Closing the Ocean's Heat and Freshwater Budgets

Dean Roemmich

OST Science Working Team Meeting
Arles France, November 2003

Thanks to those who contributed published and pre-published results, and apologies to those whose work is inadvertently omitted.

Greek oceanographer.

Viking ship.

Greek ship.

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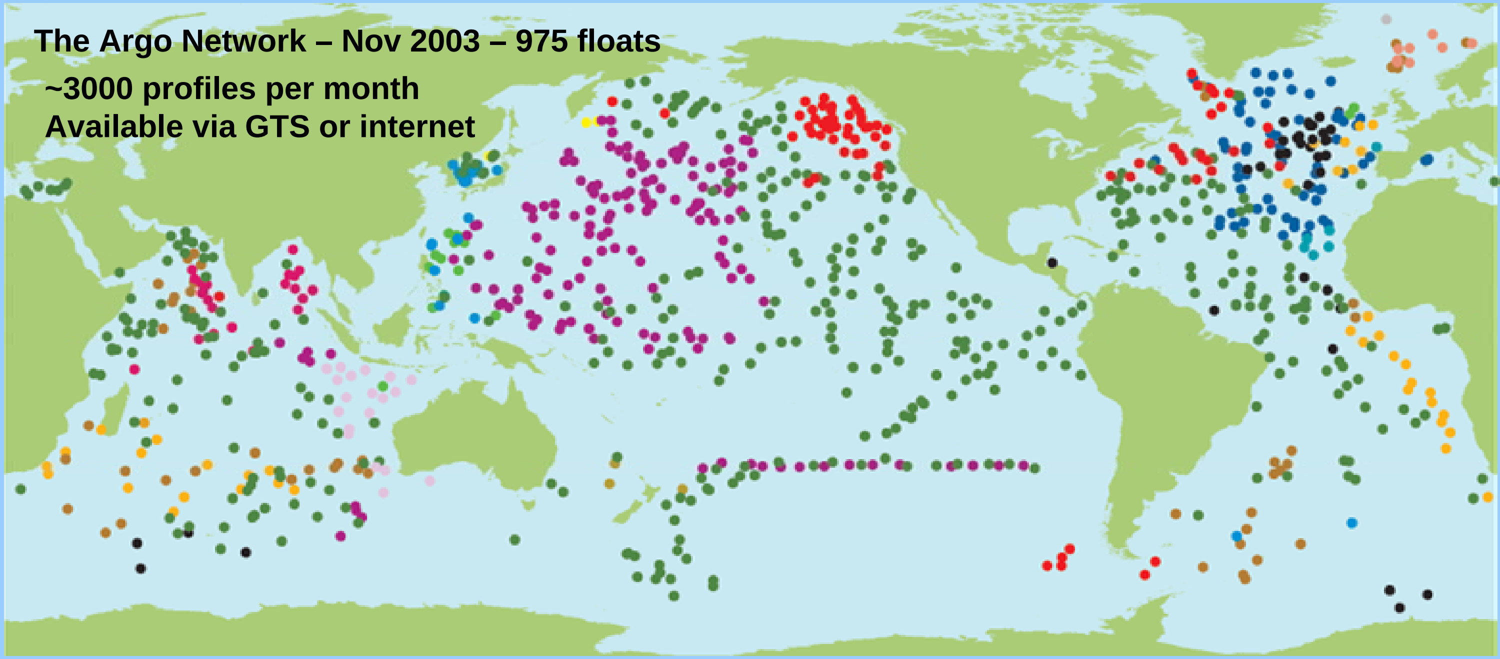
Closing the Ocean's Heat and Freshwater Budgets

The fundamental elements of the climate system are heat and water. The key to understanding the ocean's role in climate is our ability to observe how heat and water are stored in the ocean, carried by ocean circulation, and exchanged between the ocean and atmosphere.

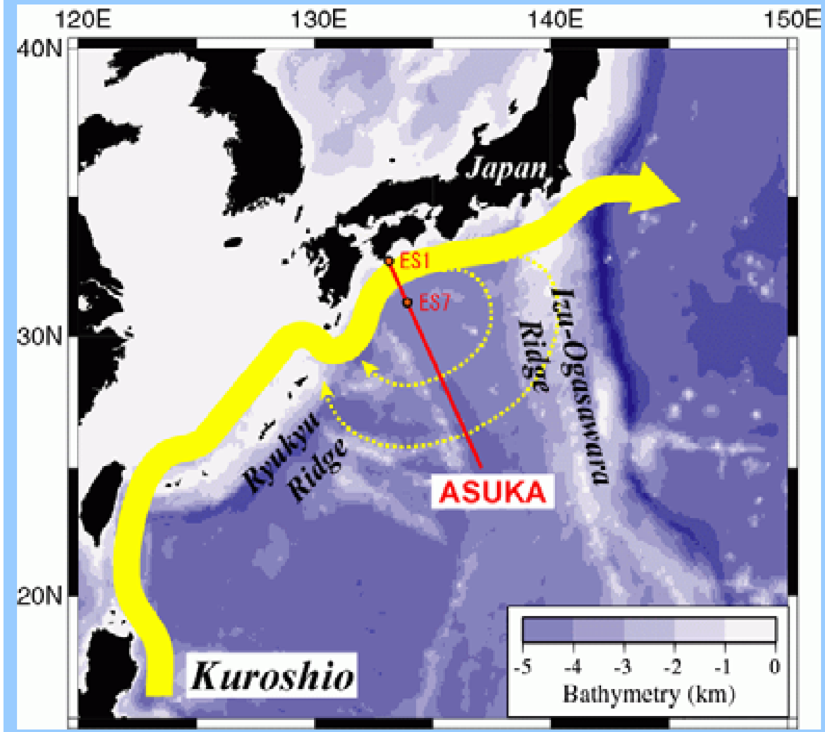
Most of the variability in altimetric height (AH) is due to anomalies in temperature and salinity. Drawing on this relationship, the combination of AH with *in situ* ocean observations has resulted in fundamental advances in estimation of mass, heat, and freshwater storage and transport during the past decade.

Closing the Ocean's Heat and Freshwater Budgets

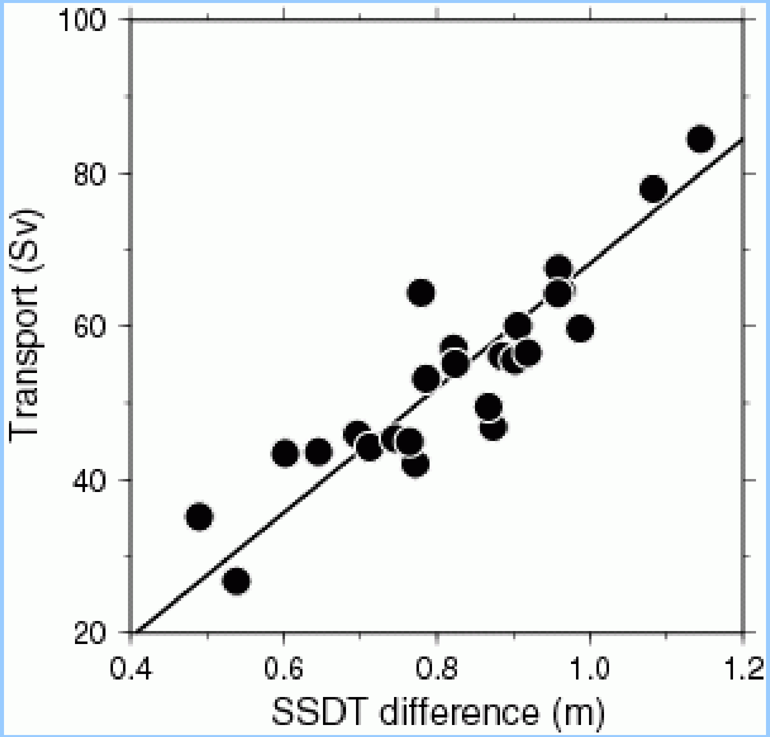
- Observing the boundary currents with AH and *in situ* data.
- Eddy heat transport.
- Basin-integrals of heat transport.
- Global heat and freshwater storage.
- Putting the pieces together.
- Looking to the next 10 years.



Boundary Currents: The Kuroshio, south of Japan

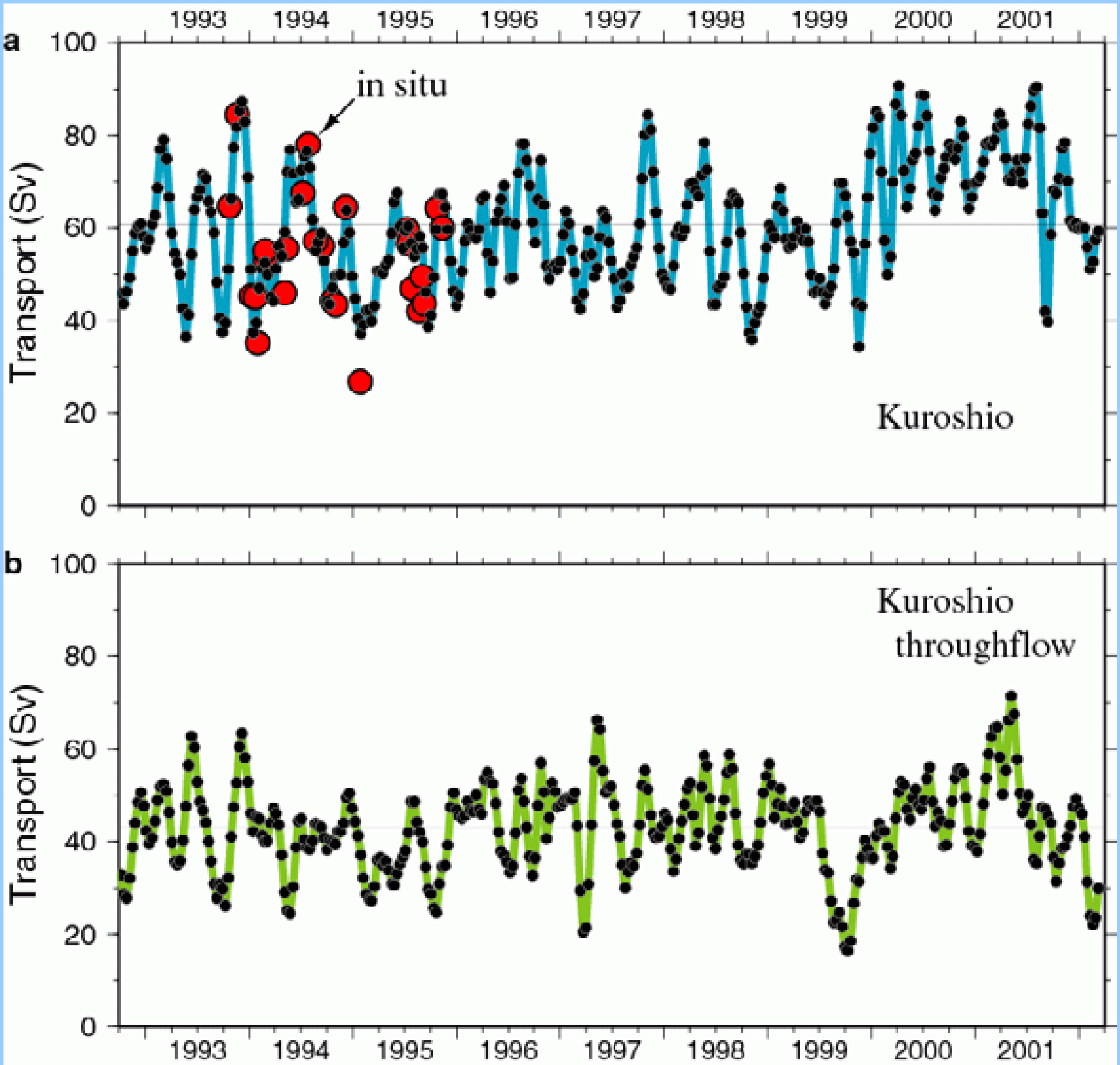


Scatter plot of the Kuroshio transport for the upper 1,000 m and the difference of sea surface dynamic topography (SSDT) across the Kuroshio.



ASUKA observational line (1993–1995) across the Kuroshio, purposefully located along a track of the TOPEX/POSEIDON altimeter

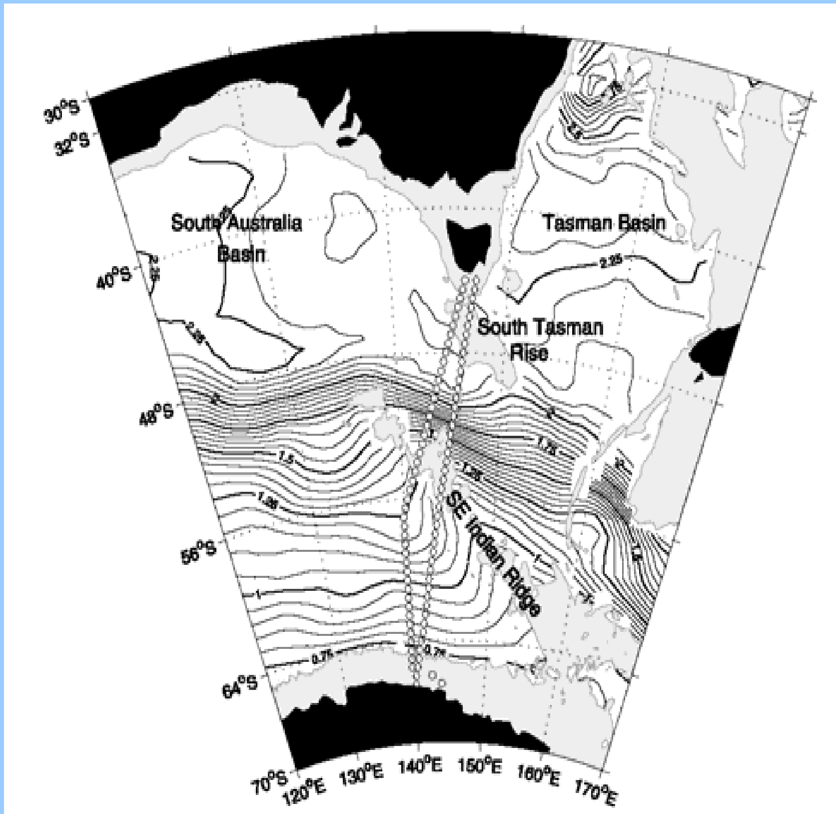
Imawaki and the ASUKA Group, 2003.



Time series of the Kuroshio transport south of Japan, estimated from T/P altimeter data using the relationship between the transport and difference of sea surface dynamic topography.

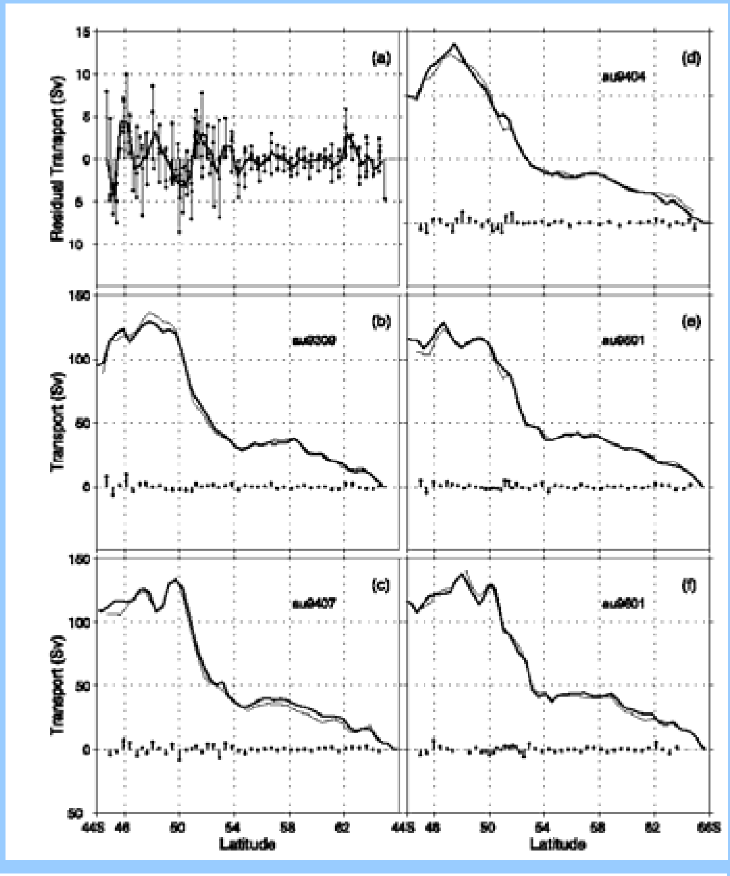
Imawaki and the ASUKA Group, 2003.

The ACC, south of Tasmania

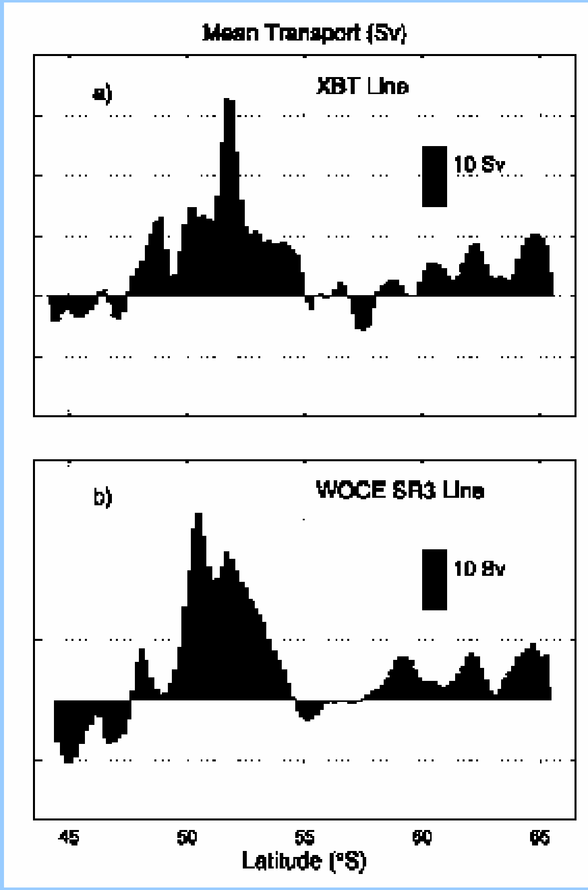


Tracks of 6 WOCE SR3 CTD transects (left) and 31 High Resolution XBT transects (right) overlain on mean dynamic topography 0/2500 dbar.

Cumulative transport from AH (thin line) versus full-depth CTD (thick line) along WOCE SR3 line.

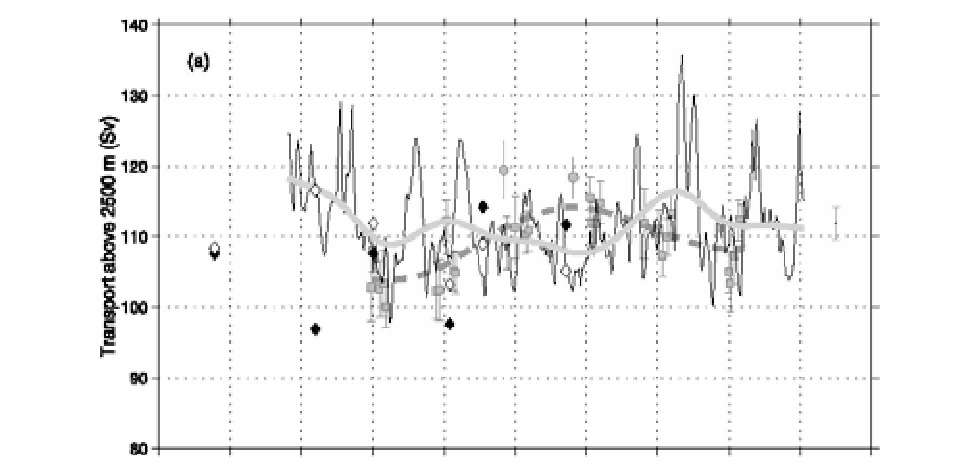


Rintoul, S, S Sokolov and J Church, JGR, 2002.



The mean volume transport per unit width (0 – 2500 m) from 31 austral summer XBT transects is very different than from 6 repeats of SR3.

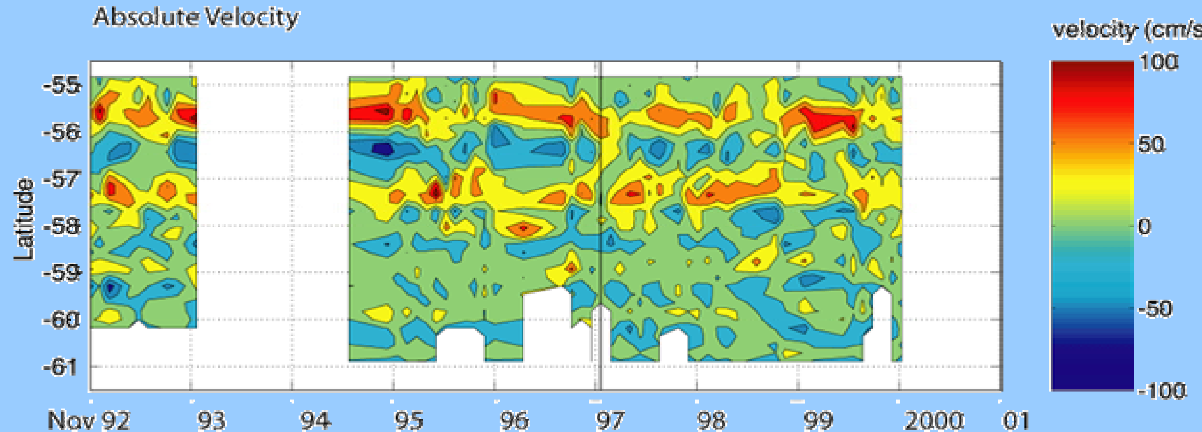
Interannual variability in 0 – 2500 m transport inferred from austral summer XBT transects (dashed line) suffers from temporal aliasing, but is correctable using AH (solid line).

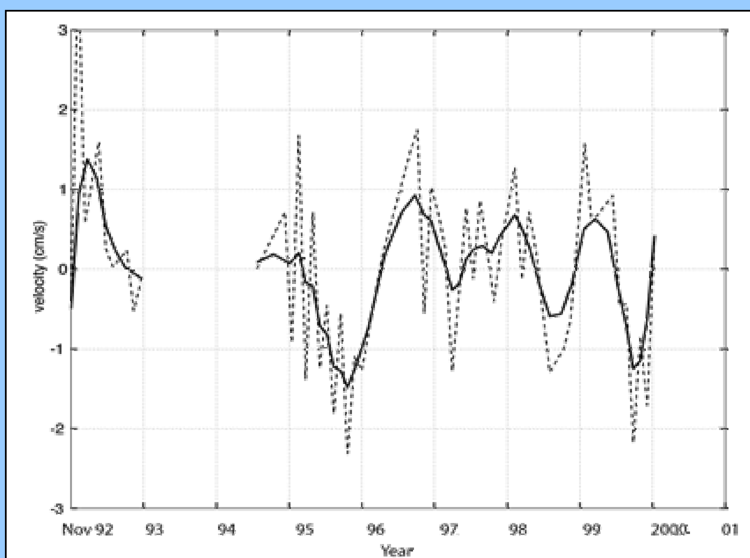


Rintoul, S, S Sokolov and J Church, JGR, 2002.

The ACC in Drake Passage

Absolute cross track velocities on WOCE section SR1b across Drake Passage from AH combined with CTD/ADCP/LADCP data.





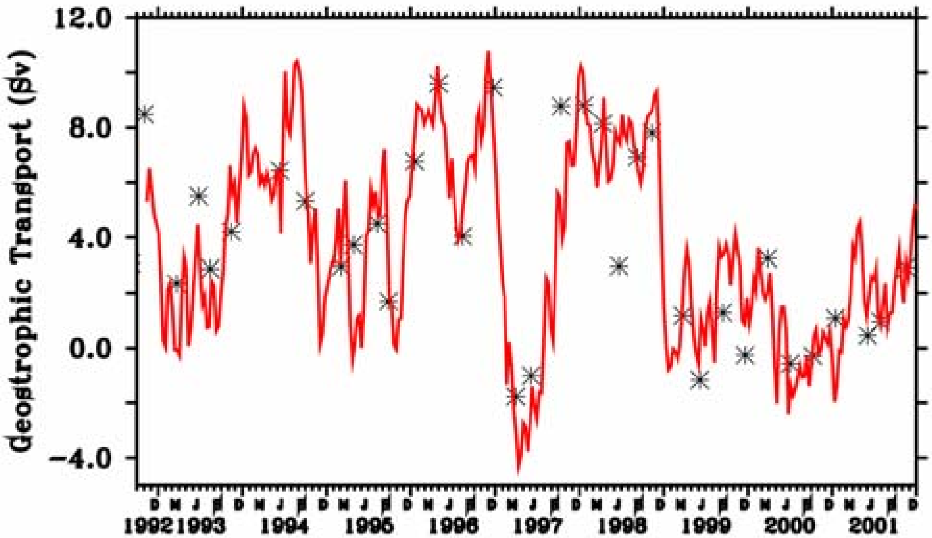
Time series of the spatial mean surface velocity through Drake Passage on WOCE section SR1b (time mean removed).

The time mean (1992 to 2001) average velocity across Drake Passage is 15.34 ± 1.09, 0.44, 2.72

cm/s (mean ± sd, se, range)

Cunningham and Pavic, 2003.

The East Auckland Current



Time-series of transport in the East Auckland Current north of New Zealand, 0 – 800 m, using AH (red) and High Resolution XBT/XCTD transects.

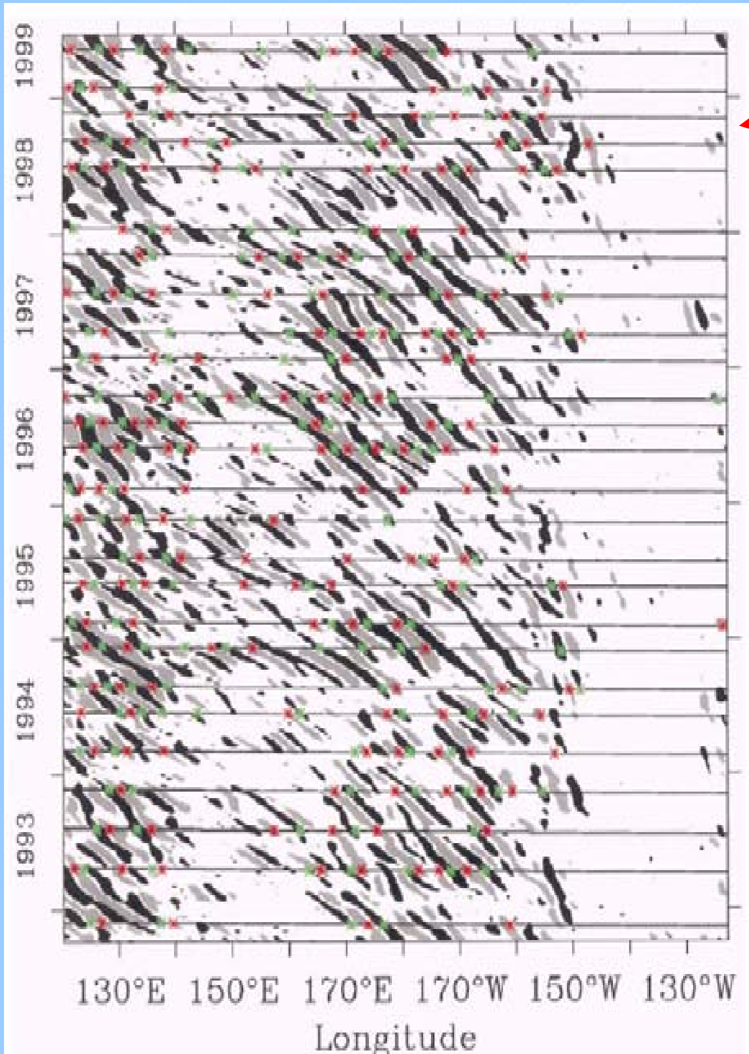
Boundary currents are a central component of ocean heat transport.

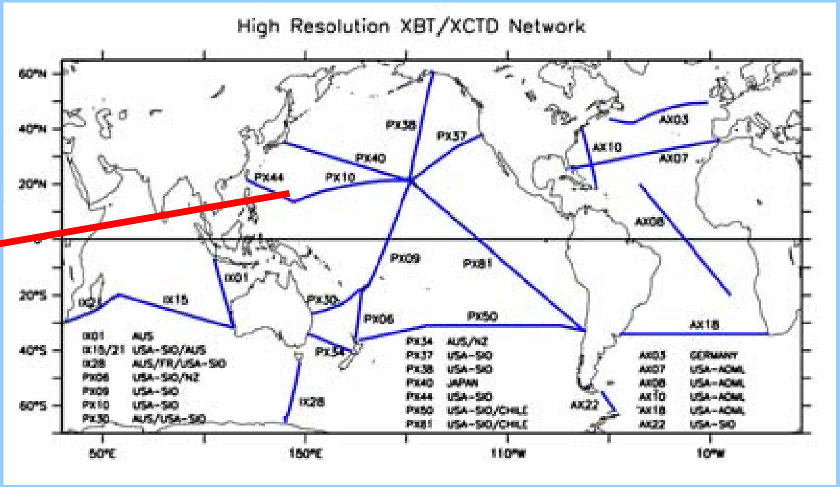
Combinations of AH and *in situ* data have proved effective for long-term observations of boundary currents in specific regions. A systematic plan is needed for observing the boundary currents on a global basis.

Glider technology and wide-swath altimetry could provide a powerful combination.

Roemmich et al, 2003.

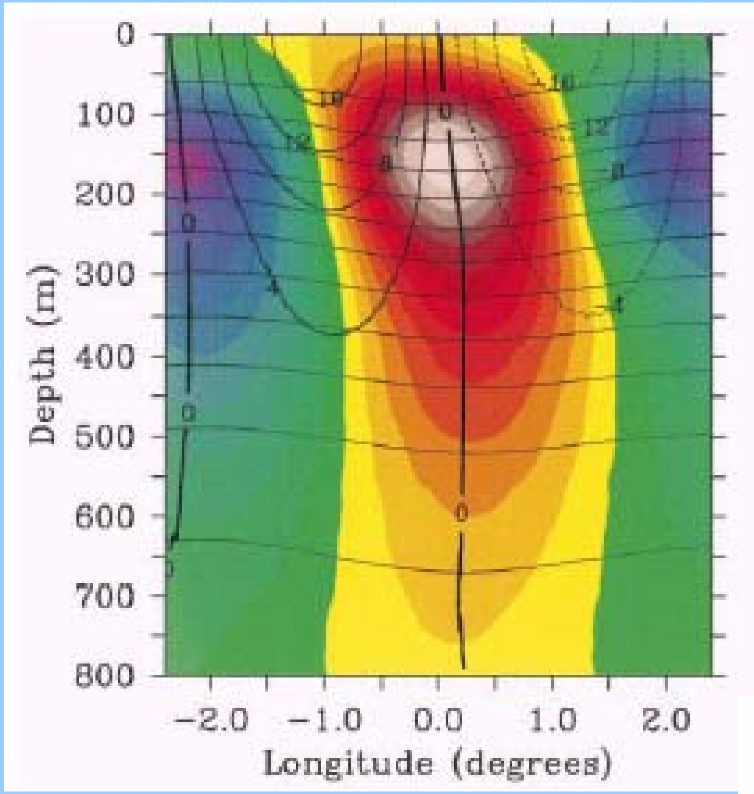
Eddy heat transport





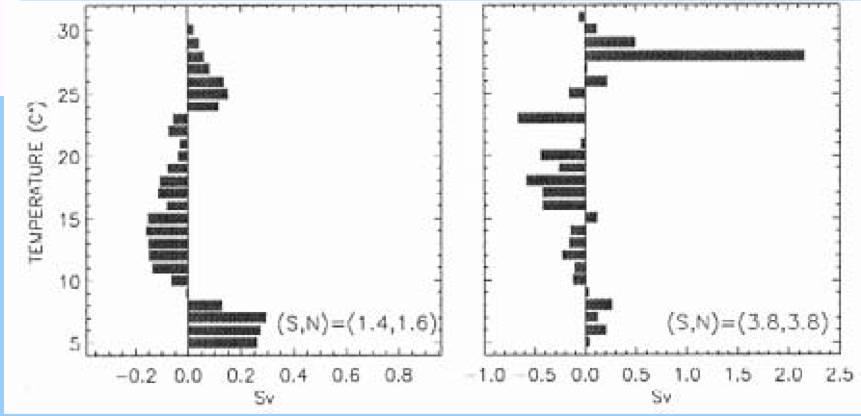
Warm and cold-core eddies are observed as steric height anomalies (red and green symbols) propagating westward at 20ºN in High Resolution XBT data, and in AH anomalies (grey and black). Mean northward heat transport due to the eddies was 0.1 pW, with substantial interannual variability.

Roemmich and Gilson, JPO, 2001



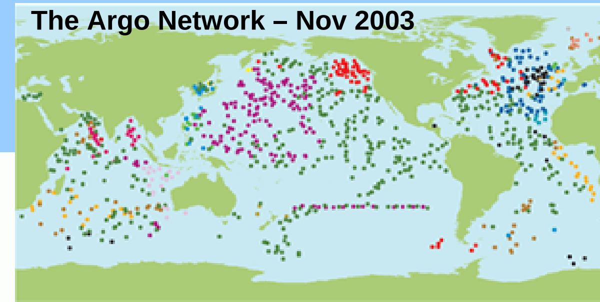
A composite of 192 warm-core eddies (temperature and geostrophic velocity anomaly) confirms the zonal tilt of the eddy center, giving rise to northward heat transport.

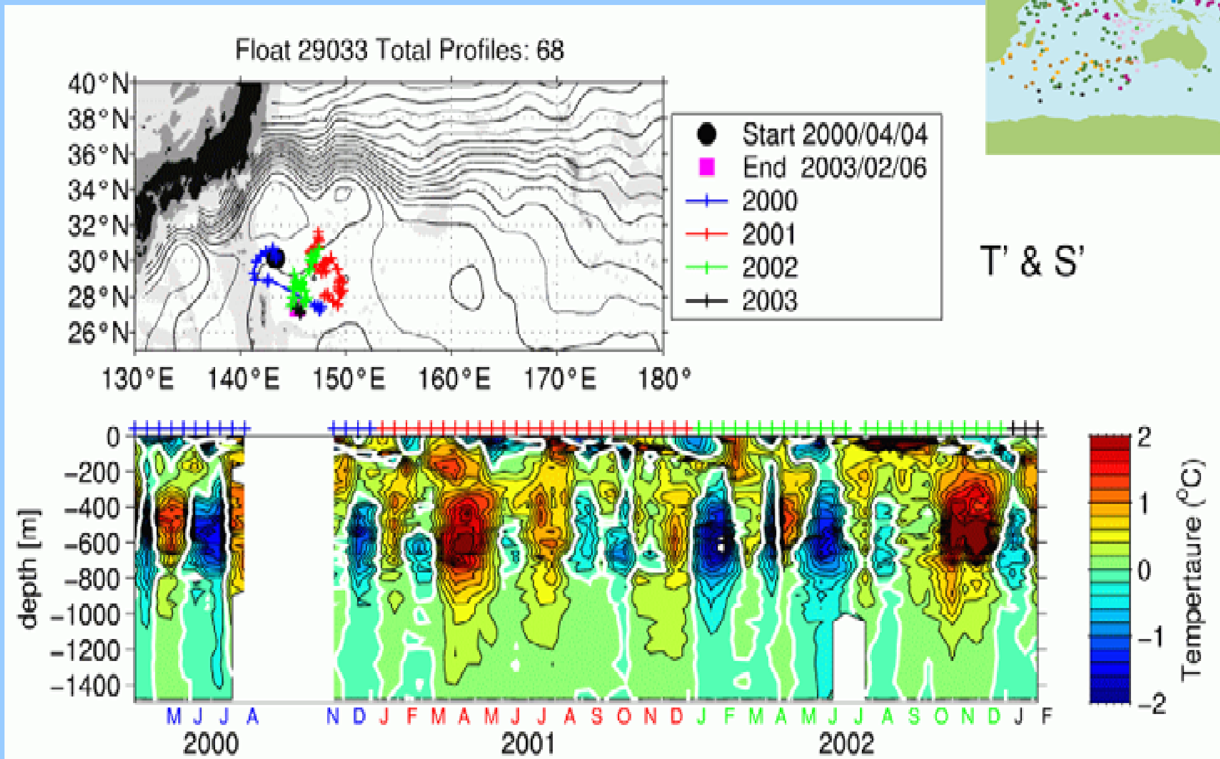
The eddy-induced overturning circulation seen in the XBT data is reproduced in a model.



Roemmich and Gilson, JPO, 2001 (left), McWilliams and Danabasoglu, JPO, 2002 (right)

Eddy heat transport (cont)

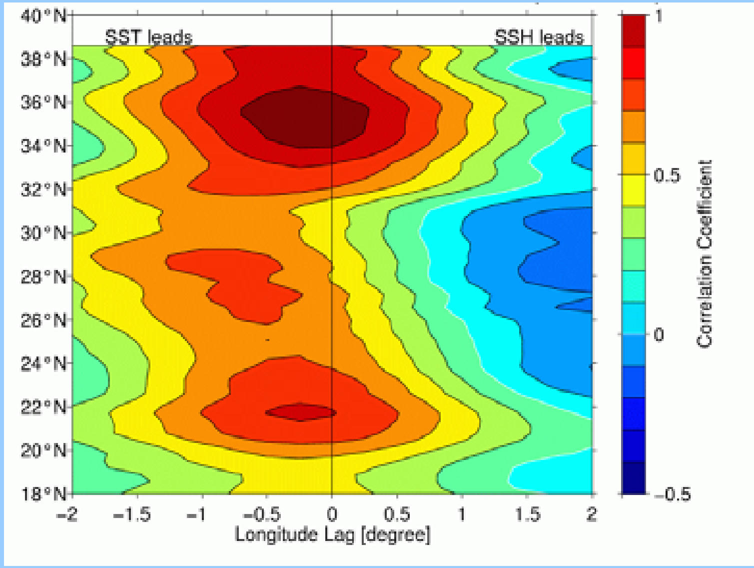




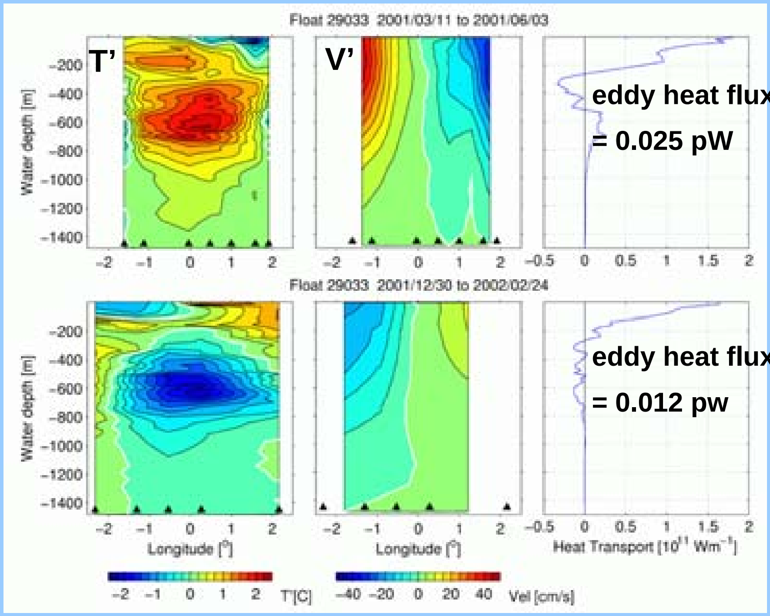
An Argo float south of the Kuroshio Extension is used to estimate eddy structure, including heat transport.

(At the first Argo Science Workshop last week in Tokyo.)

Qiu, Chen, and Hacker, 2003



Throughout the subtropical North Pacific, SST maxima (from TMI) are found systematically to the west of SSH maxima.

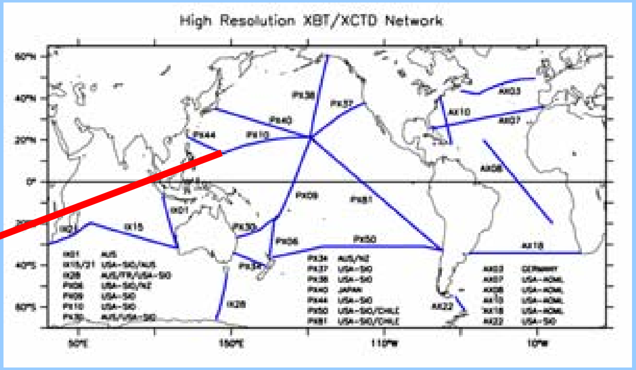


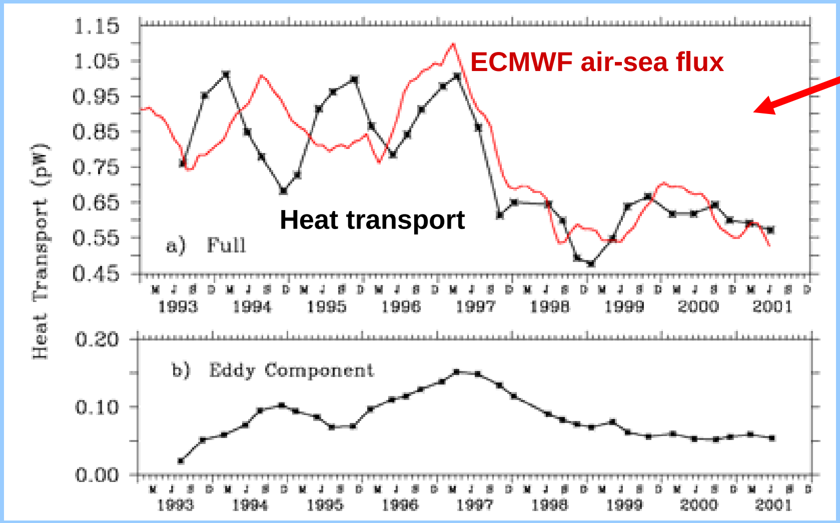
Sequences of float profiles can be used to reconstruct the spatial structure of warm and cold core eddies, with SSH used to position of profiles relative to the eddy center.

Westward displacement of surface layer temperature gives rise to northward heat transport. AH indicates about 8 eddies at a time at this latitude between 130°E and 180°E, hence 0.1 – 0.2 pW total.

Qiu et al, 2003

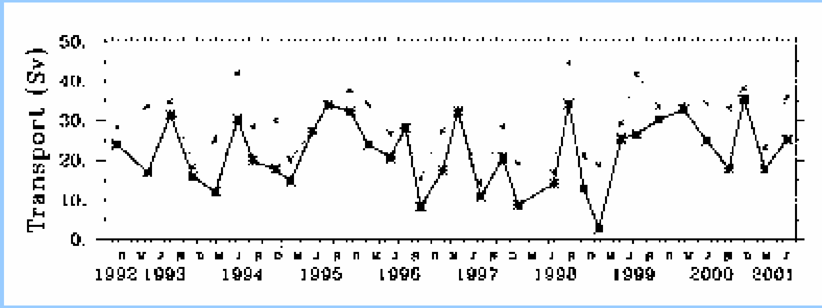
Basin-integral of heat transport (eddy plus large-scale components).





Total meridional heat transport across the same North Pacific XBT transect (1-year running mean.

AH provides information on absolute velocity and correction for temporal aliasing.

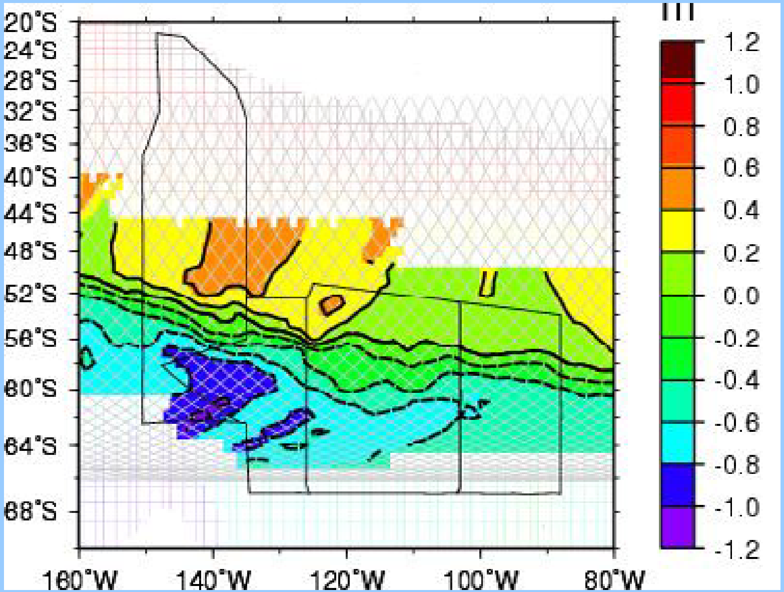


Kuroshio transport southeast of Taiwan. While it's essential to include the BC in basin-wide estimates, BC transport variability may not be correlated to basin-wide heat transport.

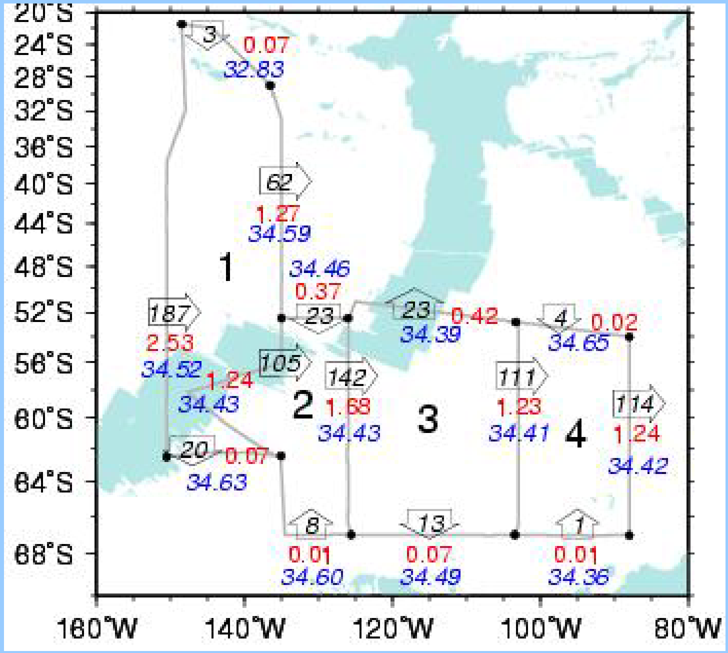
Roemmich et al, JGR, 2001 (upper), Gilson and Roemmich, JO, 2002 (lower)

Large-scale estimates – Southern Ocean

Heat transport from floats, hydrography and altimetry



Mean SSH determined using TOPEX data with meandering jet model. This SSH served as a surface constraint for the regional inverse model together with mid-depth float velocities and hydrographic transects.



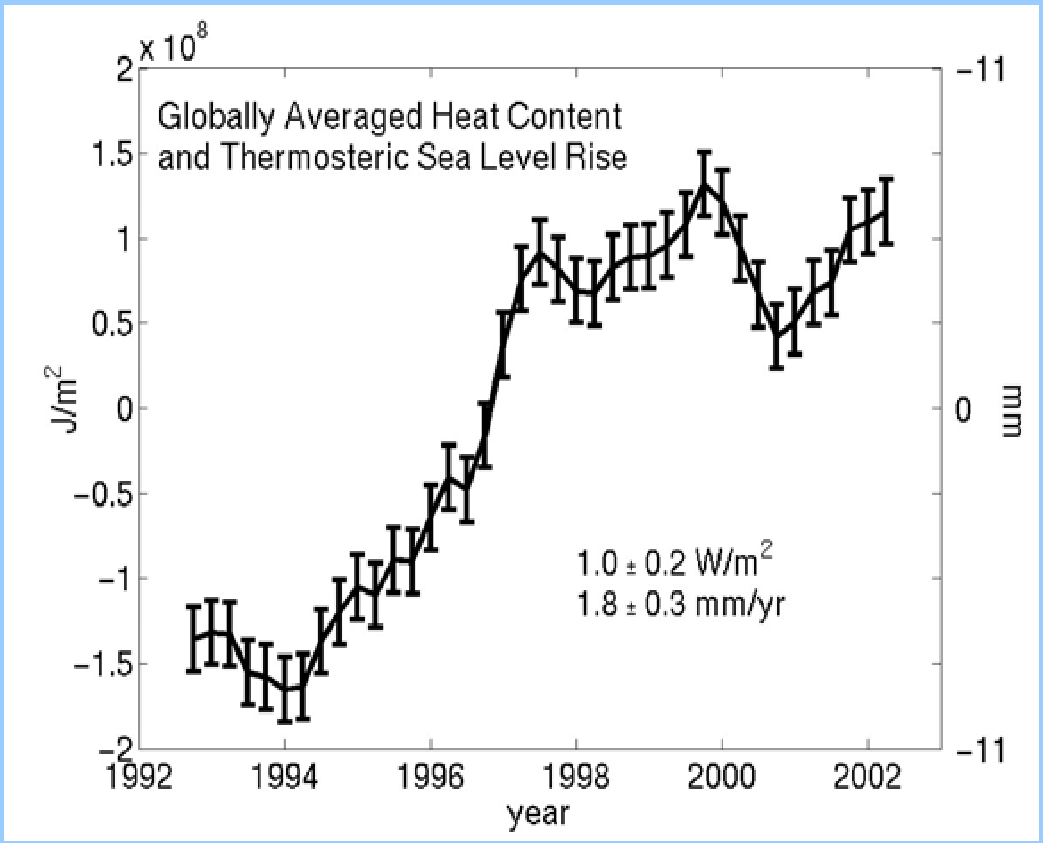
Best estimate of transport (in arrows), heat transport (red, PW), and mean salinity transported across boundaries (blue).

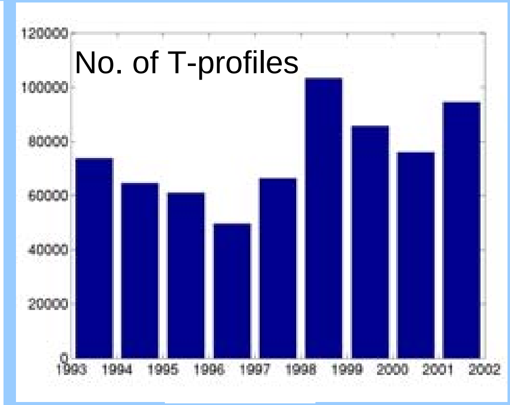
This calculation is viewed as a prototype of an "eclectic" inverse model, and might be extended to include temporal variability.

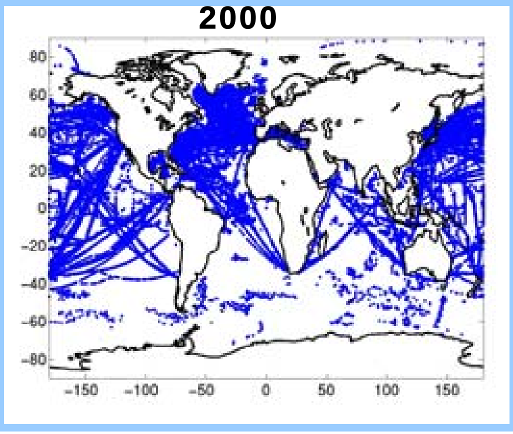
Gille, JGR, 1999

Global heat storage from AH and in situ data.

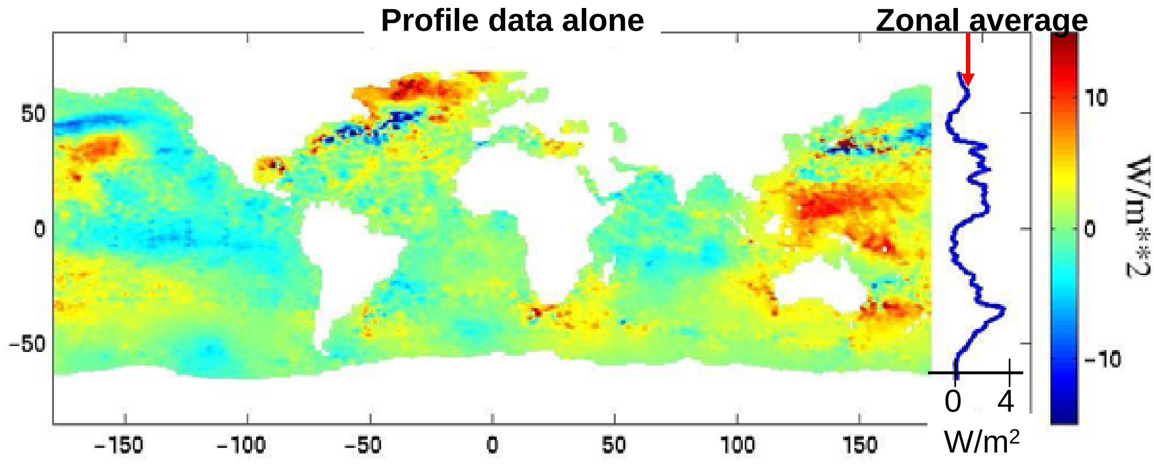
The combination of AH with profile data (Argo + XBT + CTD) provides improved estimation of interannual variability in global ocean heat content. The technique makes a first guess using the AH/heat content correlation (synthetic method), then corrects it when and where data are available.

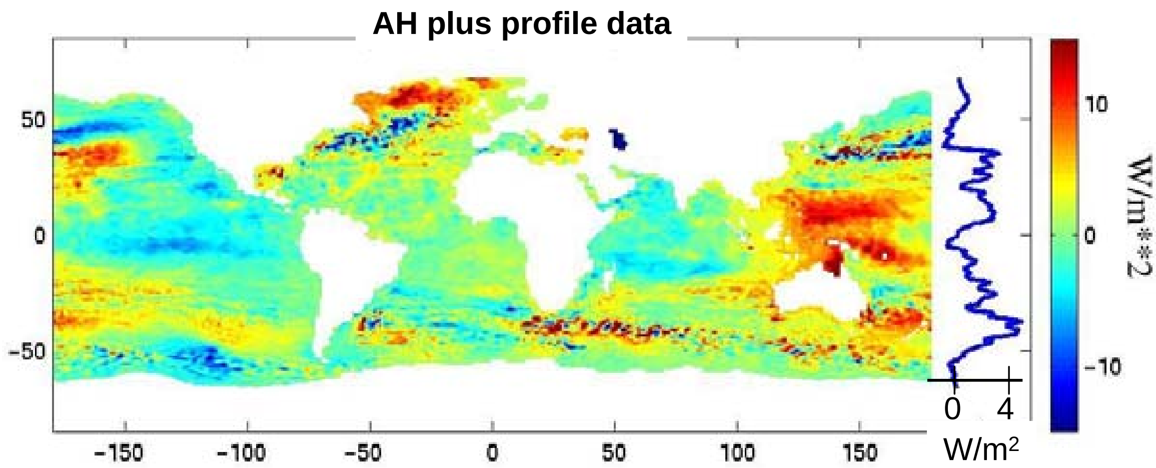






Willis, Roemmich, and Cornuelle, 2003 (see poster)

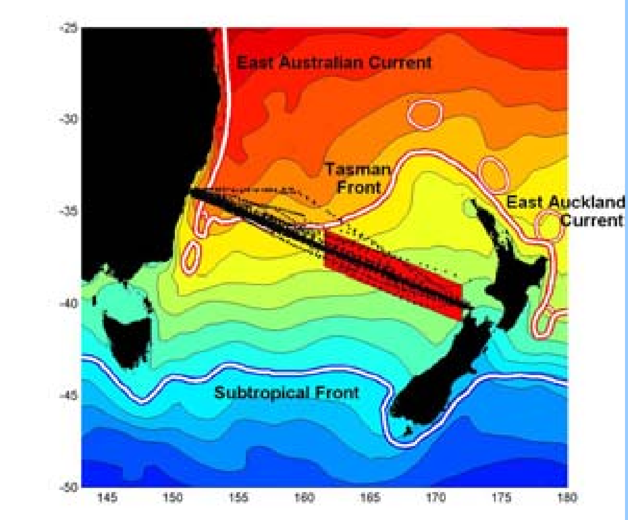




10-year trend in global ocean heat content, 0 – 750 m.

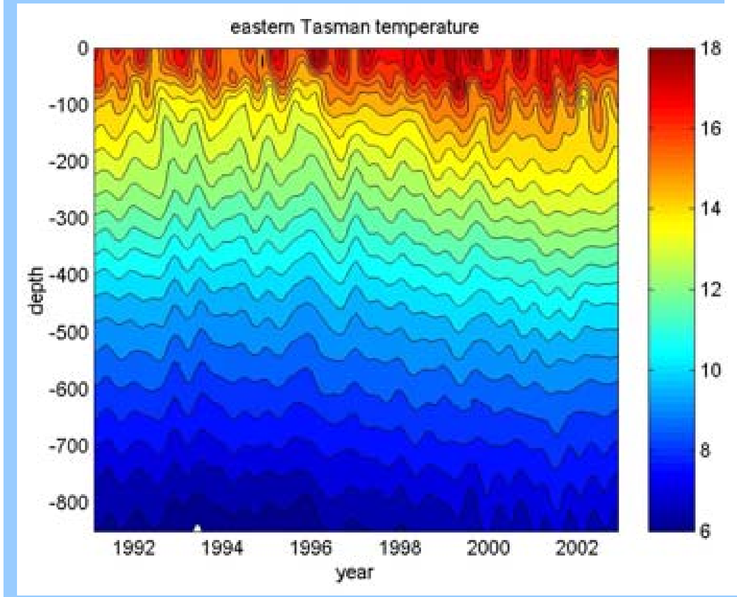
The largest heat gain is found at 40°S, where more profile data are needed.

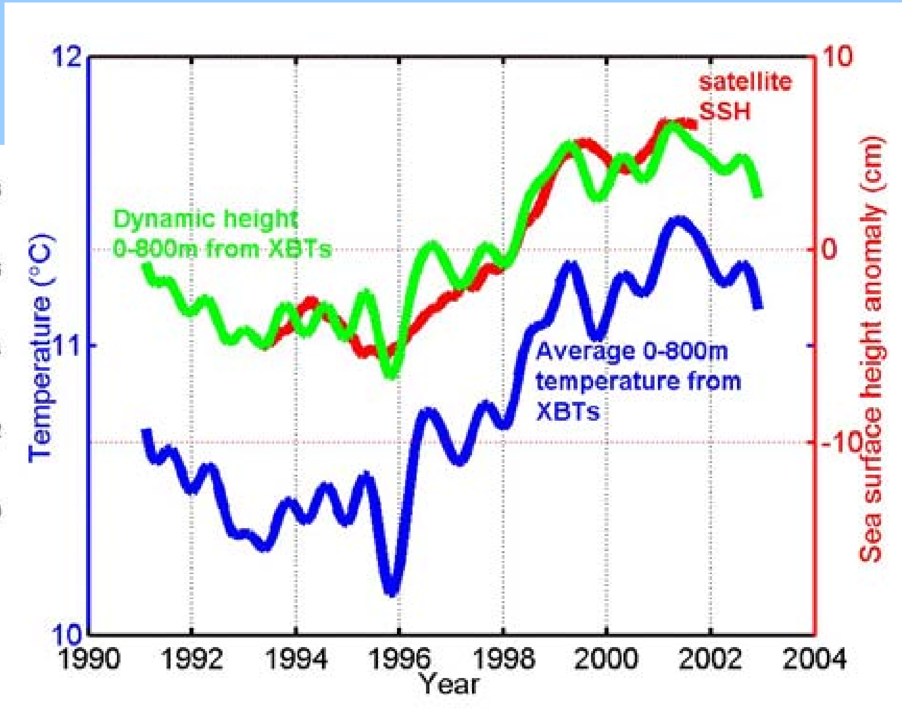
Willis et al, 2003



The mid-latitude warming in the 90's extended through the thermocline.

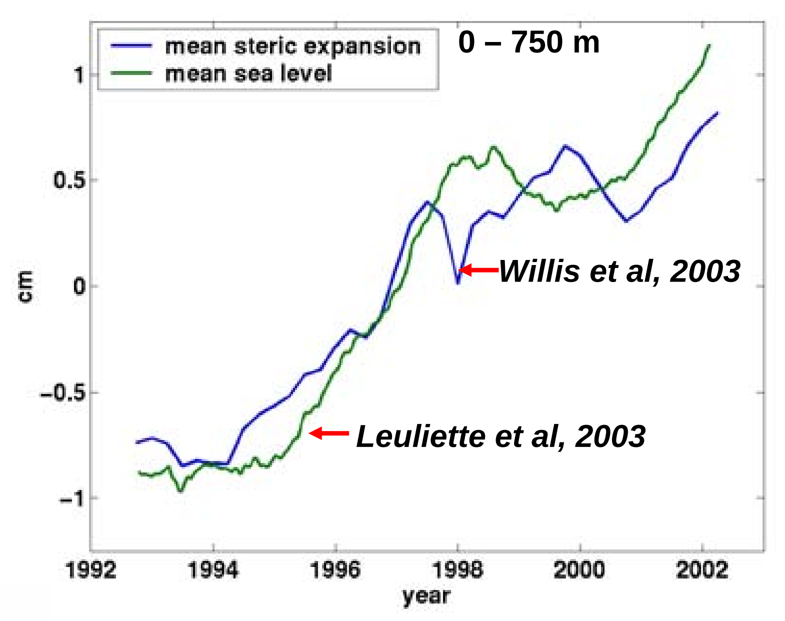
At 40ºS in the eastern Tasman Sea, a 12-year record from High Resolution XBT sections confirms the 0 – 800 m warming signal. Argo is needed for observation of such patterns on a global basis.

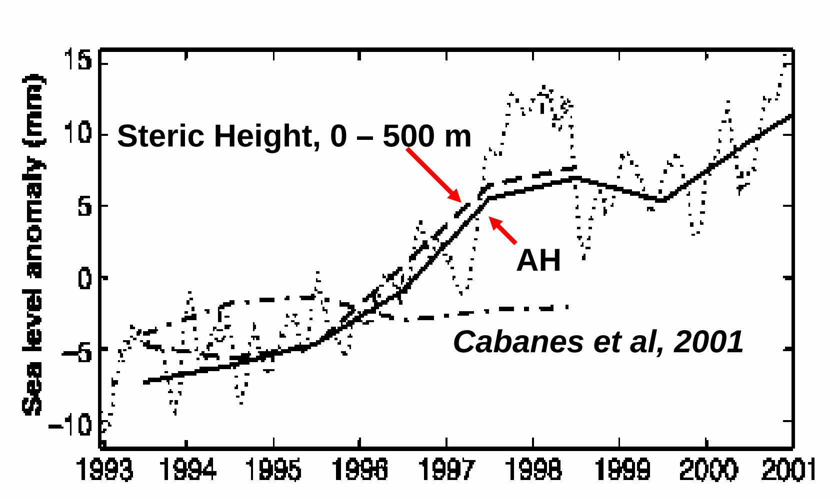




Sutton and Bowen, 2003

An important issue is the separation of sea level rise into steric expansion versus increasing mass of seawater. Argo will detect steric expansion due to both T and S, and eventually, salinity dilution due to ice melting.





While AH and SH were very similar in the first 5 years of the T/P mission, their patterns were somewhat different in the second 5 years. A longer time-series is needed to distinguish interannual variability from decadal and longer term signals.

Cabanes, Cazenave, and Le Provost, Science, 2001 (left), Willis et al, 2003, Leuliette et al, 2003 (right)

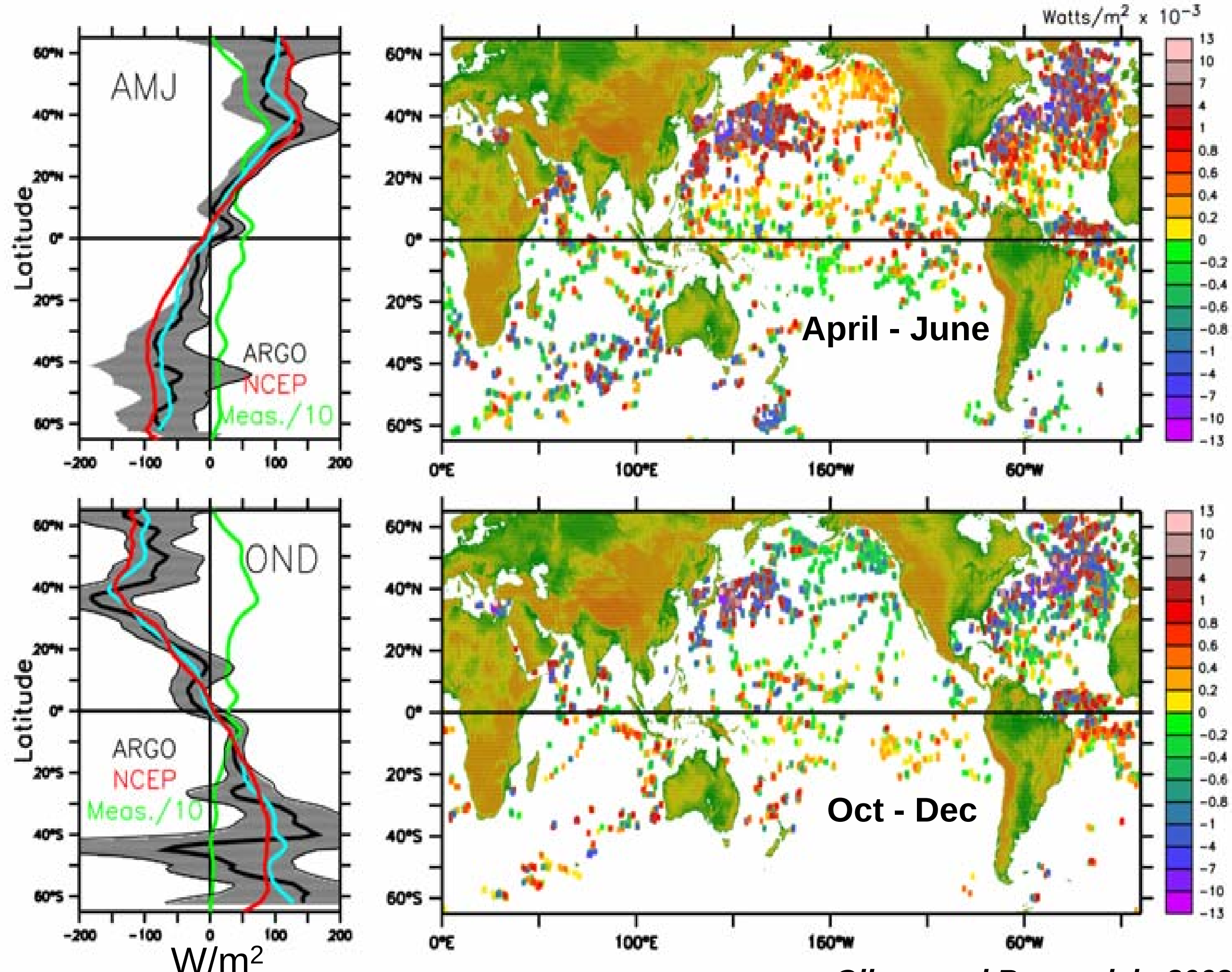
Global seasonal heat storage, from 34,000 Argo profile-pairs.

(Black) Argo heat storage, zonally averaged.

(Red) NCEP air-sea exchange, 3-year average.

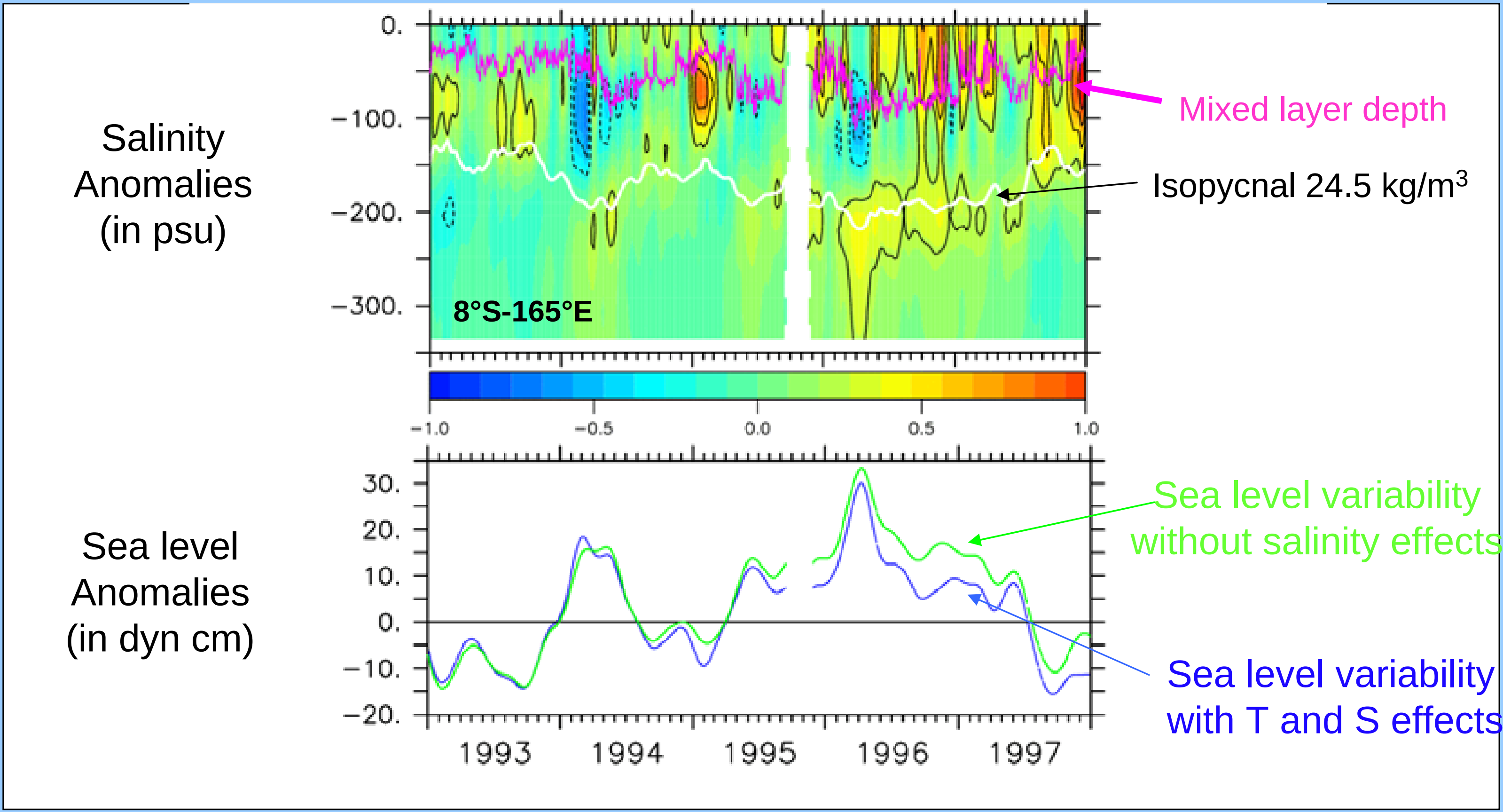
(Lt Blue) NCEP subsampled at place and time of Argo profile.

(Green) No. of profile pairs in average value.



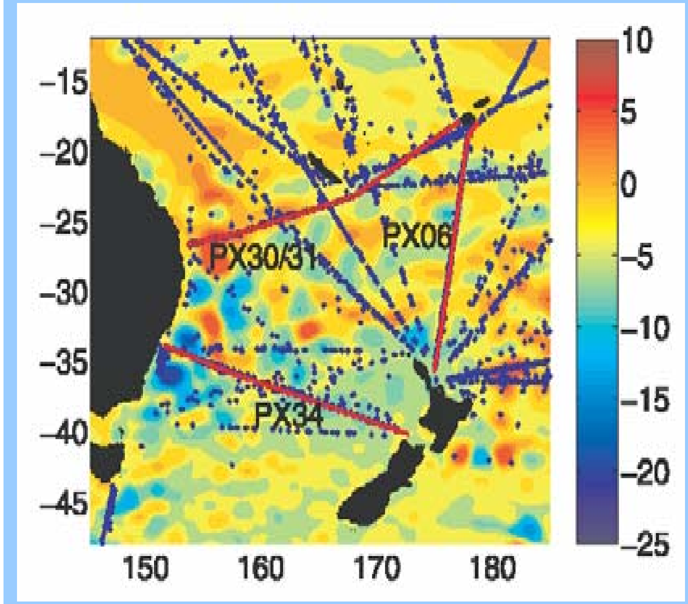
Gilson and Roemmich, 2003

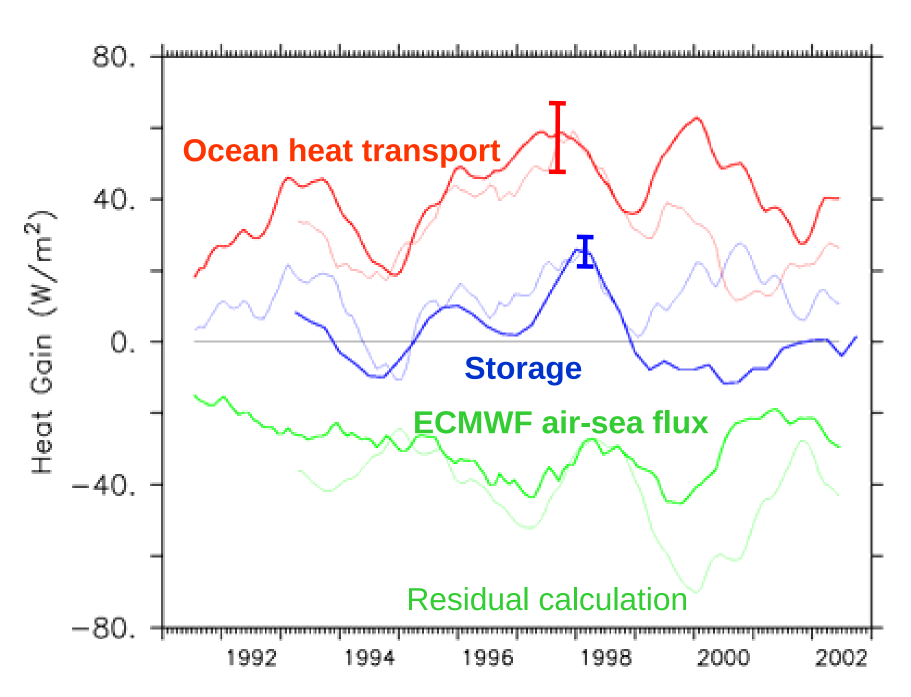
Salinity variability. **Even in the pre-Argo period, it is possible to recover much of the interannual variability in salinity using AH and T-profiles with combined T- and S- EOFs. Here, salinity anomalies 1993-97 were estimated from TAO and AH data.**



Maes and Behringer, 2000

Closing heat budgets.





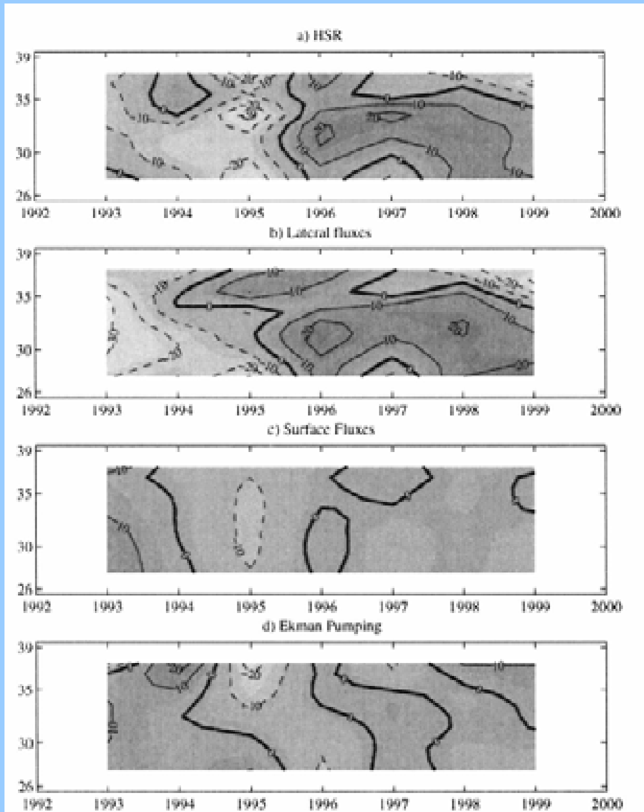
The interannual heat budget for the Tasman Box (waters > 12°C) is estimated using a combination of datasets:

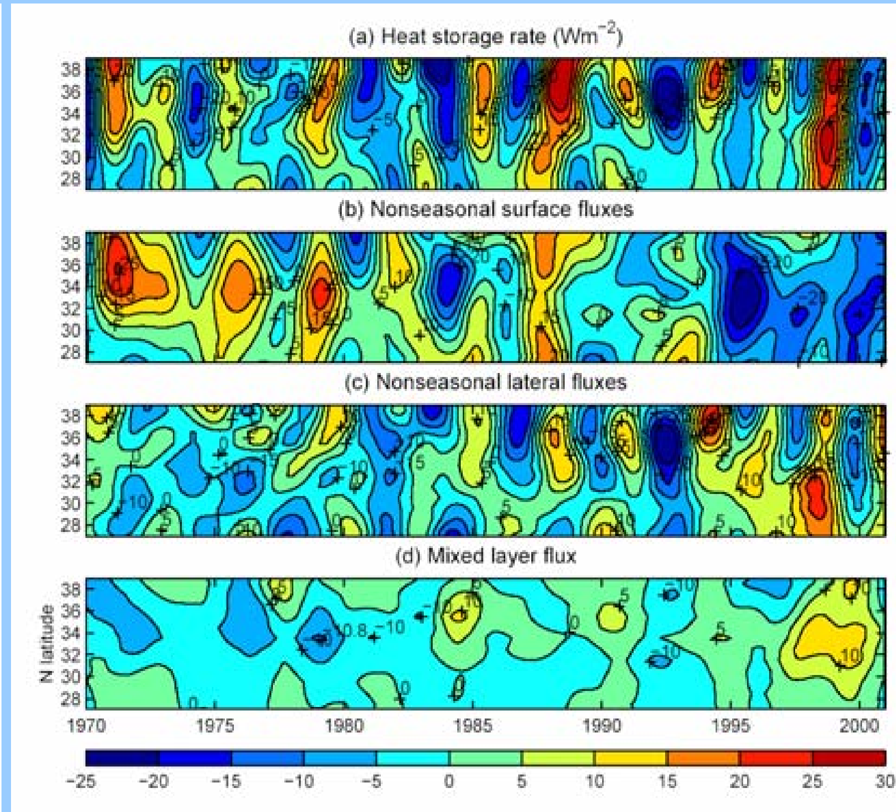
- **Storage from XBTs + CTDs + Argo, combined with AH**
- **Transport from High Resolution XBT lines and AH**
- **Air-sea flux from ECMWF surface analysis**

Implementation of Argo will lower errors on storage and transport to 5 W/m^2 or less, hence giving high S/N ratio for interannual variability.
Present errors on A-S flux can also be improved substantially using flux reference sites and improved VOS met sensors.

Roemmich et al, 2003

Syntheses (contd): Other studies utilize AH in the context of simple models to estimate mixed layer variability in closed heat budget studies.

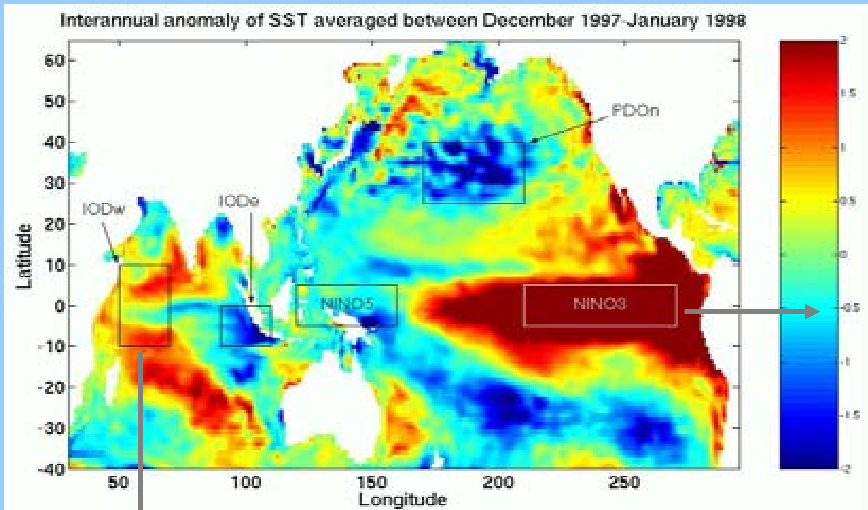


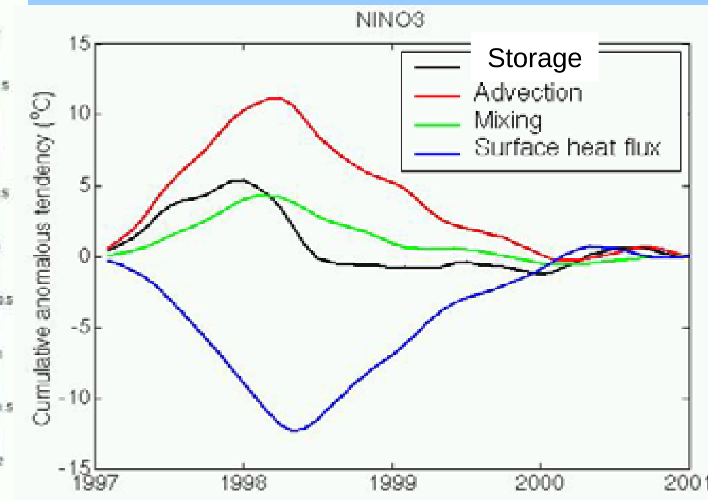


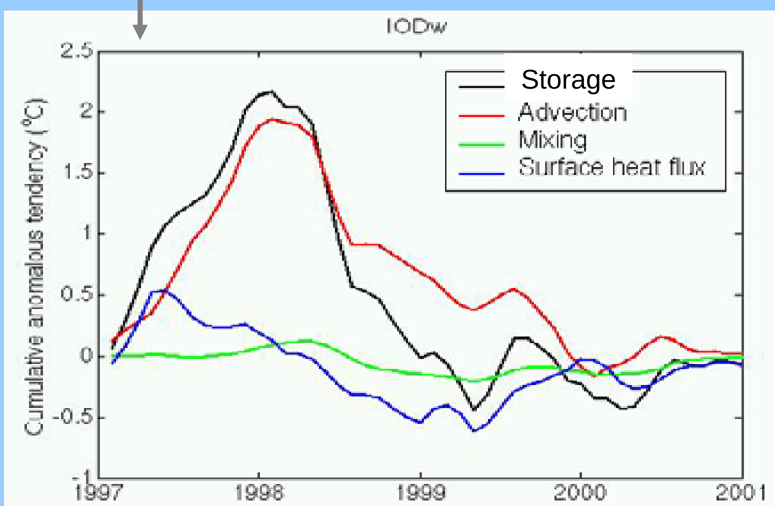
These studies demonstrate the importance of lateral fluxes in interannual variability of mixed layer temperature, particularly in WBC extension regions.

Vivier et al, 2002 (left), Kelly,2003, (right), see also Qiu, JPO, 2000.

Syntheses (contd): Data assimilation modeling.
Interannual budget of ML temperature: ENSO vs. IOD







Similarity

Advection assists warming/cooling both for NINO3 and IODw.

Difference

NINO3: advection >> storage change,

large damping by heat flux.

IODw: advection ~ storage change,

small damping by heat flux.

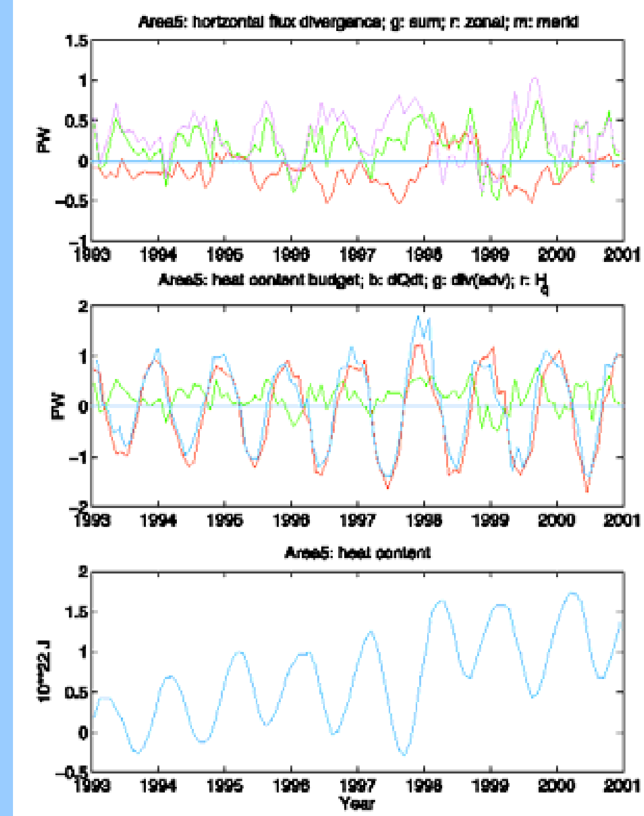
Lee et al. (2003)

Putting it all together:

Where are we headed?

Many disparate datasets – altimetric height, scatterometer winds, Argo, etc., can be integrated using data assimilation models. At right is shown the Tasman regional heat budget from the ECCO model.

It is necessary to proceed cautiously, measuring all components of the heat balance with high signal-to-noise ratio (on interannual time-scales and spatial scales of thousands of km) in order to test and improve the models.



Stammer and the ECCO group, JGR, 2003

Conclusions

- **During the T/P era, fundamental progress has been made in the estimation of ocean heat storage and transport through the combination of AH with *in situ* datasets.**
- **The importance of lateral heat advection has been demonstrated in interannual variability of surface layer heat balances in WBC systems, in eddy-rich interior regions, and in the equatorial zone.**
- **With the first 11 years of high precision altimetry, we have only begun to understand the role of the ocean in the planetary heat and hydrological cycles. We now have the opportunity to complete the capability for comprehensive observation and synthesis of the climate system (satellite and *in situ* obs, plus models).**