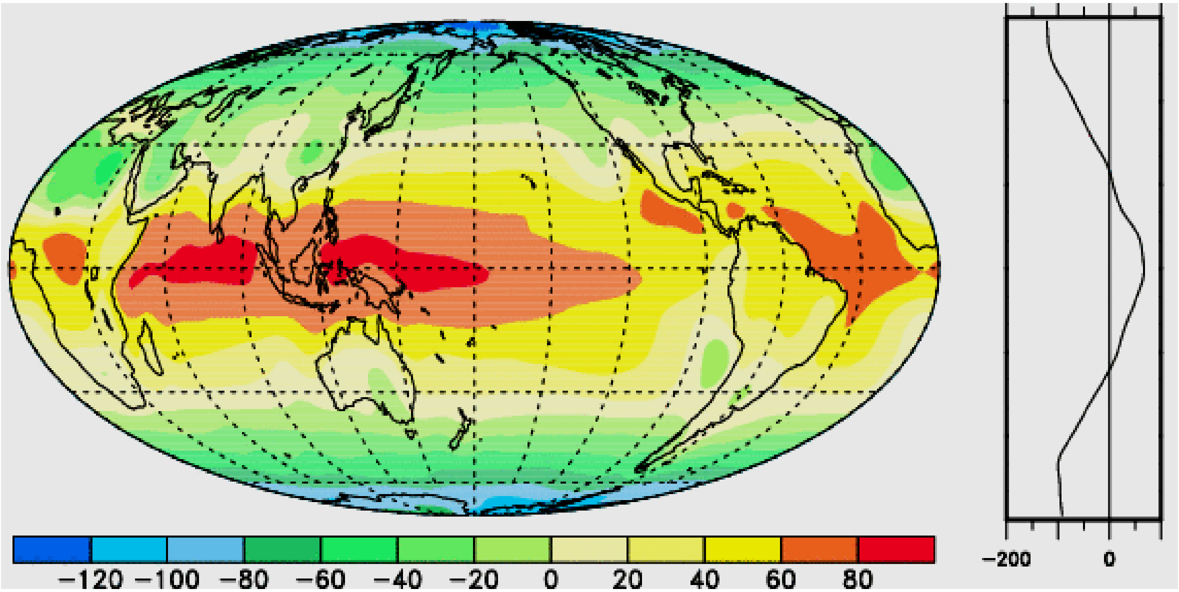



$$\nabla.F_O = - F_s$$

# Top of atmosphere net radiation



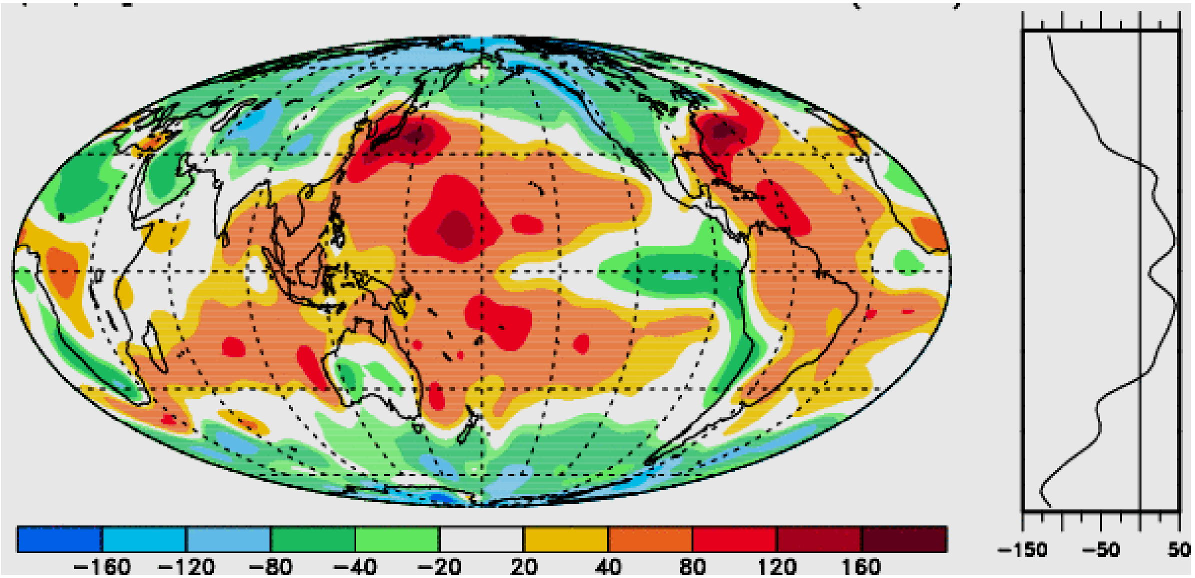
# Net Radiation TOA




Difference due to ocean transports

# Total atmos "heating" $Q_1 - Q_2$

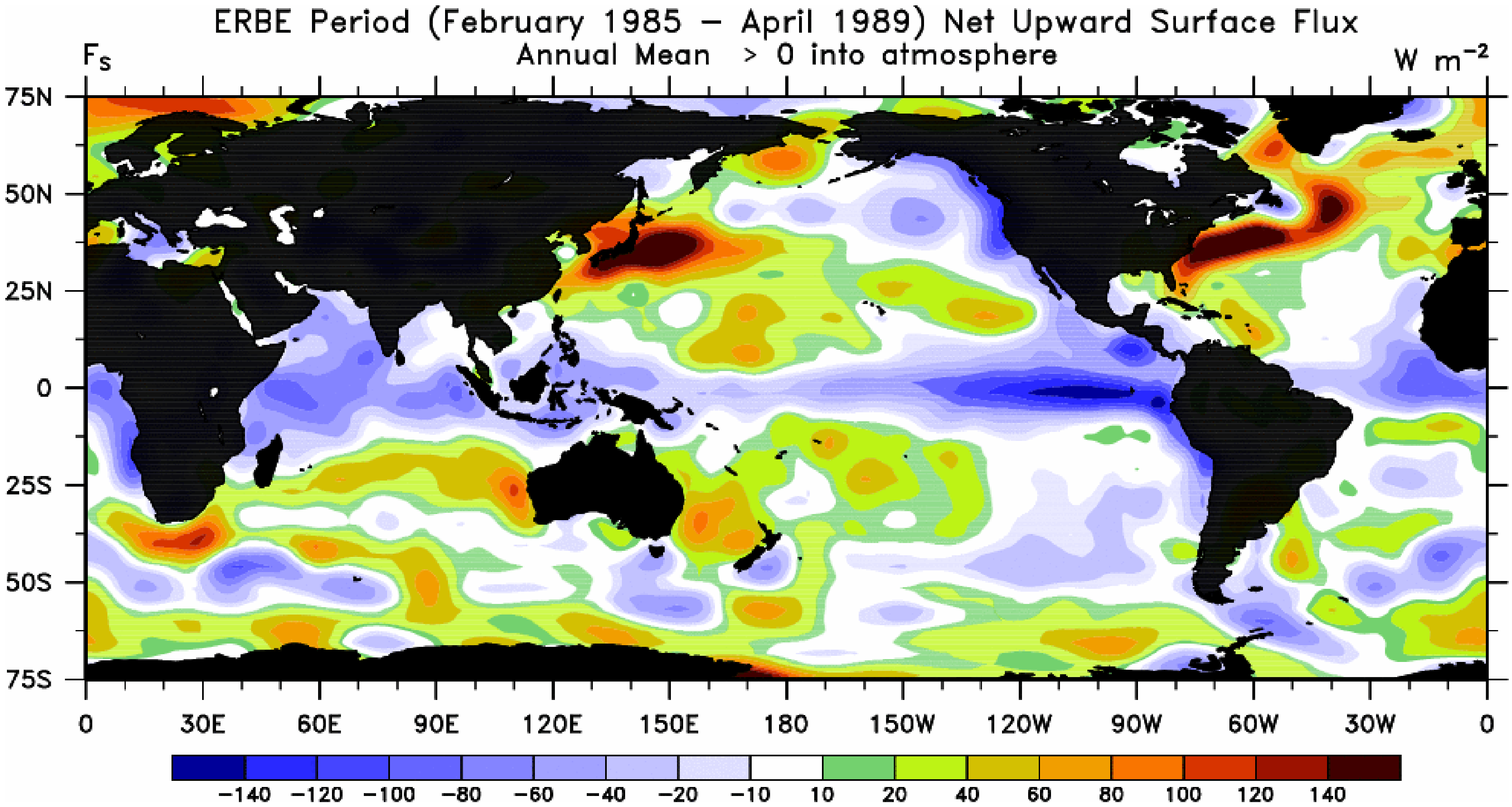
Includes moistening




Trenberth & Stepaniak, 2003

NCAR

# Annual mean net surface flux

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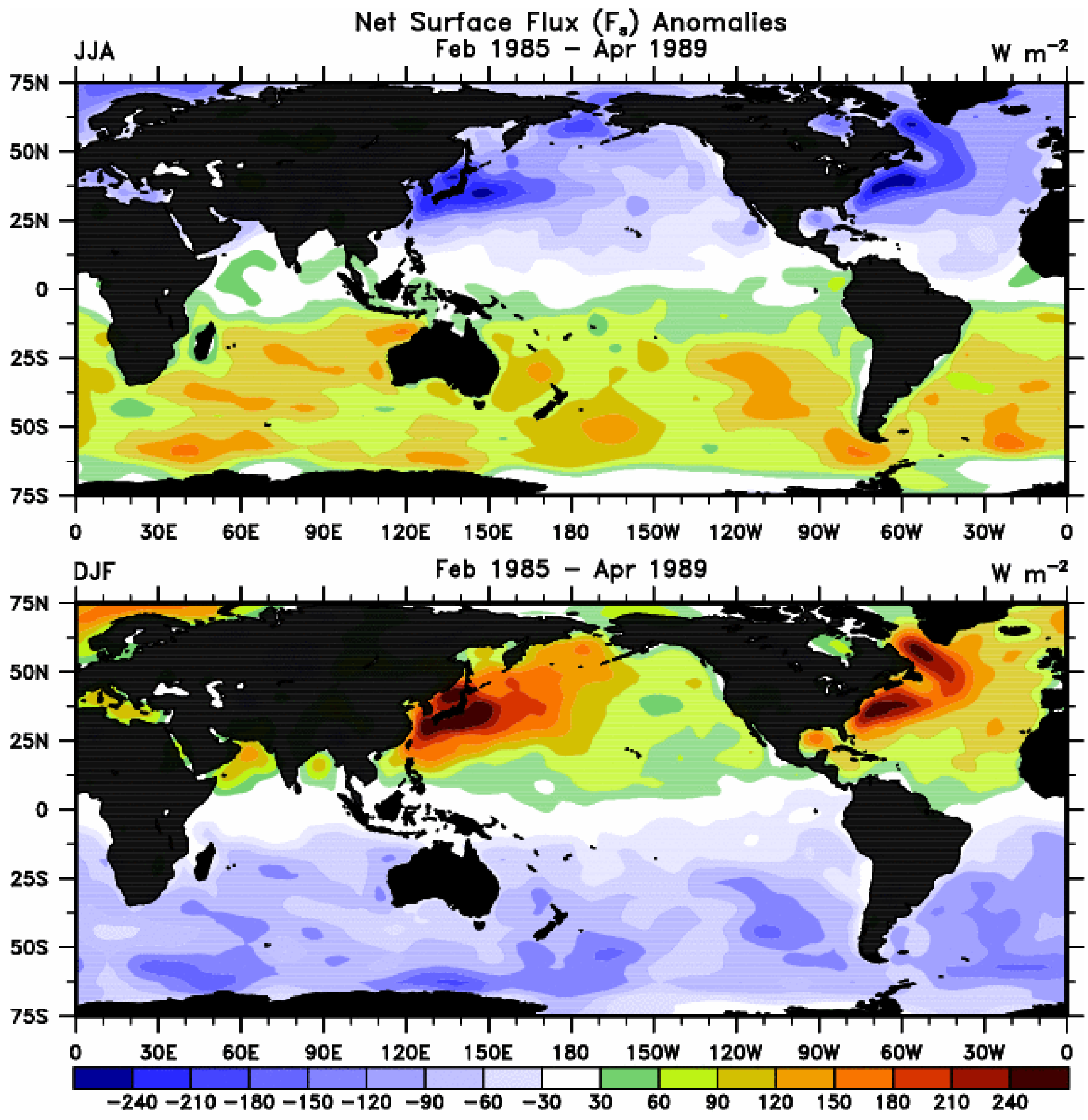


Departures from annual mean:

**Equivalent ocean heat content**

(Ignores annual cycle in ocean heat transports)

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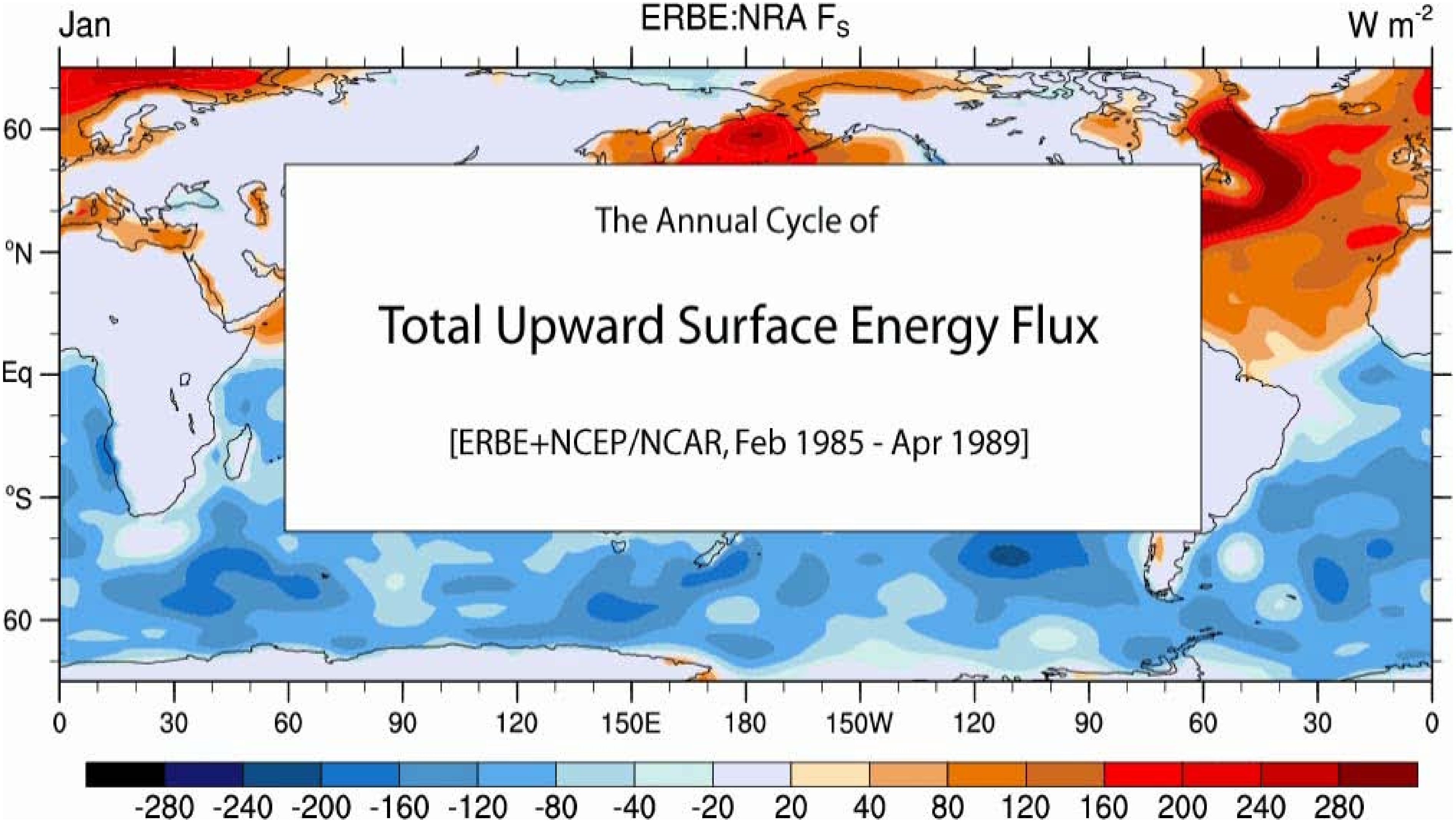
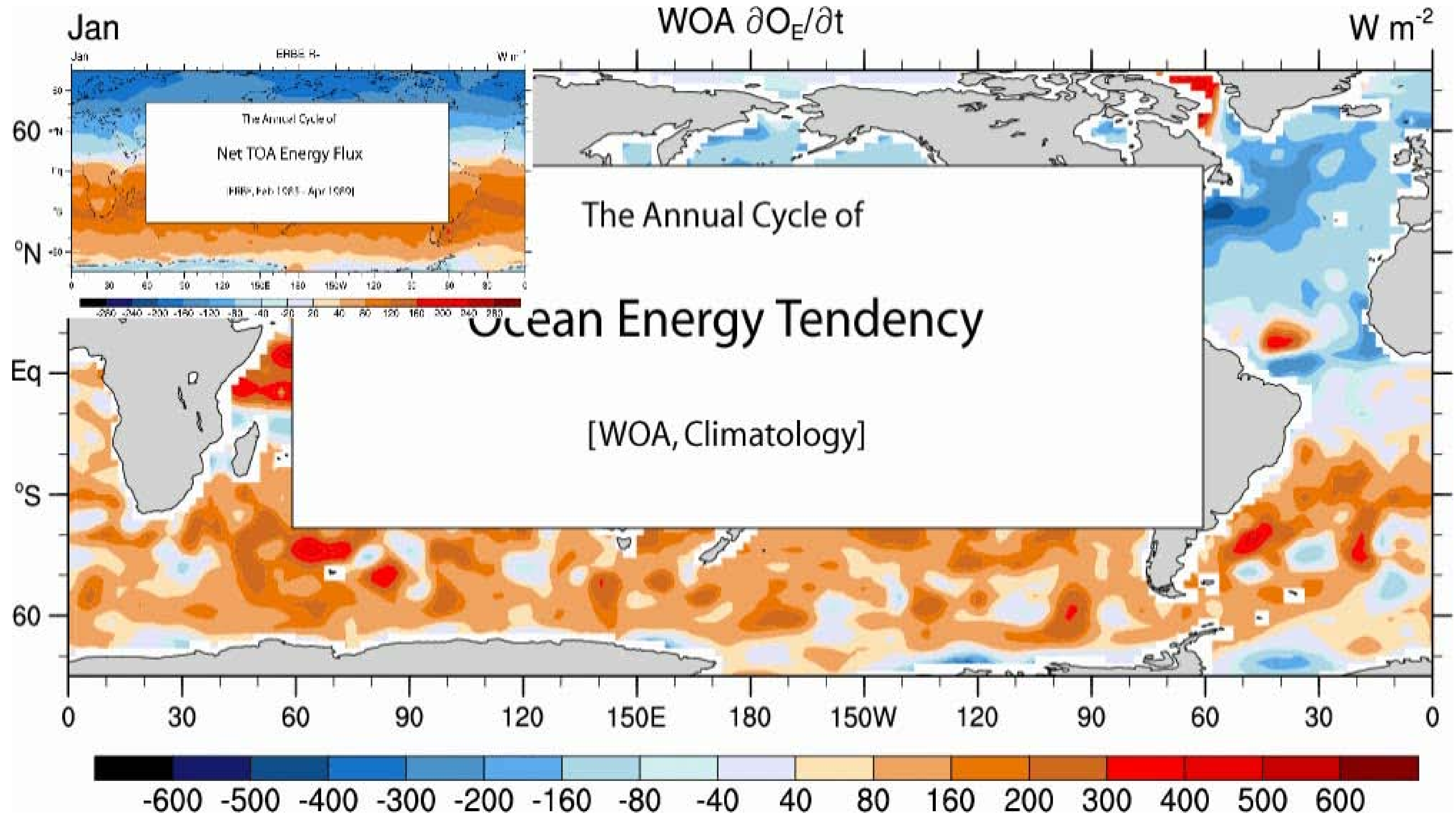
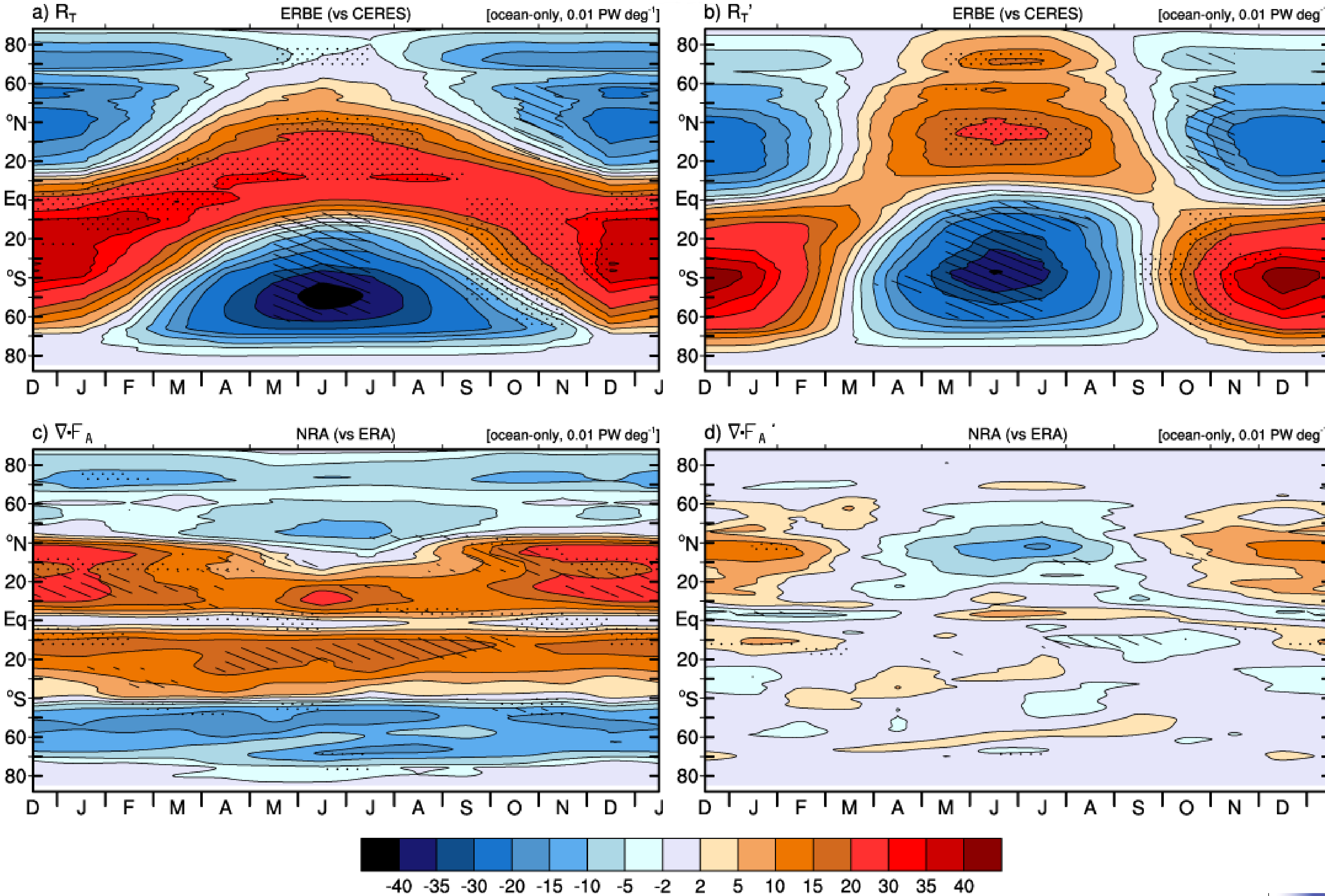


Jan
ERBE:NRA $F_S$
W $m^{-2}$
The Annual Cycle of
Total Upward Surface Energy Flux
[ERBE+NCEP/NCAR, Feb 1985 - Apr 1989]
60
°N
Eq
°S
60
0
30
60
90
120
150E
180
150W
120
90
60
30
0
-280
-240
-200
-160
-120
-80
-40
-20
20
40
80
120
160
200
240
280



Jan
WOA ∂O_E/∂t
W m-2
The Annual Cycle of
Ocean Energy Tendency
[WOA, Climatology]
The Annual Cycle of
Net TOA Energy Flux
60 °N
Eq
60 °S
0 30 60 90 120 150E 180 150W 120 90 60 30 0
-600 -500 -400 -300 -200 -160 -80 -40 40 80 160 200 300 400 500 600

# Ocean only

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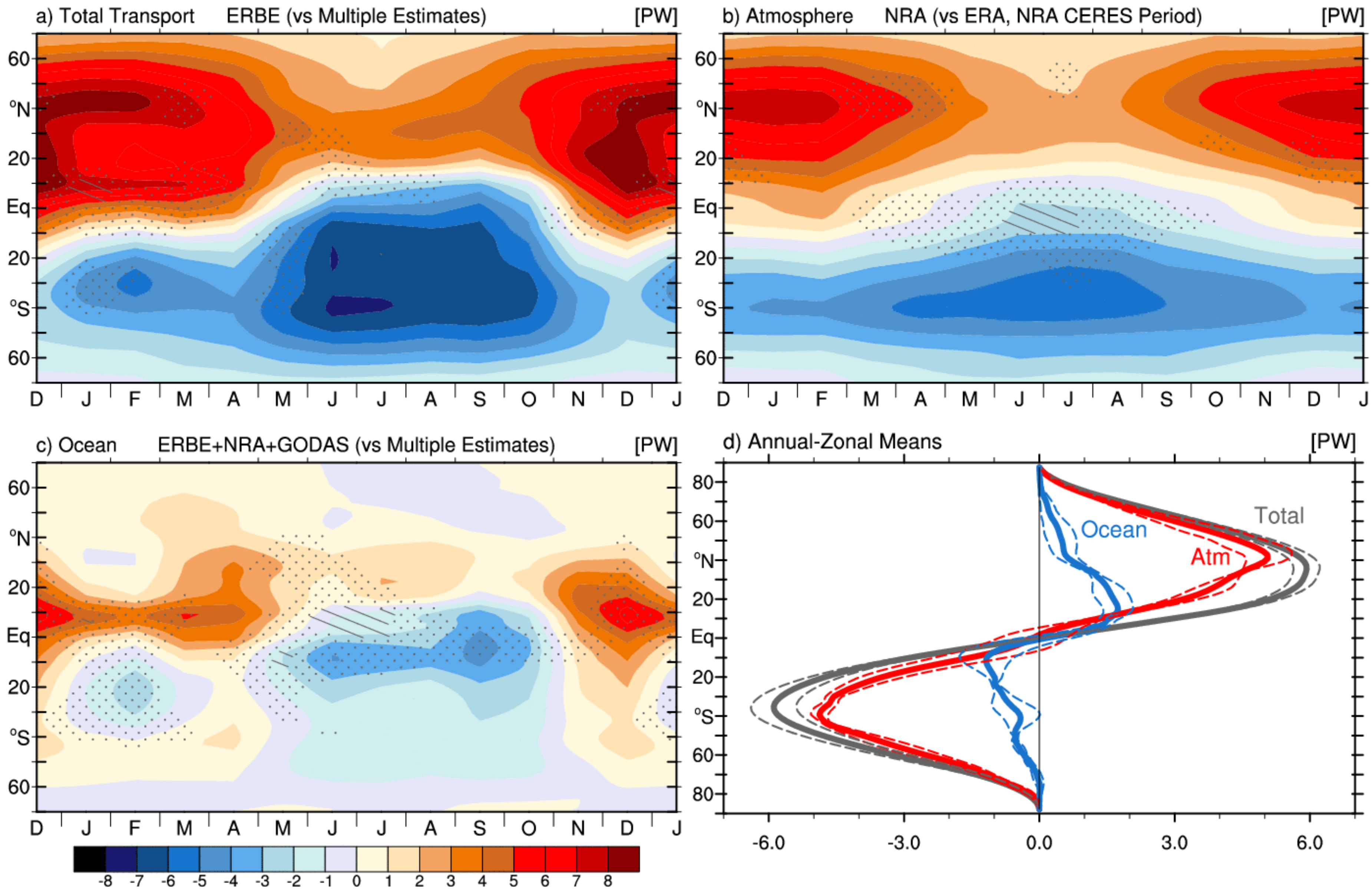


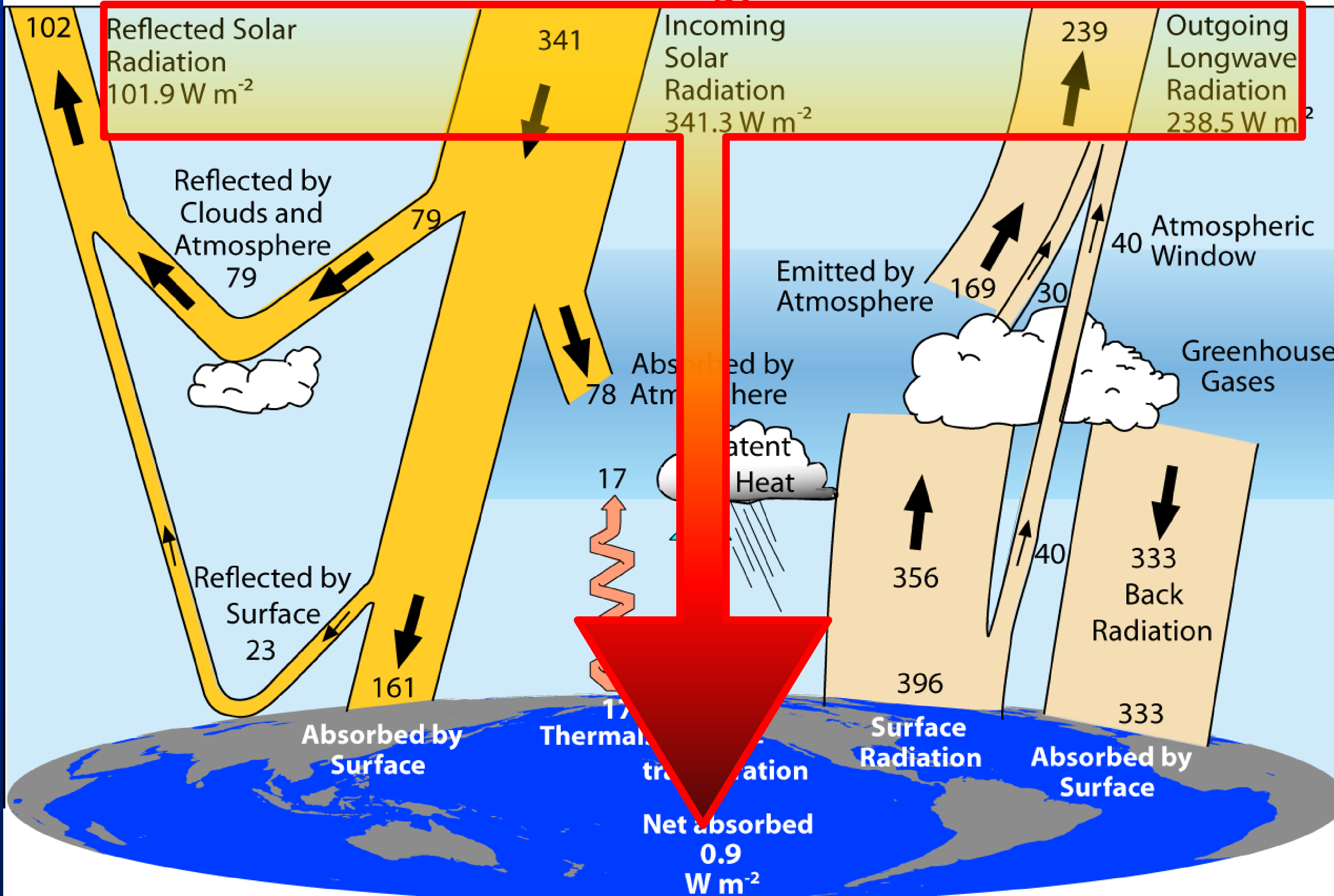

# ERBE-period meridional energy transport

NCAR

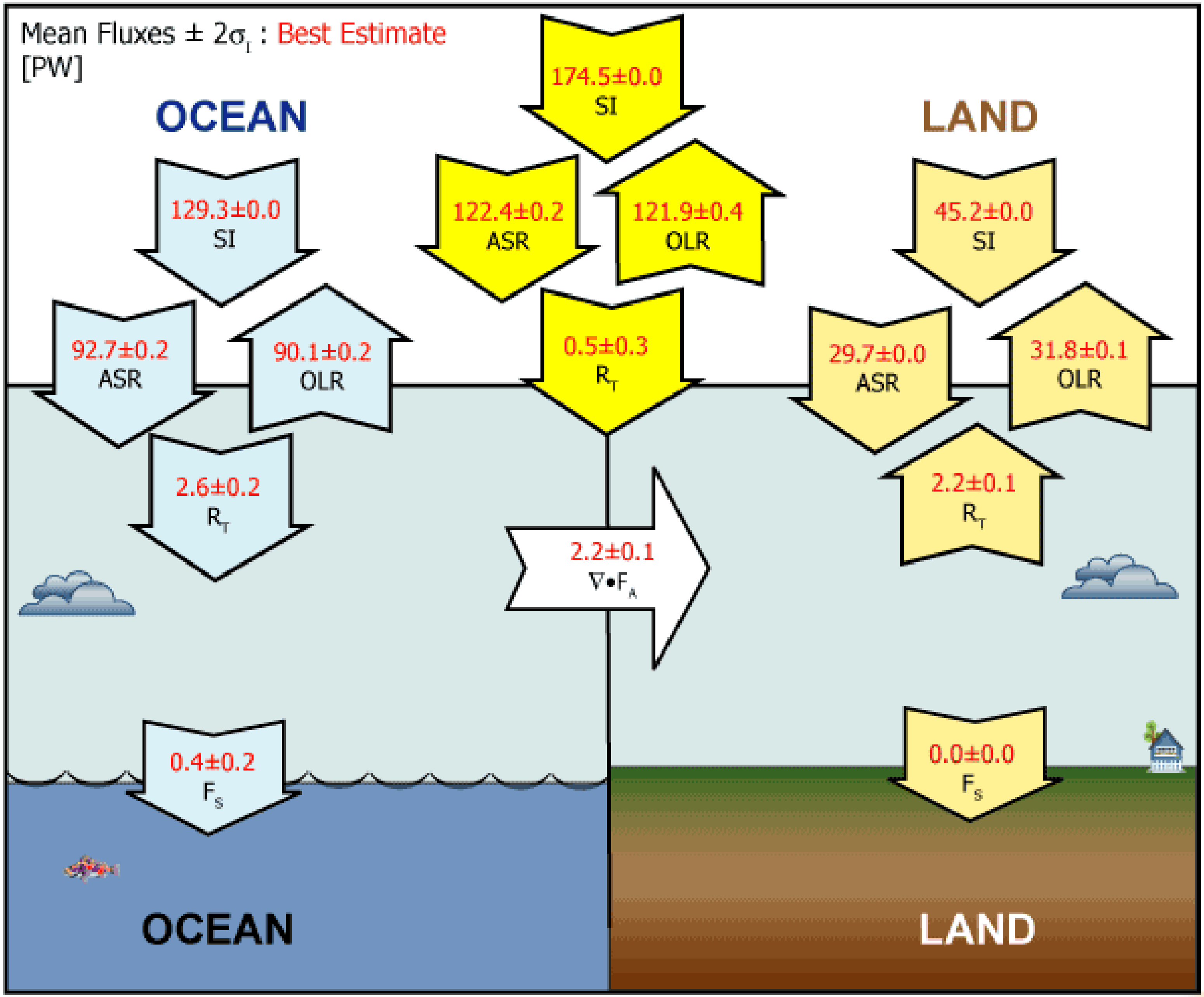
# The changing climate

NCAR

# Global Energy Flows W m$^{-2}$




Trenberth et al 2009




CERES period March 2000 to May 2004

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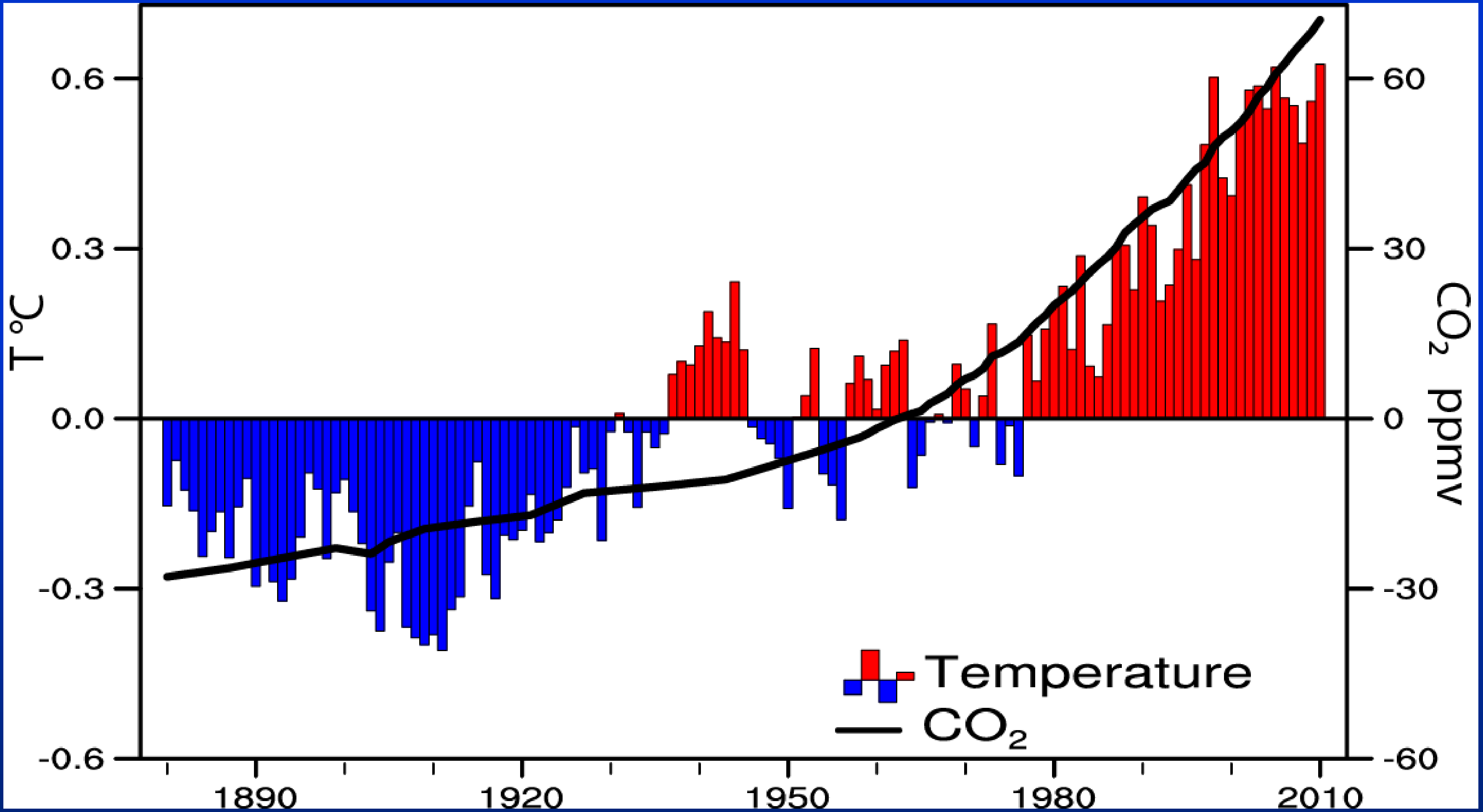
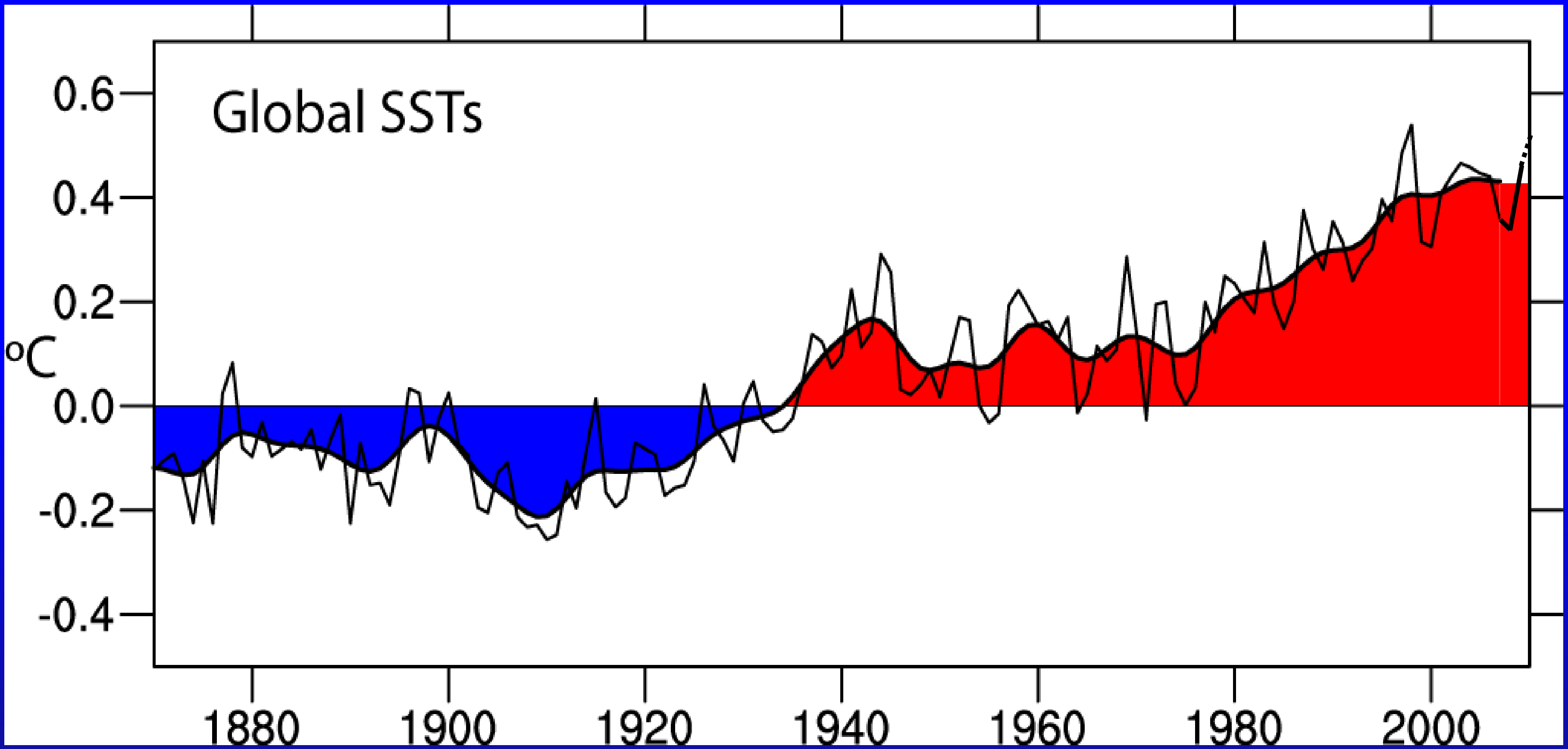
# Global temperature and carbon dioxide: anomalies through 2010



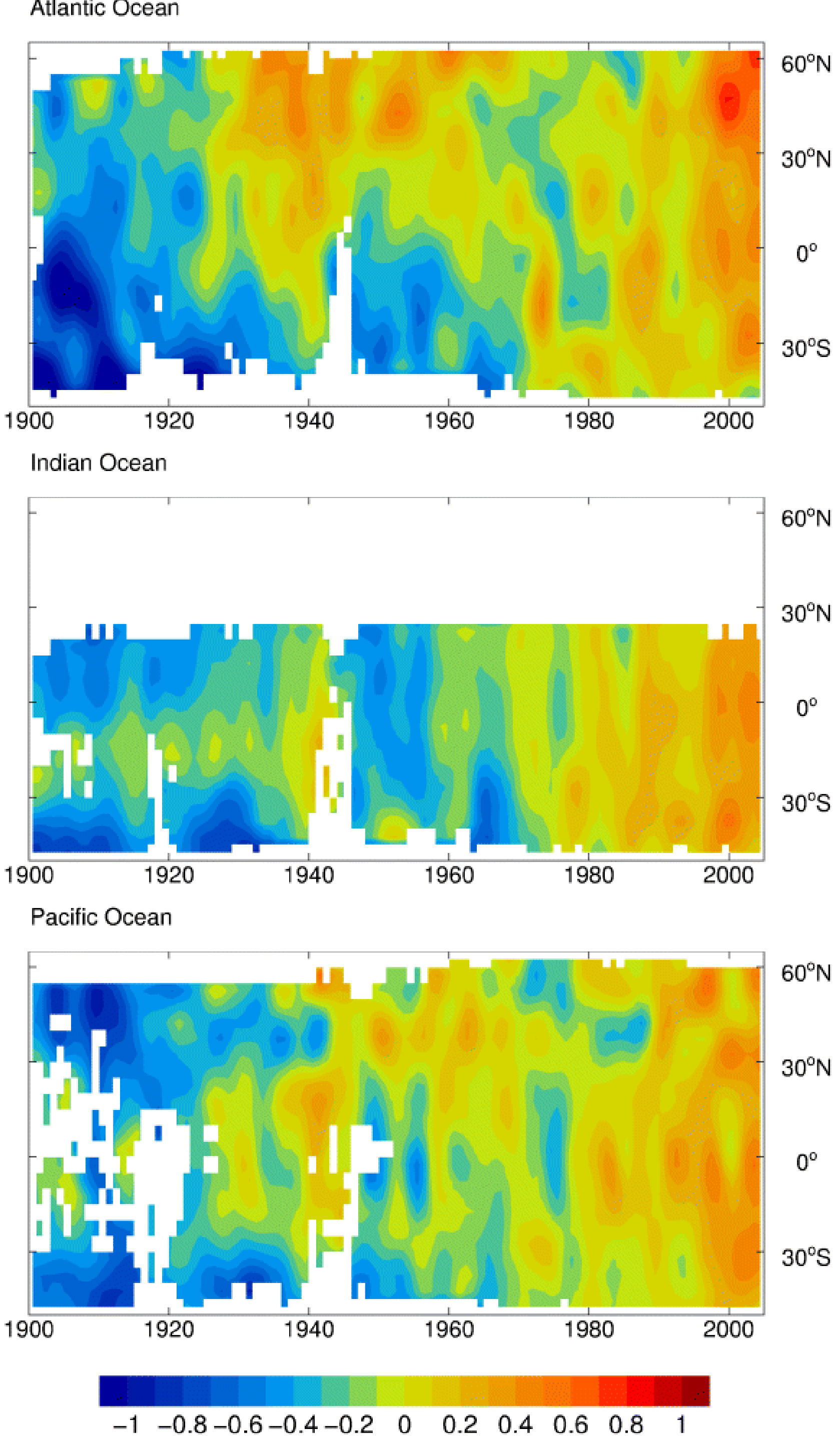

Base period 1900-99; data from NOAA

IPCC

# Global SSTs are increasing: base period 1901-70




Through 2009
Data: Hadley Centre, UK




**Changes in SSTs** zonally averaged relative to 1961-90

Atlantic: N vs S

Indian: Steady warming

Pacific: tropics leads (ENSO, PDO)

Deg C

NCAR

# Global increases in SST are not uniform. Why?

- Tropical Indian Ocean has warmed to be competitive as warmest part of global ocean.
- Tropical Pacific gets relief from global warming owing to ENSO?
- Atlantic has MOC/THC

The historical patterns of SST are NOT well simulated by coupled models!

Relates to ocean uptake of heat and ocean heat content.

The result is an imprint on global weather patterns:

NCAR

# Ocean heat content and sea level

Global warming from increasing greenhouse gases creates an imbalance in radiation at the Top-Of-Atmosphere: now order 0.9 W $m^{-2}$.

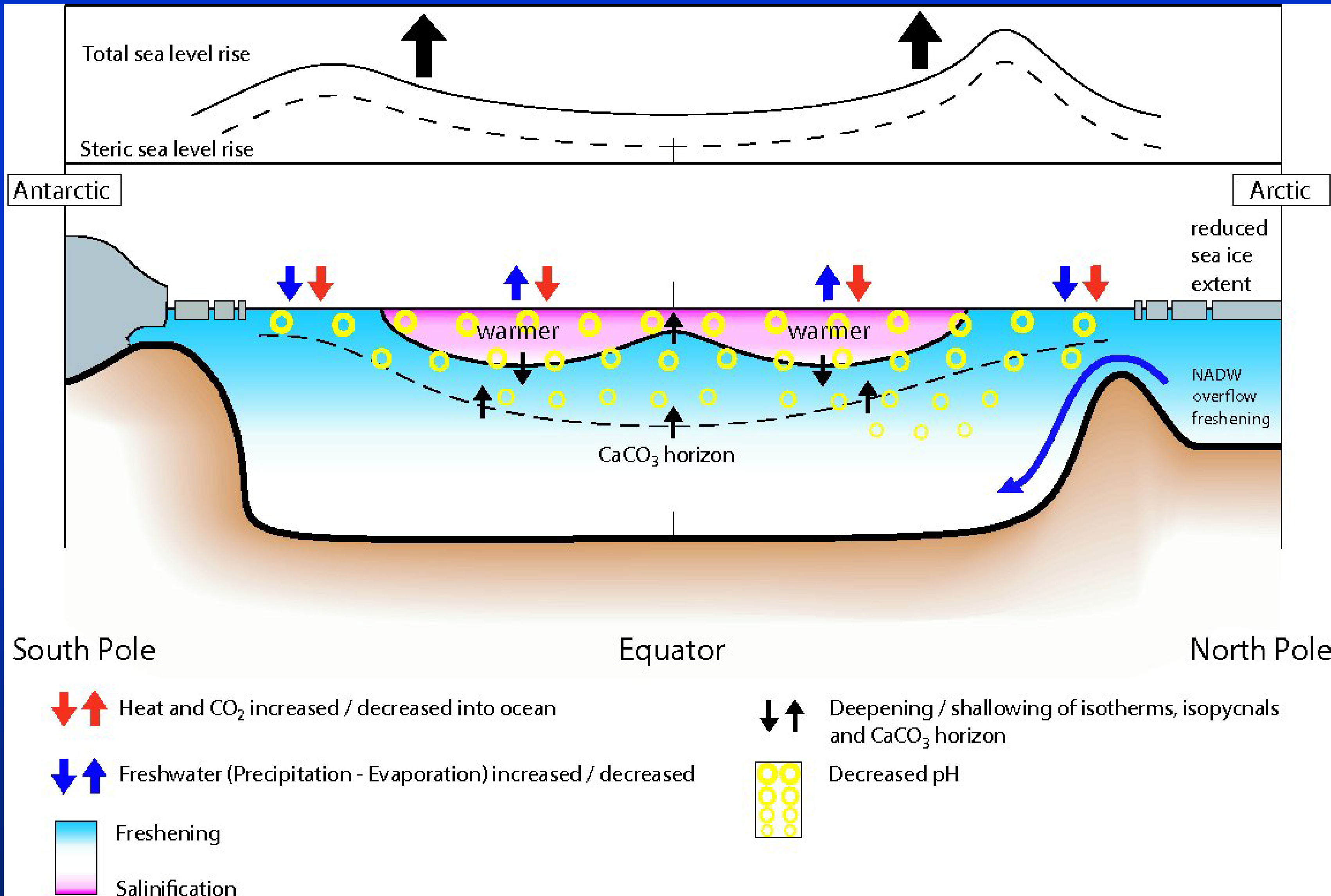
**Where does this heat go?**

**Main sink is ocean: thermosteric sea level rise associated with increasing ocean heat content.**
**Some melts sea ice: no change in SL**
**Some melts land ice.**

SL increases much more per unit of energy from land-ice melt: ratio about 30 to 90 to 1.
**Sea-ice melt does not change sea level.**

# Changes in ocean state

from 1950-1960's to 1990-2000's (IPCC 2007 Figure 5.18)

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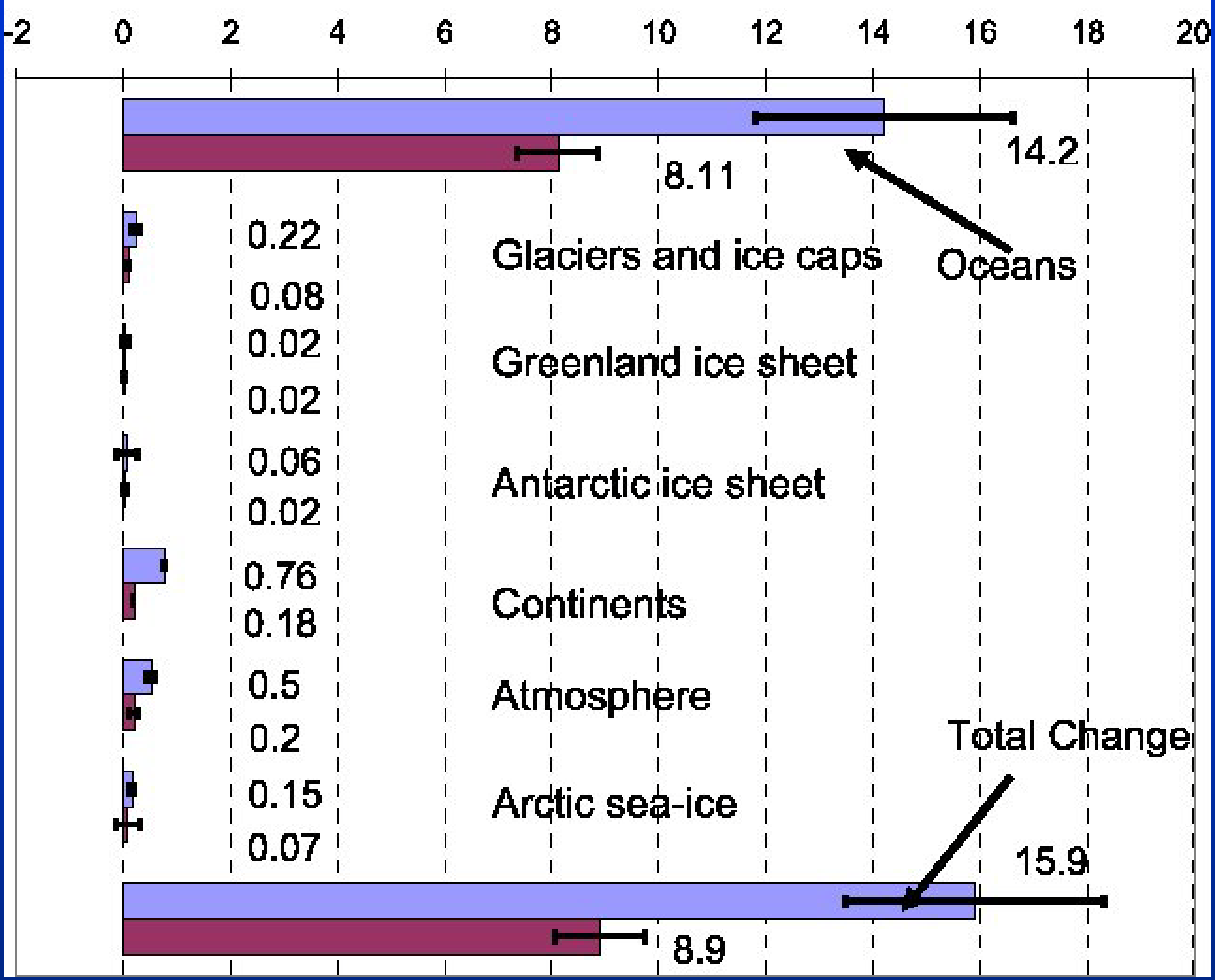
# Energy content change $10^{22}$ J

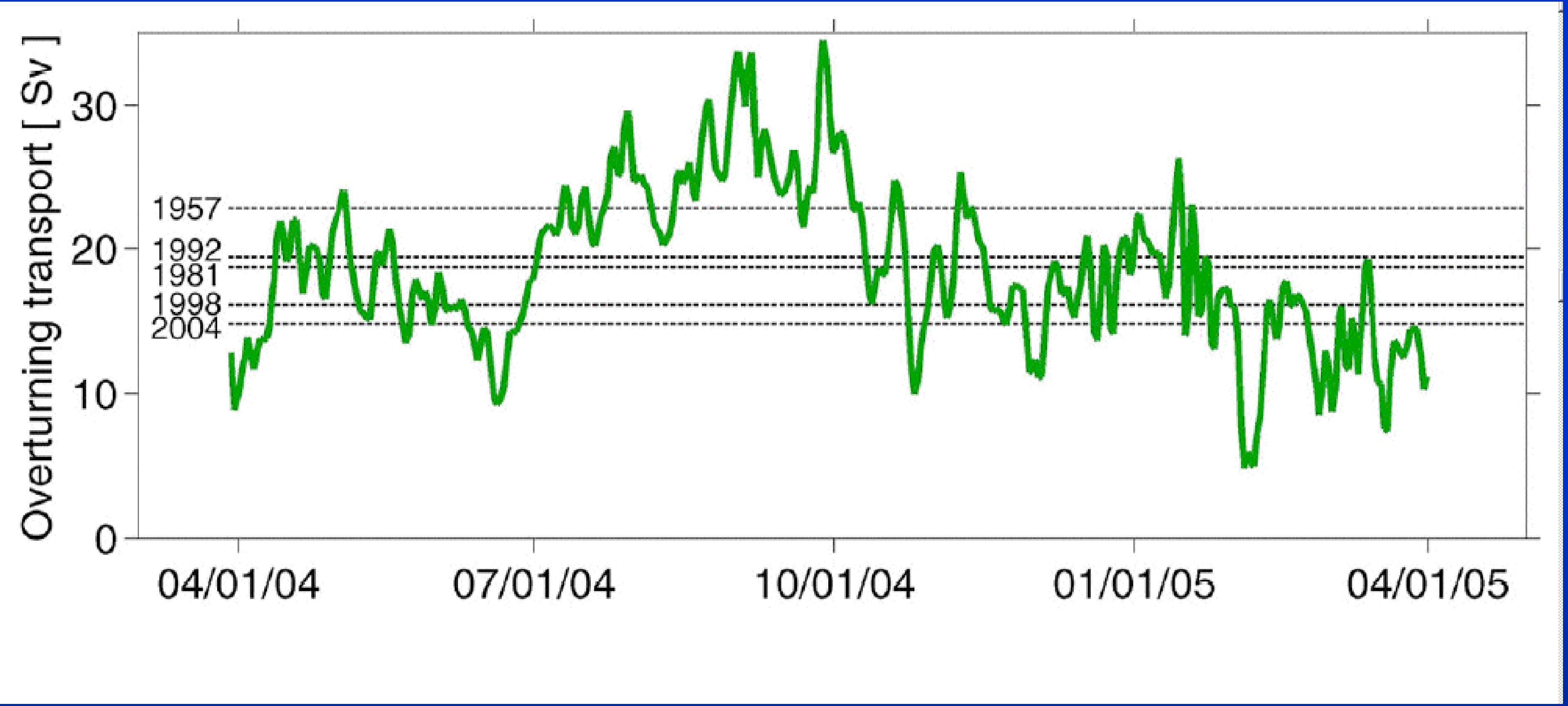



1961-2003 (Blue bars)

1993-2003 (Burgundy bars)

Figure 5.4
IPCC AR4

# AMOC: Sampling Issues



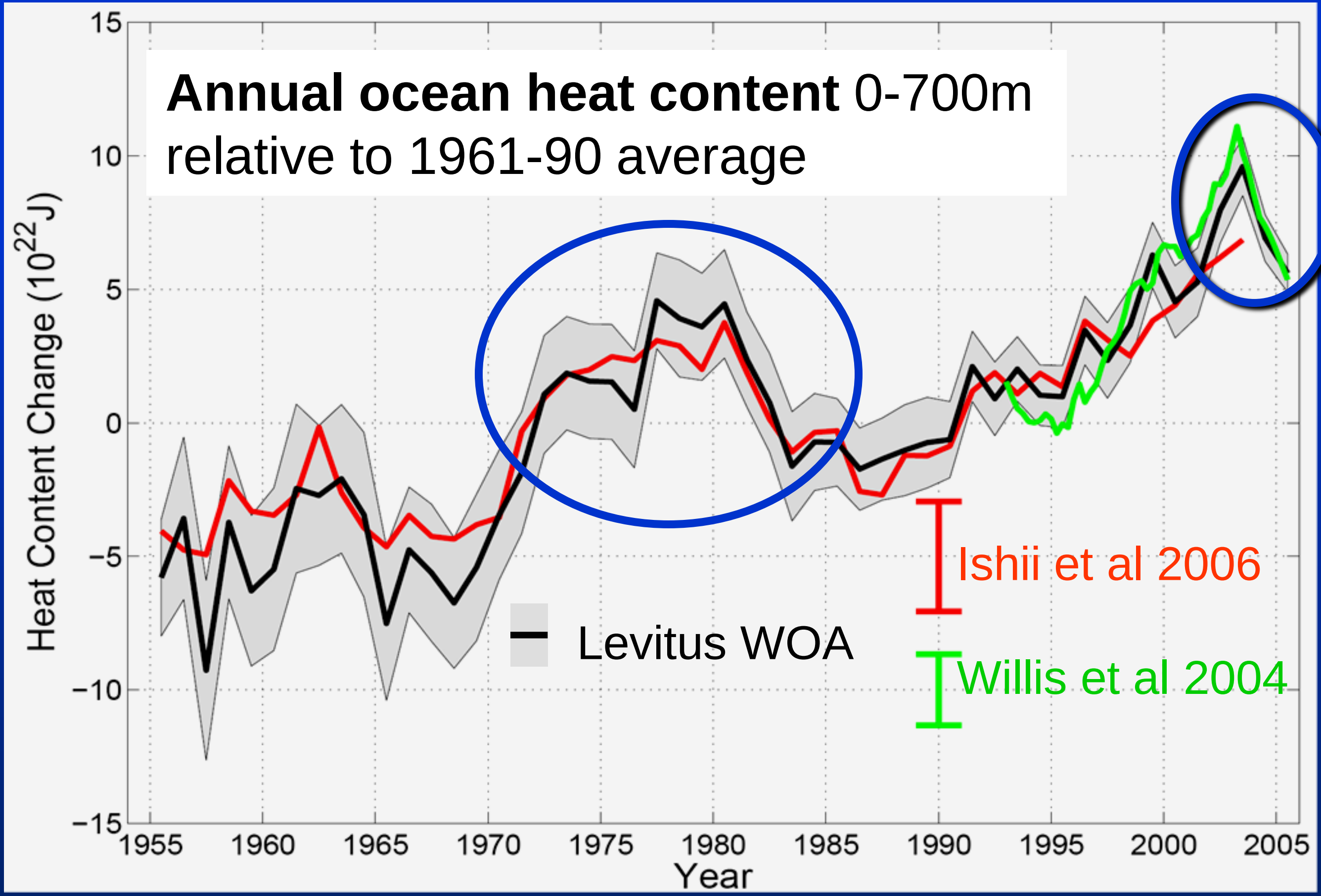

The overturning transport 26.5N above 1000 m (green line), and the five snapshot estimates from hydrographic sections by Bryden et al., (2005). All time series have been smoothed with a three-day low pass filter. As modified from Baringer and Meinen (2008).

# Is ocean warming accelerating?

**IPCC: Causes of decadal variability not well understood**

- cooling due to volcanism?
- artefact due to temporally changing observing system?

→ **No statement on acceleration possible in AR4**



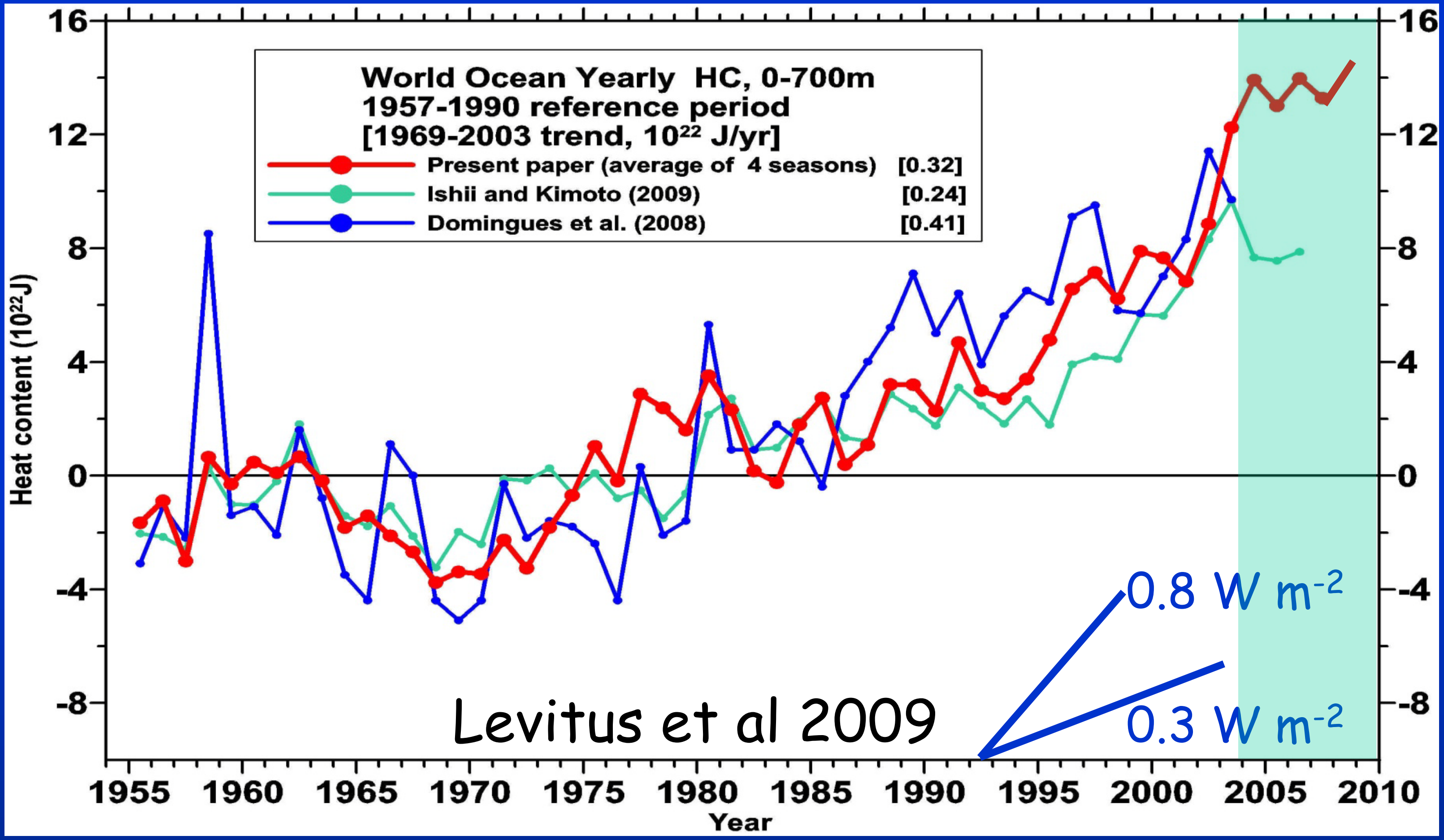

Since then:

Argo problems

XBT drop rate problems

identified

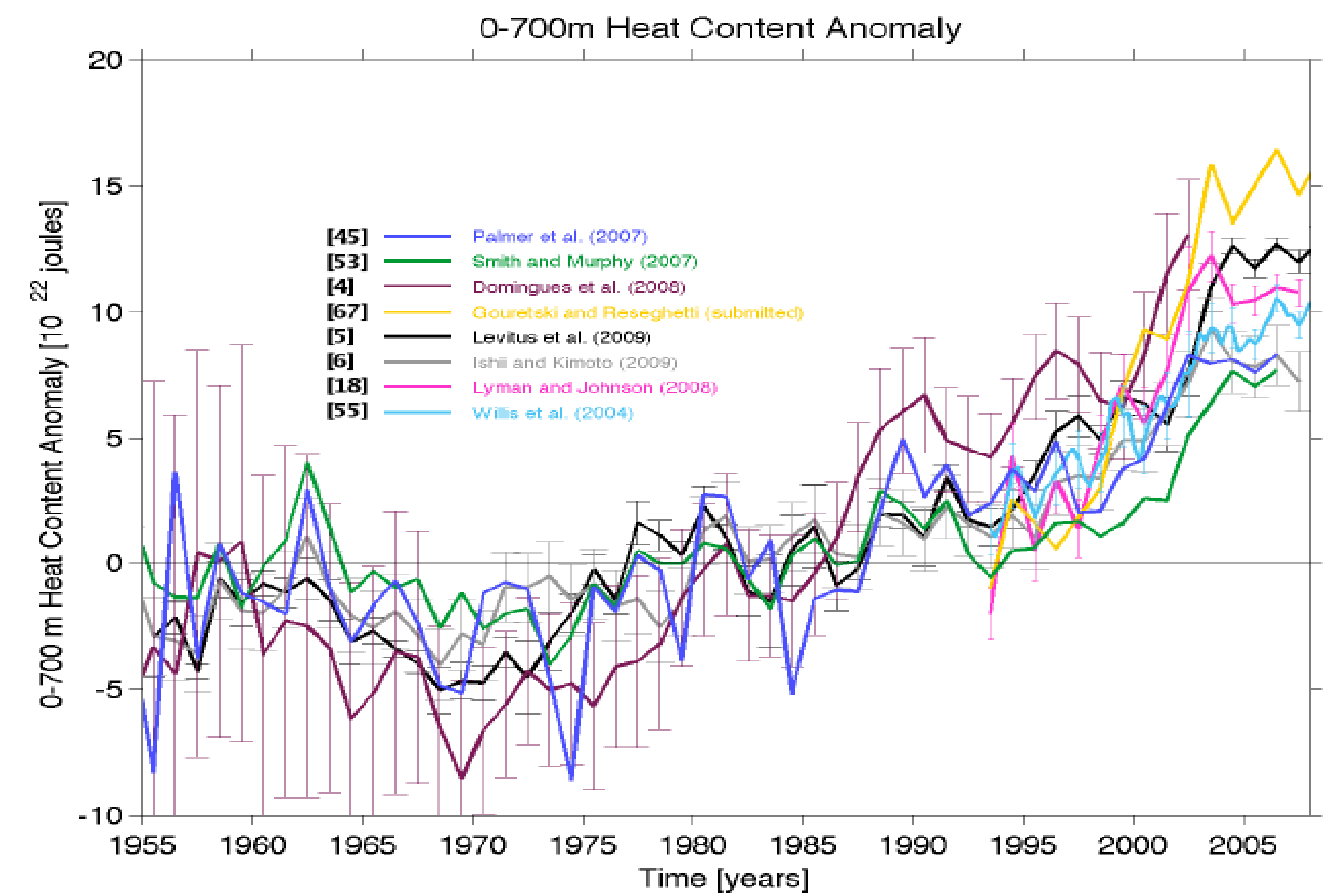
# Revised ocean heat content




Yearly time series of ocean heat content ($10^{22}$ J) for the 0-700 m layer from Levitus et al (2009), Domingues et al. (2008) and Ishii and Kimoto (2009) with a base period of 1957-1990. Linear trends for each series for 1969-2007 given in the upper portion of the figure.

IPCC

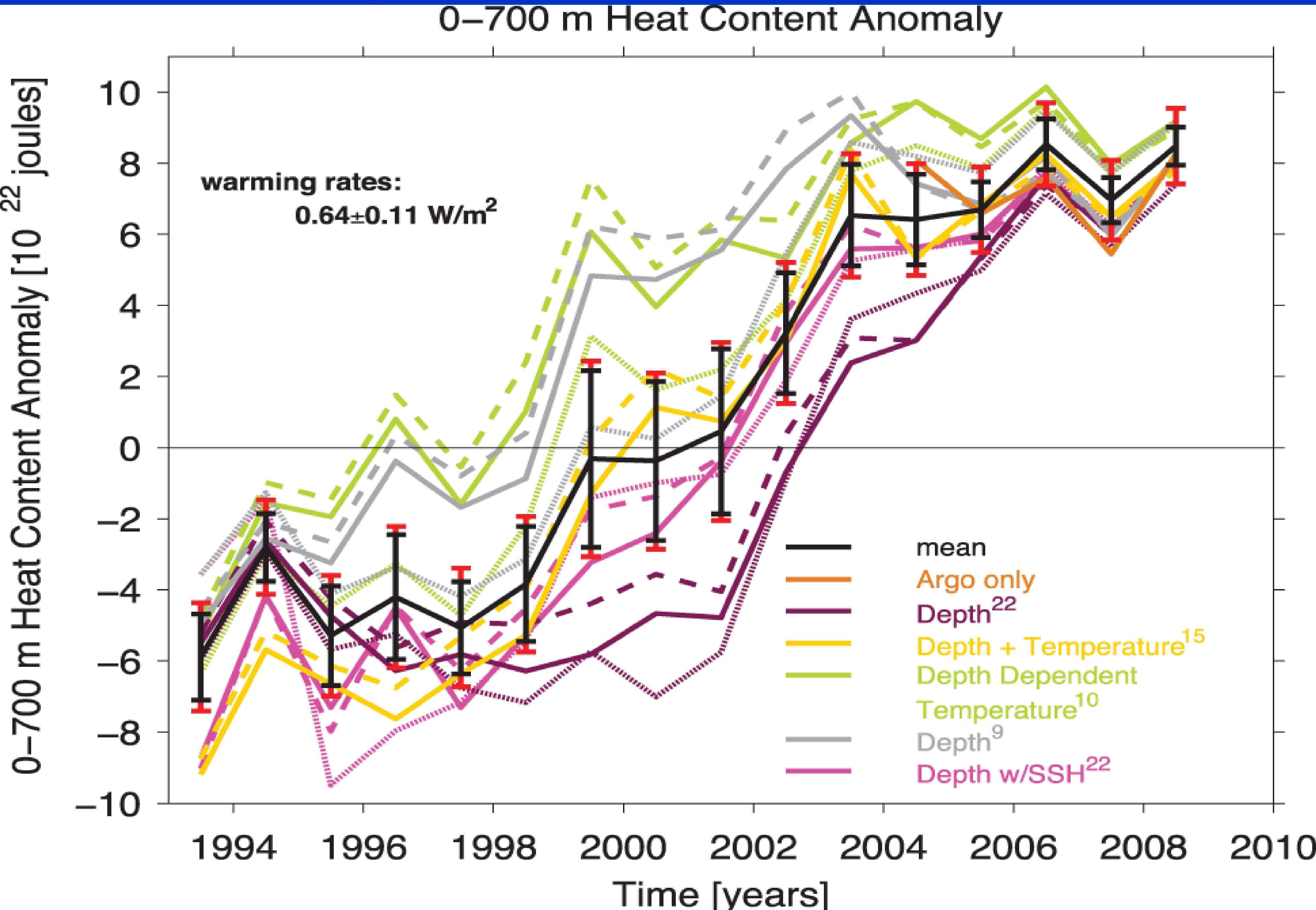
# Ocean heat content to 700 m



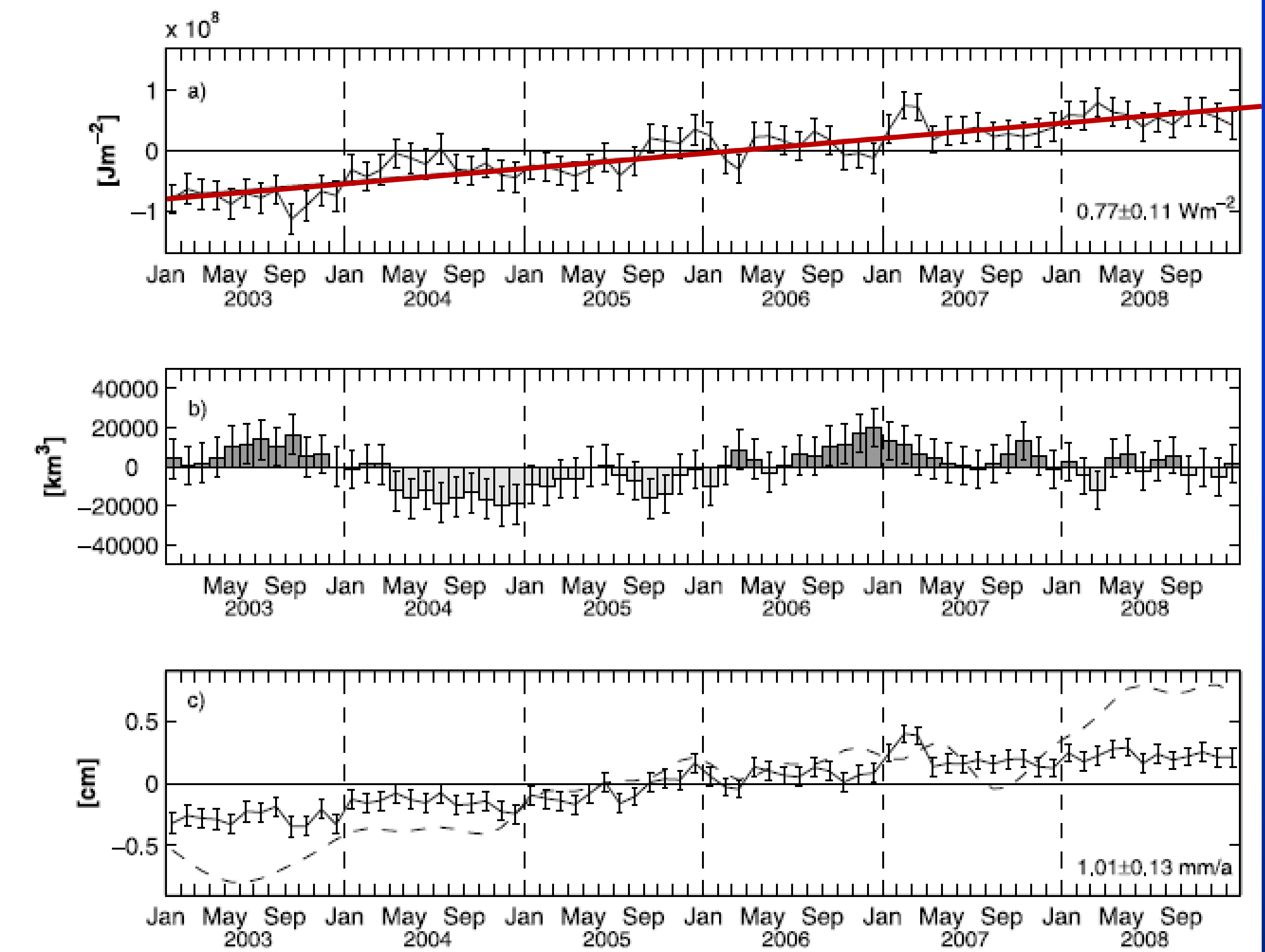

Palmer et al OceanObs'09

IPCC

# Lyman et al 2010 Nature



# Ocean heat content 0-2000m




OHC
0.77 W $m^{-2}$
gl ocean
0.54 W $m^{-2}$
Global

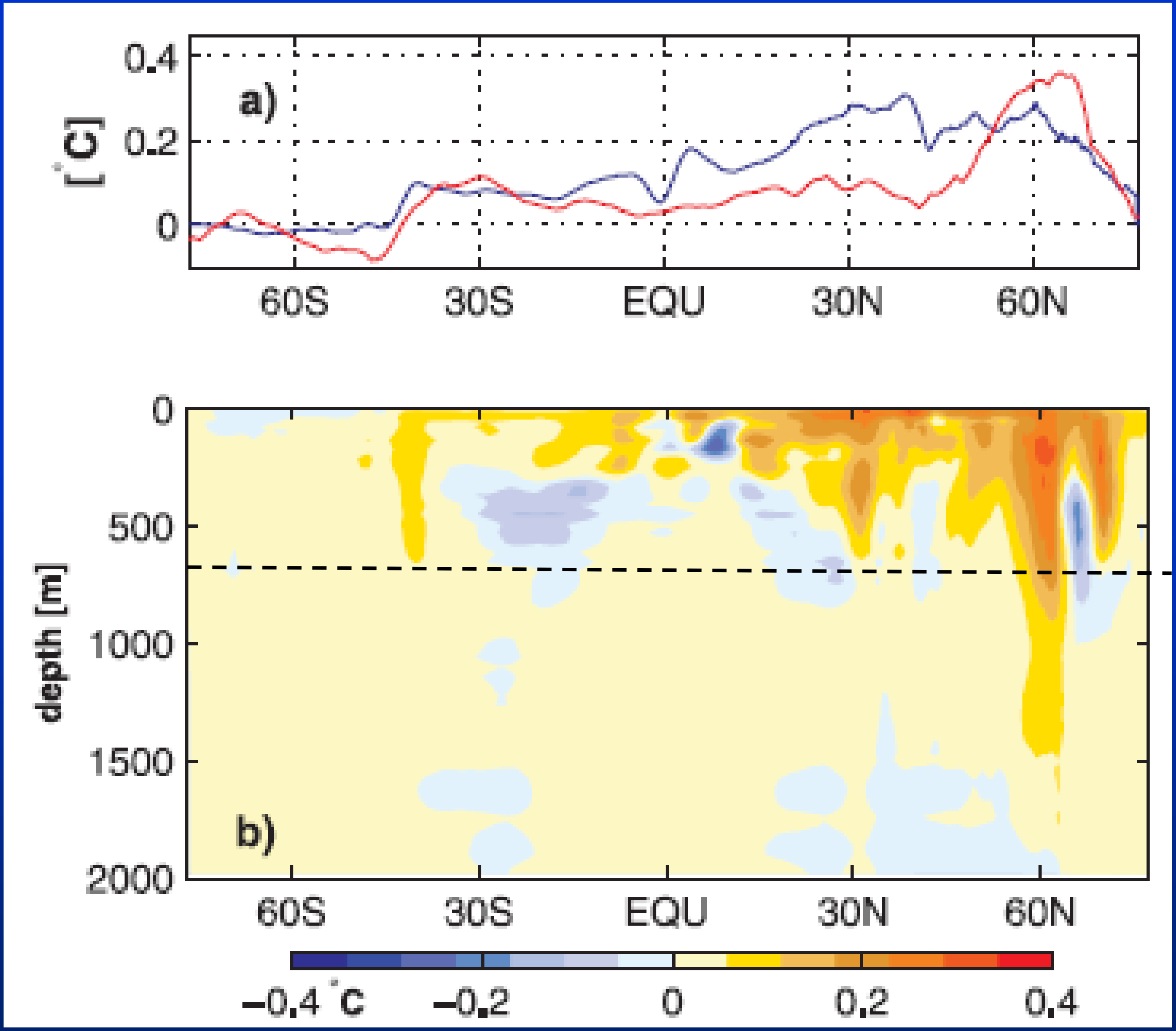
Fresh water

Sea level and thermosteric OHC

Von Schuckmann et al JGR 2009

IPCC

# Ocean heat content 0-2000m




SST (red)
2003-2008 –
1990-2008
10 m depth
ARIVO –
WOA05

Temps

Difference for
2003-2008
From WOA05
Levitus et al

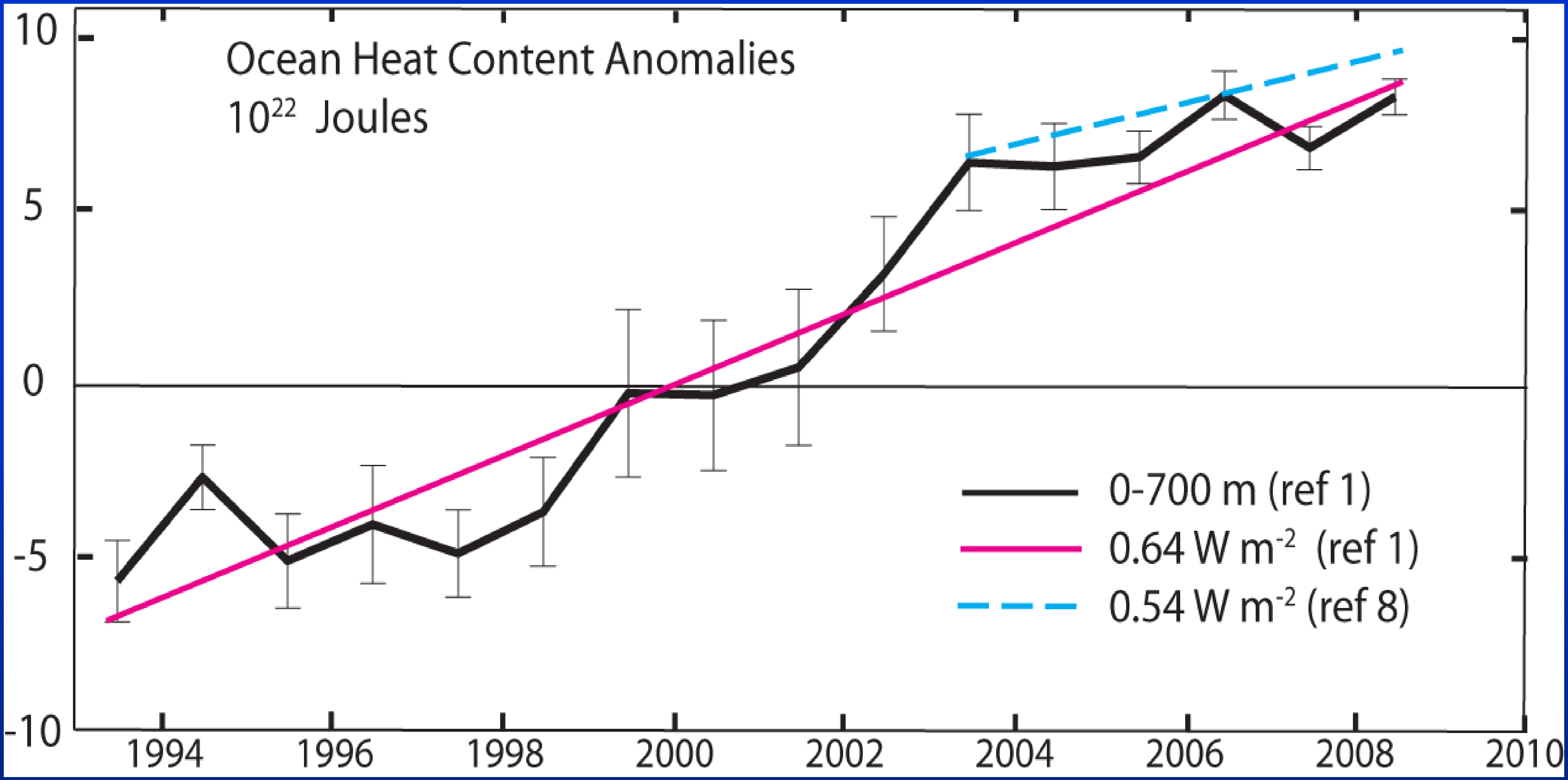
Von Schuckmann et al JGR 2009

# Comments on Von Schuckman

- VS did not provide 0-700 m OHC vs 0 to 2000m
- Some floats are programmed to go only to 1000 m and do not go to 2000 m, so that coverage decreases with depth
- How come all the error bars are the same even though coverage is increasing?
- How good is the quality of the sensors over this time? Up to 30% report negative pressures at the surface.

IPCC

# Ocean heat content is increasing




1. Lyman et al 2010 : to 700m
8. von Schuckmann et al 2009 :to 2000m

From Trenberth 2010 *Nature*

# Ocean fresh water

Or

The ocean salinity budget

The single most important role of the oceans in climate is that they are wet!

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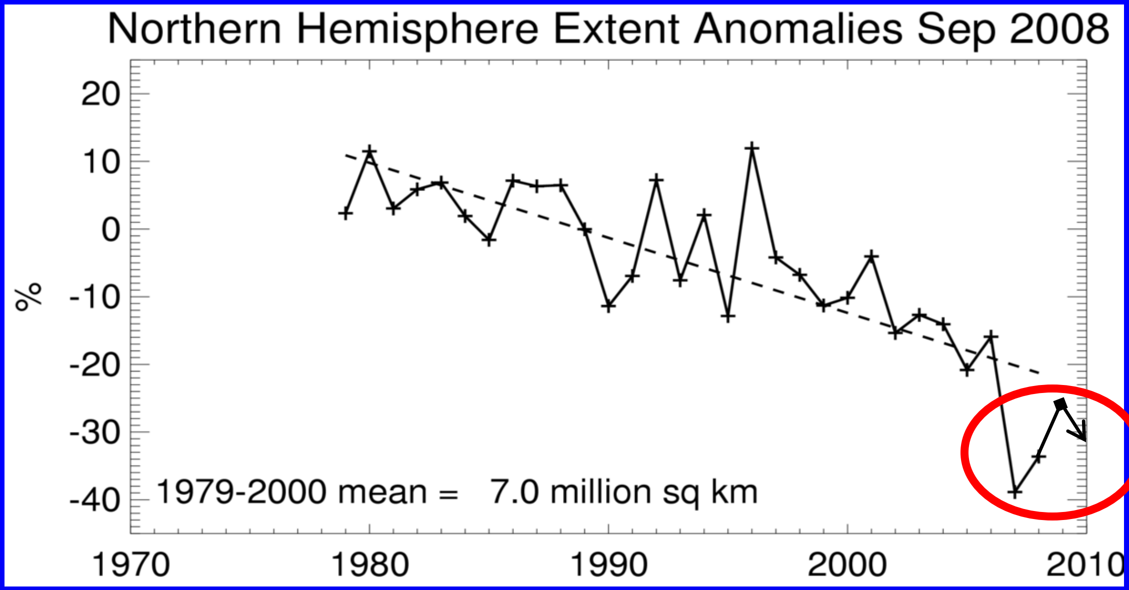
# Melting ice

IPCC estimated melting ice contribution to SL rise was 1.2 mm/yr for 1992 to 2003.

- How much is missed?
- Is the Antarctic and Greenland melt a transient or not?
- Many glaciers are not monitored
- Ocean warming may change basal melting: poorly known
- Ice sheets, buttressing by ice shelves poorly modeled
- Concern future SL rise underestimated
- Need process studies and improved models
- Changes salinity: fresh water budget
  - affects ocean currents (MOC)

IPCC

# Snow cover and Arctic sea ice are decreasing

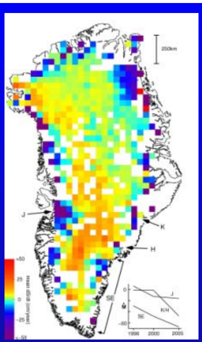


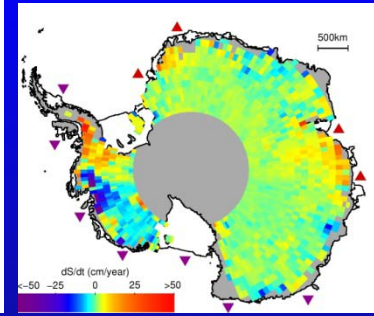

Arctic sea ice area decreased by 2.7% per decade (Summer: -7.4%/decade) up to 2006:

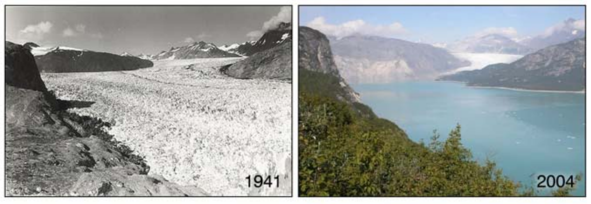
2007: 22% ($10^6$ $km^2$) lower than 2005

2008: second lowest

2010: third lowest

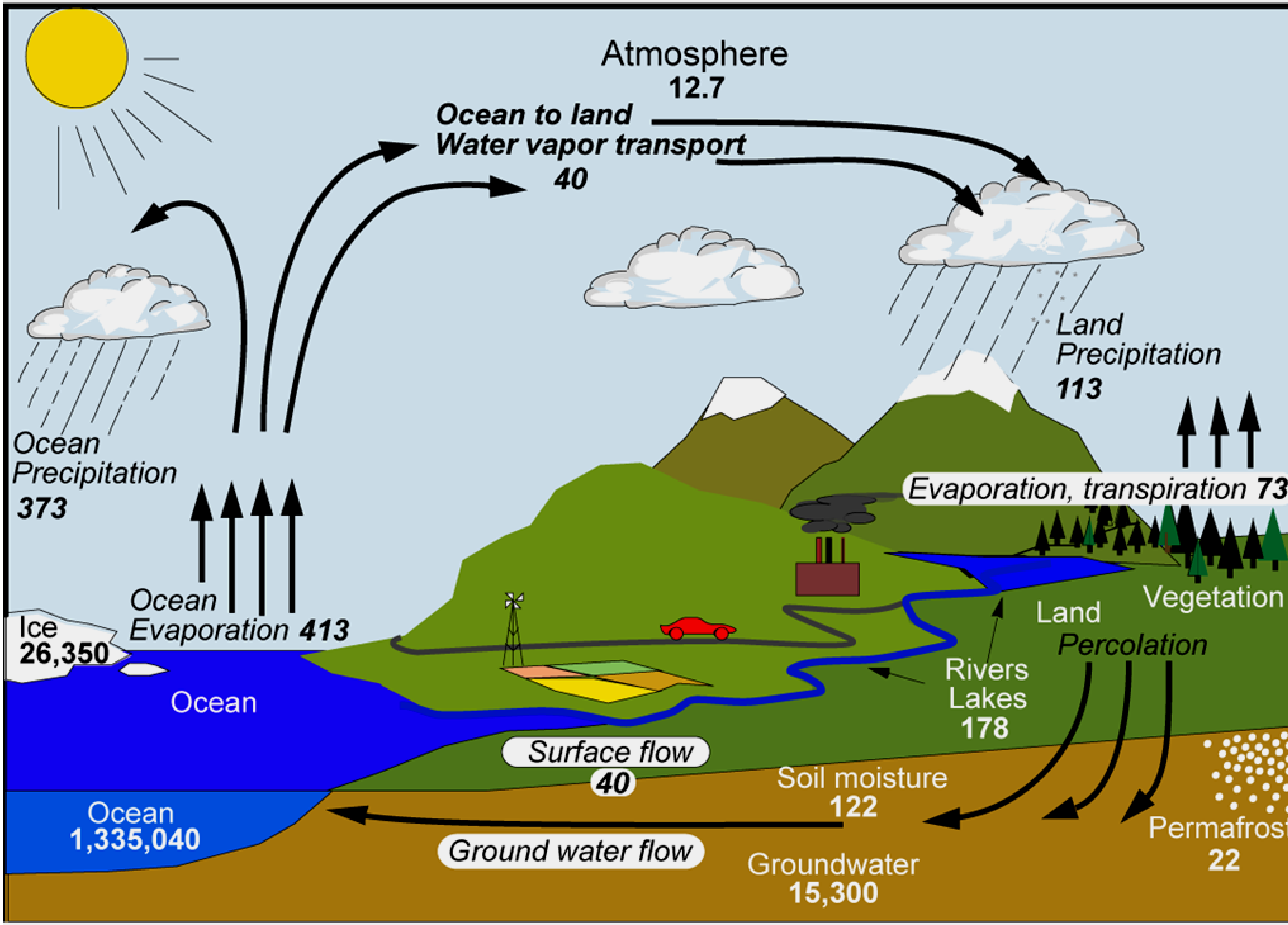





- Greenland and Antarctica ice sheets and glaciers are shrinking: Accelerated rate especially from 2002 to 2006?
- To melt $10^6$ $km^2$ ice 1 m thick (2007) to 10°C = $3.4 \times 10^{20}$ J
- Globally per year since 2004 this is 0.02 W $m^{-2}$

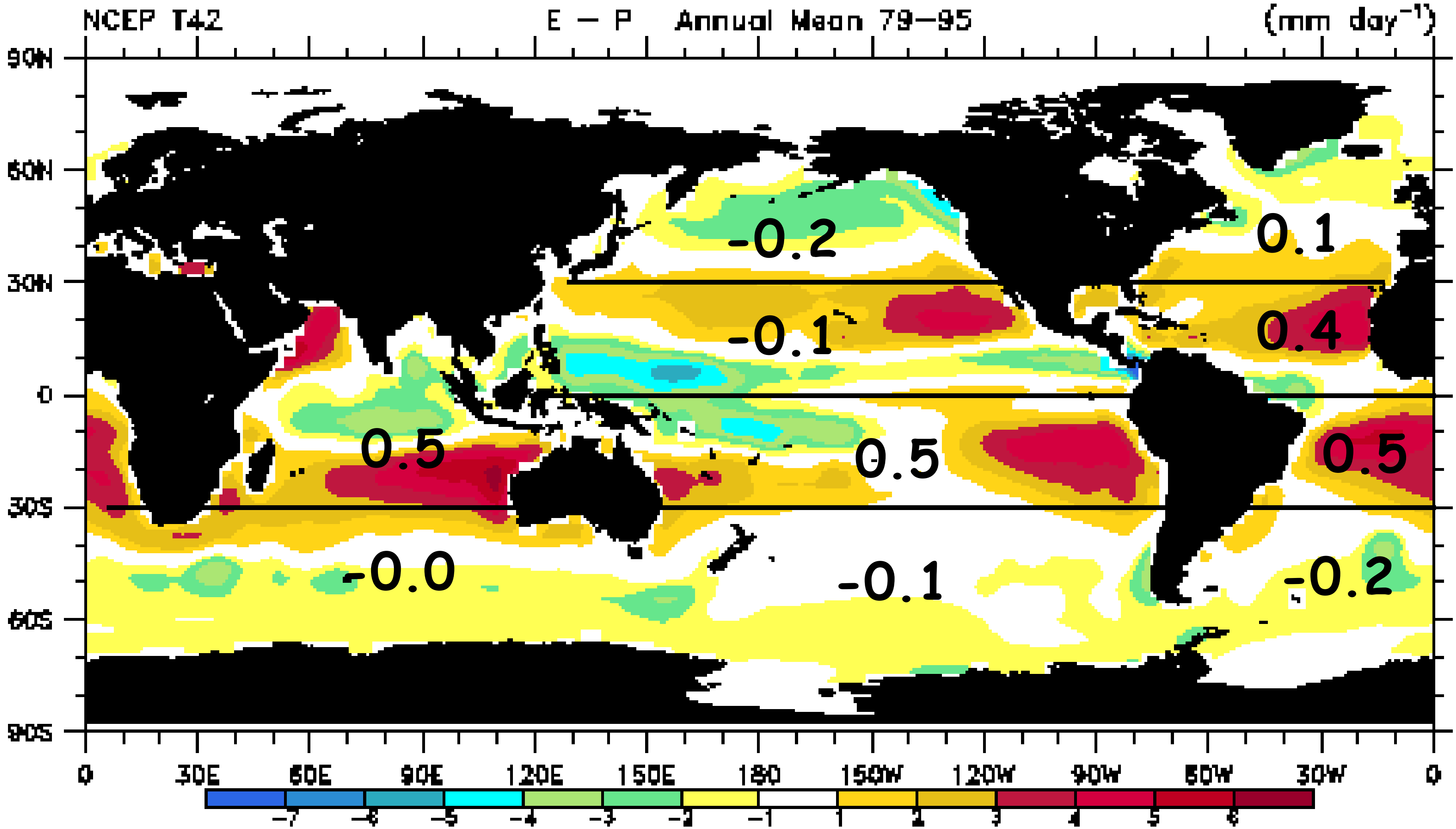
# Hydrological Cycle

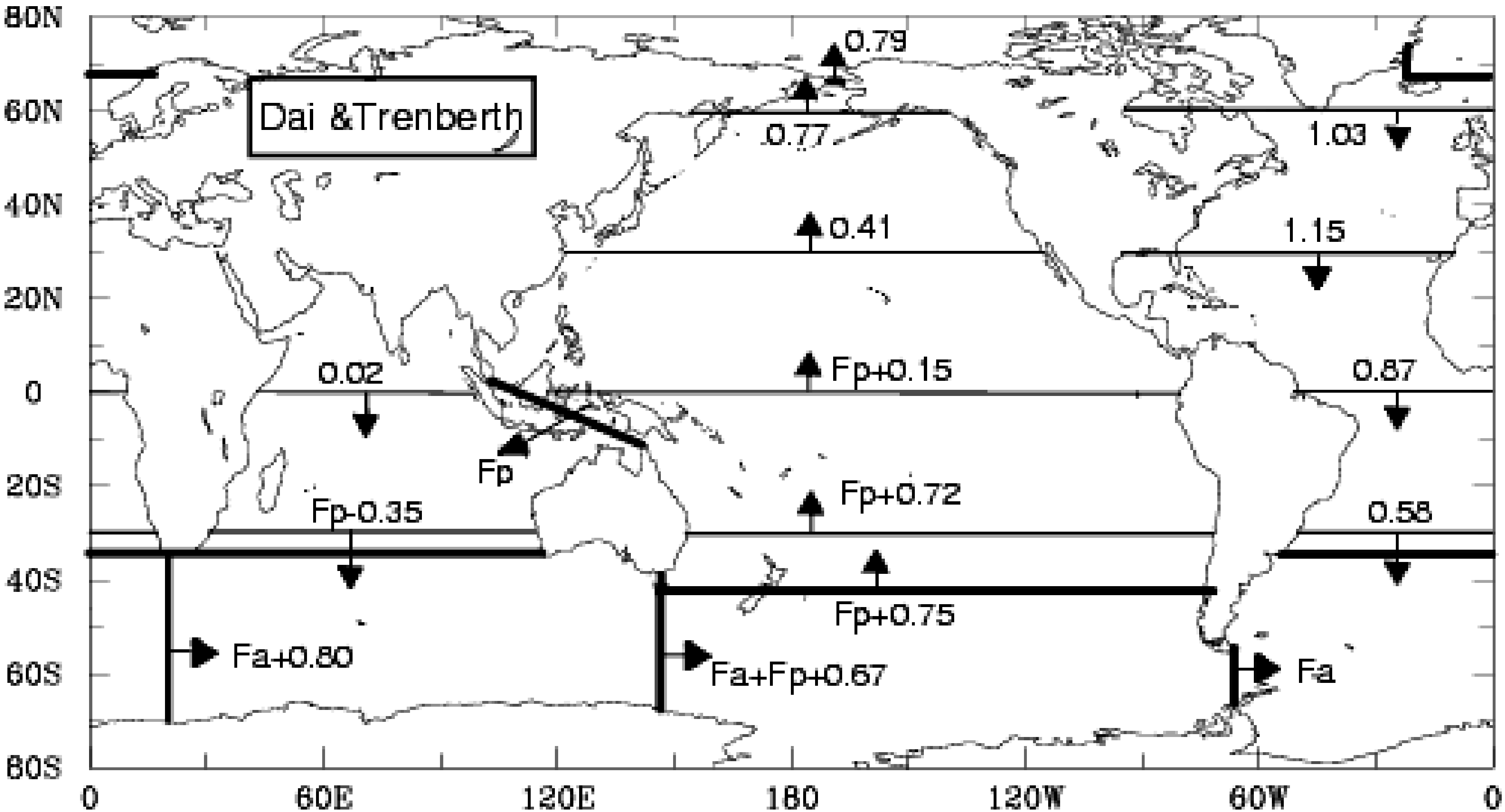



Units: Thousand cubic km for storage, and *thousand cubic km/yr* for exchanges

Trenberth et al 2007

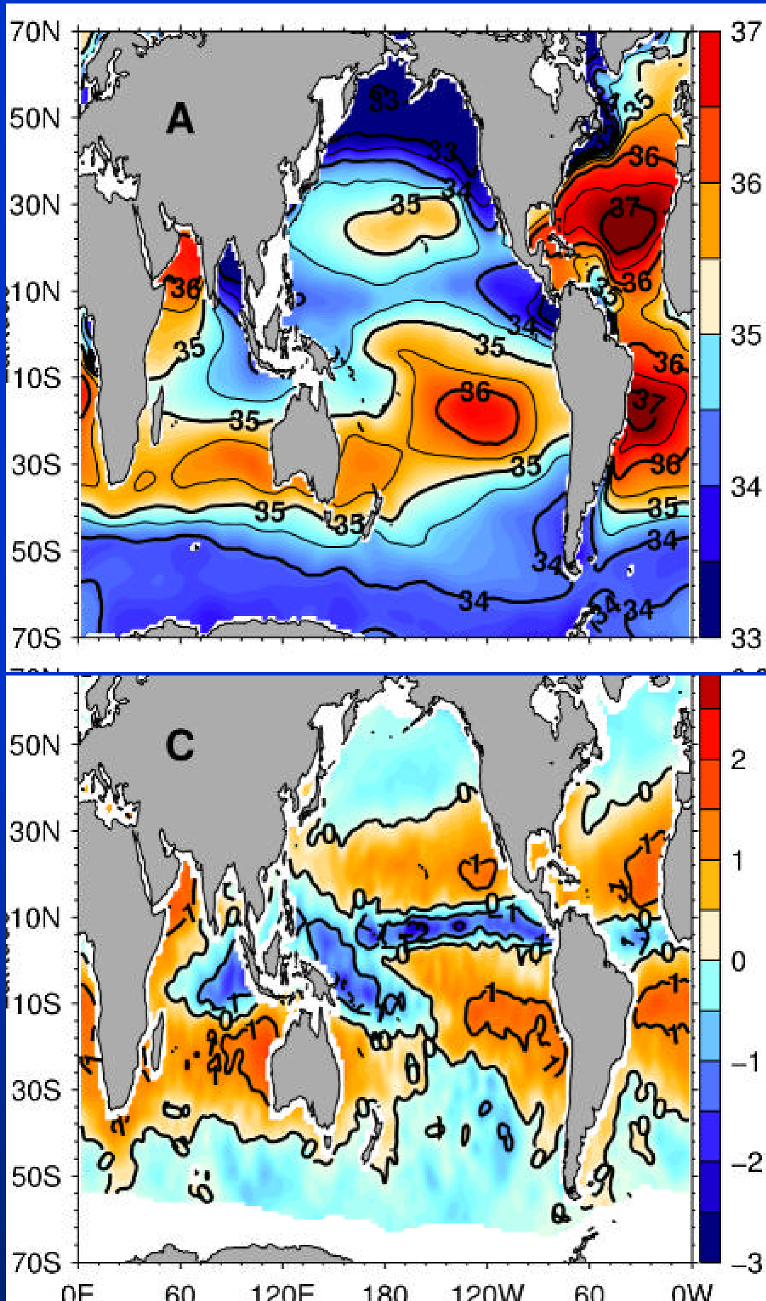
# Divergences of water fluxes from E-P estimates over the oceans; values in Sv:

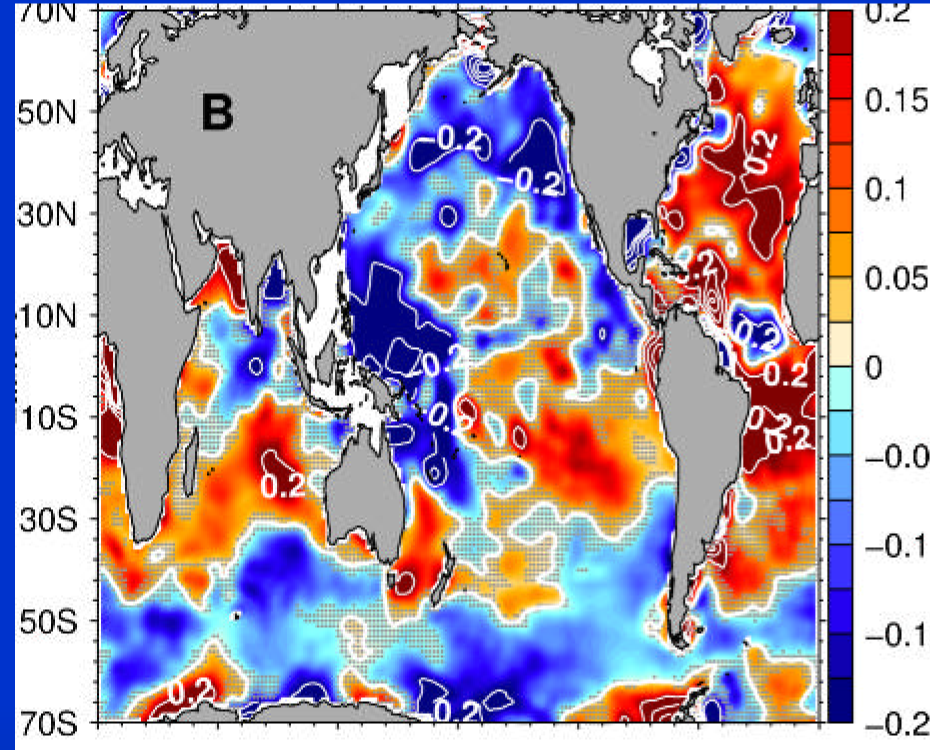





New estimate of fresh water transport in ocean from new values of E-P over ocean plus new river discharge estimates from Dai and Trenberth (2002)

Holfort and Siedler (2001) get –0.55 Sv at 30°S.



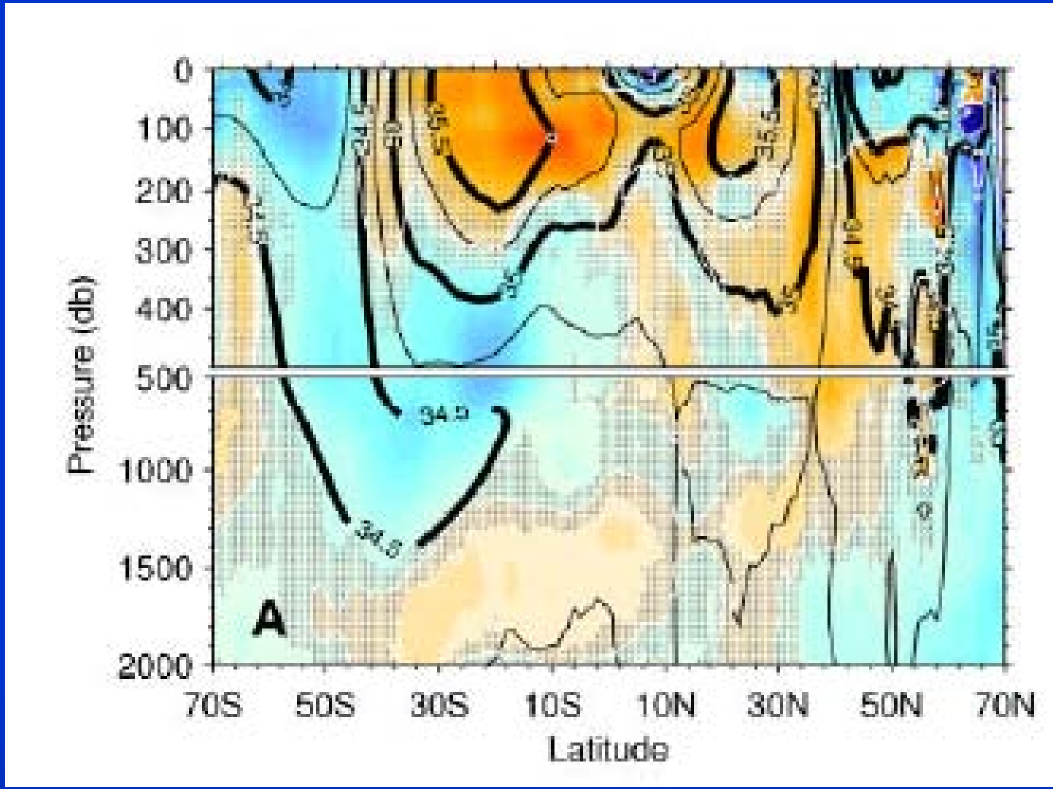

A. Mean salinity 1951-2000

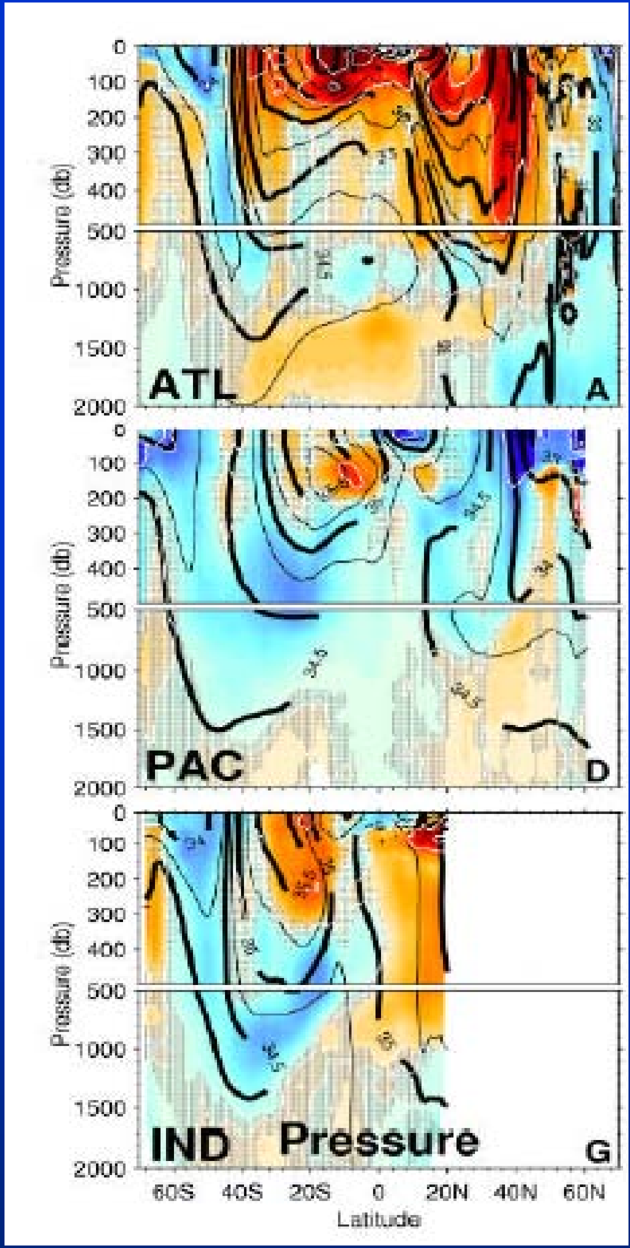
C. Mean E-P 1980-1993 $m^3/yr$

B. Linear trends pss/50yr (top)

Durack and Wijffels 2010 JC

IPCC



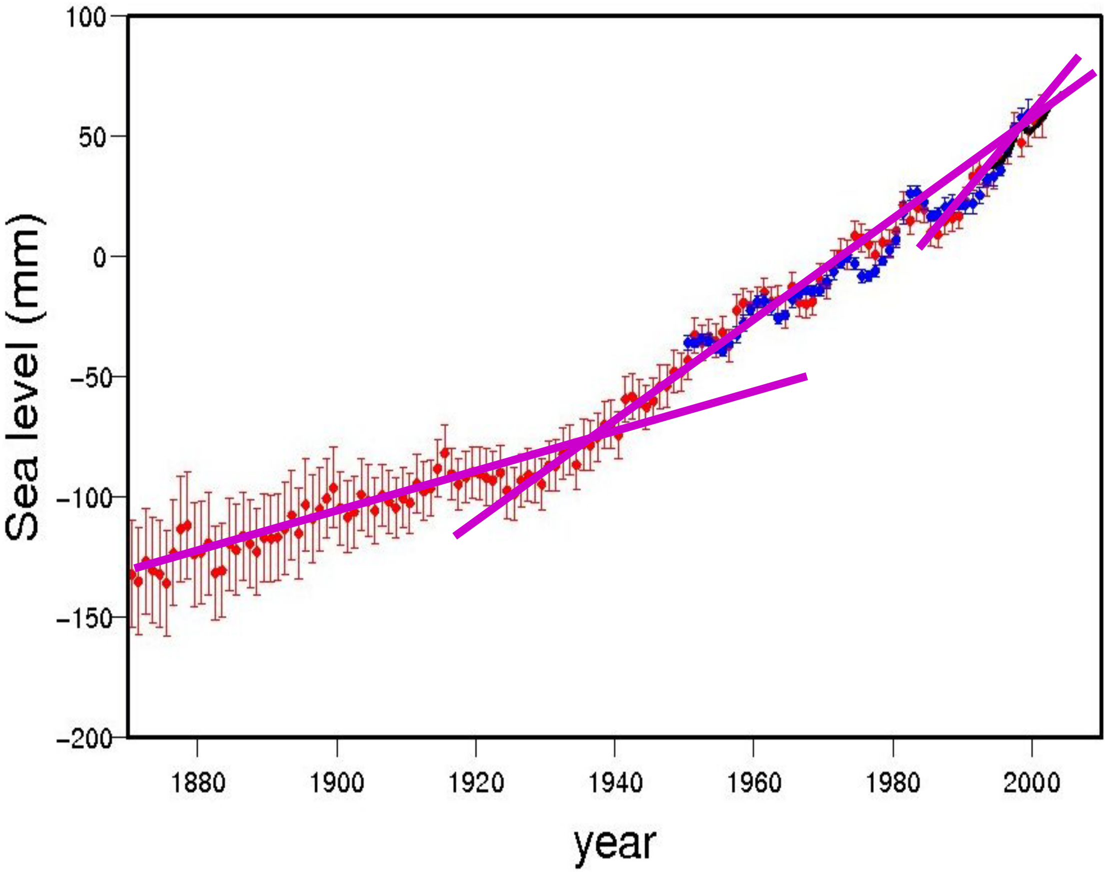

Linear trends pss/50yr

Durack and Wijffels 2010 JC

Subduction on isopycnals appears to account for much of the subsurface changes

IPCC

# Sea level is rising in 20th century




Rates of sea level rise:

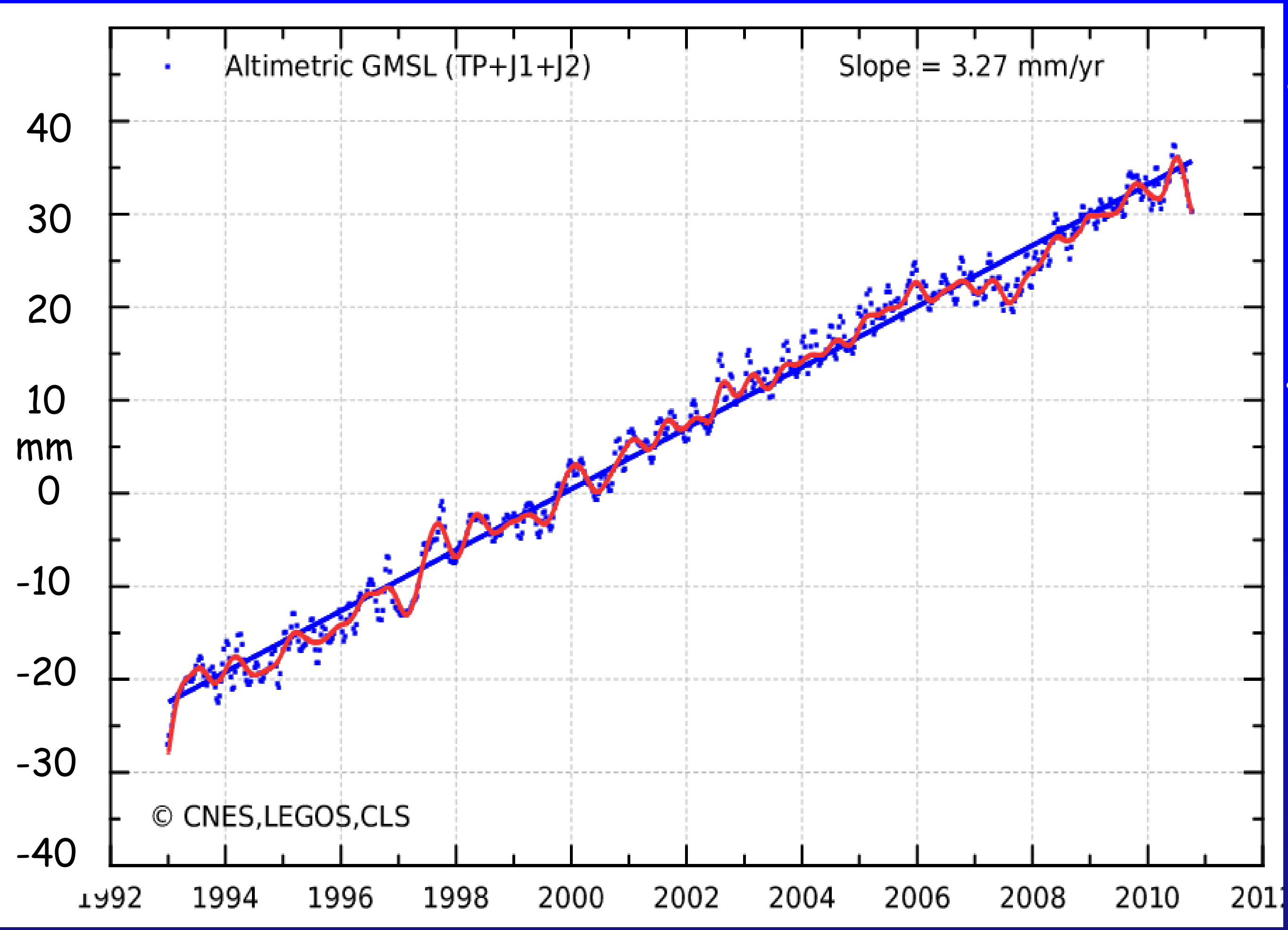
- $1.8 \pm 0.5$ mm yr$^{-1}$, 1961-2003
- $1.7 \pm 0.5$ mm yr$^{-1}$, 20th Century
- $3.1 \pm 0.7$ mm yr$^{-1}$, 1993-2003

Sea level rise:

- 0.17m ± 0.05 m 20th Century

NCAR

# Sea level is rising:
## from ocean expansion and melting glaciers



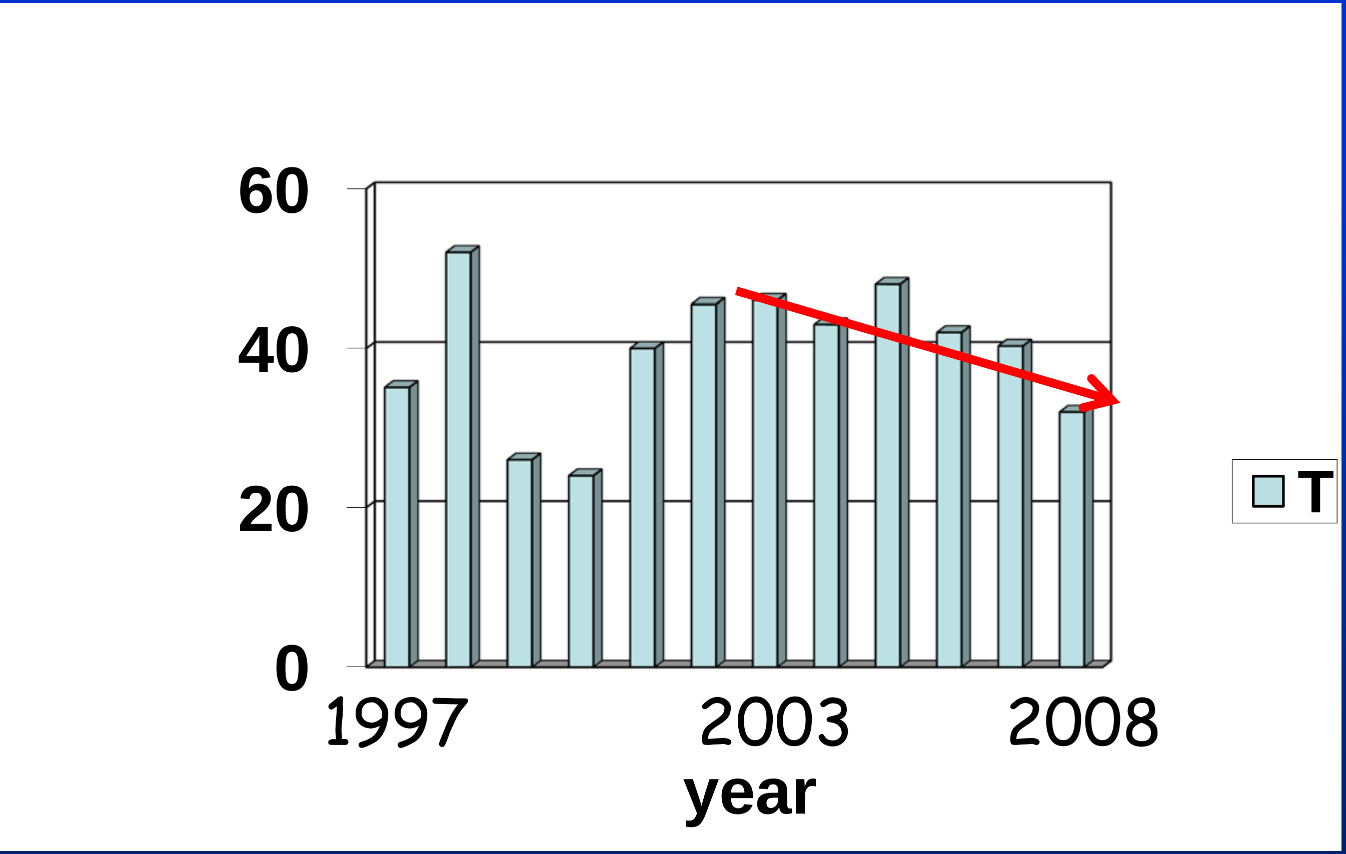

Since 1992 Global sea level has risen 55 mm (2.2 inches)

To 2003: 60% from expansion as ocean temperatures rise, 40% from melting glaciers

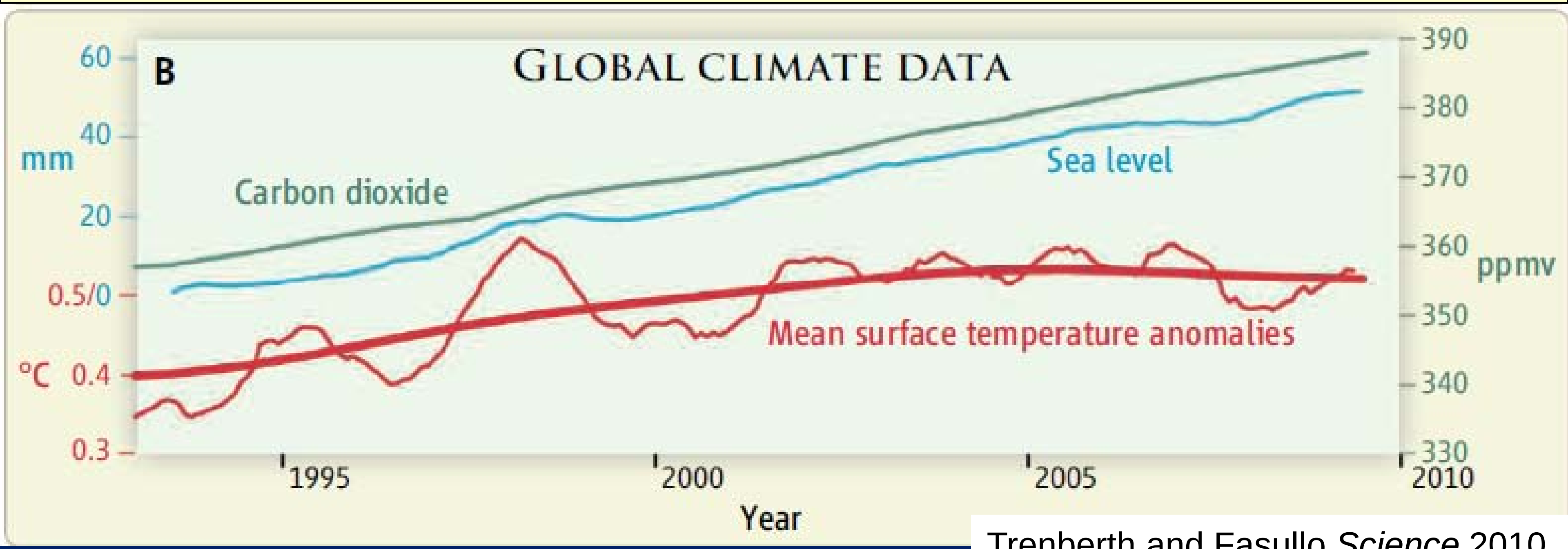
AVISO: from TOPEX, Jason 1, Jason 2. Ann cy removed, IB, GIA applied

# What about 2003 to 2008?

Global mean surface temperatures

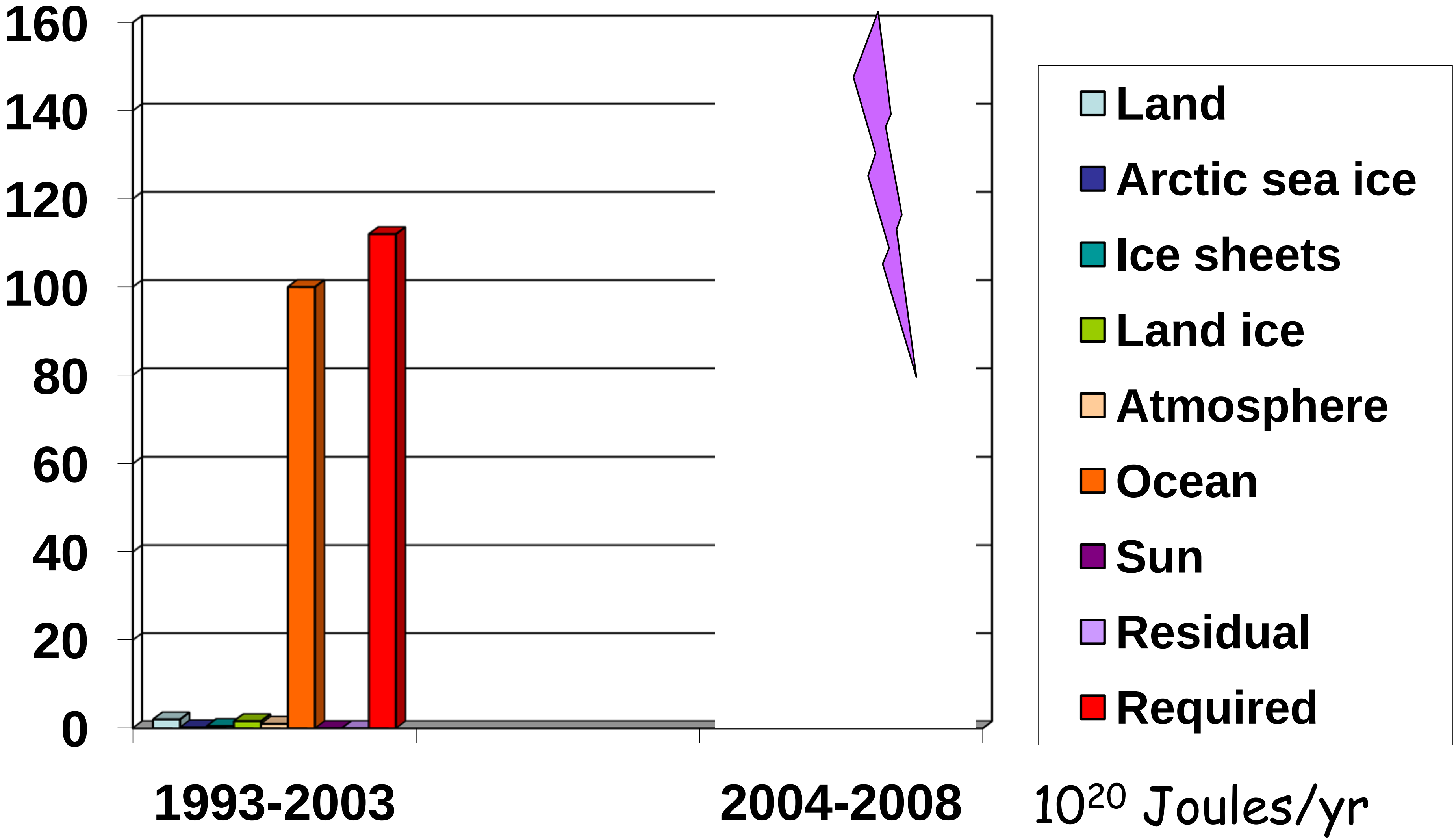


Can we track energy since 1993 when we have had good sea level measurements?



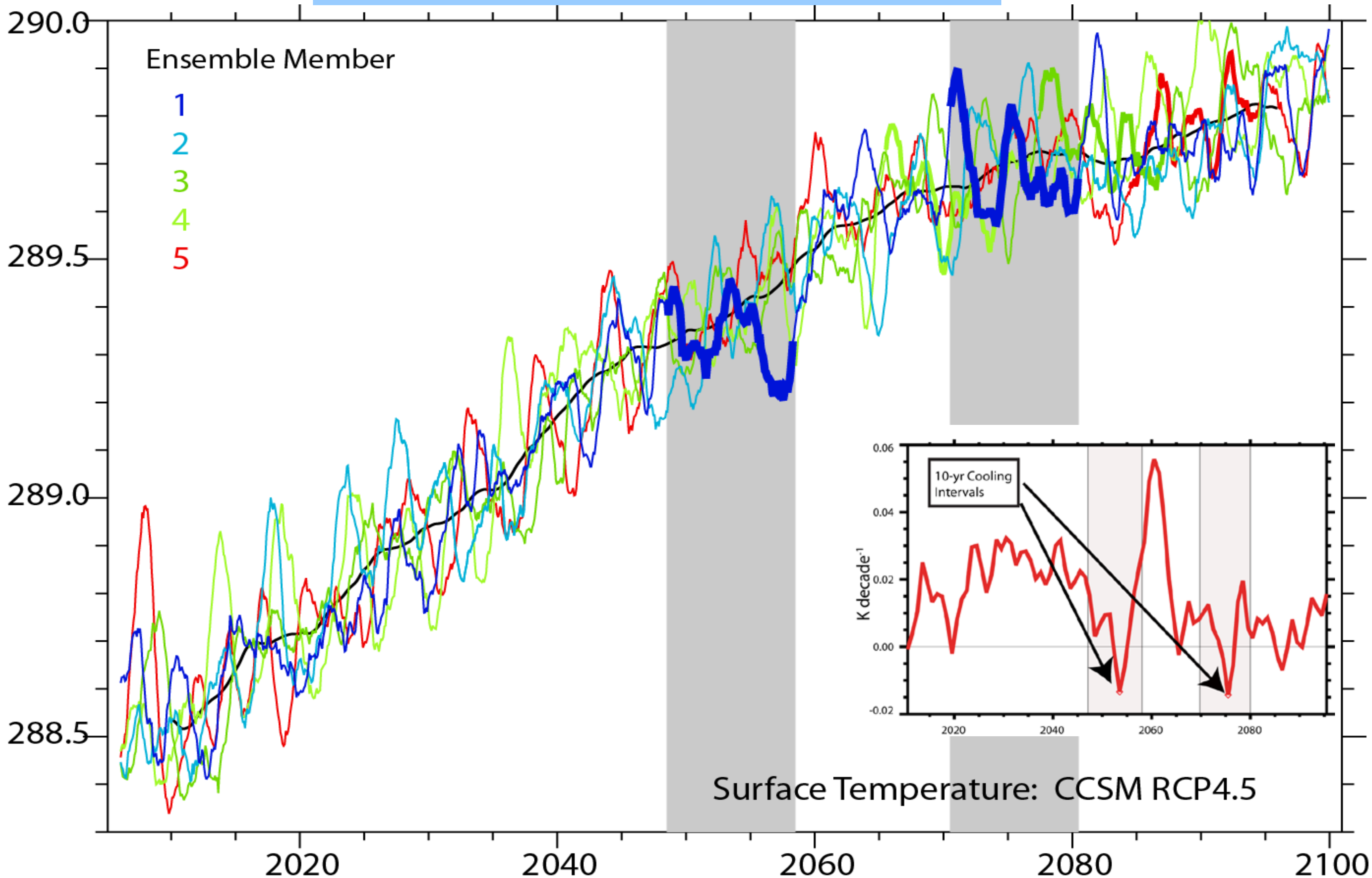

Trenberth and Fasullo *Science* 2010

# Where does energy go?



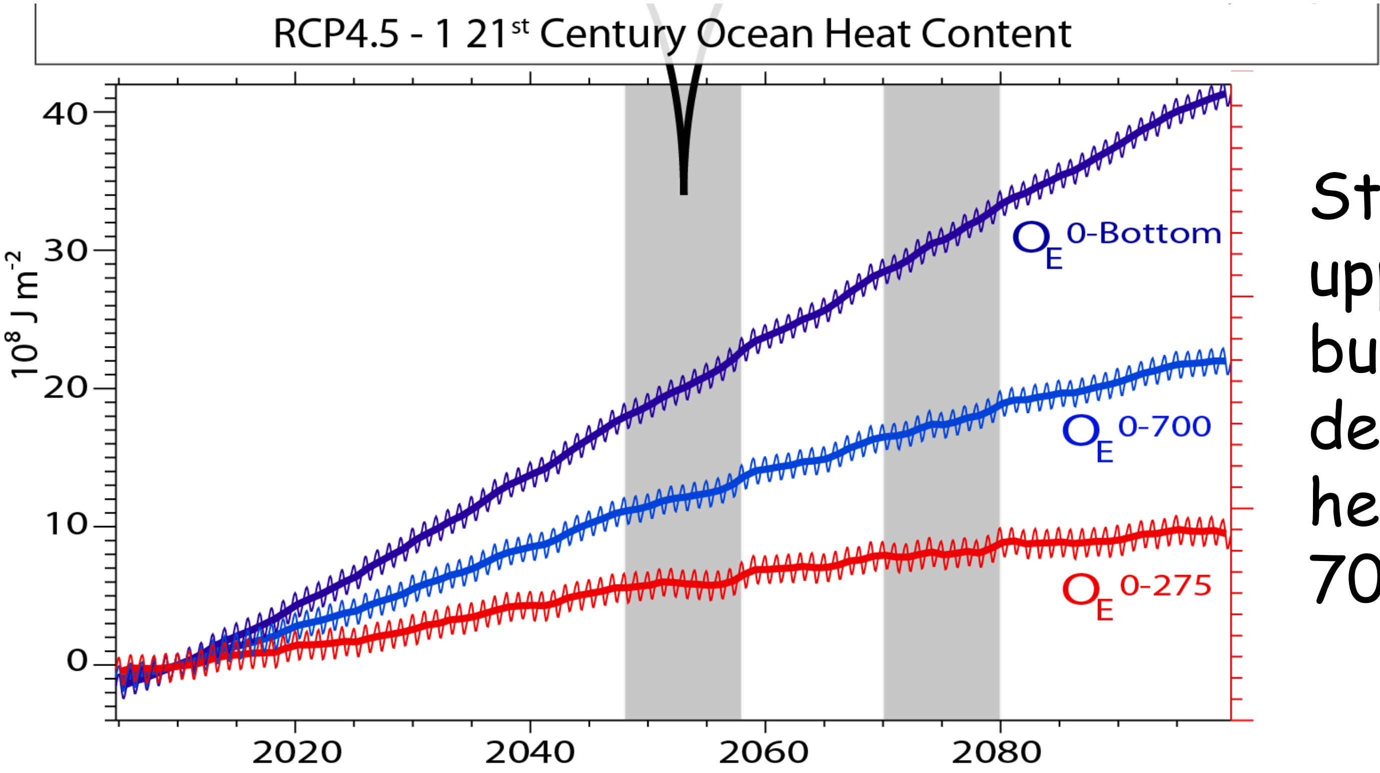

Trenberth 2009

# Missing energy in CCSM4?




In CCSM4, during periods with no sfc T rise, the energy imbalance at TOA remains about 1 W $m^{-2}$ warming. So where does the heat go?

In CCSM4, during periods with no sfc T rise, the energy goes into the deep ocean, somehow.




Stasis also in upper OHC; but not for full depth ocean: heat below 700 m

NCAR

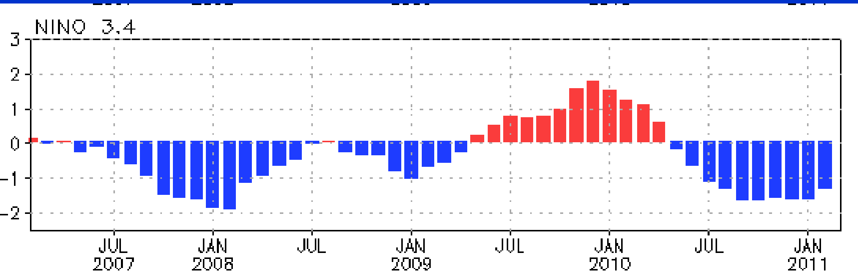
# Where does the heat go?

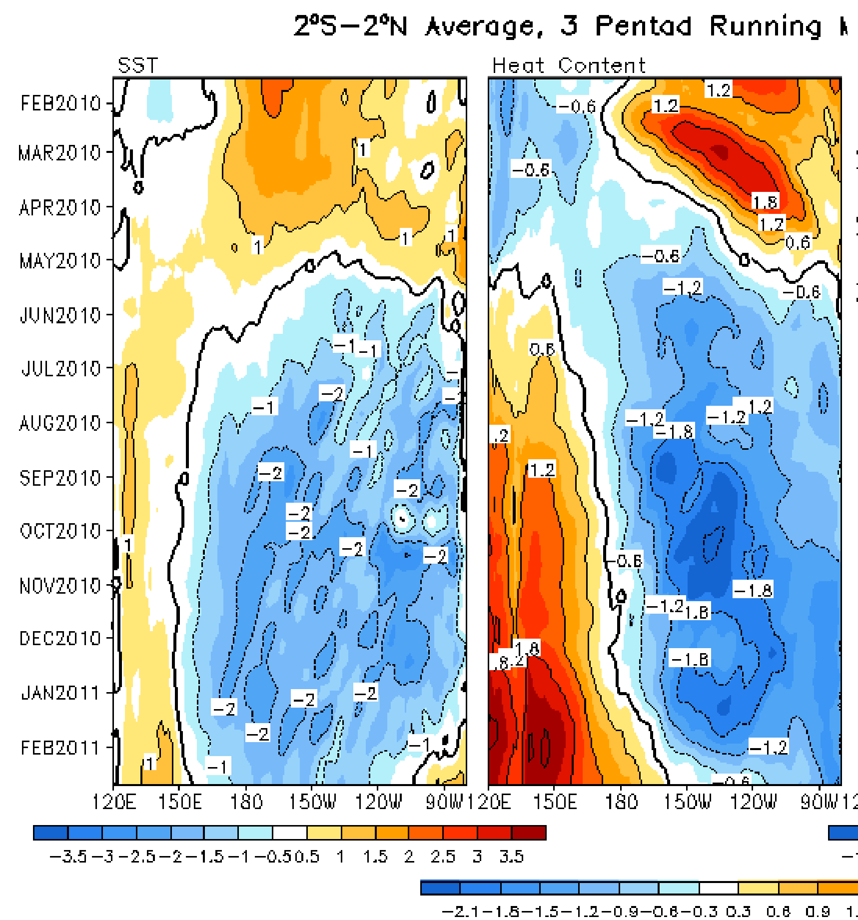
*Questions regarding the mechanisms driving variability in deep ocean heat content remain. Both the CCSM4 and observations suggest that ENSO plays a necessary, if not sufficient, role. Strong recent ENSO events, including the El Niño of 1997/98 and the La Niña of 2007/08 exert a strong influence on trends in global temperature computed across this period.*

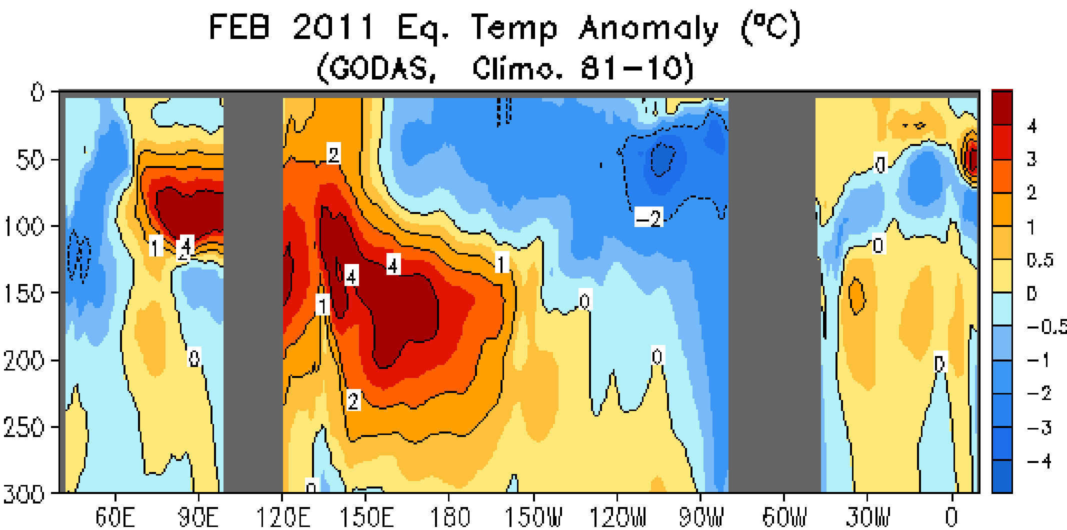
*Similarly, cooling decades from the CCSM4 are bounded by El Niño events at their initiation and La Niña events are their termination. Yet other intervals bounded by El Niño and La Niña are not accompanied by significant cooling. Our current work focuses on understanding this variable association between ENSO and global temperature trends.*

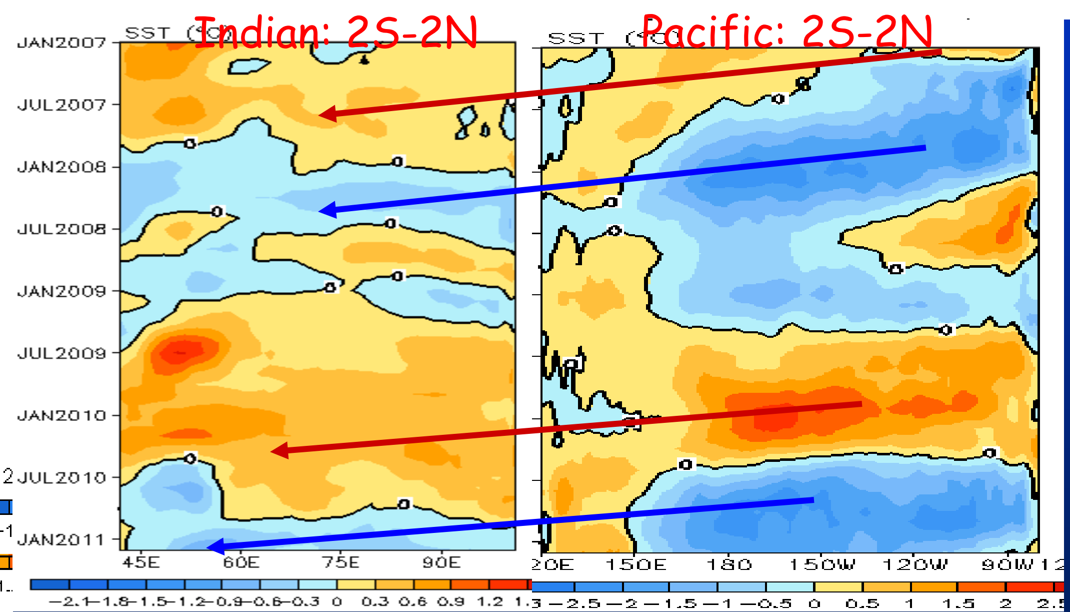
# Evolution of recent ENSO

## Equatorial Pacific SST (°C), 0-300m Heat Content (°C)



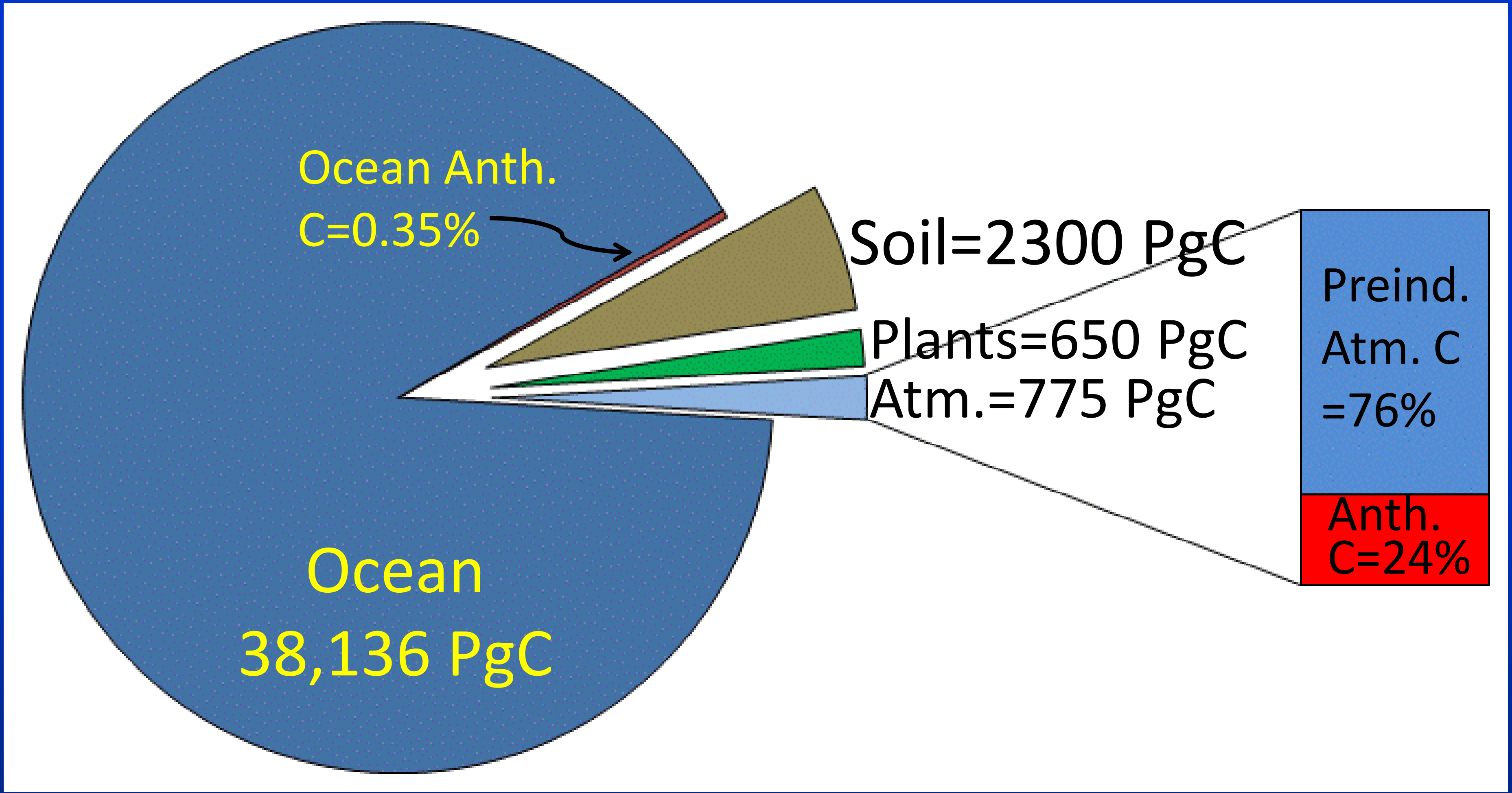



# Other issues

- Ocean carbon
- Acidification
- Ocean color

IPCC

# Carbon Inventories of Reservoirs that Naturally Exchange Carbon on Time Scales of Decades to Centuries

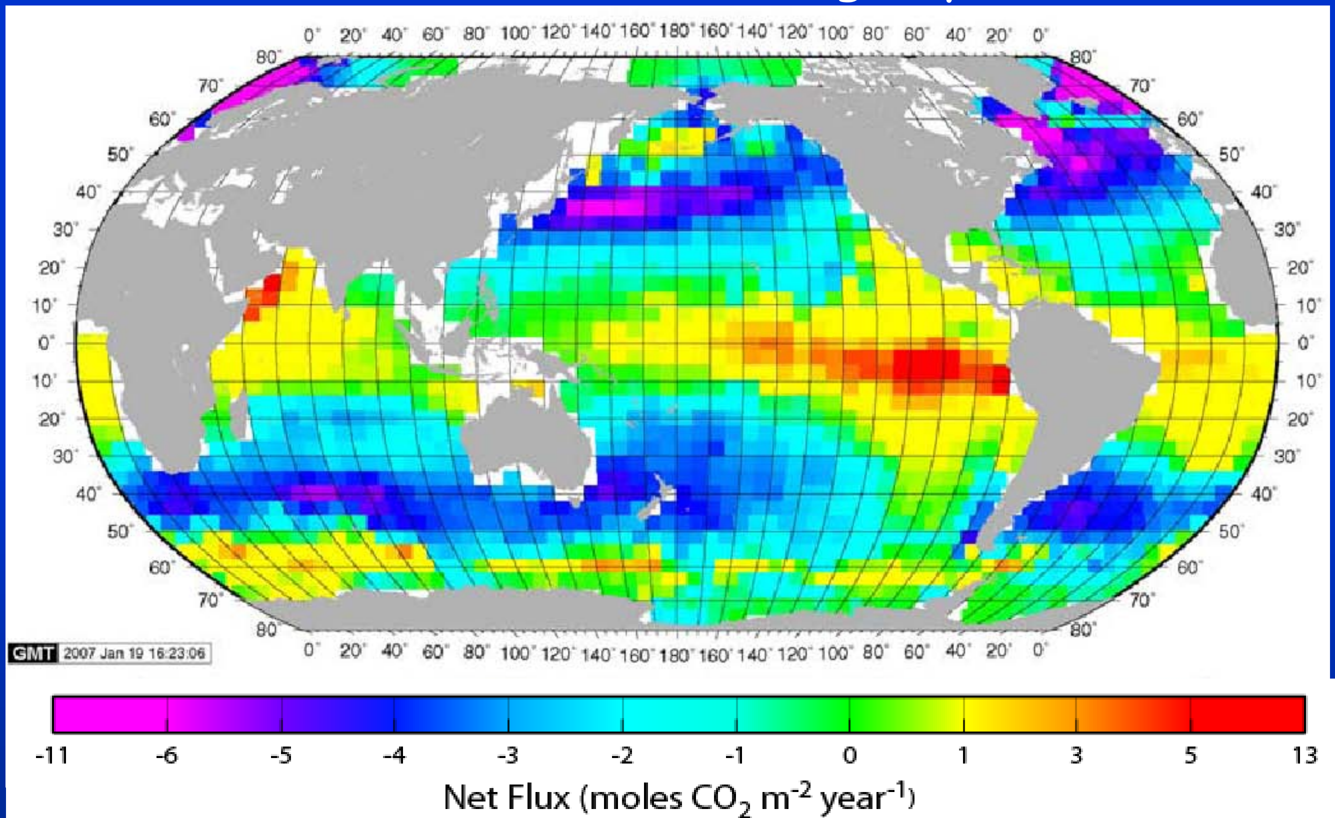



- Oceans contain ~90% of carbon in this 4 component system
- anthropogenic component is difficult to detect

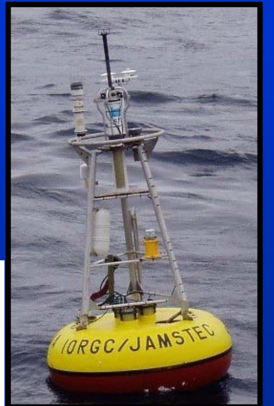
IPCC

# Annual mean air-sea $CO_2$ flux for 2000

Based on 3 million measurements since 1970
Global flux is 1.4 Pg C/yr

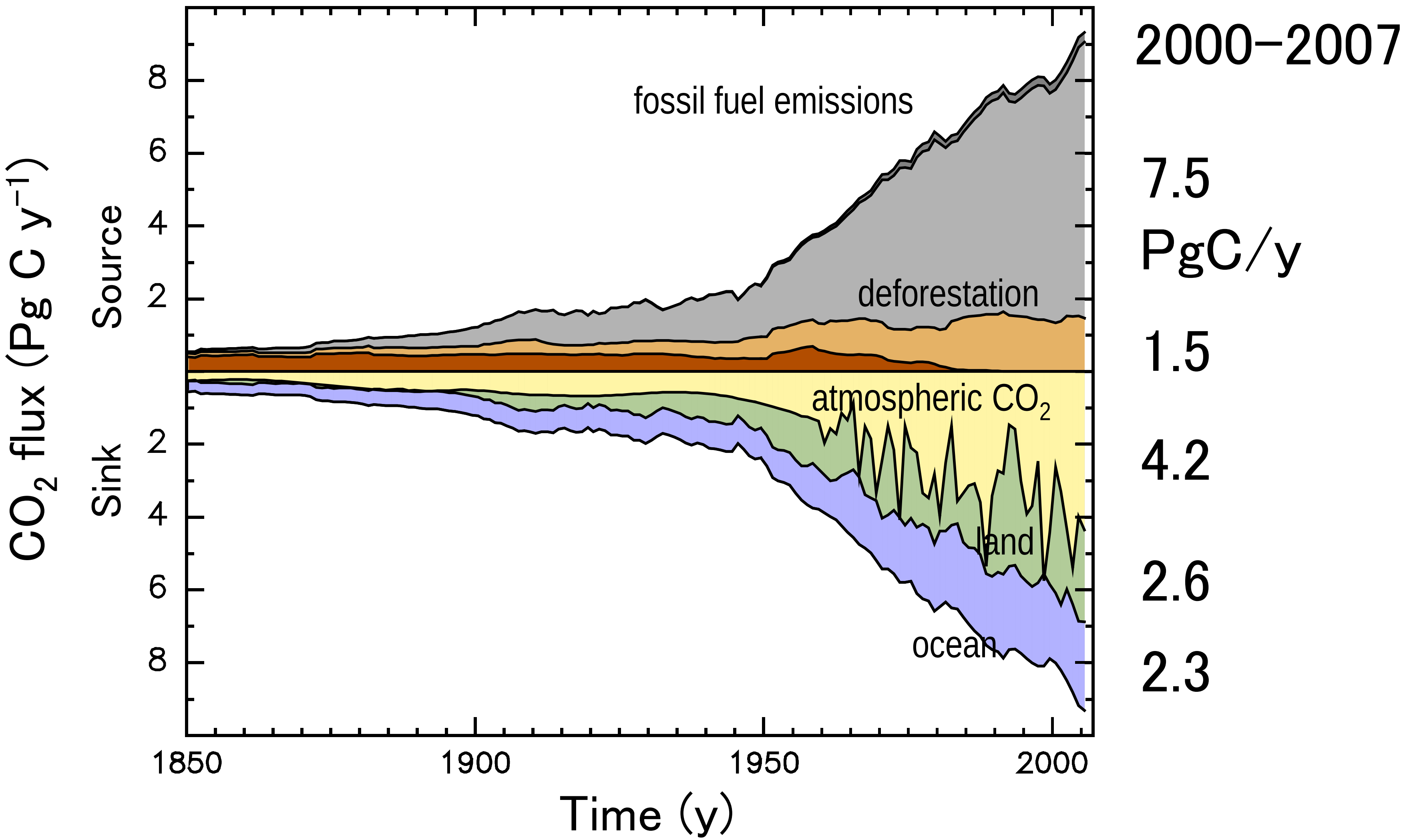








Takahashi et al., Deep Sea Res. II, 2009


# Global $CO_2$ budget 1850-2006




Canadell et al. (2007)
Global Carbon Project (2008)

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 1930's "Dust Bowl" era in North America, given 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 assimilated into models:

**Need better observing system!**