Earth's Energy Imbalance

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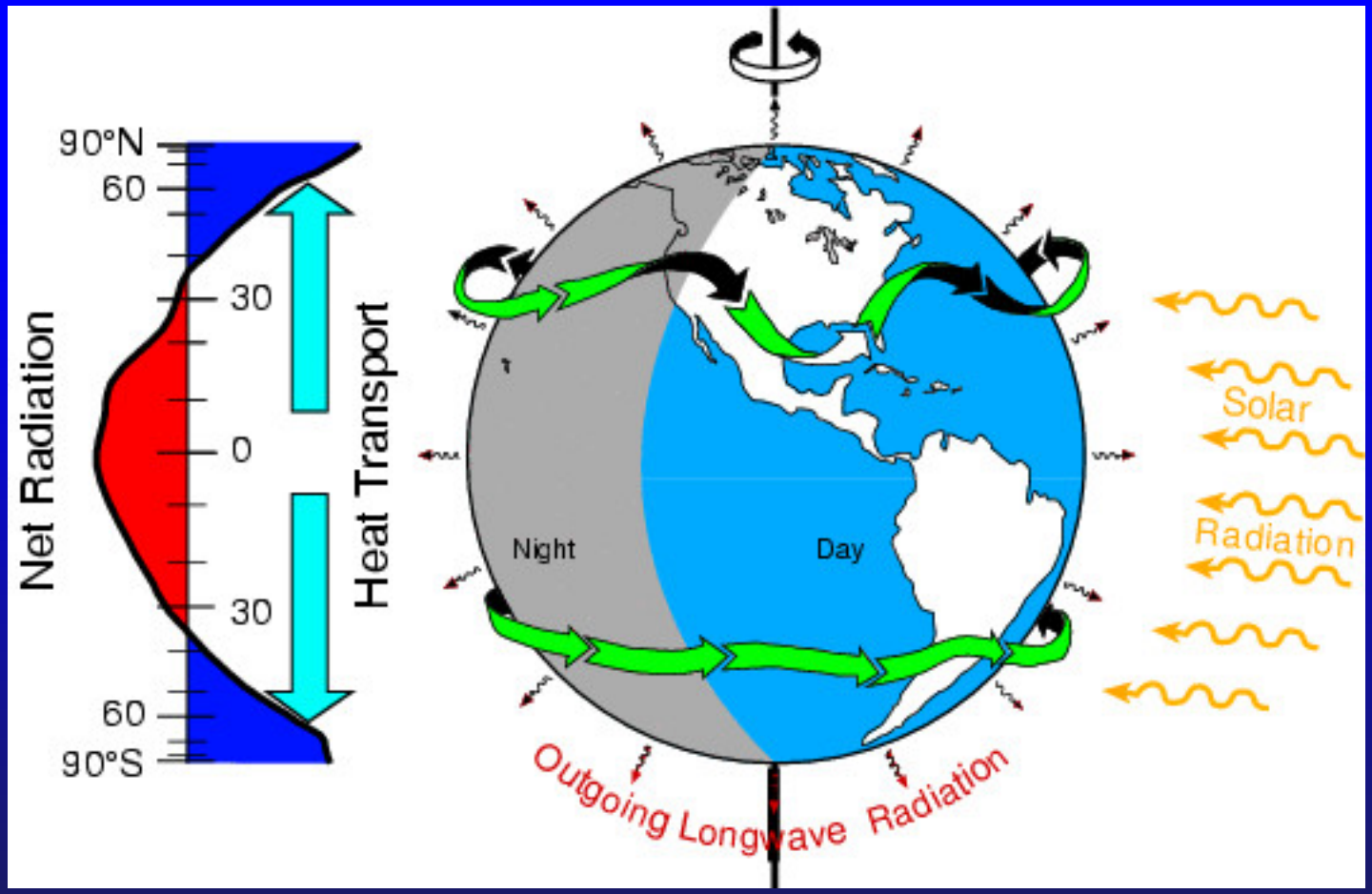


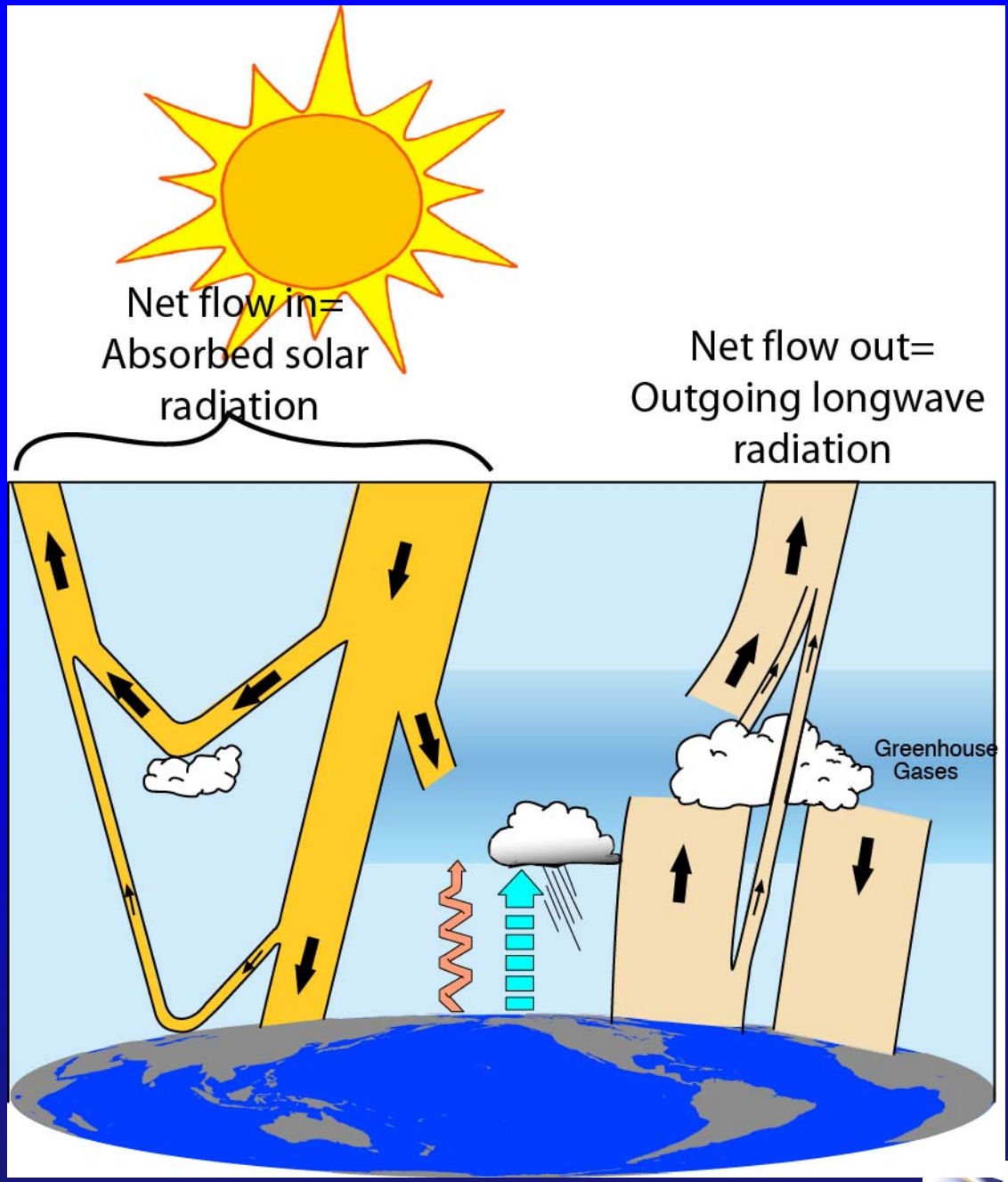
Global warming:

Under no climate change, the net flow of energy in from the sun is balanced by the net radiation out to space.

ASR=OLR

With global warming there is a net energy imbalance as heat trapping gases lower OLR:

Net = ASR -OLR



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Earth's Energy Imbalance: How do we measure it?

1. Direct measurements from space of ASR, OLR, Net
2. Take inventory of where all the energy has gone
3. Use climate models with specified forcings
4. Use atmospheric reanalyses

1. Not accurate enough, but good for relative changes
2. Best, but is there some energy missing? Likely not consistent over time.
3. Depends on how good the model and the forcings are.
4. Useless, although maybe changes over time might be useful?

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Global warming means more heat: Where does the heat go?

1. Warms land and atmosphere
2. Heat storage in the ocean (raises sea level)
3. Melts land ice (raises sea level)
4. Melts sea ice and warms melted water
5. Evaporates moisture ⇒ rain storms, cloud
   ⇒ possibly reflection to space

>90%

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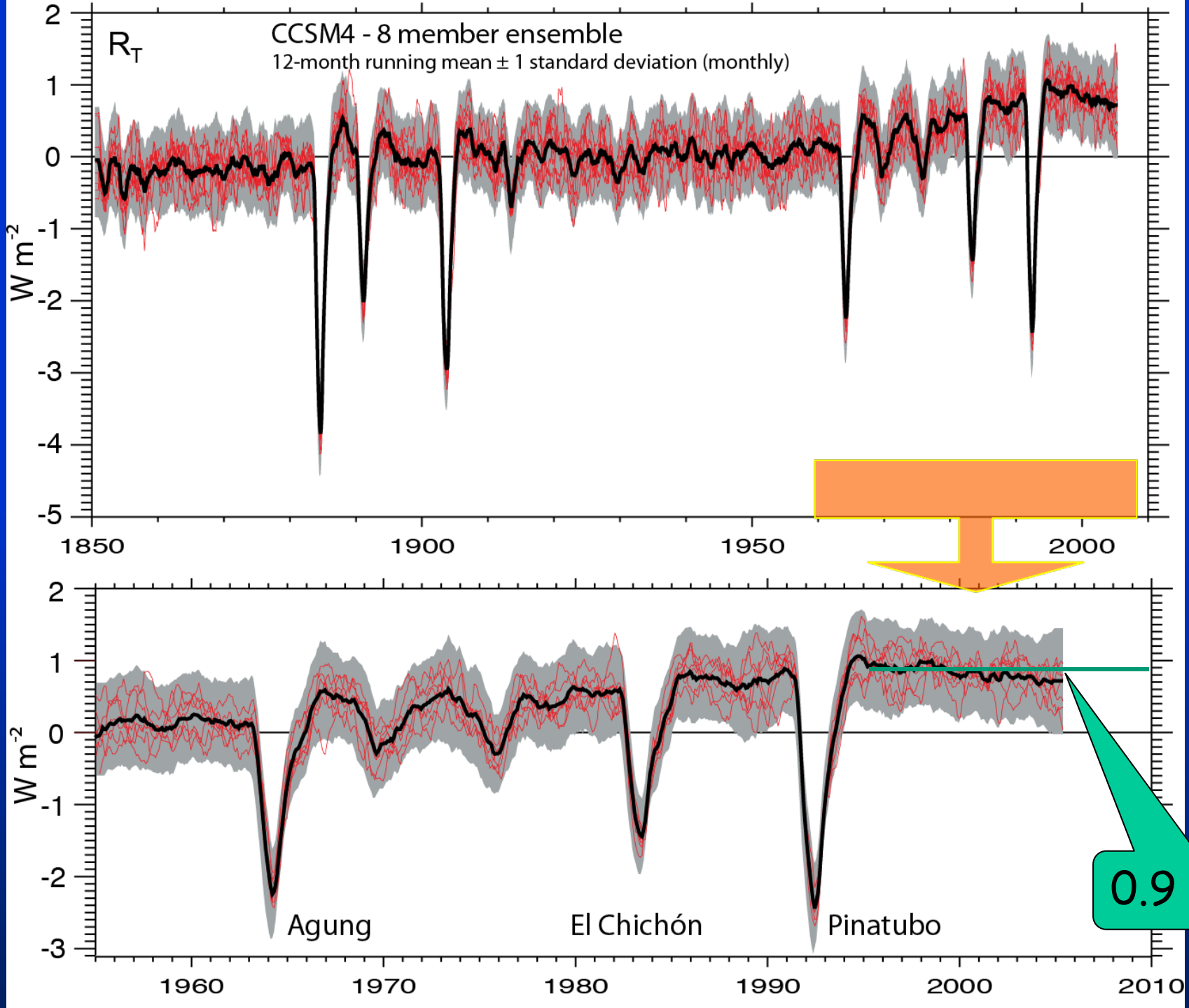
R_T
CCSM4 - 8 member ensemble
12-month running mean ± 1 standard deviation (monthly)
W m^{-2}
2
1
0
-1
-2
-3
-4
-5
1850
1900
1950
2000
Agung
El Chichón
Pinatubo
1960
1970
1980
1990
2000
2010
Rel to ens. mean
Mo s.d. 0.62
12-mo s.d. 0.25 W m^{-2}
0.9 W m^{-2}

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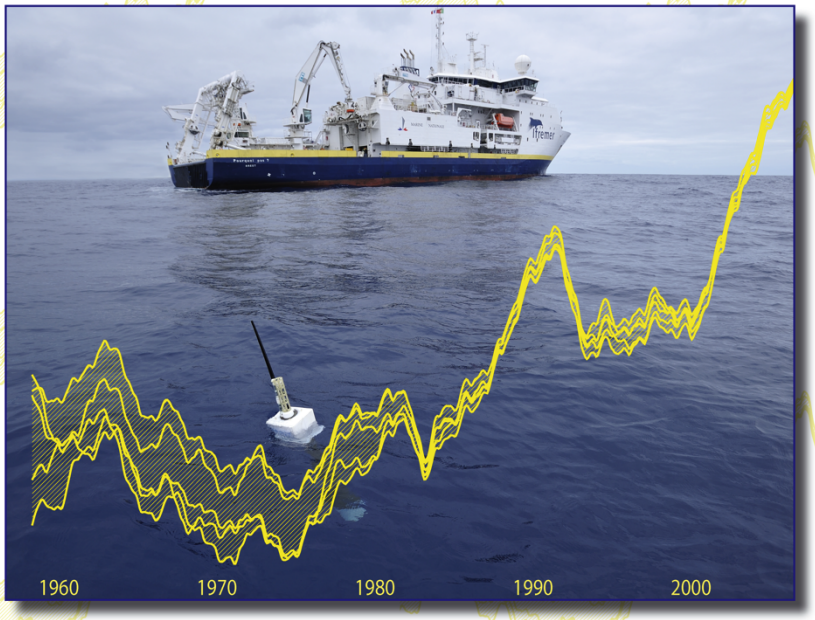

Distinctive climate signals in reanalysis of global ocean heat content • Sudden changes in cosmic rays indicate Voyager 1 entered new region of space • More hurricanes to hit Western Europe due to global warming

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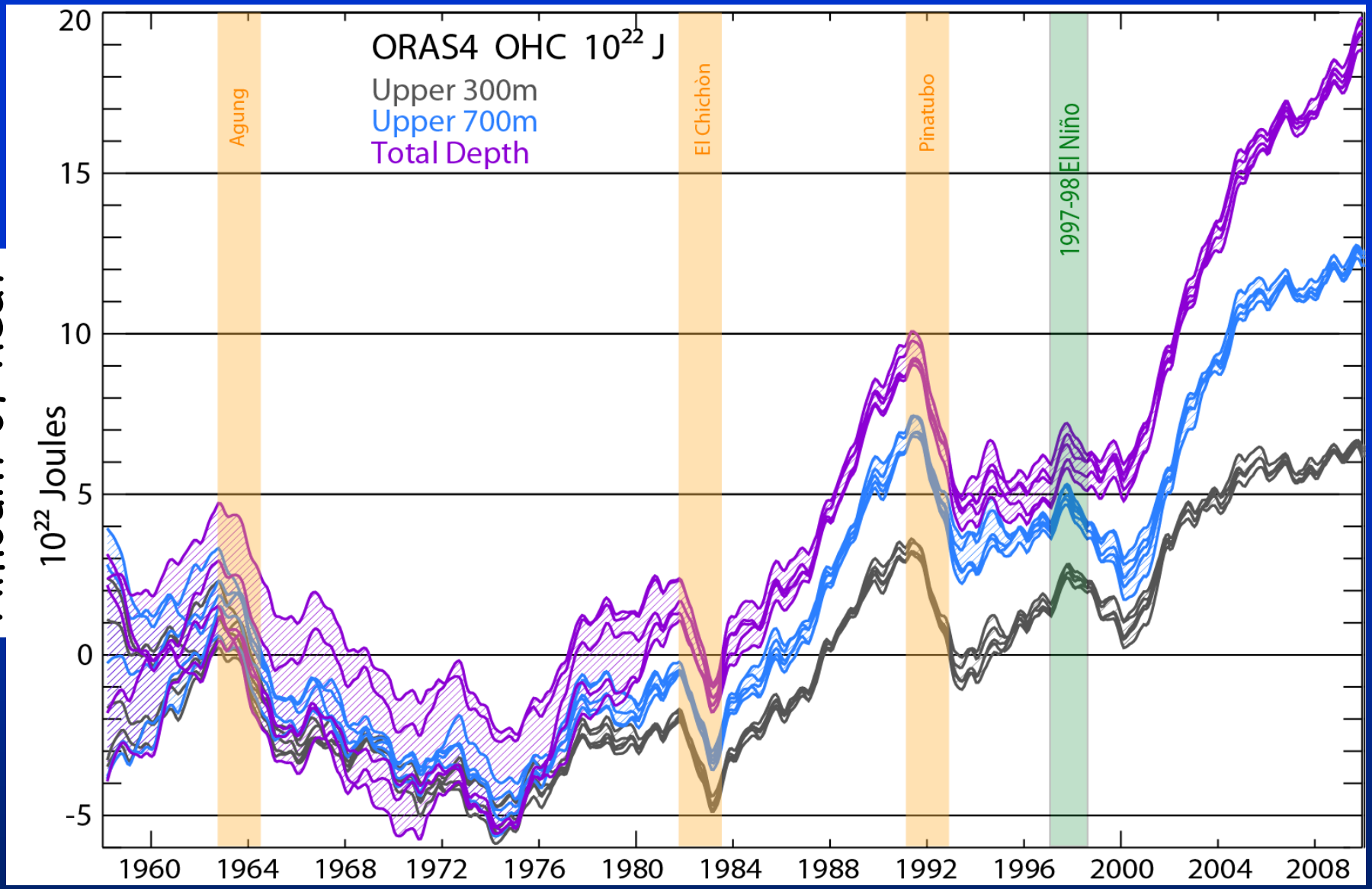
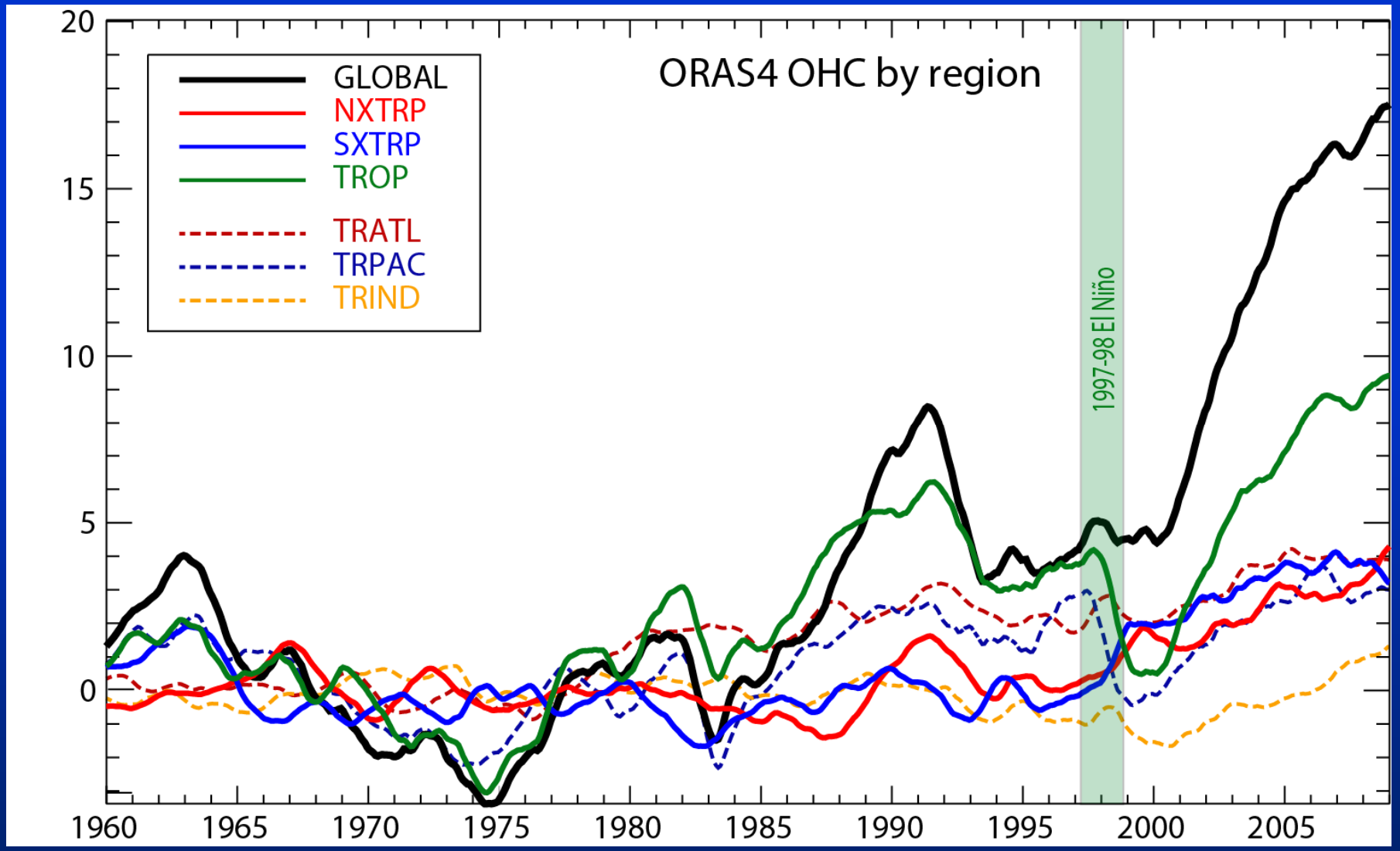
ECMWF Ocean Reanalysis v4: ORAS4

- Balmaseda et al. Quart J R Met Soc 2013
- 5 member ensemble; perturbed initial states
- 52-year reconstruction for 1958 through 2009
- NEMO ocean model 1° 42 level 3Dvar
- Bias corrected using Argo era
- Sfc fluxes from ERA, relaxed to obs SST (2-3 days)
- Corrected XBTs, altimetry
- 10 day cycle

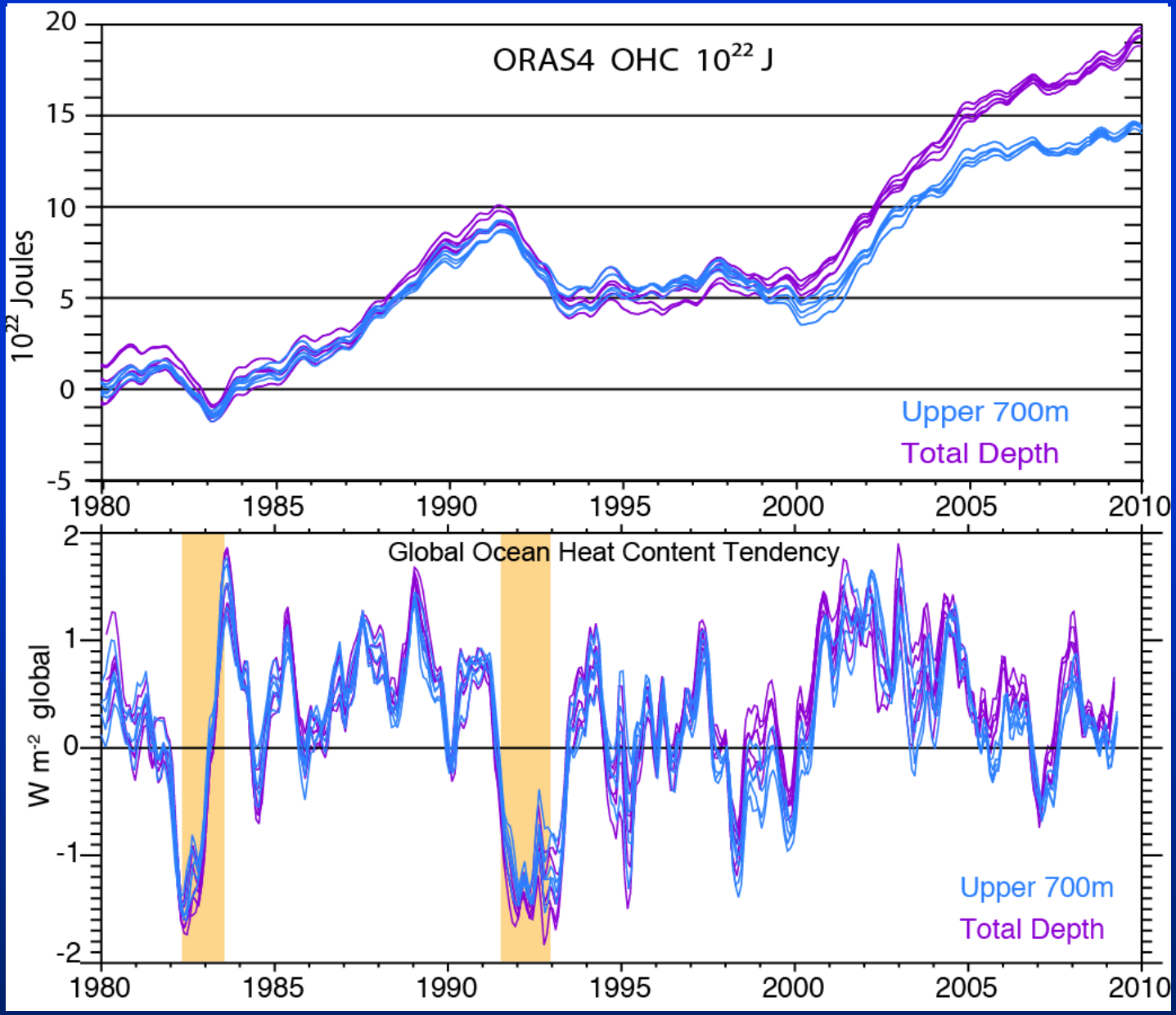
Global Ocean Heat Content



Balmaseda, Trenberth and Källén 2013


ORAS4 OHC by region
GLOBAL
NXTRP
SXTRP
TROP
TRATL
TRPAC
TRIND
1997-98 El Niño
20
15
10
5
0
1960
1965
1970
1975
1980
1985
1990
1995
2000
2005

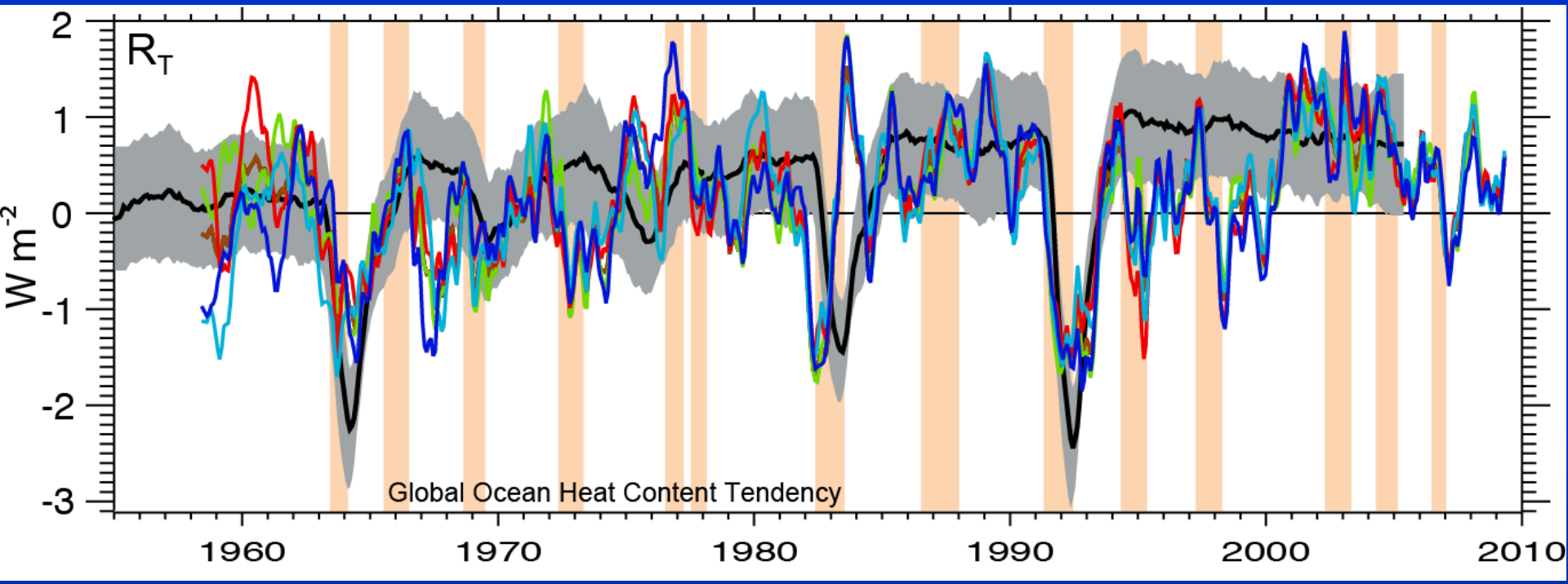
OHC from ORA4 and rates of change



12-mo running means

Diff: 0.21 W m^{-2} 2000s

Rates of change of OHC from ORAS4



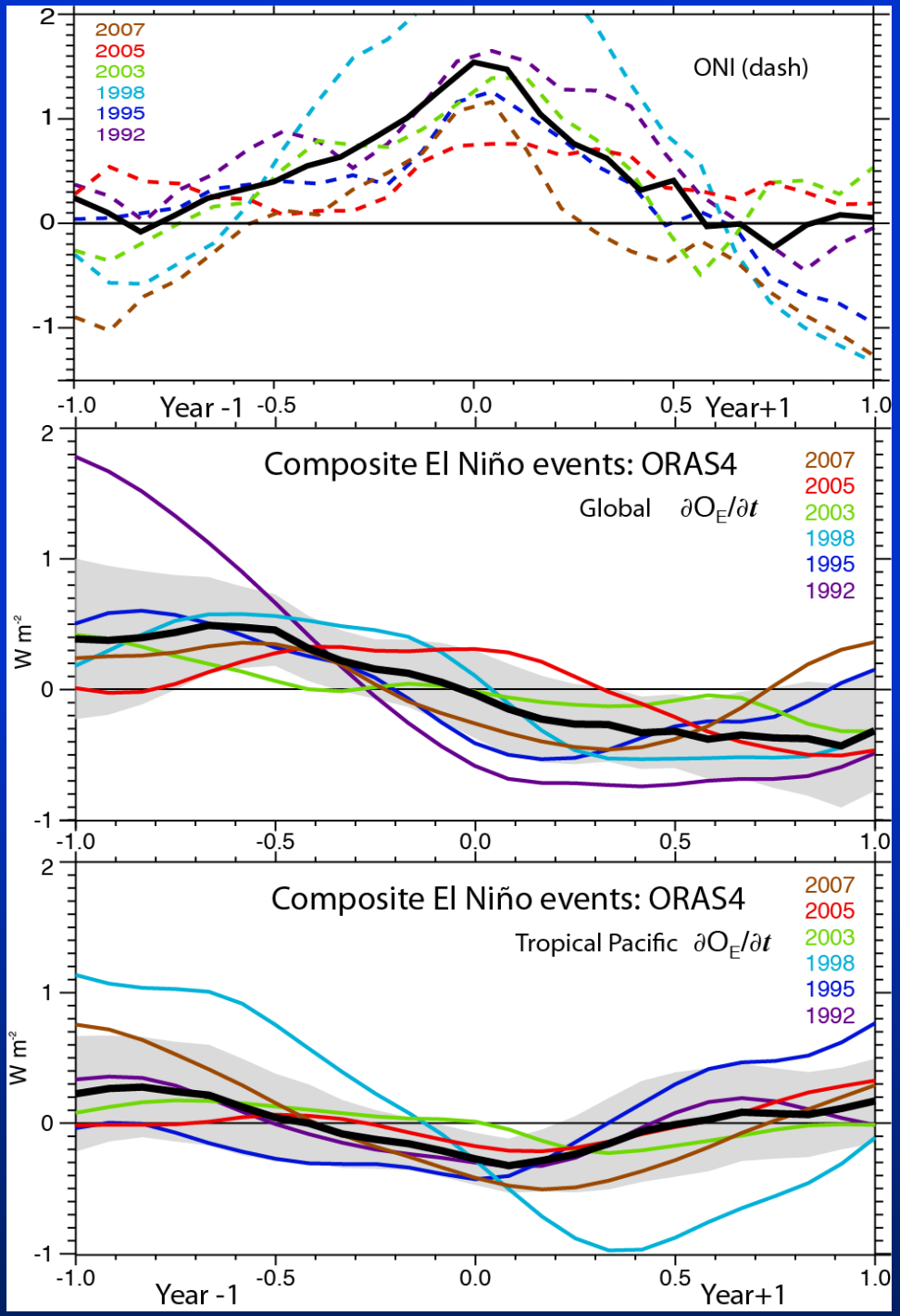
Full depth 5 member ensemble members of ORAS4 OHC in global W m^{-2}.
The ensemble mean and monthly standard deviation of CCSM4 TOA radiation R_T.
El Niño events are marked by the orange bars, as defined by the ONI index of NOAA.

ENSO in ORAS4

TOGA-TAO/Triton array was mainly established 1992-93

These are normalized to be global W m^{-2}.

The tropical Pacific Ocean first then the global ocean loses heat over an El Nino event



ENSO and volcanic events conflated

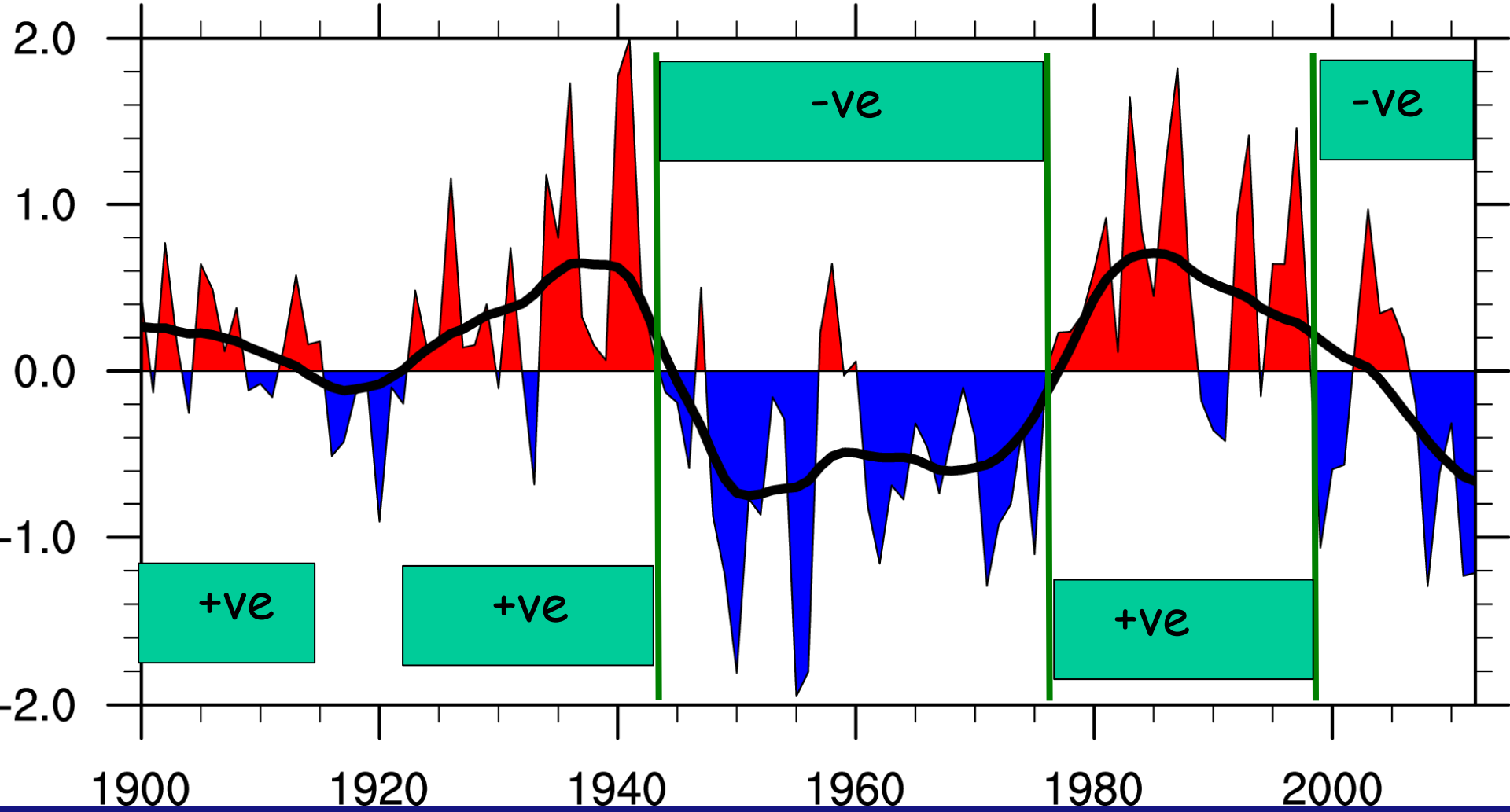
El Niño events occurred

1) July 1963-January 1964 vs Agung Feb-Mar 1963;
2) May 1982-June 1983 vs El Chichon Mar-Apr 1982; and
3) May 1991-July 1992 vs Pinatubo June 1991.

Decadal variability

Given the stronger and more frequent La Niña events since 1998 – related to the PDO – a major question is what role these variations are playing?

PDO Index



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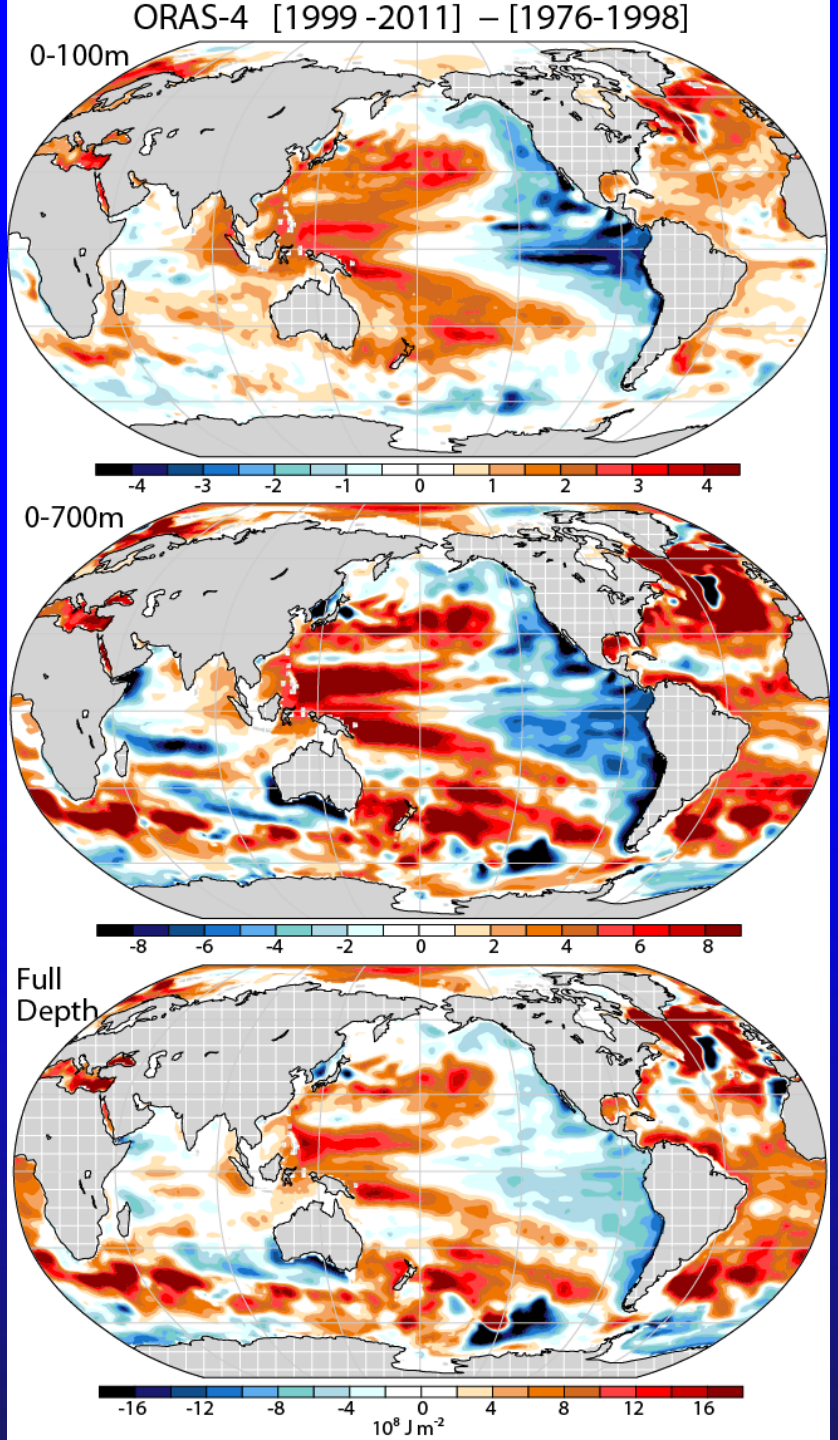
OHC
0-100m

0-700m

Full
depth



Note
different
color scales

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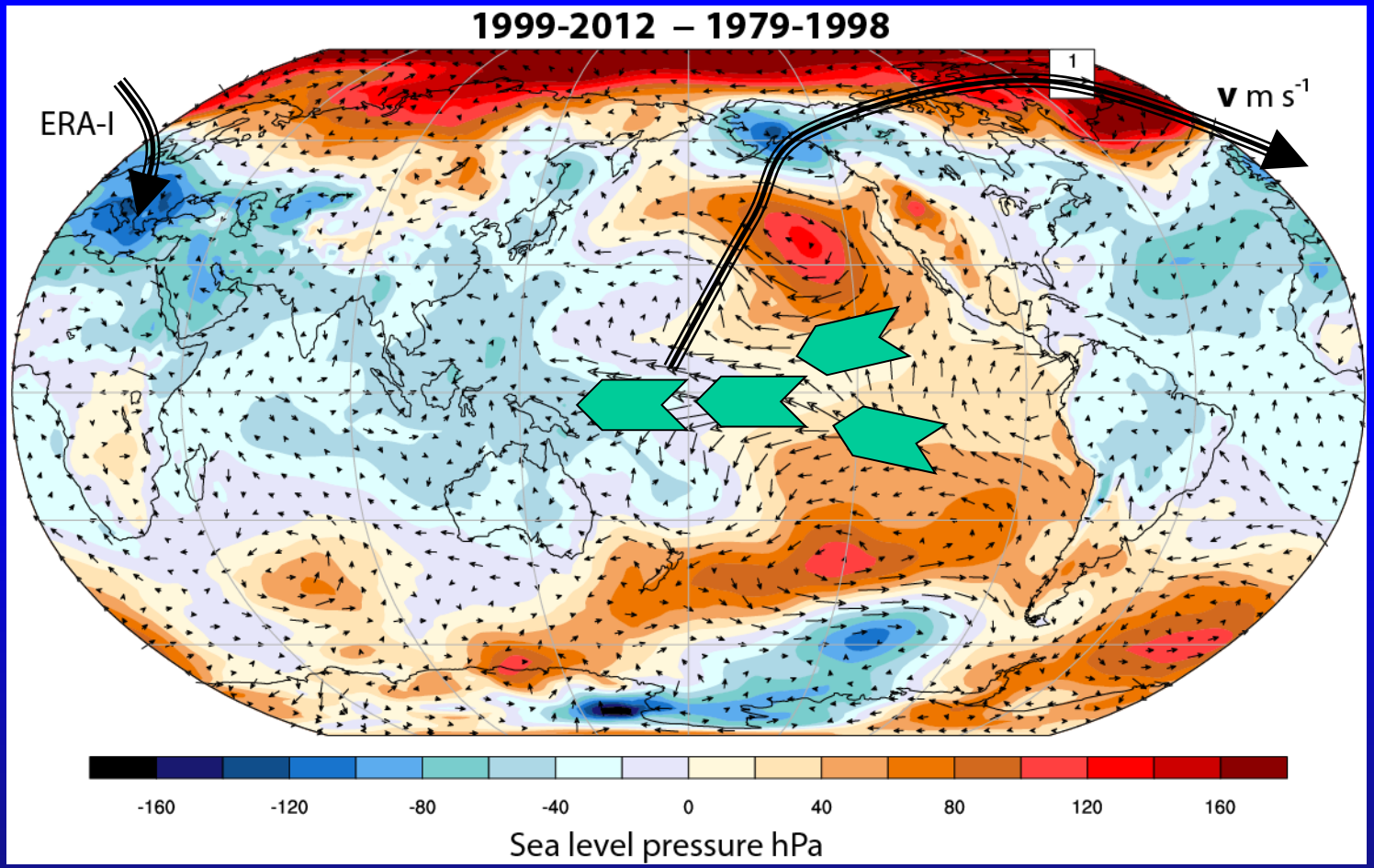
SLP and surface winds
ERA-I



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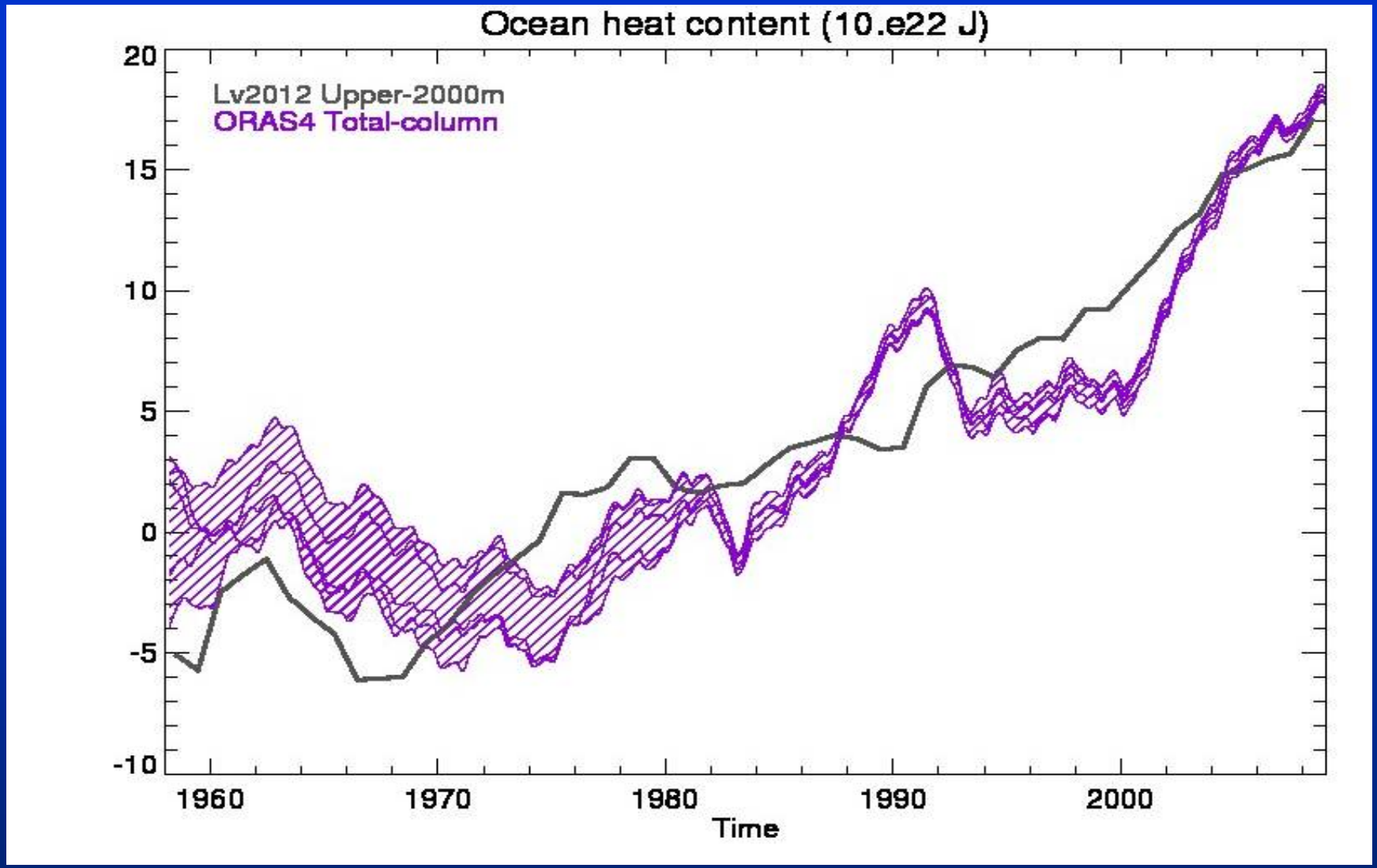
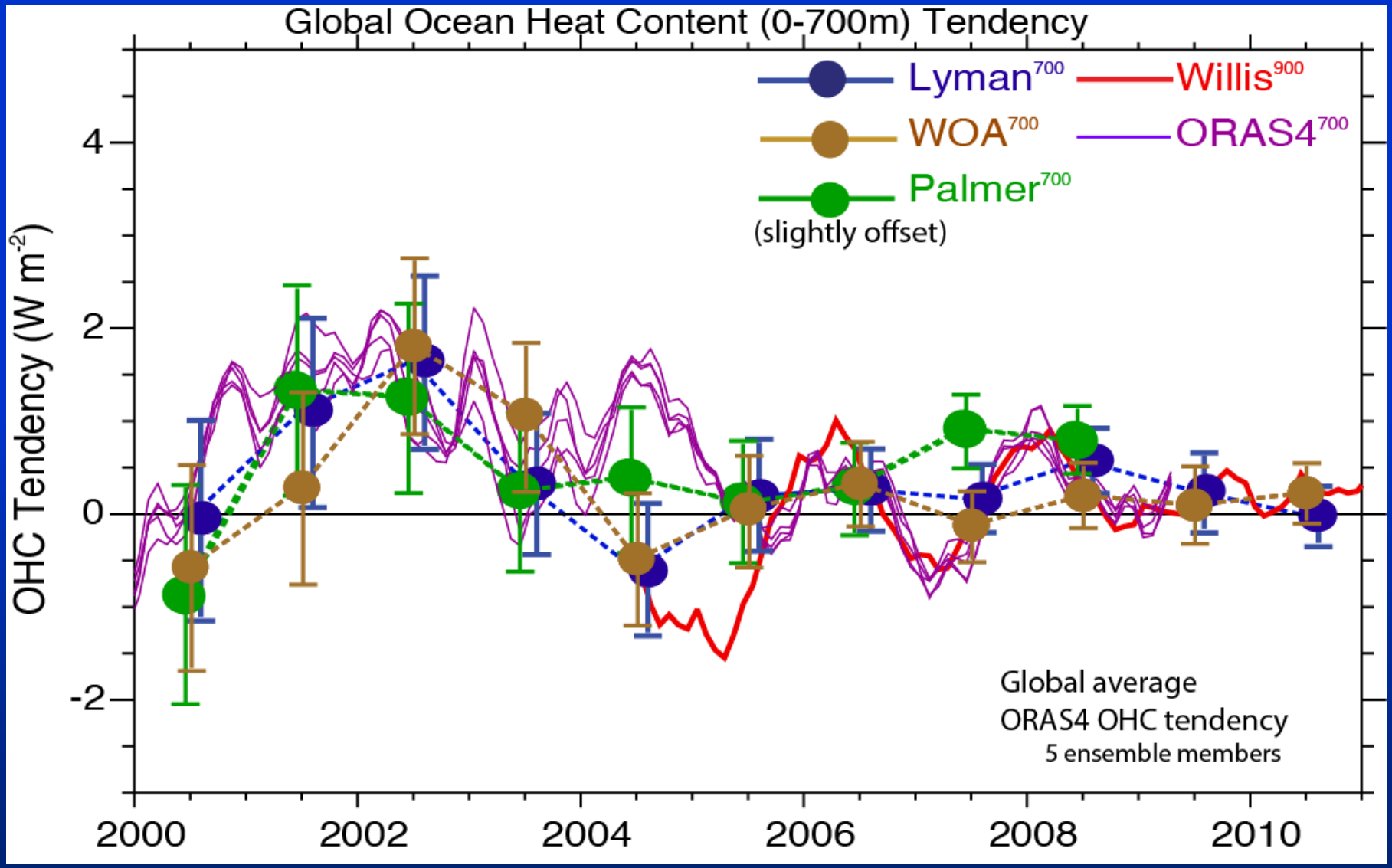
ORAS4 vs WOA


Ocean heat content (10.e22 J)
Lv2012 Upper-2000m
ORAS4 Total-column
20
15
10
5
0
-5
-10
1960
1970
1980
1990
2000
Time

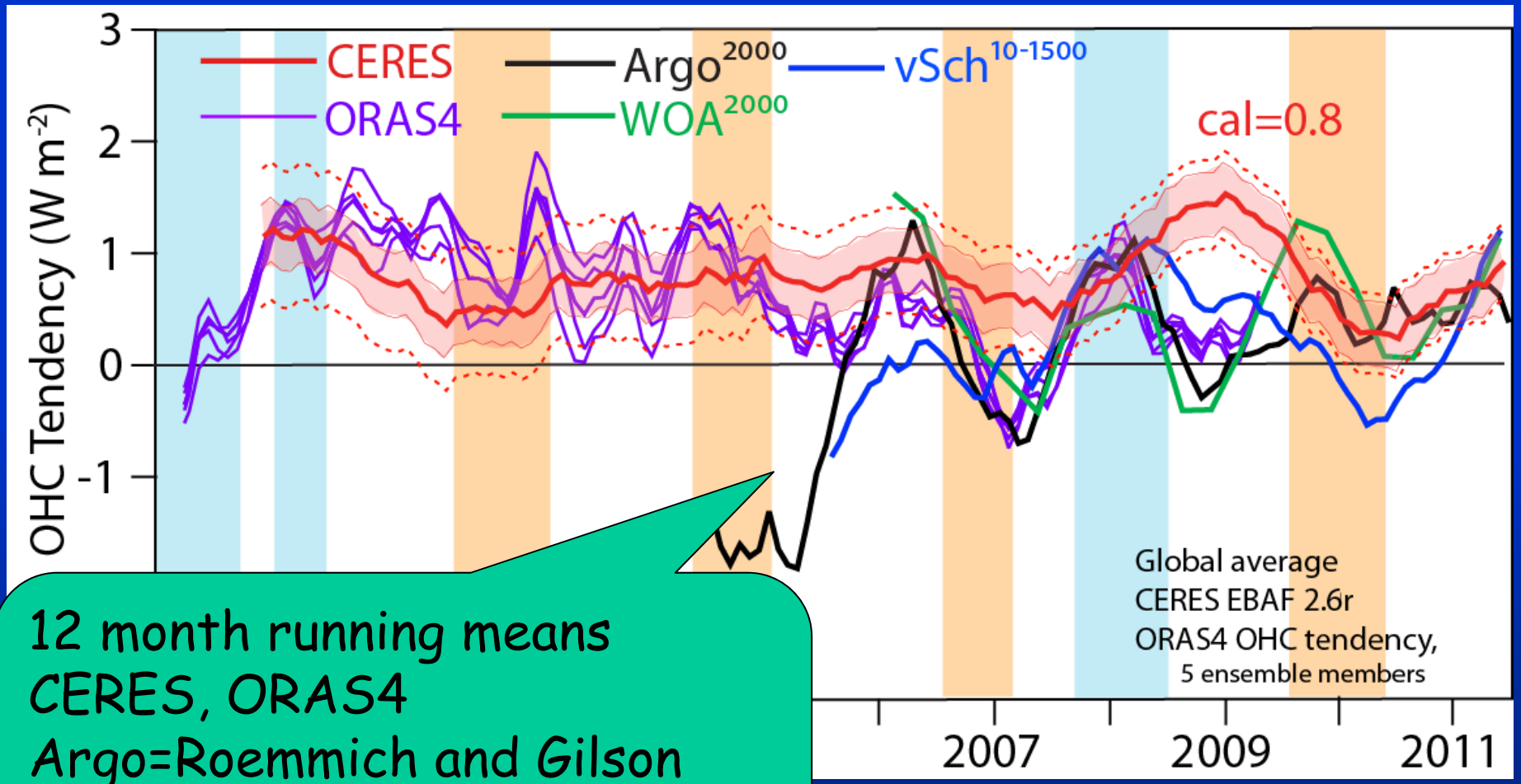
Linear OHC trends: ocean W m^{-2}

	1975-2009	1980s	1990s	2000s
Total (ocean)	0.47 ± 0.03	0.58 ± 0.15	-0.26 ±0.13	1.19 ± 0.11
Global	**0.33**	**0.41**	**-0.18**	**0.84**

0.91 W m^{-2} when melting ice etc included.


Global Ocean Heat Content (0-700m) Tendency
Lyman700
Willis900
WOA700
ORAS4700
Palmer700
(slightly offset)
OHC Tendency (W m-2)
4
2
0
-2
2000
2002
2004
2006
2008
2010
Global average
ORAS4 OHC tendency
5 ensemble members

CERES vs ORAS4



12 month running means
CERES, ORAS4
Argo=Roemmich and Gilson
WOA = Levitus et al.
vSch = von Schuckmann

OHC vs CERES

- There is not great agreement between OHC changes and CERES
- ORAS4 fluctuations are supported by other OHC analyses
- At times there are marked significant discrepancies, notably:
  - 2002 (CERES low vs OHC)
  - 2007 (CERES high vs OHC)
  - 2009 (CERES high vs OHC)

While the error bars are large, there appears to be either:

- **missing energy, or**
- **mismatches in CERES vs OHC**

Key signals in ORAS4

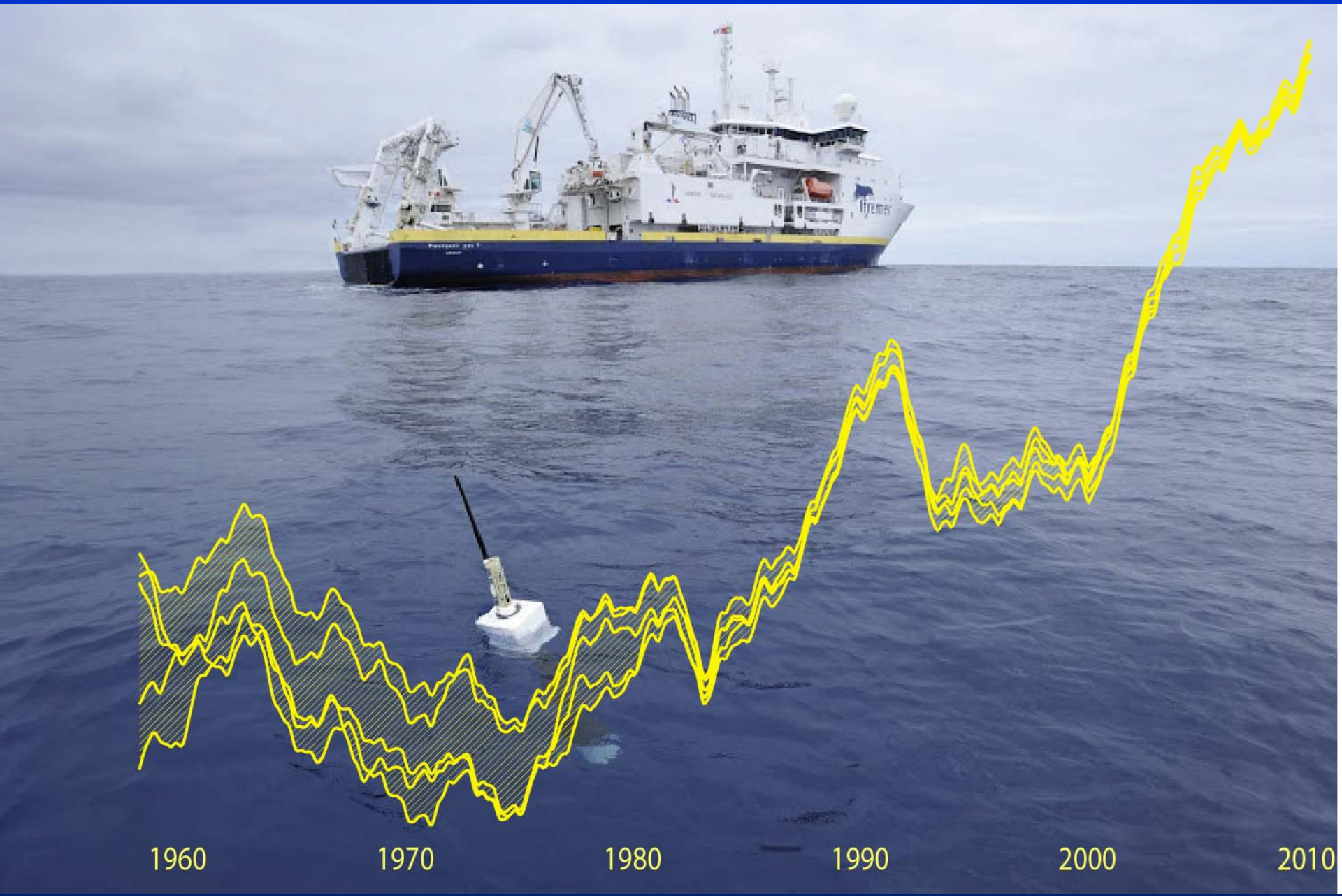
- During the last decade, the ocean has warmed at a higher rate than in the preceding record, even when the impact of Argo is taken into account.
- About 30% of the warming occurs in depths below 700m. This involvement of the deep ocean in the heat uptake is unprecedented.
- Volcanic eruptions, ENSO and the deep ocean contribute identifiable signals to the character of ocean heat content changes.
- The increasing disparity of warming in different layers arises largely from changes in the surface winds, and remains even when the Argo is withdrawn.

Earth's energy imbalance

- Varies from day to day with clouds and weather
- Varies from year to year with ENSO
- And with sharp drops with volcanic eruptions
- Varies with the PDO
- The net imbalance of energy in the 2000s went from order 1 W m^{-2} to 0.8 W m^{-2} with the quiet sun and minor volcanic activity

Missing energy?

- Some missing energy appears to be in the deep ocean and unprecedented heating of the deeper ocean is occurring.
- It is related to La Niña/ negative PDO
- During the positive phase of PDO, more heat is deposited at shallow depths, while in –ve PDO more heat is deposited below 700 m depth.



Cover of GRL with Balmaseda et al 2013