Ocean circulation and the mass and heat budgets of large ocean regions

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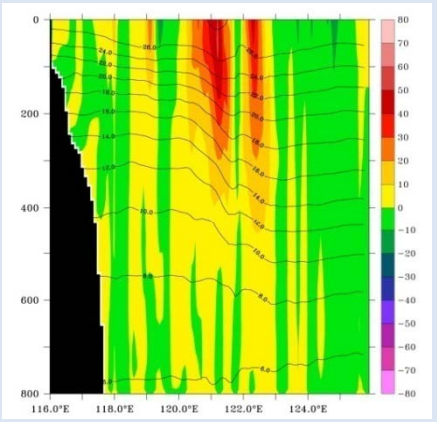
First XBT Science Workshop
Melbourne July 7-8, 2011

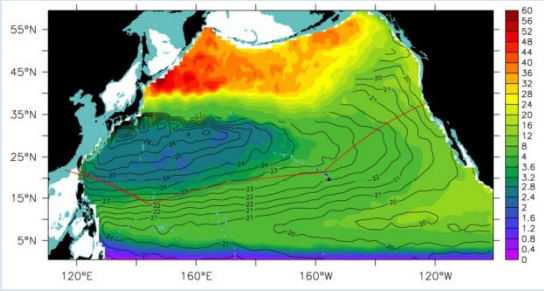
Outline

- Part I: The High Resolution XBT (HRX) Network samples the world's boundary currents - the subtropical WBCs and EBCs, the low latitude WBCs, and the ACC.
  - Global in scope (i.e. all 5 subtropical WBCs)
  - Enhanced BC sampling is highest priority, OO'09.
  - Argo provides complementary absolute and/or deep relative reference level velocities.
  - The HRX Network integrates the BCs and interior.

- Part II: Closing the mass and heat budgets of large ocean regions – the North Pacific example.
  - Mean budgets close, with a shallow overturning circulation of 13 Sv and 0.75 pW of heat transport into the region north of PX37/10/44.
  - Time-varying budgets remain a challenge, but significant interannual variability is seen during the well-measured Argo era: ~3 Sv in volume transport and ~.2 pW.

Upstream Kuroshio near Taiwan



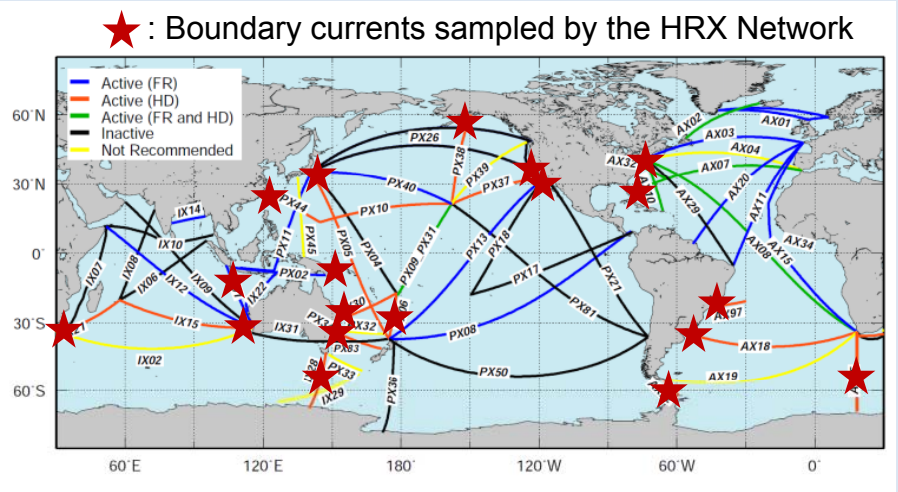


HRX Line PX37/10/44

HRX: Observing the world's boundary current systems

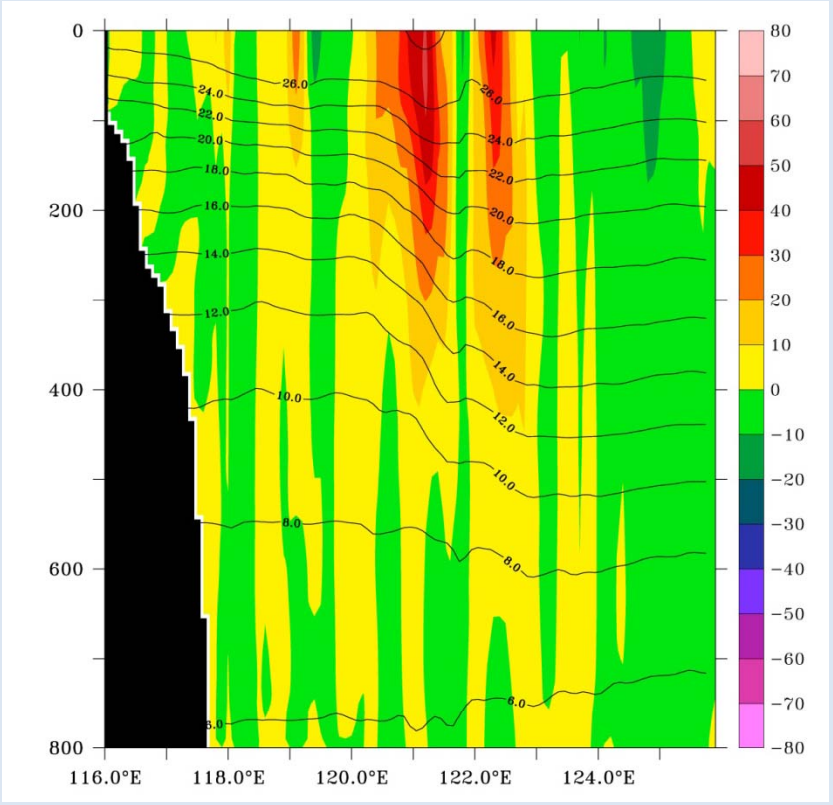
HRX transects are sampling:

- Kuroshio (3 HRX tracks)
- Gulf Stream (3 HRX tracks)
- Agulhas
- Brazil Current
- East Australian Current (2 HRX tracks)
- East Auckland Current and Tasman Outflow
- Eastern boundary currents (California Current, Alaska Current, Leeuwin Current, …)
- Low latitude WBCs: Solomon Sea, Indonesian Throughflow
- Antarctic Circumpolar Current (3 HRX tracks)
- …



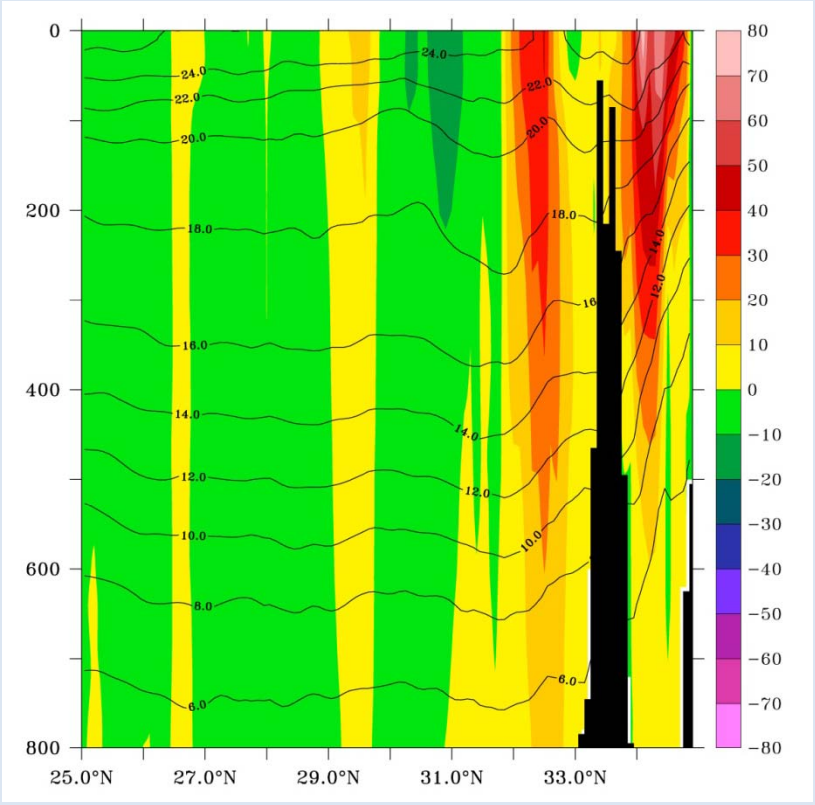
AOML status map

“Upstream” Kuroshio near Taiwan, PX44

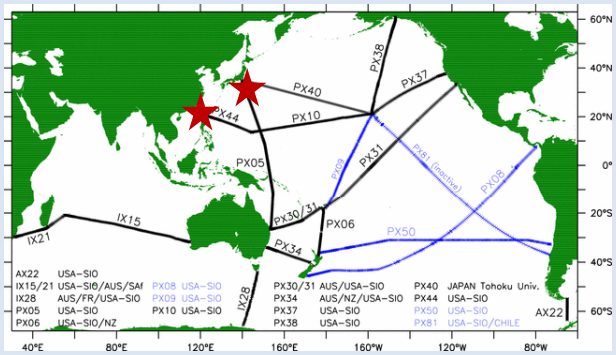


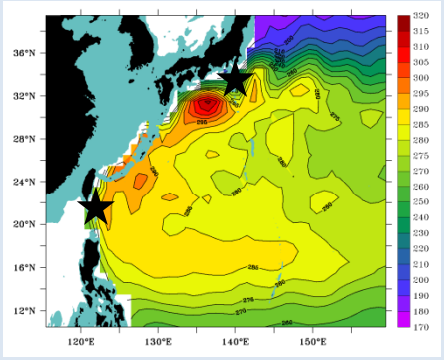
w/Argo ref. velocity; 0-800m Kuroshio 21 Sv (120ºE – 123ºE); similar to Gilson and Roemmich (2002)

“Downstream” Kuroshio near Yokohama, PX05



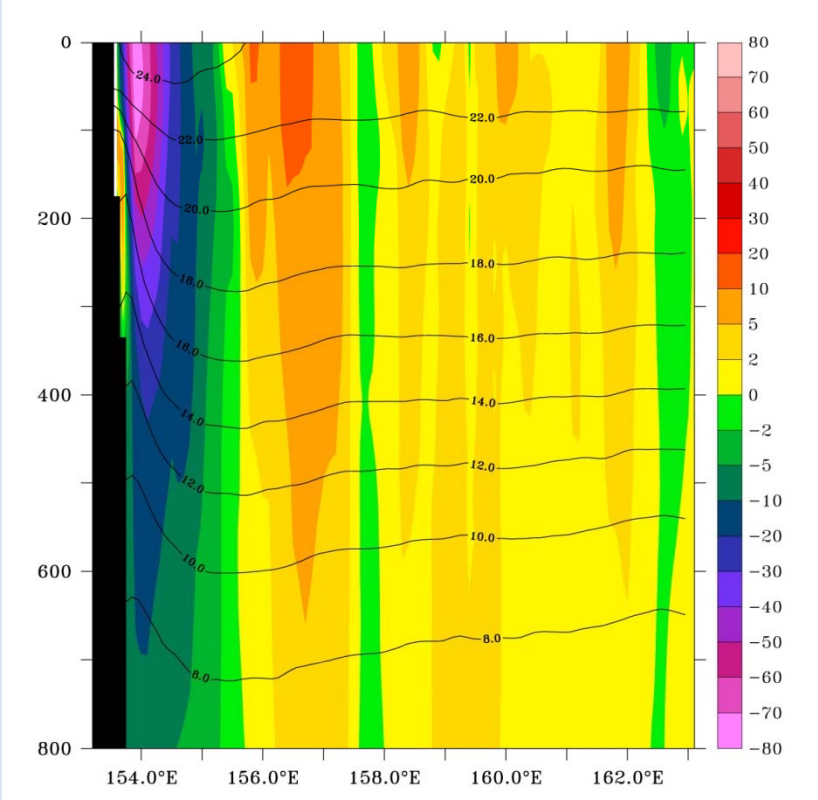
w/Argo ref. velocity; 0-800m Kuroshio 39 Sv
Consistent with Imawaki et al (2001) “throughflow”





Argo Steric Height, 0/2000 dbar

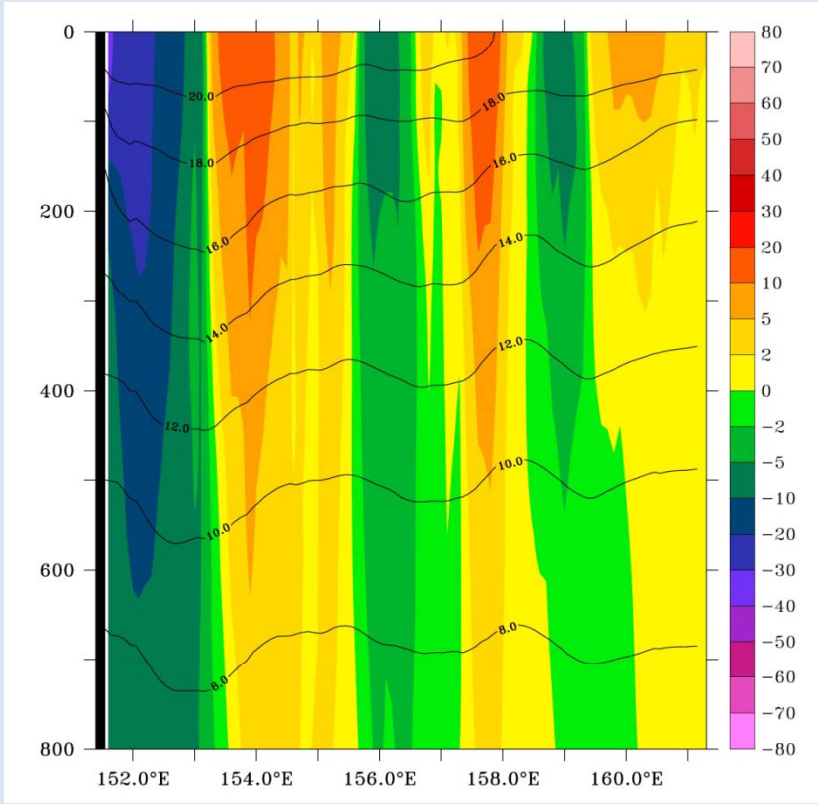
East Australian Current near Brisbane, PX30



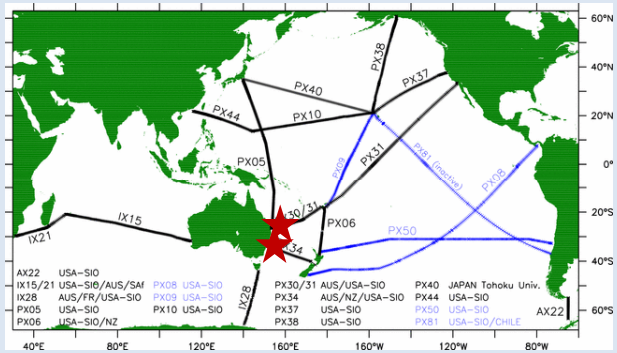
w/Argo ref. velocity; 0 – 800m EAC transport -23 Sv

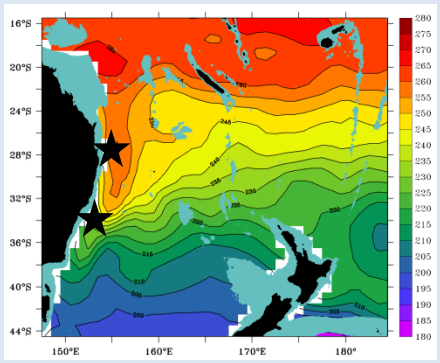
V_{max} and transport similar to Mata et al., 2000

EAC “overshoot” near Sydney, PX34



w/Argo ref. velocity; EAC -16 Sv; recirculation 8 Sv

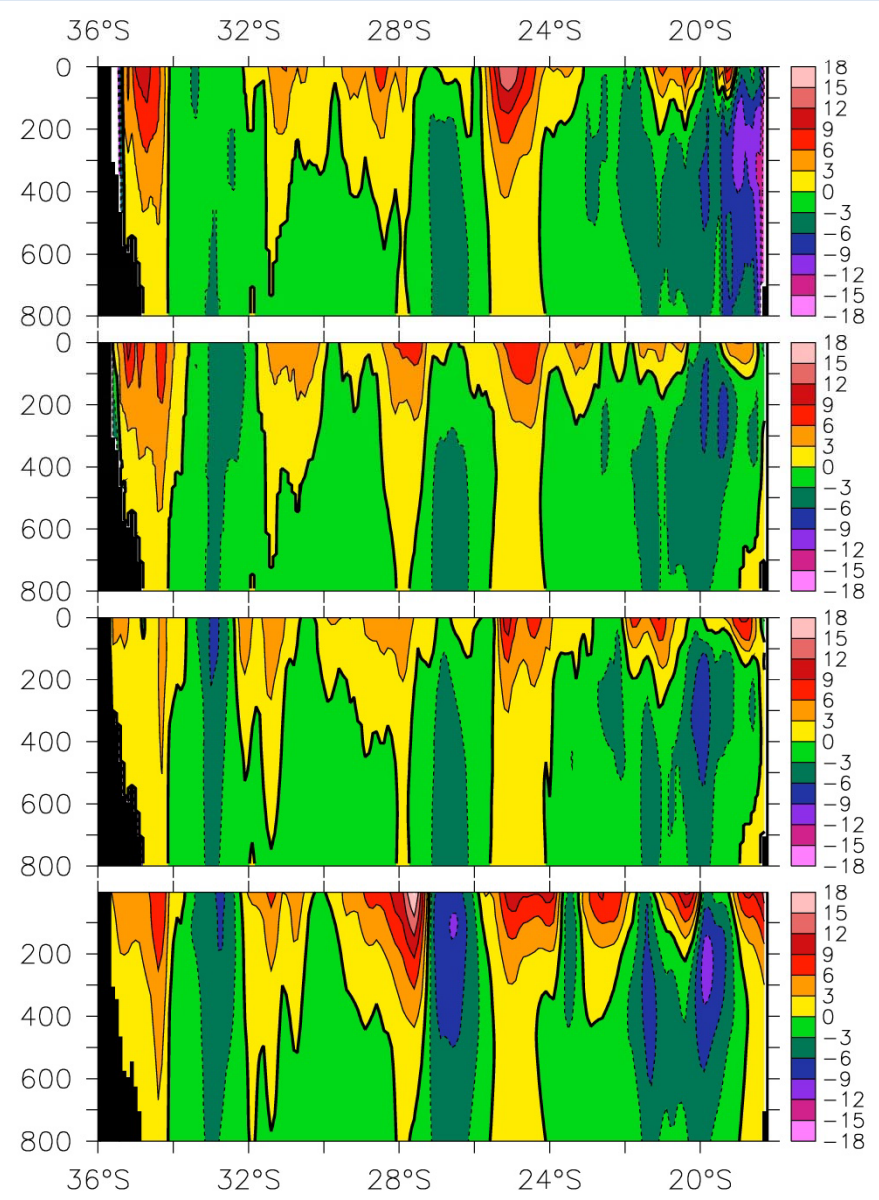


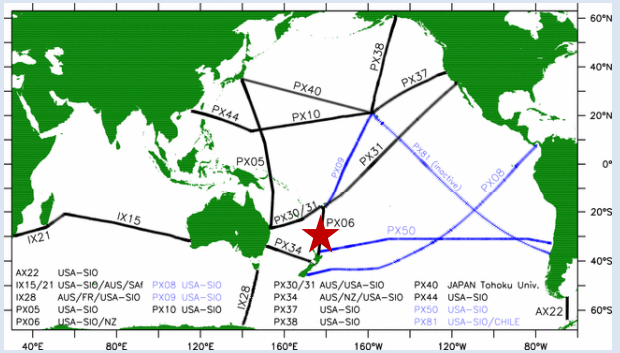


Argo Steric Height, 0/2000 dbar

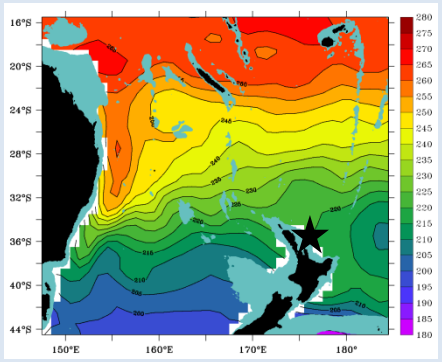
CSIRO is the lead partner for HRX PX30 and PX34

East Auckland Current and Tasman outflow, PX06



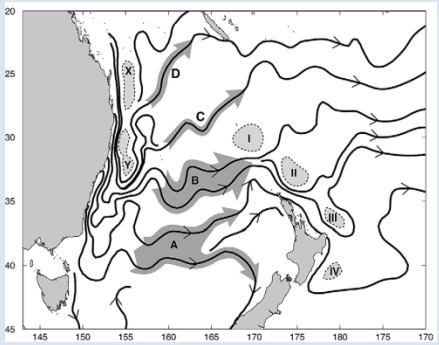


PX06 velocity 1986-1994



Argo Steric Height 0/2000

PX06 velocity 1995-2003



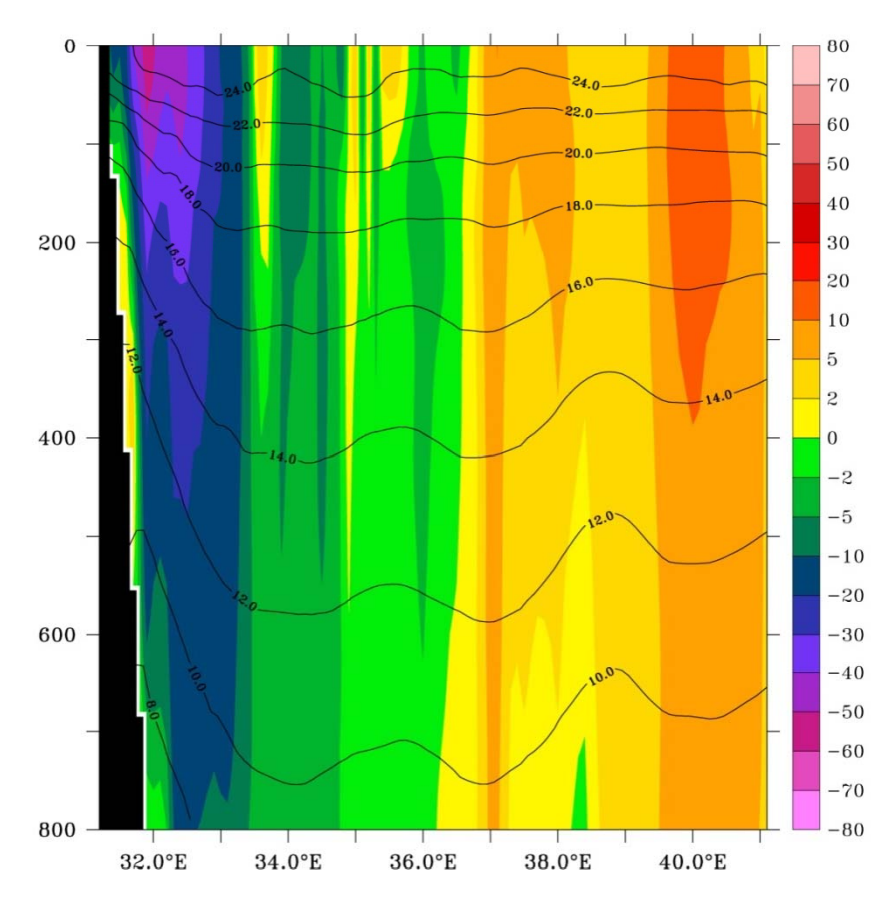
Ridgway and Dunn (2003)

PX06 velocity 2004-2011

Argo velocity 2004-2011, across PX06 line
High resolution mapping

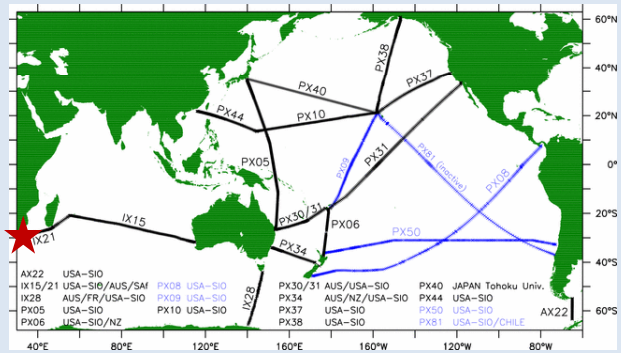
Downward trend in EAuC and S. Fiji jet?

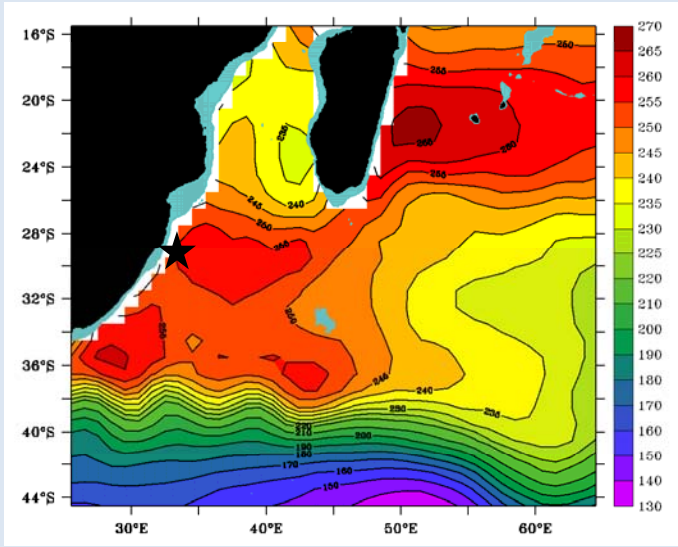
Agulhas Current near Durban, IX21



w/Argo ref. velocity; 0 – 800m Agulhas transport -26 Sv (to 33.4°E)

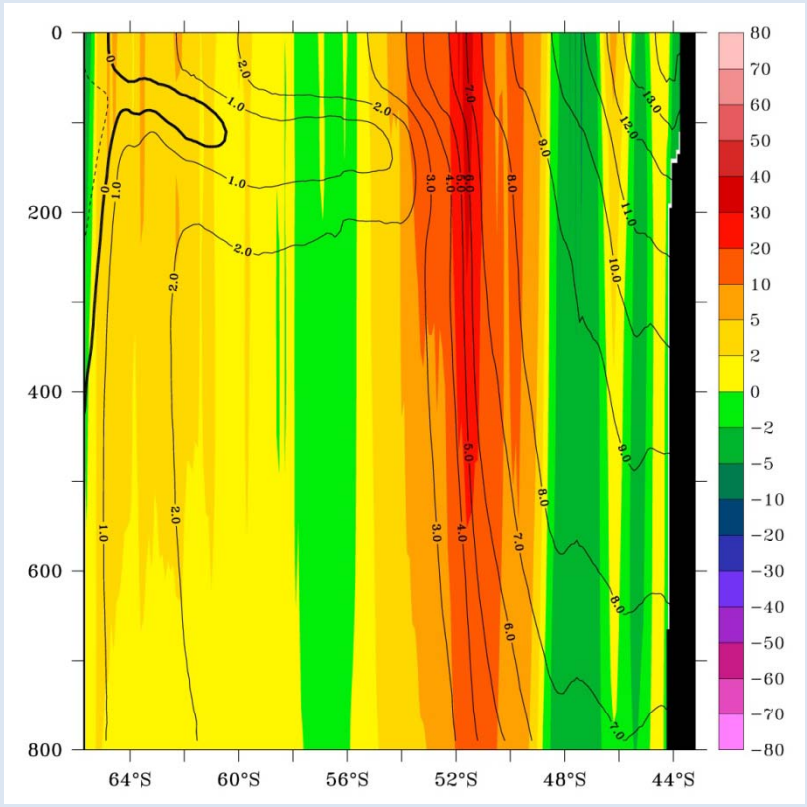
The Agulhas appears weaker here than in a moored array, Bryden et al. (2005). Needs a closer look. Lack of Argo data close to coast?





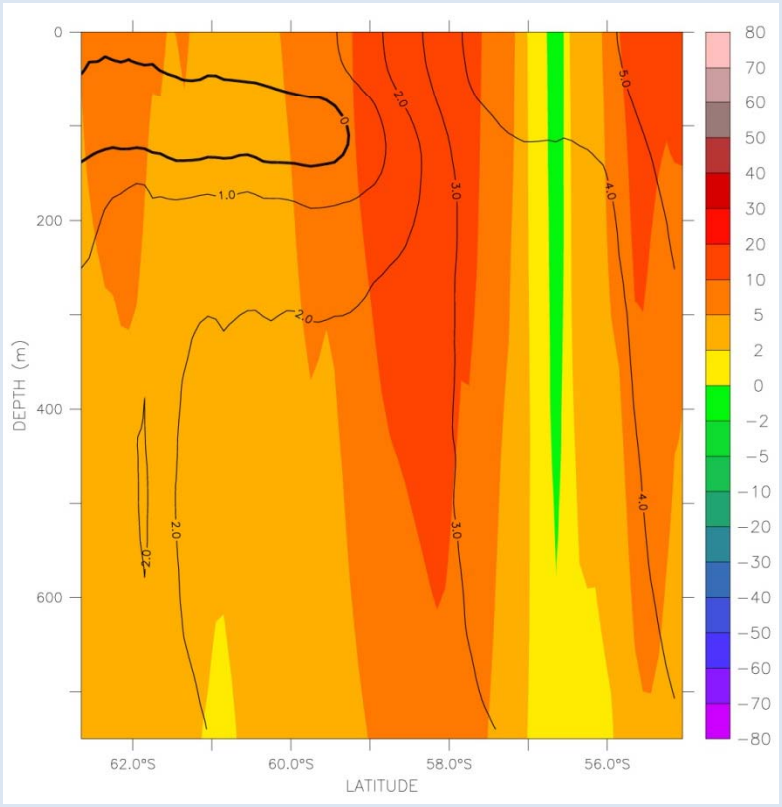
Argo Steric Height 0/2000

Antarctic Circumpolar Current south of Tasmania, IX28

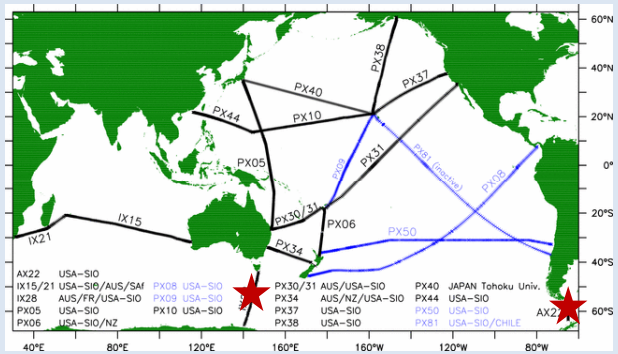


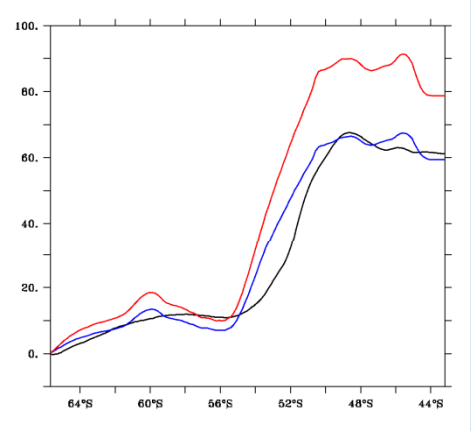
w/Argo reference velocity; CSIRO is lead partner

ACC in Drake Passage, AX22



w/Argo reference velocity; Fig by J. Sprintall

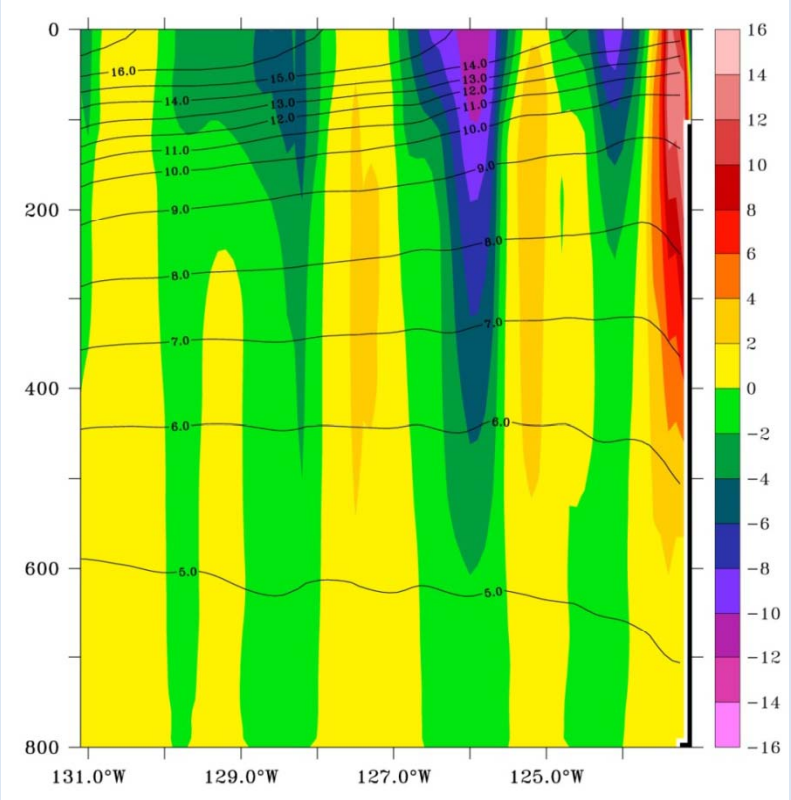




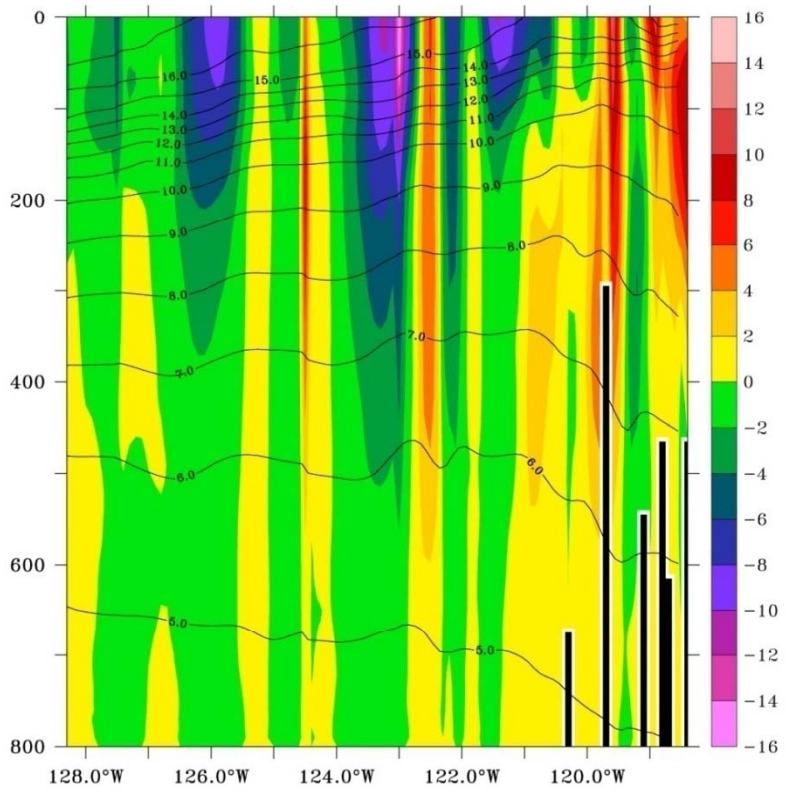
IX28 Transport integrals (Sv)

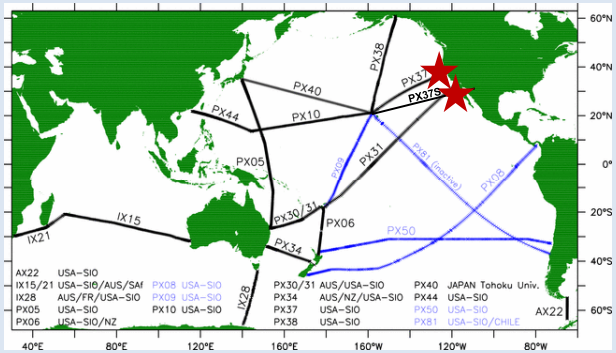
Red: Argo 0-2000 m, 147°E
Blue: Argo 0-800 m, 147°E
Black: XBT 0-800 m with Argo reference velocity
Rintoul et al (2002): 0-2500 m, 106 Sv from SR3

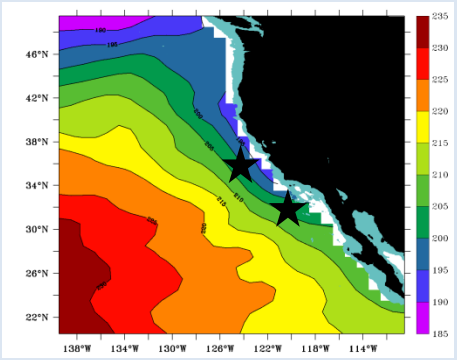
“Upstream” California Current System near San Francisco, PX37



“Downstream” CCS near Los Angeles, PX37S



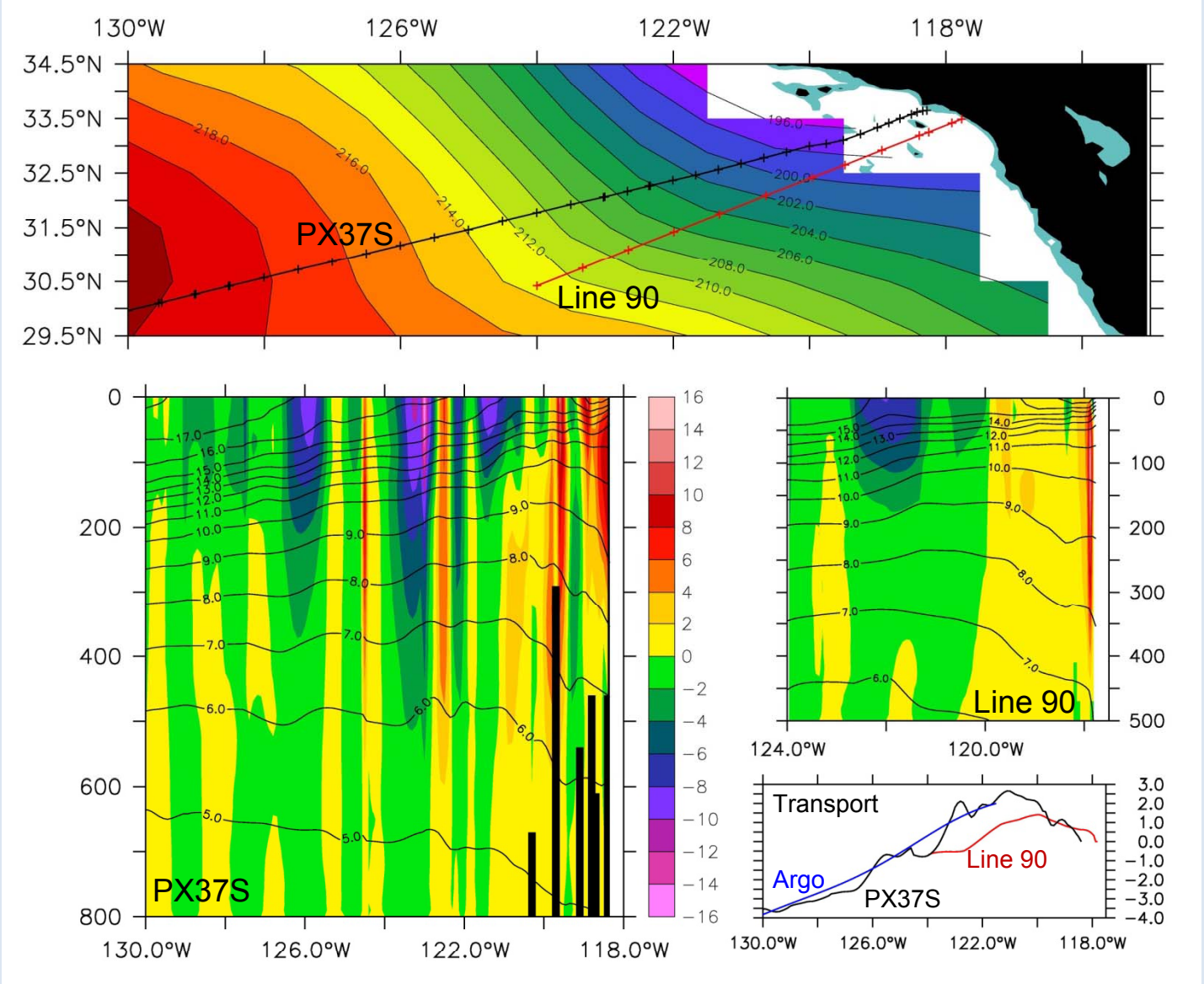




The “real” boundary current is the northward California Undercurrent, not the southward California Current.

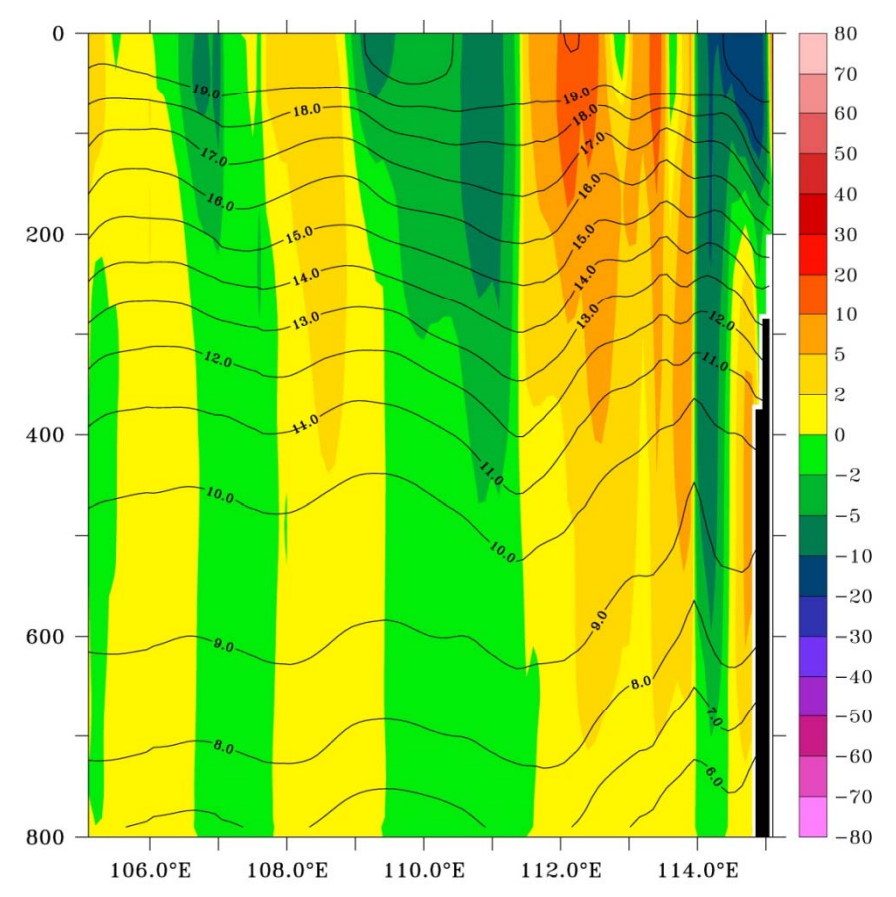
Argo Steric Height 0/2000

Integrating the ocean observing system: HRX, Argo, CalCOFI

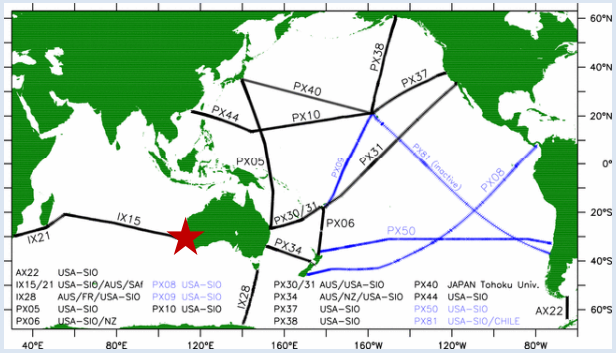


Transports are about 2.5 Sv for the California Undercurrent and -5 Sv for the CC out to 127°W. Comparisons with glider transects along CalCOFI lines 90 and 80 are promising.

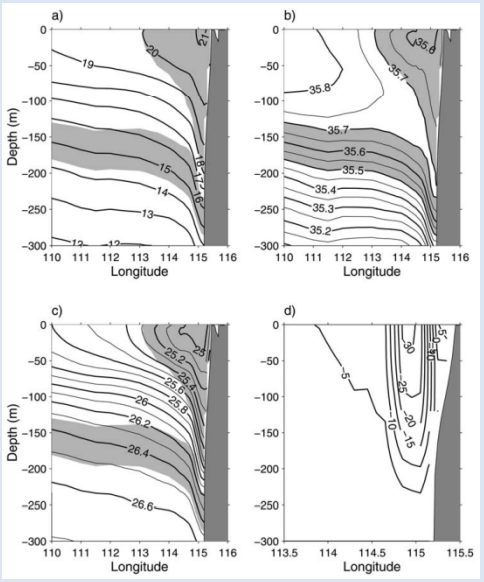
Leeuwin Current near Fremantle, IX15

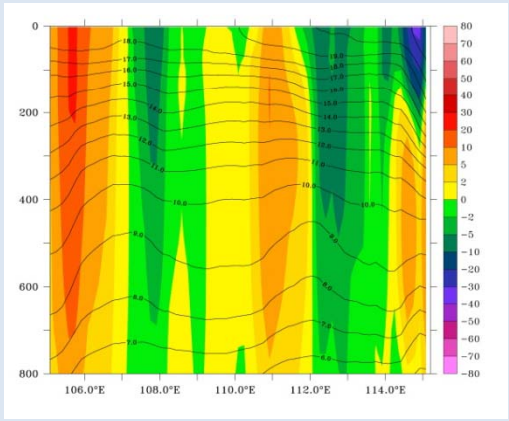


Transport, 0-800 m, 113.9°E to coast: 4 Sv



Feng et al., 2003

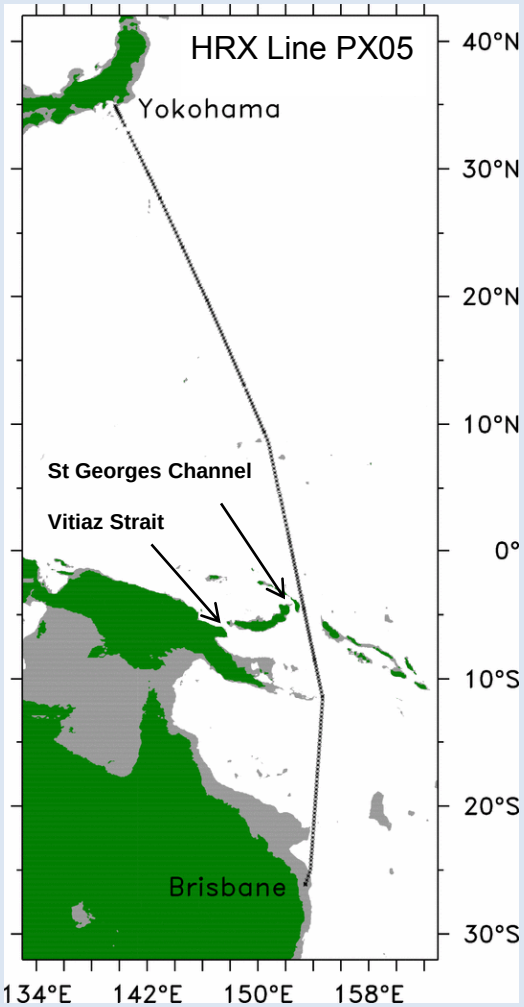


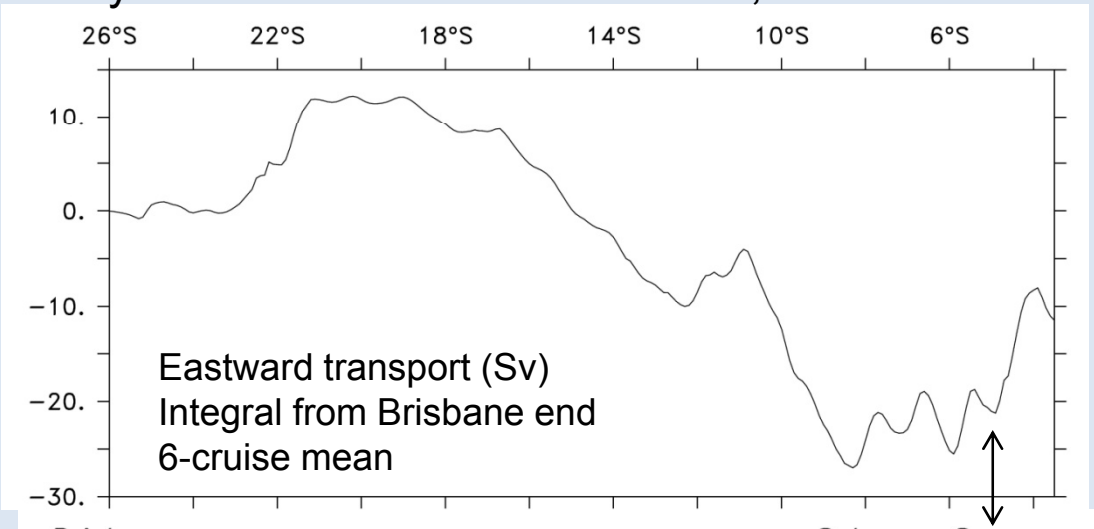


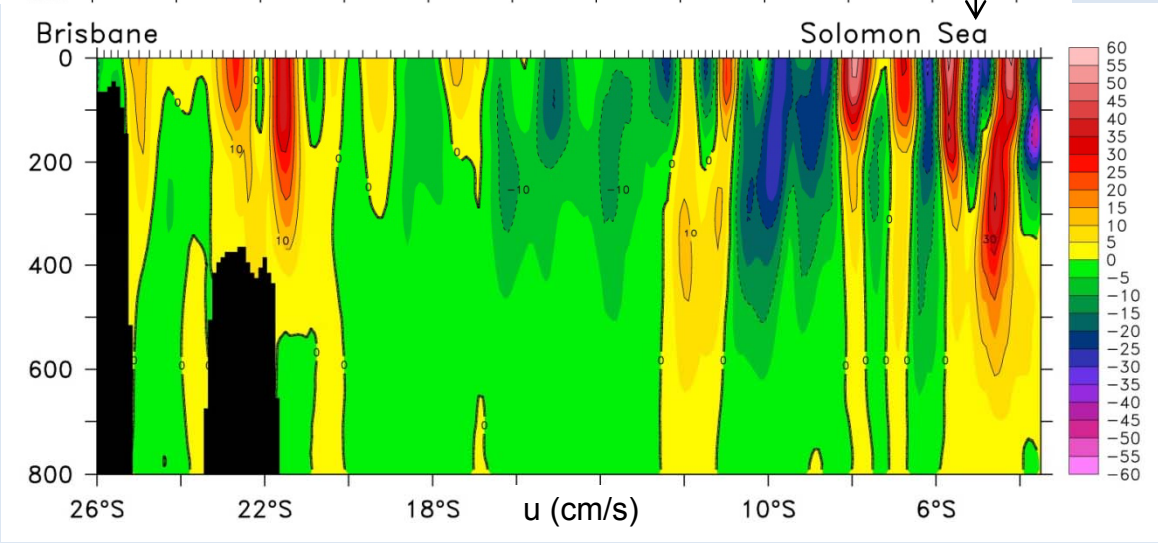
Argo: mapped at high resolution along 32°S
V-mean relative to 800 m (colors), T (contours)

Because of the granularity of the mean ocean, along-current and across-current gradients can cause apparent differences.

Low latitude western boundary currents in the Solomon Sea, PX05







PX05 crosses the EAC, Solomon Sea, and the Kuroshio as well as the tropical current systems.

Passing close to New Ireland at 5°S, net transport to that latitude (-20 Sv) is similar to estimates of the combined transport through Vitiaz Strait and St Georges Channel (e.g. Sokolov and Rintoul, 2000).

Argo will provide a reference velocity for the 800 m XBT data. Glider transects are also measuring transport.

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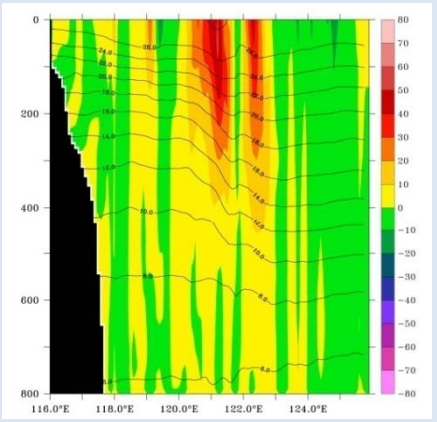
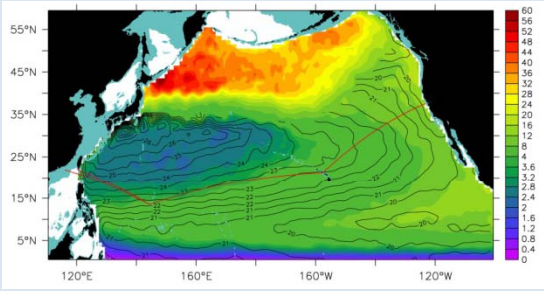
Upstream Kuroshio near Taiwan





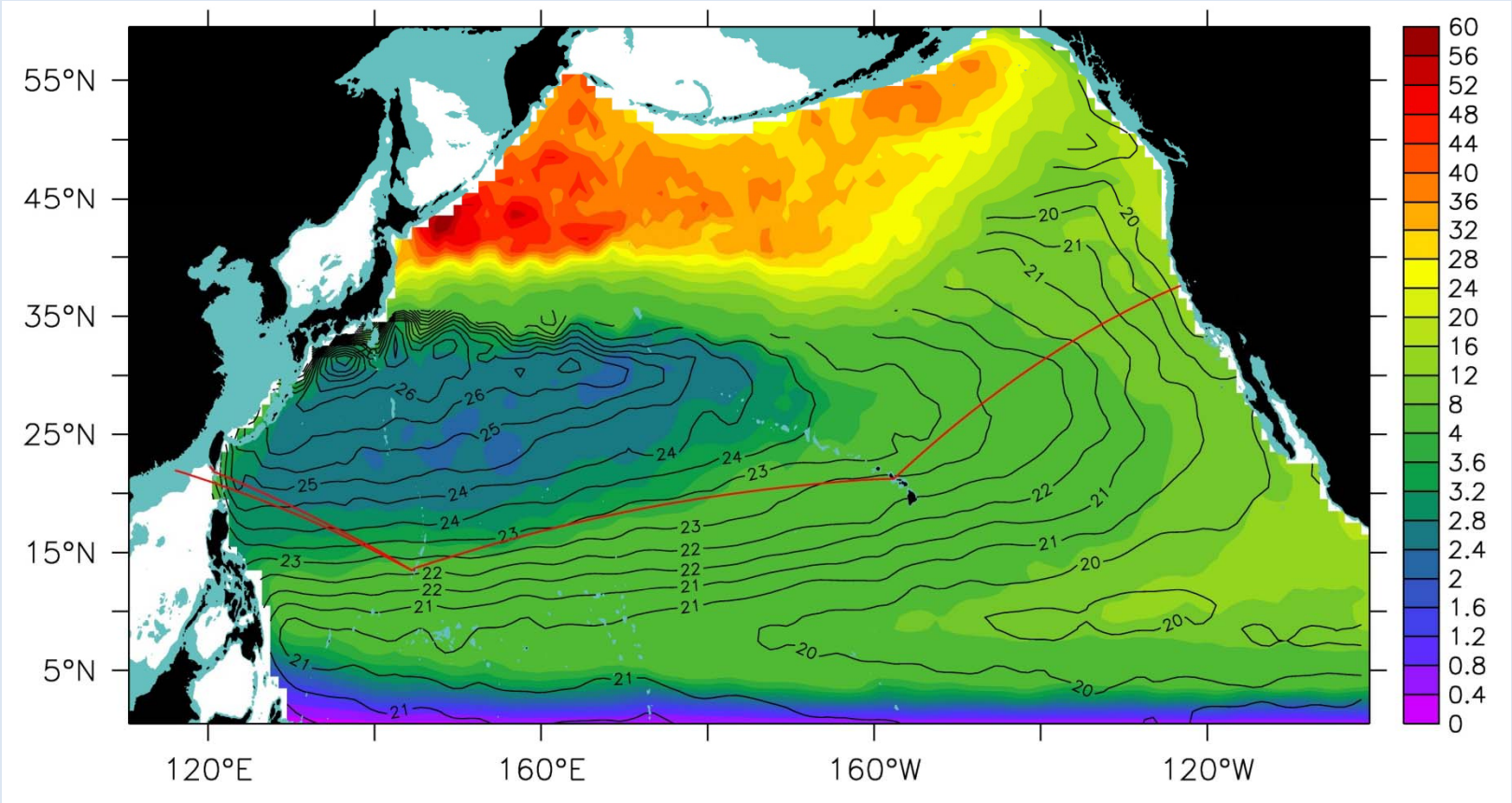
HRX Line PX37/10/44

Closing the mean and time-varying mass and heat budgets on regional to ocean scale: North Pacific Ocean

- Geostrophic transport
  - HRX transects provide shear 0-800 m
  - *Argo provides a deep reference velocity (800/2000) and a trajectory-based estimate of V_{800}
  - Altimetry is used to estimate and correct temporal aliasing of quarterly HRX cruises
- * Ekman transport from wind stress (Quikscat climatology and reanalyses).
- * Heat storage from Argo.
- * Time-varying vertical advection from Argo.
- Air-Sea heat flux from observations, reanalyses, *or as a residual*? This is the most poorly known term in the balance.

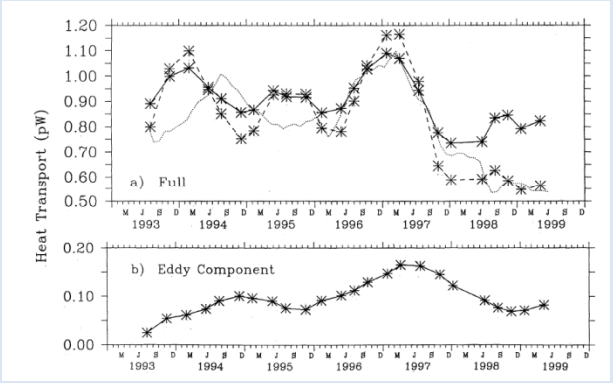
* Indicates quantities that are much better measured now than in 2001

Large-scale context: Mean circulation in the thermocline



HRX Line PX37/10/44 (Red, Taiwan and H.K. tracks) in relation to the acceleration potential (contours) and potential vorticity (colors) on σ_θ = 25.5. Winter outcropping regions are shown without contours.

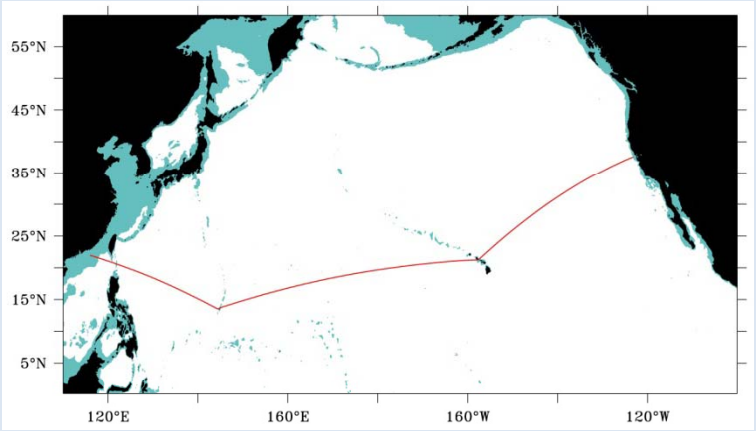
Previous work focused on PX37/10/44



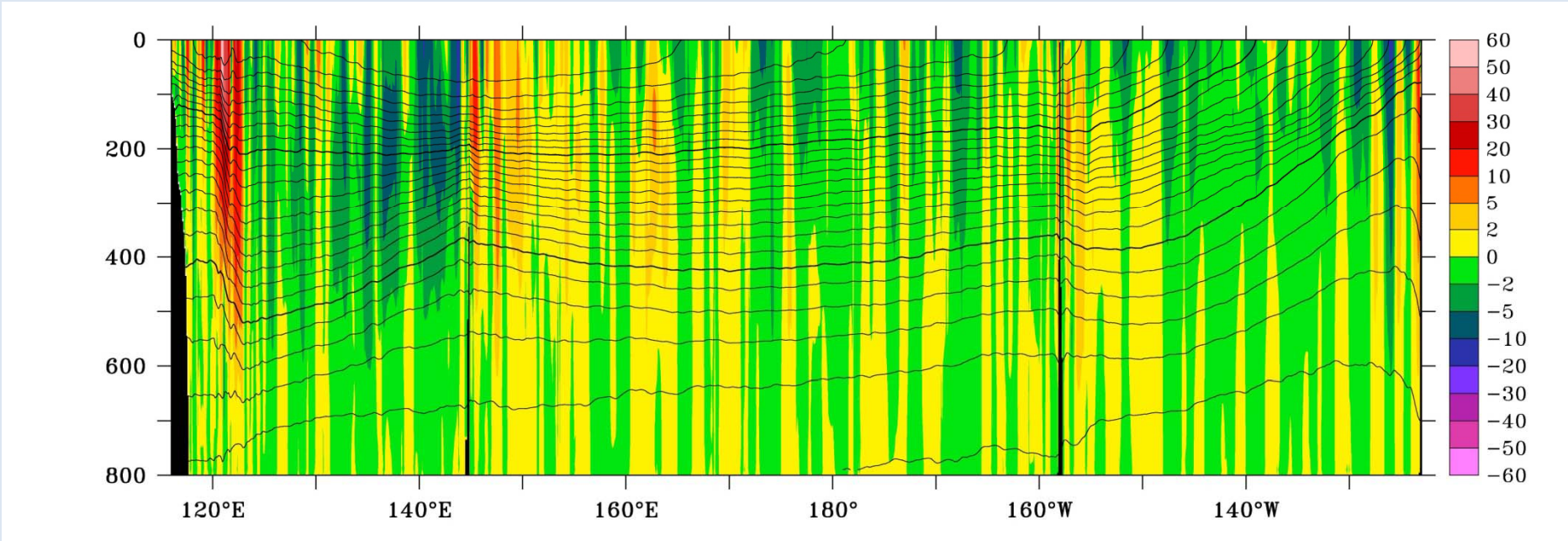
Roemmich et al., 2001

- Gilson, J, D. Roemmich, B. Cornuelle and L.-L. Fu, 1998. Relationship of TOPEX/Poseidon altimetric height to the steric height and circulation in the North Pacific. *Journal of Geophysical Research, 103,* 27947-27965.
- Hautala, S. and D. Roemmich, 1998. Subtropical Mode Water in the Northeast Pacific Basin. *Journal of Geophysical Research, 103*, 13055-13066.
- Roemmich, D. and J. Gilson, 2001. Eddy transport of heat and thermocline waters in the North Pacific: A key to interannual/decadal climate variability. *Journal of Physical Oceanography, 31,* 675-687.
- Roemmich, D., J. Gilson, B. Cornuelle and R. Weller, 2001. The mean and time-varying meridional heat transport at the tropical/subtropical boundary of the North Pacific Ocean. *Journal of Geophysical Research, 106,* 8957-8970. (Mean: 0.83 pW)
- Gilson, J. and D. Roemmich, 2002. Mean and temporal variability in Kuroshio geostrophic transport south of Taiwan (1993-2001). *Journal of Oceanography, 58*, 183-195.
- Douglass, E., D. Roemmich, and D. Stammer, 2006. Interannual variability in northeast Pacific circulation, *Journal of Geophysical Research, 111*, C04001, doi:10.1029/2005JC003015.
- Uehara, H., S. Kizu, K. Hanawa, Y. Yoshikawa, and D. Roemmich, 2008. Estimation of heat and freshwater transports in the North Pacific using high-resolution expendable bathythermograph data. *Journal of Geophysical Research, 113,* C02014, doi:10.1029/2007JC004165.
- Douglass, E.M., D. Roemmich and D. Stammer, 2010. Interannual variability in North Pacific heat and freshwater budgets. *Deep-Sea Research II 57,* 1127-1140. (Mean: 0.74 pW)
- Auad, G. , D. Roemmich and J. Gilson, 2011. The California Current System in relation to the northeast Pacific Ocean circulation. Submitted to *Progress in Oceanography*.

The mean across-track velocity (cm/s), 1993 – 2010, is filamented, even after 75 transects.



Hong Kong Guam Honolulu San Francisco



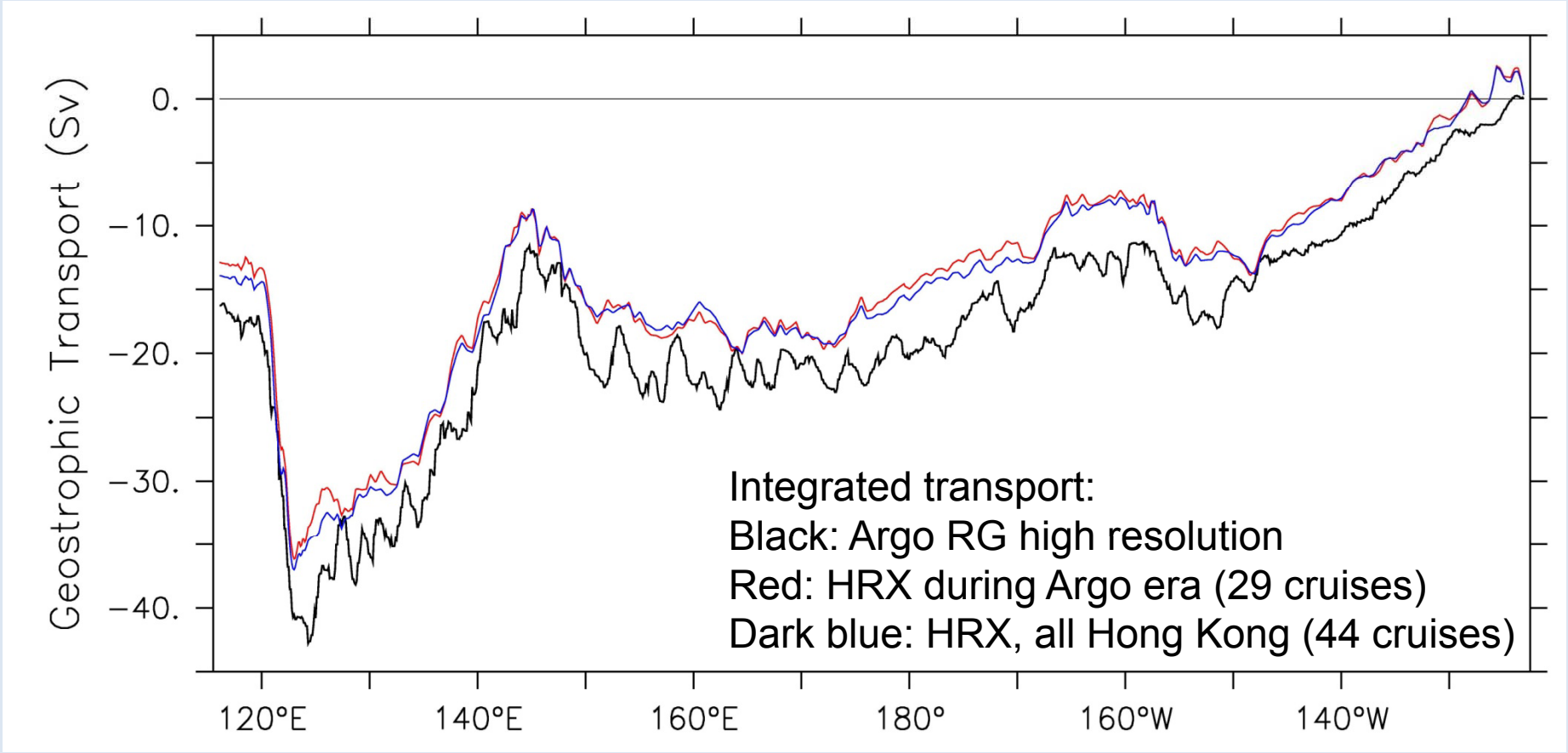
Kuroshio

North Equatorial Current

North Hawaii Ridge Current

California Current System

Geostrophic volume transport

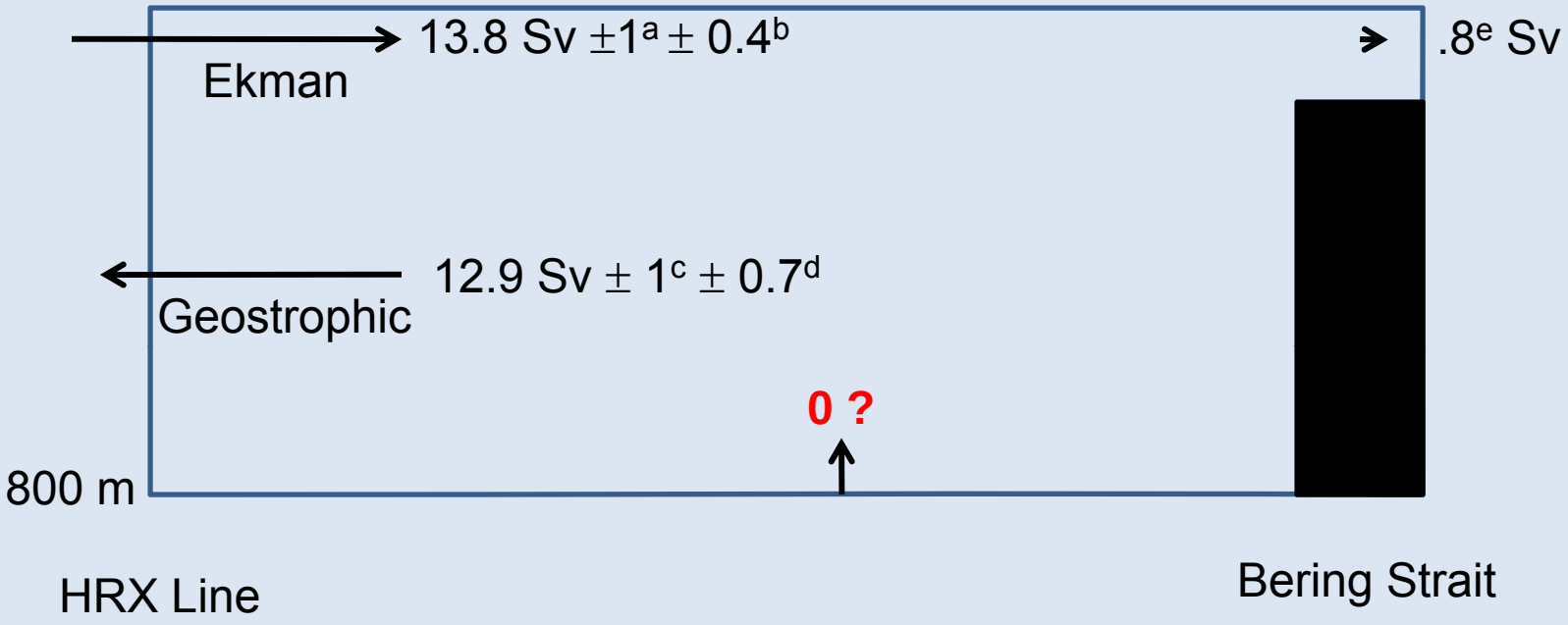


Argo era: 29 cruises; mean -12.9 Sv; σ = 3.66 Sv; Std error = 0.7 Sv

Differences between PX37 and Argo:

- At high spatial resolution Argo has larger errors in the temporal mean
- Argo misses the northward EBC

The time-mean MOC

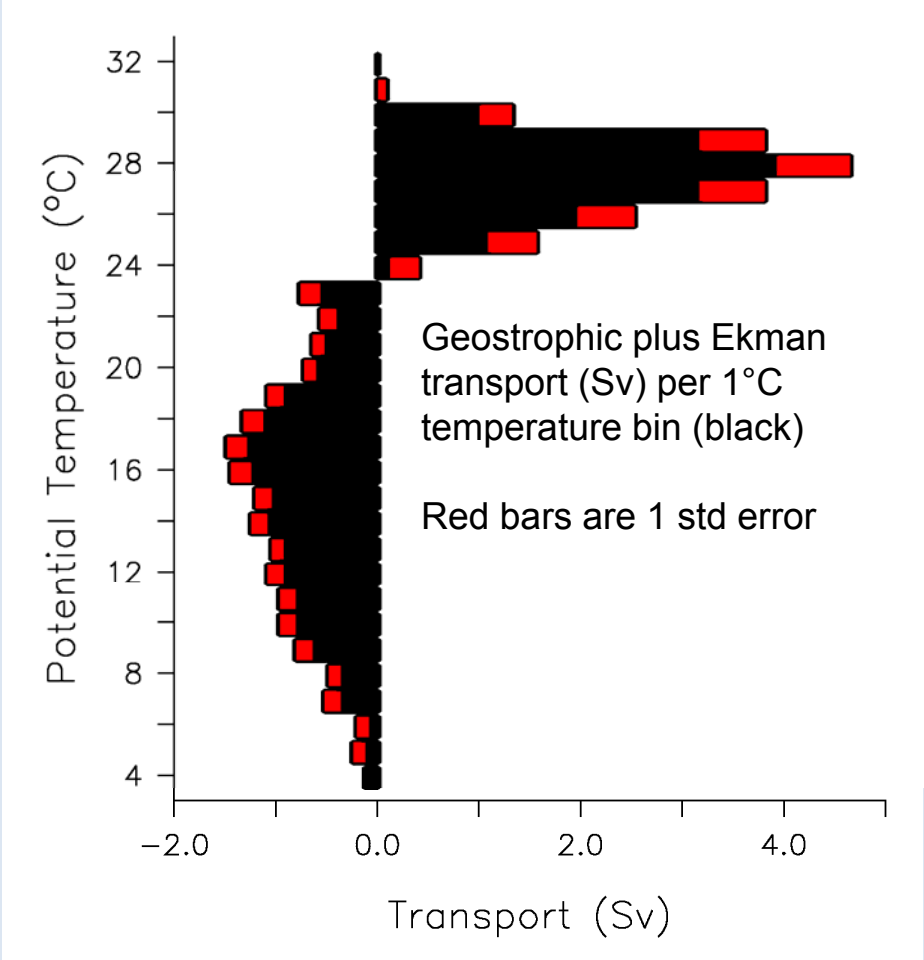


Notes:

a. Based on Quikscat (Risien and Chelton, 2008) with Large and Pond drag coefficient and with (14.7 Sv) or without (12.8 Sv) COARE boost (1.15)
b. Standard error based on sampling uncertainty, 2004-2011.
c. Error in transport due to 800 m velocity based on comparison of Argo relative and trajectory velocity
d. Standard error based on 29-cruise sampling uncertainty
e. Roach et al. (1995)

Systematic errors were not considered in the earlier work.

The time-mean heat transport



Maximum southward transport is STMW (17°C)
Coldest significant southward transport is NPIW

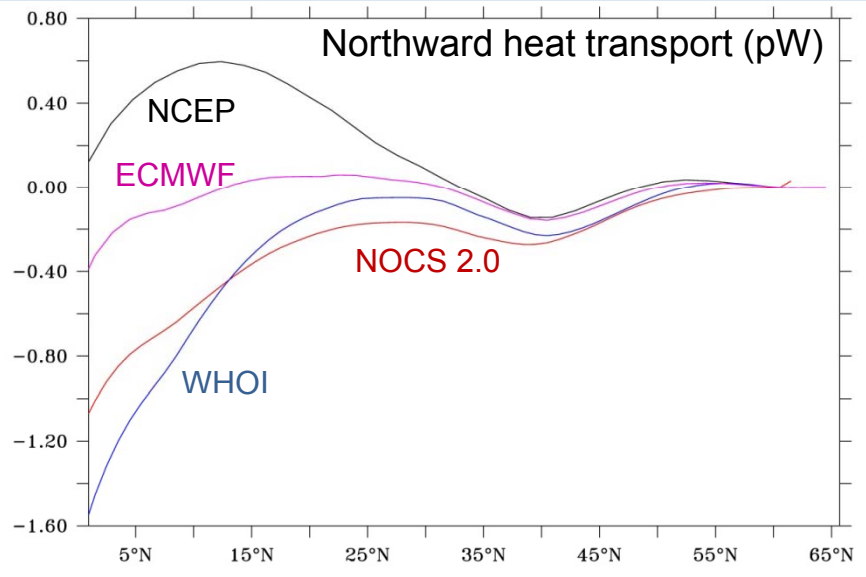
For the 13 Sv MOC, HT= 0.75 pW.

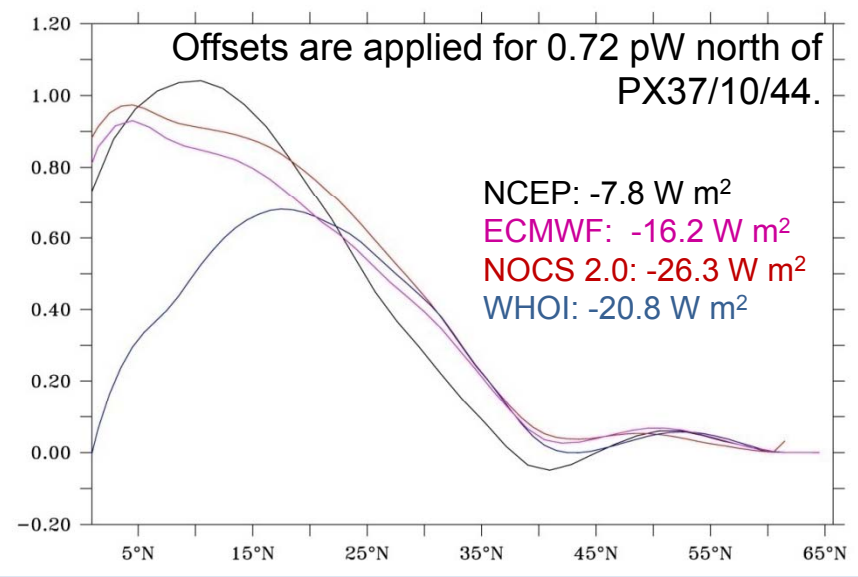
Uncertainty in the MOC is ~10%, 0.075 pW. Further 0.03 pW uncertainty due to horizontal recirculation (difference between Argo relative and trajectory estimates).

Net heat storage 2004-2010, is .03 pW (Argo T_{av} of the region, 0-800 m, increases by .06°C)

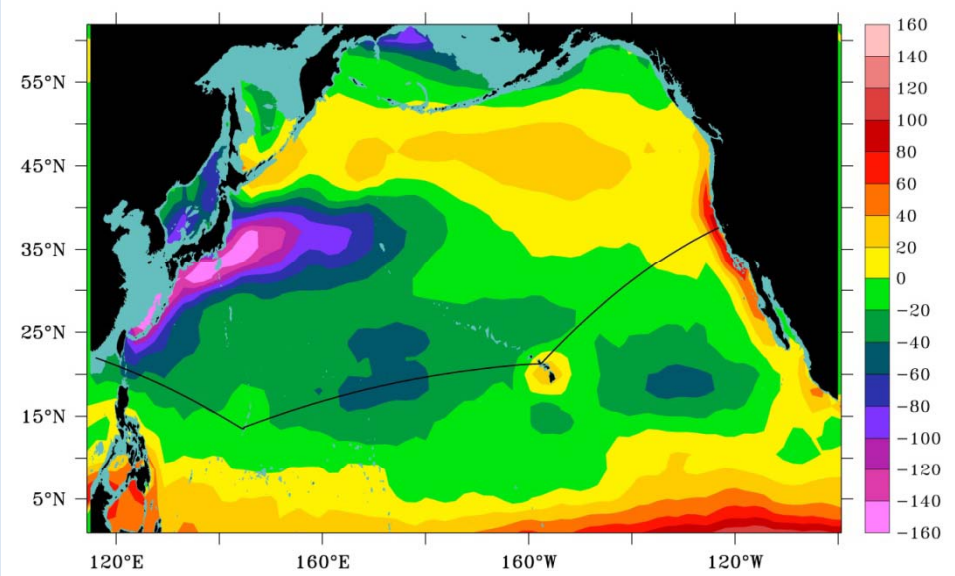
Therefore the air-sea heat loss by the ocean is 0.72 pW $\pm$ 0.1 (21 W/m^2 $\pm$ 3)

Heat transport from air-sea fluxes: Mean value for the Argo era



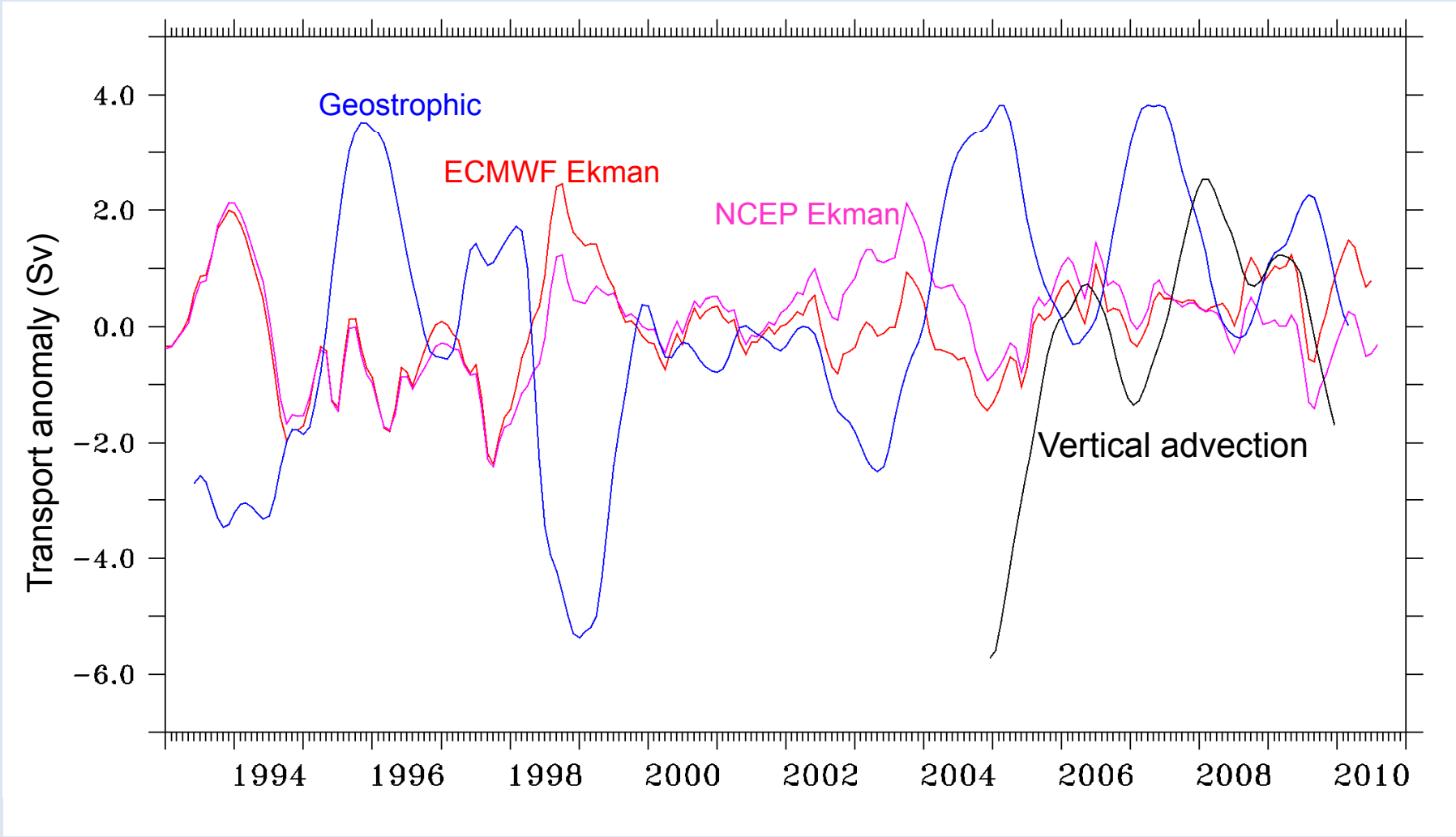


NCEP, 2004-2010, Mean-7.8 W m²



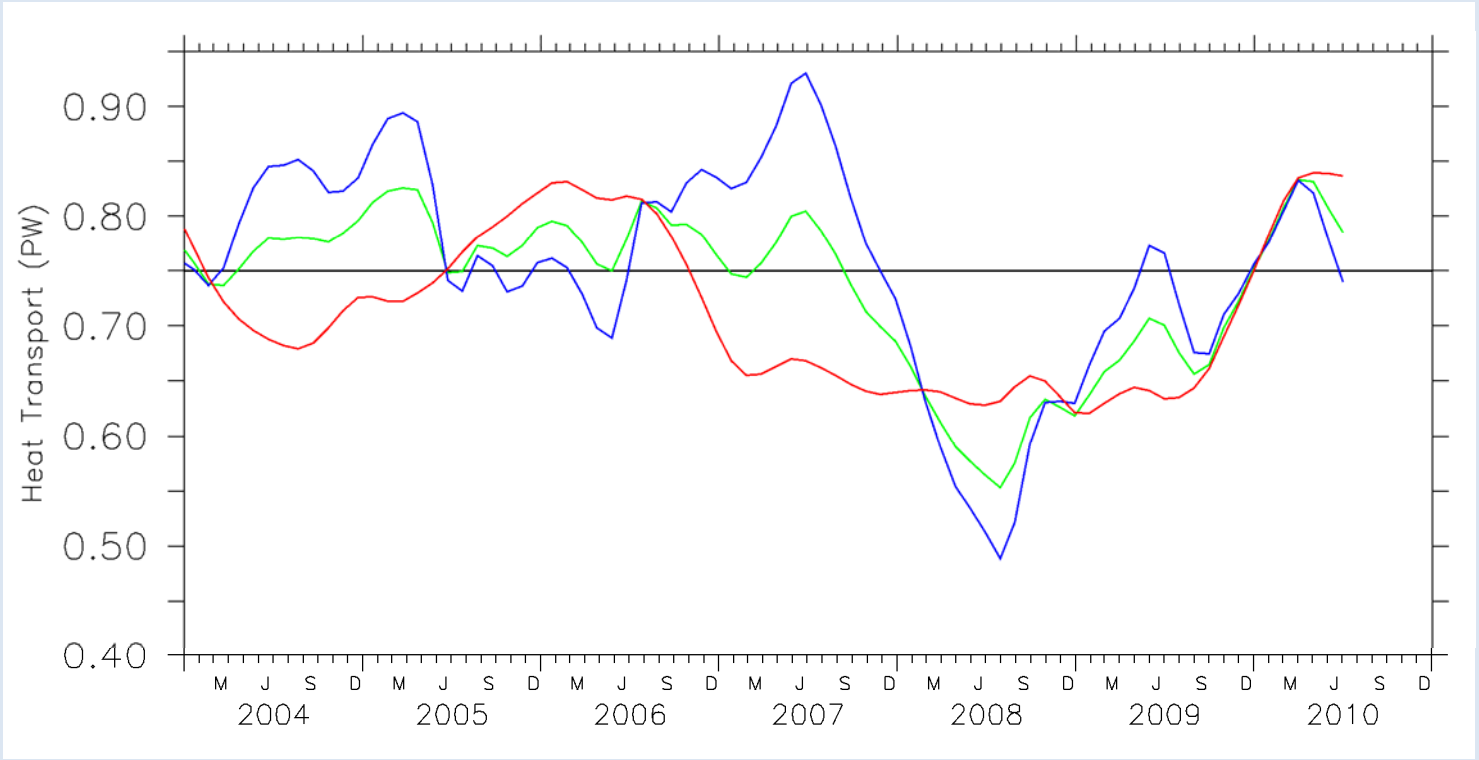
The time-varying volume transport:

Anomalies in Ekman transport, geostrophic transport, and vertical advection[a]



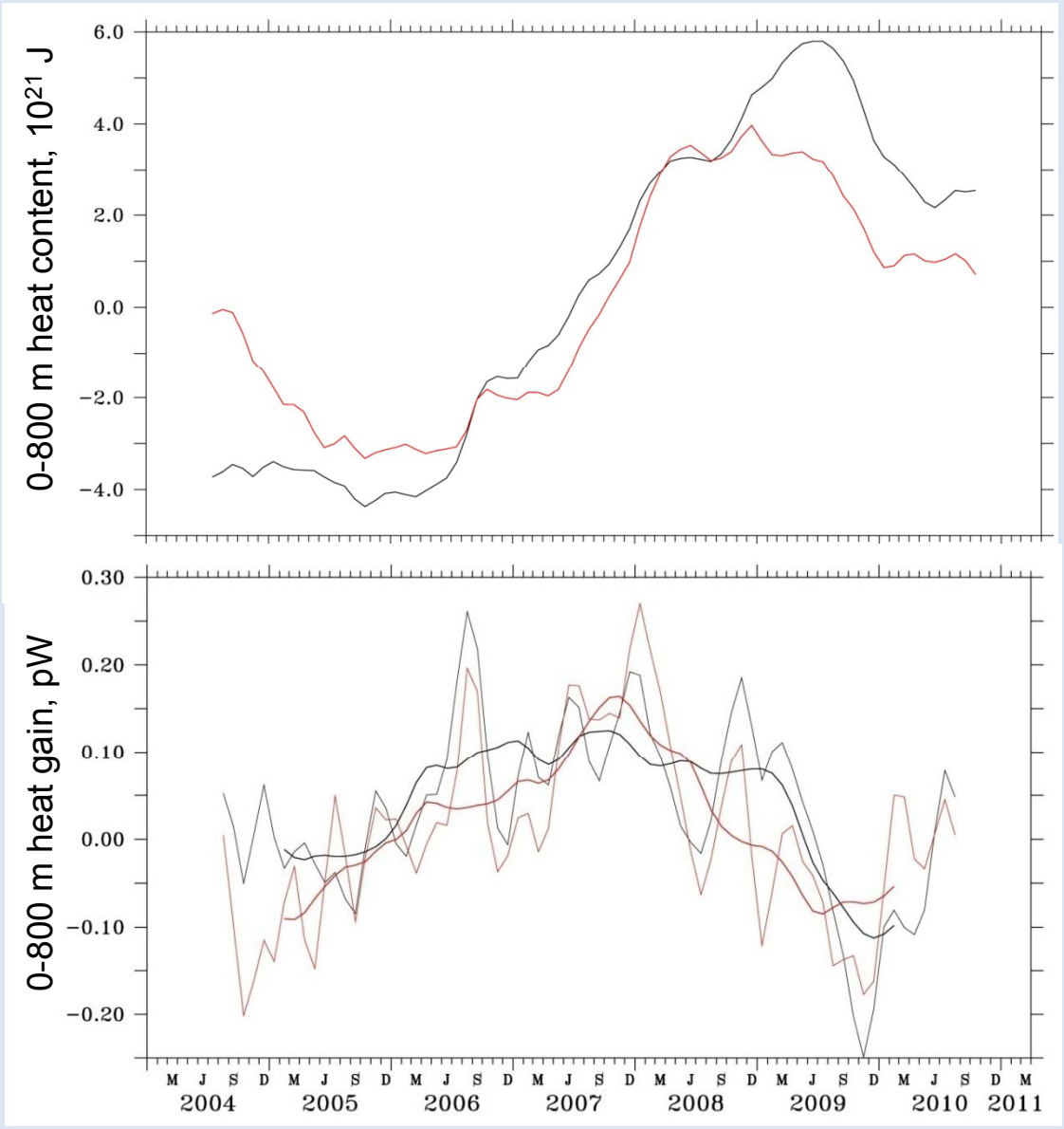
[a]Vertical advection is estimated from the time derivative of T'/(dT/dz)

Heat Transport



Differences due to closing the transport residual (Ekman+geostrophic):
Blue: barotropic ($T_{residual}$ = 3.6°)
Green: baroclinic ($T_{residual}$ = 13.9°)
Red: assume error in Ekman ($T_{residual}$ = 25.6°)

Next steps: Include vertical advection?
Use altimetry for time-varying V_{ref} and to correct aliasing

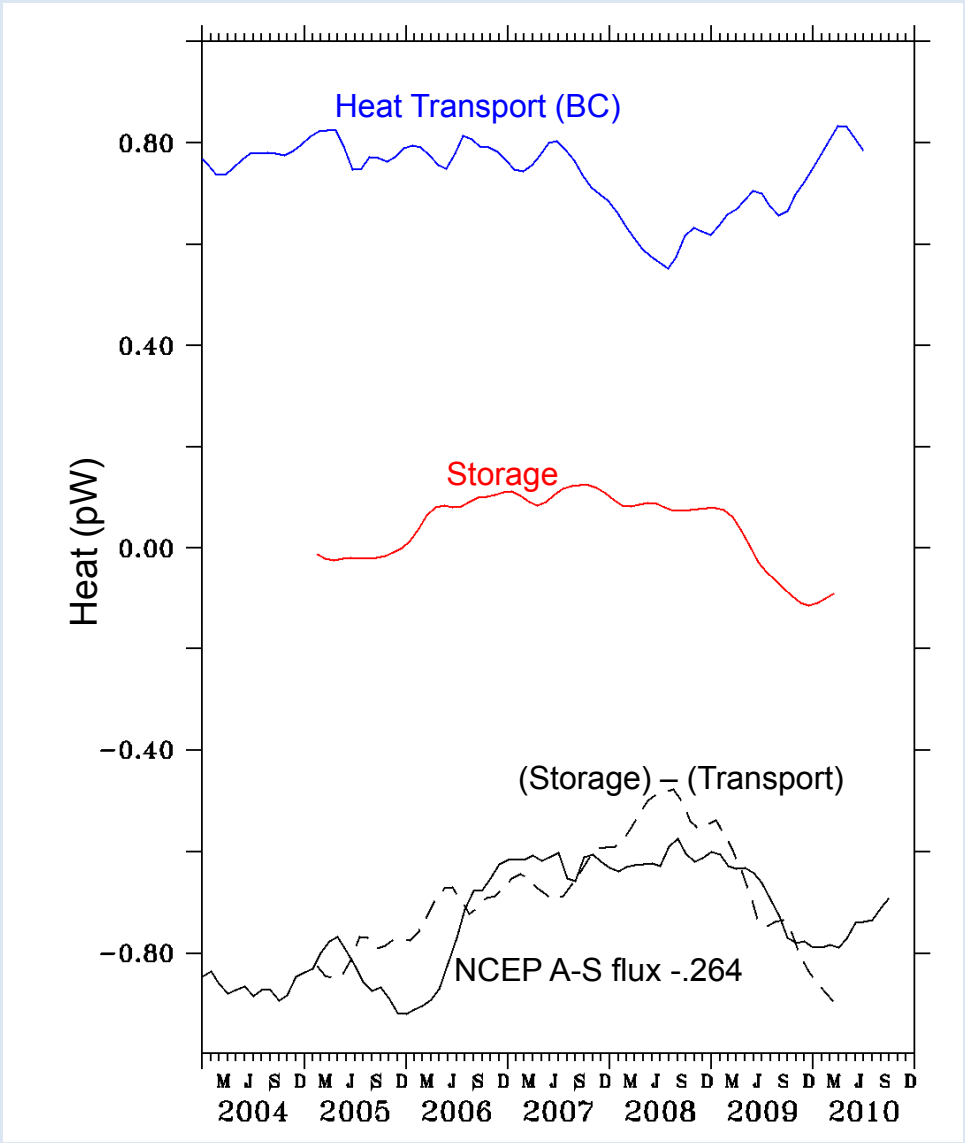


Heat Storage

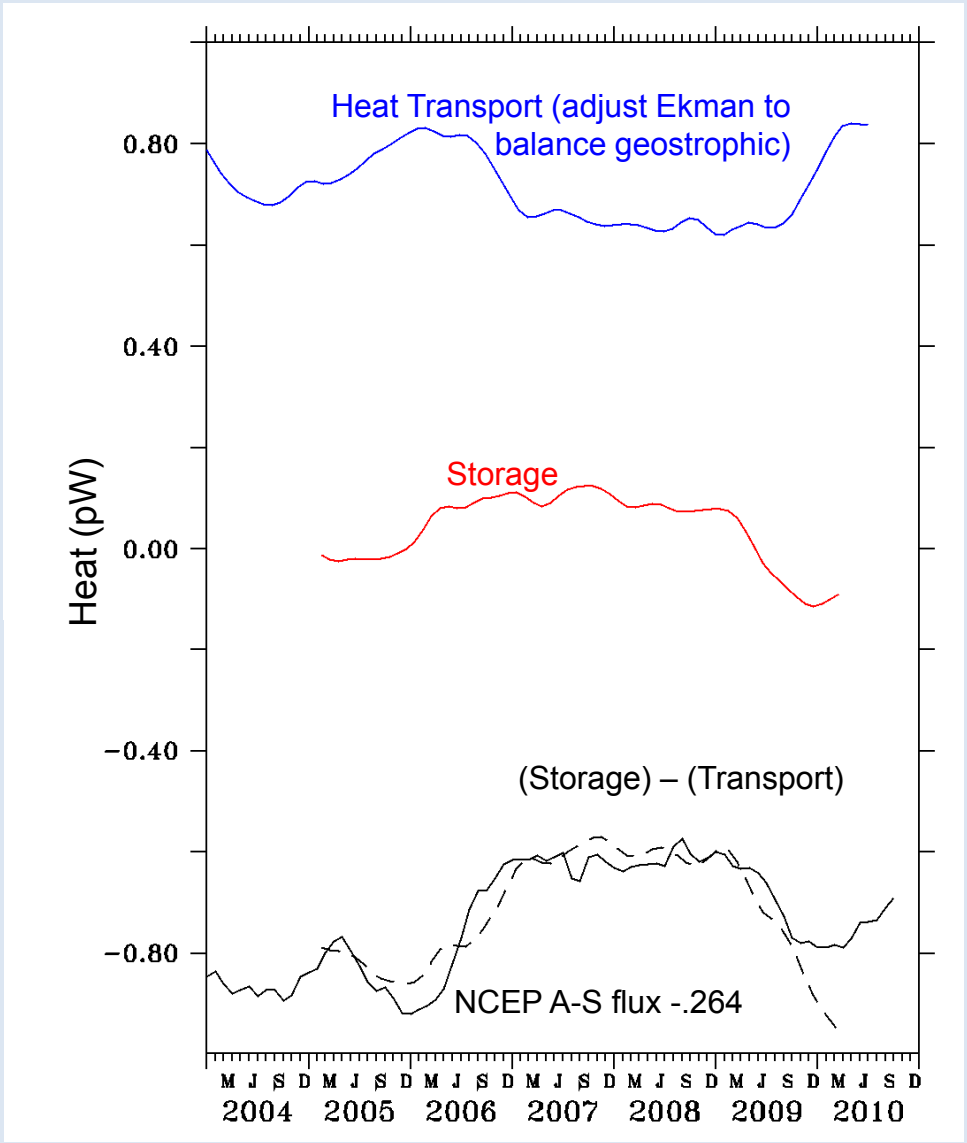
The region north of PX37/10/44 was gaining heat in 2007 and losing heat in late 2009. These may be ENSO-related.

Black: Based on T_{av} above 800 m mean density surface, 12 month running mean
Red: Based on T_{av} 0-800 (no adjustment for vertical displacement)

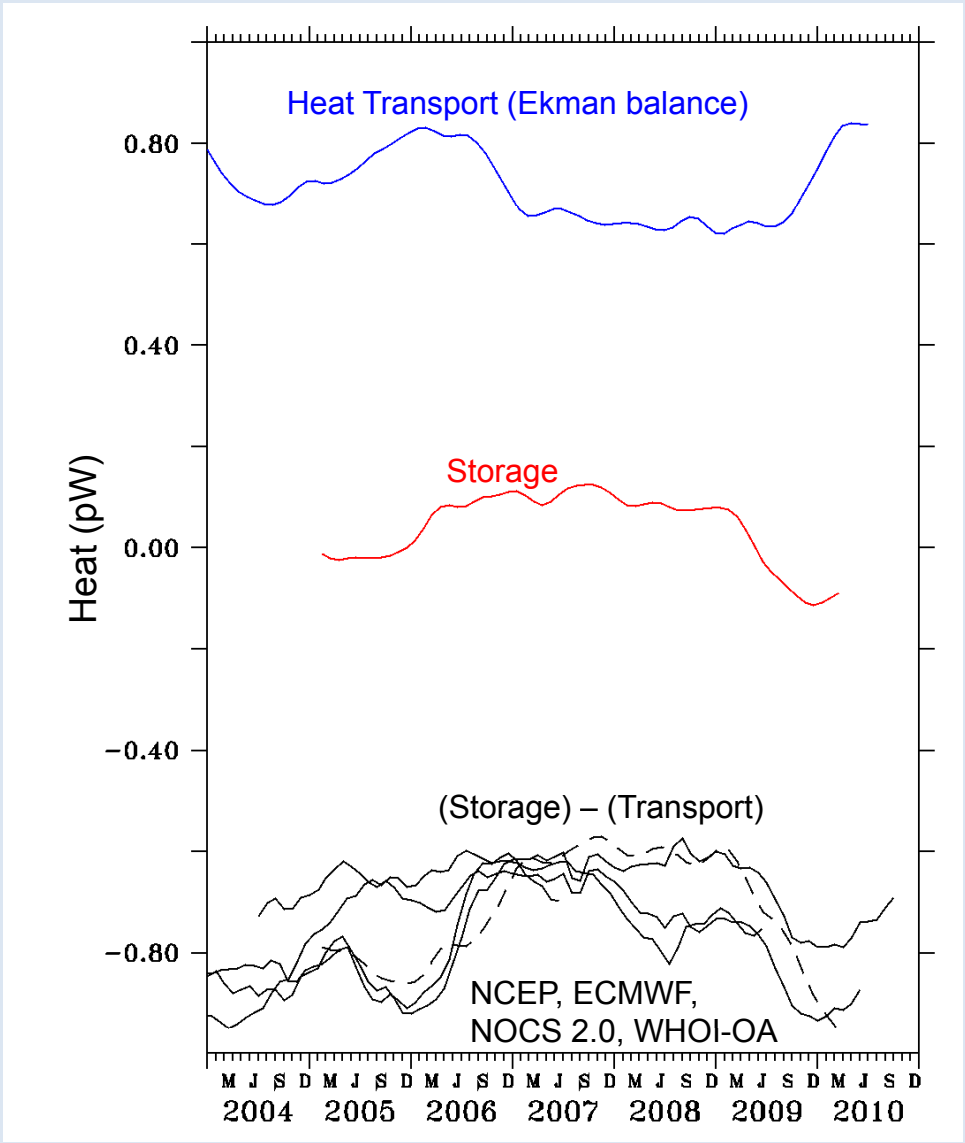
Heat Balance #1



Heat Balance #2



Heat Balance #3



Conclusions:

Variability not large in the Argo era (so far)

Remaining uncertainty in the anomalies > 0.1 pW

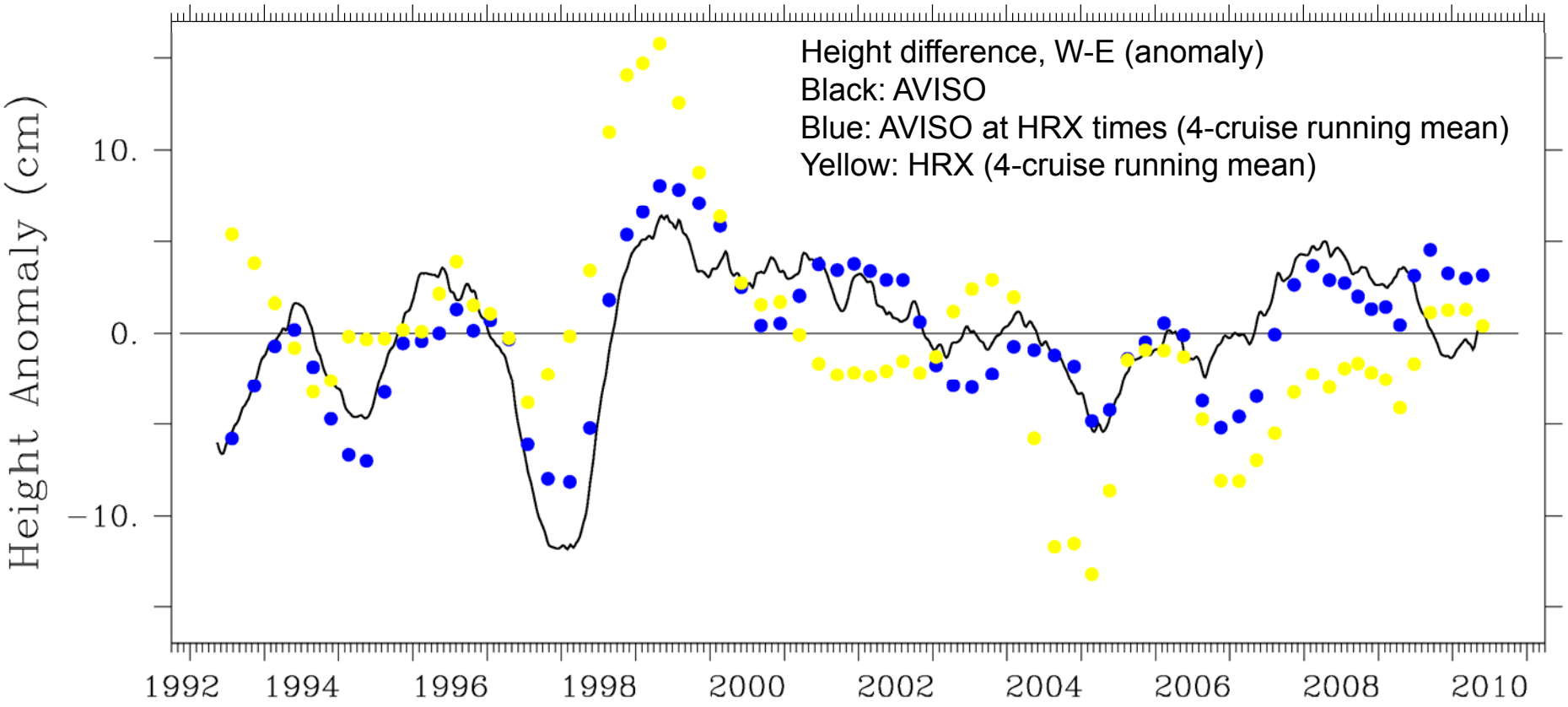
Further improvements coming (e.g. HRX/Argo/altimetry synthesis) for better understanding of the time-varying mass budget.

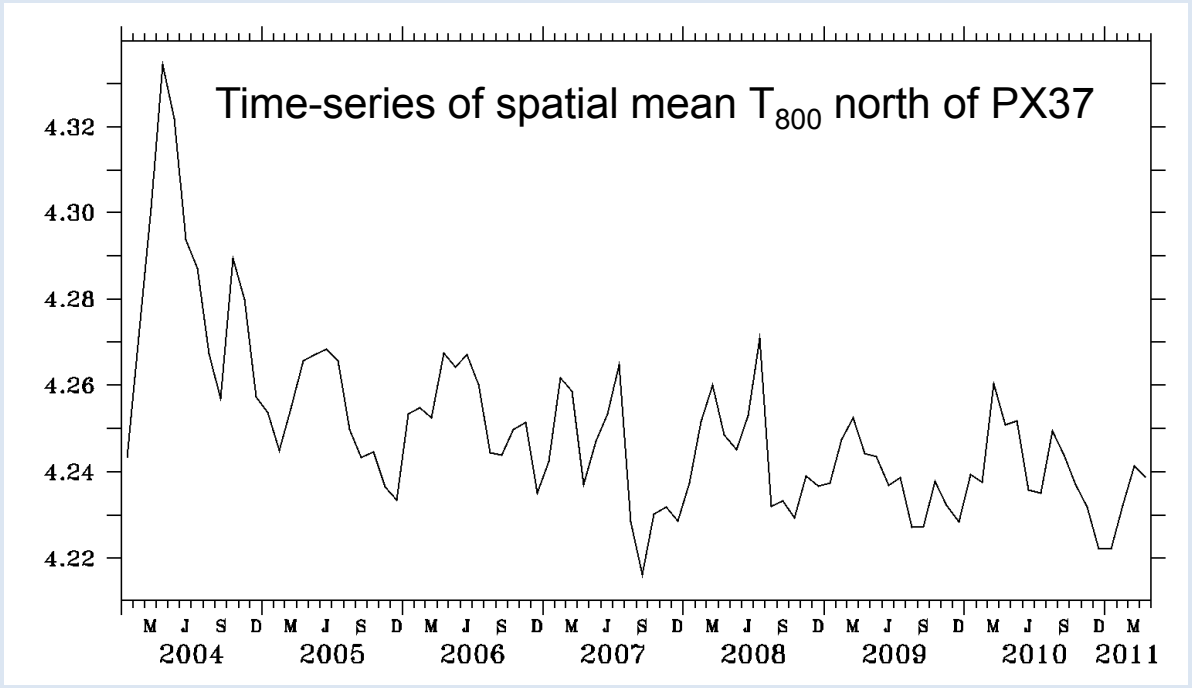
All A-S flux estimates have mean adjusted

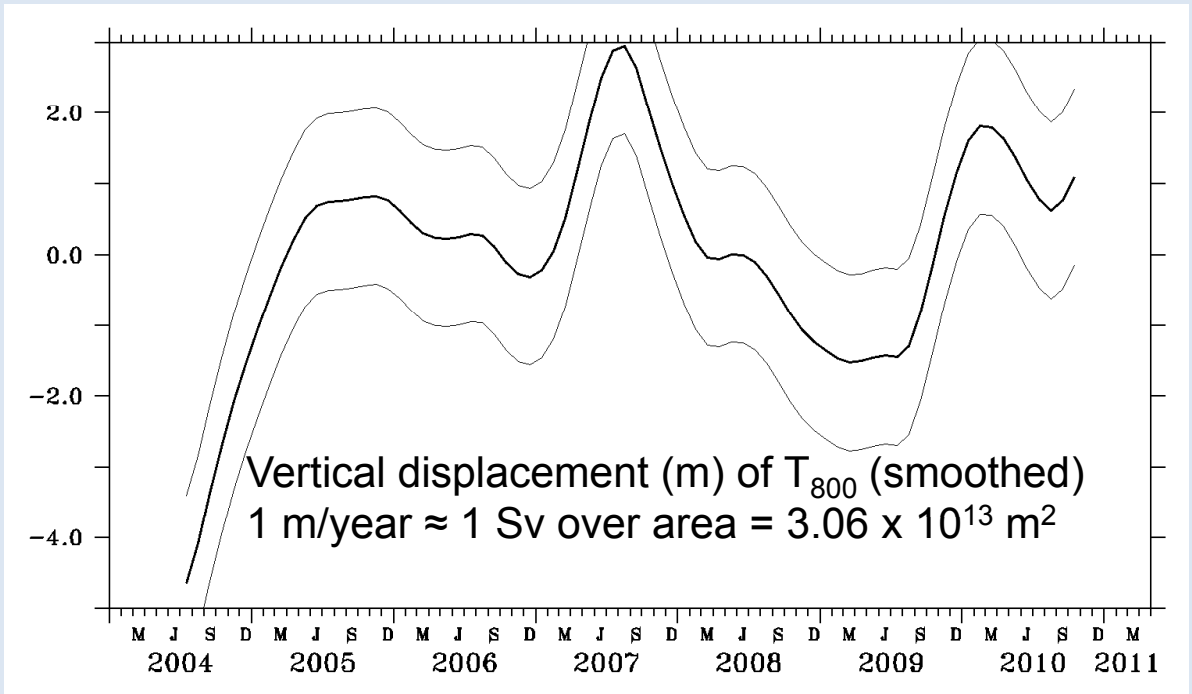
Value[a] of the HRX Network

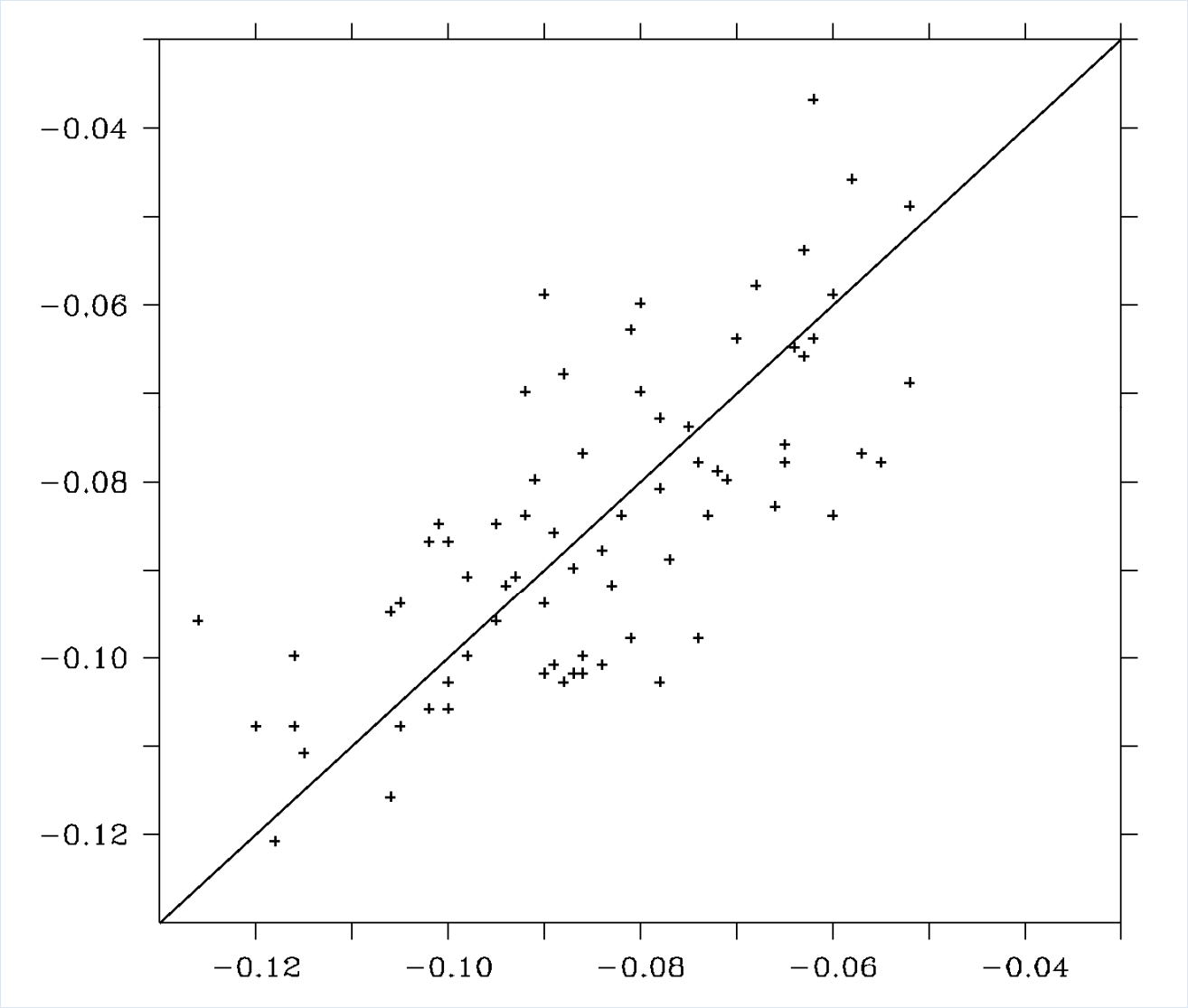
- Ocean circulation:
  - The HRX Network samples the boundary currents *and* the ocean interiors at high spatial resolution for transport estimation.
  - It provides a tool for integrating the observing system.
  - The combination of HRX, Argo, and altimetry mitigates the limitations of the individual datasets.
- Mass, heat, and freshwater budgets:
  - Estimates of reference velocities, heat storage, vertical advection, and Ekman transport are all much improved in the past decade.
  - Time mean balances have good confidence.
  - Time varying balances remain a challenge, but progress is being made.

[a] 8 PhD theses at Scripps Institution of Oceanography, Tohoku University, University of Tasmania


Height difference, W-E (anomaly)
Black: AVISO
Blue: AVISO at HRX times (4-cruise running mean)
Yellow: HRX (4-cruise running mean)
Height Anomaly (cm)
10.
0.
−10.
1992
1994
1996
1998
2000
2002
2004
2006
2008
2010


Time-series of spatial mean T_{800} north of PX37
4.32
4.30
4.28
4.26
4.24
4.22
M J S D M J S D M J S D M J S D M J S D M J S D M J S D M
2004 2005 2006 2007 2008 2009 2010 2011


2.0
0.0
−2.0
−4.0
Vertical displacement (m) of T_{800} (smoothed)
1 m/year ≈ 1 Sv over area = 3.06 x 10^{13} m^2
M J S D M J S D M J S D M J S D M J S D M J S D M J S D M
2004 2005 2006 2007 2008 2009 2010 2011


−0.04
−0.06
−0.08
−0.10
−0.12
−0.12
−0.10
−0.08
−0.06
−0.04