Argo:
Past Achievement,
Future Risks and Opportunities

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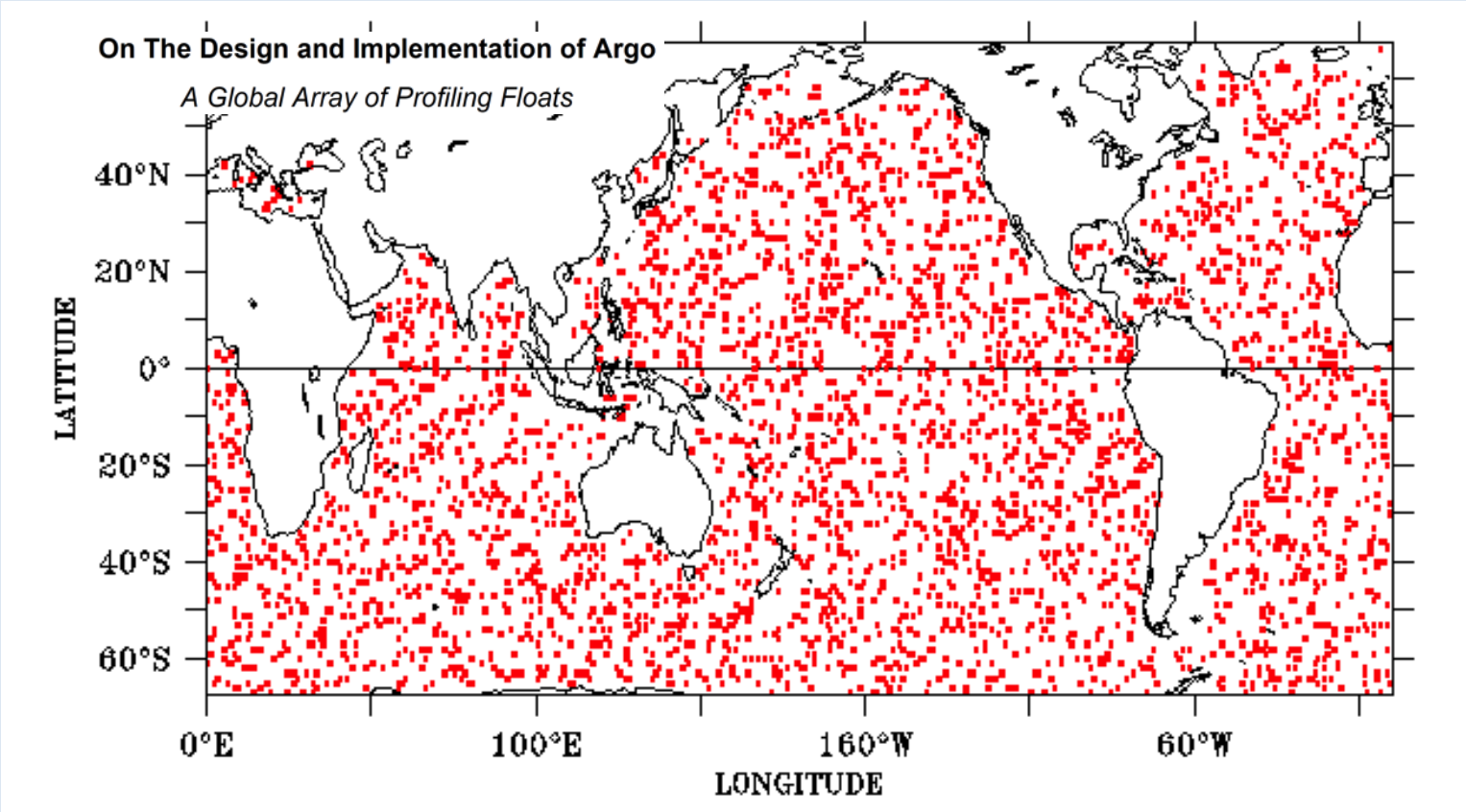
Outline

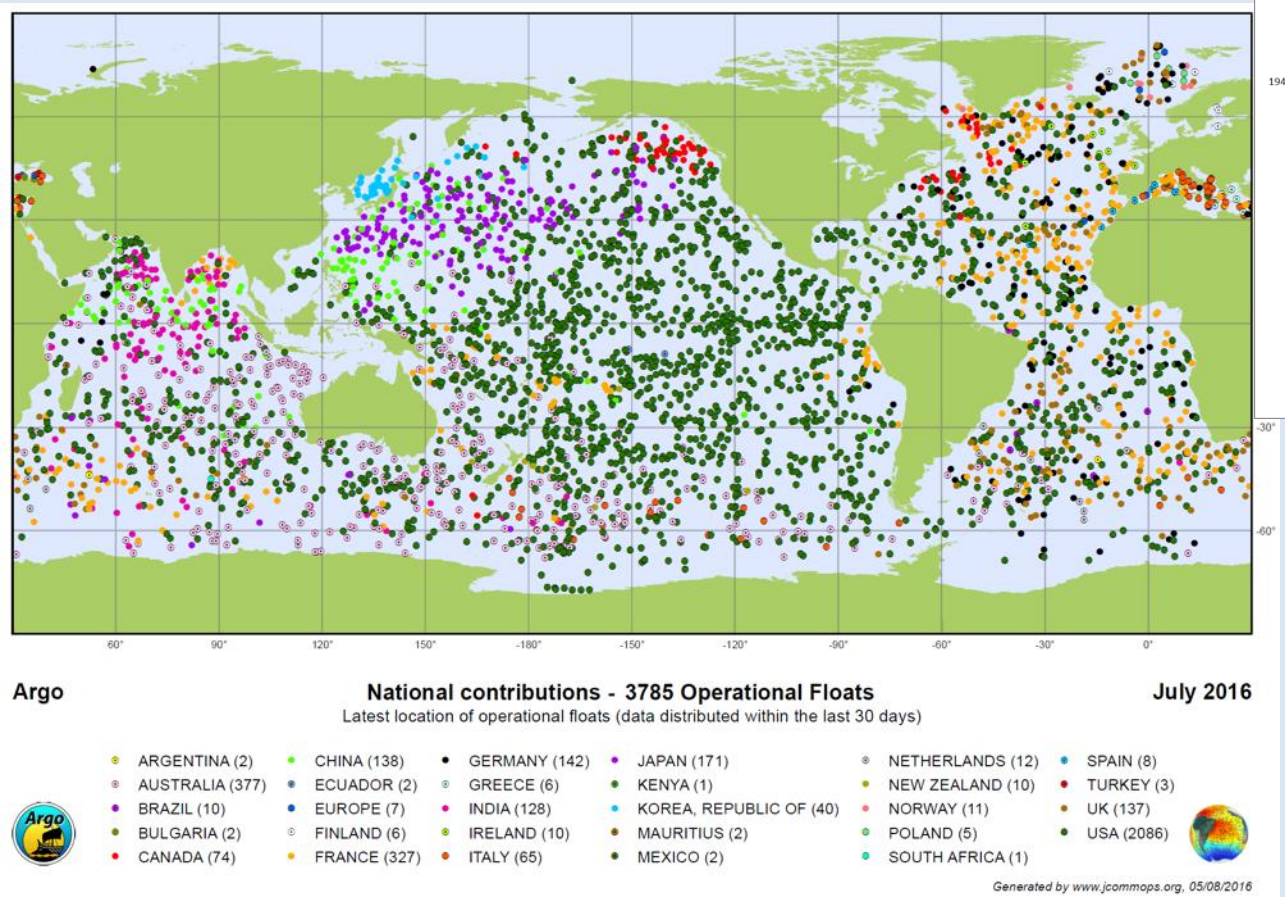
- From Argo the idea to Argo today
- The value of Argo
  - Global change research
  - Tropical Pacific variability (ENSO)
  - Absolute 1000-m reference velocity and shear
  - Basic research and education
  - Model assimilation/initialization
- Enhancements to Argo's global upper ocean mission
  - Marginal seas
  - Equatorial variability
  - Seasonal ice zones
  - Western boundary current regions
- New Argo missions
  - Deep Argo
  - Bio/Biogeochemical Argo
- Summary and challenges

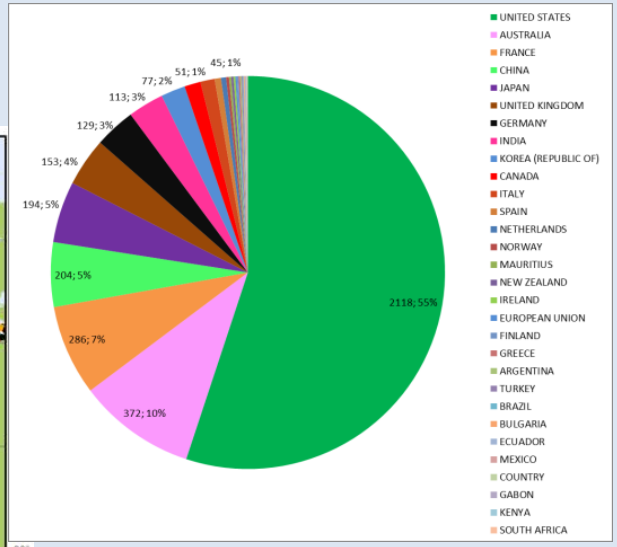
Argo in 1998
an idea



From the 1998 Argo Design document: See http://www.argo.ucsd.edu/argo-design.pdf

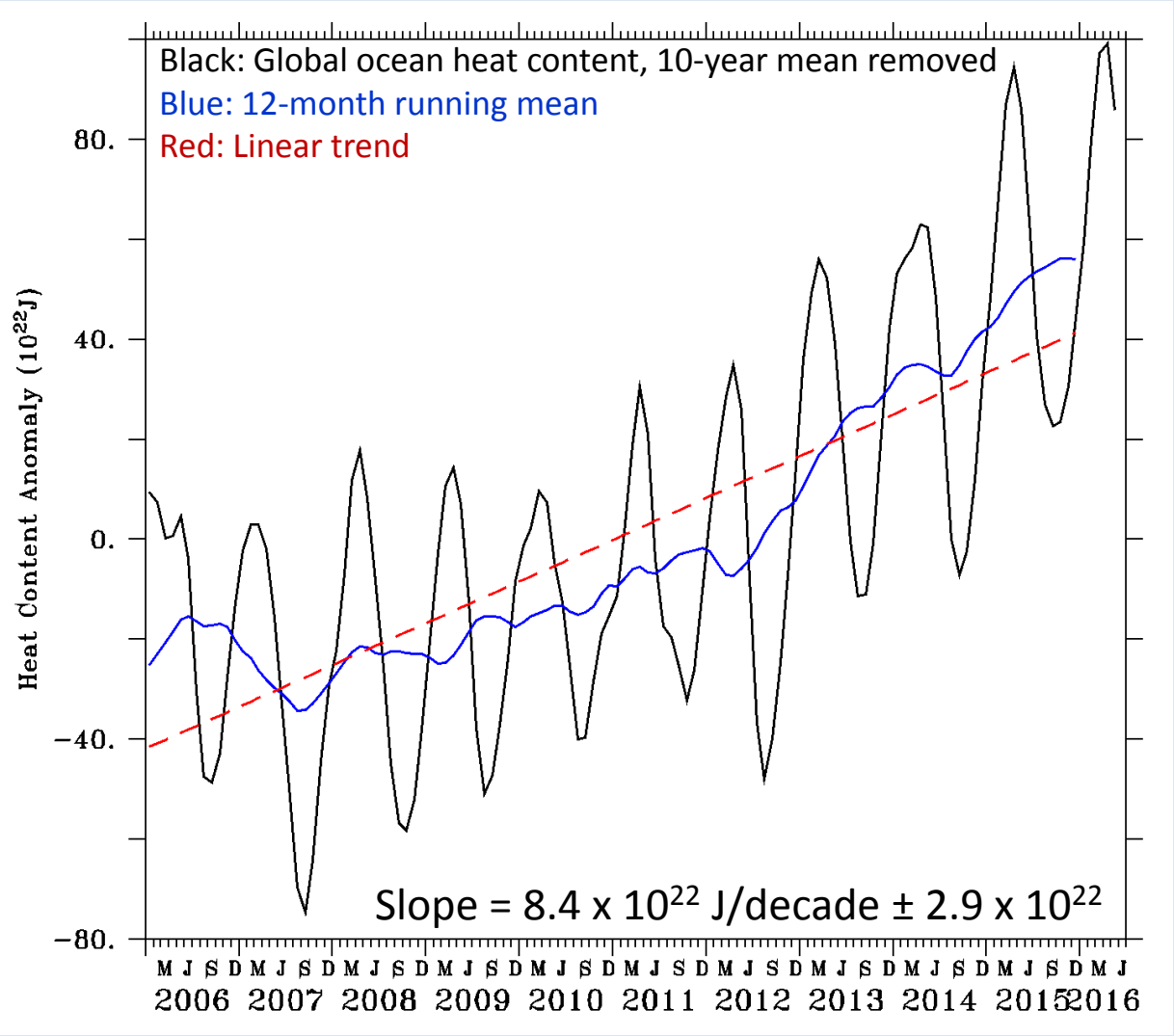
Argo in 2016





- Today's Argo array is remarkably similar to the original 1998 design, with contributions from 30 nations.
- Over 1.3 million T/S profiles and trajectories have been acquired, presently > 10,000 per month.
- Argo data quality is better than expected, thanks to SeaBird and the Argo Data Management Team.
- Ongoing improvements include completeness and consistency of trajectory data (Format 3.1).
- Ongoing conversion to Iridium communications results in longer float lifetime and reduced bio-fouling.

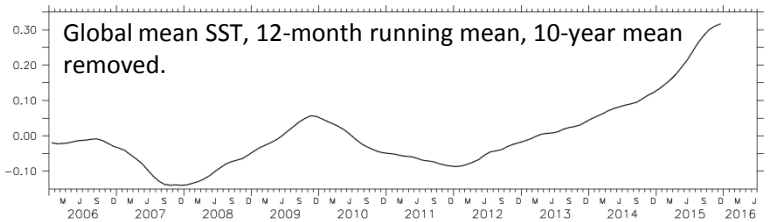
Argo and global ocean heat content



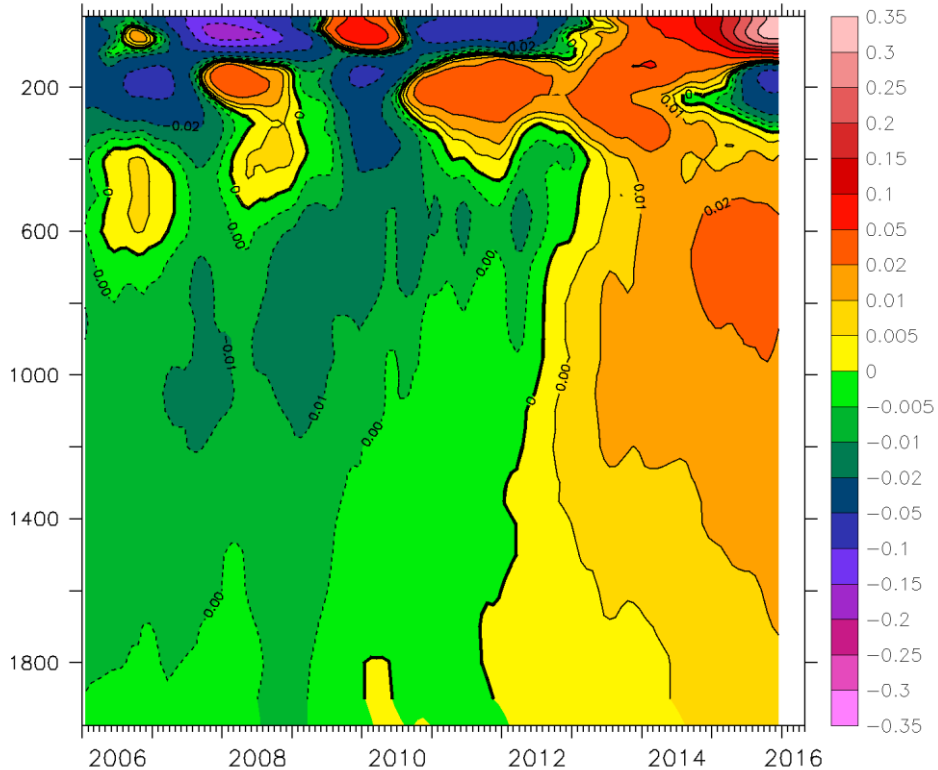
- Net heat gain in the climate system is dominated by the ocean (> 90%).
- Global ocean heat gain, 0 – 2000 m, is observed by Argo with unprecedented accuracy. 8.4 x 10^{22} J/decade ± 2.9 (95% confidence)

Figure: Updated from Wijffels et al, Nature Climate Change, 2016.

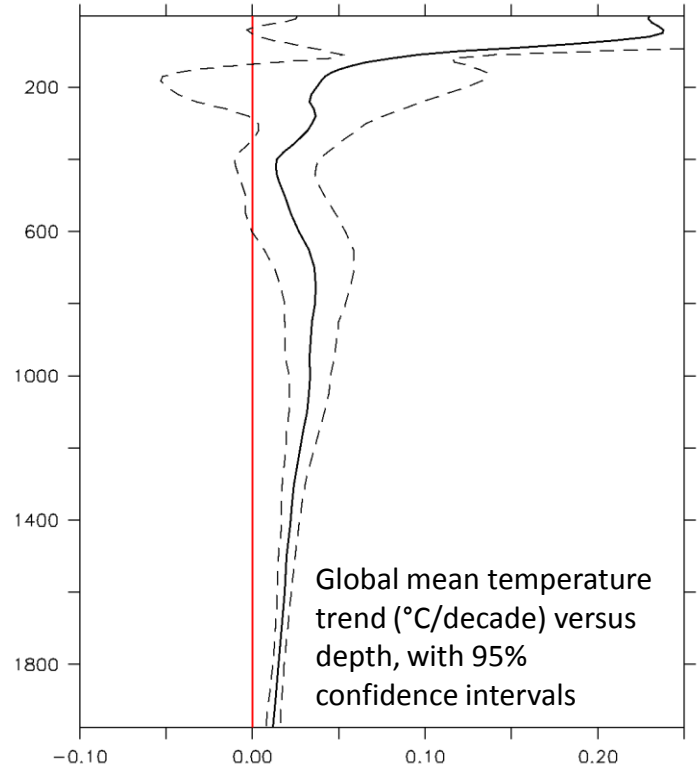
Argo and global ocean heat content



Global mean SST is dominated by ENSO, resulting in the appearance of a warming "hiatus" that is offset by variability between 100 and 400 m. Water column heat gain, 0 – 2000 m, shows unabated global warming.



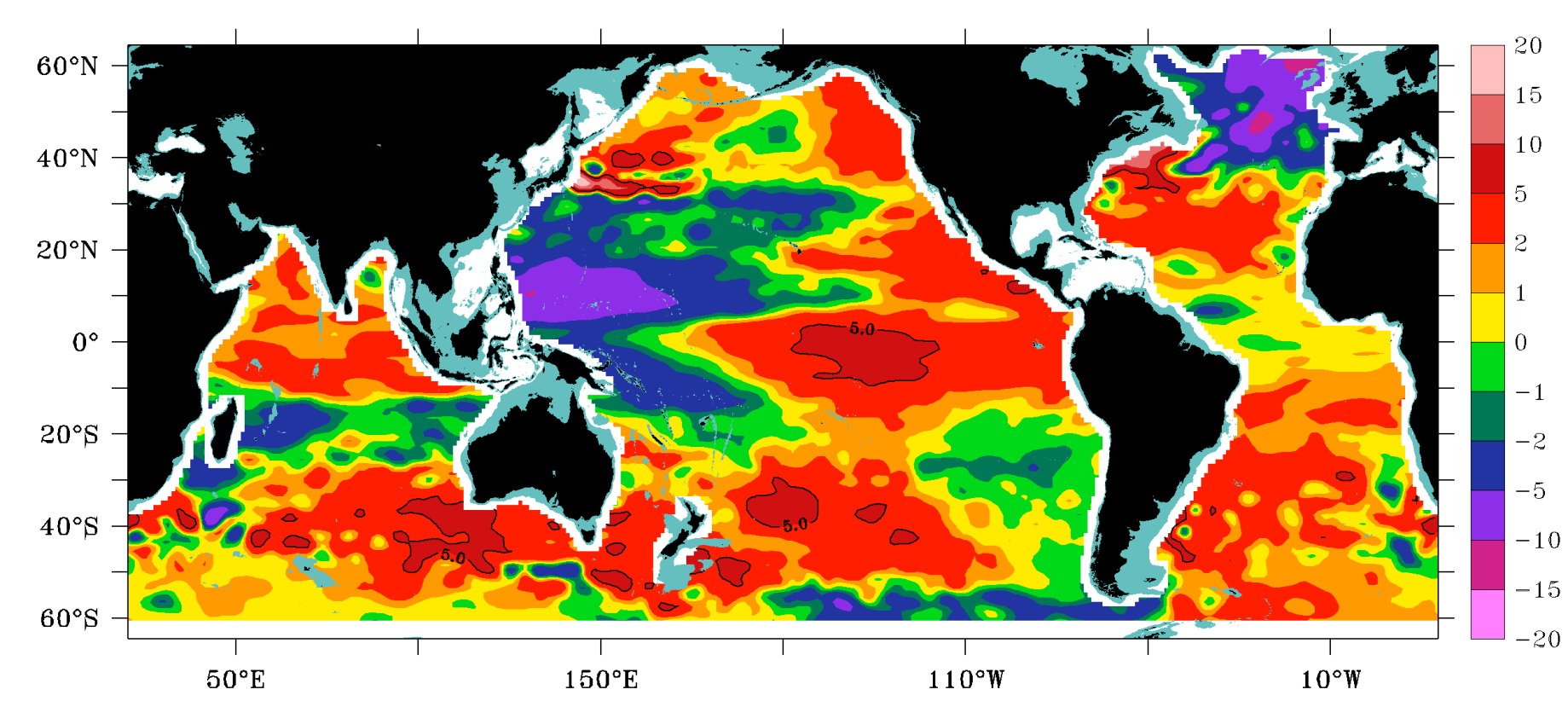
Global mean temperature anomaly vs. depth, 12-month running mean



Figures: Updated from Wijffels et al, Nature Climate Change, 2016.

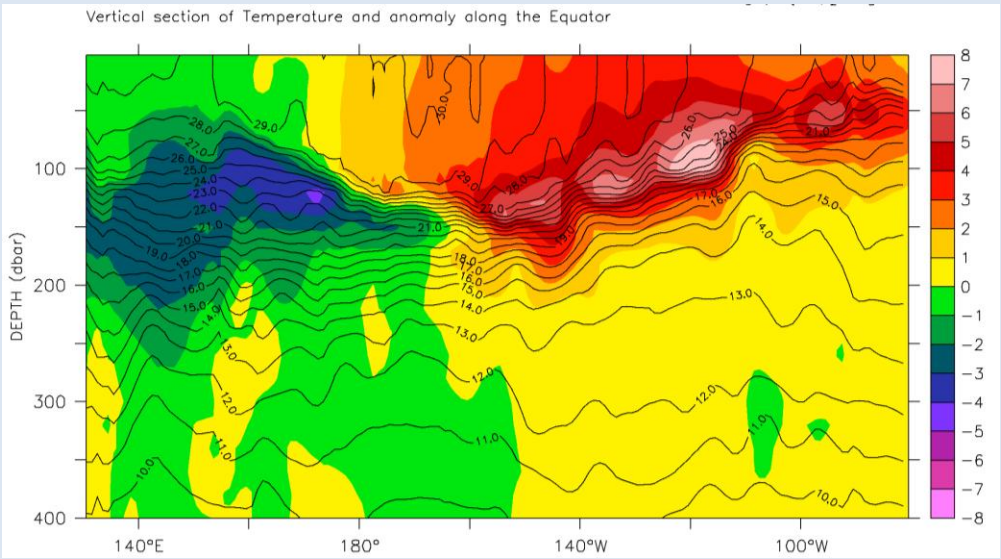
Argo and global ocean heat content

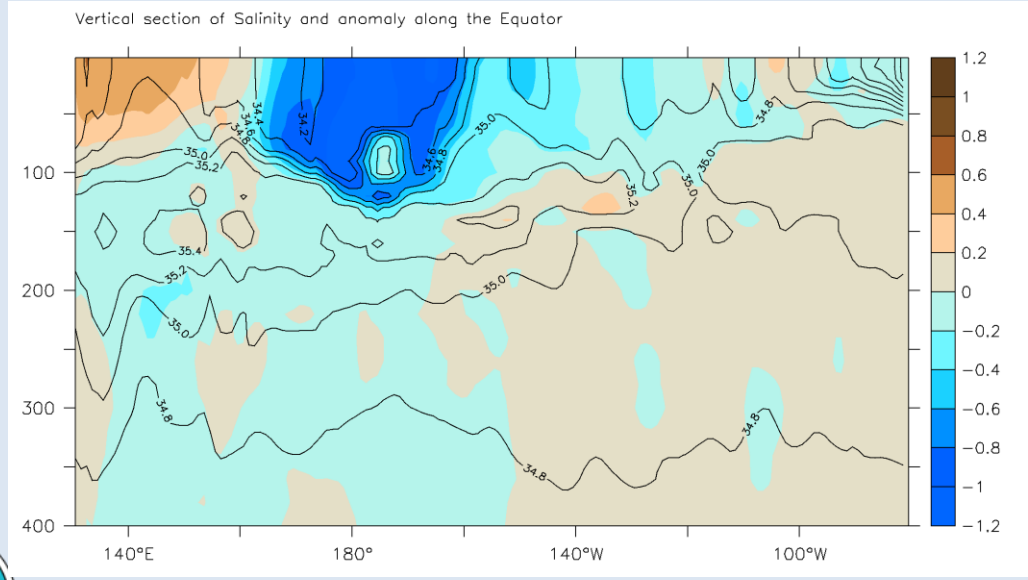
Heat gain (W/m^2), 0 – 2000 m, 2006 – 2016.



The spatial pattern of ocean heat gain is dominated by the Southern Hemisphere, with a broad maximum around 40°S due to warming in all three oceans.

Argo and tropical Pacific variability



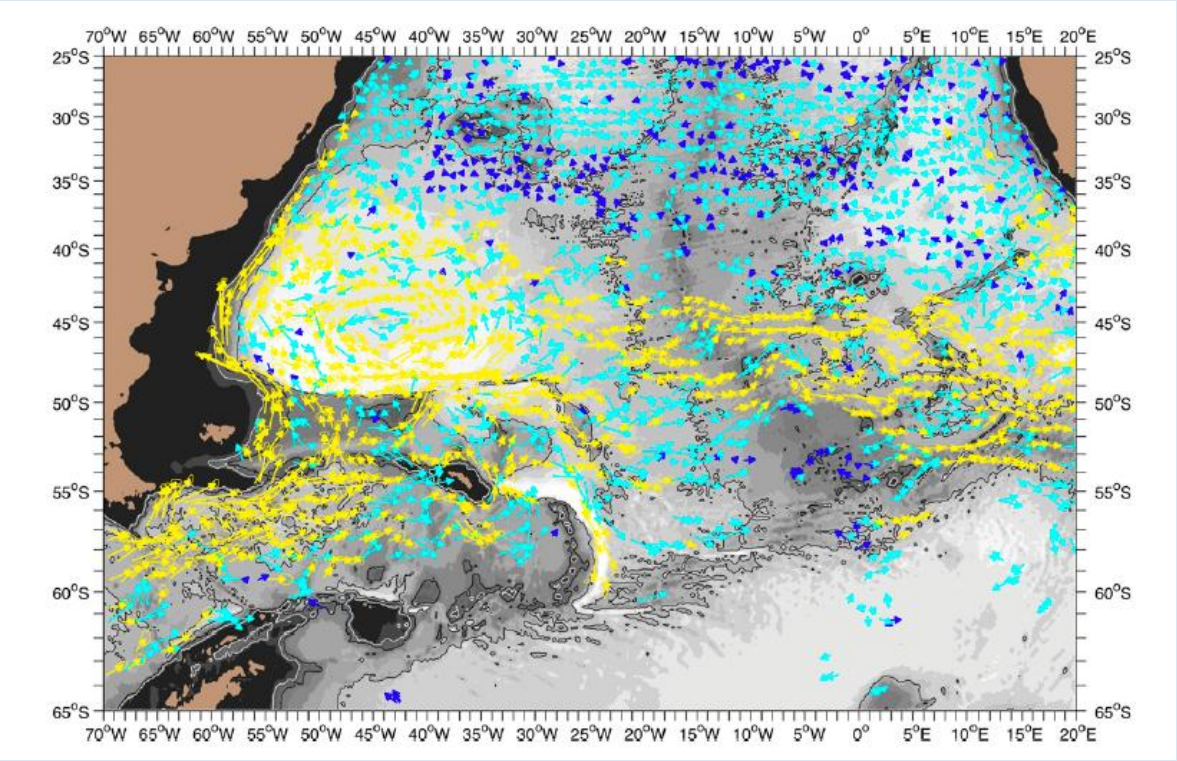


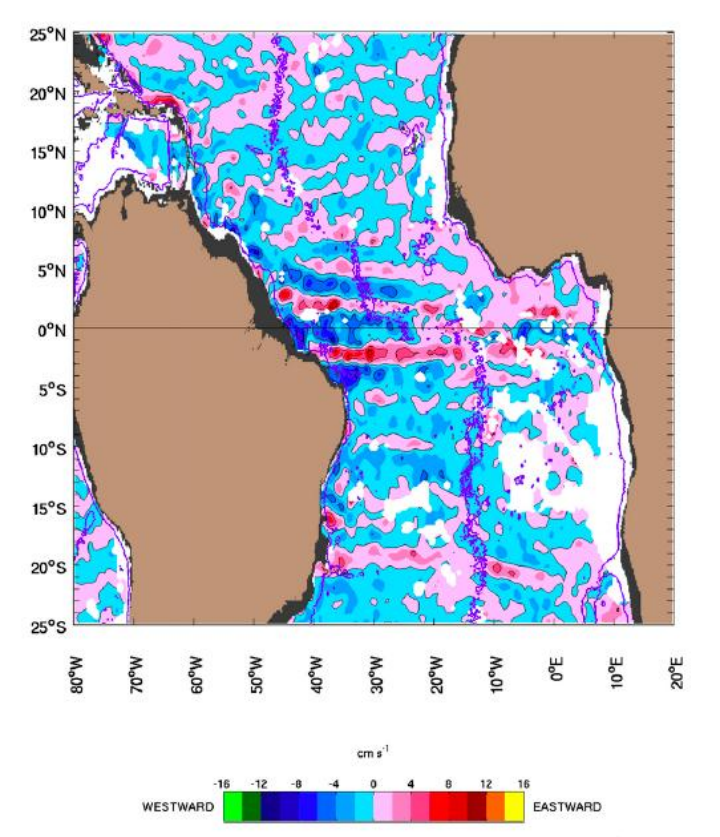
Vertical sections of temperature and temperature anomaly, salinity and salinity anomaly along the Pacific Equator, using Argo profiles from 13 – 23 October 2015.

Argo provides spatial resolution that was not previously possible, and measures salinity in addition to temperature.

The fresh pool at the dateline has anomalous salinity 0-100m equivalent to 2.5 m of freshwater (caused by anomalous P-E and zonal advection)

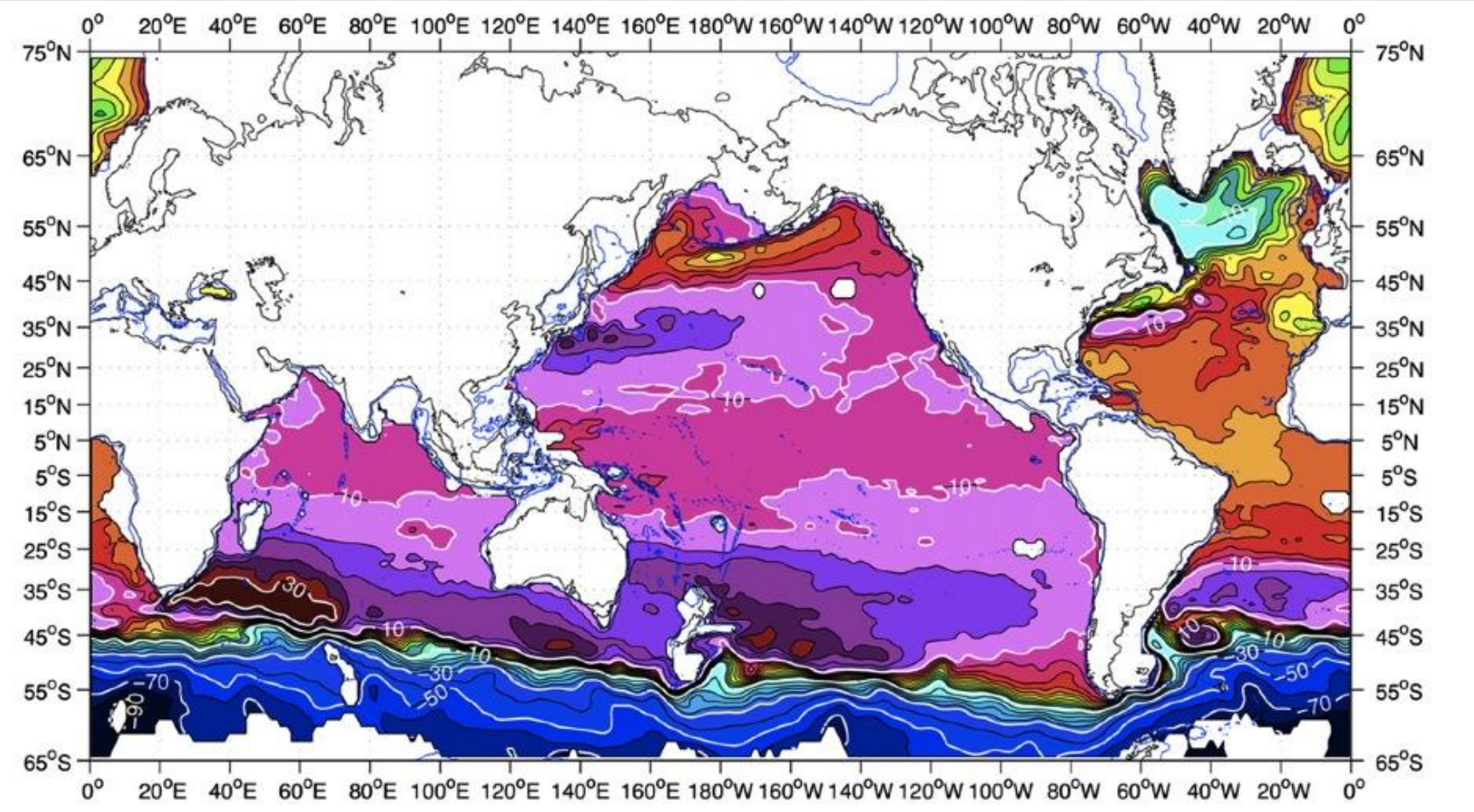
Argo trajectories give unprecedented details of ocean circulation at 1000m





Ollitrault and Colin De Verdiere, 2014

Argo-based 1000m dynamic topography

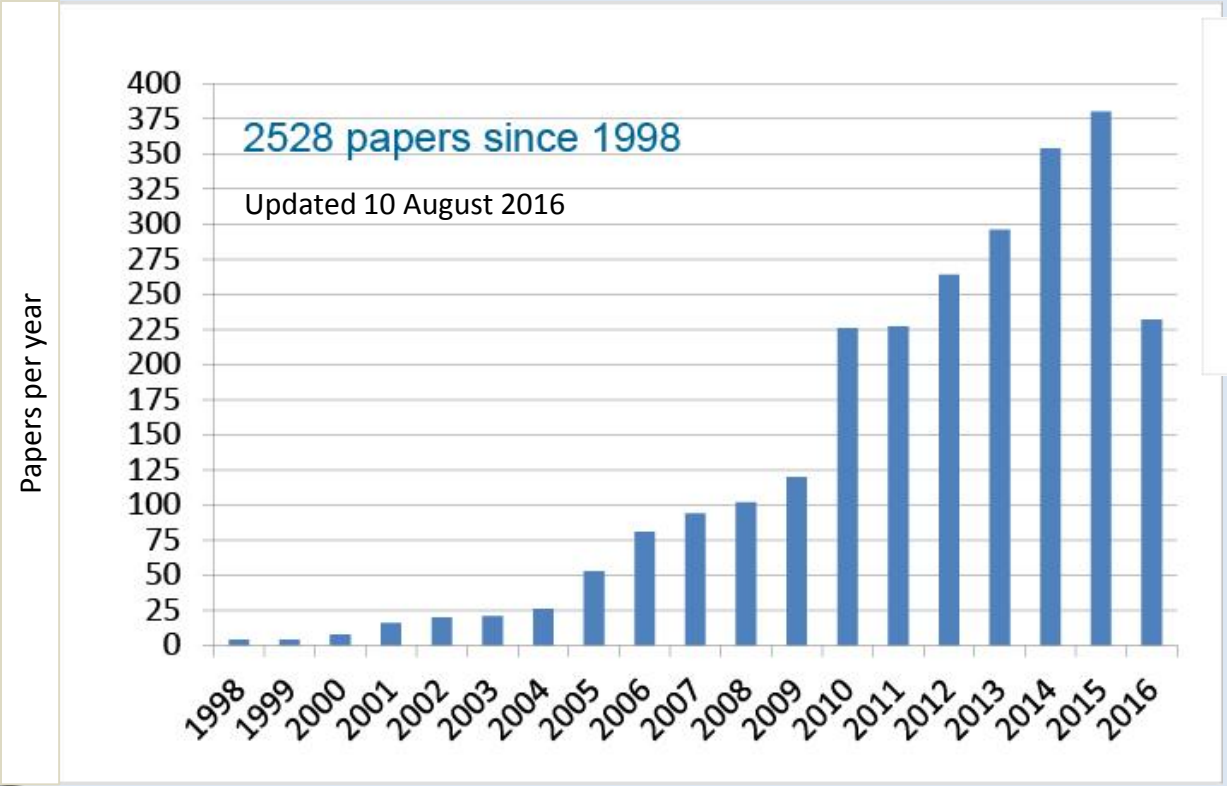


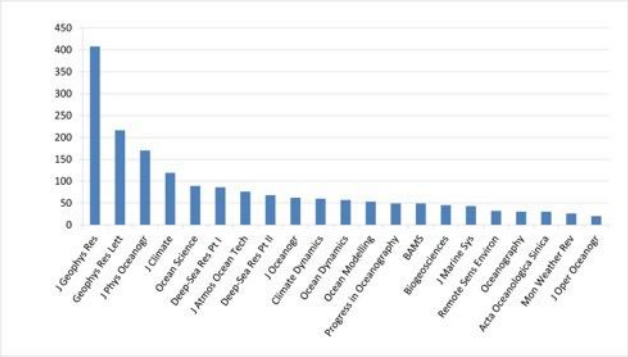
Ollitrault and Colin De Verdiere, 2014

Argo's value:

- Basic research
- Ocean data assimilation modeling/forecasting
- Education

Argo bibliography: papers that explicitly mention use of Argo data
http://www.argo.ucsd.edu/Bibliography.html

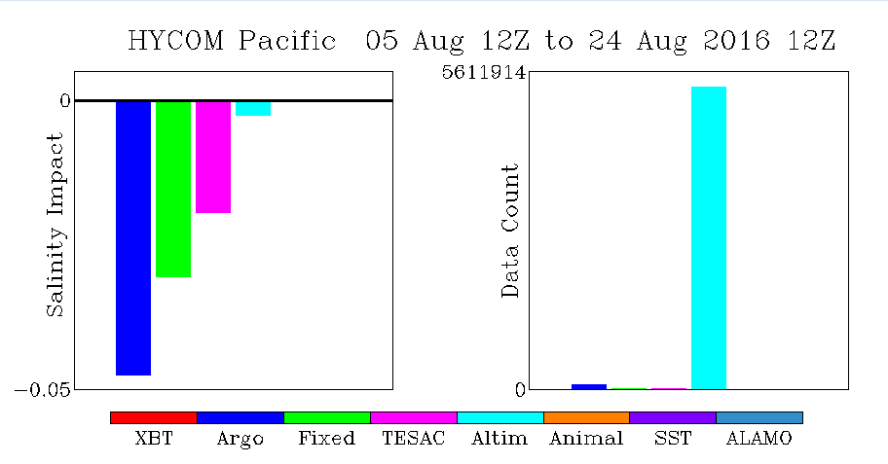


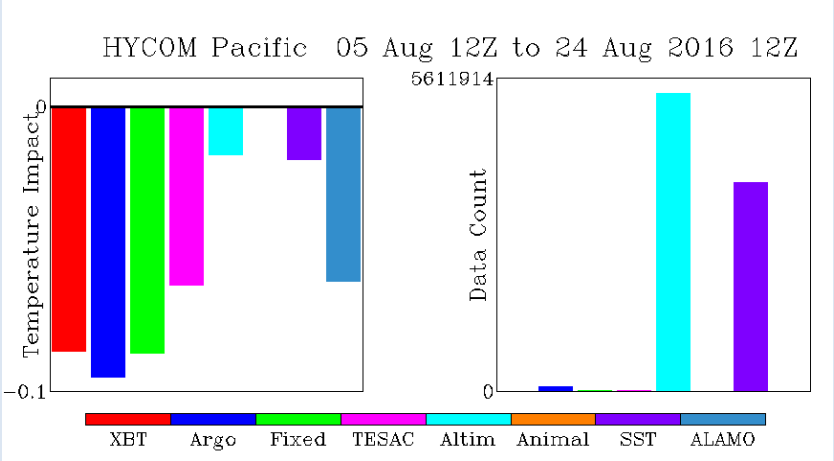


Argo is transforming the field of large-scale oceanography.

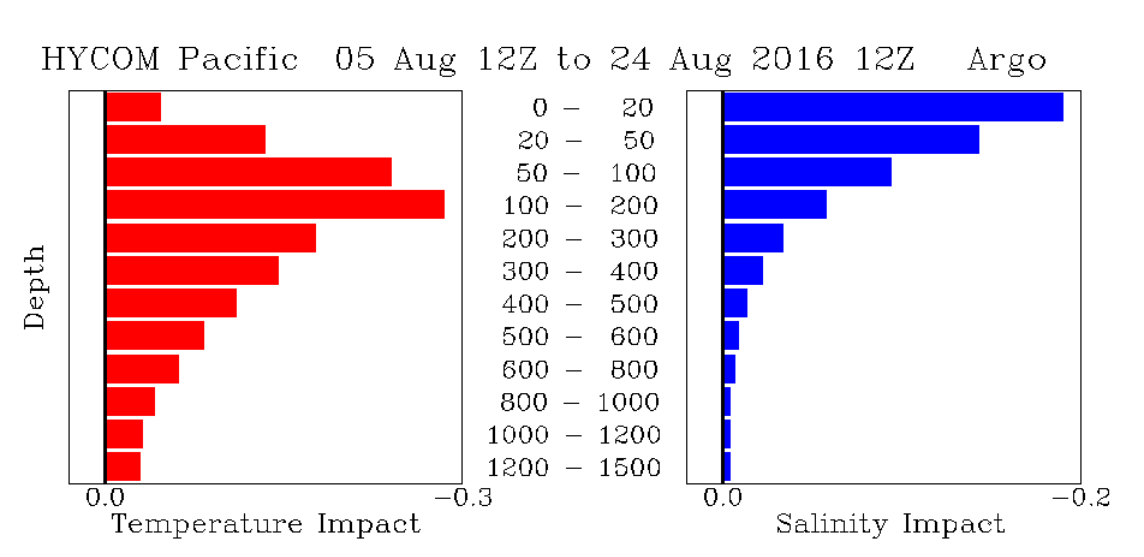
Ocean data assimilation modeling/forecasting

Argo profiles are used by all global ocean data assimilation systems



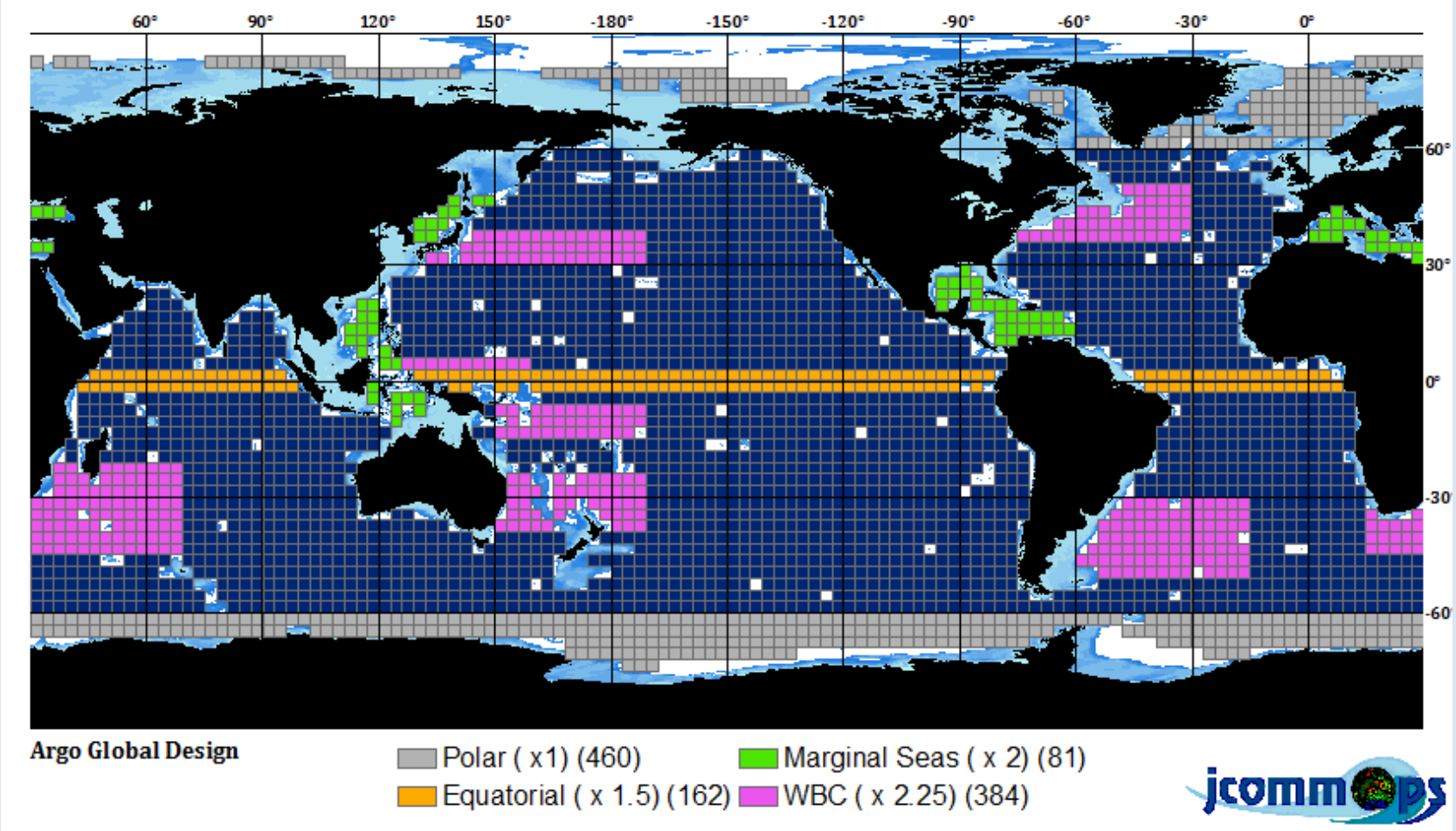


As measured by impact per observation (lowering of 48-hour forecast error), the global HYCOM model run by the US Navy shows Argo to have the strongest impact for T and S



T and S impact (negative number indicates lower forecast error) versus depth shows that Argo provides valuable information at all depths. Figures courtesy of J. Cummings

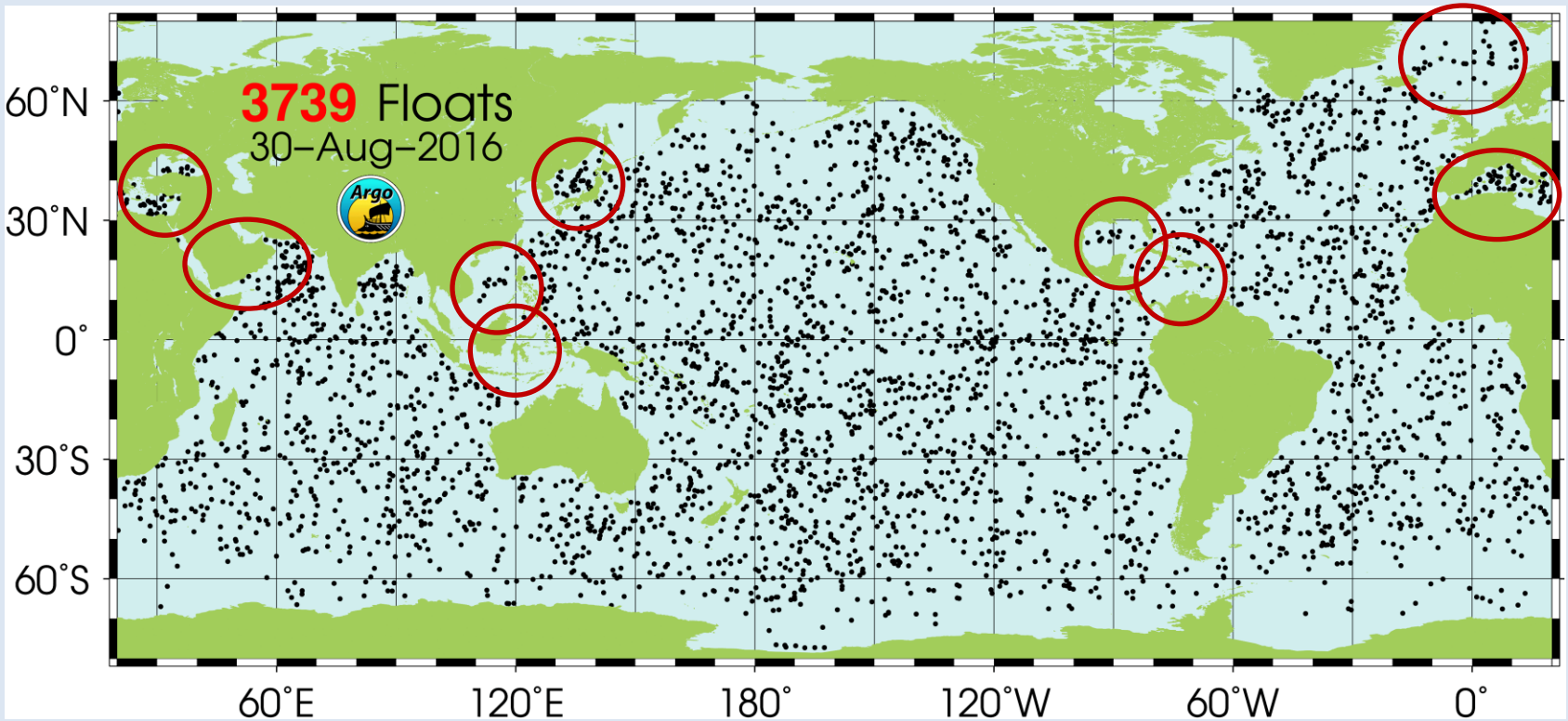
Going forward: A Global Argo Design Towards spatial completeness



- Same mission – tracking the slow manifold - but more spatially complete and better signal to noise
- Double sampling in WBCs and equatorial regions
- Marginal Seas: enhanced sampling - determined by regional partnerships
- Seasonal Ice zone: normal sampling [Fast-ice zone requires different technology]

Marginal Seas

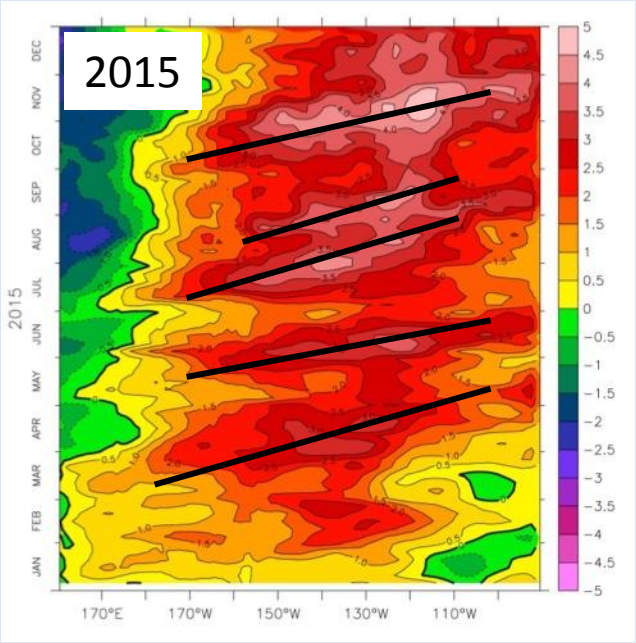
- Target density 2 x global design = 2 floats every 3° x 3°
- Feasible due to high bandwidth communications leading to less grounding
- Demand for biogeochemistry and optics is high
- Implementation can only happen within strong functioning GOOS regional alliances which are able to overcome EEZ sensitivities

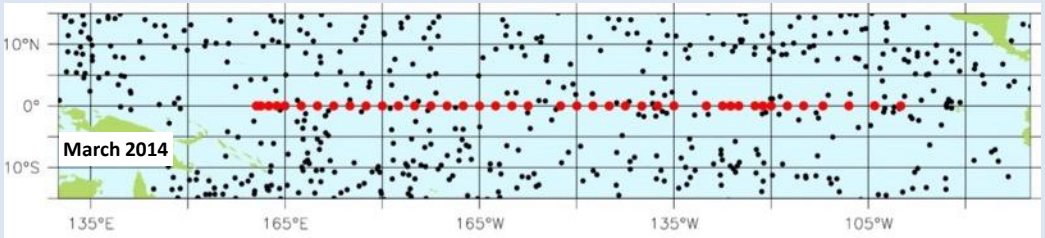


About 200 active floats are in marginal seas

Equatorial Enhancement

- Improved spatial resolution of intraseasonal to interannual variability – critical for observation of ENSO/monsoon/IOD
- A successful Argo pilot deployment was carried out following the decline of TAO in 2013. 41 faster cycling (7-days) floats were deployed by US Argo along the Pacific equator in early 2014 (below right). These are providing an unprecedented view of intraseasonal (Kelvin wave) propagation (below left).
- **GOOS-OOPC TPOS 2020** will deliver a design recommendation



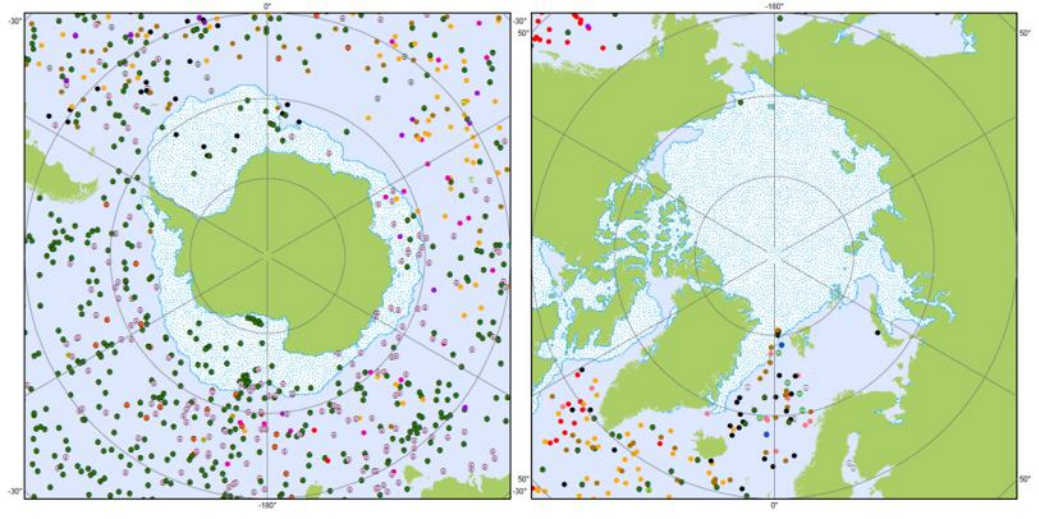


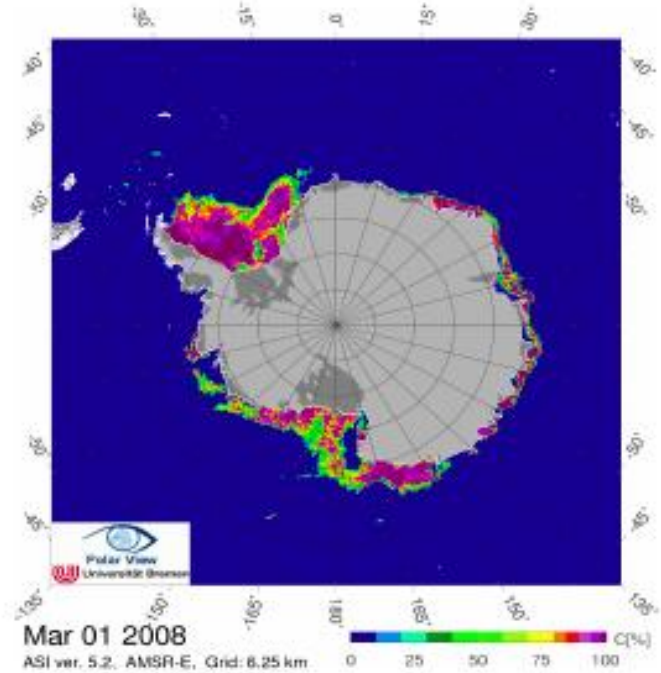
Location of 41 Argo floats (red) deployed in early 2014

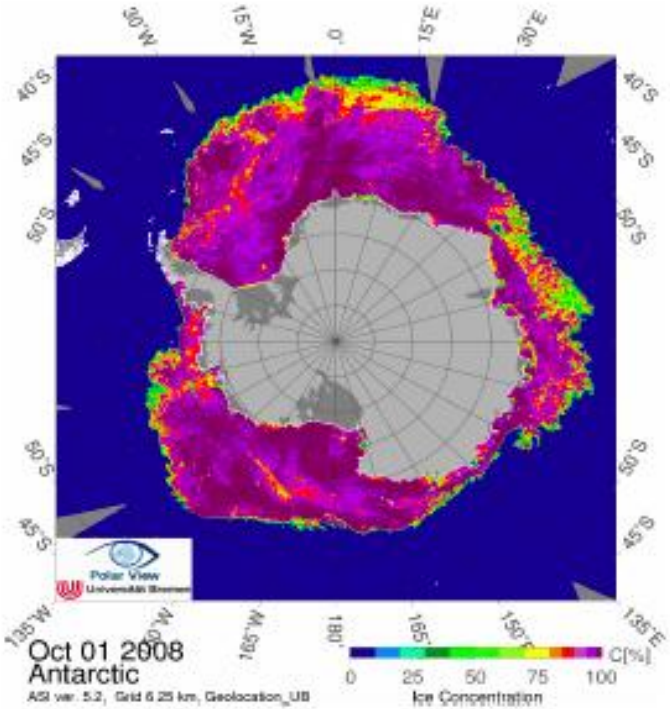
Hovmuller diagram of 0-200m vertically-averaged temperature anomaly in 2015, showing the sequence of Equatorial Kelvin waves propagating eastward in the thermocline through the year.

Seasonal Sea-Ice Zone

- A blind spot in the GOOS – needs to be urgently addressed due to links between ocean warming – ice sheet loss – future sea level rise.
- Arctic- 78 active floats north of 60°N.
- Antarctic- 164 active floats south of 60°S. Deployment opportunities are limiting.
- Floats use an “Ice-avoiding” algorithm to remain below ice during winter.



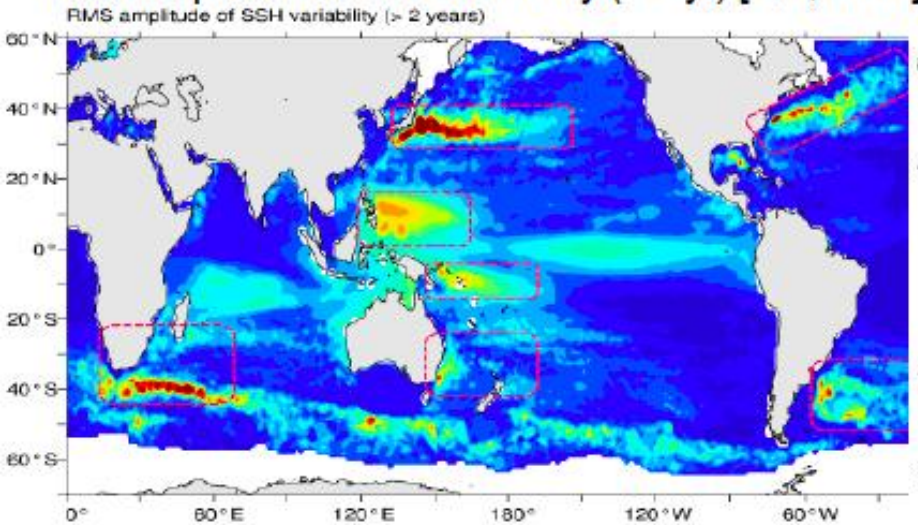




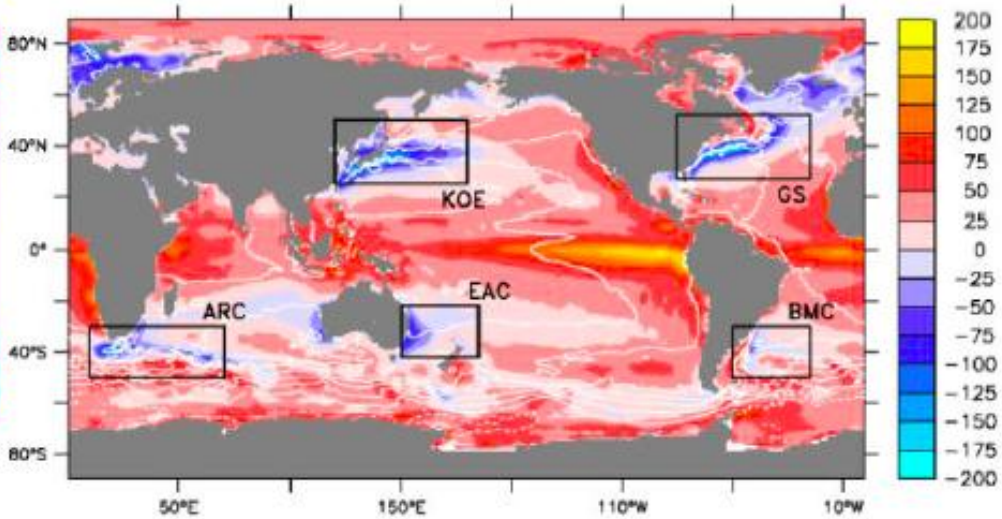
Western Boundary Current Enhancements

- High eddy activity drives a lower signal/noise ratio for Argo's target space/time scales. Enhanced resolution needed.
- Due to process studies and regional interest, the Kuroshio/Oyashio system has been a pilot of this coverage enhancement.
- Further guidance will come from the **OOPC Western Boundary Current project.**

RSM amplitude of SSH variability (> 2 yr) [Qiu, 2012]



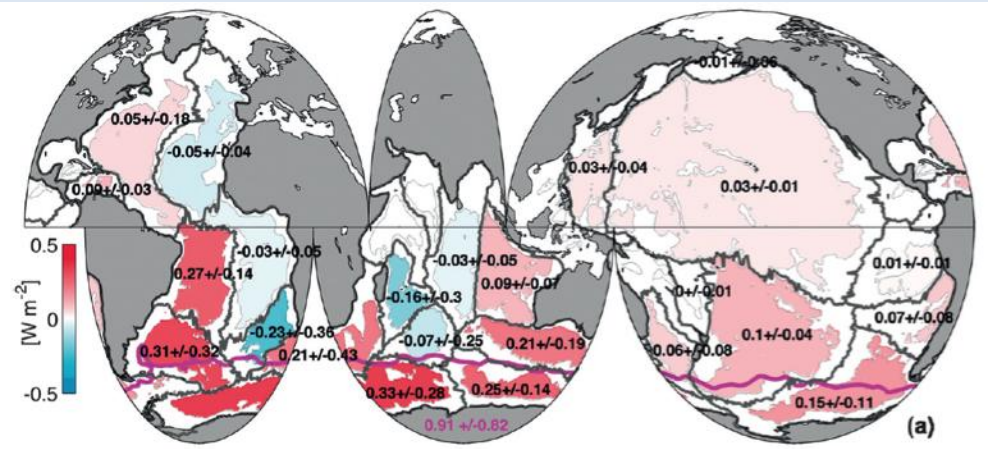
Mean net surface heat flux (Wm^{-2}) [Cronin et al, 2010]



New Missions?
Deep Argo

Why?

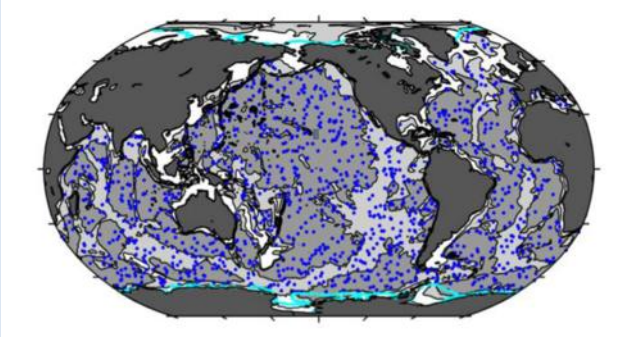
- Sparse repeat ship data show that the ocean below Argo is warming consistently, particularly in the Southern Hemisphere.
- This matters for sea level rise and the Earth's energy budget.
- Model initialization/assimilation requires data below 2000 m.



Bottom Water warming from 1990's to 2000's
Purkey and Johnson (2010)

Report of the Deep Argo Implementation Workshop
http://www.argo.ucsd.edu/DAIW1report.pdf

Deep Argo

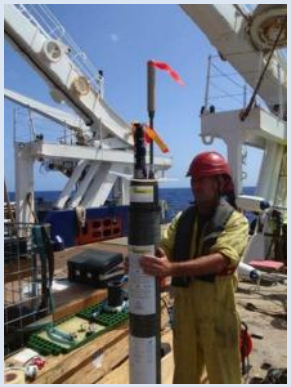


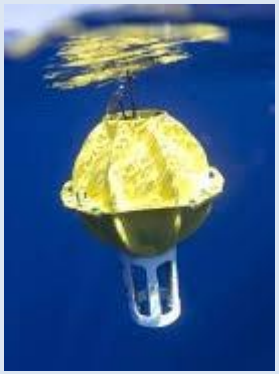
Strawplan for 1228 Deep Argo floats at nominal 5° x 5° spacing (Johnson et al, JAOT, 2015) over the global ocean where depth exceeds 2000 m.

Status

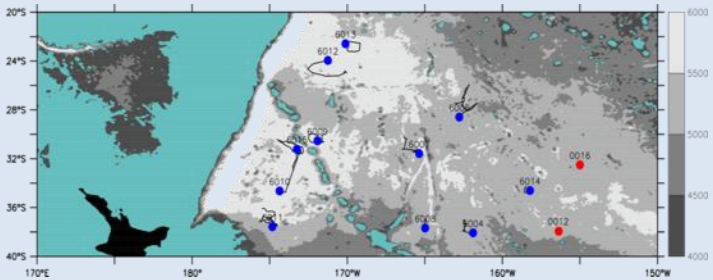
- Four Deep Argo float models have been developed and tested.
- A new CTD sensor (SBE-61) is under parallel development with improved stability and accuracy.
- A Deep Argo Workshop was held to develop a science and implementation prospectus, global design, and costing - to feed into the **GOOS Deep Ocean Observing Strategy**
- 3 coordinated regional Deep Argo pilots are being deployed in the N. Atlantic, S. Pacific, and Southern Ocean

Deep NINJA (left) and Deep PROVOR (below) 4000 m floats.





Deep APEX (below left) and Deep SOLO (below center) 6000 m floats. Location of 13 active Deep SOLO (blue) and Deep APEX (red) floats (below right) in the SW Pacific Basin



New Missions: Bio/BGC-Argo

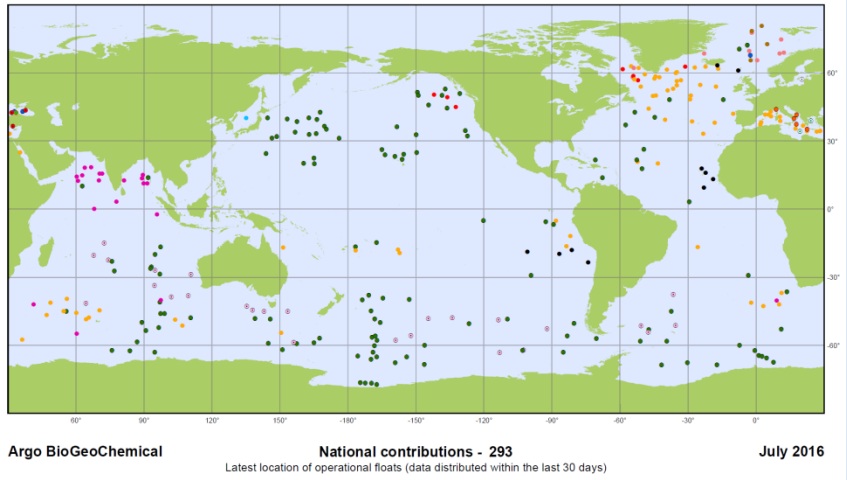
Why

- Understand the fundamental bio-geochemical cycling in the oceans, and thus the foundation of biological productivity patterns and carbon uptake
- To track any long term trends – e.g there is already evidence of significant ocean oxygen changes

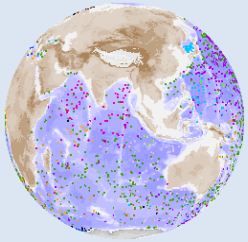
Status

- > 200 floats already carry oxygen – QC and sensor stability work is progressing well
- Nitrate, pH (acidity), and bio-optical sensors have been developed and now deployed on a subset of Argo floats
- 2 major open ocean arrays (Atlantic and Southern Ocean) are rolling out and in one marginal sea (Med Sea)
- Major progress on data handling and QC – partnership with the Argo Data System
- Strong links to **GOSHIP/IOCCP/GOOS.**

Location of 293 active floats carrying one or more Bio-Geochemical sensors.



Summary and Challenges



GOOD NEWS

- The Argo array is currently in a **healthy** state.
- Many **enhancements** and extensions are gaining momentum, developing as part of the integrated GOOS, following the FOO pathway
- Research and operational uptake continues to grow.
- Deep Argo will provide global full ocean-depth coverage.

BAD NEWS

- Several major contributors (US, Australia, Japan) will see significant **declines** in deployments due to flat (below inflation) or decreased funding. Growth by Europe and China programs will not likely compensate for this.
- We have coped in the past by increasing float lifetimes but this well has probably run dry.
- Thus there is a real potential we will see **degradation of array densities** in the next few years.