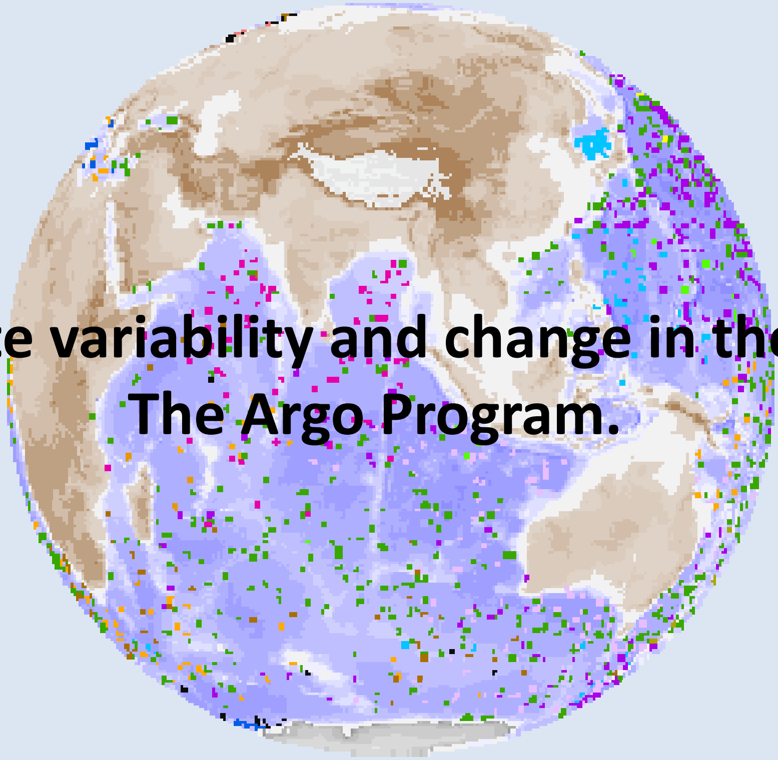

Observing climate variability and change in the global oceans: The Argo Program.

Dean Roemmich

Argo Steering Team Co-Chair

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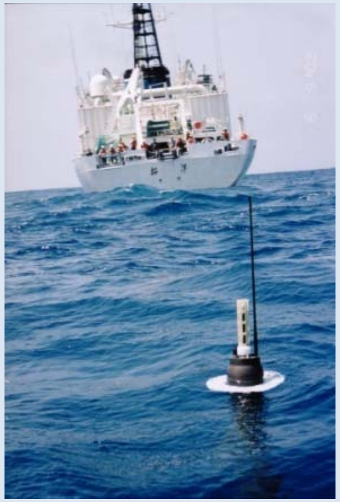
Ocean Surface Topography Science Team

San Diego, October 19, 2011



Outline

- Autonomous instruments: transforming subsurface ocean observations.
- What are we learning about the global ocean?
  - ➢ Mean fields (temperature, salinity, and circulation)
  - ➢ Seasonal variability
  - ➢ Interannual variability (ENSO)
  - ➢ The Argo era
  - ➢ Multi-decadal trends
  - ➢ Centennial change – Challenger to Argo

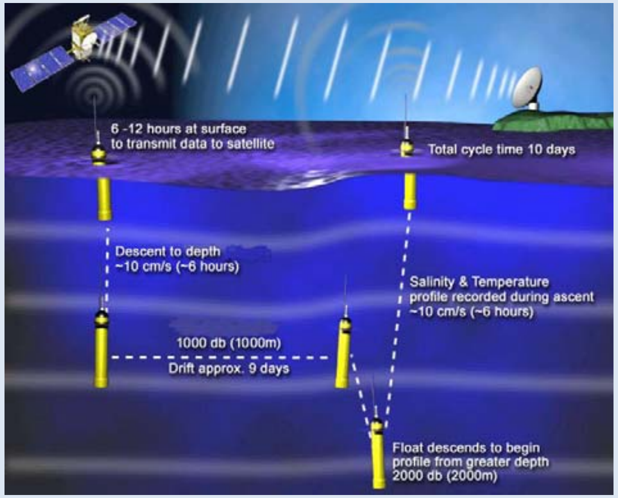
} Argo + historical data

The profiling float: transforming global ocean observations

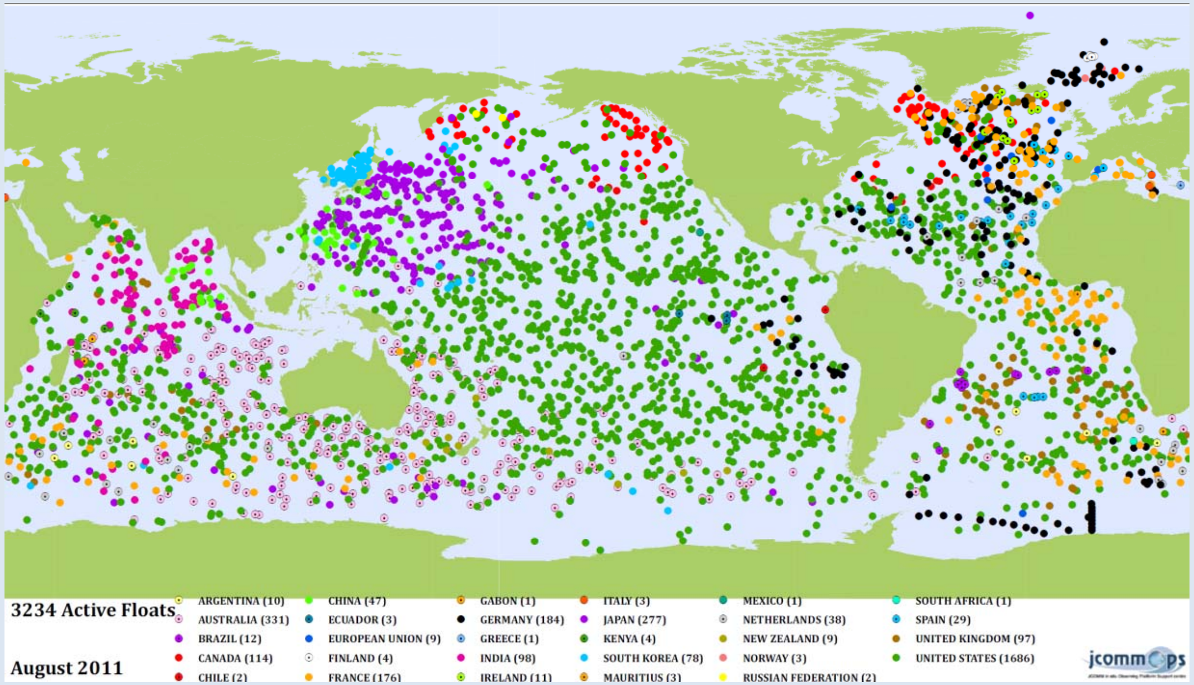
3200 free-drifting Argo floats collect high-quality temperature/salinity (T/S) profiles, 0 – 2000 m, and velocity at 1000 m, every 10 days.

Heat (from T) and freshwater (from S) are fundamental elements of climate.

In future, Argo will measure not only T and S, but also oxygen, nutrients, pH, and biological parameters.



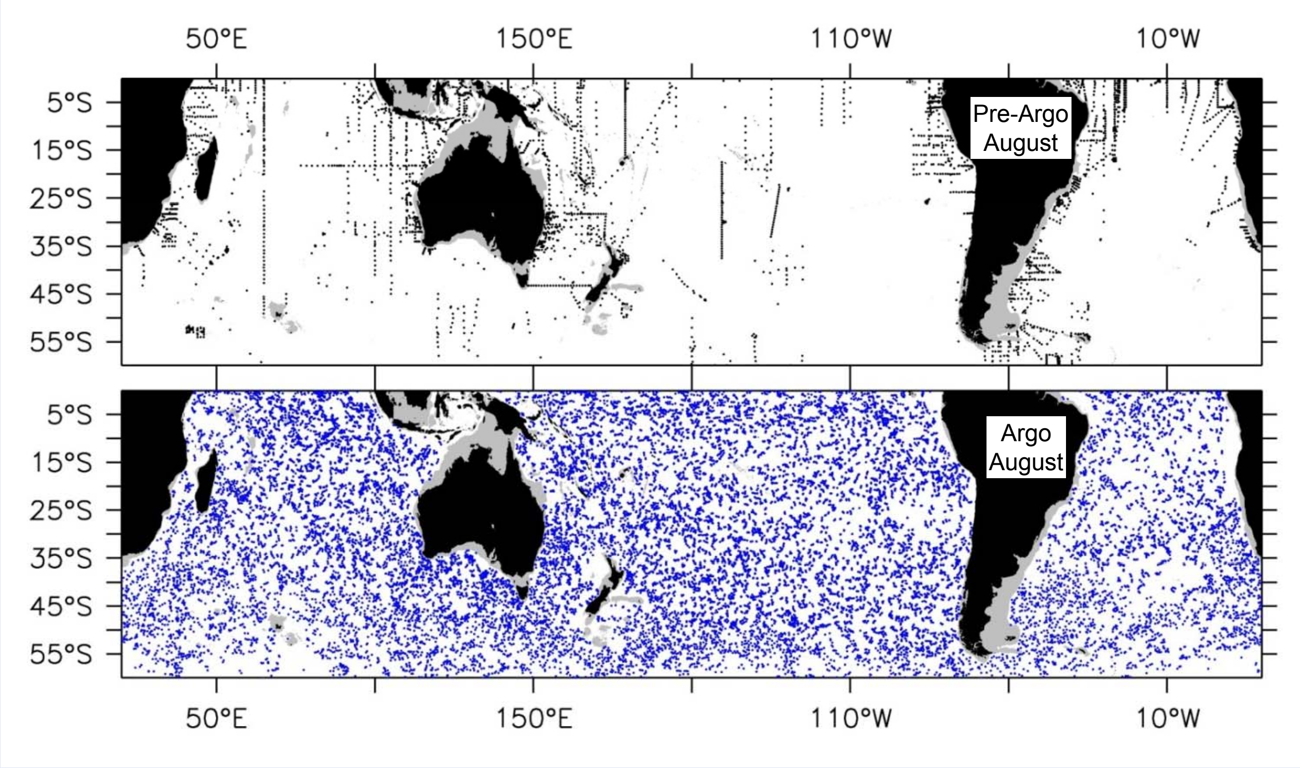
Schematic of an Argo float cycle.



No nation could implement Argo alone; cooperation is essential.
All of the data are freely and immediately available (www.argo.net).

The significance of global coverage

Throughout the history of oceanography, subsurface data collection required a ship (or mooring) to be present. *The profiling float removed this limitation.*



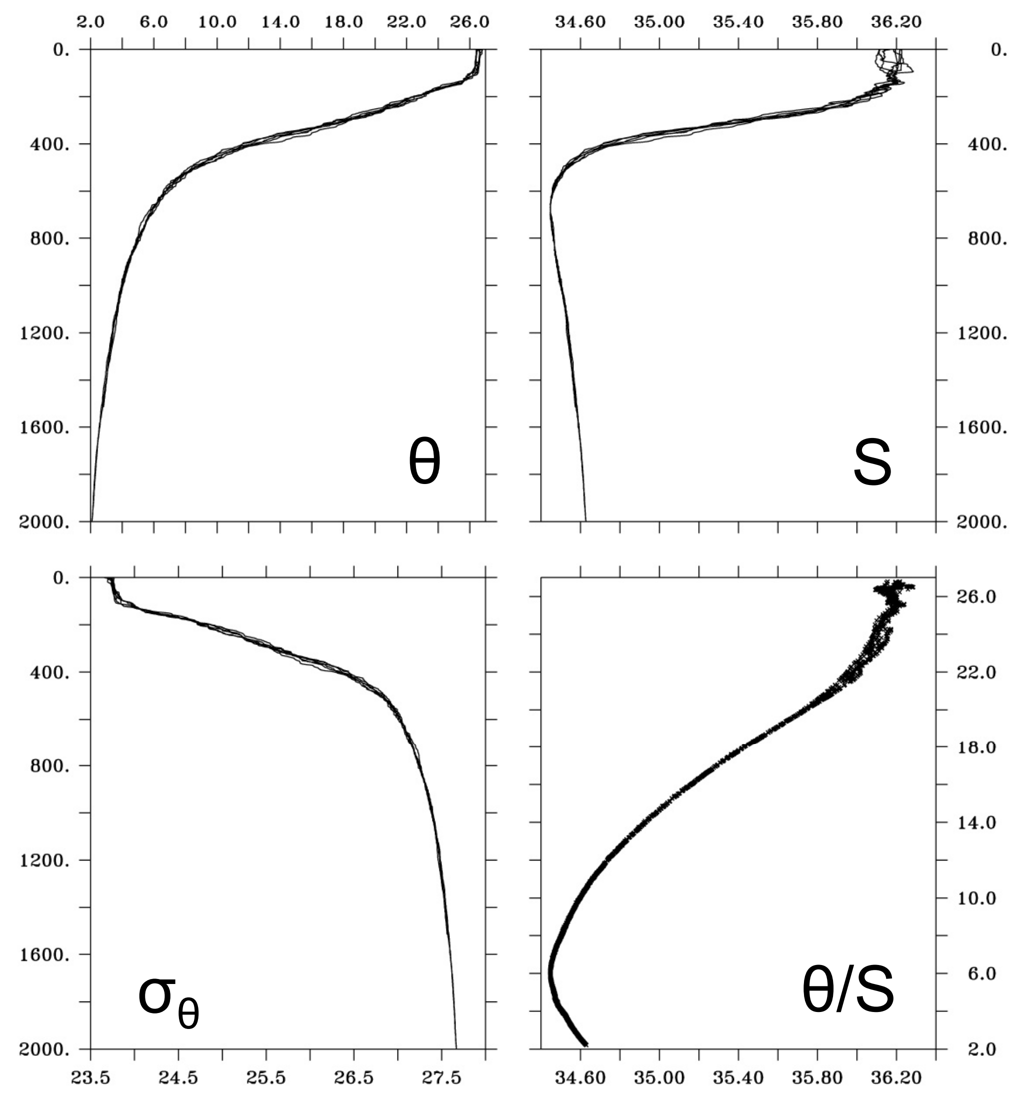
Before Argo: All August T,S profiles > 1000 m, 1950-2000.

2005 - 2010: Argo August T,S profiles > 1000 m.

The global nature of Argo makes it effective for:

- Combining with other global observations (e.g. satellite altimetry)
- Observing the patterns and evolution of global climate variability (e.g.: El Niño)
- Comparing the modern ocean with previous “transect” data (e.g.: WOCE, Challenger,…

Advancing float technology



WMO ID 5903762, 16°S, 153°W

Float technologies continue to improve, and capabilities now include:

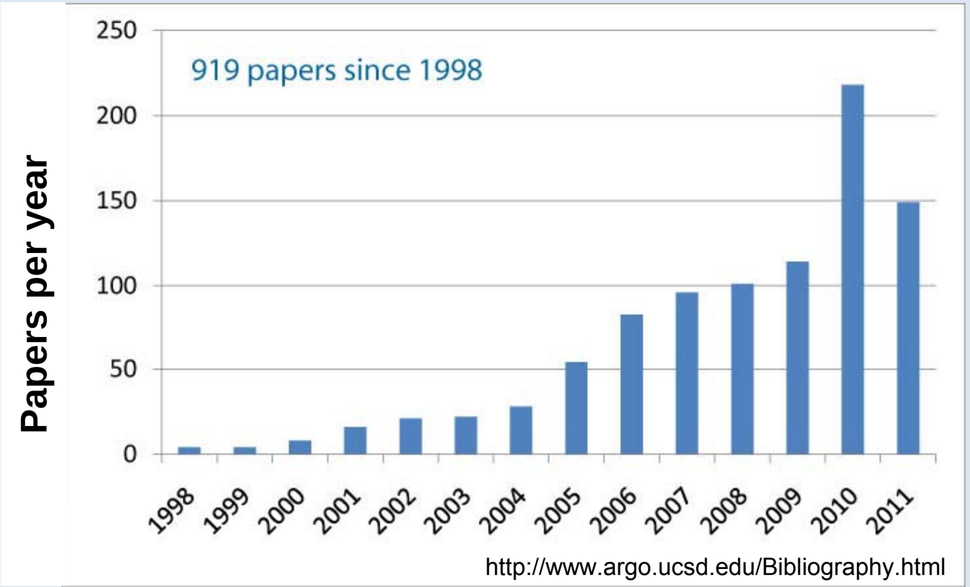
- Increased lifetime (> 300 cycles)
- Profiling to 2000 m anywhere in the world
- Measurements near the sea surface (1 decibar)
- High vertical resolution (2 decibar bin-averaged data; 1 decibar in the top 10 bins)
- 2-way communication, so mission can be changed.
- Lightweight, and smaller than earlier floats.

The future:

- Deep-ocean Argo floats are under development.
- Added sensors will enable observations of biogeochemical impacts of climate variability and change.

Who uses Argo data?

Research papers using Argo data:



Research topics include water-mass properties and formation, air-sea interaction, ocean circulation and transport, mesoscale eddies, ocean dynamics, and seasonal-to-decadal climate variability and change.

Also: Education and Outreach

See: http://www.argo.ucsd.edu/Educational_Use.html

Operational forecasting/analysis

--!>

Country	Center	Project Website	Project Example	Type	Region	T and S
Australia	CSIRO/BRAN/BoM	**Bluelink**	**B of M** and the **Bluelink Project**	Ocean forecast	Australian waters	T + S
Australia	BoM/CSIRO	**POAMA**	**POAMA**	Climate analysis and forecast	Global, but focus on tropics	T
France	Mercator Ocean	**Mercator**	**Mercator**	Ocean analysis + forecast	N + Trop Atlantic, Med Sea, Global	T + S
France	Coriolis	**Coriolis**	**Coriolis**	Ocean analysis	N + Trop Atlantic, Global	T + S
EU (Italy)	INGV	**MFS**		Ocean analysis + forecast	Mediterranean	T
EU (Norway)	NERSC	**Diadem/Topaz**		Ocean analysis + forecast (+ ecosystem)	Atlantic/Nordic/ Arctic	T+S used to check forecasts
EU(UK)	ECMWF	**Seasonal Forecasting System**		Seasonal ocean analysis forecasts	Global	T + S
Japan	JMA	**COMPASS-K**	**JMA**	Ocean analysis (currents, subsurface temperatures)	NW Pacific	T + S
Japan	JMA	**ODAS**	**JMA**	Ocean analysis + ENSO forecasts	Global but focus on Eq Pacific	T + S
UK	Met Office	**GloSea**	**GloSea**	Seasonal climate forecasts	Global	T + S
UK	Met Office	**FOAM**	**FOAM**	Ocean forecasting	Global nested model	T + S
USA	ECCO: JPL and SIO/MIT	**ECCO**		Ocean analysis	Global	T + S
USA	FNMOC Monterey	**COAMPS**		Ocean forecast	Global	T + S
USA	NCEP	**GODAS**	**USGODAE/GODAS**	Seasonal to interannual forecast	Global	T only
USA	NASA	**NSIPP**		Seasonal/Interannual climate	Global	T + S
USA	NAVOCEANO	**NCOM**		Ocean forecast	Global	T + S

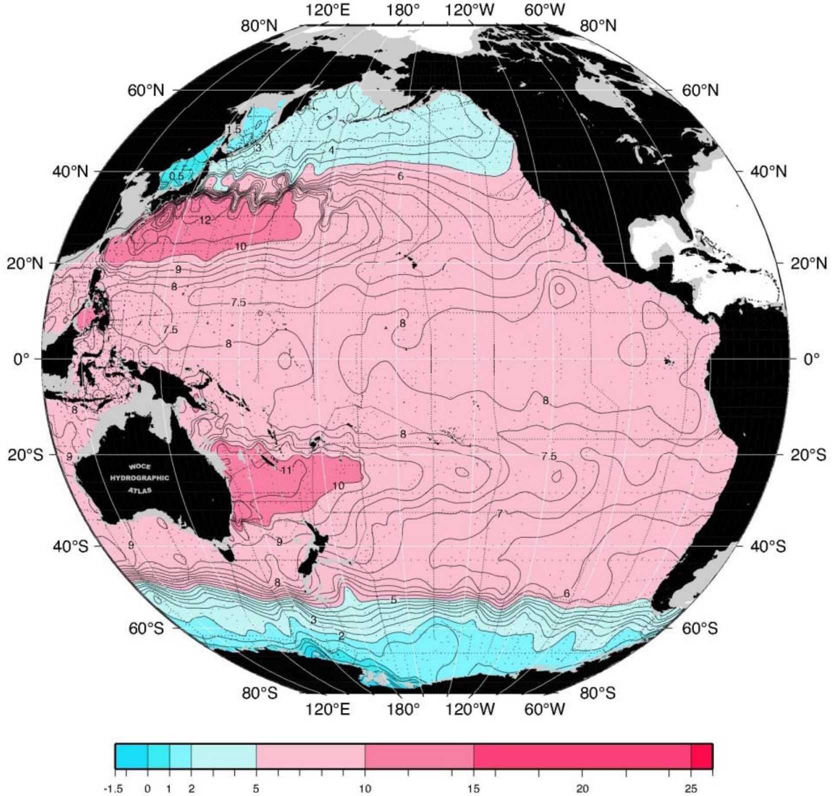
Operational centers around the world use Argo data in ocean state estimation, short-term forecasting and seasonal to decadal prediction.
http://www.argo.ucsd.edu/Use_by_Operational.html

All Argo data freely available via the internet (http://www.argo.net) and GTS.

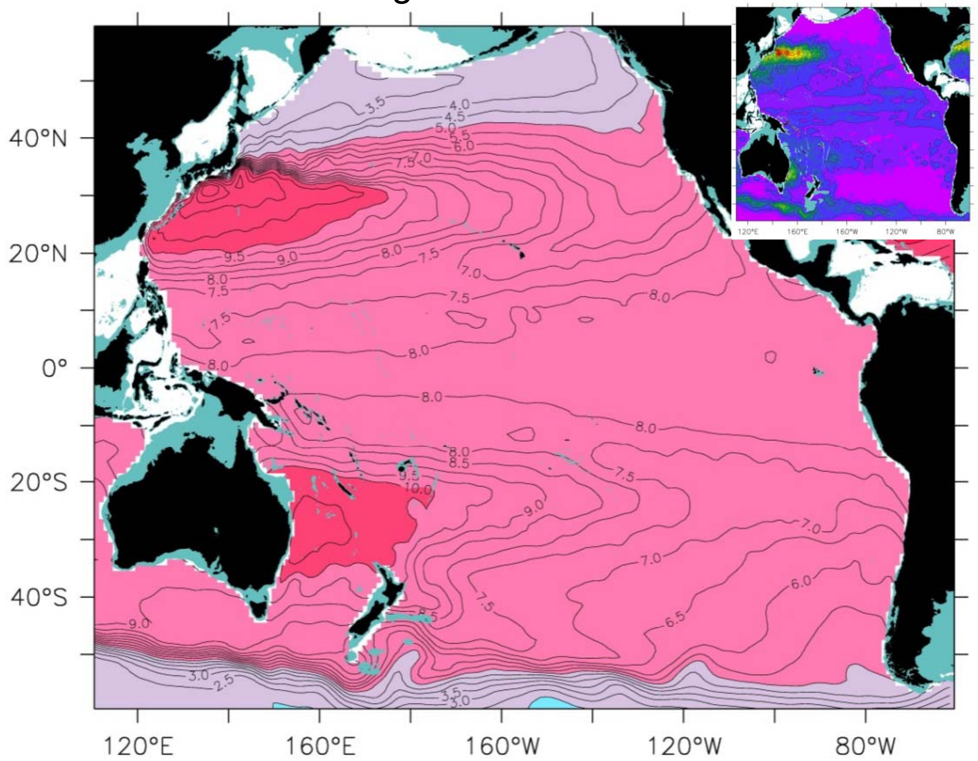
MEAN FIELDS

Argo and WOCE “mean fields”

Potential temperature (°C) 500 m
WOCE Pacific Atlas, Talley (2007)



Potential temperature (°C) 500 m
Argo 2005-2010 mean



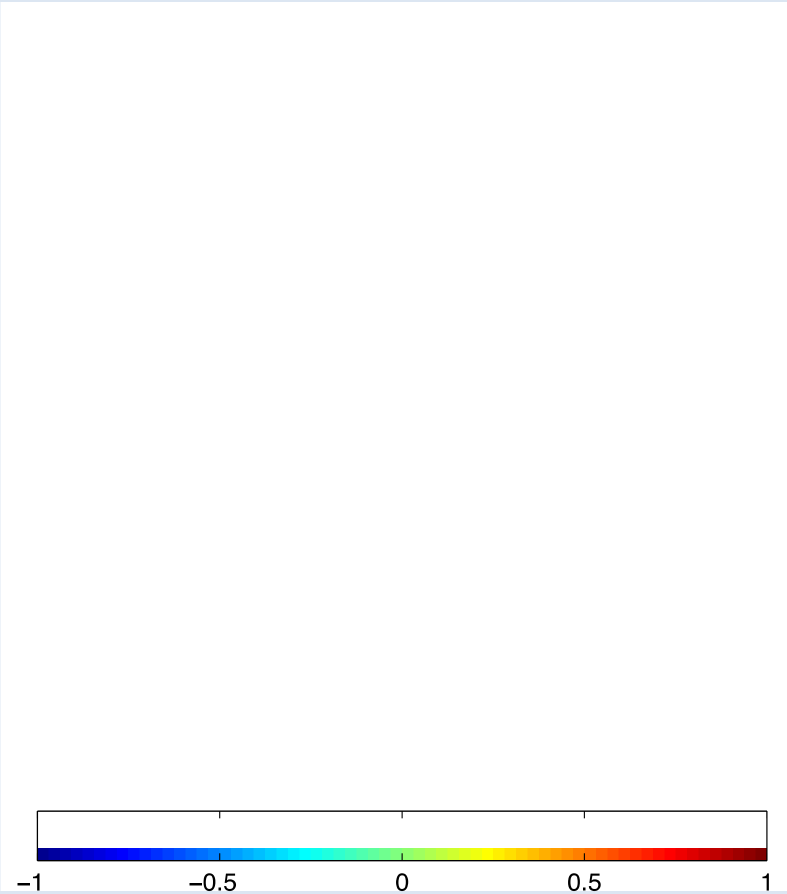
From a few thousand profiles:
WOCE produced neither a snapshot or a time mean, but rather a multi-year composite of snapshots from many transects. The sampling errors are difficult to estimate.

From a few hundred thousand profiles:
Argo provides both time means and snapshots, with realistic error estimates. (Inset plot: standard deviation of monthly temperatures)

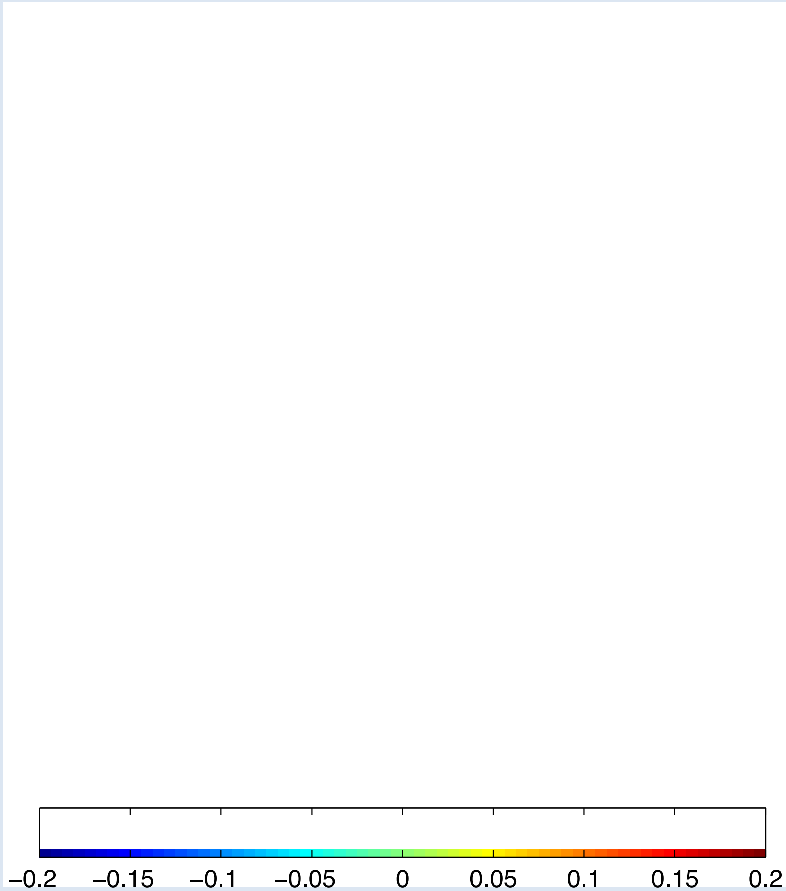
North Atlantic time-mean upper ocean circulation

Extended optimal interpolation, combining altimetry, geoid, surface drifters, Argo profiles & displacements, along with dynamical constraints, to map upper ocean velocity, geostrophic velocity, temperature, salinity & potential vorticity.

Mapped surface elevation [m]



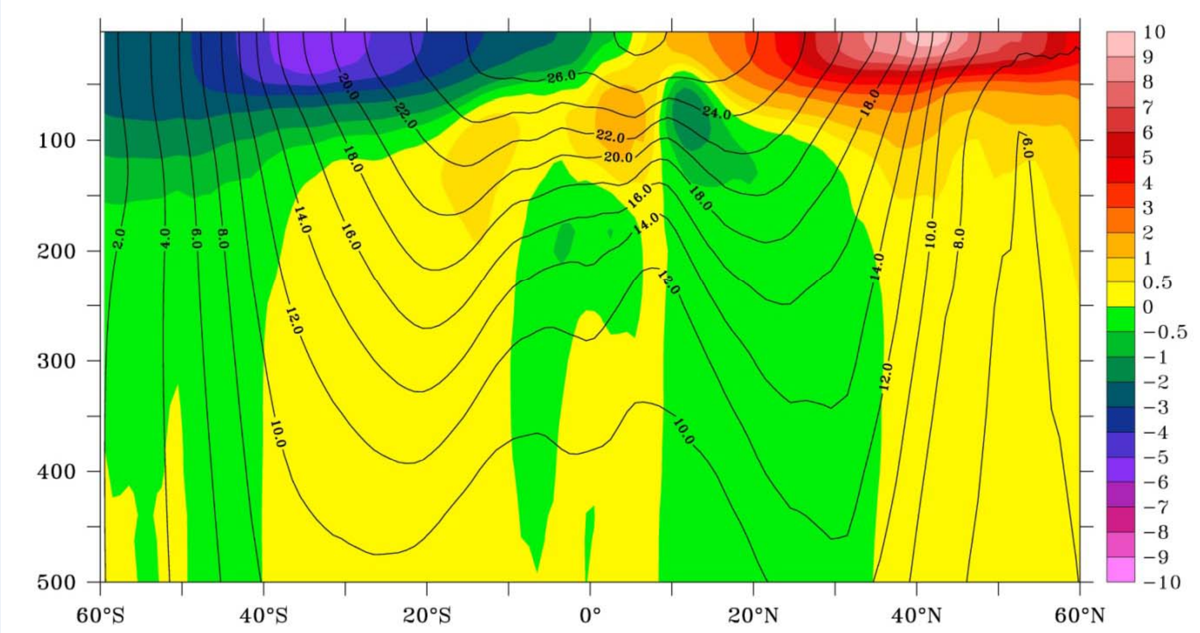
Mapped 1000 dbar pressure [m]



Jayne et al., 2011 Argo and Altimetry Workshop

SEASONAL VARIABILITY

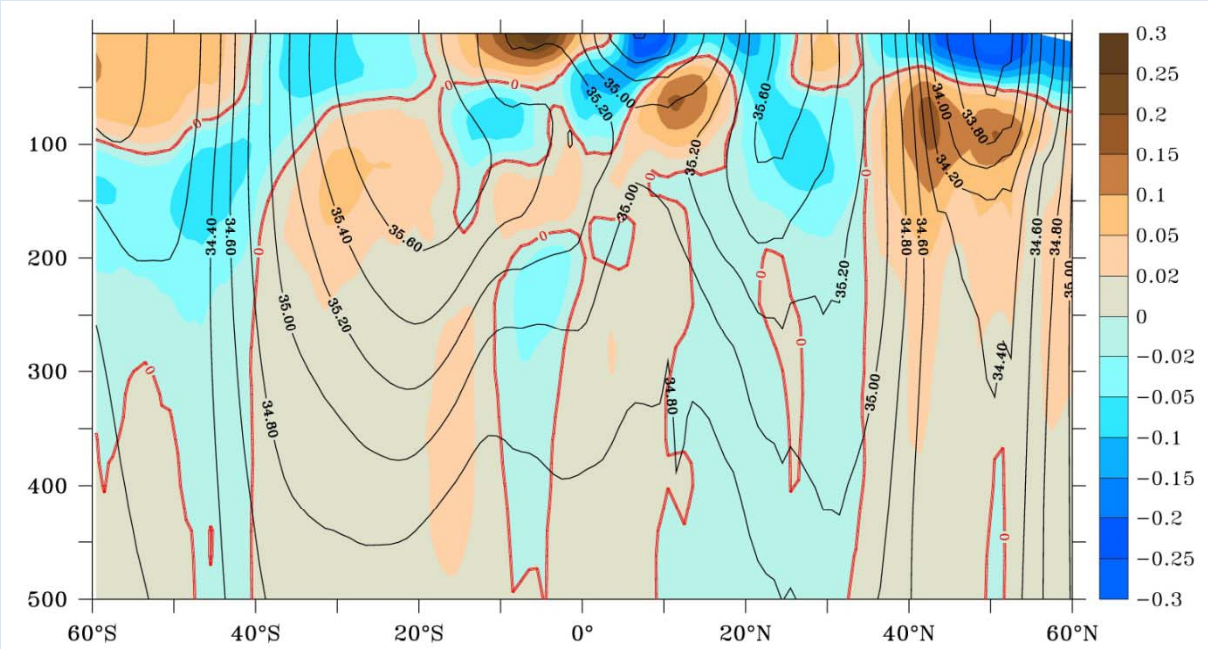
Seasonal contrast



Zonal average of Sep – Mar temperature difference (color shading)

Zonal average temperature (contours)

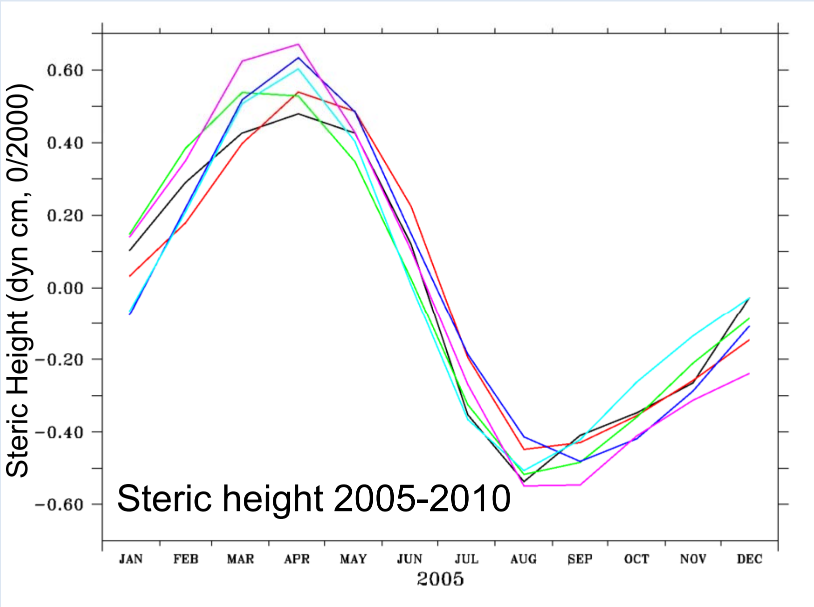
2005-2010



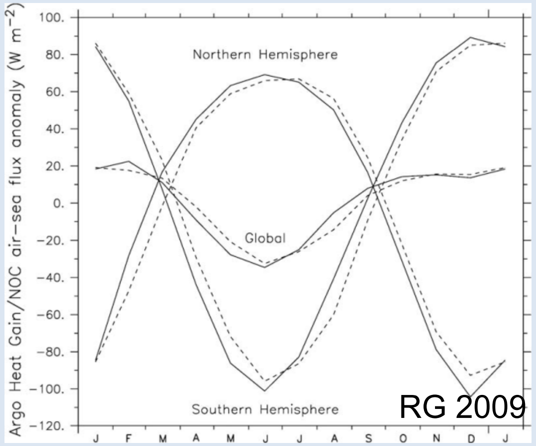
Same for salinity.

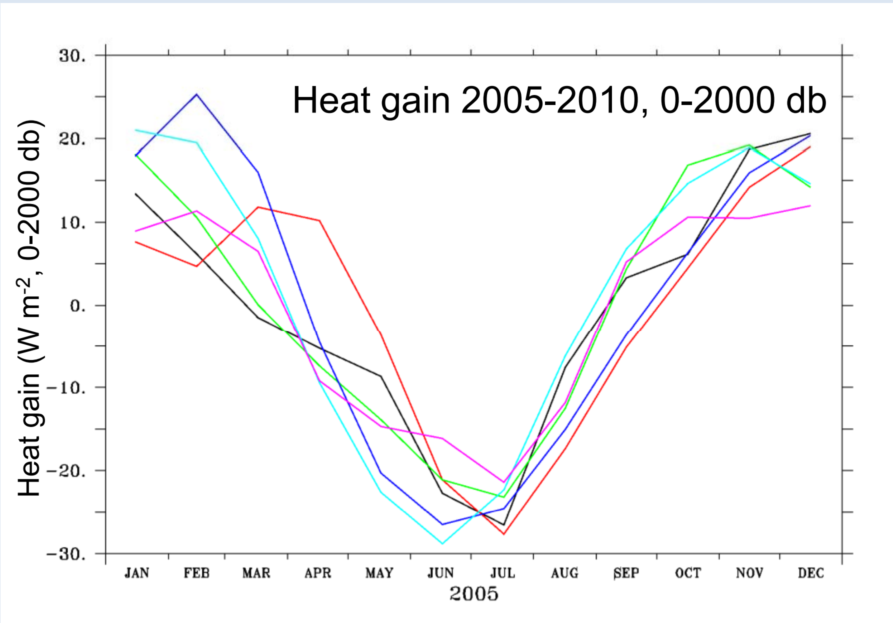
Sea surface changes are due to air-sea exchange of heat and water. Sub-surface changes are largely due to ocean dynamics.

Steric height and heat gain



Globally-averaged steric height is controlled by southern hemisphere ocean temperature.





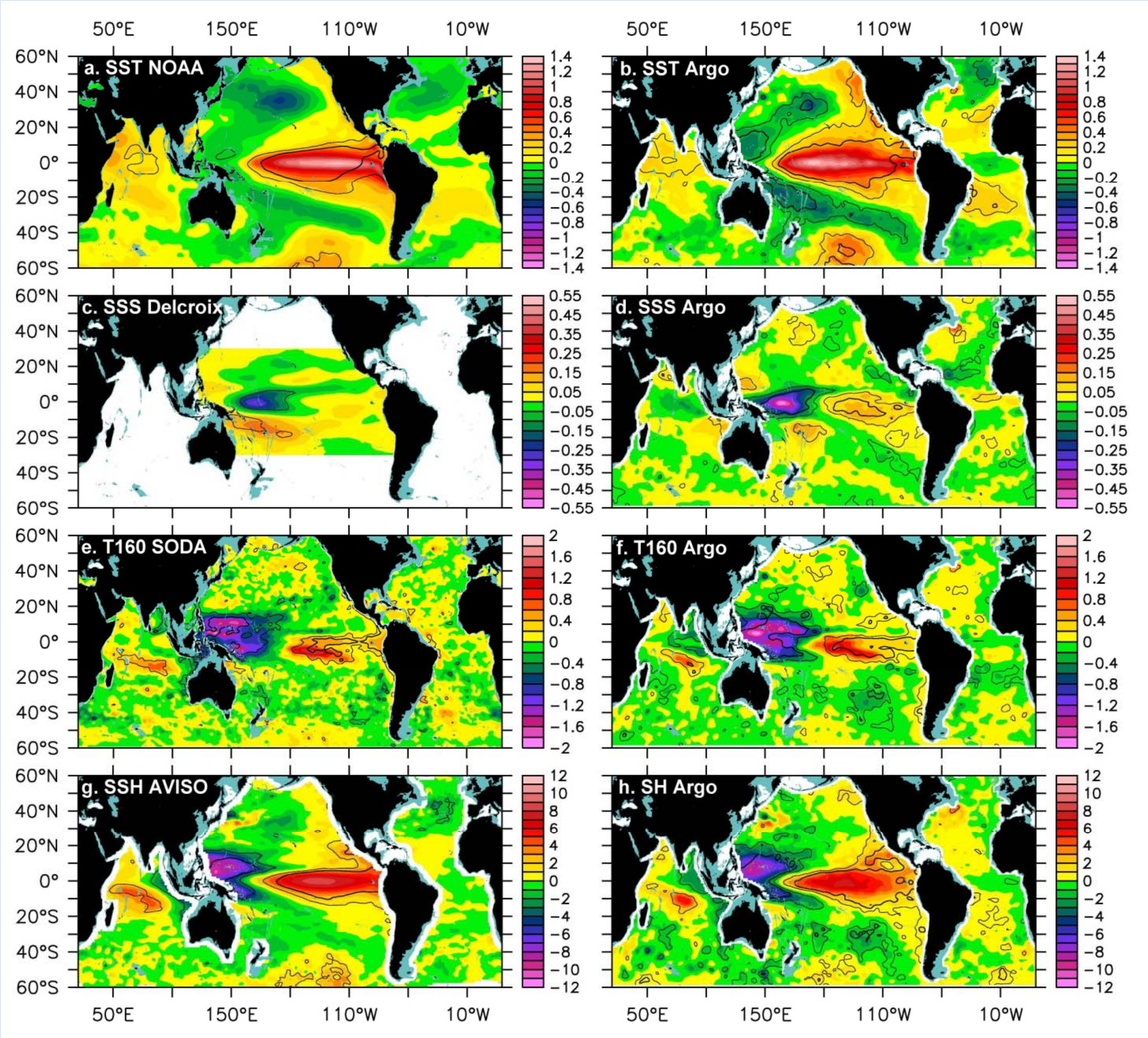
The northern and southern hemisphere oceans gain and lose heat seasonally at about 80 W/m^2.

In the global (ocean) average of about **20 W/m^2**, the southern hemisphere dominates because of the larger ocean area.

Good agreement is seen between seasonal Argo heat storage and NOCS air-sea fluxes.

INTERANNUAL (ENSO) VARIABILITY

The global ocean imprint of ENSO

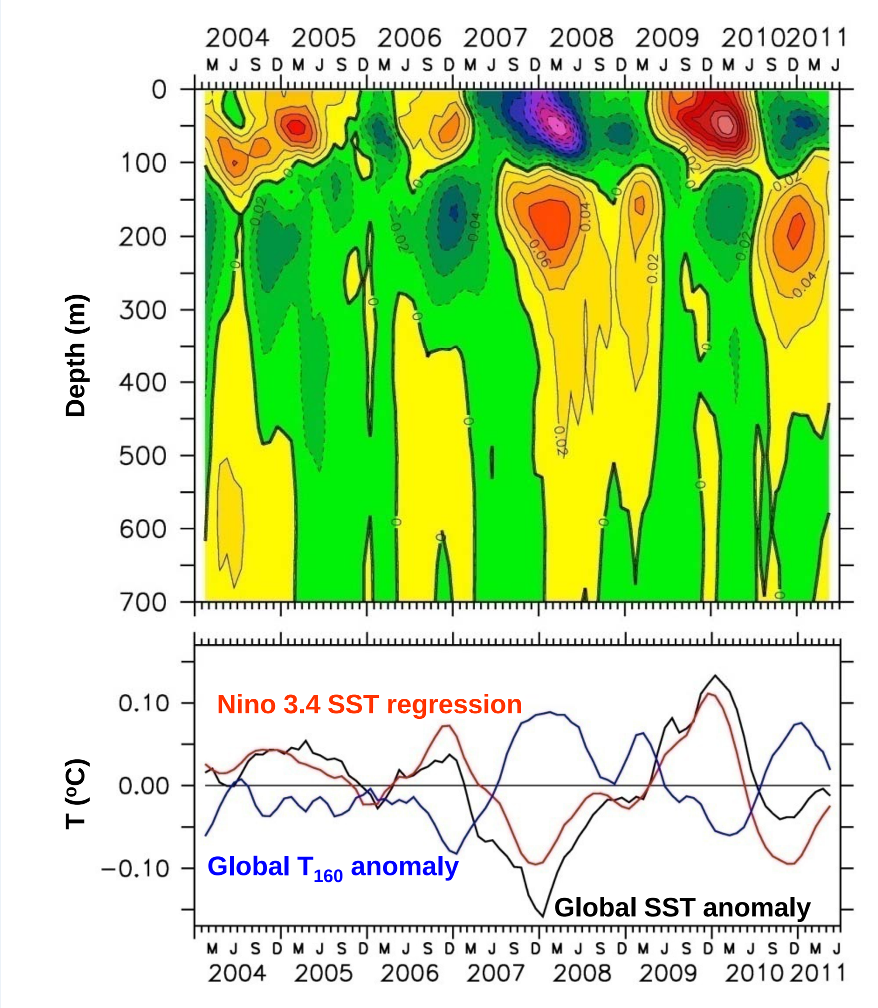


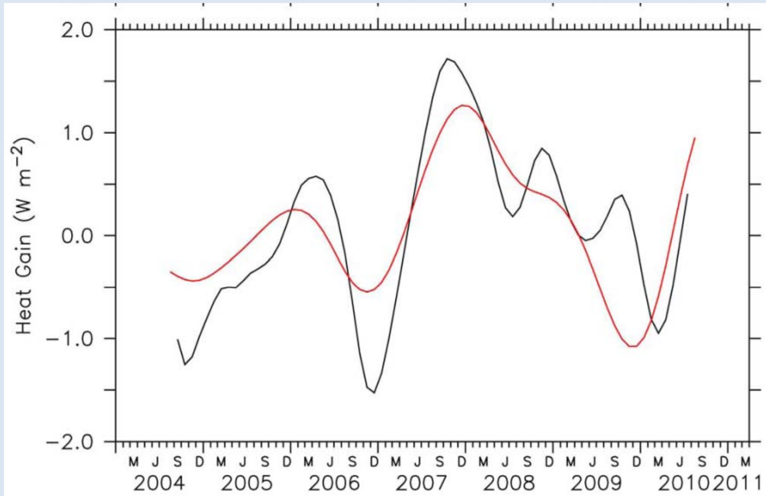
Linear regressions onto Niño 3.4 SST are shown for Argo SST, SSS, T160 and SH, as well as longer time-series. From: Roemmich and Gilson, 2011.

Argo is revealing the global pattern of ENSO variability in surface and subsurface properties, needed for better understanding and prediction.

Global El Niño/La Niña variability

Time-series of globally-averaged temperature and salinity vs depth





For the combined layers (0-500 m), the ocean loses heat during El Niño and gains heat during La Niña. Black: smoothed heat gain, 0-500 m. Red: linear regression of Niño 3.4 index onto heat gain.

(Roemmich and Gilson, 2011)

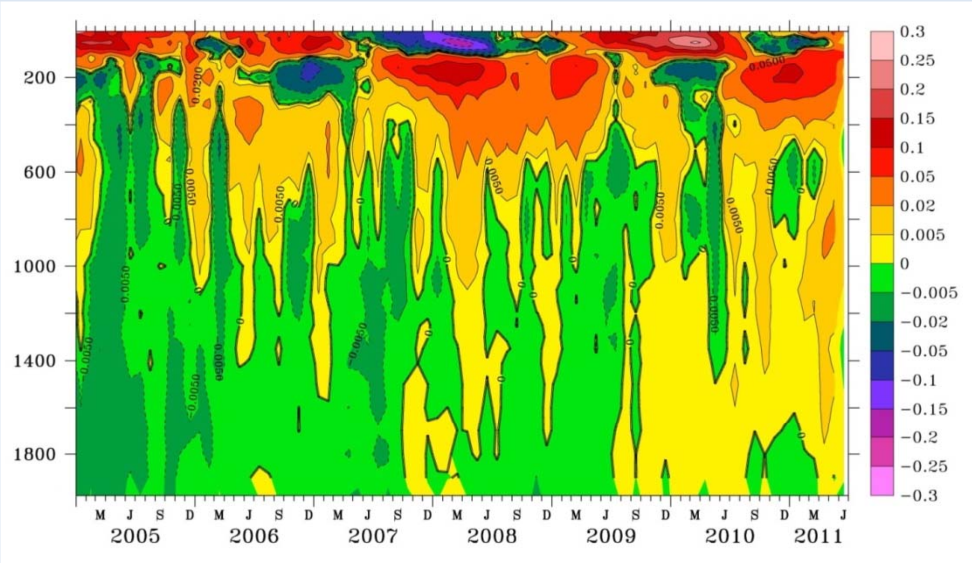
Tropical Pacific temperature anomalies do ***not*** average out in global means.

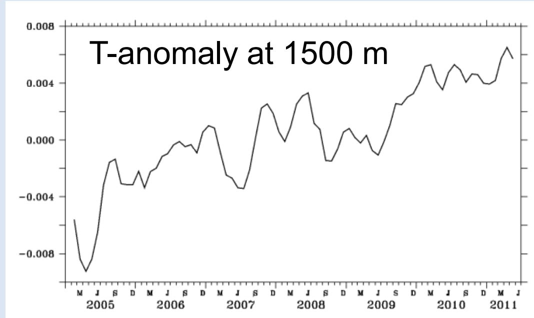
Moreover, surface layer (0-100m) anomalies are opposite to the 100-500m layer.

Interannual heat content fluctuations in the individual layers are up to 3.3 x 10^{22} J/yr (**2 W/m²**).

THE ARGO ERA

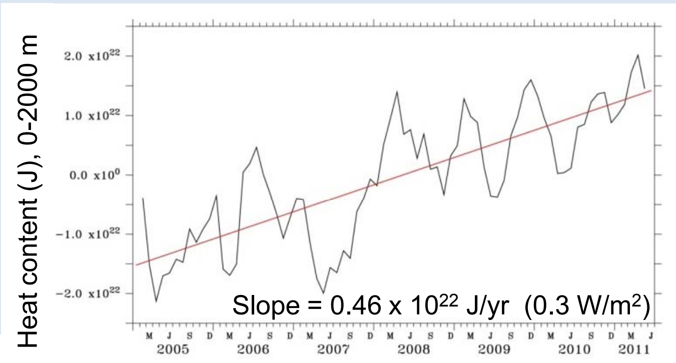
Globally-averaged temperature anomaly, °C

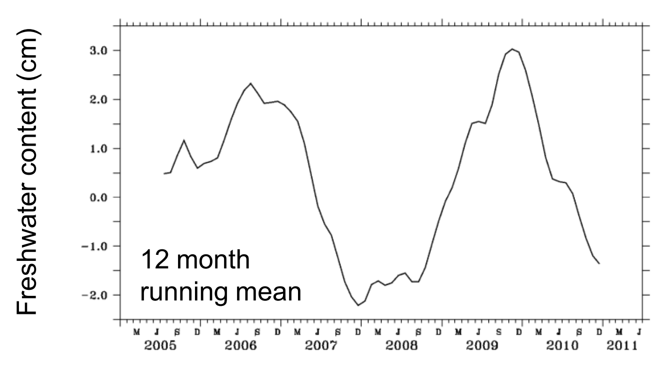




Below 500 m, the interannual (ENSO) variability is not seen, replaced by a longer time-scale.

The Argo time-series is not yet long enough to estimate global change trends.





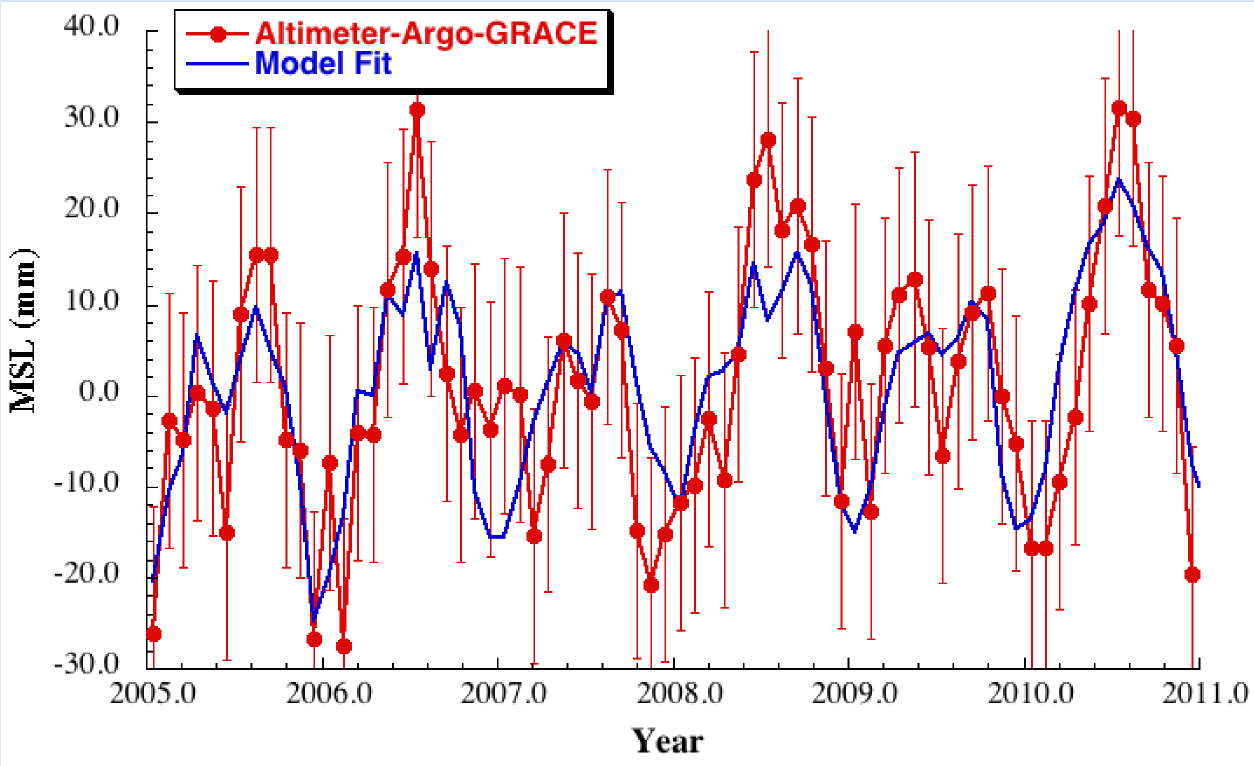
The trend in vertically-averaged temperature is about .002 °C/year

A 1-dbar systematic pressure error results in a vertically-averaged temperature error of 0.01 °C

6 cm of freshwater lowers the average salinity, 0-2000 m, by .001 psu

This large (ENSO-related) signal is not seen in altimetric height. Indonesian Seas???

Combining Argo, altimetry, and GRACE



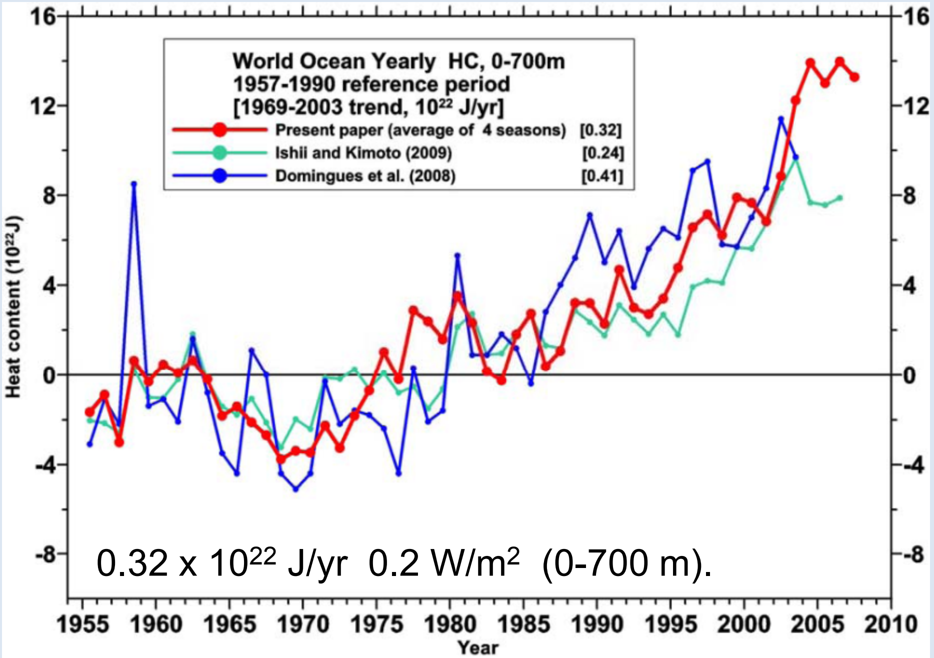
Chambers and Willis, Can a combination of altimetry, Argo, and GRACE detect deep ocean warming? (Argo and Altimetry Workshop)

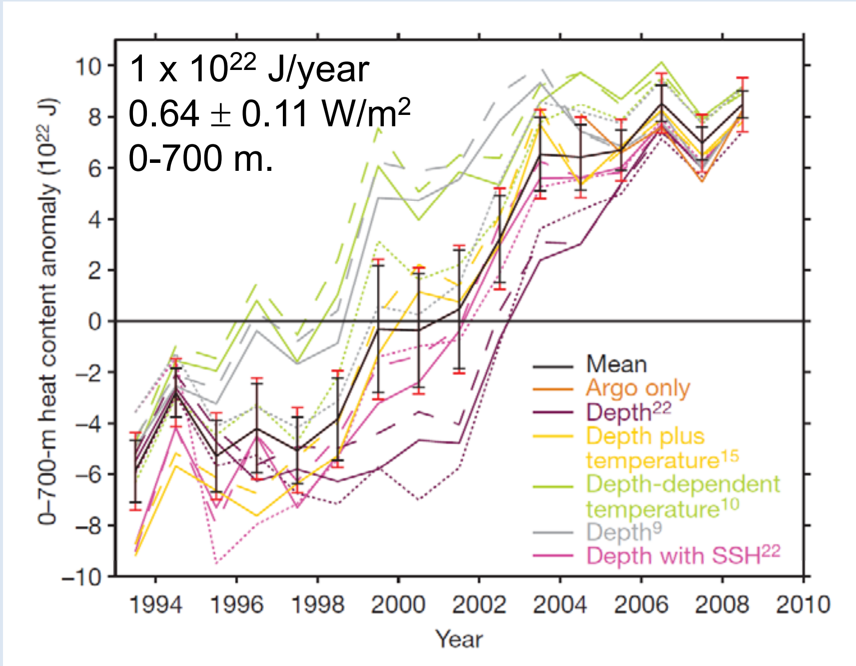
- Average residuals south of 50°S
- $y = a_0 + a_1*(t-2003) + a_2*SWH$
- a_1 = 1.2 ± 1.0 mm/year (95% confidence), suggesting warming below 1000 m (consistent with Purkey and Johnson, 2010)
- a_2 = 0.024 ± 0.004 (95% confidence), or 2.4%SWH error

MULTI-DECADAL CHANGE

Ocean heat content: Argo and historical data

The major sources of uncertainty in heat content from historical data are XBT fall-rate error and sparse sampling.

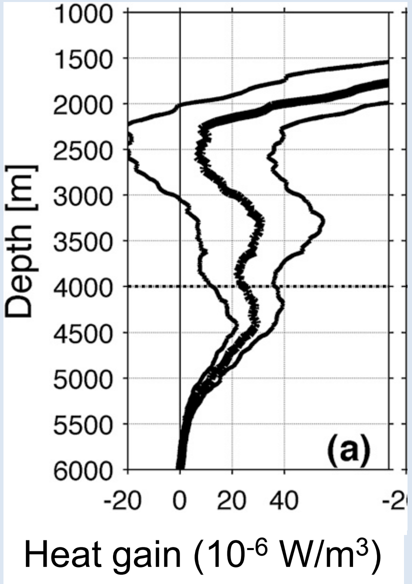




Levitus et al. (2009) 50-yr heat gain: May be an underestimate. Add about .1 x 10^{22} J/yr for 700-2000 m (Levitus et al, 2005).

Lyman et al. (2010). Different XBT fall-rate corrections, but same mapping technique and climatology.

How much heat is in the deep ocean below 700 m? below 2000 m?

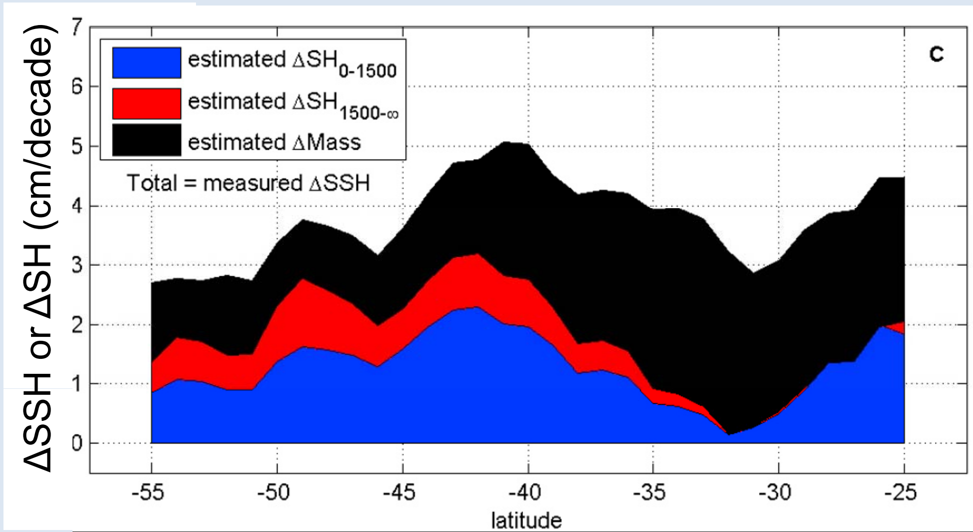


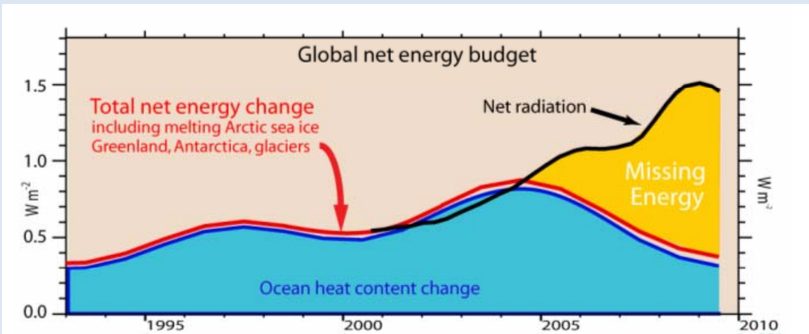
Purkey and Johnson (2010) analyzed repeating (sparse) deep hydrographic transects.

Heat gain below 2000 m was 0.07 W/m^2 $\pm$ 0.06

Sutton and Roemmich, 2011, estimated ΔSH in proportion to ΔSSH using WOCE, Argo, and altimetry data.

Heat gain south of 20°S was 1 x 10^{22} J/yr, 1.1 W/m^2 (total water column)



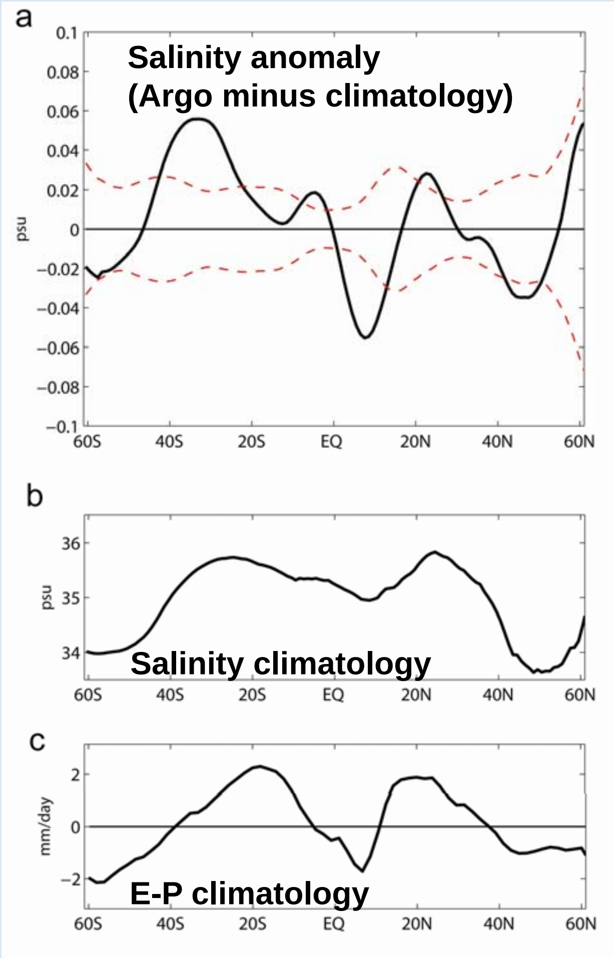


Trenberth and Fasullo, 2010, Trenberth et al., 2009. Net downward radiation 2000-2004 of 0.9 $\pm$ 0.5 W/m^2 Missing energy??

The Argo Program is presently developing "Deep Argo" profiling floats.

The 50-year salinity record

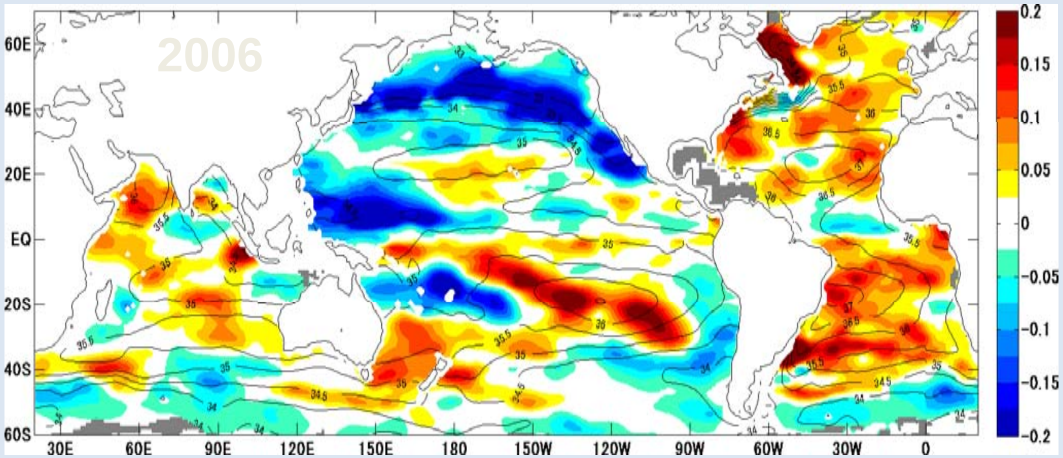
Salinity change consistent with an increase in the global hydrological cycle.



Zonal averages, from Hosoda et al. (2011, Argo and Altimetry Workshop)

Surface layer salinity has increased in the salty regions and decreased in the fresh regions.

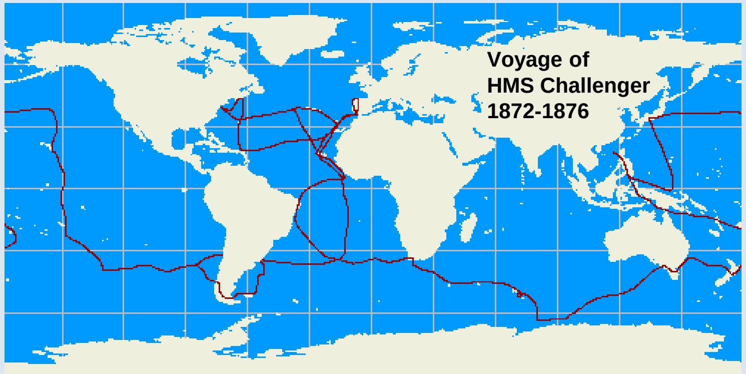
In a steady state net E-P is balanced by horizontal advection (u • ∇S) and mixing. The change in ∇S likely indicates an increase in global rates of evaporation and precipitation, by 3-4% Hosoda *et al.* (2009, 2011). Also Helm et al (2010), Durack and Wijffels (2010).



Argo minus climatological salinity, 0-100 m avg, Hosoda et al (2011, Argo and Altimetry Workshop)

CENTENNIAL CHANGE: ARGO AND CHALLENGER

Centennial change: Argo and Challenger



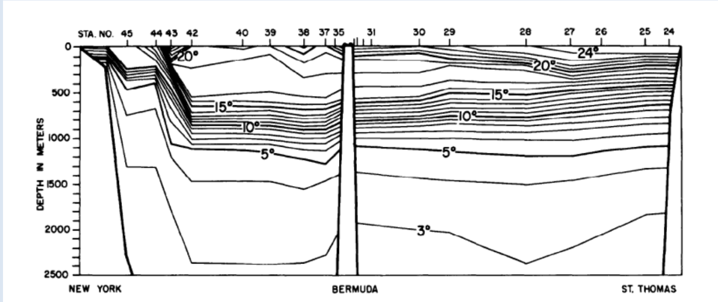


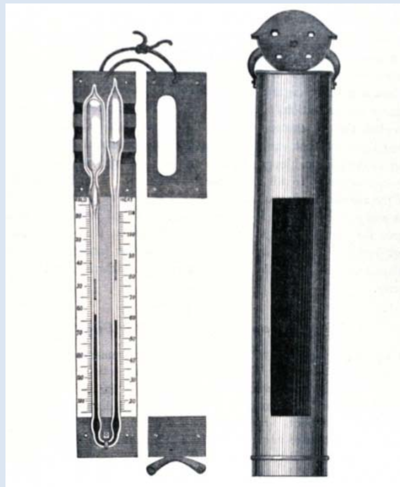
Figure 11.3A *Challenger* section (1873) from New York to Bermuda to Virgin Islands. (Tizard et al., 1885b, p. 135.)

Challenger temperature section, New York-St Thomas (Worthington 1976)

In the first global oceanographic expedition, HMS Challenger obtained 263 temperature profiles, 1872 – 1876, using pressure-protected min/max thermometers.

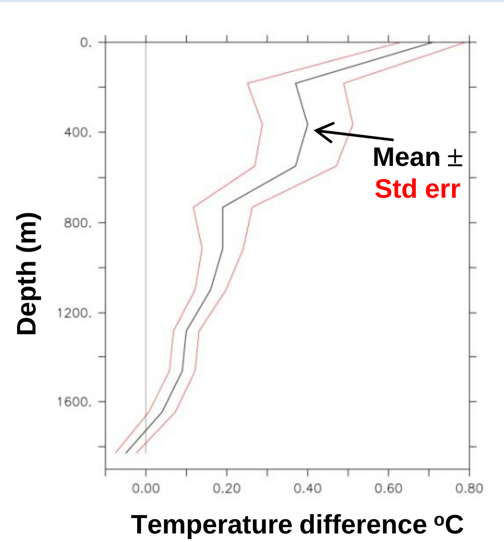
Since Argo measures temperature everywhere, we have 263 profiles of “Argo-minus-Challenger” temperature difference.

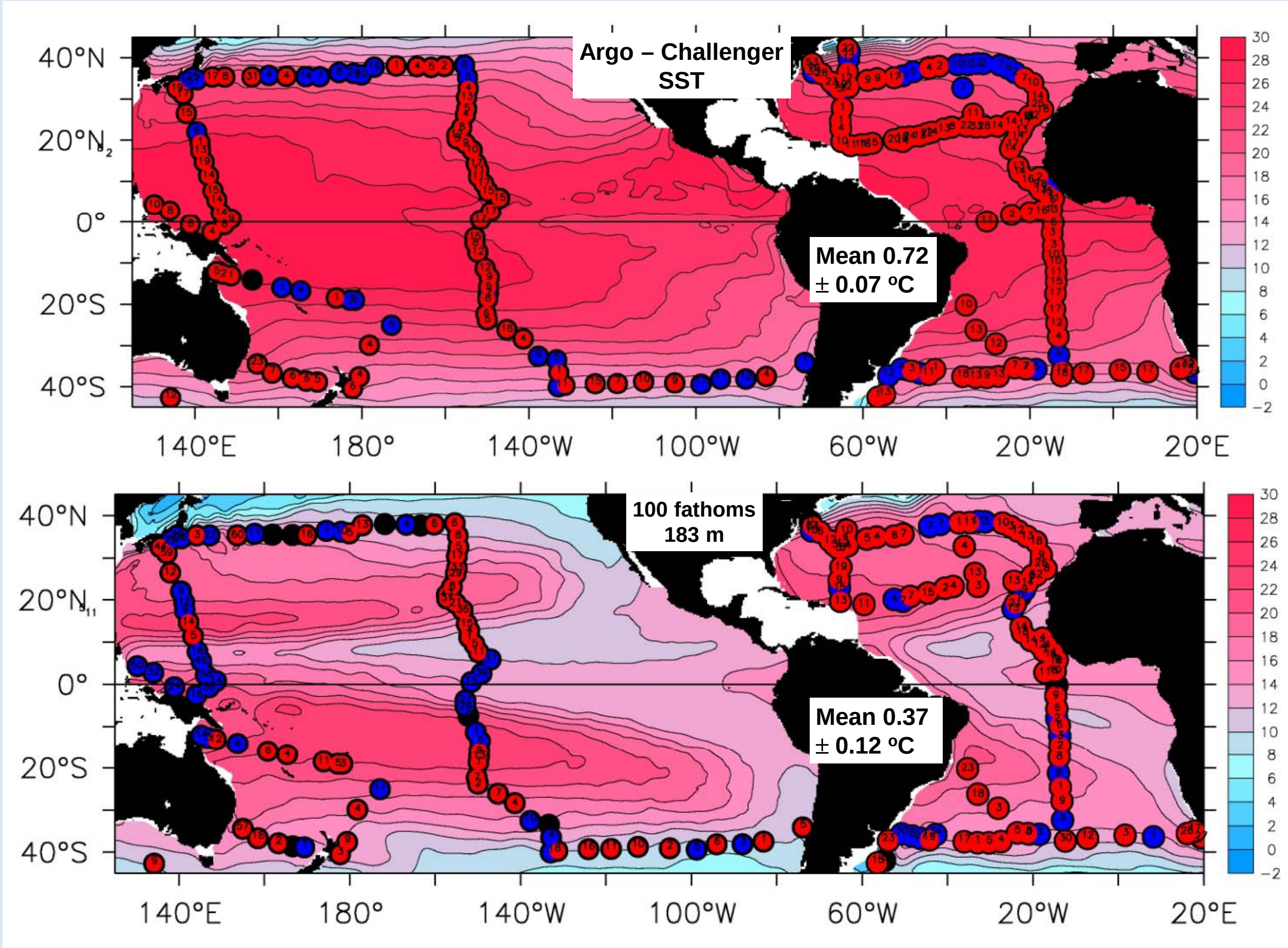
Challenger-to-Argo is the maximum time interval possible (> 130 years) for the instrumental record of (subsurface) ocean temperature change.



Min/max protected thermometer from HMS Challenger (Fig from Tait, 1881)

Centennial change: Argo and Challenger



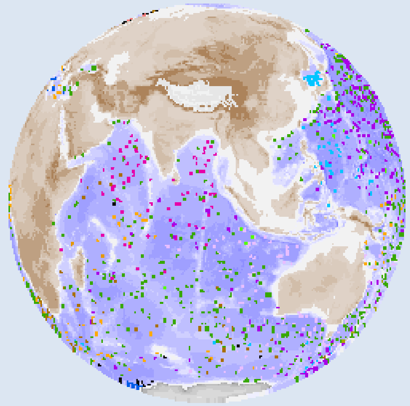


Right: ΔT at 0 and 100 fathoms (red(+)/blue(-), tenths ºC)

Left: Global mean ΔT vs depth. Uncertainties remain regarding depths and T versus pressure corrections of Challenger measurements.

Heat gain, 0-1000 m: 0.3 x 10^{22} J/yr (0.2 W/m²) Roemmich, Gould, and Gilson (in prep)

Summary: heat and freshwater signals in the global ocean



- Seasonal cycle :
  - Heat 20 W/m^2; good agreement with A-S flux
  - Dynamical signals (adiabatic) obscure thermodynamical ones
- Interannual (ENSO) variability:
  - Heat 2 W/m^2; ocean loses heat during El Nino
  - Freshwater 3 cm (missing Indonesia?); ocean fresher during El Nino
- Decadal/Centennial global change:
  - Heat 0.2 – 0.6 W/m^2 (0-700 m) depending on time period (ranging from 15 years to 135 years); Deep Argo needed to close heat and sea level budgets effectively.
  - Cannot accurately detect long-term storage in short records.
  - Increasing sea surface salinity contrast implies hydrological cycle enhanced
  - Freshwater trend difficult to observe.
- The ocean observing system should be global, including the deep ocean, marginal seas and high latitudes.