Reconciling Differences in Upper Ocean Heat content

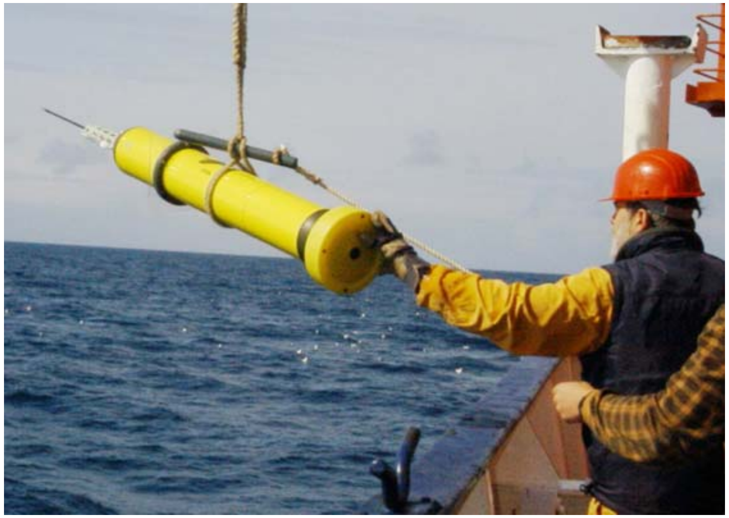
Simon A. Good, Viktor V. Gouretski, Masayoshi Ishii, Gregory C. Johnson, Matthew D. Palmer, Doug M. Smith & Josh K. Willis

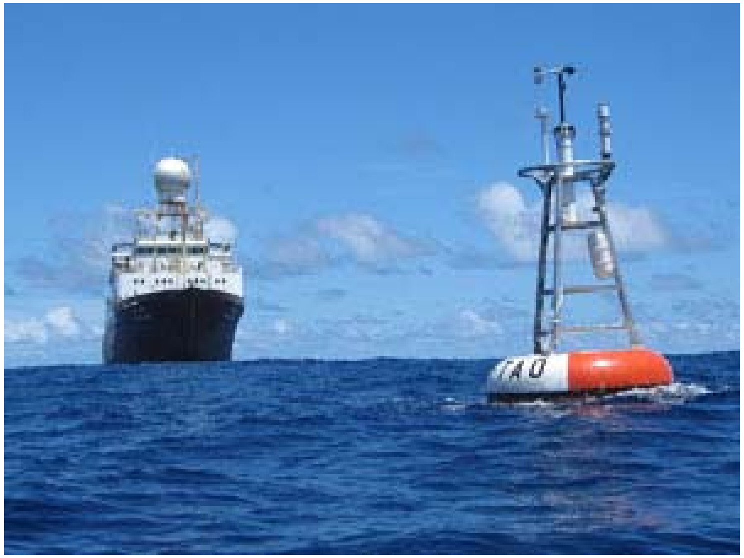
Climate Budgets

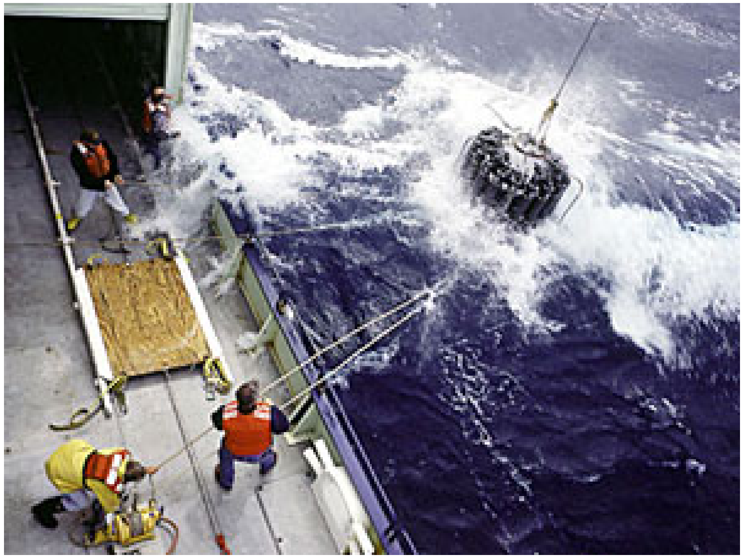
- Freshwater budget
  - Thermosteric – Altimeter vs. estimates of freshwater input (Glaciers)
- Close Heat Flux budget
  - Year to year changes in ocean heat content vs. Top of atmosphere estimates

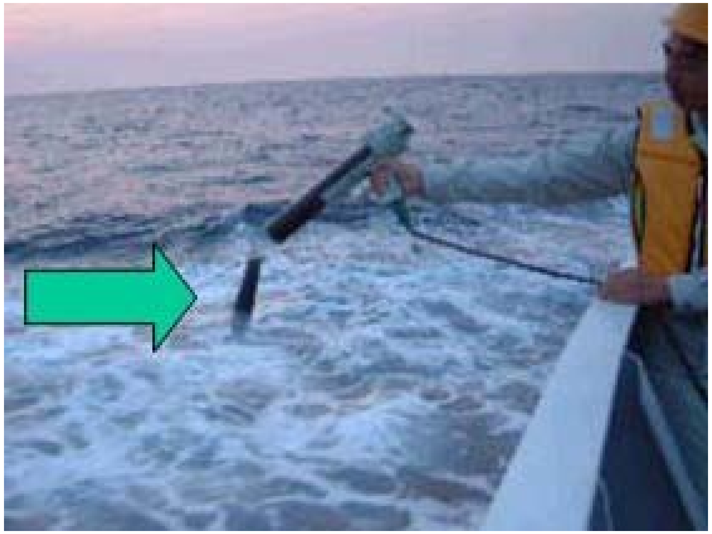
Road map

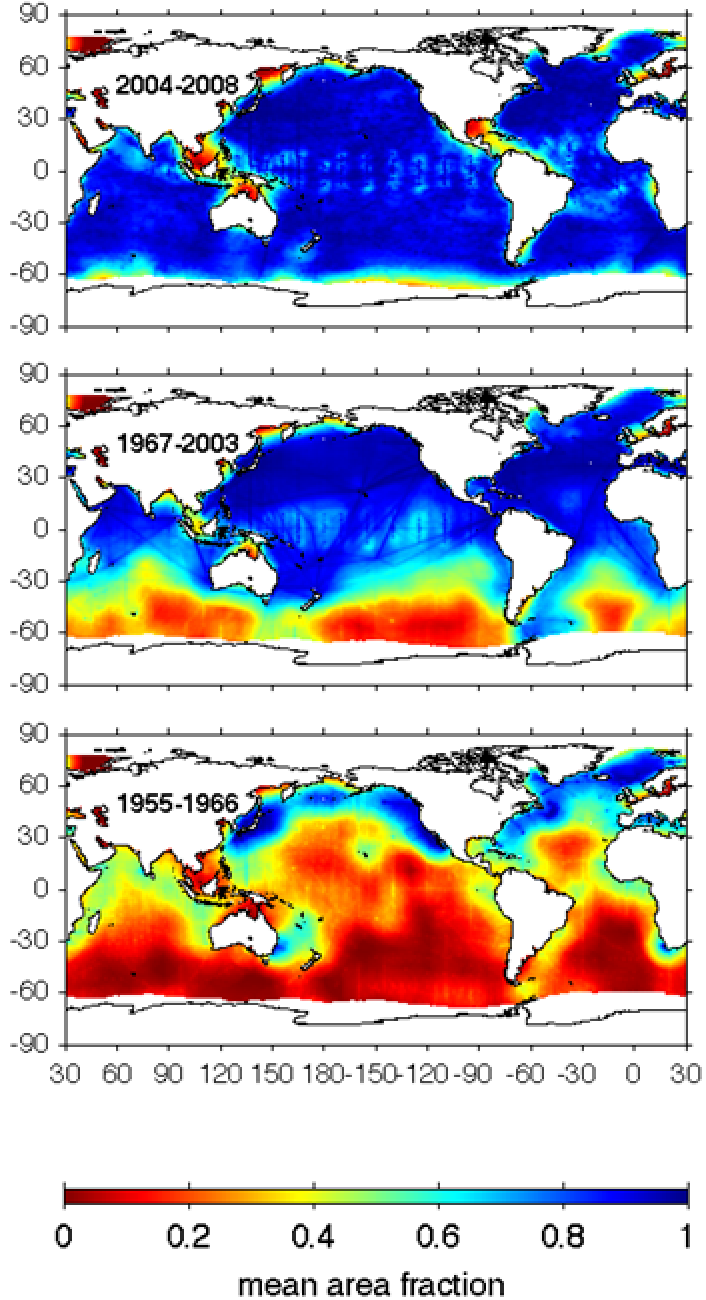
- Measuring ocean heat content anomaly (OHCA)
- Uncertainty in OHCA




TAO

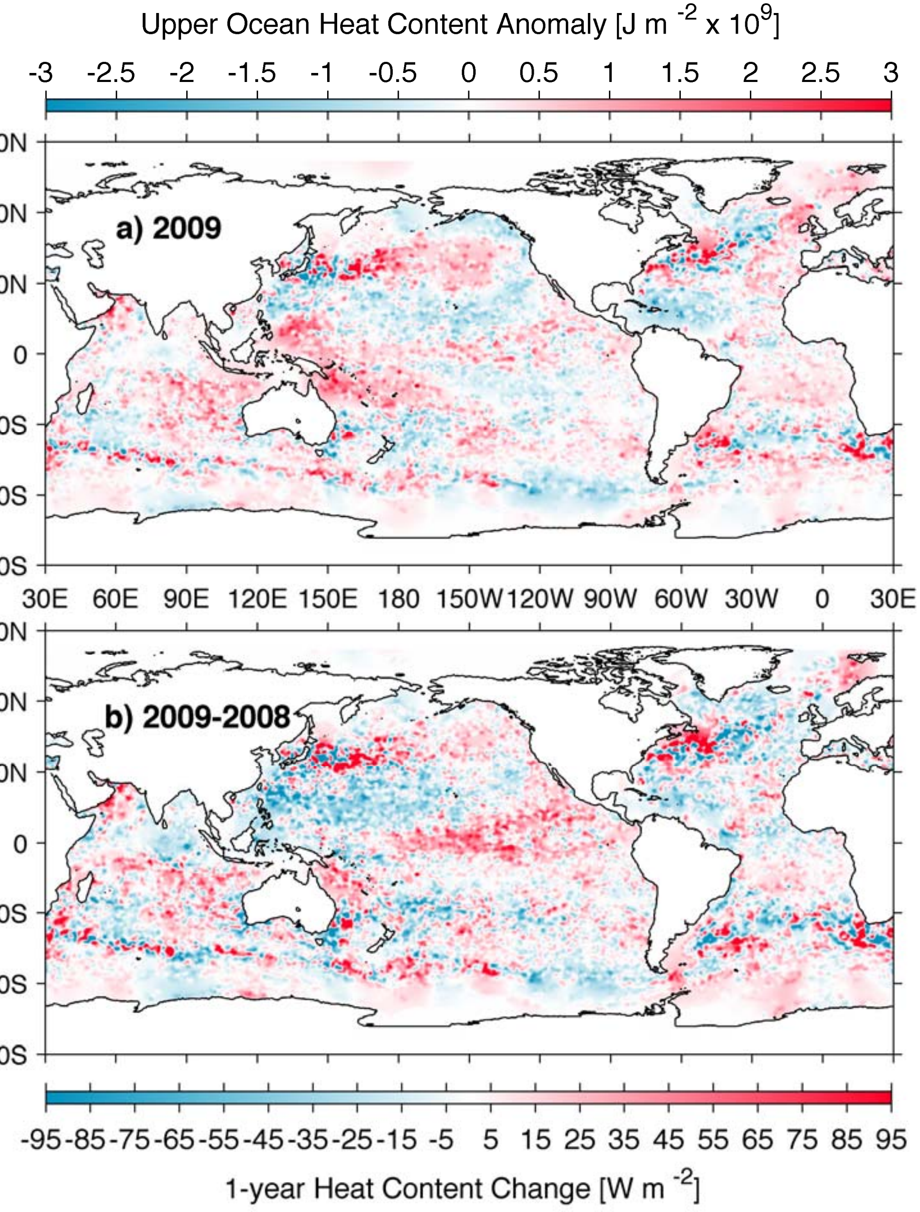


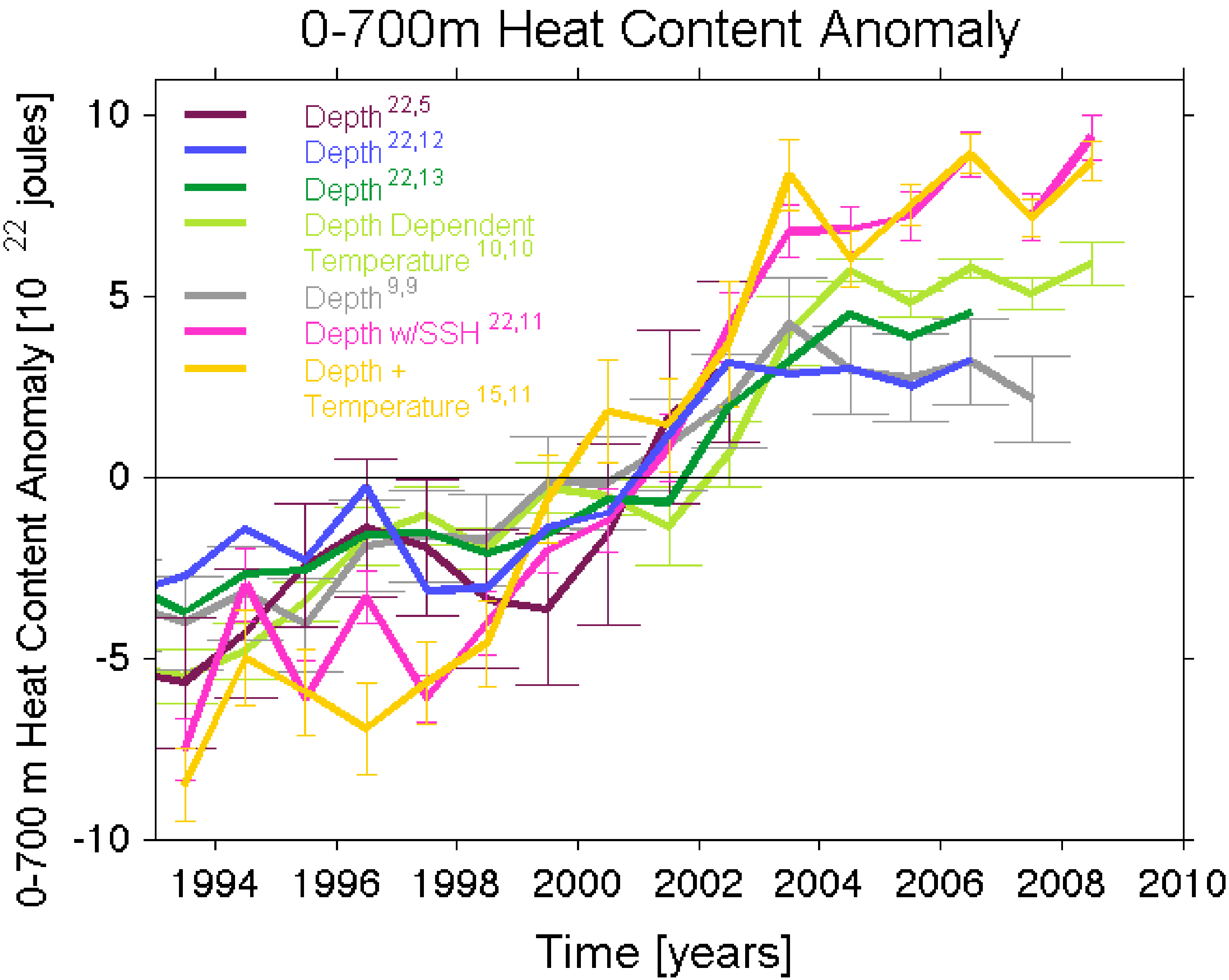



2004-2008
1967-2003
1955-1966
90
60
30
0
-30
-60
-90
30 60 90 120 150 180 -150 -120 -90 -60 -30 0 30
0
0.2
0.4
0.6
0.8
1
mean area fraction

Mapping

- 0-700 m
- Removed a mean and an annual cycle
- Binned into 1-year bins
- Objective map ~ 100 km and ~ 1000 km (Zang and Wunsch 2001)





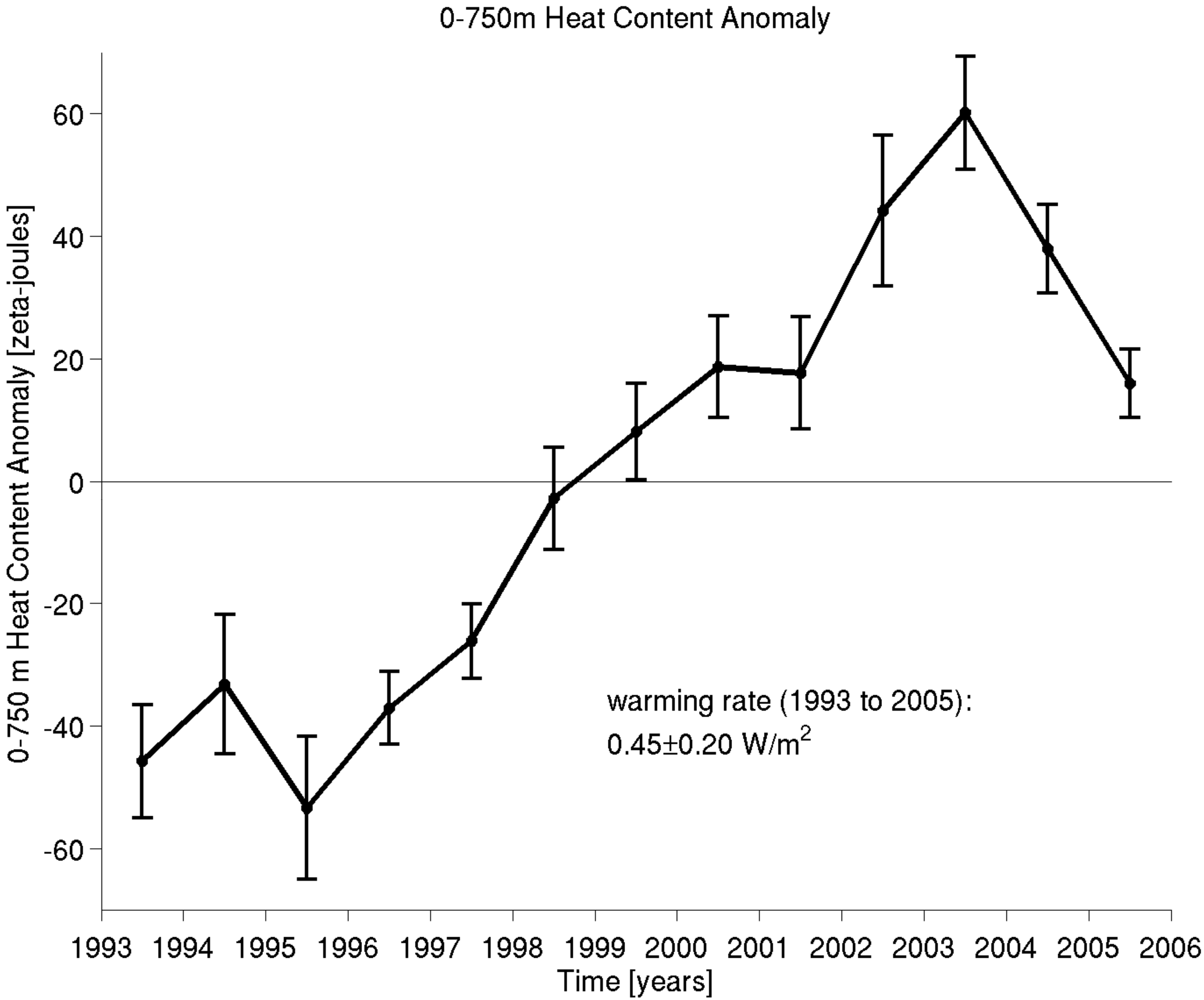
[22] Wijffels (2008) CTD pairs, Depth

[22] Wijffels (2008) Altimeter SSH, Depth

[10] Levitus (2009) CTD pairs, Depth Dependent Temperature

[9] Ishii (2009) CTD pairs, Depth (time)

[15] Gouretski (2010) CTD pairs, Depth and Temperature



0-750m Heat Content Anomaly
0-750 m Heat Content Anomaly [zeta-joules]
60
40
20
0
-20
-40
-60
warming rate (1993 to 2005):
0.45±0.20 W/m2
1993
1994
1995
1996
1997
1998
1999
2000
2001
2002
2003
2004
2005
2006
Time [years]

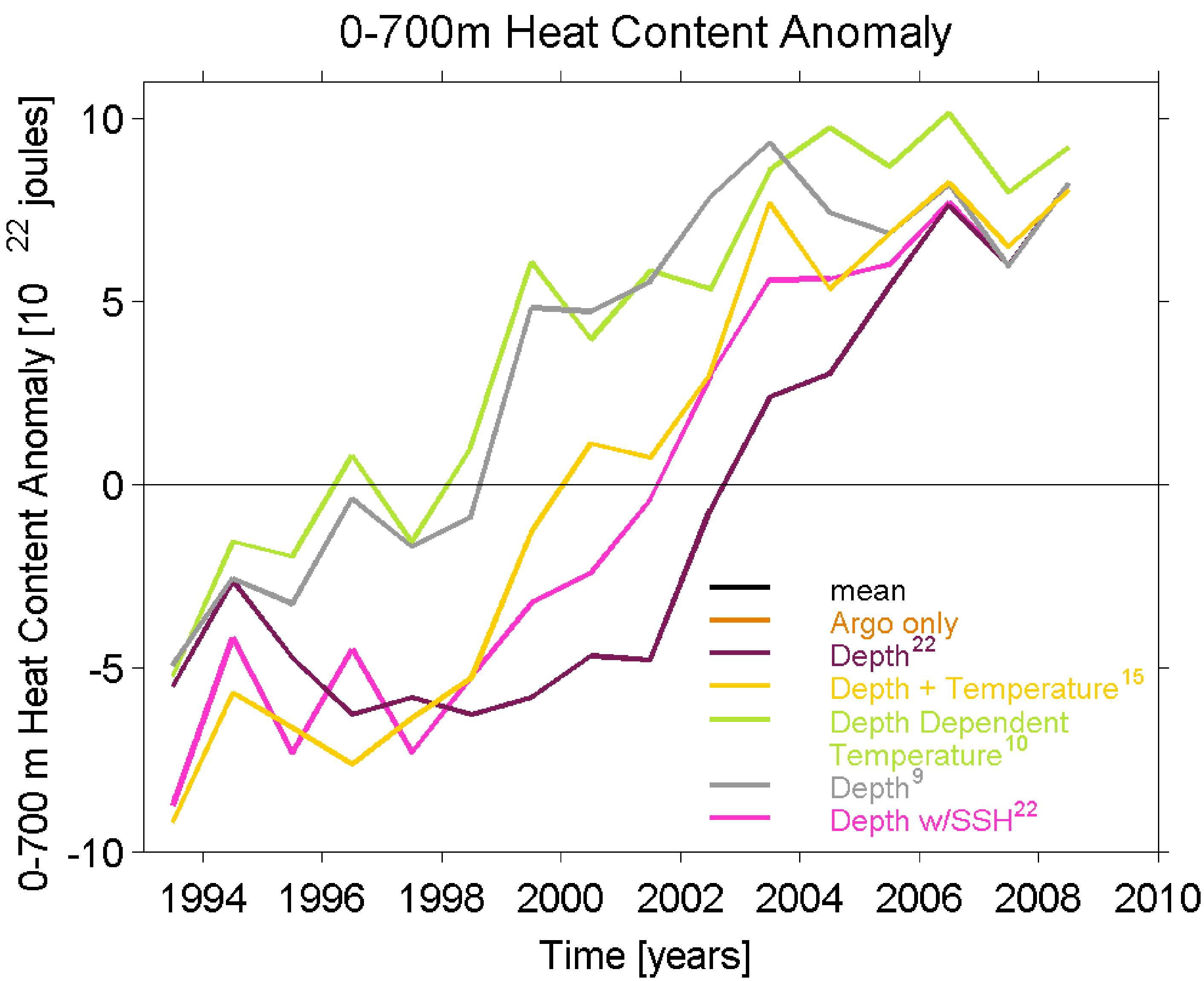
Types of Uncertainty

- Systematic
  - we know about (XBT fall rate correction)
  - we don’t know about
- Random
- Mapping
- Climatology
- Sampling
  - distribution of data
    - Spatial
    - temporal
  - Resolution of Variability
    - Eddies
    - Gyres
    - Global mean

XBT Uncertainty

The XBT correction is hard to apply.

- Meta-data
- Want to make sure that you are correcting the same profiles



Just xbt corrections only

[22] Wijffels (2008) CTD pairs, Depth
[22] Wijffels (2008) Altimeter SSH, Depth
[10] Levitus (2009) CTD pairs, Depth Dependent Temperature
[9] Ishii (2009) CTD pairs, Depth (time)
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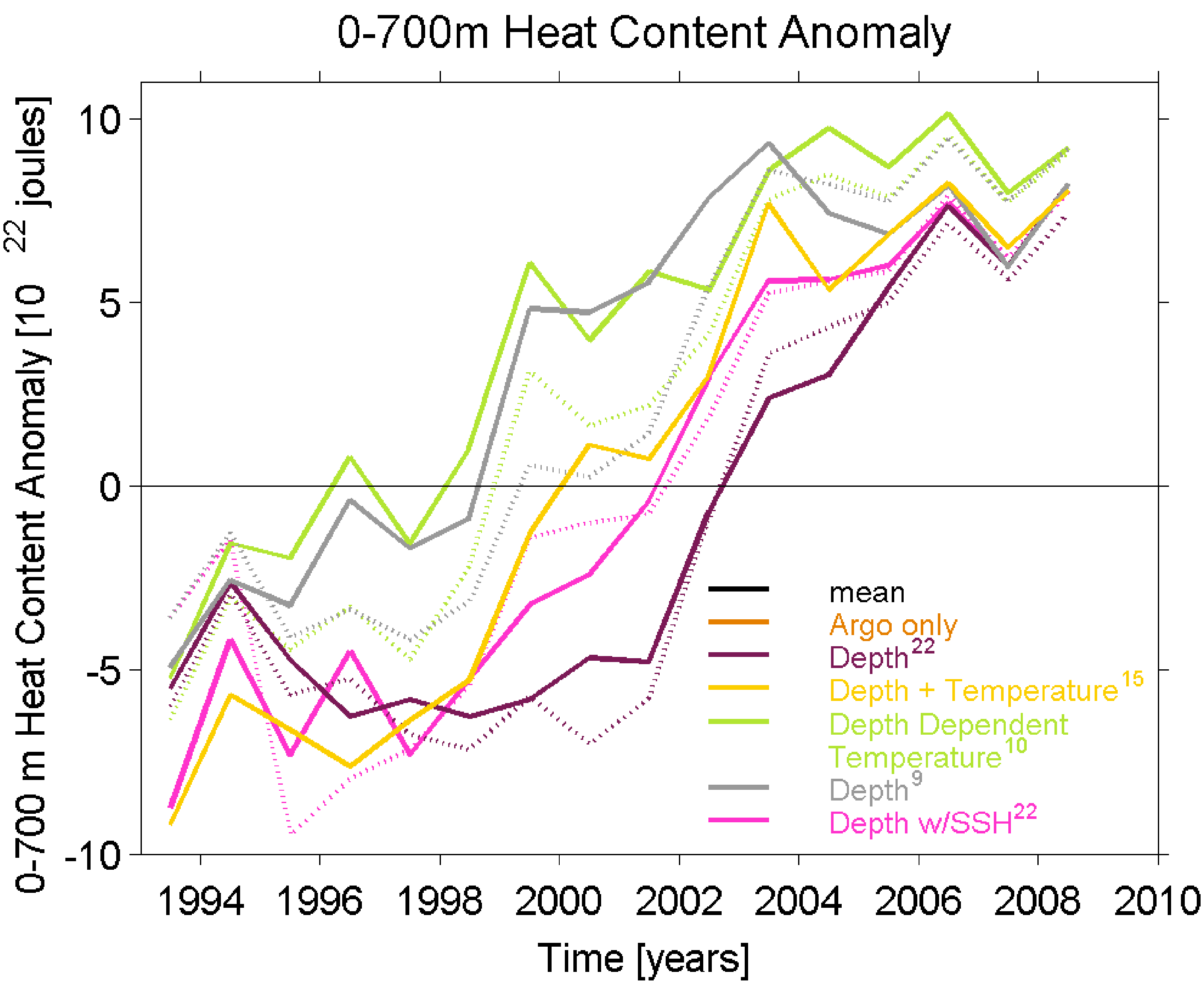

Just the climo

[22] Wijffels (2008) CTD pairs, Depth
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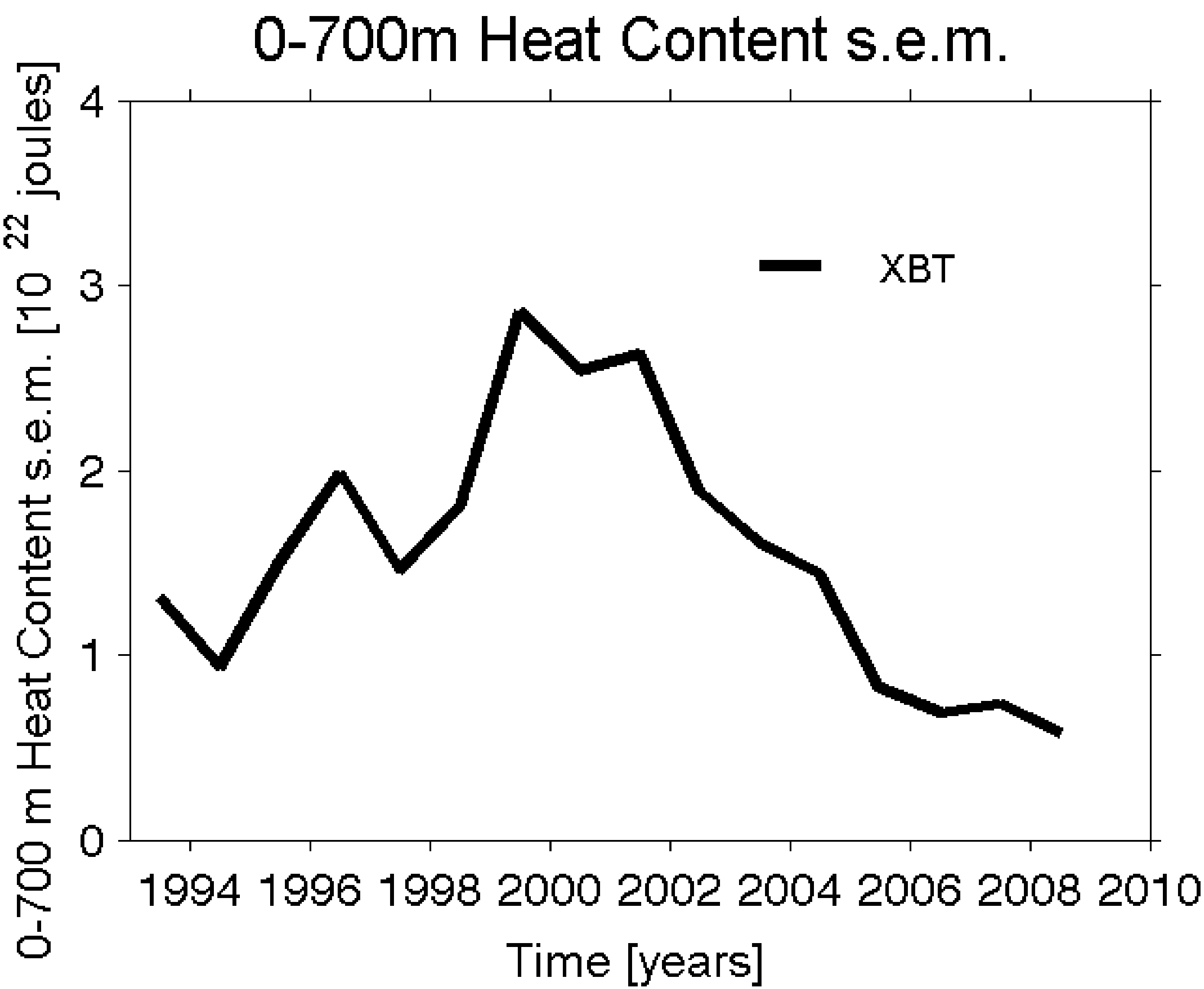
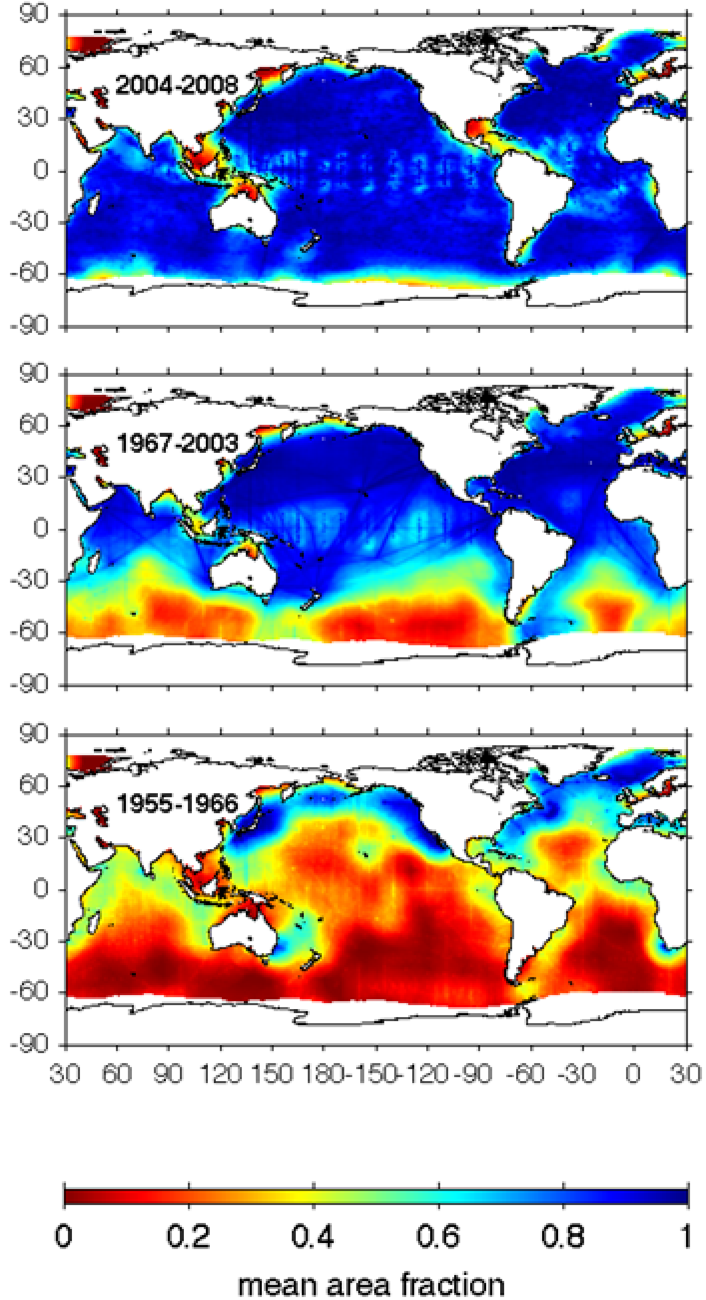
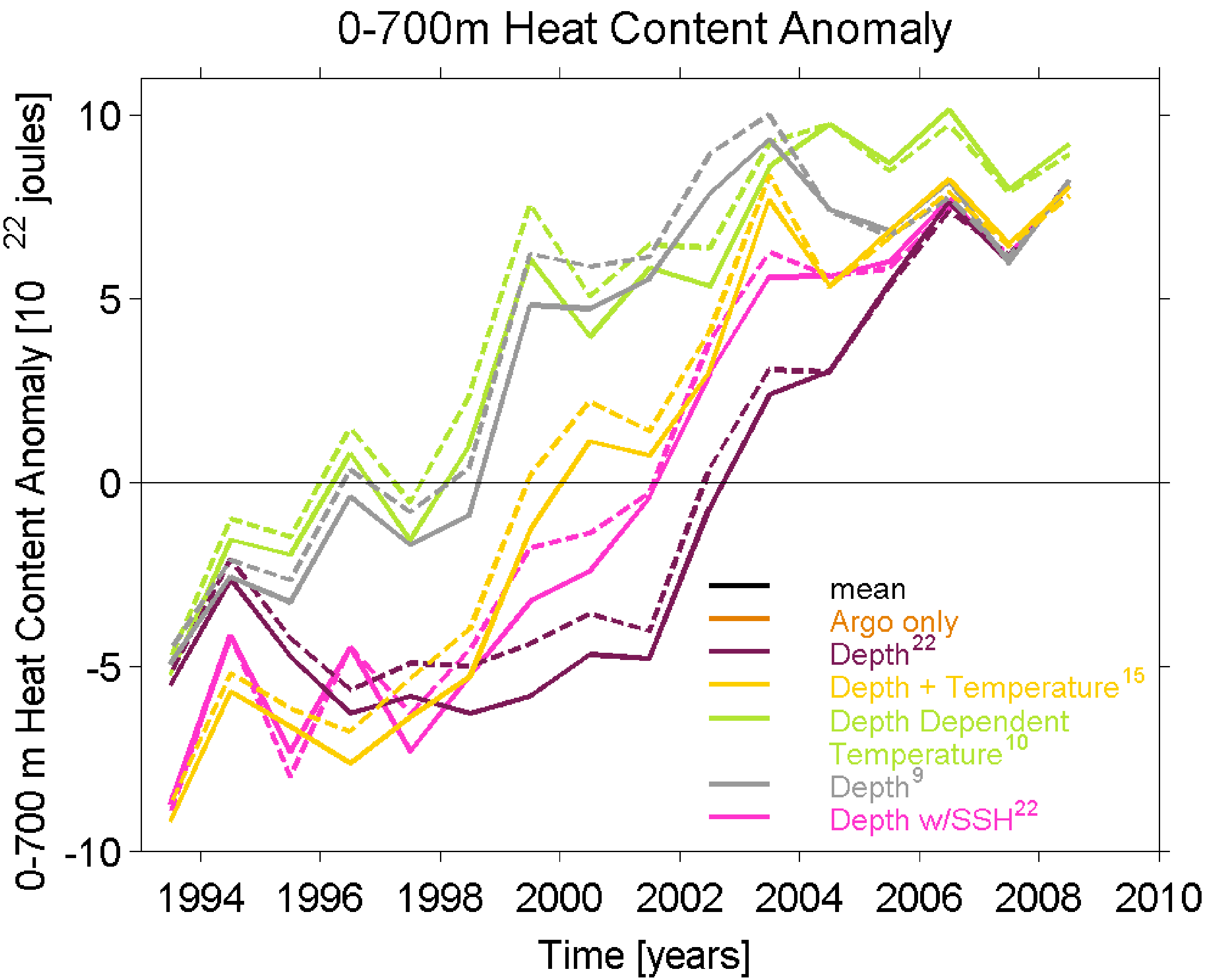


0-700m Heat Content s.e.m.
XBT
0-700 m Heat Content s.e.m. [10 22 joules]
0
1
2
3
4
1994
1996
1998
2000
2002
2004
2006
2008
2010
Time [years]

Climatological Uncertainty


90
60
30
0
-30
-60
-90
2004-2008
1967-2003
1955-1966
30 60 90 120 150 180 -150 -120 -90 -60 -30 0 30
0
0.2
0.4
0.6
0.8
1
mean area fraction



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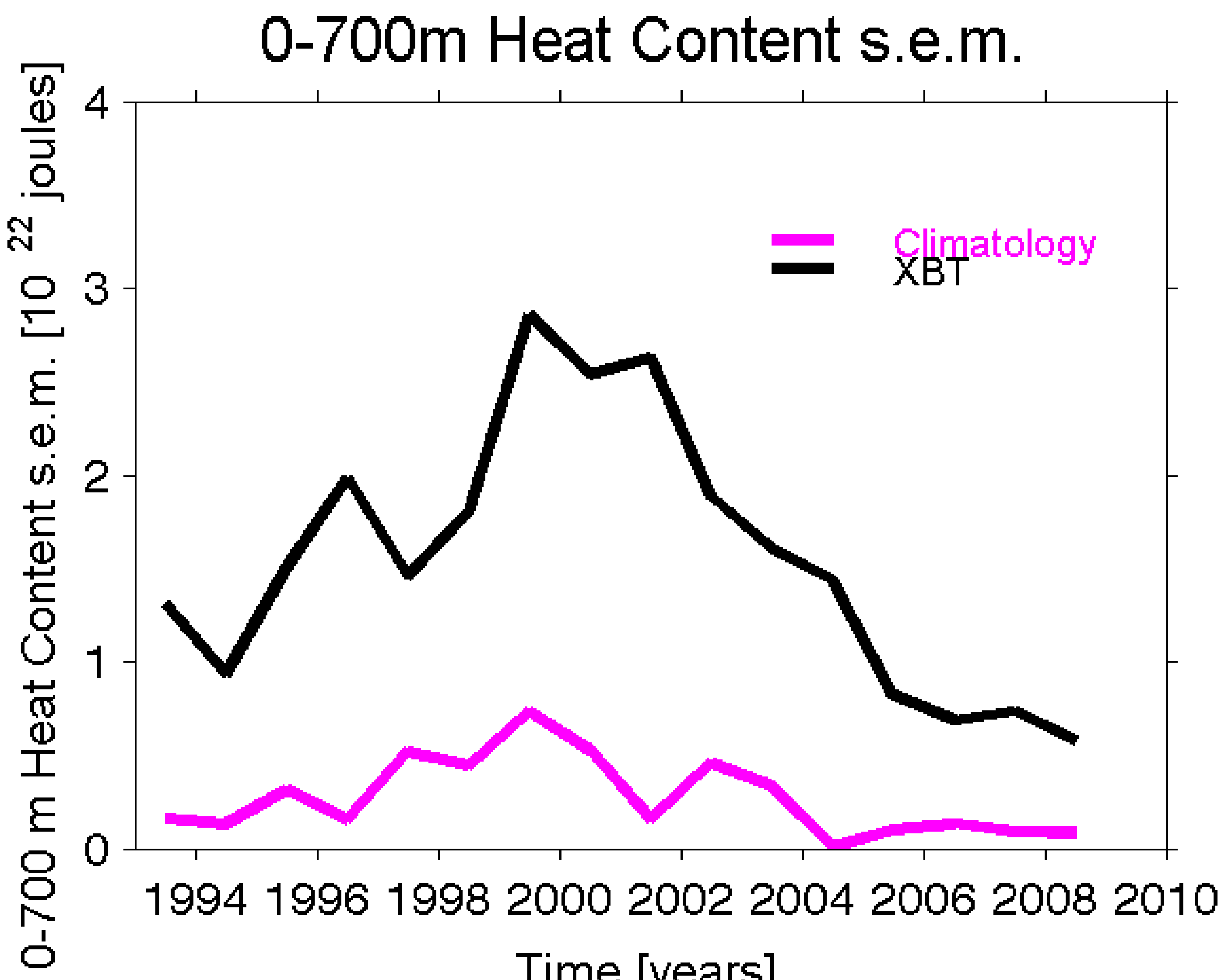
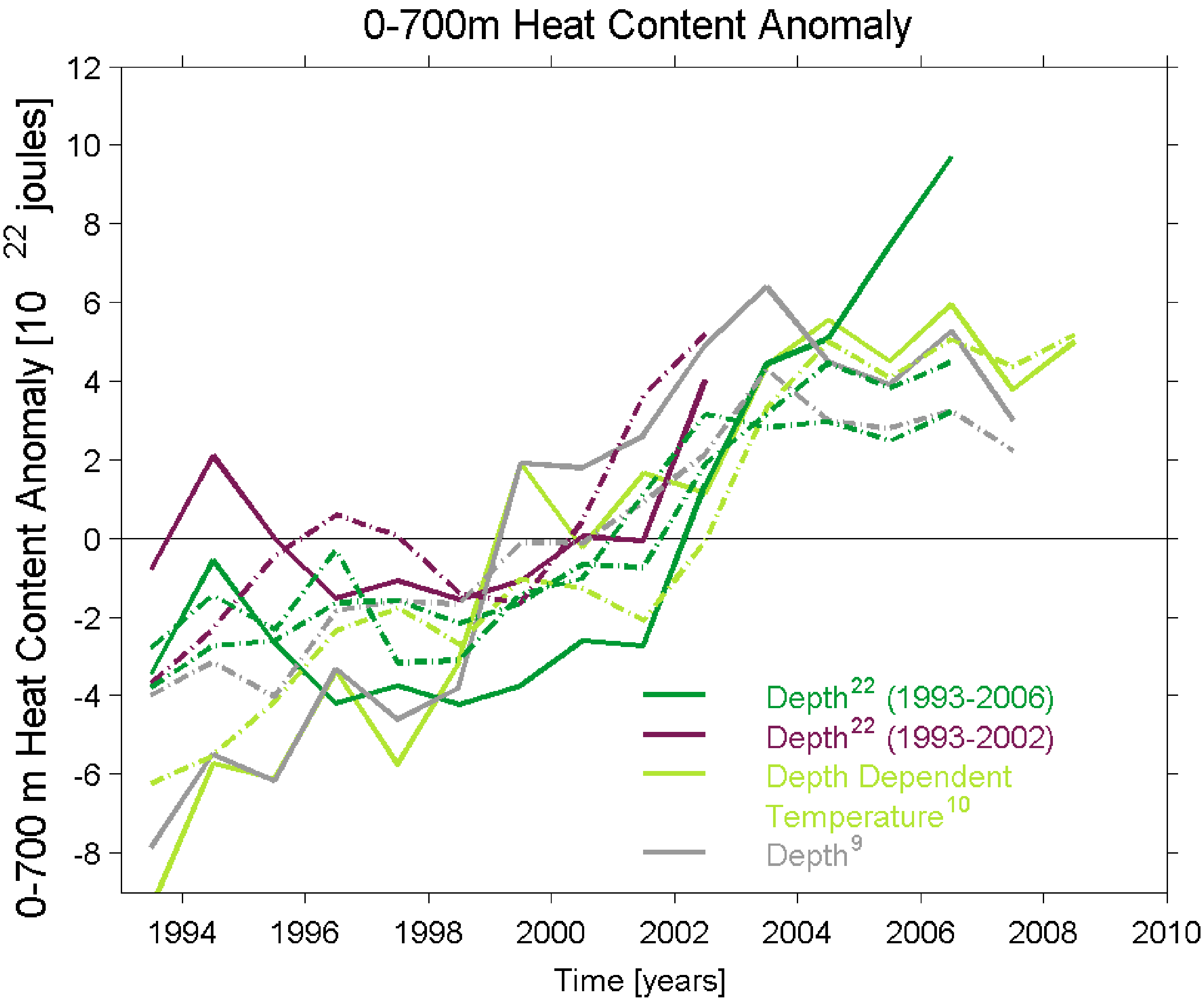
[15] Gouretski (2010) CTD pairs, Depth and Temperature

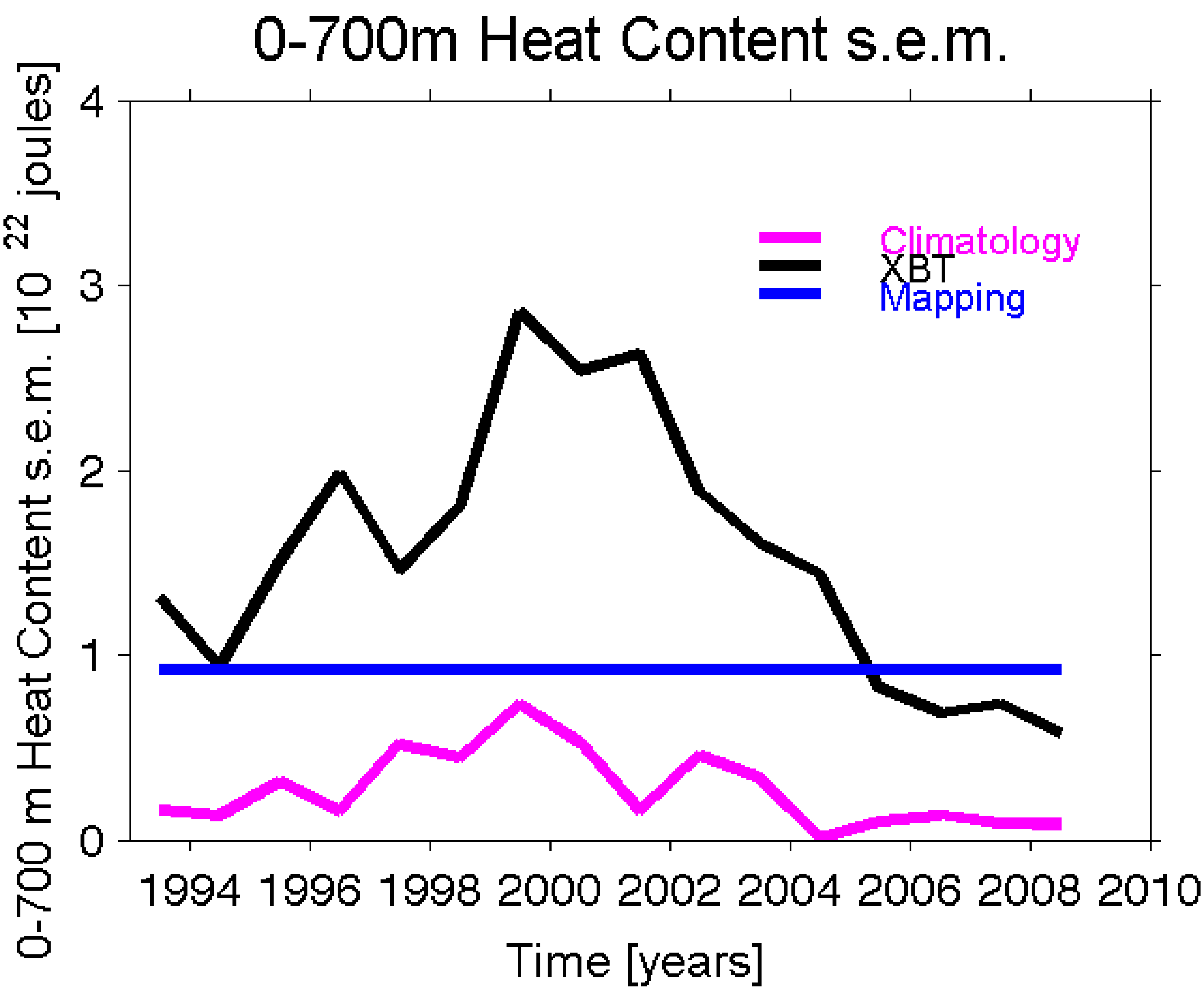
Simons only


0-700m Heat Content s.e.m.
Climatology
XBT
0-700 m Heat Content s.e.m. [10 22 joules]
0
1
2
3
4
1994
1996
1998
2000
2002
2004
2006
2008
2010
Time [years]

Mapping Uncertainty

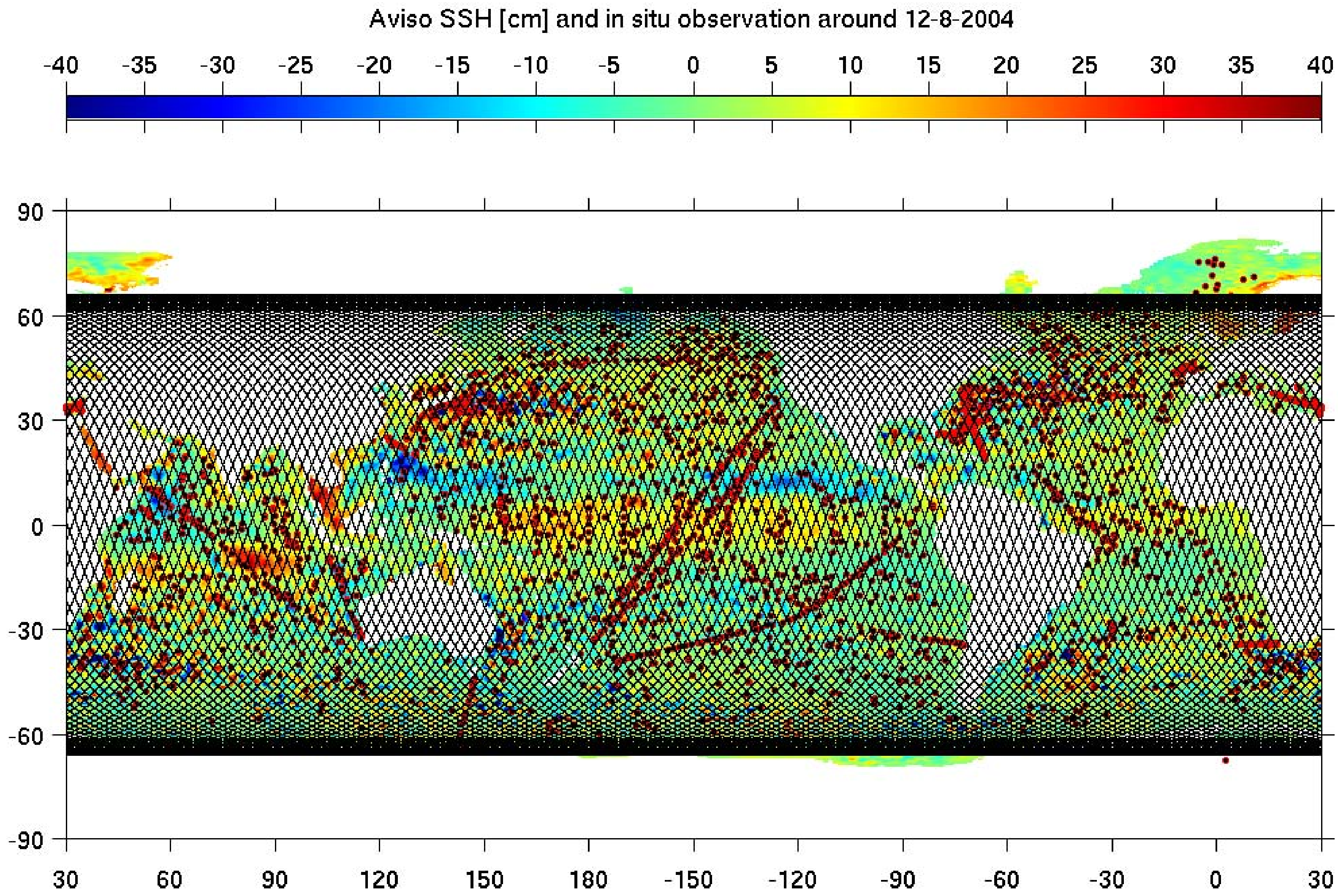


22 Wijffels (2008) CTD pairs, Depth
22 Wijffels (2008) Altimeter SSH, Depth
10 Levitus (2009) CTD pairs, Depth Dependent Temperature
9 Ishii (2009) CTD pairs, Depth (time)
15 Gouretski (2010) CTD pairs, Depth and Temperature

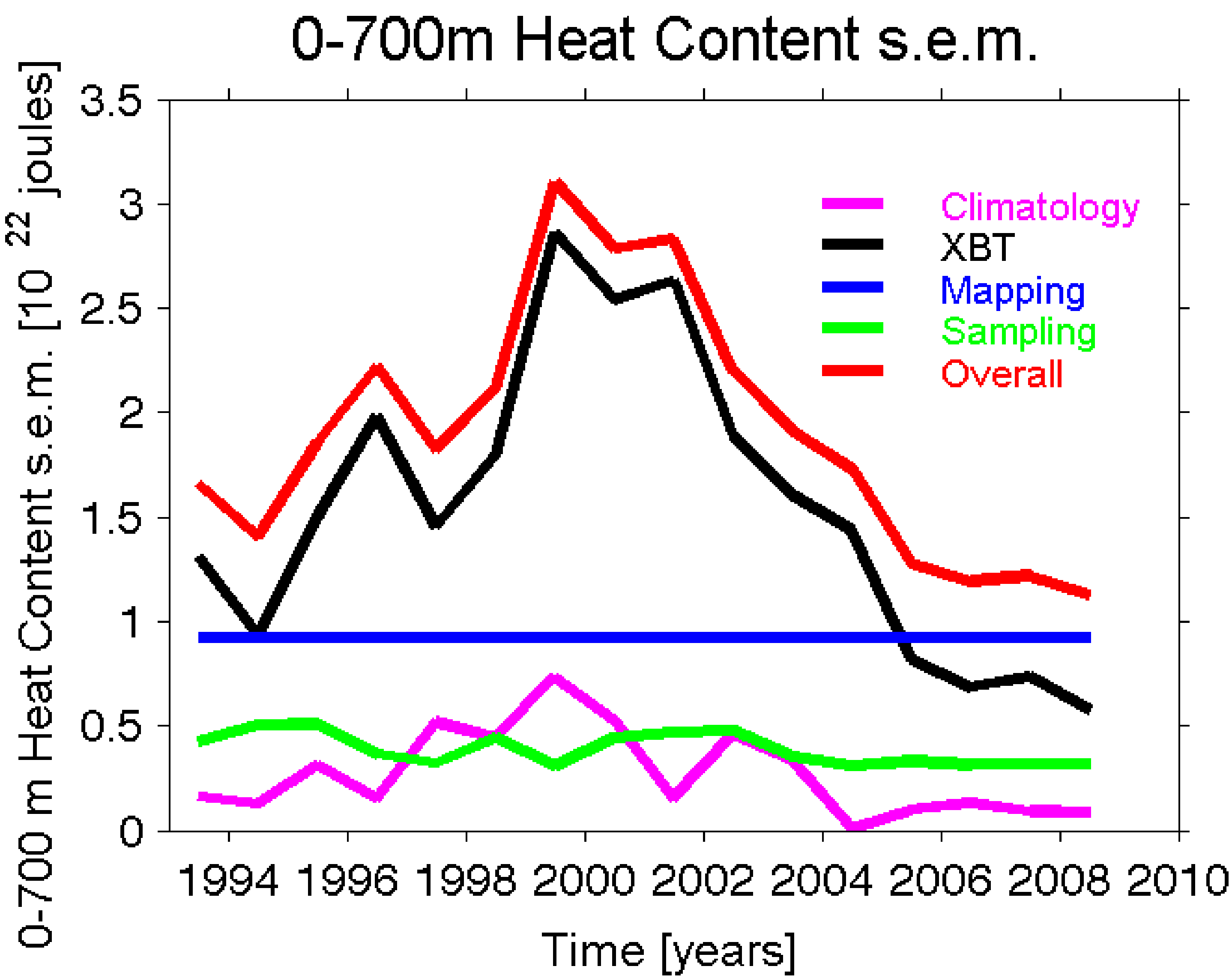


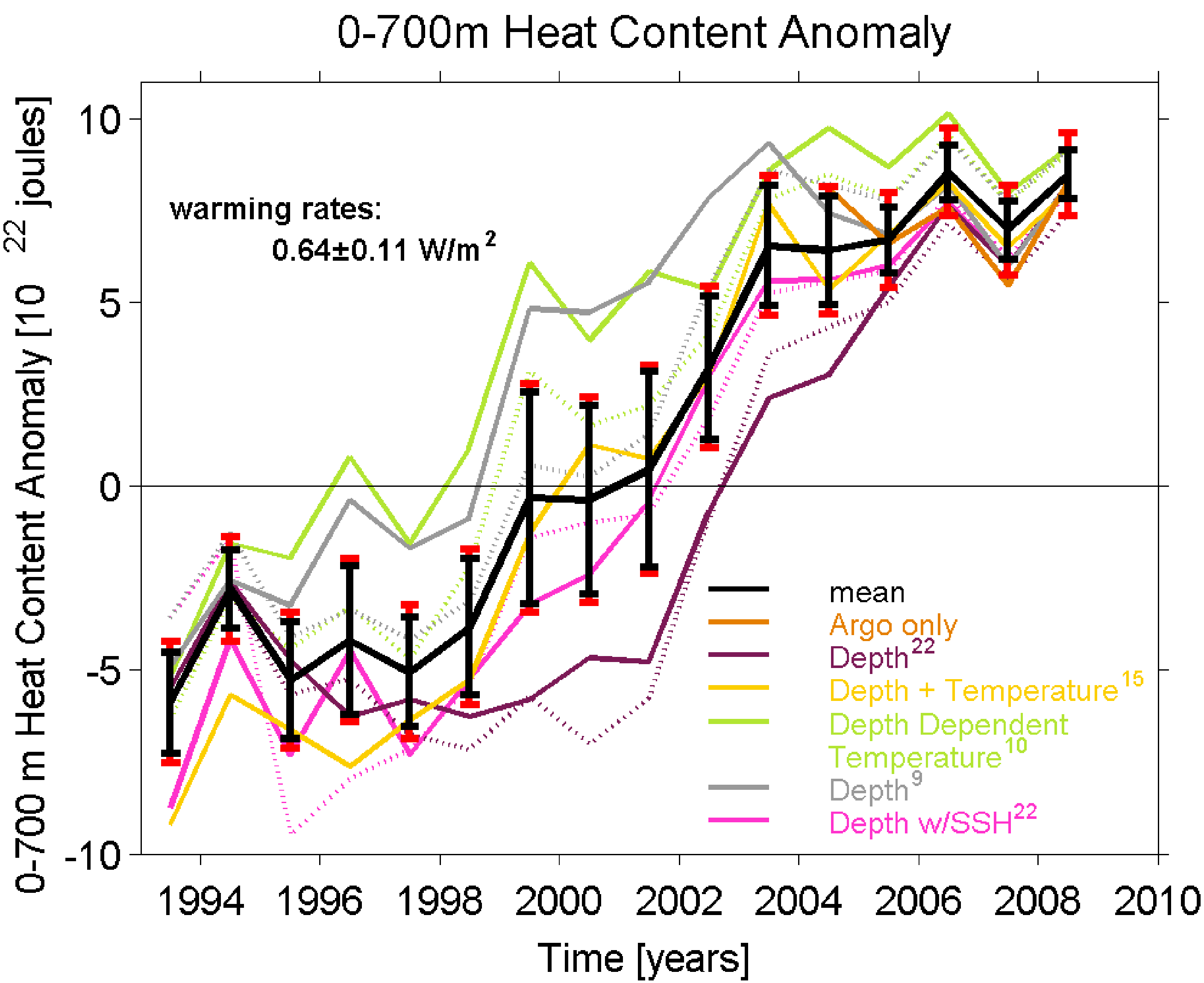
0-700m Heat Content s.e.m.
0-700 m Heat Content s.e.m. [10 22 joules]
4
3
2
1
0
Climatology
XBT
Mapping
1994 1996 1998 2000 2002 2004 2006 2008 2010
Time [years]

Sampling Uncertainty



Lyman & Johnson 2008


0-700m Heat Content s.e.m.
0-700 m Heat Content s.e.m. [10 22 joules]
3.5
3
2.5
2
1.5
1
0.5
0
1994
1996
1998
2000
2002
2004
2006
2008
2010
Time [years]
Climatology
XBT
Mapping
Sampling
Overall



Mean of xbt correction solid and doted (show mean and black errors)

[22] Wijffels (2008) CTD pairs, Depth
[22] Wijffels (2008) Altimeter SSH, Depth
[10] Levitus (2009) CTD pairs, Depth Dependent Temperature
[9] Ishii (2009) CTD pairs, Depth (time)
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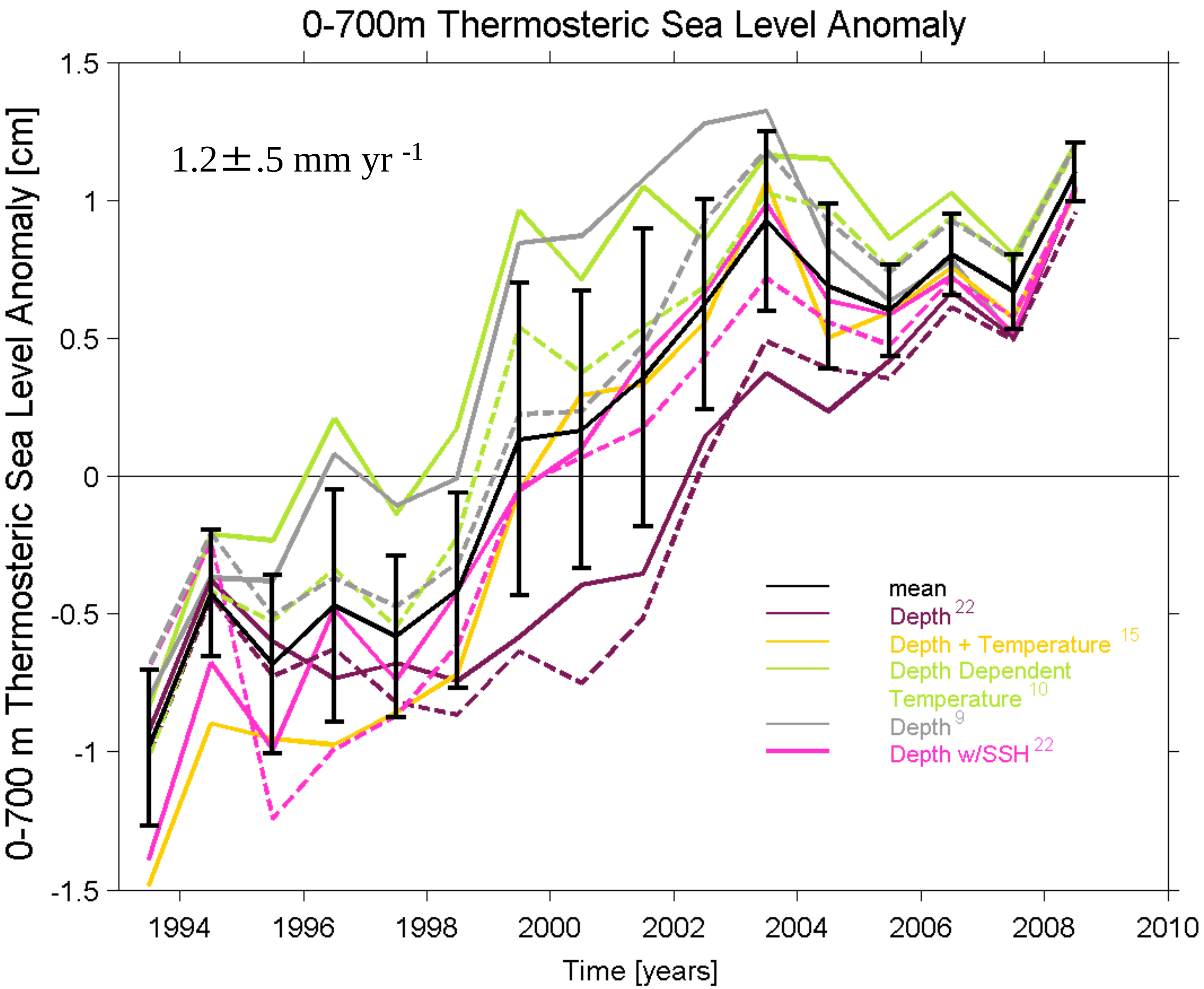

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Conclusions

- XBT uncertainty dominates
- Robust Warming despite uncertainty from XBT correction
- 1-3 year interannual variability is not significant.

- Best XBT corrections database.

XBT Corrections

- [22] Wijffels (2008) CTD pairs, Depth
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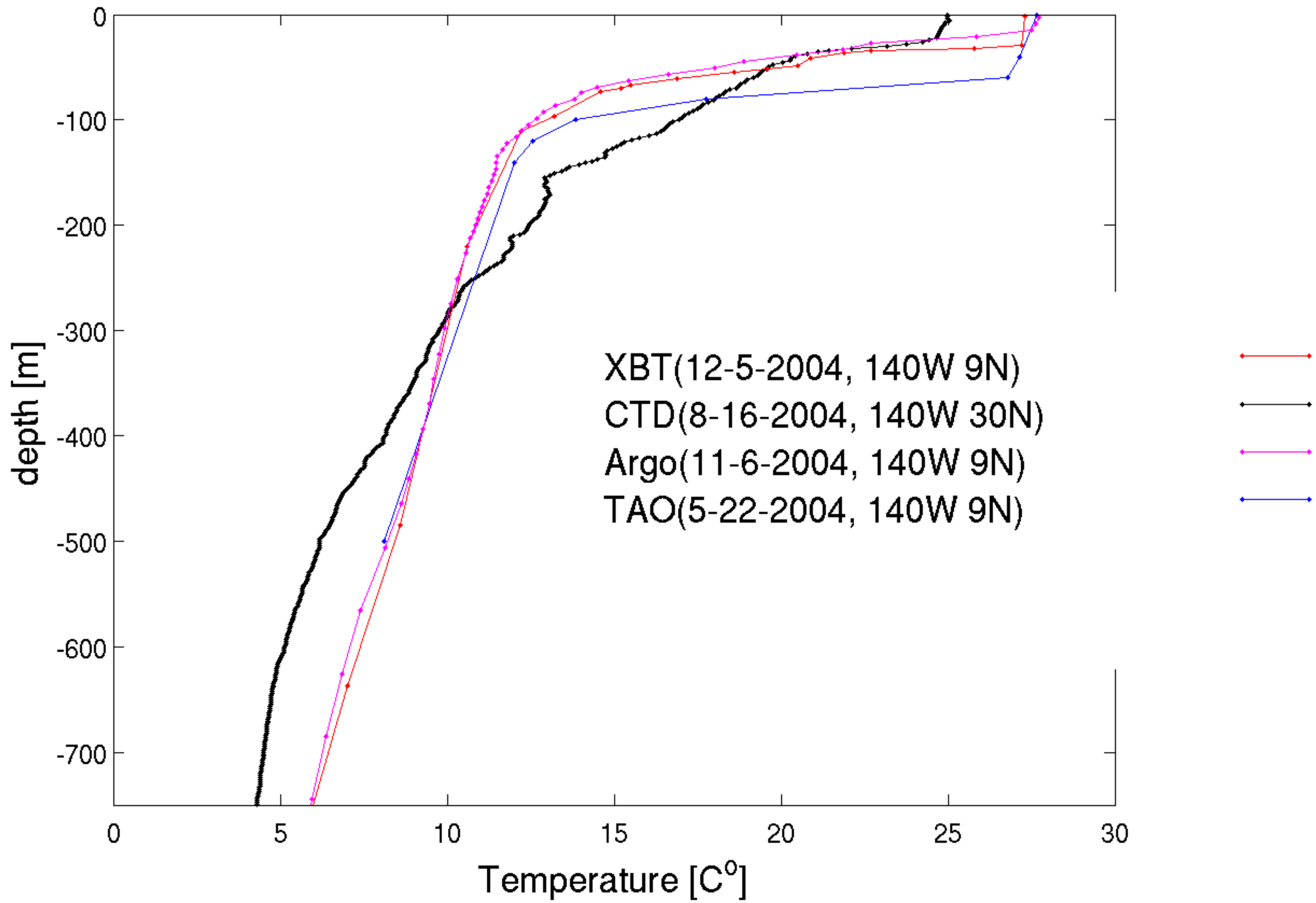
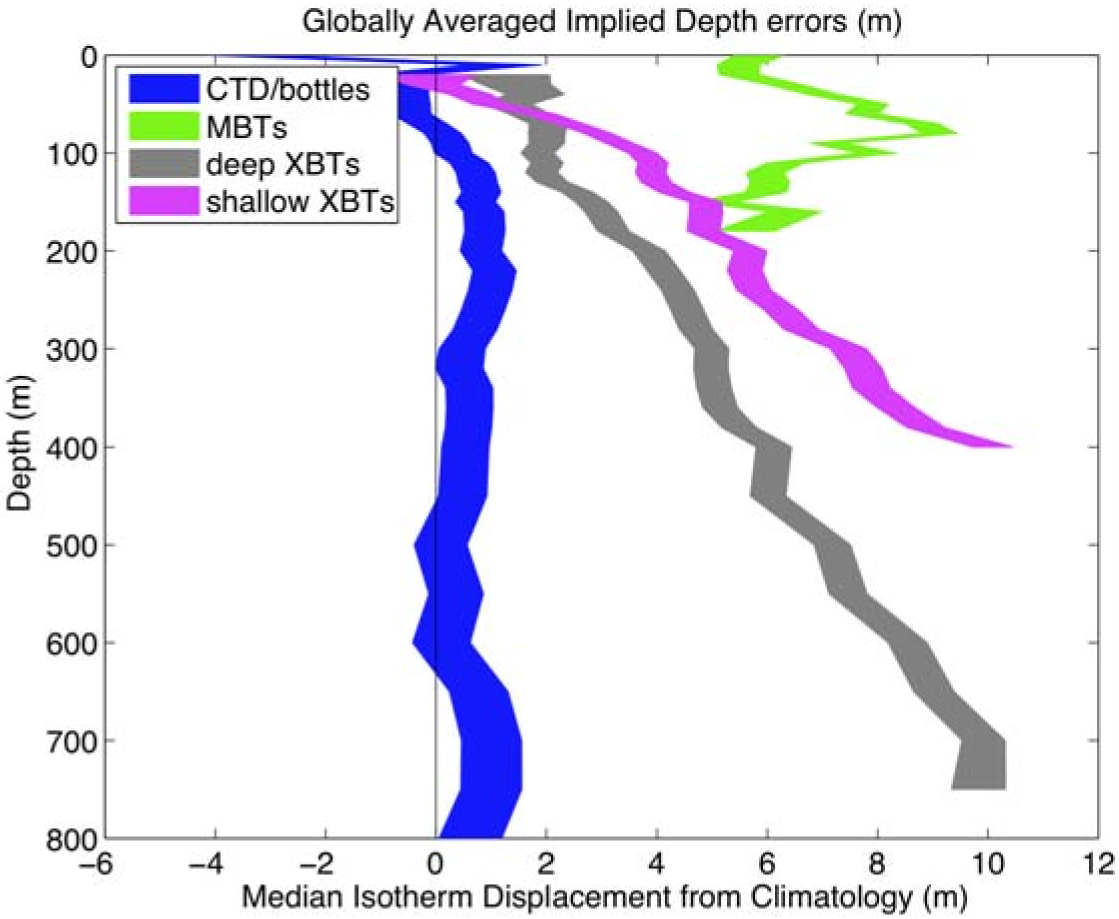
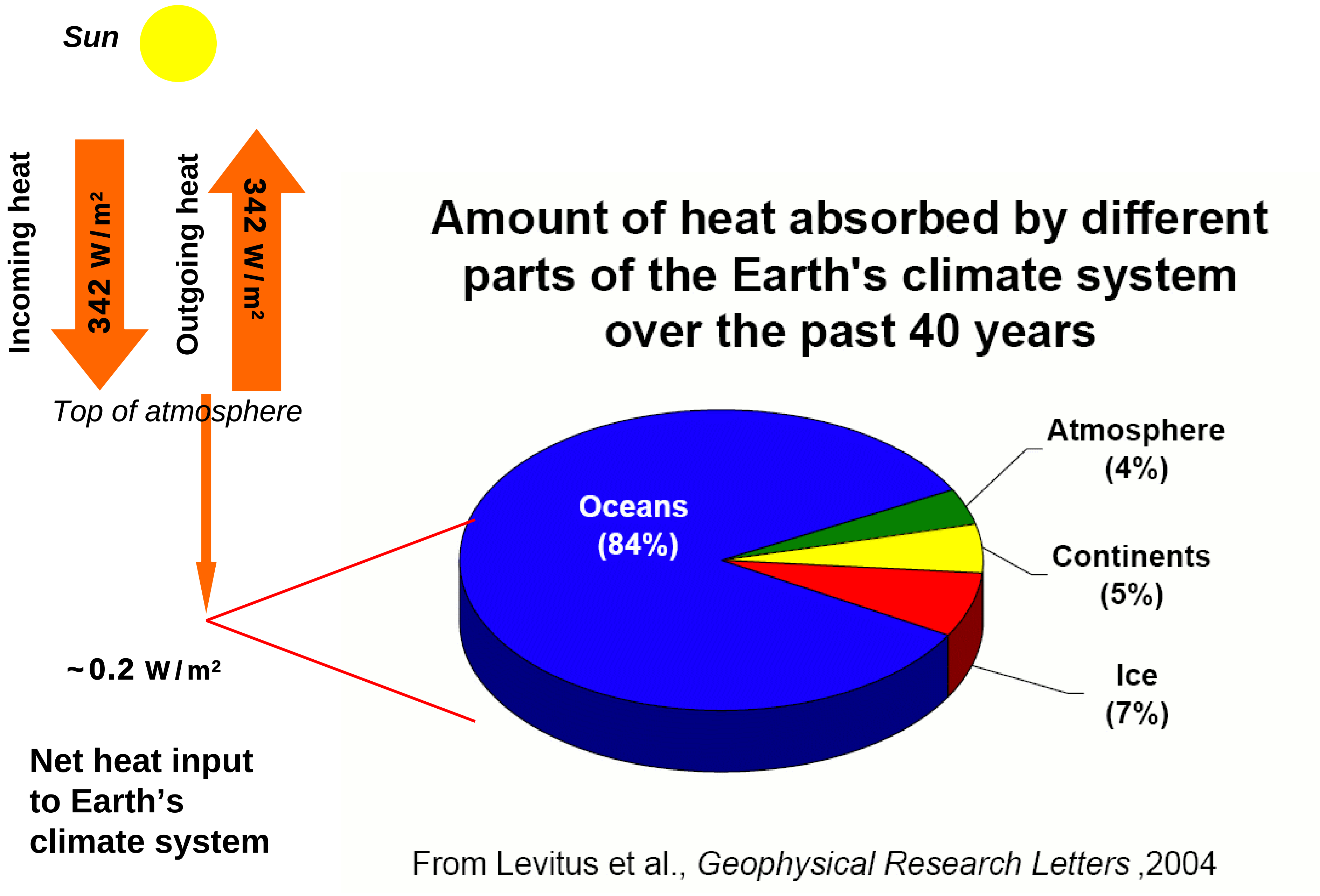


XBT(12-5-2004, 140W 9N)
CTD(8-16-2004, 140W 30N)
Argo(11-6-2004, 140W 9N)
TAO(5-22-2004, 140W 9N)
depth [m]
0
-100
-200
-300
-400
-500
-600
-700
Temperature [C^o]
0
5
10
15
20
25
30

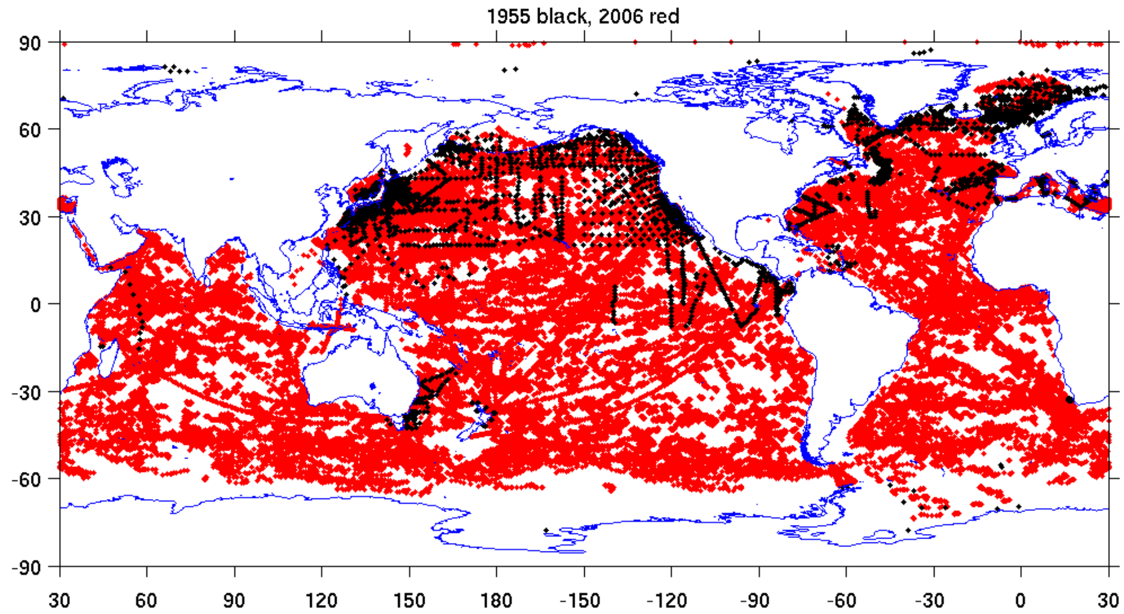


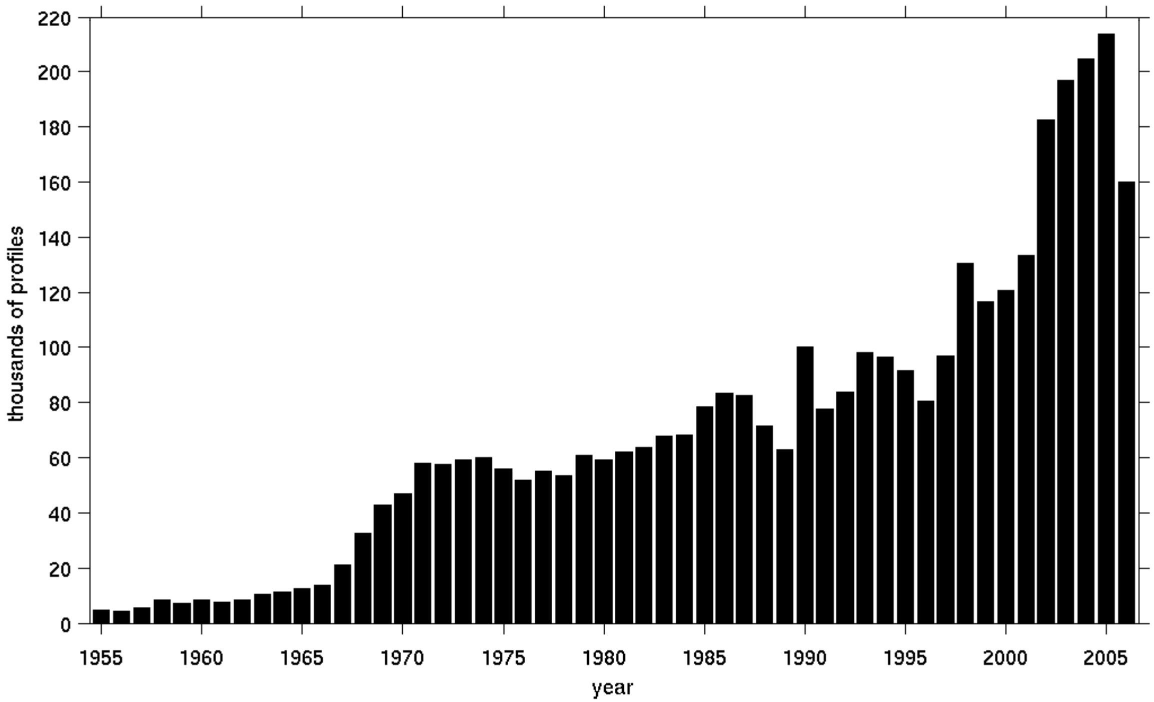
Wijffels (2008)

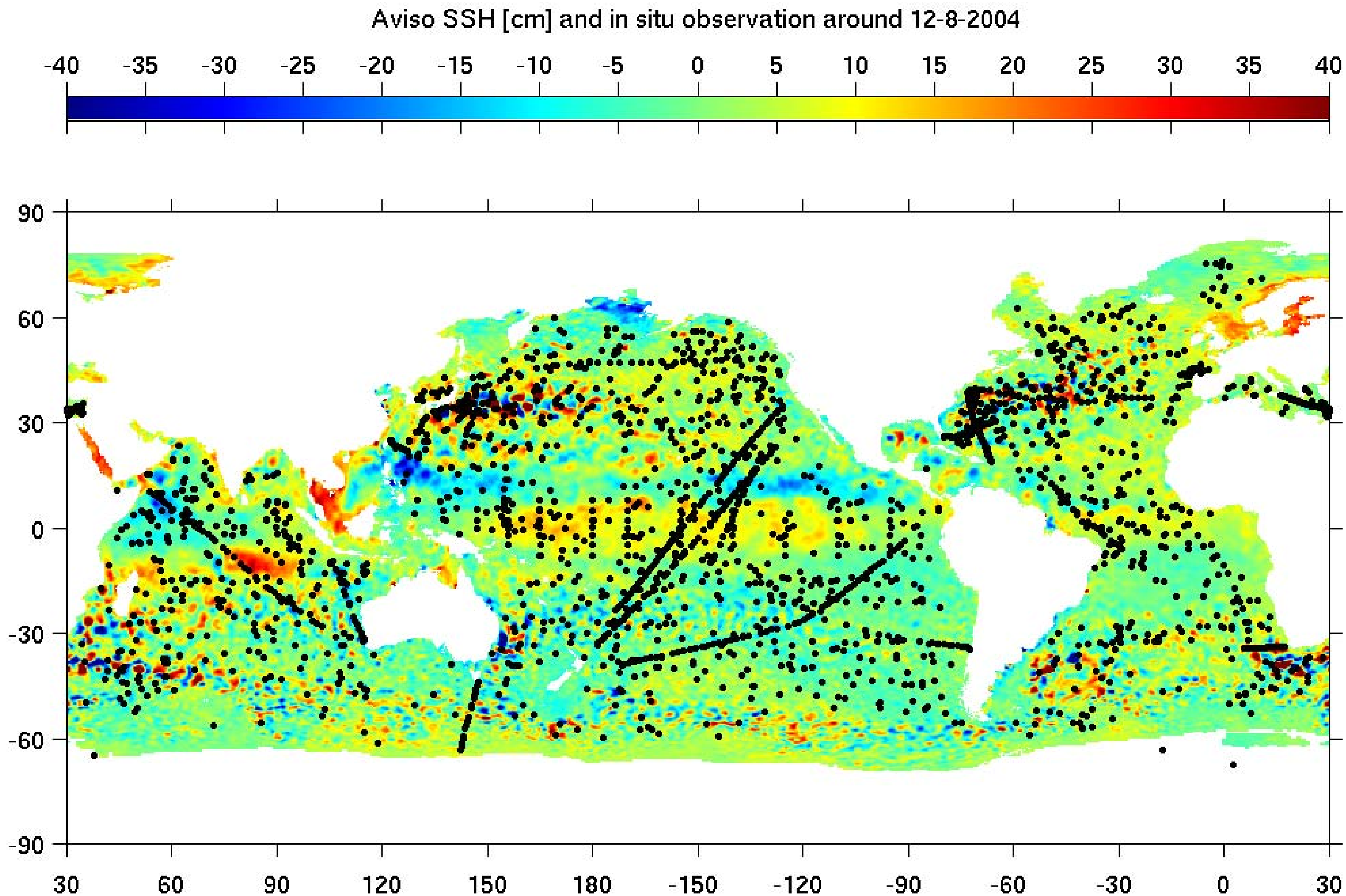

Sun
Incoming heat
342 W / m²
Outgoing heat
342 W / m²
Top of atmosphere
~0.2 W / m²
Net heat input to Earth's climate system
Amount of heat absorbed by different parts of the Earth's climate system over the past 40 years
Oceans (84%)
Atmosphere (4%)
Continents (5%)
Ice (7%)
From Levitus et al., Geophysical Research Letters ,2004

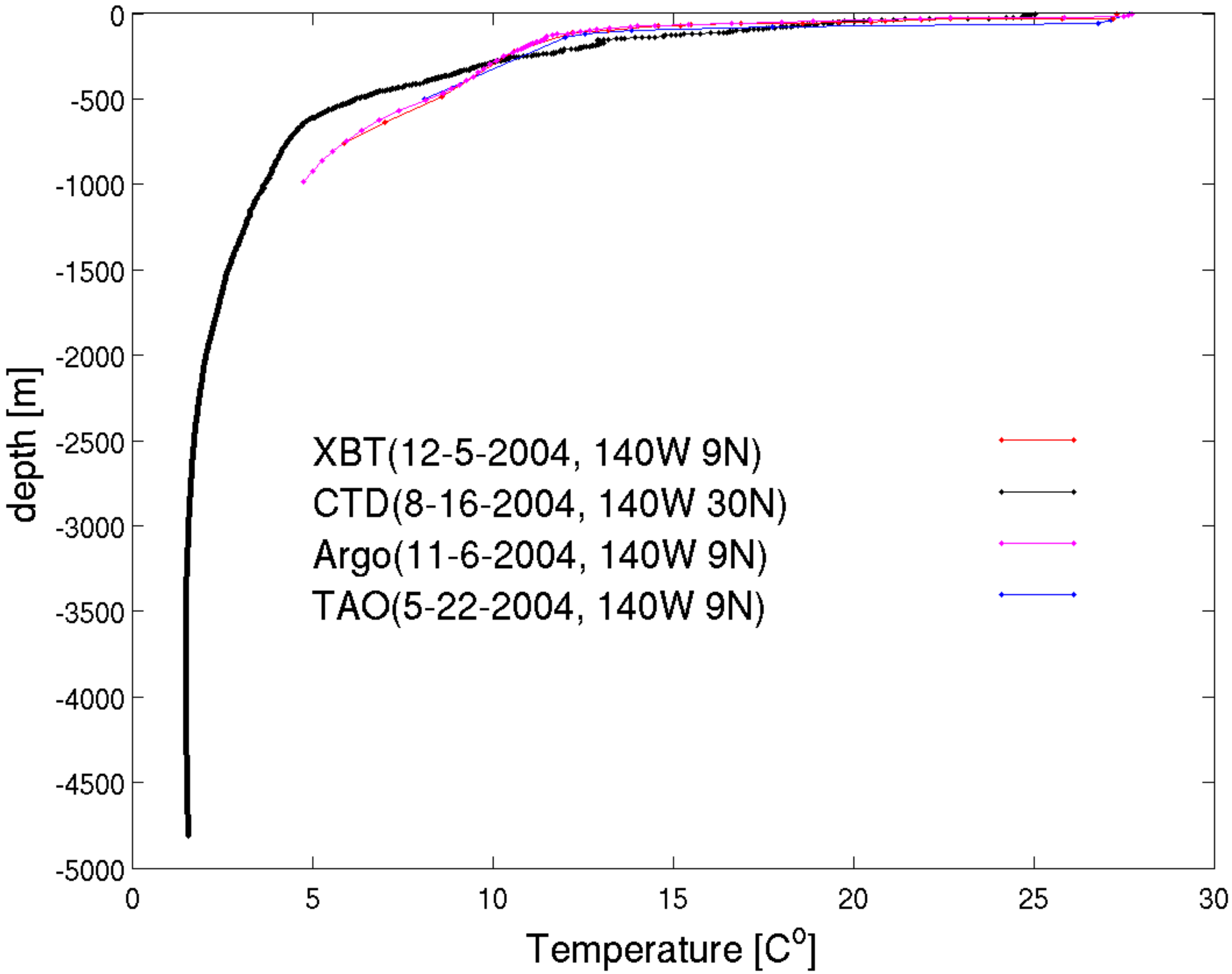
Unknown Biases

- Argo (depth offset in the Atlantic)
- XBT (Fall rate)


1955 black, 2006 red
90
60
30
0
-30
-60
-90
30 60 90 120 150 180 -150 -120 -90 -60 -30 0 30


thousands of profiles
0 20 40 60 80 100 120 140 160 180 200 220
1955 1960 1965 1970 1975 1980 1985 1990 1995 2000 2005
year

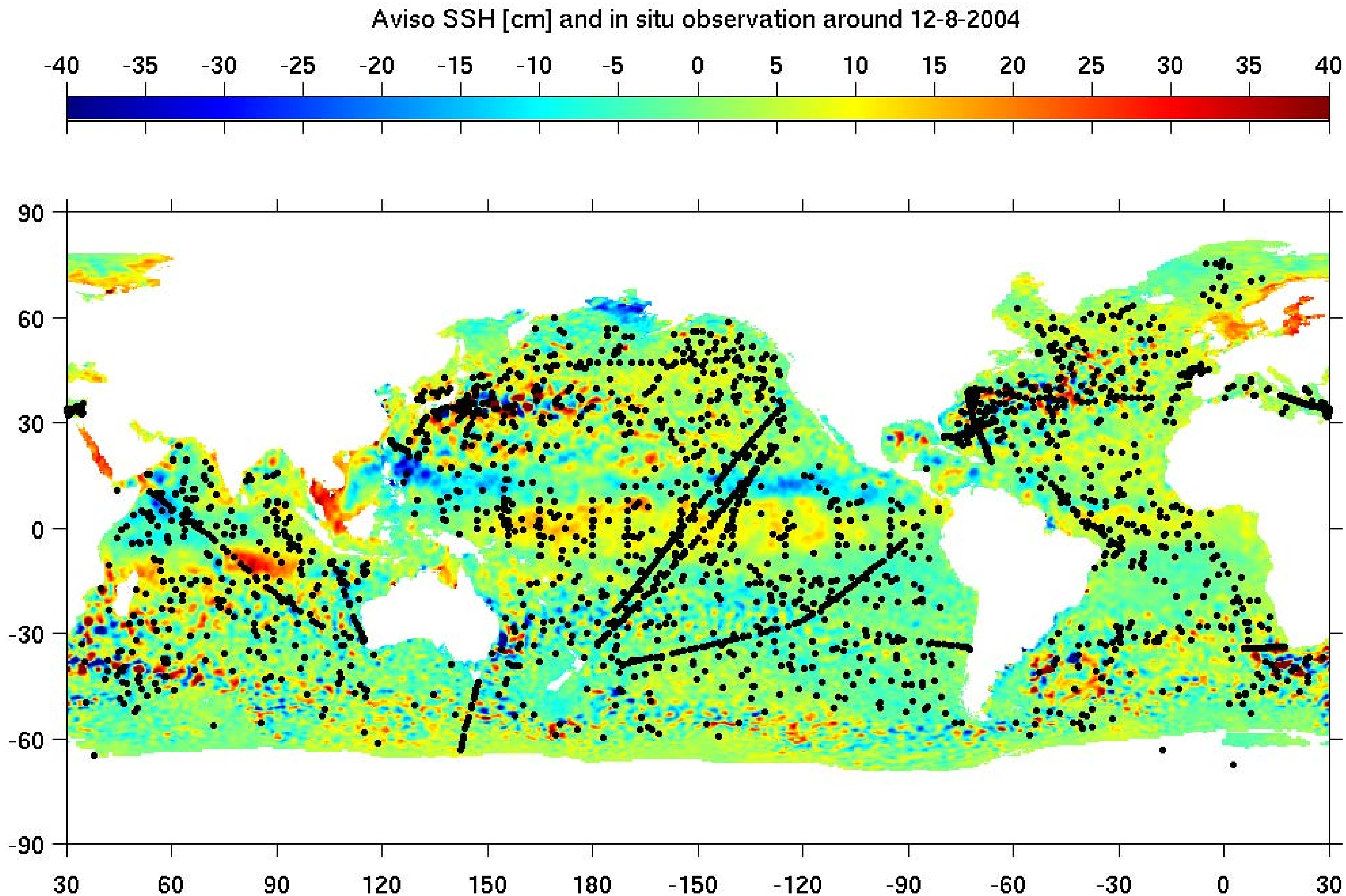

Aviso SSH [cm] and in situ observation around 12-8-2004
-40 -35 -30 -25 -20 -15 -10 -5 0 5 10 15 20 25 30 35 40
90
60
30
0
-30
-60
-90
30 60 90 120 150 180 -150 -120 -90 -60 -30 0 30



0
-500
-1000
-1500
-2000
-2500
-3000
-3500
-4000
-4500
-5000
depth [m]
0
5
10
15
20
25
30
Temperature [C^o]
XBT(12-5-2004, 140W 9N)
CTD(8-16-2004, 140W 30N)
Argo(11-6-2004, 140W 9N)
TAO(5-22-2004, 140W 9N)

Sampling error

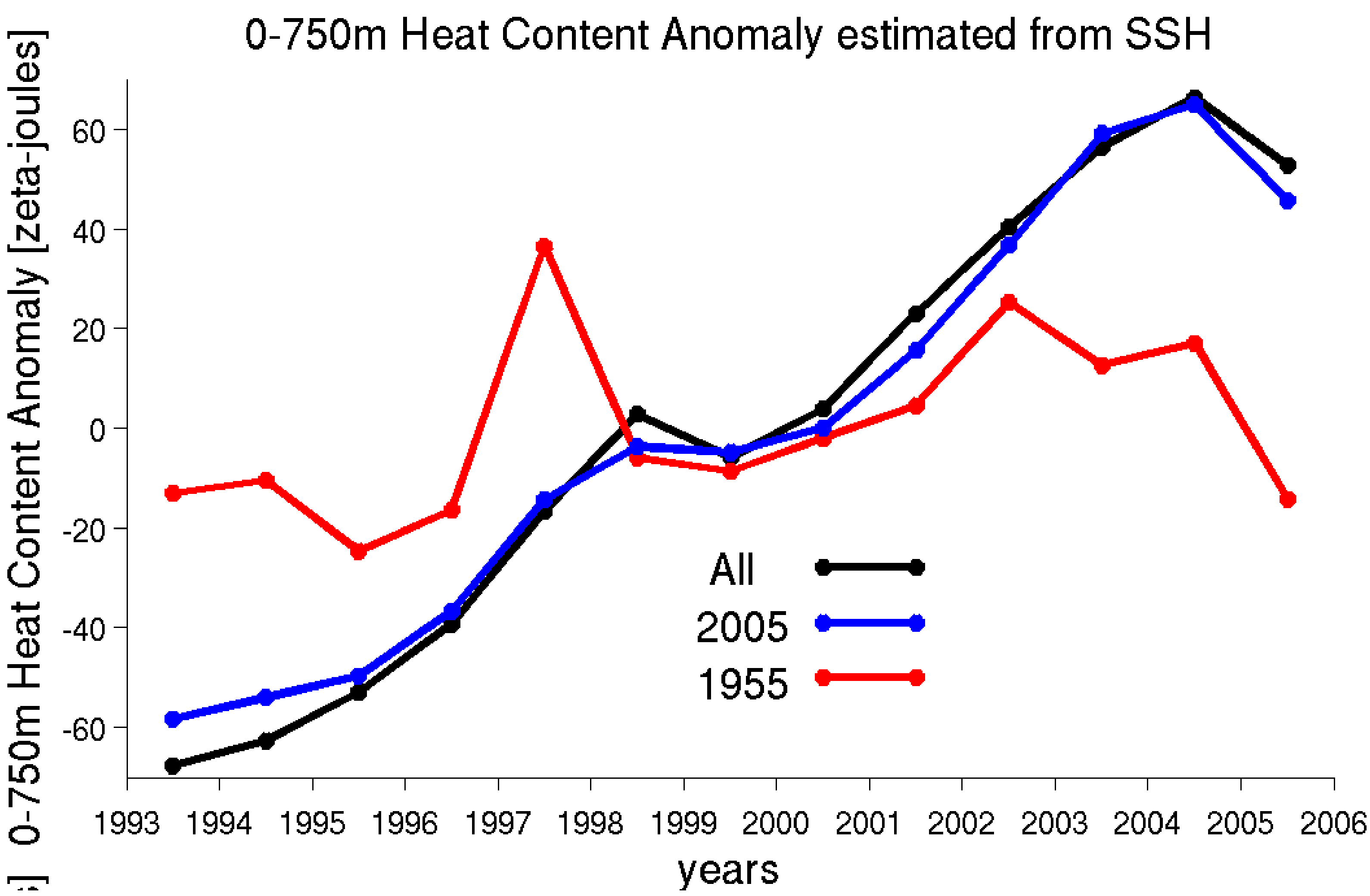
- Sub-sample a model
- Sub-sample Altimeter data (SSH)



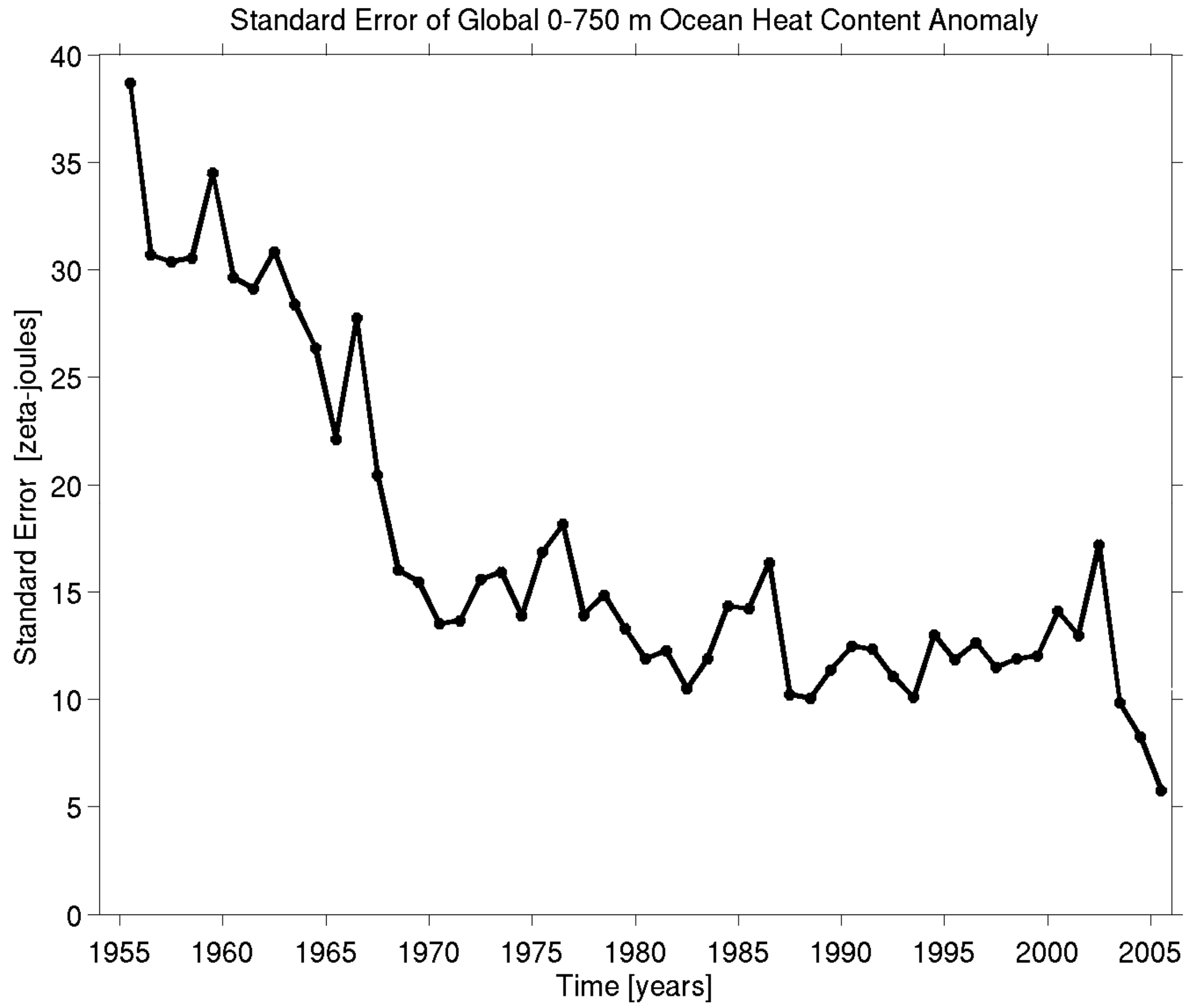
Aviso SSH [cm] and in situ observation around 12-8-2004
-40 -35 -30 -25 -20 -15 -10 -5 0 5 10 15 20 25 30 35 40
90 60 30 0 -30 -60 -90
30 60 90 120 150 180 -150 -120 -90 -60 -30 0 30

SSH and Heat content

- Heat content is regressed regionally onto SSH to yield a regression coefficient alpha (Willis et al 2004).
- Alpha is empirical
  - Partially corrects for temperature-salinity compensation
  - Variability <750m
- For the global integral, Alpha = 51 zeta-joules cm^{-1}



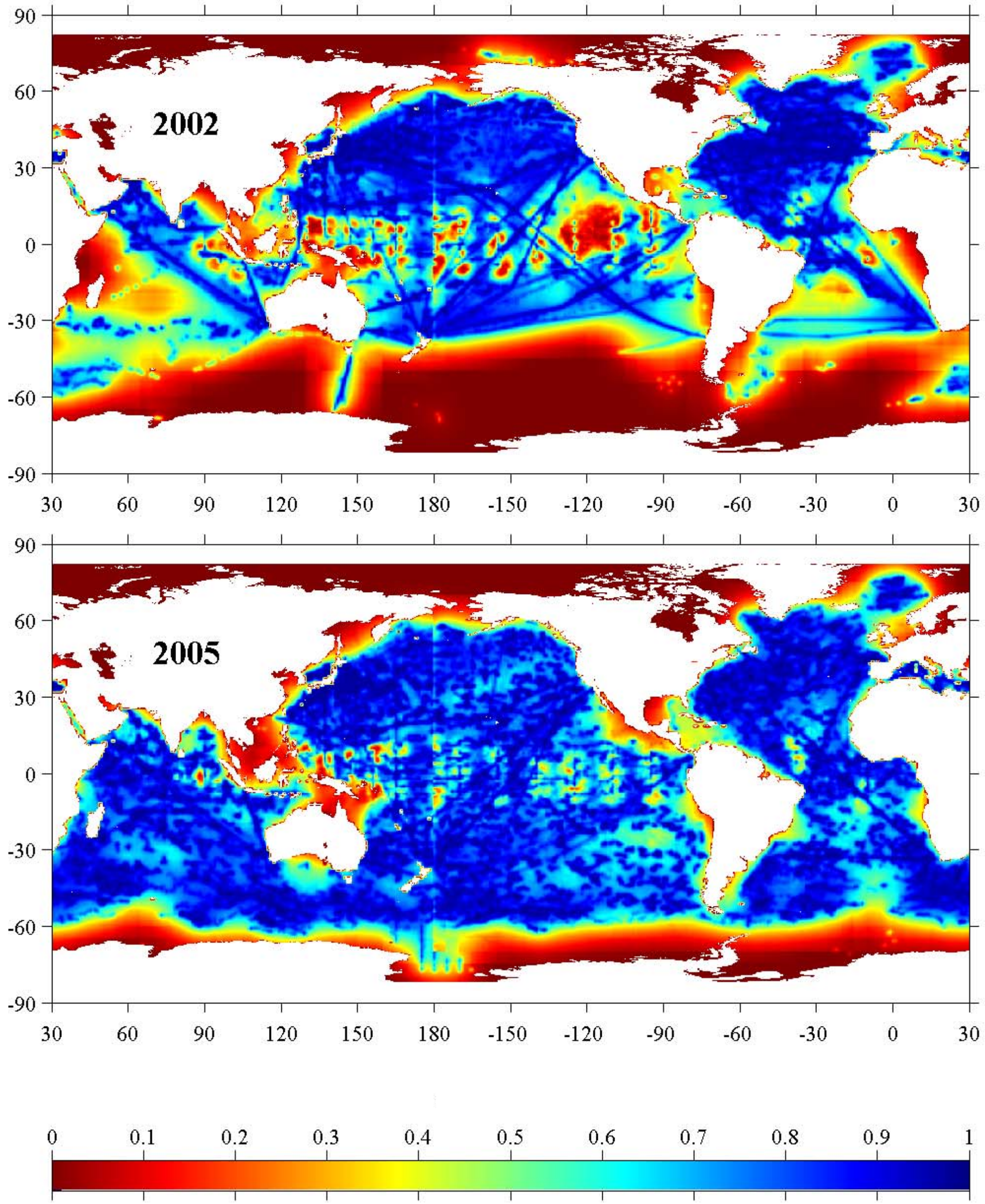
$$sampling\_error\_SSH(N) = \left[\frac{\sum_{i=1993}^{2005}\left[SSH_{total}(i) - SSH_{sub\_N}(i)\right]^2}{13}\right]^{1/2}$$



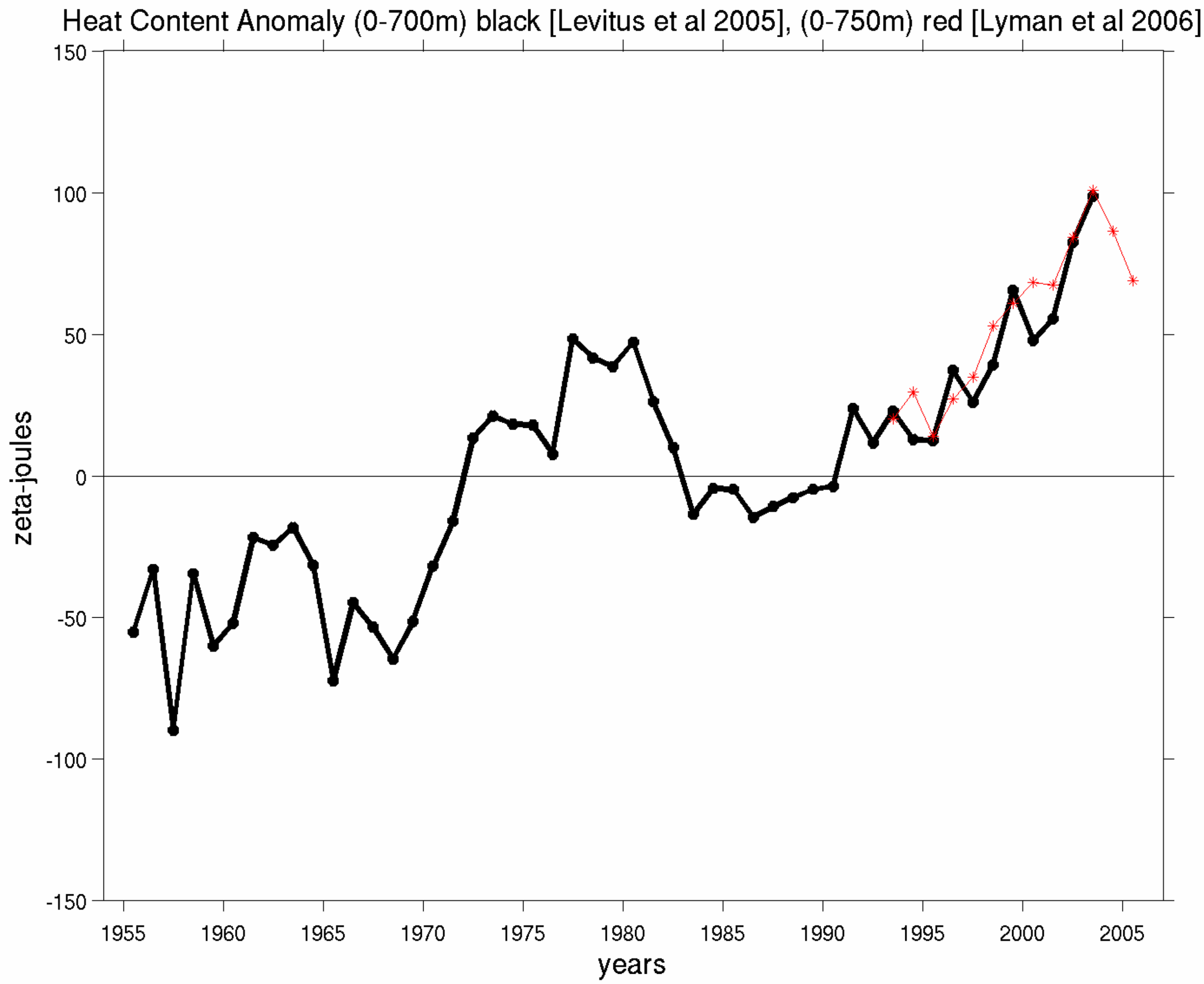
Argo

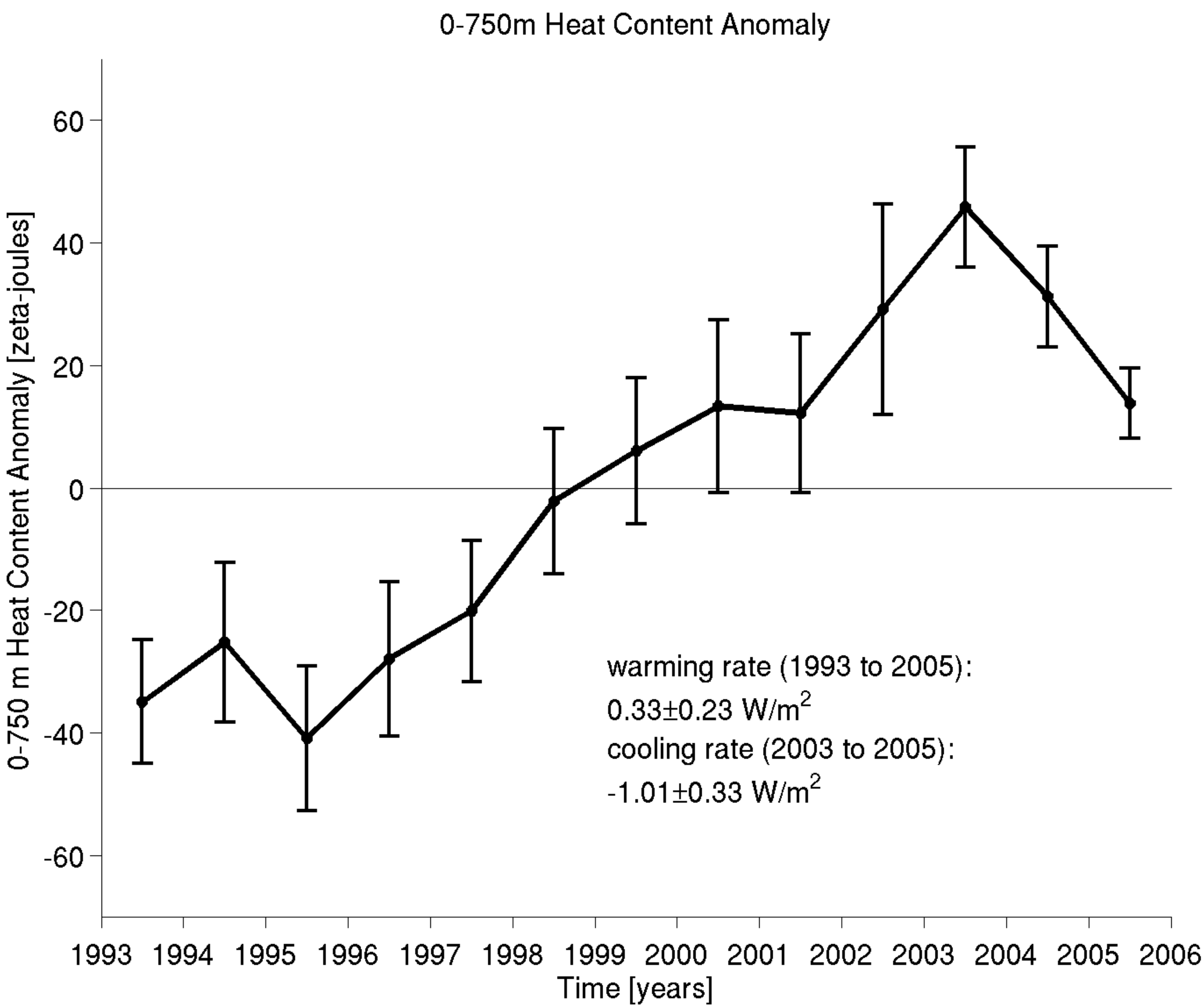
$$standard\_error\_OHCA(N) = \left[\left(standard\_error\_Aviso\right)^2 + \left(sampling\_error\_SSH(N)\right)^2\right]^{1/2}$$

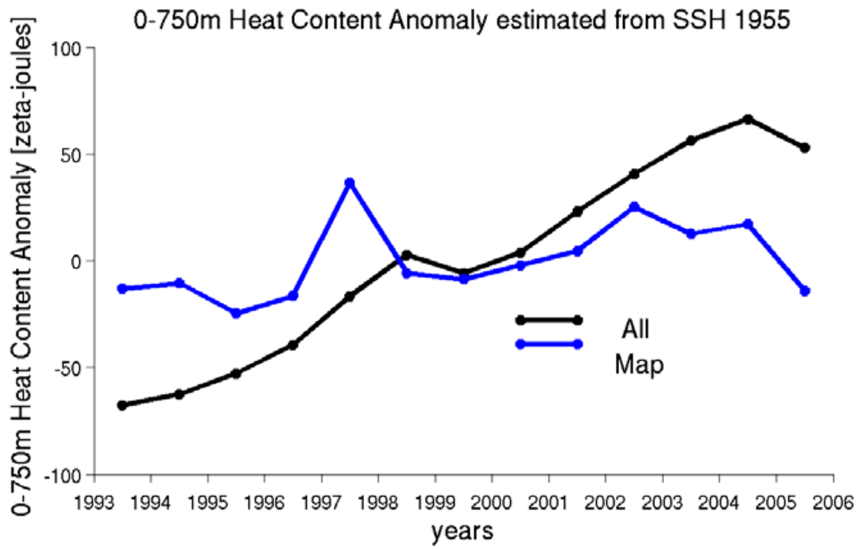
where, $standard\_error\_Aviso = 2$ zeta - joules



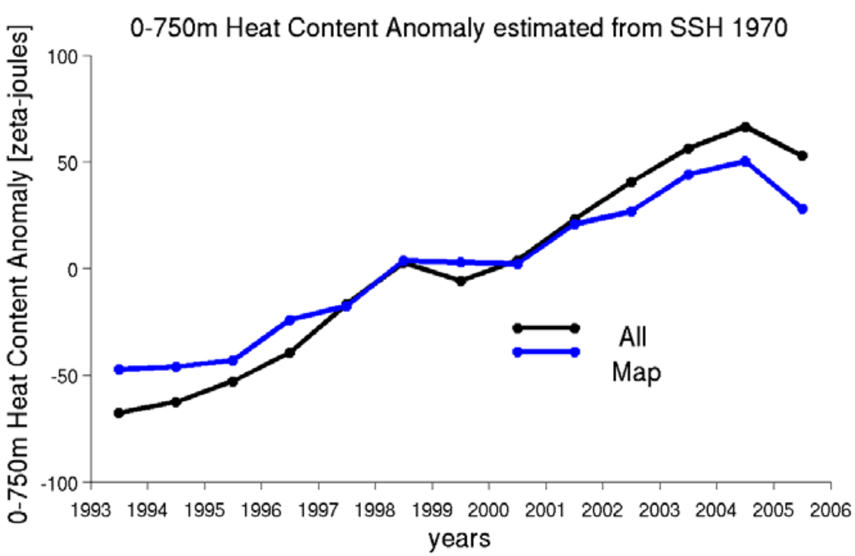
2002
2005
90
60
30
0
-30
-60
-90
30
60
90
120
150
180
-150
-120
-90
-60
-30
0
30
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1


Heat Content Anomaly (0-700m) black [Levitus et al 2005], (0-750m) red [Lyman et al 2006]
150
100
50
0
-50
-100
-150
zeta-joules
1955
1960
1965
1970
1975
1980
1985
1990
1995
2000
2005
years

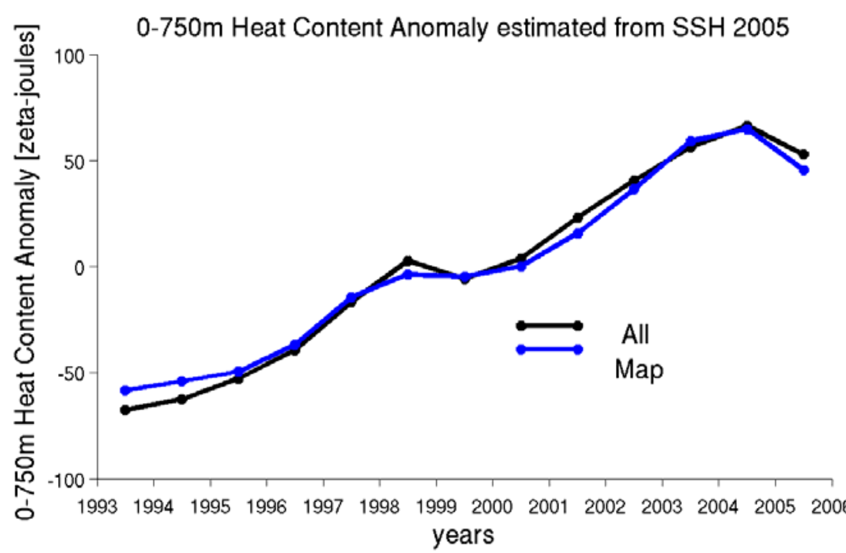

0-750m Heat Content Anomaly
0-750 m Heat Content Anomaly [zeta-joules]
60
40
20
0
-20
-40
-60
1993
1994
1995
1996
1997
1998
1999
2000
2001
2002
2003
2004
2005
2006
Time [years]
warming rate (1993 to 2005):
0.33±0.23 W/m2
cooling rate (2003 to 2005):
-1.01±0.33 W/m2



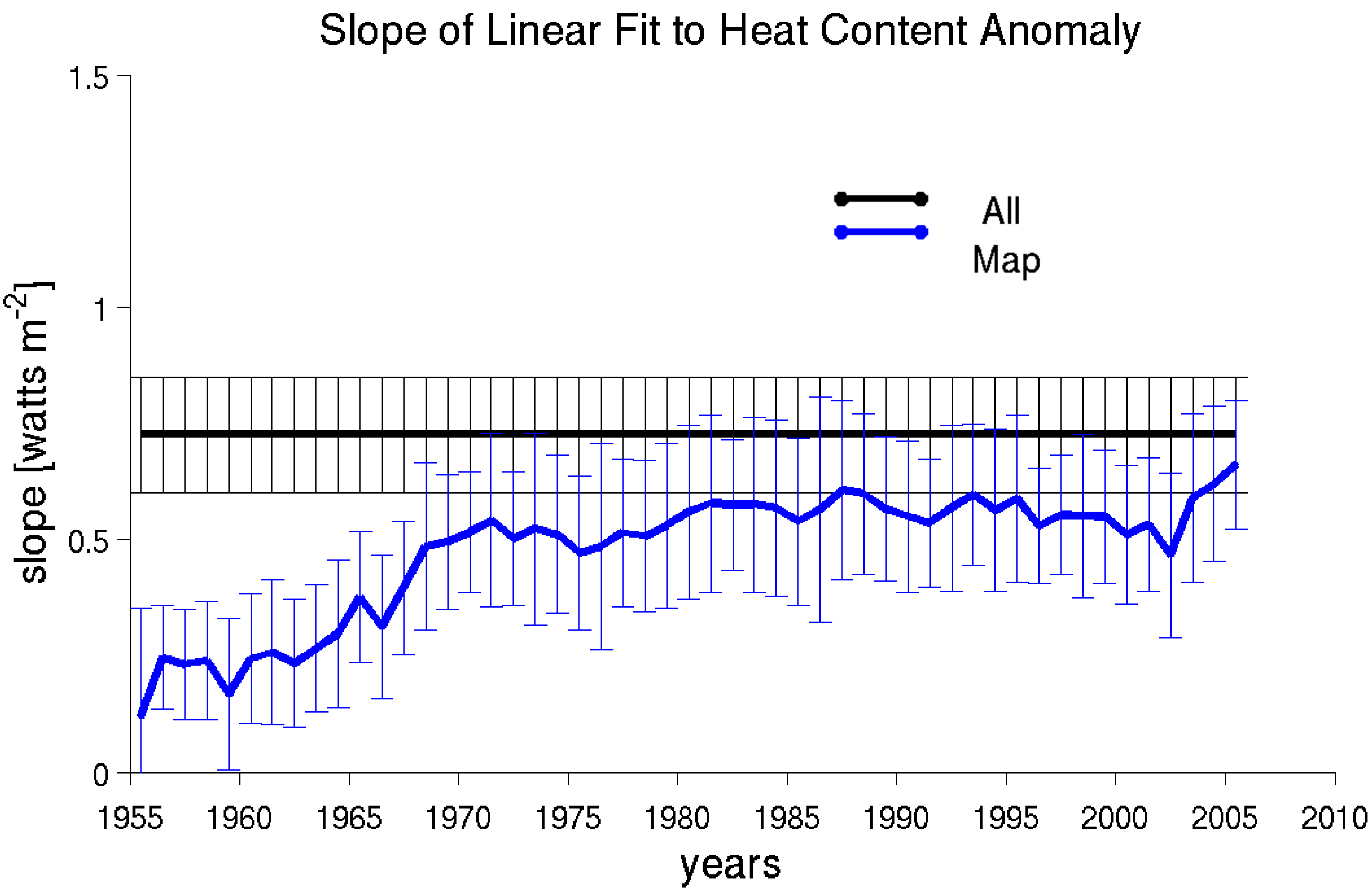
0-750m Heat Content Anomaly estimated from SSH 1955
0-750m Heat Content Anomaly [zeta-joules]
100
50
0
-50
-100
1993 1994 1995 1996 1997 1998 1999 2000 2001 2002 2003 2004 2005 2006
years
All
Map



0-750m Heat Content Anomaly estimated from SSH 1970
0-750m Heat Content Anomaly [zeta-joules]
100
50
0
-50
-100
1993 1994 1995 1996 1997 1998 1999 2000 2001 2002 2003 2004 2005 2006
years
All
Map



0-750m Heat Content Anomaly estimated from SSH 2005
0-750m Heat Content Anomaly [zeta-joules]
100
50
0
-50
-100
1993 1994 1995 1996 1997 1998 1999 2000 2001 2002 2003 2004 2005 2006
years
All
Map



Slope of Linear Fit to Heat Content Anomaly
slope [watts m-2]
1.5
1
0.5
0
1955
1960
1965
1970
1975
1980
1985
1990
1995
2000
2005
2010
years
All
Map

Spatial average

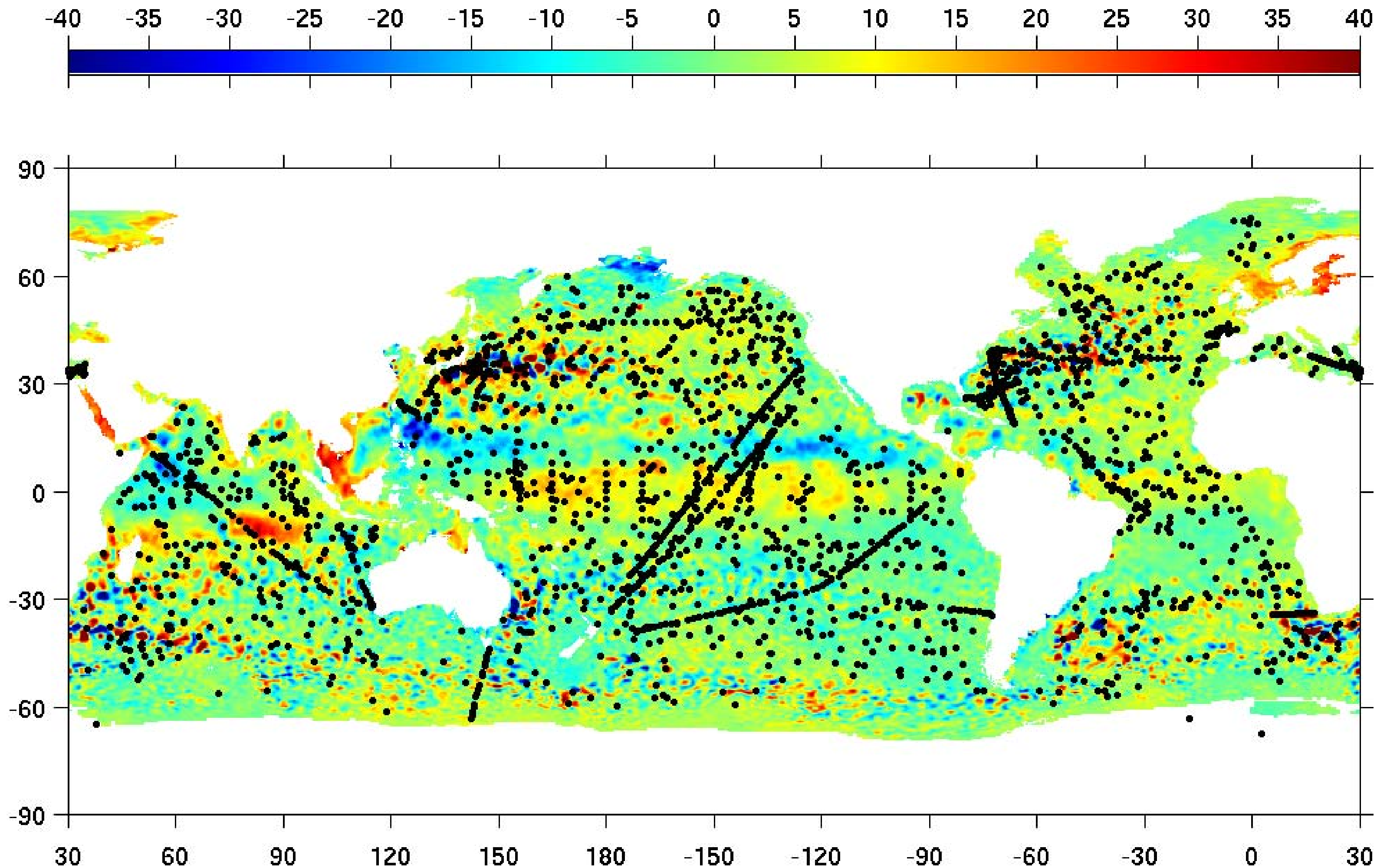
- Spatial Mean of the maps (Assume i.e. the map resolves the global mean)

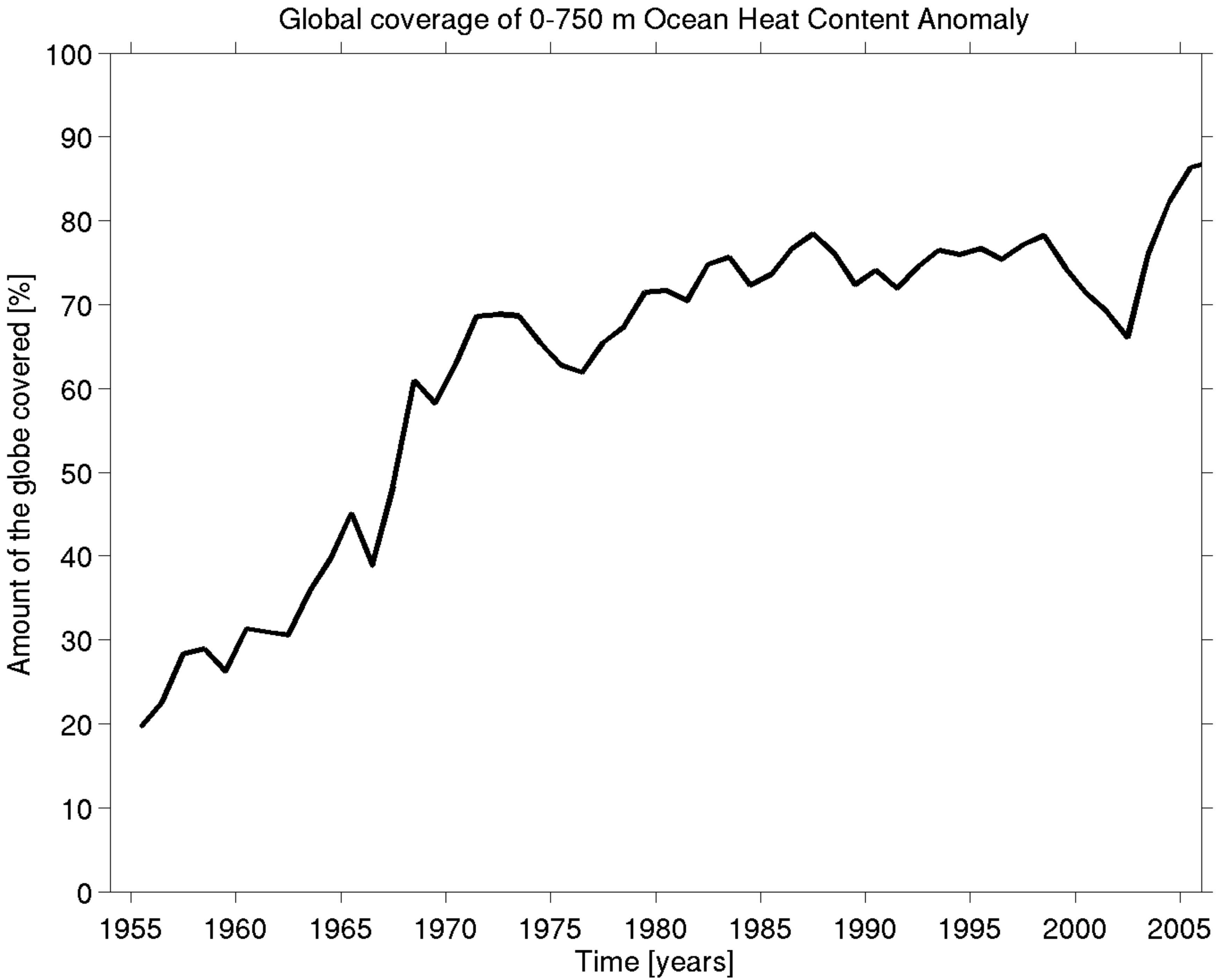
$$Mean \approx Mean_{map}$$

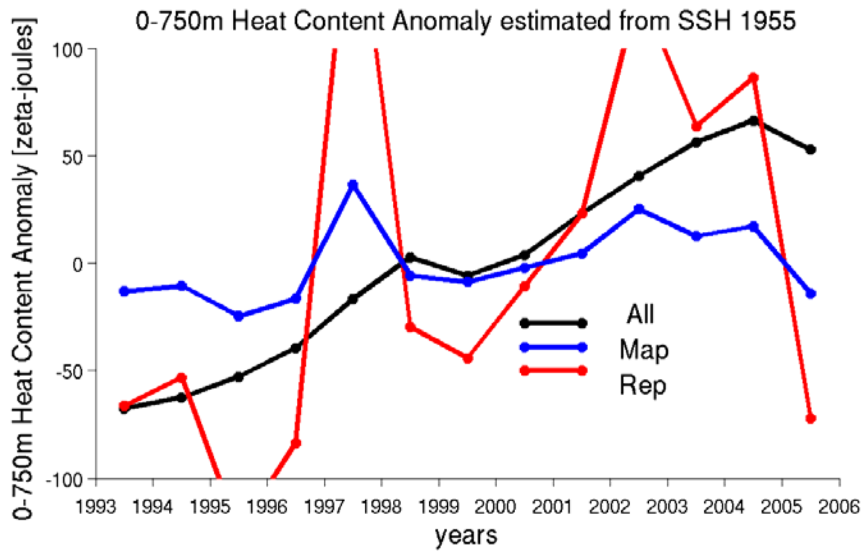
- Representative Spatial Mean (Assume i.e. mean is the same over the area represented in the map and the area outside the mapping)

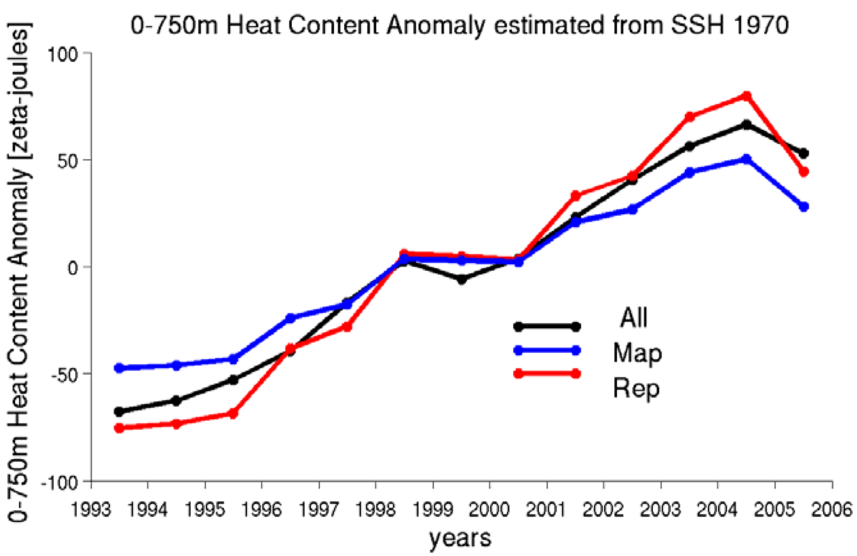
$$Mean \approx \frac{Mean_{map} \times Area}{Area_{map}}$$

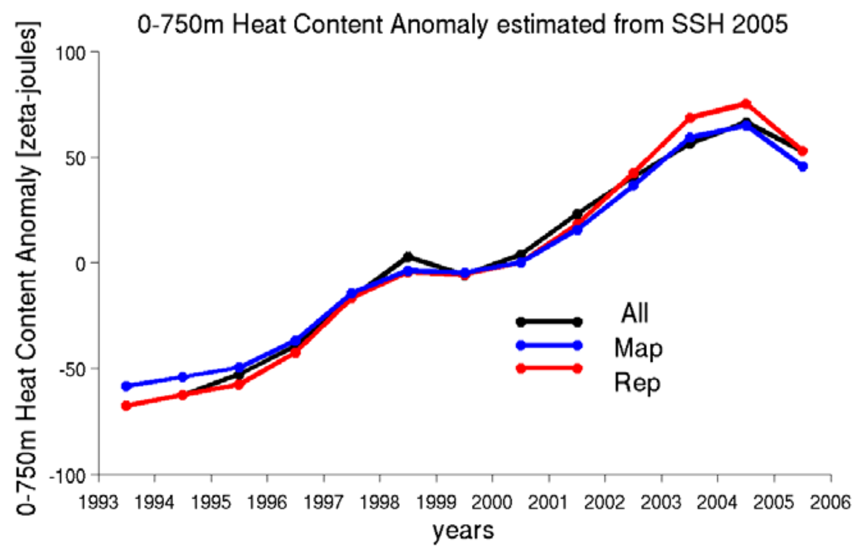
Aviso SSH [cm] and in situ observation around 12-8-2004

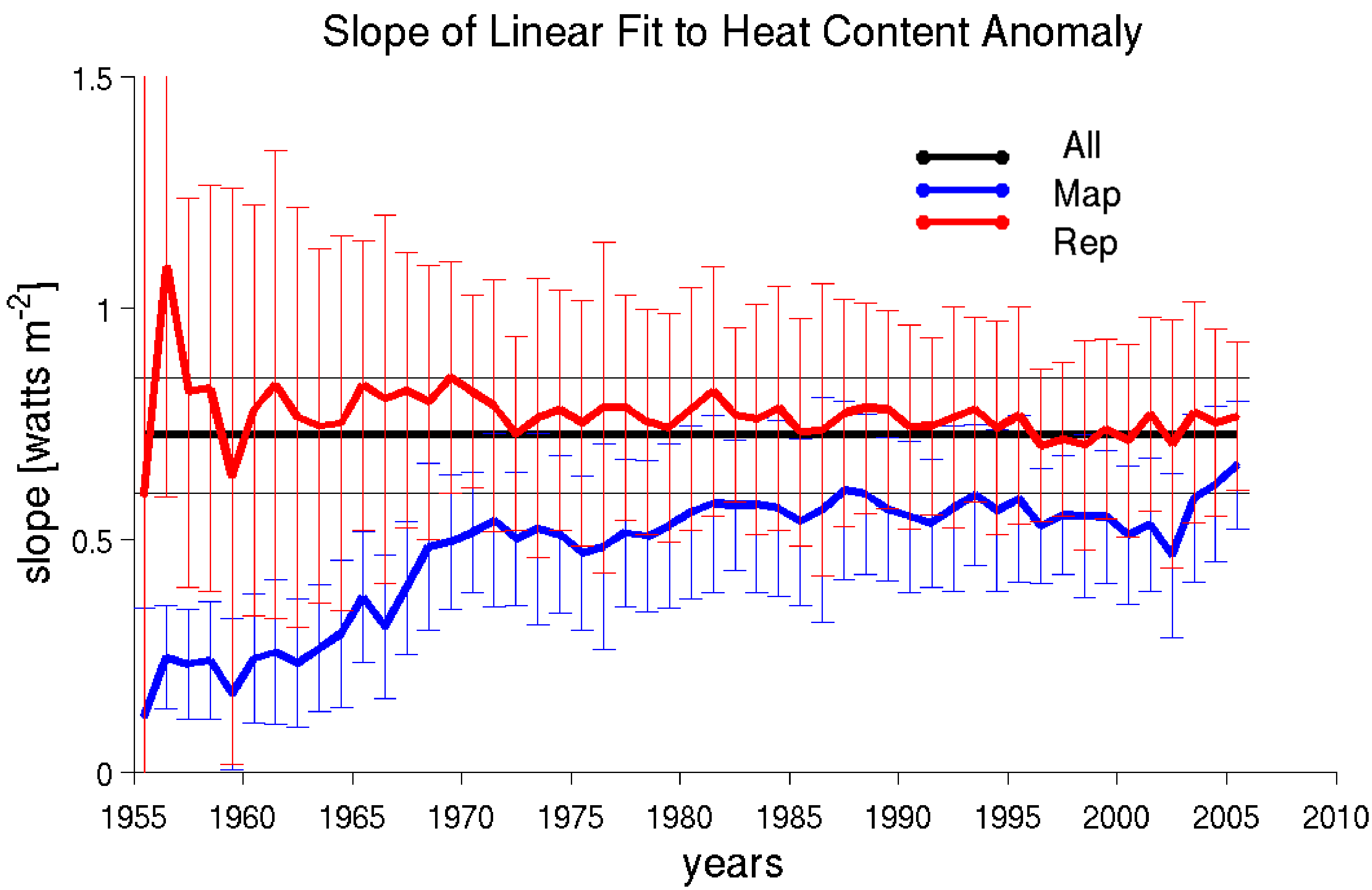



Global coverage of 0-750 m Ocean Heat Content Anomaly
Amount of the globe covered [%]
Time [years]
100
90
80
70
60
50
40
30
20
10
0
1955
1960
1965
1970
1975
1980
1985
1990
1995
2000
2005

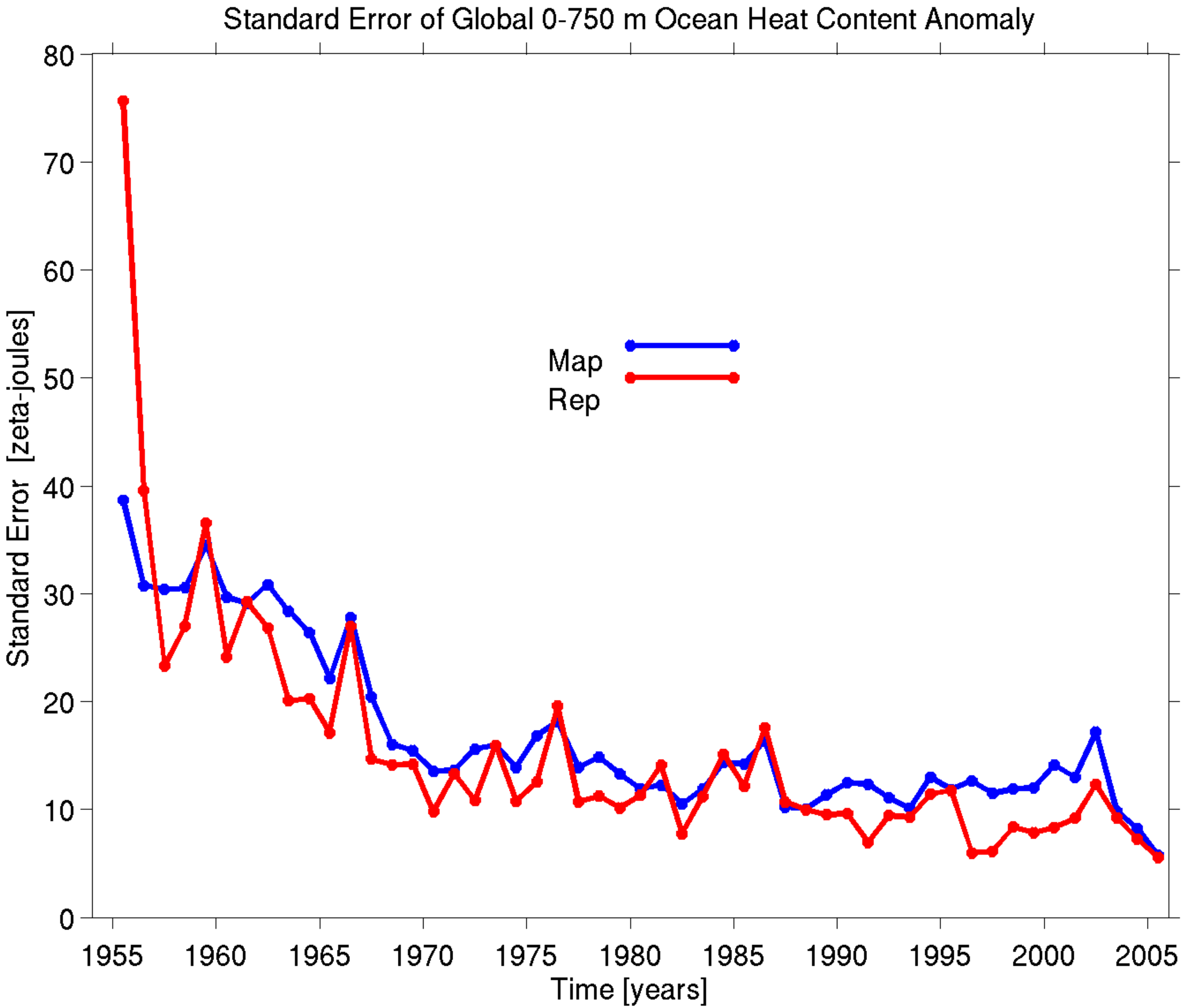

0-750m Heat Content Anomaly estimated from SSH 1955
0-750m Heat Content Anomaly [zeta-joules]
100
50
0
-50
-100
1993 1994 1995 1996 1997 1998 1999 2000 2001 2002 2003 2004 2005 2006
years
All
Map
Rep


0-750m Heat Content Anomaly estimated from SSH 1970
0-750m Heat Content Anomaly [zeta-joules]
100
50
0
-50
-100
1993 1994 1995 1996 1997 1998 1999 2000 2001 2002 2003 2004 2005 2006
years
All
Map
Rep

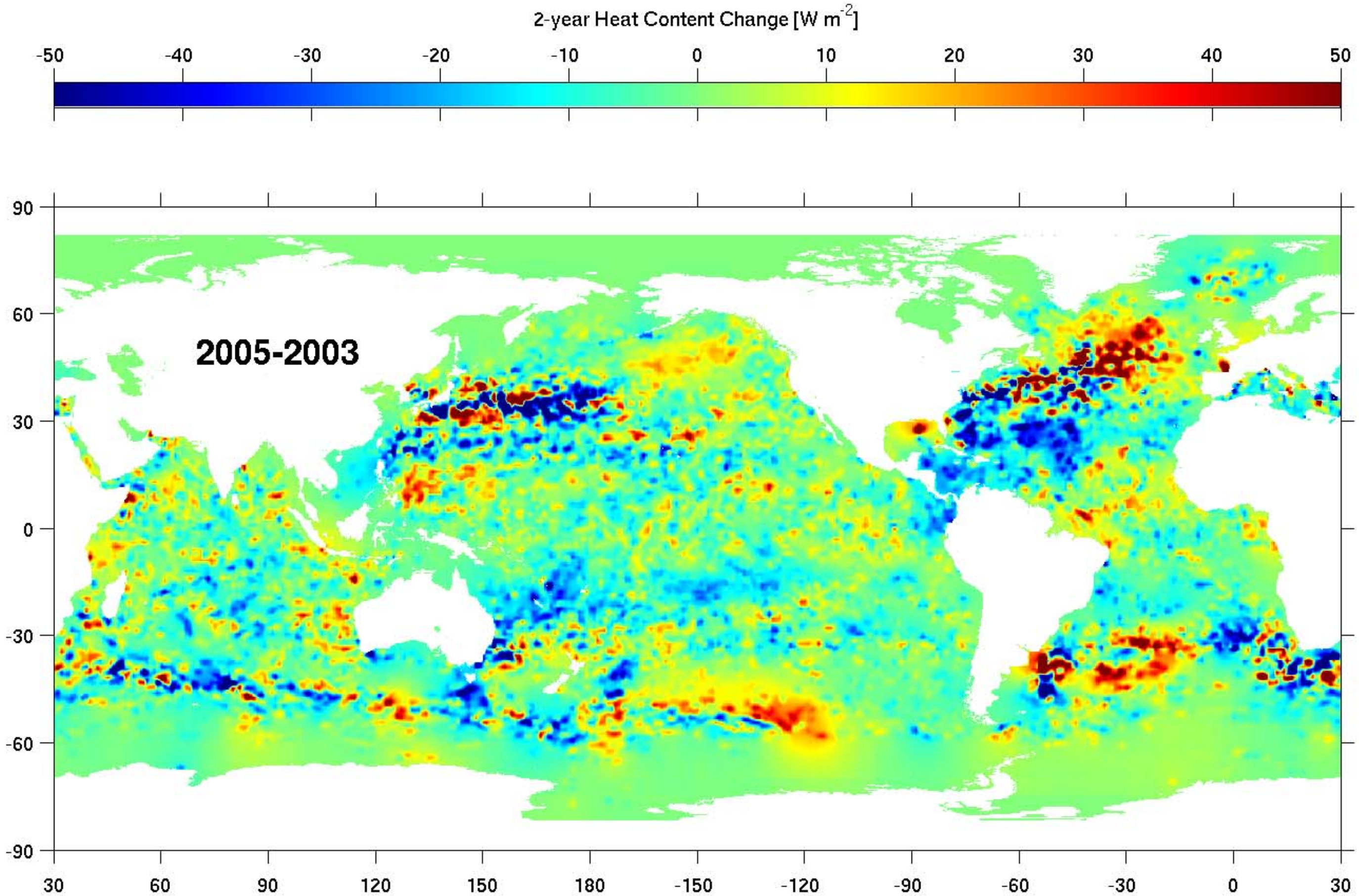

0-750m Heat Content Anomaly estimated from SSH 2005
0-750m Heat Content Anomaly [zeta-joules]
100
50
0
-50
-100
1993 1994 1995 1996 1997 1998 1999 2000 2001 2002 2003 2004 2005 2006
years
All
Map
Rep



Slope of Linear Fit to Heat Content Anomaly
1.5
1
0.5
0
slope [watts m-2]
1955
1960
1965
1970
1975
1980
1985
1990
1995
2000
2005
2010
years
All
Map
Rep



Standard Error of Global 0-750 m Ocean Heat Content Anomaly
Standard Error [zeta-joules]
Time [years]
Map
Rep
0
10
20
30
40
50
60
70
80
1955
1960
1965
1970
1975
1980
1985
1990
1995
2000
2005



2-year Heat Content Change [W m-2]
-50
-40
-30
-20
-10
0
10
20
30
40
50
2005-2003
90
60
30
0
-30
-60
-90
30
60
90
120
150
180
-150
-120
-90
-60
-30
0
30

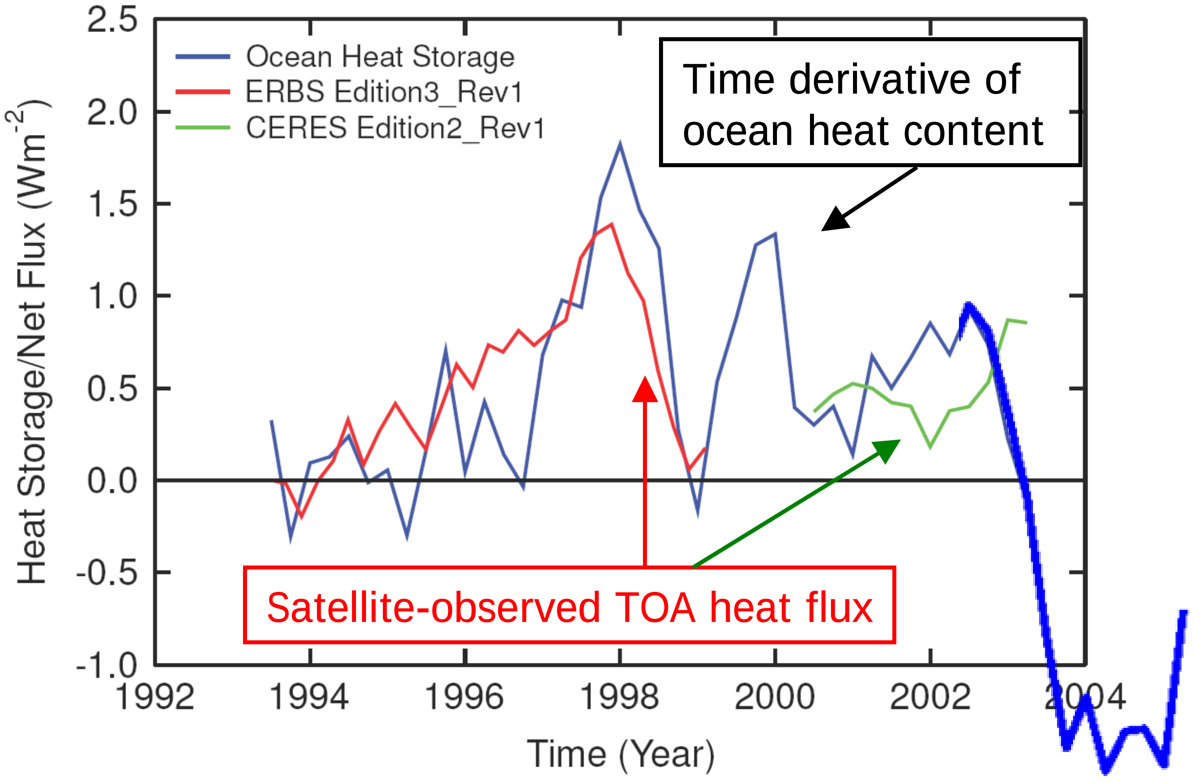
Where did the heat go?

32 ± 11 zeta-Joules=

- 5° C atmospheric temperature increase (volume average)
- melt enough land-bound ice to raise sea level by 24 cm
- Melt all of Earth's sea ice (3 times)
- Evaporate water equivalent to 5 cm of sea level (3 cm, atmosphere)
- 120 Sv ° C implies a 8 ° C change in a 15 Sv Atlantic meridional overturning circulation (1 Sv $=10^6\ m^3\ s^{-1}$)

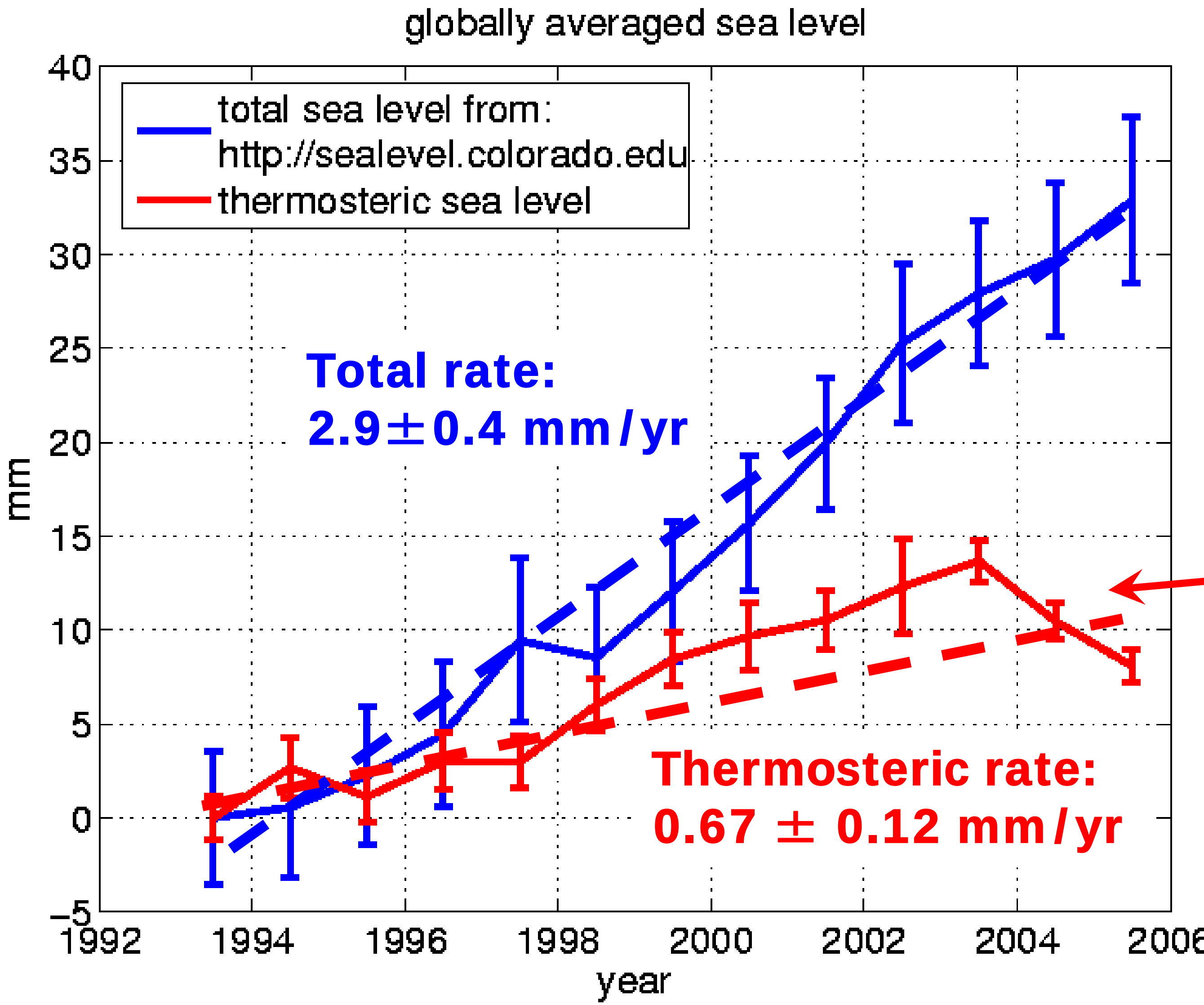
Toward closing the global radiation budget

Satellite measurements of net flux at the top of the atmosphere, should roughly agree with ocean heat storage variability



From Wong, T., B. Wielicki, R. B. Lee, G. L. Smith, K. Bush, and J. Willis, *J. Climate*, 2006

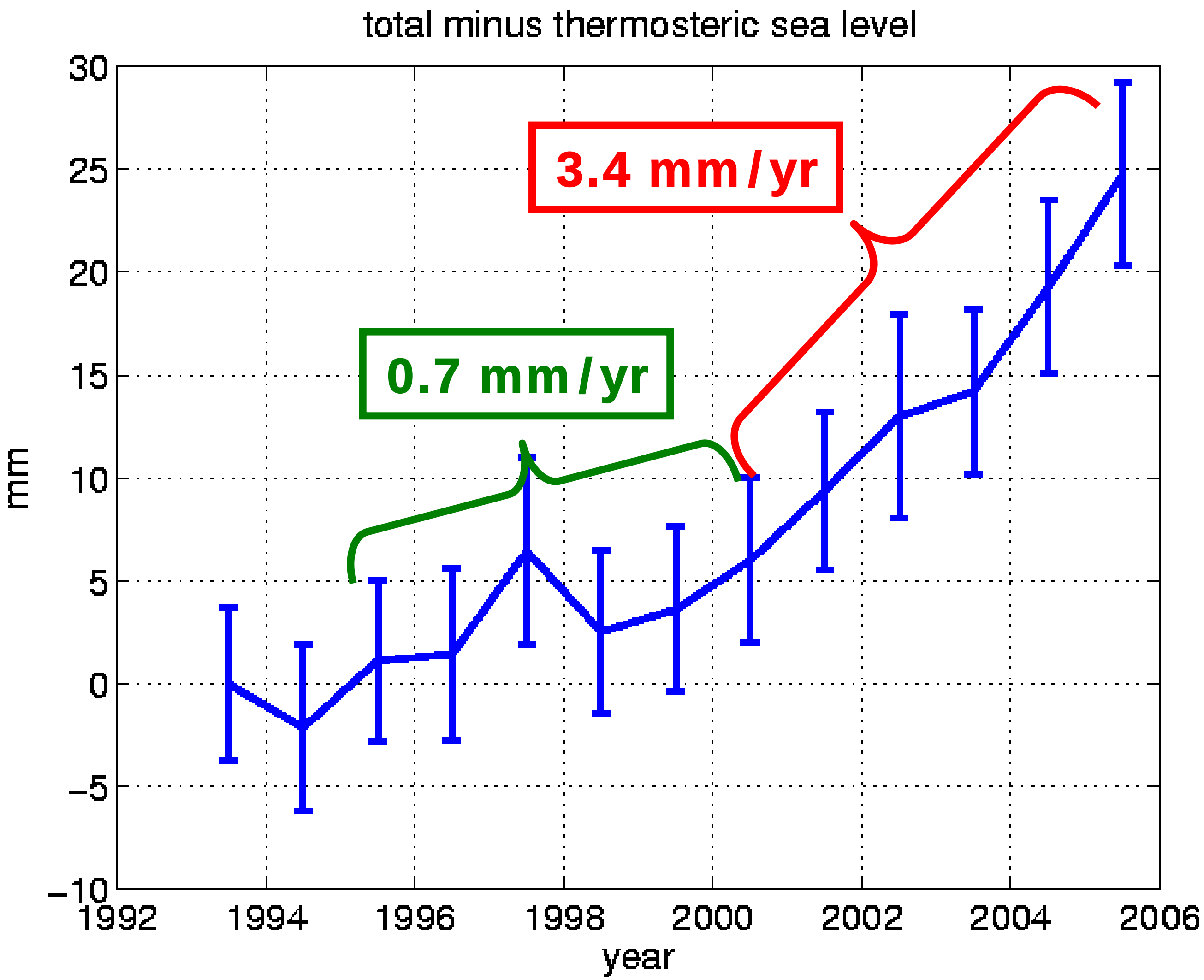
Thermosteric sea level change



Sea level continued to rise despite cooling and *decrease* in thermosteric sea level

~ 6 mm drop in thermosteric sea level

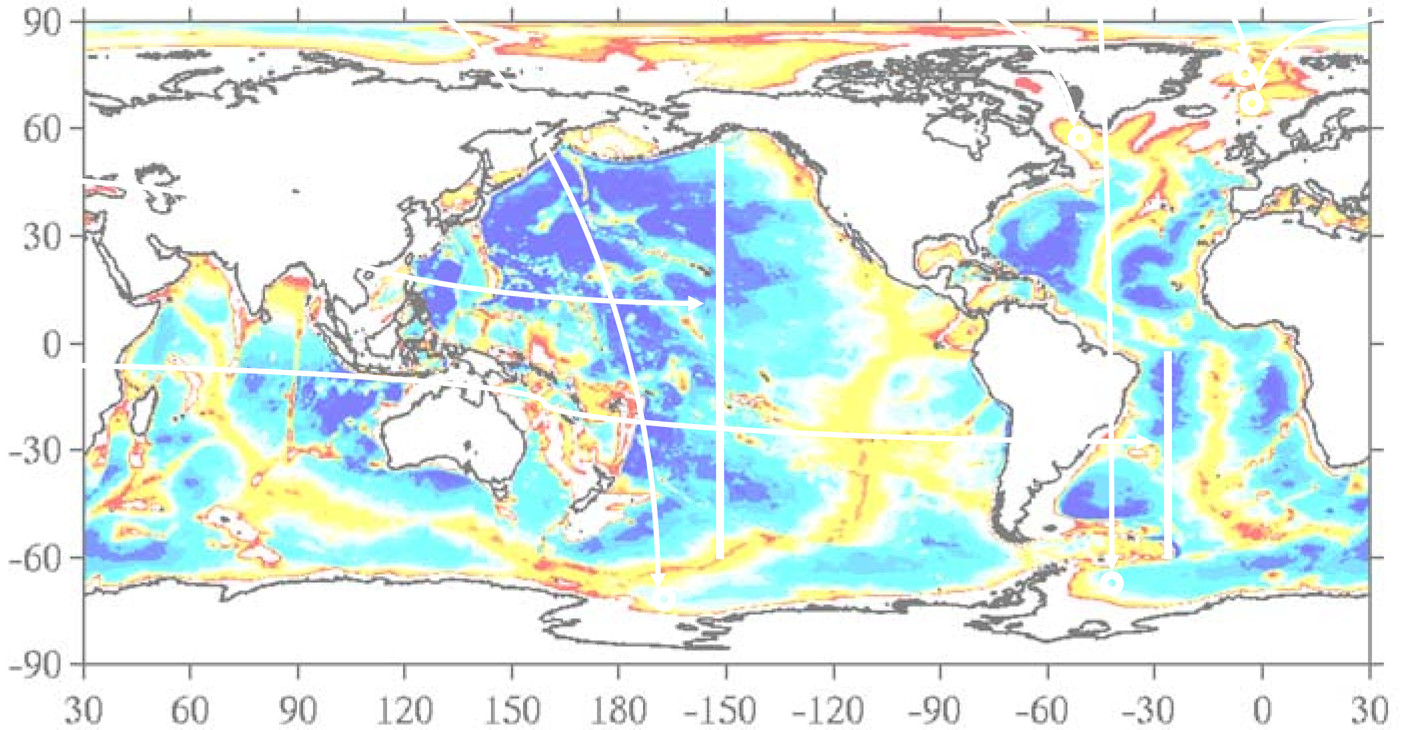
Sea level change due to freshwater input



Note the steady increase in the rate of freshwater input

Average rate:
2.1±0.8 mm/yr

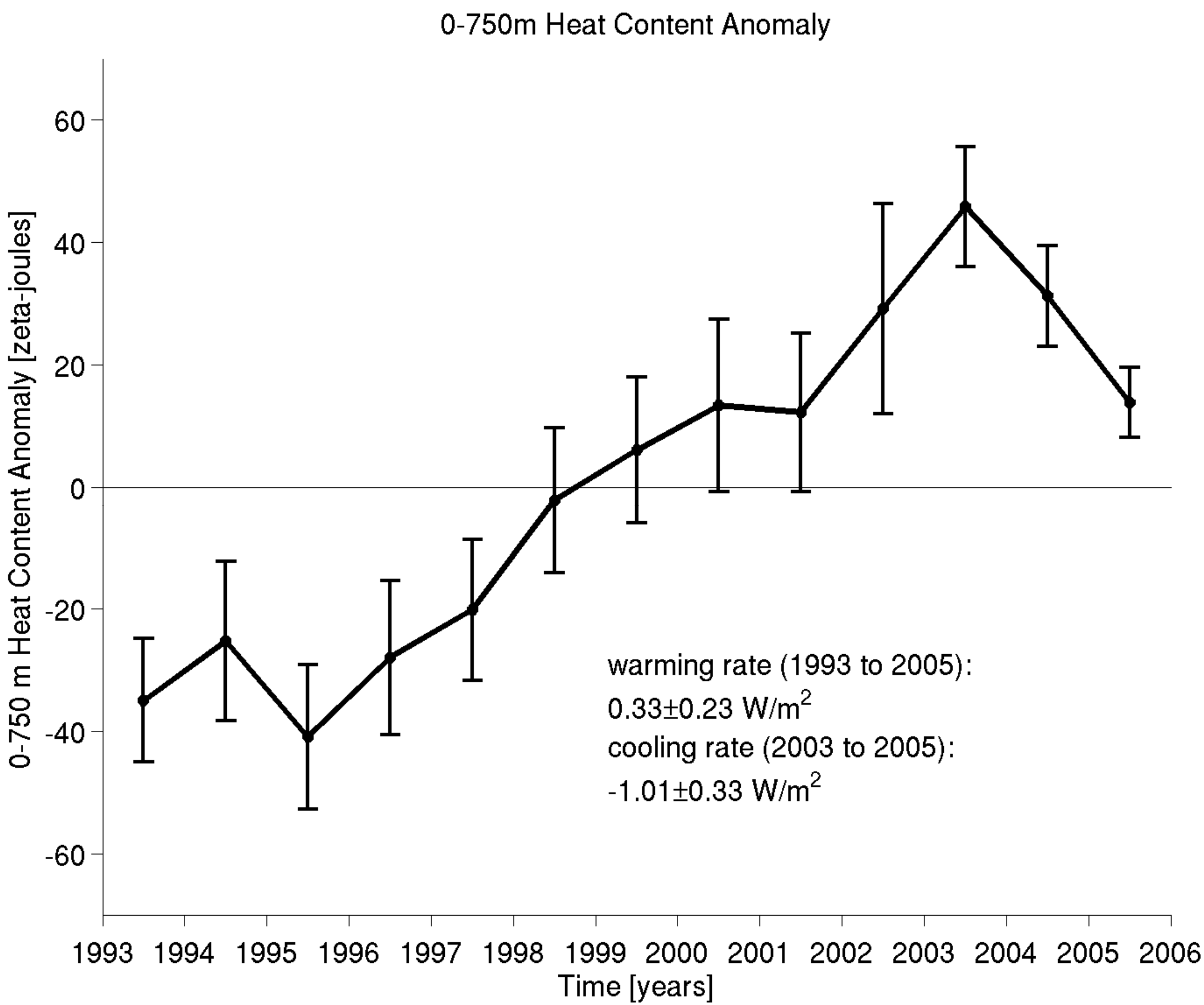
Discussion



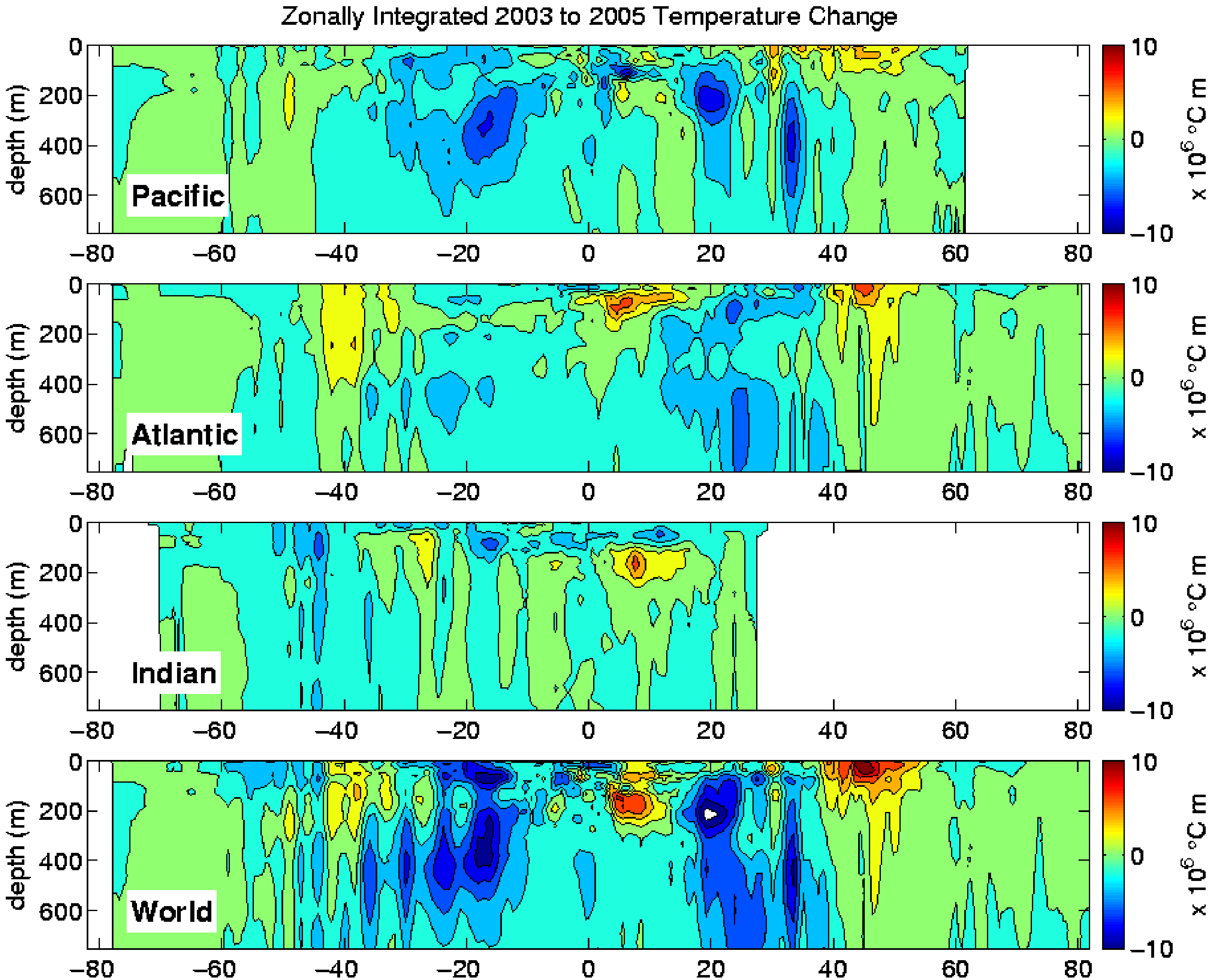
- Crude local/regional estimates suggest significant abyssal contribution
- Source regions locally 4 to 28 W m-2 over small areas (e.g. Labrador Sea)
- Interior oceans regionally 0.1 - 0.5 W m-2 over larger areas (e.g. Pacific)
- Time scales & spatial patterns?
    - N Atlantic -> Decadal (NAO)
- A few time-series & 10-year repeat sections!
    - What about the Antarctic?
    - What about the Indian, Pacific, & S. Atlantic?
- Need improved abyssal observing system

Conclusions

- Argo has increased the spatial resolution of annual estimates of global 0-750 m heat content and will extend the estimate to >1000m.
- Spatial mean of the Maps Yields Biased decadal trend low.
- Representative spatial mean produces an unbiased estimate of the decadal trend.
- We can see a 32 $\pm$ 11 zeta-Joule heat loss from 2003-2005.
- Where did the heat go?
  - Space?
  - Deep?
  - Combination?


0-750m Heat Content Anomaly
0-750 m Heat Content Anomaly [zeta-joules]
60
40
20
0
-20
-40
-60
warming rate (1993 to 2005):
0.33±0.23 W/m2
cooling rate (2003 to 2005):
-1.01±0.33 W/m2
1993
1994
1995
1996
1997
1998
1999
2000
2001
2002
2003
2004
2005
2006
Time [years]

Additional Slides – warming v. depth



Zonal integral of ocean temperature.

Note: much of the cooling at 400 m depth occurs in the tropical S. Pacific

We really want to know $\sum_{\substack{i=0,I \\ j=0,J}} m_{i,j} dA_{i,j} = M_r$, where

$m_{i,j}$ is the real mean at every grid point and

M_r is the total of the real spatial mean.

$$\sum_{\substack{i=0,I \\ j=0,J}} \langle m_s \rangle_{i,j} dA_{i,j} = M_s$$

$$M_s = m_s \sum_{\substack{i=0,I \\ j=0,J}} \langle 1 \rangle_{i,j} dA_{i,j}$$

Where

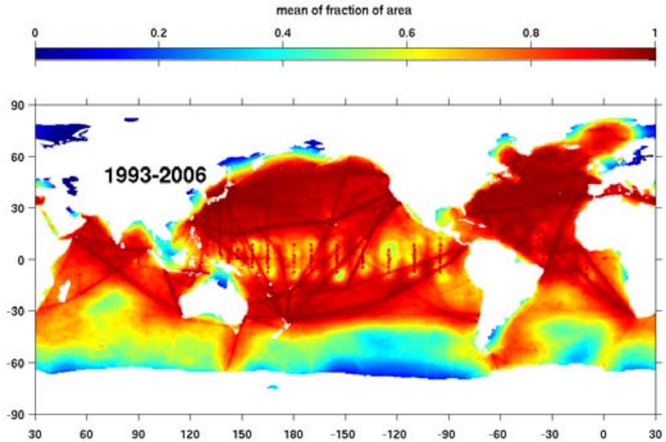
$\langle 1 \rangle_{i,j}$

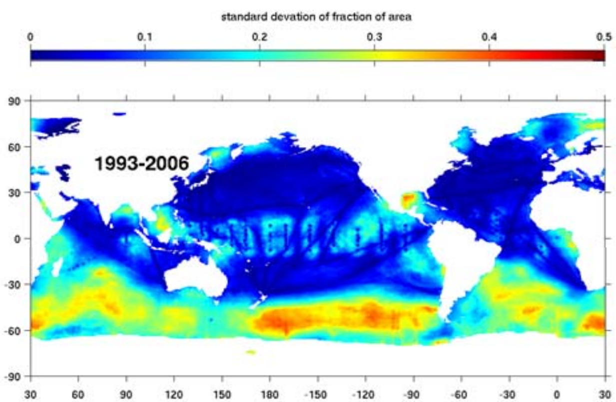
is 1 mapped to location i,j from the data positions. Then

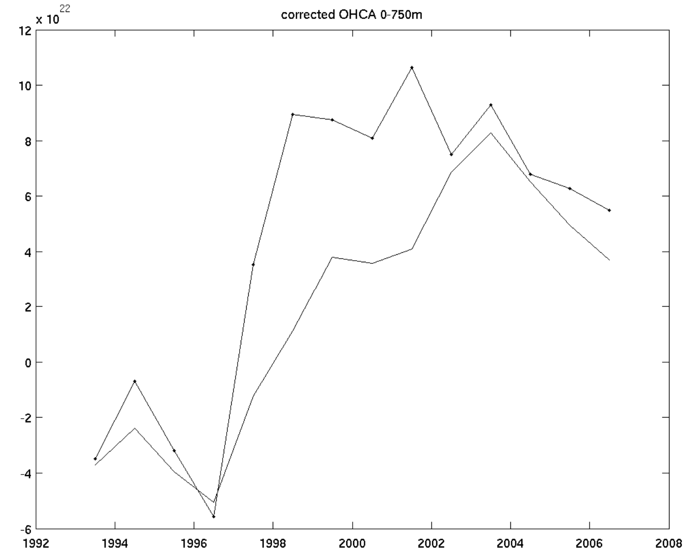
$$m_{i,j} \approx m_s = \frac{M_s}{\sum_{\substack{i=0,I \\ j=0,J}} \langle 1 \rangle_{i,j} dA_{i,j}}$$

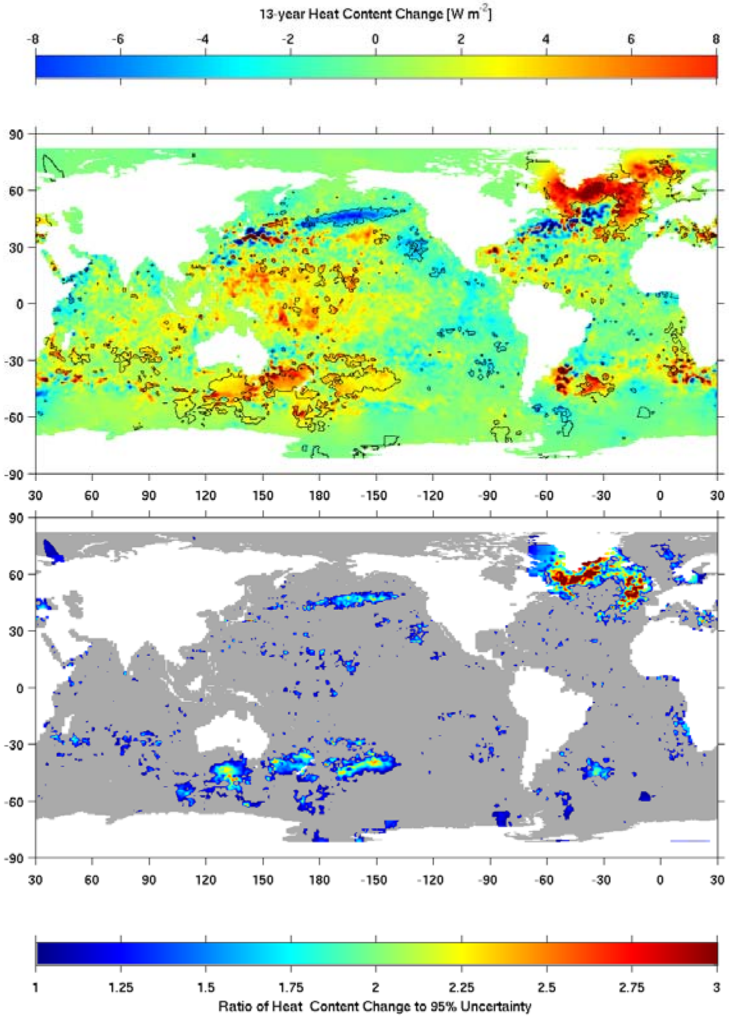
and ,

$$M_r = \sum_{\substack{i=0,I \\ j=0,J}} m_{i,j} dA_{i,j} \approx \frac{M_s \sum_{\substack{i=0,I \\ j=0,J}} dA_{i,j}}{\sum_{\substack{i=0,I \\ j=0,J}} \langle 1 \rangle_{i,j} dA_{i,j}} = \frac{M_s \times A}{\sum_{\substack{i=0,I \\ j=0,J}} \langle 1 \rangle_{i,j} dA_{i,j}}$$

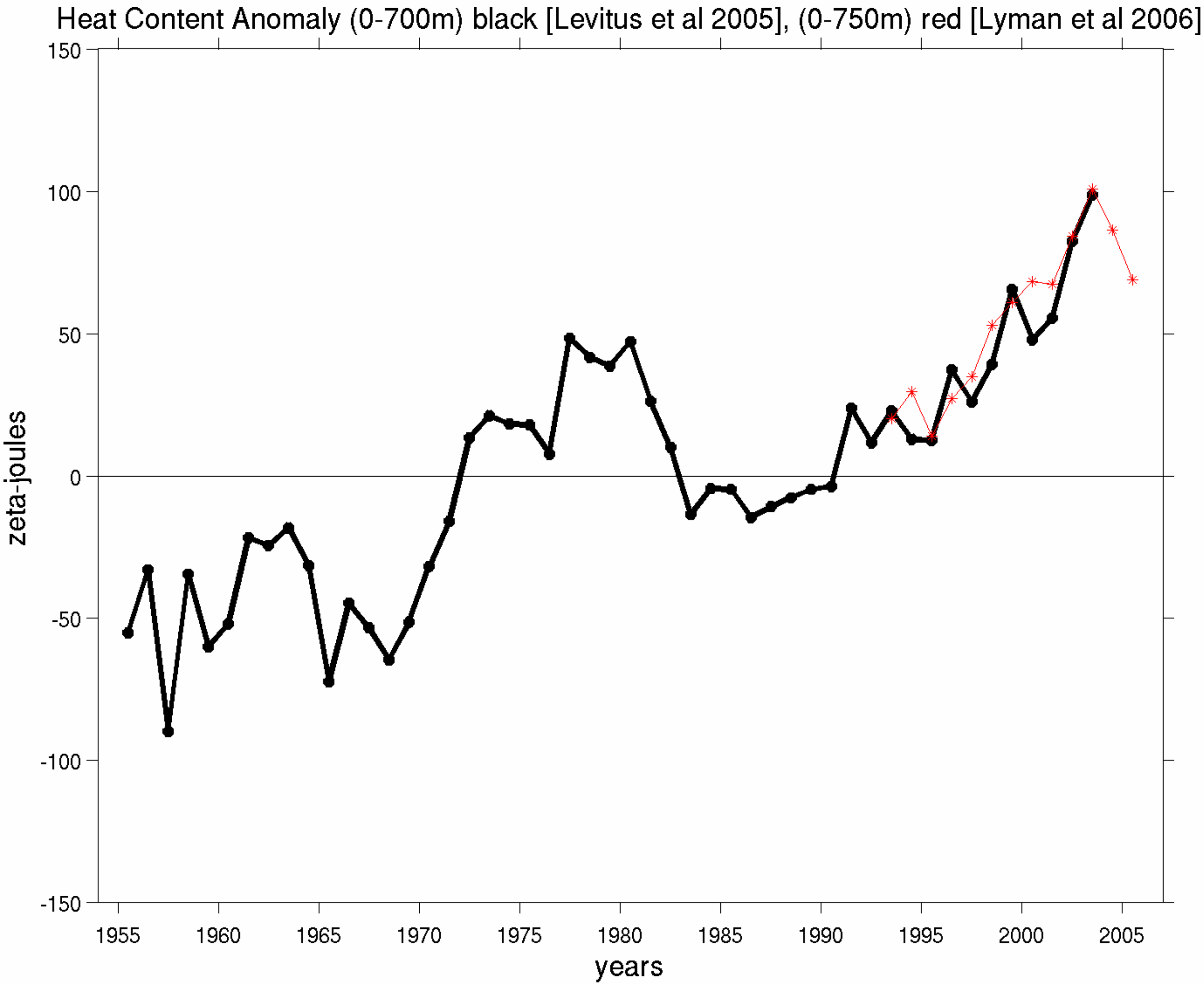

mean of fraction of area
0
0.2
0.4
0.6
0.8
1
1993-2006
90
60
30
0
-30
-60
-90
30
60
90
120
150
180
-150
-120
-90
-60
-30
0
30


standard devation of fraction of area
0
0.1
0.2
0.3
0.4
0.5
1993-2006
90
60
30
0
-30
-60
-90
30
60
90
120
150
180
-150
-120
-90
-60
-30
0
30


corrected OHCA 0-750m
x 10^22
12
10
8
6
4
2
0
-2
-4
-6
1992
1994
1996
1998
2000
2002
2004
2006
2008



13-year Heat Content Change [W m-2]
-8
-6
-4
-2
0
2
4
6
8
90
60
30
0
-30
-60
-90
30
60
90
120
150
180
-150
-120
-90
-60
-30
0
30
1
1.25
1.5
1.75
2
2.25
2.5
2.75
3
Ratio of Heat Content Change to 95% Uncertainty



1 zeta-joule = 1 x 10^{21} joules

≈ twice yearly world energy consumption

≈ 10,000 nuclear bombs