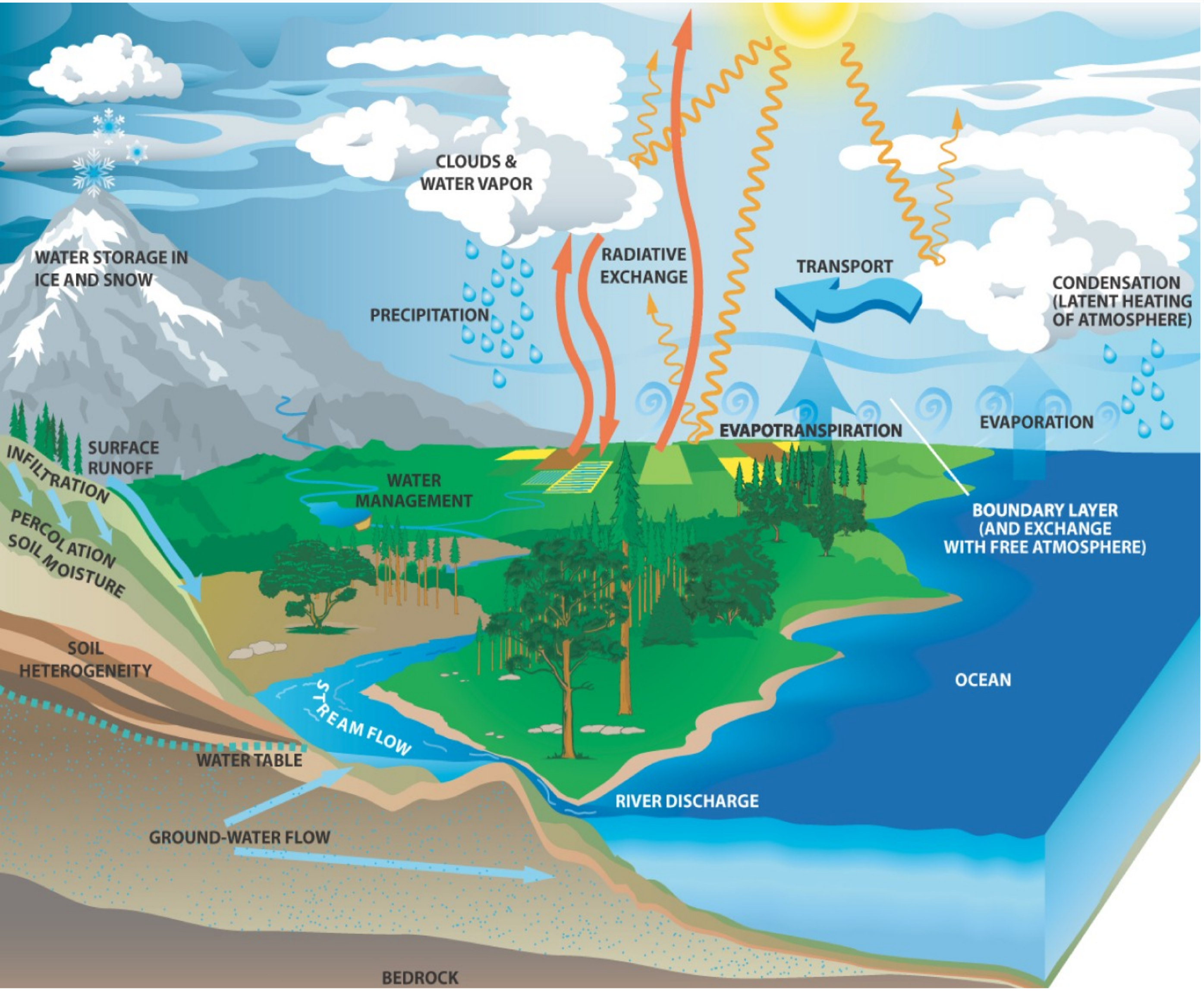
Need for sustained and improved ocean observations and synthesis for water cycle studies

Subra Bulusu
Satellite Oceanography Laboratory
Department of Earth and Ocean Sciences
University of South Carolina
sbulusu@geol.sc.edu

Acknowledgements:
Dean Roemmich, Raymond Schmitt, Thierry Delcroix

Global Water Cycle



More than three-fourths of the global water cycle consists of the annual rainfall and evaporation fresh water exchange between the ocean and the atmosphere.

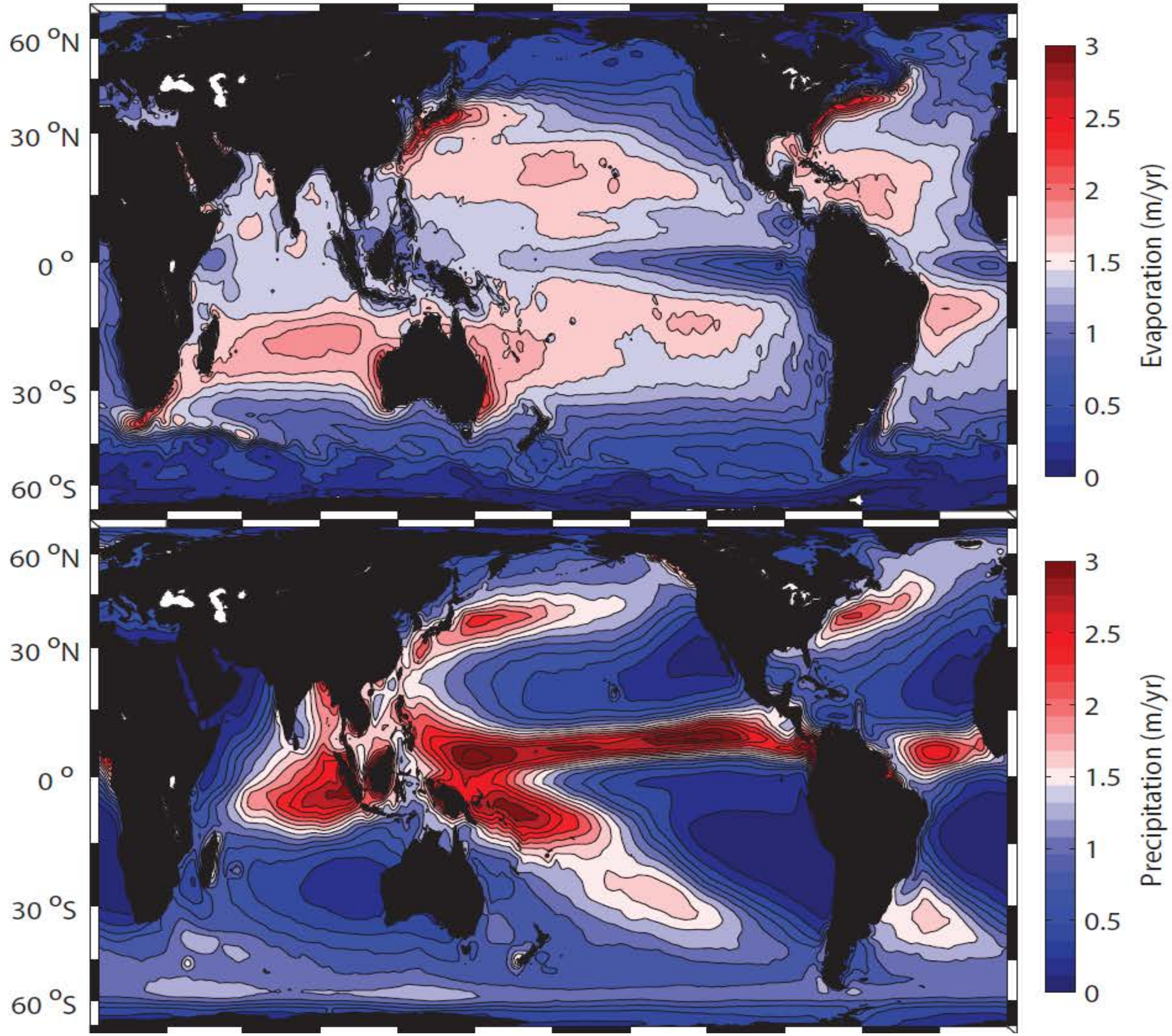
No climate issue will have as much impact on society as changes in global water cycle

Evaporation and Precipitation

Net E =13 Sv

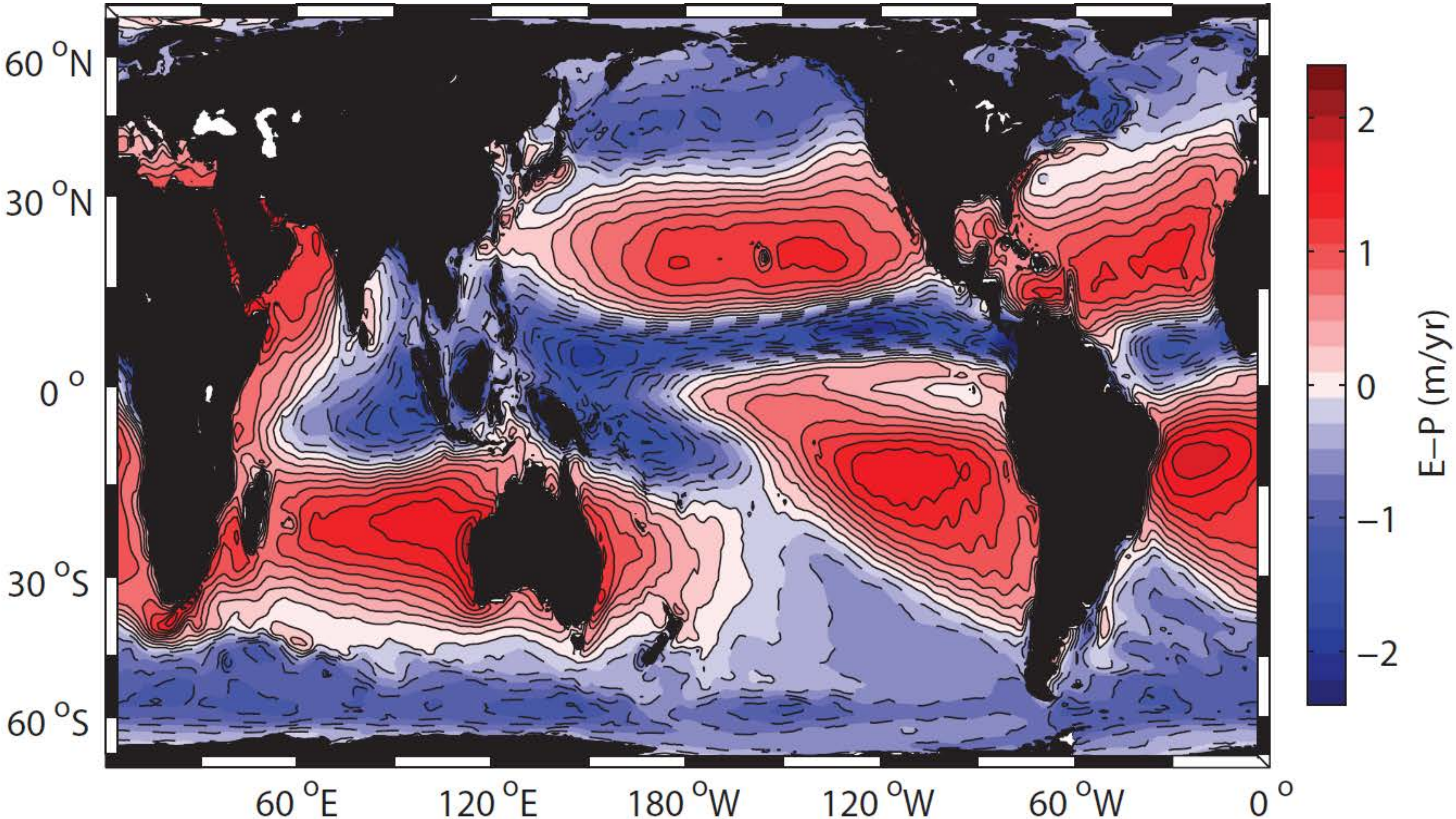
Net P = 12.2 Sv

Net River = 1.25 Sv



Schanze, Schmitt & Yu, 2010 J. Mar. Res.

Net Evaporation - Precipitation



Schanze, Schmitt & Yu, 2010 J. Mar. Res.

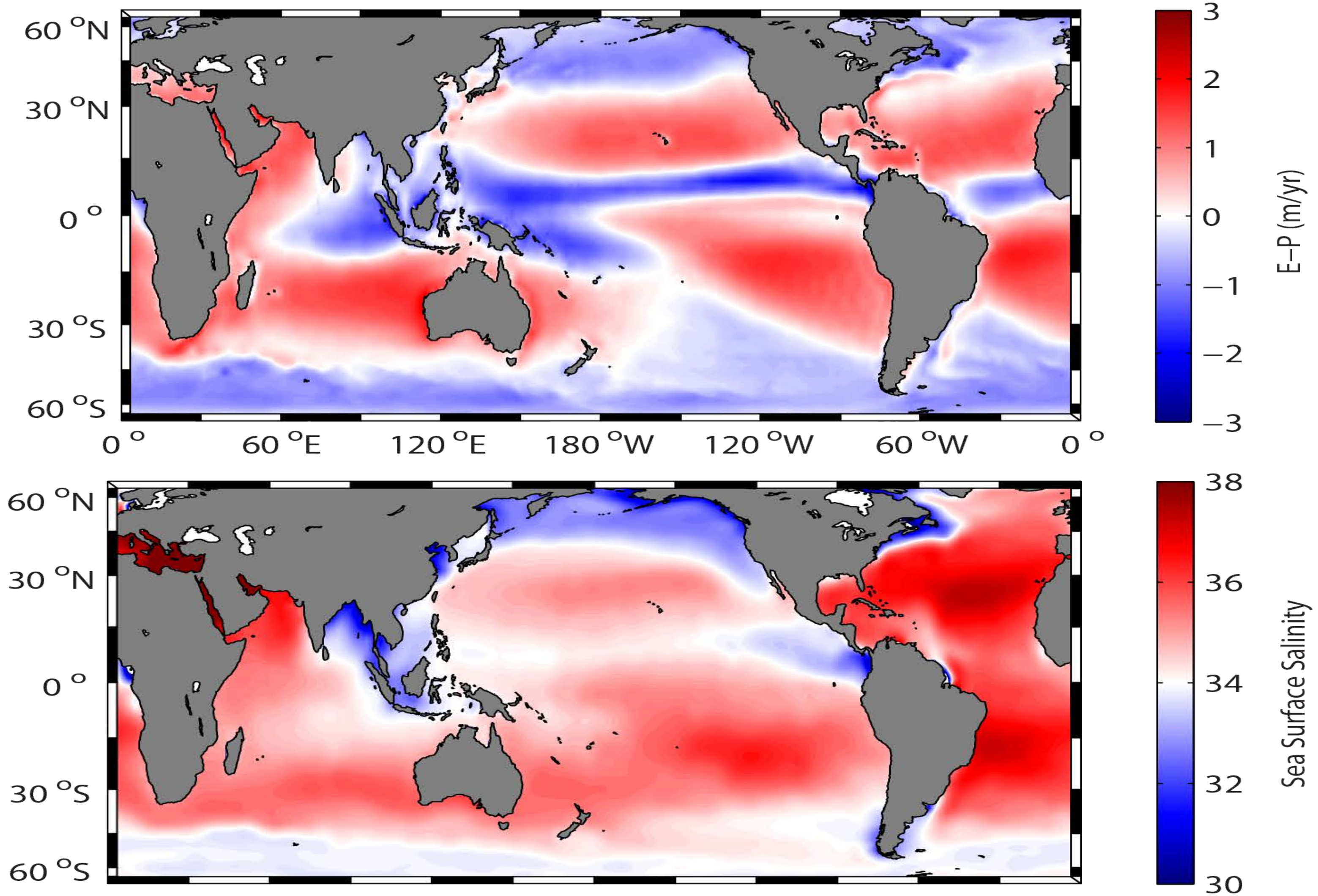
Oceanic water budgets

P+R \ E	OAFlux	NCEP-1	NCEP-2	ERA-40	ERA-Int	CORE.2	MERRA
GPCP	+0.46	-0.41	-2.24	-1.00	-1.15	-0.69	+0.22
NCEP-1	+1.05	+0.18	-1.65	-0.45	-0.54	-0.11	+0.81
NCEP-2	+3.28	+2.42	+0.59	+1.65	+1.70	+2.13	+3.05
ERA-40	+3.87	+3.04	+1.30	+2.41	+2.70	+2.70	+3.61
CMAP	+0.90	+0.03	-1.80	-0.53	-0.71	-0.26	+0.66
CORE.2	+1.01	+0.15	-1.69	-0.45	-0.60	-0.14	+0.78
MERRA	+0.47	-0.40	-2.23	-1.30	-1.14	-0.69	+0.23

Global annual Oceanic water budget (P+R)-E balances between precipitation products (rows) and evaporation products (columns) in SV. Positive imbalances indicate an apparent excess input of fresh water to the ocean, negative valuaes indicate net water loss. Fluxes are averaged between 1987-2006. The combined river discharge (~1.25 SV) from Dai and Trenberth (2002) and Dai et al., (2009) has been added to the precipitation products.

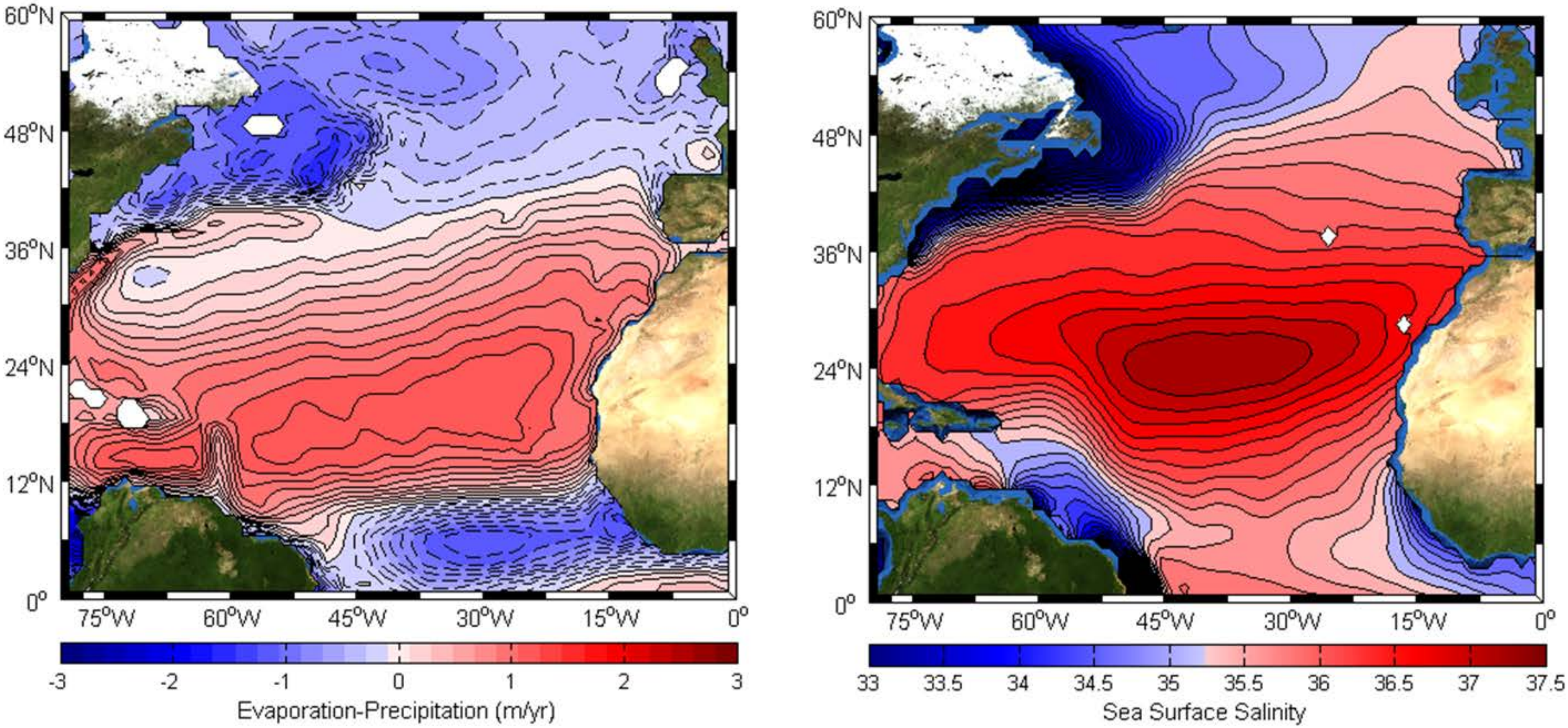
Schanze, 2012 Thesis

Evaporation – Precipitation & Salinity



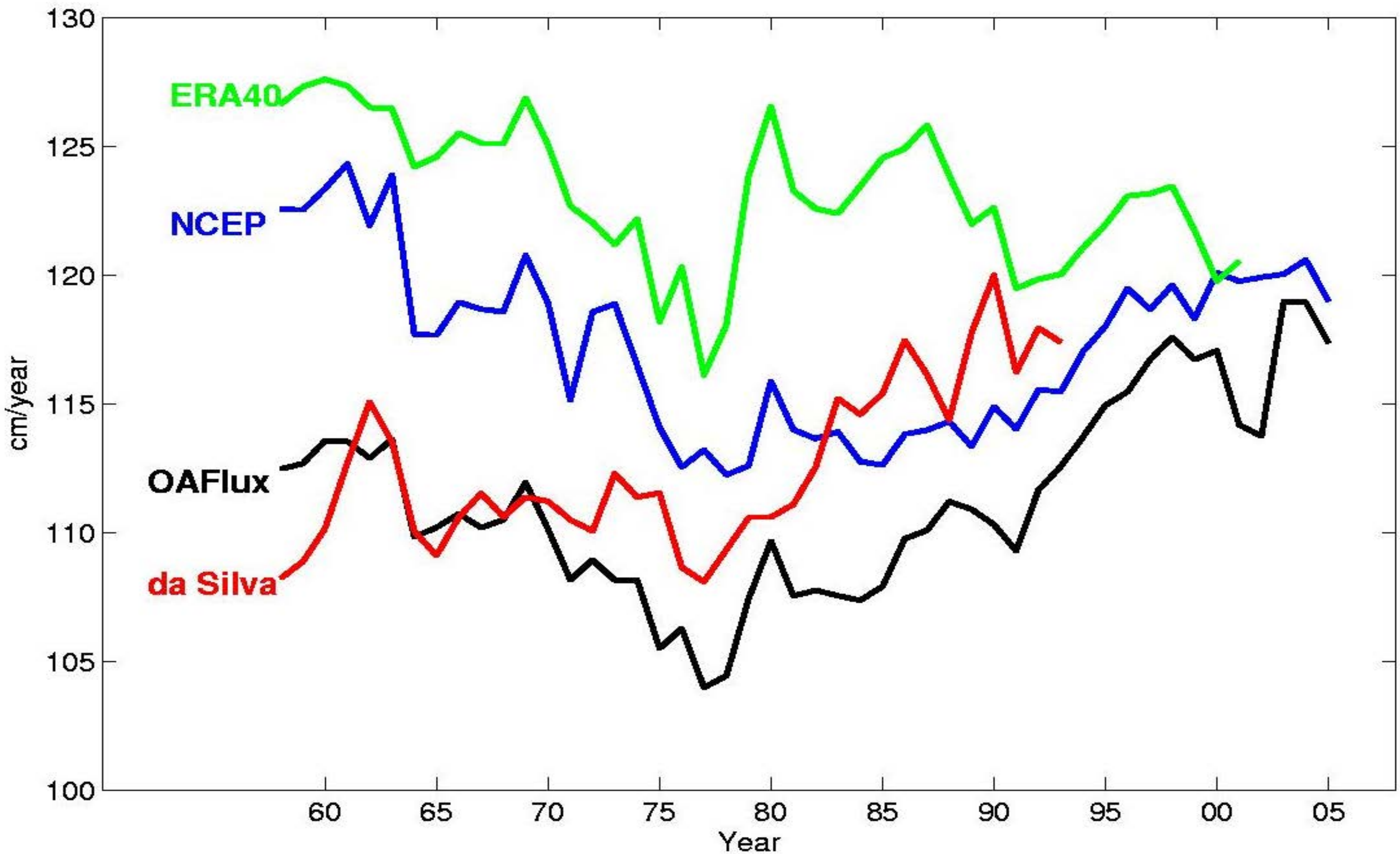
North Atlantic Evaporation - Precipitation

highly correlated



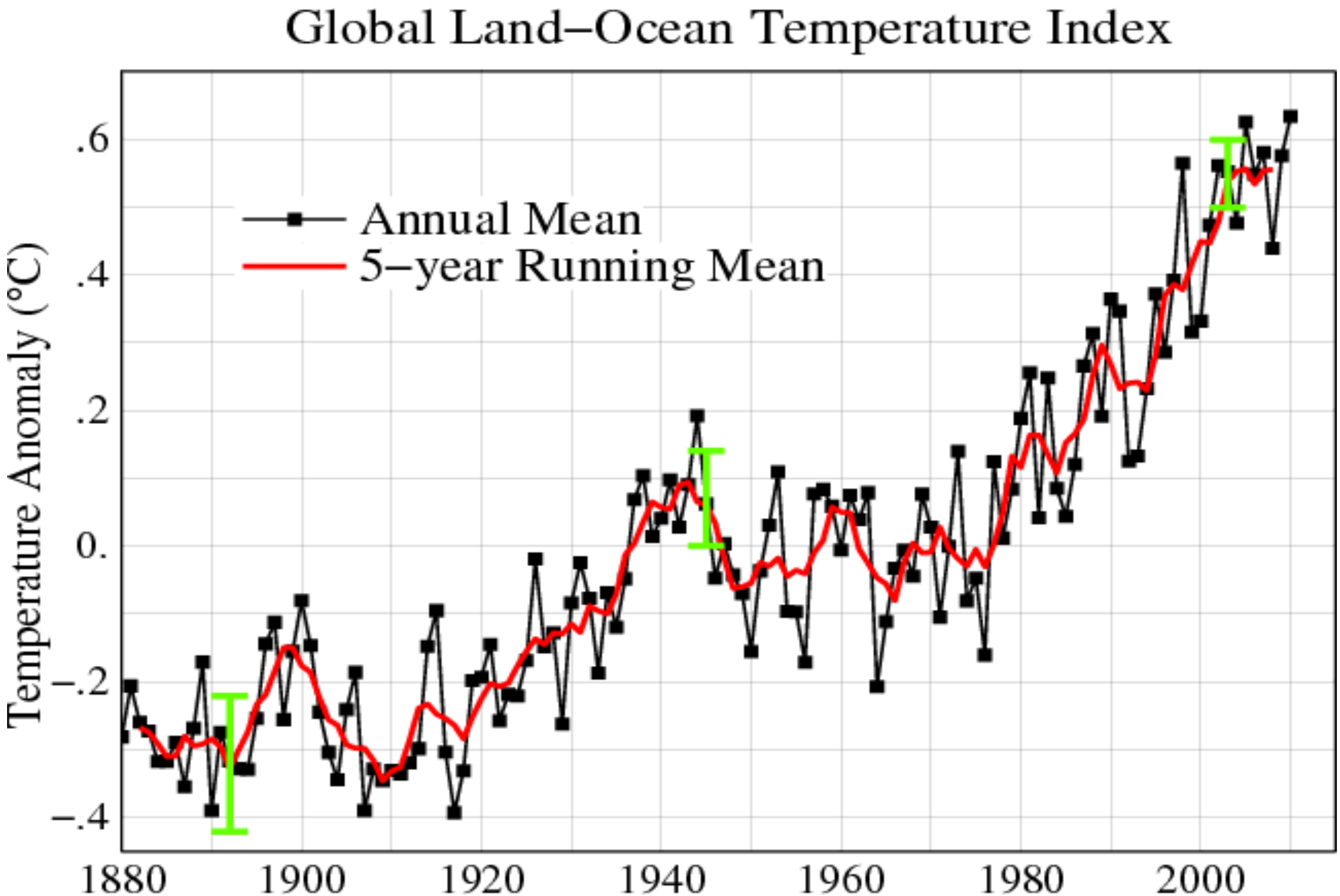
Note: the E-P zero line is close to vegetation/dry land boundary in Africa

Evaporation Trends in 4 Climatologies



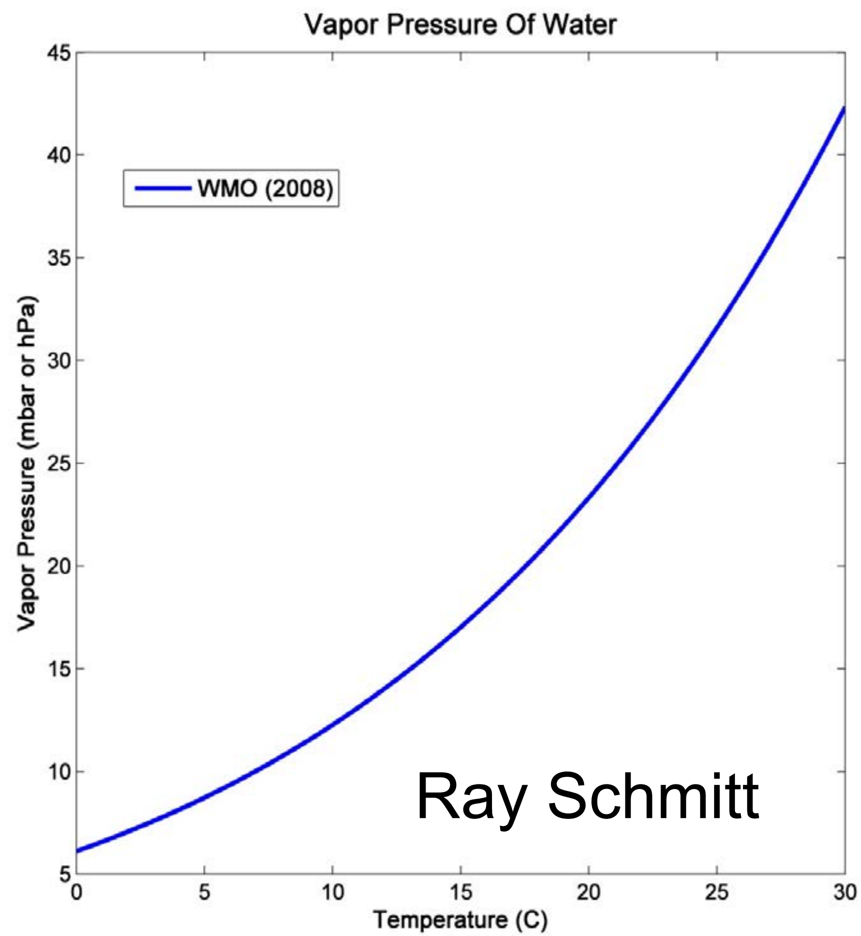
(Yu, 2007)

Temperatures are rising



The Water Cycle will Accelerate with Global Warming

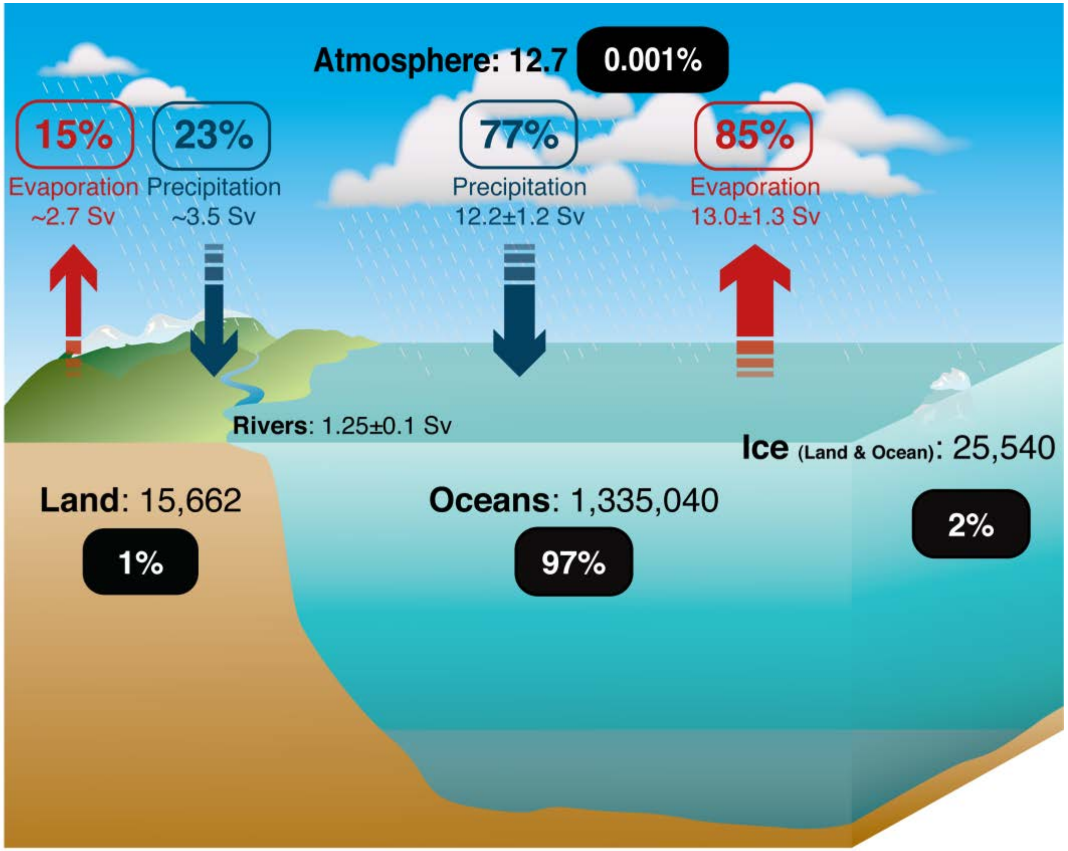
- A warmer atmosphere will carry more water vapor, because of the exponential increase of vapor pressure with temperature.
- 1°C change in temp ~7% increase in vapor-carrying capacity of atmosphere.
- An enhanced water cycle will change the distribution of salinity in the upper ocean.



A key climate question for society is whether the water cycle is presently changing?

Why look at Ocean Salinity?

- ~80% of total Earth surface fluxes occur at the ocean surface
- 97% of the Earth's free water is contained in the ocean
- Evaporation makes water saltier, rainfall makes the water fresher

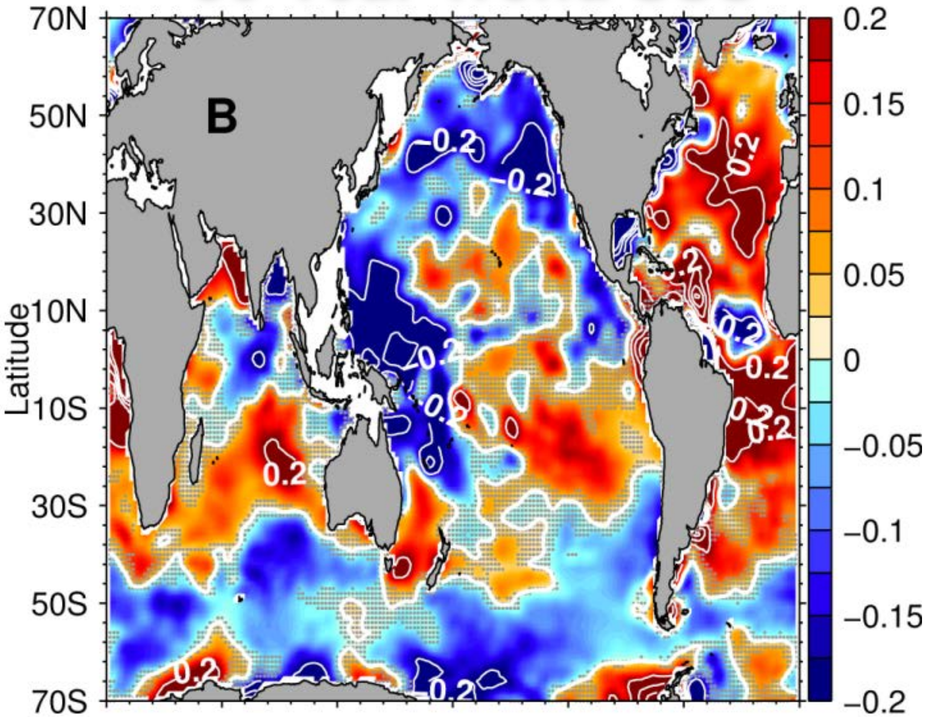


Reservoirs represented by solid boxes: 10^3 km^3, fluxes represented by arrows: Sverdrups (10^6 m^3 s^{-1})
Sources: Baumgartner & Reichel, 1975; Schmitt, 1995; Trenberth et al., 2007; Schanze et al., 2010; Steffen et al., 2010

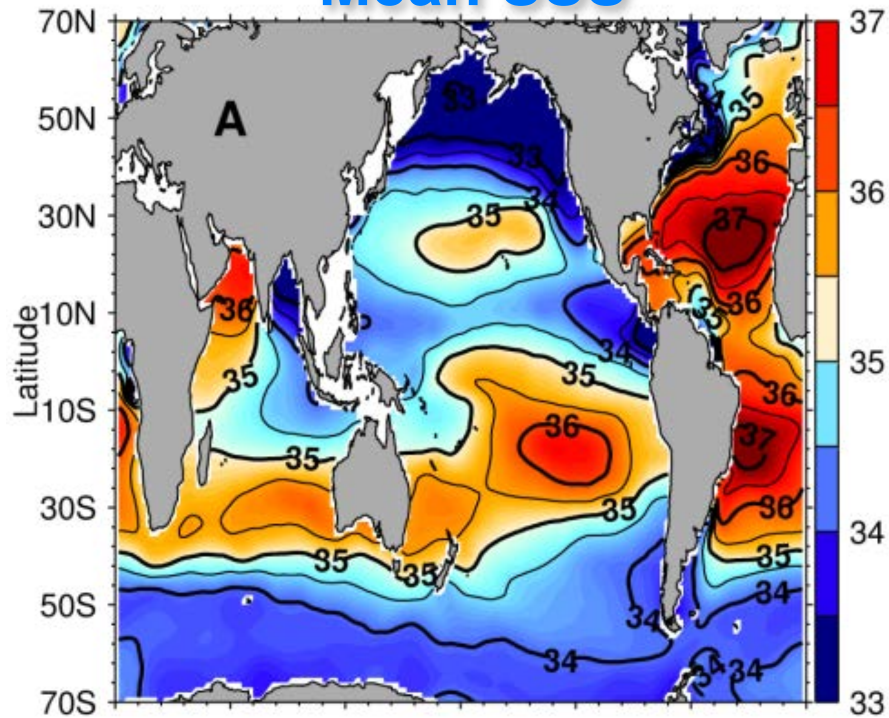
50-Year Trends in Ocean Surface Salinity

- Surface salinity trends show remarkable similarity to the mean spatial pattern
- Inter-basin contrasts increase (saltier Atlantic, fresher Pacific)

50-Year Trend SSS



Mean SSS

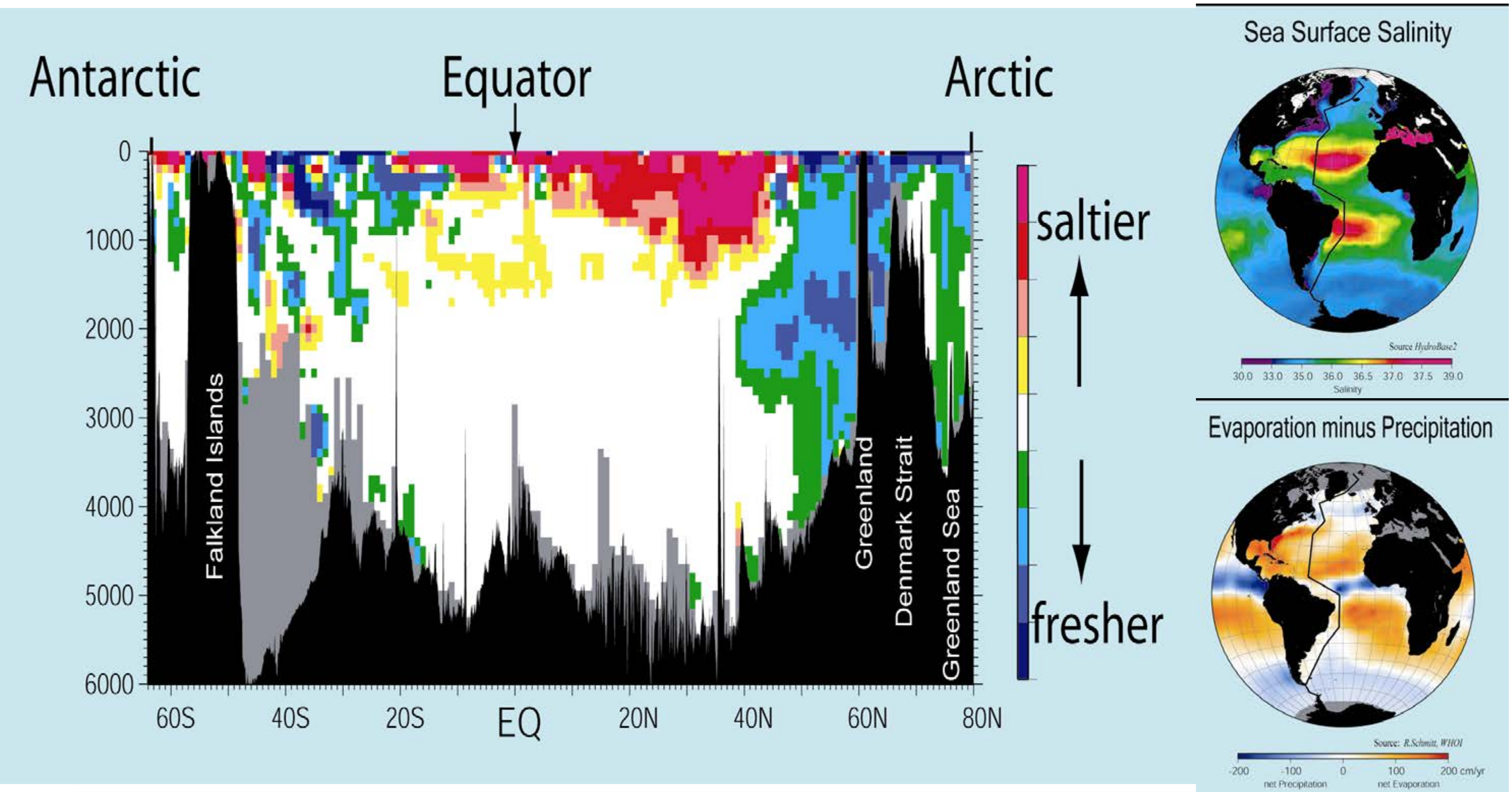


Warming-driven amplification of the Earth’s hydrological cycle
Due to simple physics - warm air carries more water vapour

Durack and Wijffels, 2010

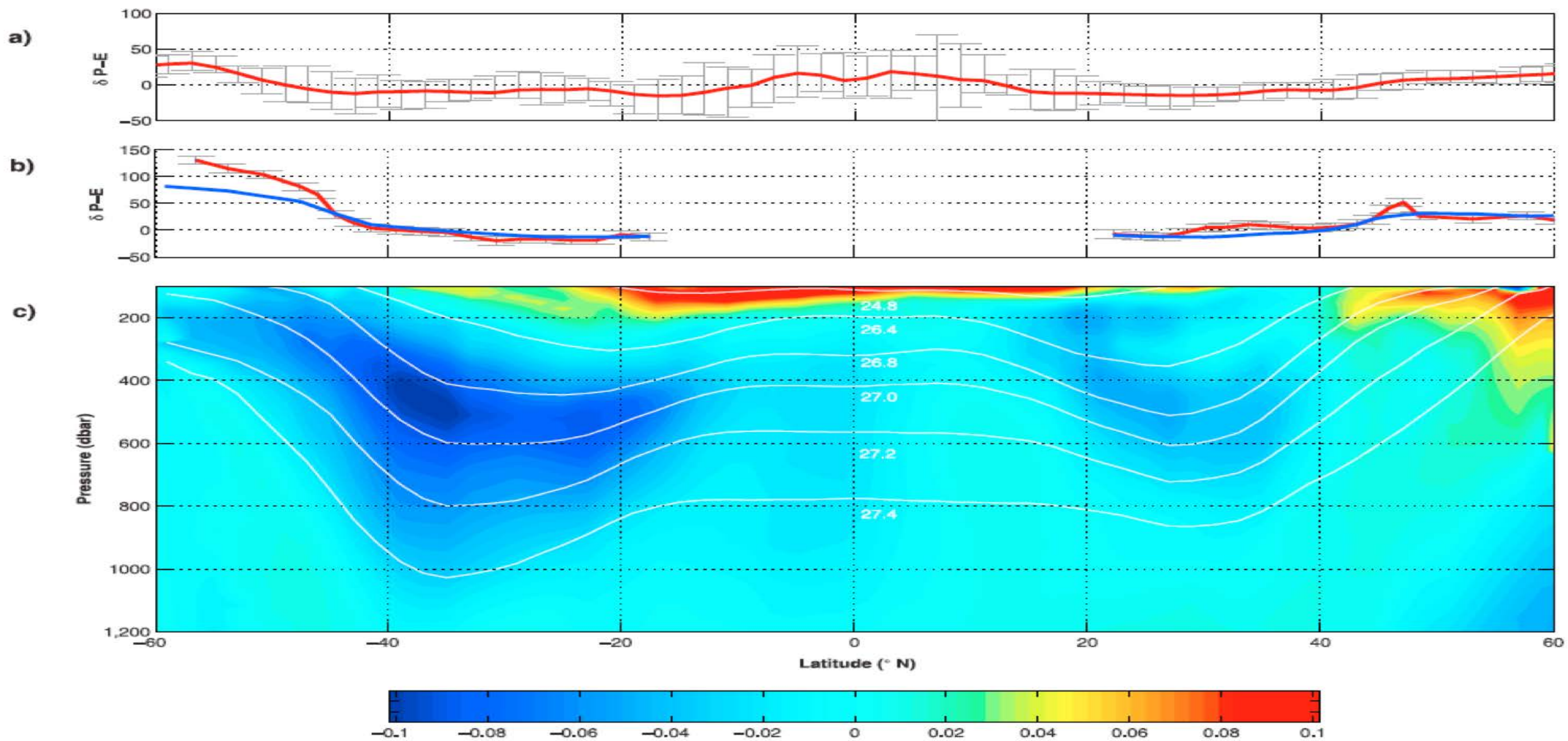
Trends in Atlantic Salinities

Atlantic Ocean Salinity Changes 1990s compared to 1960s



Curry et al. (2003)

Salinity & P-E



Zonally averaged changes in salinity and inferred changes in precipitation-minus-evaporation (P-E). (a) Projected change in P-E (mm yr−1) from ten IPCC-class models for the period 1970 to 2000. The red line is an average change across each 2° latitude band (x-axis), while the error bars show the 10% and 90% percentile range. P-E changes over land are included in this analysis and are assumed to be transferred immediately to the oceans as runoff. (b) Inferred difference in P-E (mm yr−1), using salinity observations, at the ocean surface of each isopycnal layer (~1970 to 2005). The red line illustrates the inferred P-E difference between 1970 and 2005, while the blue line illustrates the inferred P-E difference between 1970 and 1992. Error bars are shown to two standard deviations. (c) Zonally averaged salinity difference along density layers, where blue represents freshening and red represents an increase in salinity.

Helm et al. 2010

Trends Salinities

SSS trends indicate significant changes are underway in the global water cycle, (which is primarily an ocean-atmosphere phenomena)

- High salinity regions getting saltier
- Low salinity regions getting fresher

→Unless ocean mixing and transport is changing, this represents the best evidence we have for an intensification of the global water cycle.

→Models are underestimating the salinity changes!

How much has the water cycle intensified?

$$i_1 = \left(\frac{V_1 - V_2}{R_1} \right)$$

$$\delta i_1 = \left(\frac{\delta (V_1 - V_2)}{R_1} \right)$$

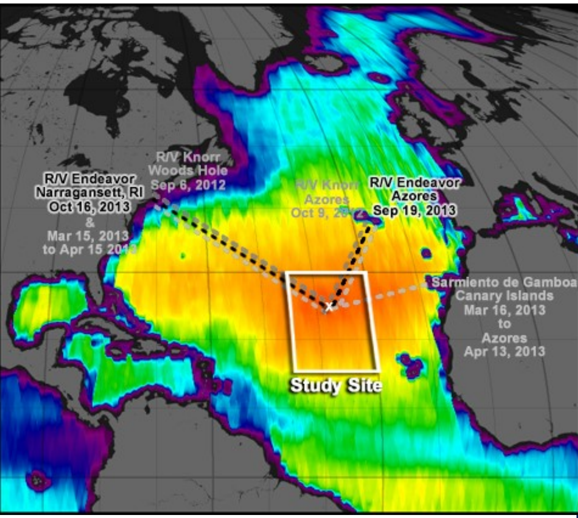
Voltage = salinity
Current (i) = E-P
Resistance = Ocean mixing processes that dissipate salinity variance.

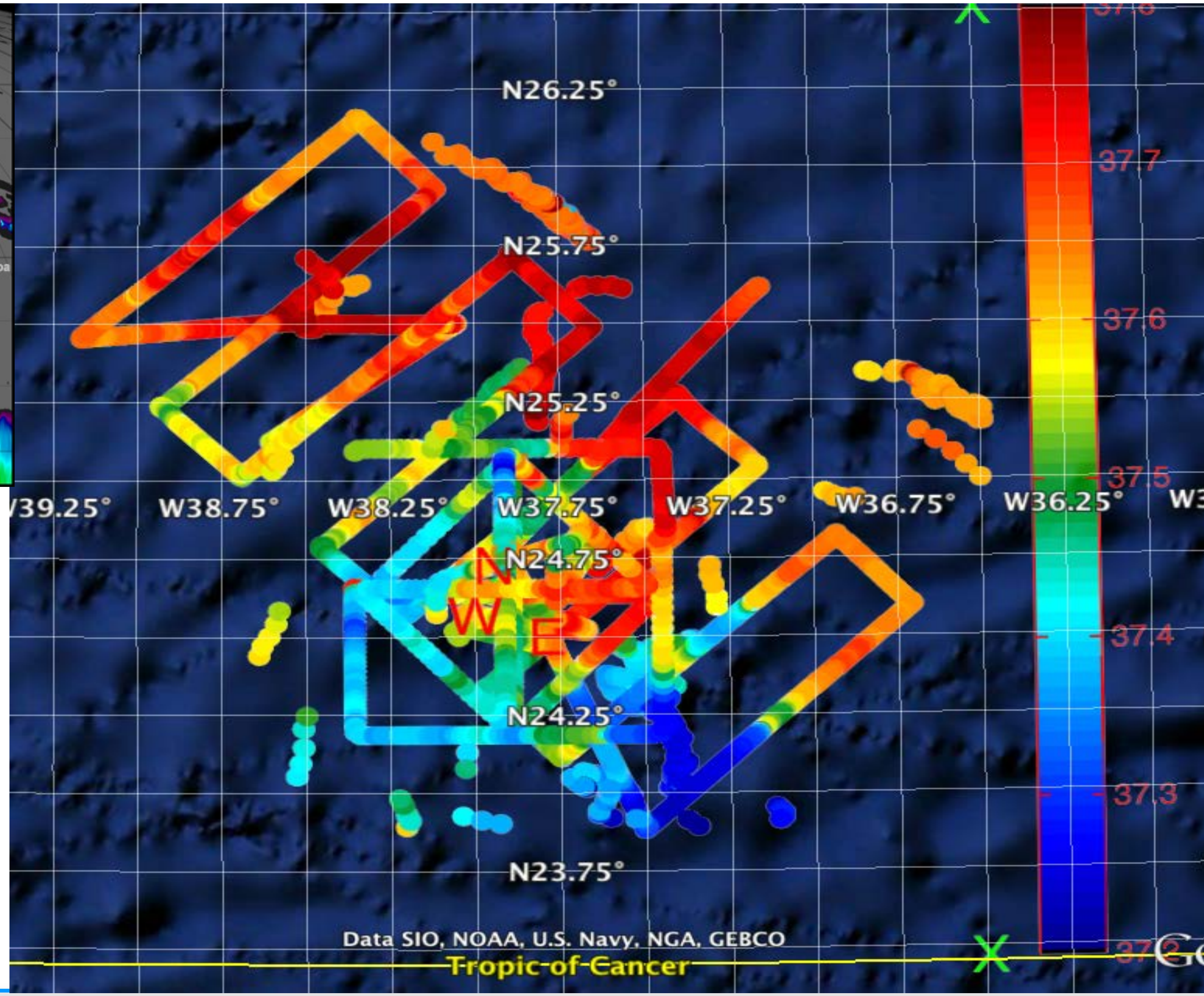
Unless "R" of the ocean has changed, changes in SSS variance should be proportional to changes in E-P forcing. Durack and Wijffels (2010) report changes of +0.2 in high salinity regions (S=37), -0.2 in low salinity regions (S=33) over 5 decades ($\delta\Delta S/\Delta S$ ~ 0.1). This suggests an intensification of the water cycle of order 2% per decade!

Raymond Schmitt

Salinity Processes Upper Ocean Regional Study (SURS)

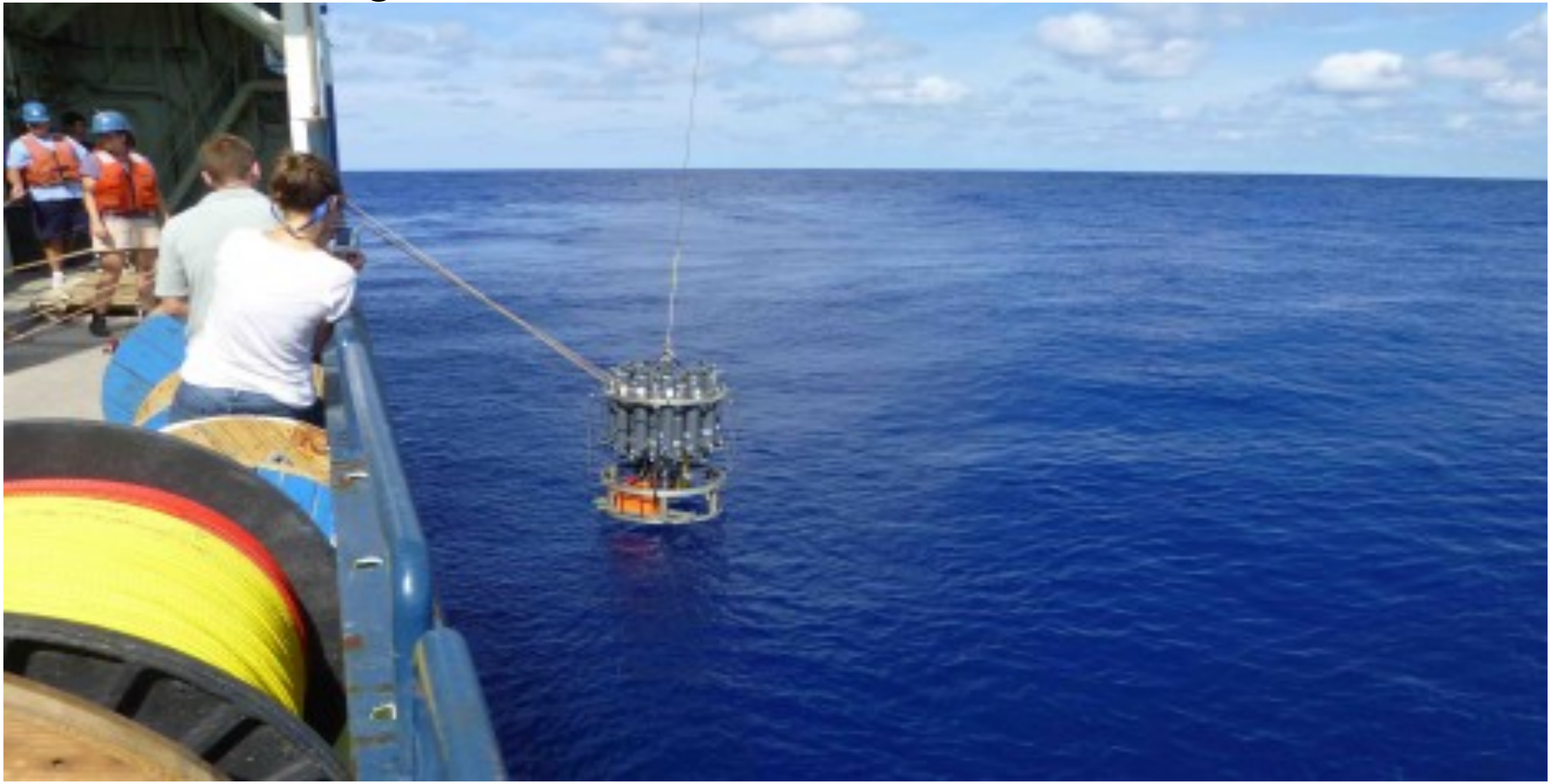
Salinity Maximum of North Atlantic





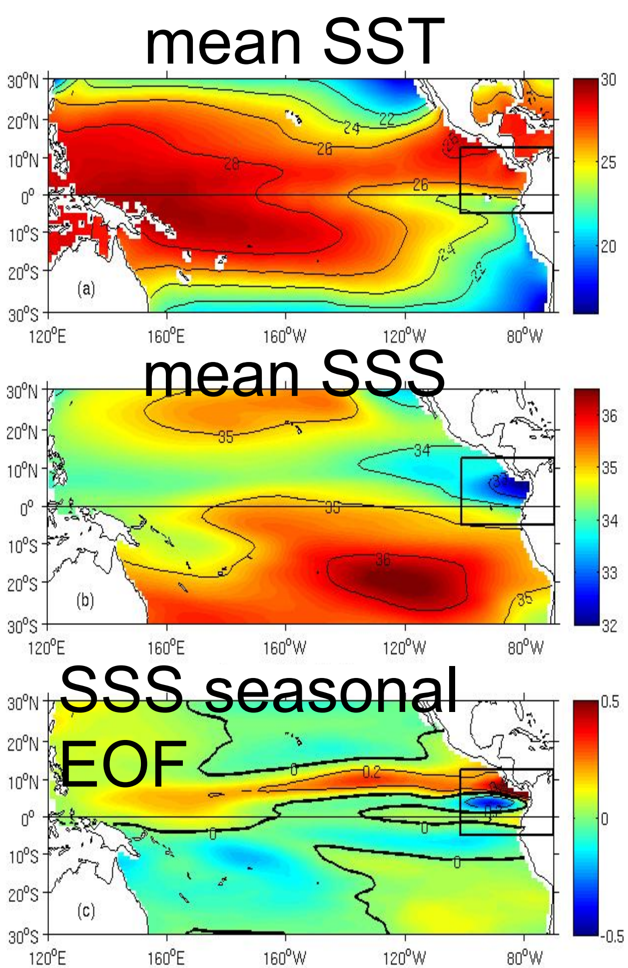
Salinity Processes Upper Ocean Regional Study (SURS)

Highest SSS observed in the afternoon of the calmest days. Suggests traditional bulk formula with no evaporation with no wind cannot be right….



Ray Schmitt

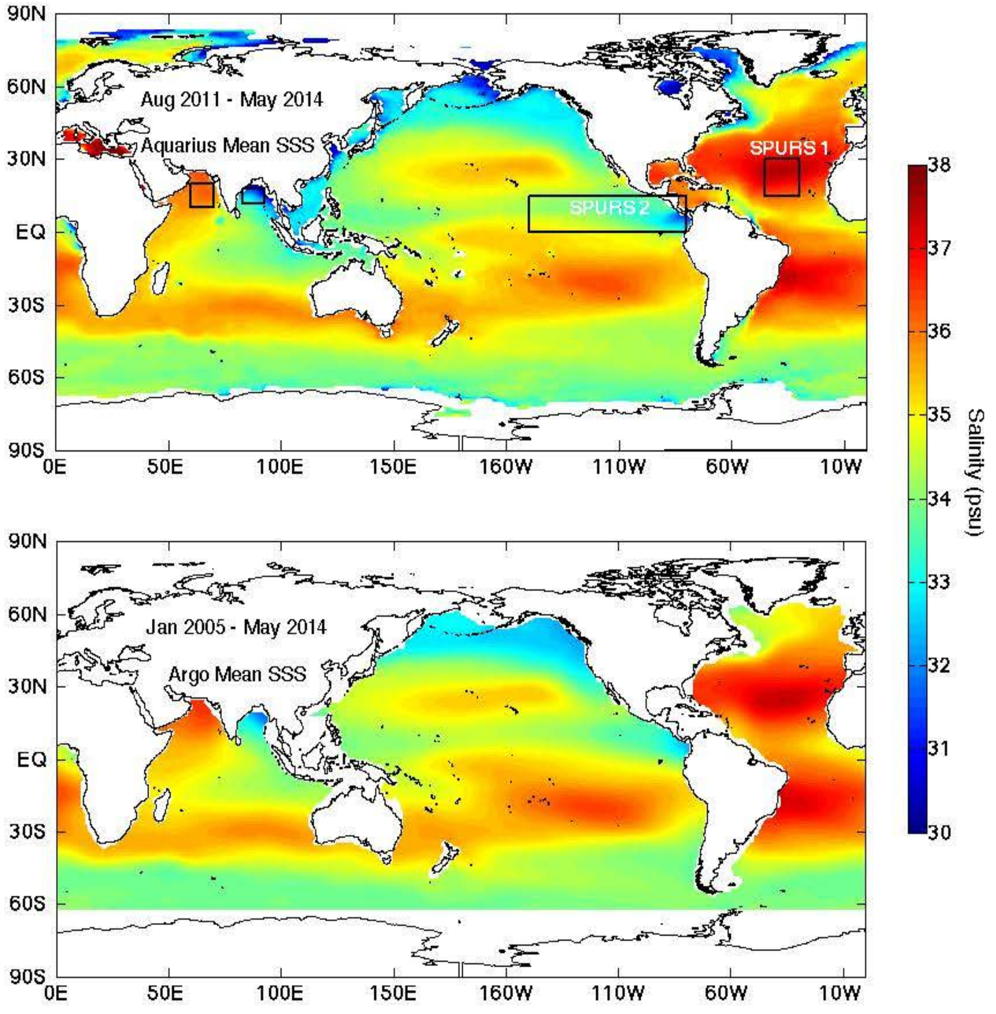
SPURS II: Why focus on SSS in this region?



- Between 2 climate relevant features: Eastern Pacific warm pool and equatorial cold tongue
- Minimum in SSS (<33: Far Eastern Pacific Fresh Pool) and maximum seasonal variability
- Strong air-sea-land interactions in this region: monsoon, gap winds... (*e.g. Xie et al. 2005, Fiedler and Talley 2006, Kessler 2006*)
- Potentially active role of salinity stratification on regional climate (*de Boyer Montegut et al. 2007*)
- Good test ground for new SSS satellite products (SMOS, Aquarius)

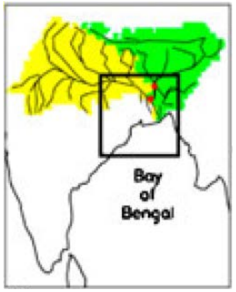
Delcroix et al., 2011

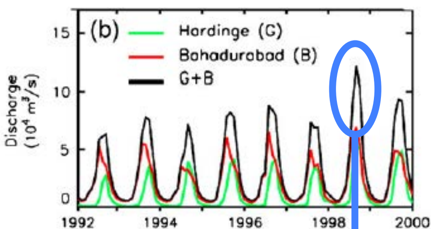
SPURS III: Arabian Sea/Bay of Bengal?



Impact of river discharges in Bay of Bengal

Ganges +
Brahmaputra





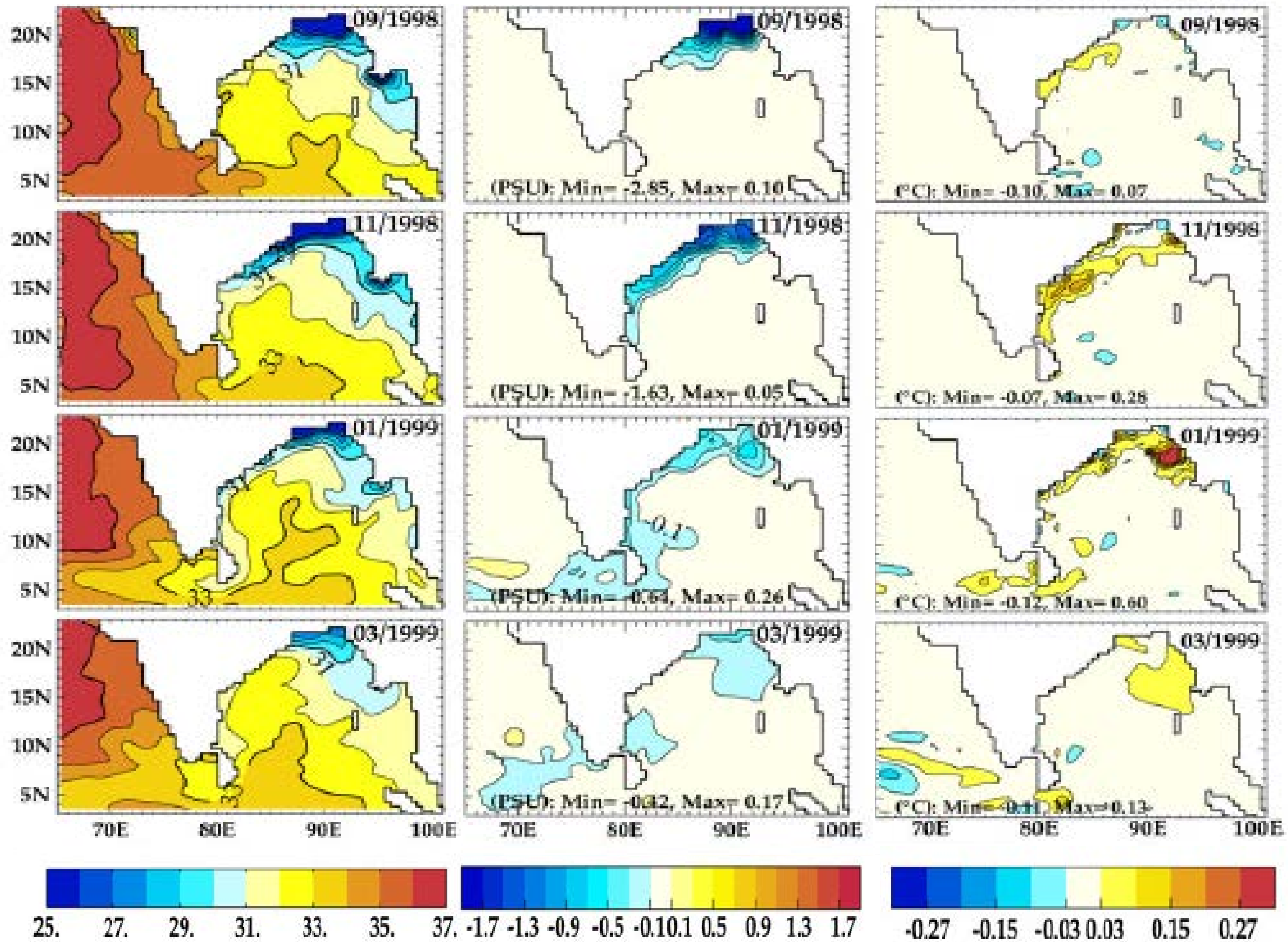
1998: strong discharge

Model simulations with or without interannual runoff anomaly

SSS with seasonal runoff

\+ interannual runoff anomaly

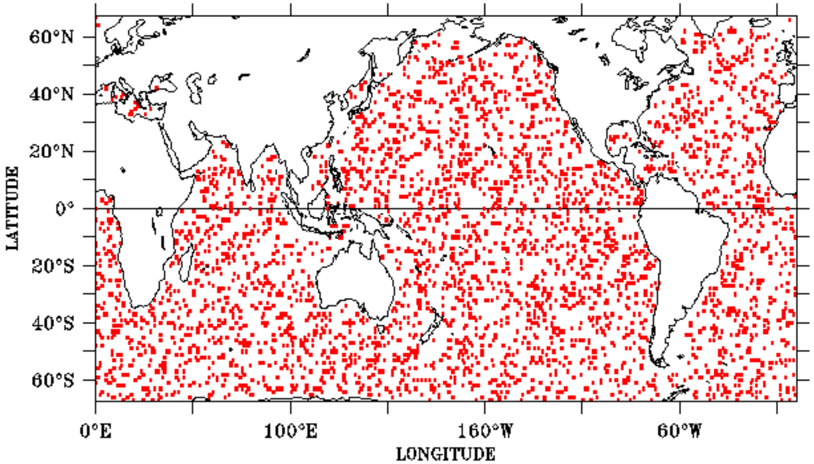
resulting SST anomaly



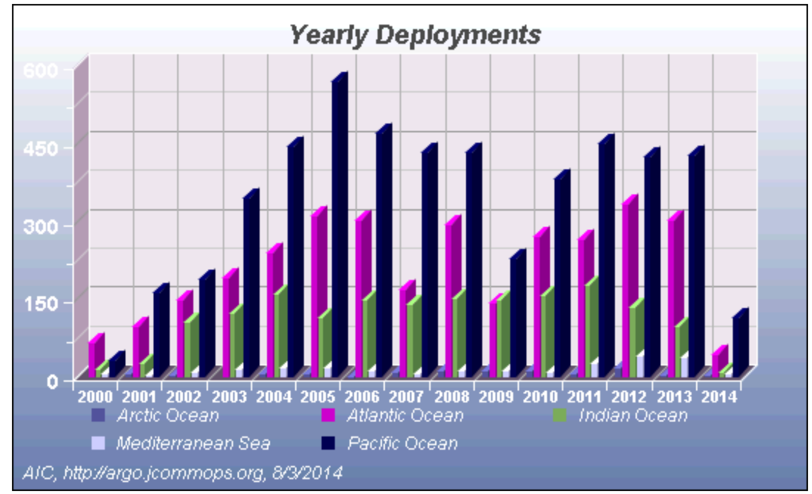
(Durand, Papa, Rahman & Bala, 2011)

ARGO floats

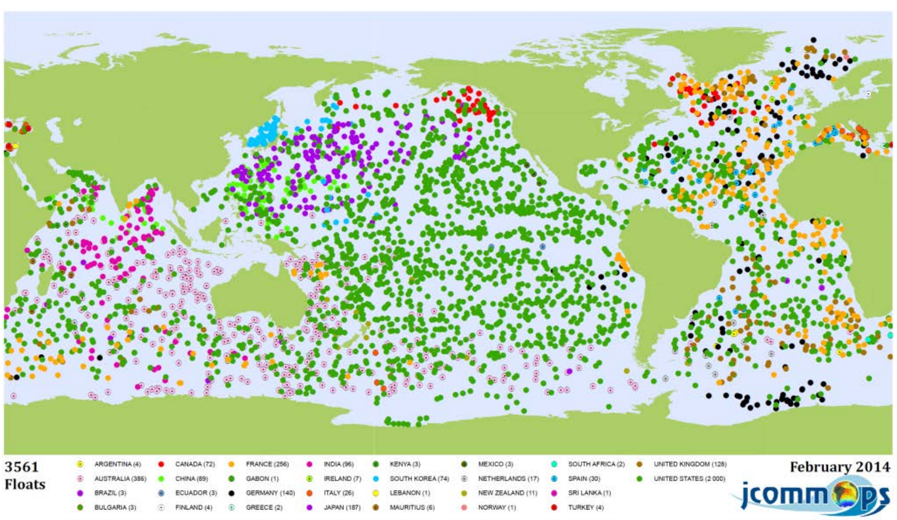
A Global Array of Profiling Floats



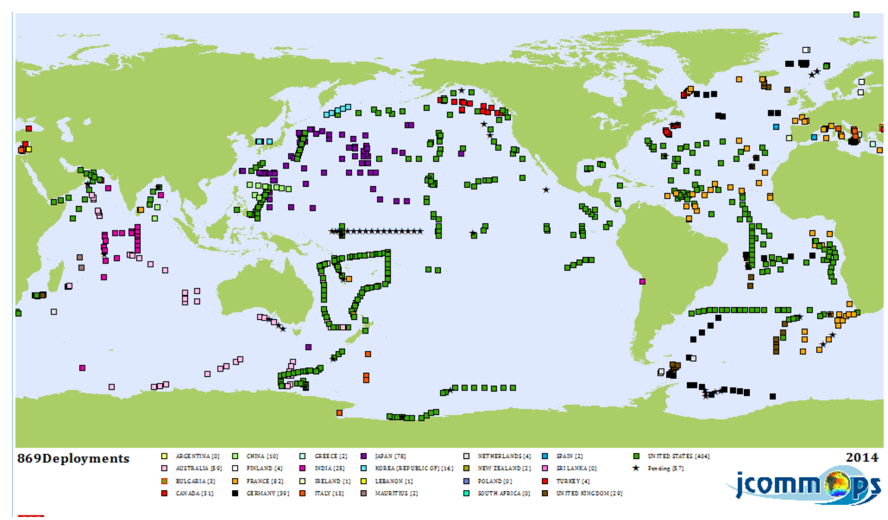
Concept diagram: Argo was planned in 1998



Yearly deployments – 863 in 2013



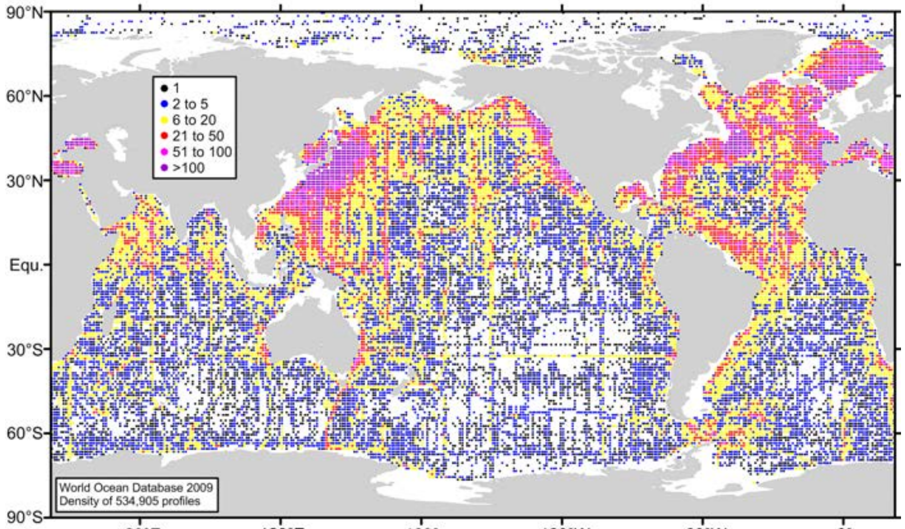
The Argo array in 2014: 3500 floats, 30 nations

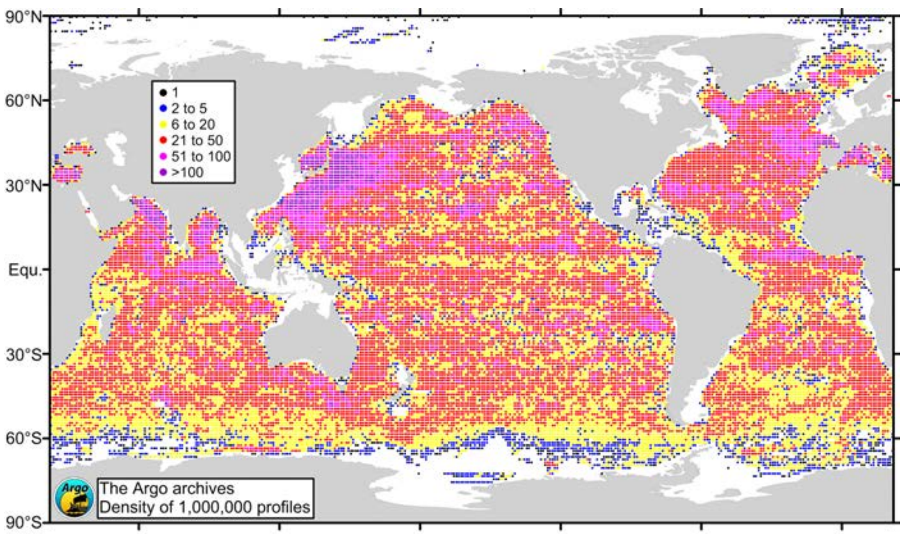


2013 deployments

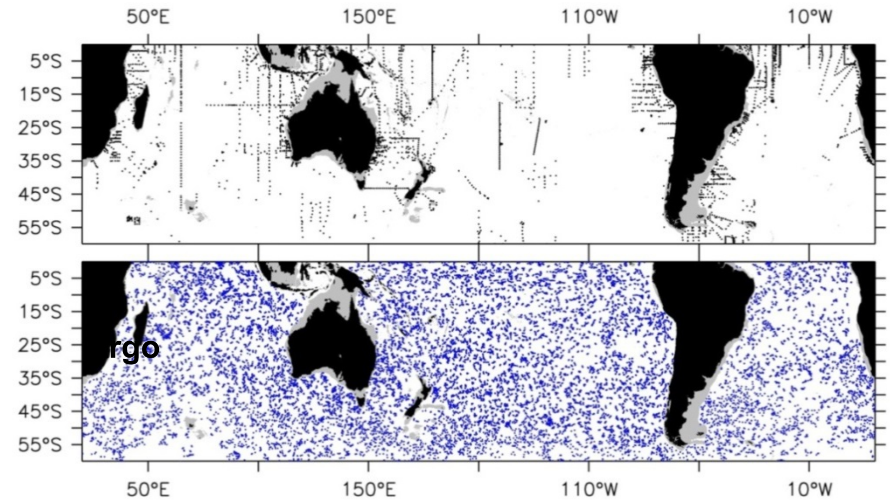
Argo transformed *global-scale* oceanography into *global* oceanography.

20th Century: 500,000 T/S profiles > 1000 m





All August T/S profiles (> 1000 m, 1951 - 2000).



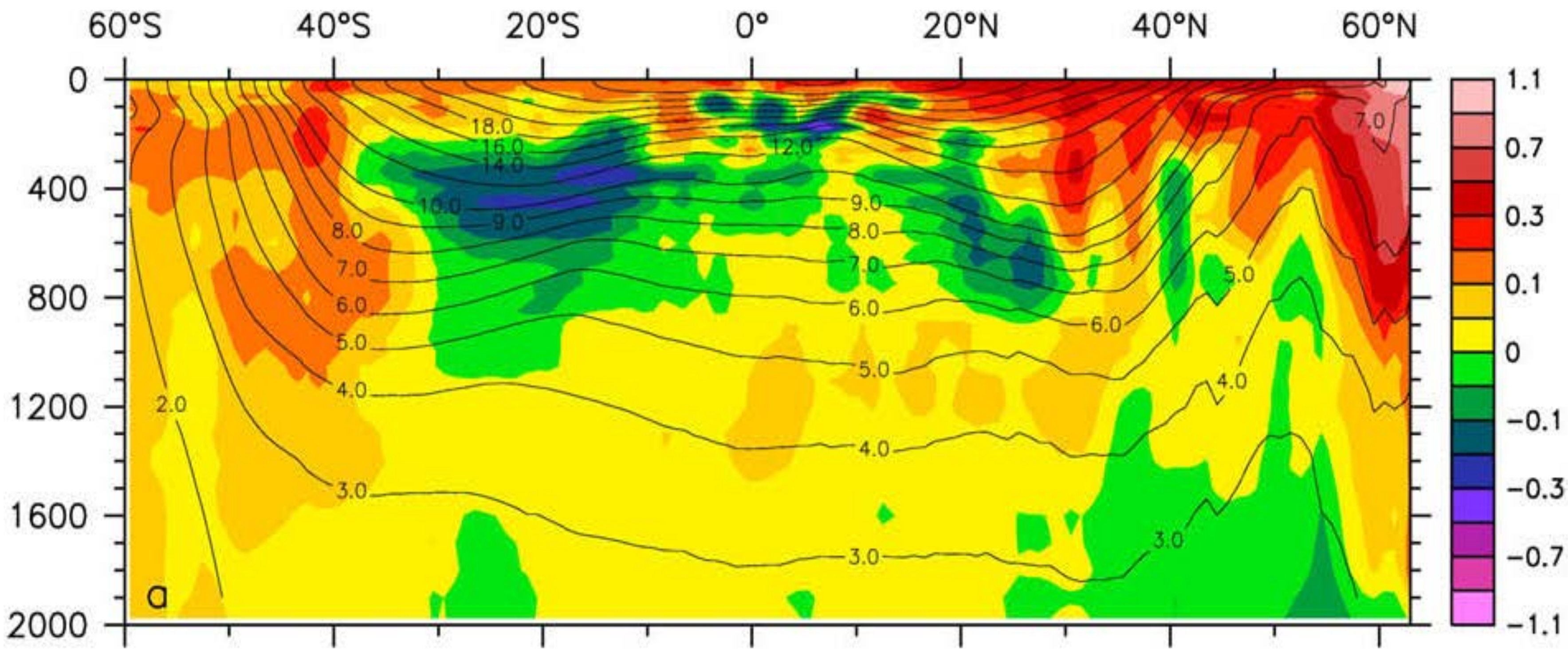
5 years of August Argo T,S profiles (2008-2012).

The World Ocean Circulation Experiment was a global survey of 8,000 T/S profiles in 7 years (1991-1997).

Argo is a global survey of 10,000 T/S profiles every month.

Argo: 1,000,000 T/S profiles milestone achieved in 2012.

How does the 'Argo Ocean' compare to historical measurements?



[Roemmich and Gilson, 2009]

Argo atlases differ consistently with pre-Argo atlases:

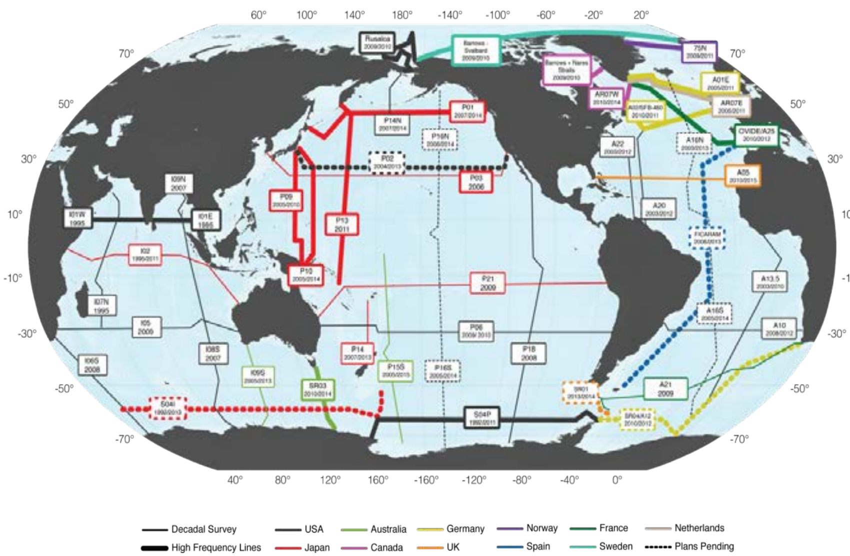
- warmer - mostly near the surface but also at depth in some places
- There are distinct salinity changes

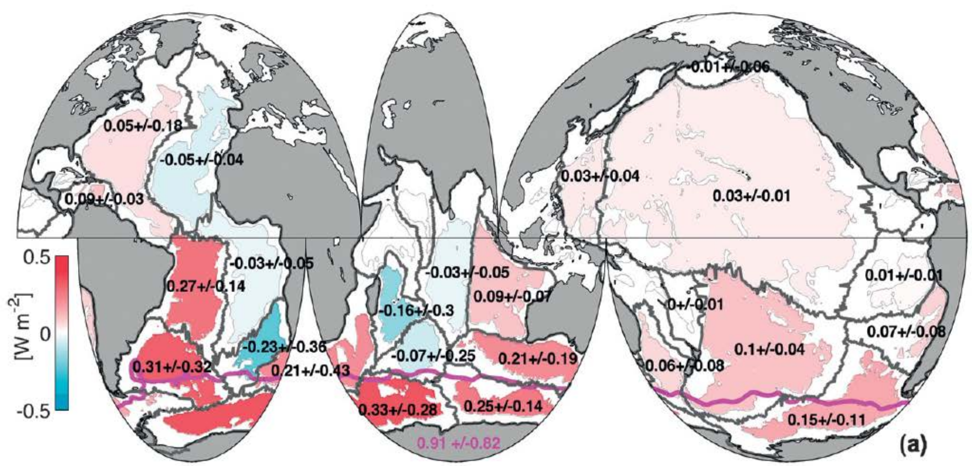
Zonally averaged temperature versus latitude (contours, Argo Climatology) and zonally averaged temperature difference (Shading, Argo minus World Ocean Atlas 2001)

New Missions ?
Deep Argo

Why?

- Sparse repeat ship data show us 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
- Ocean and climate forecasters also want data below 2000 m

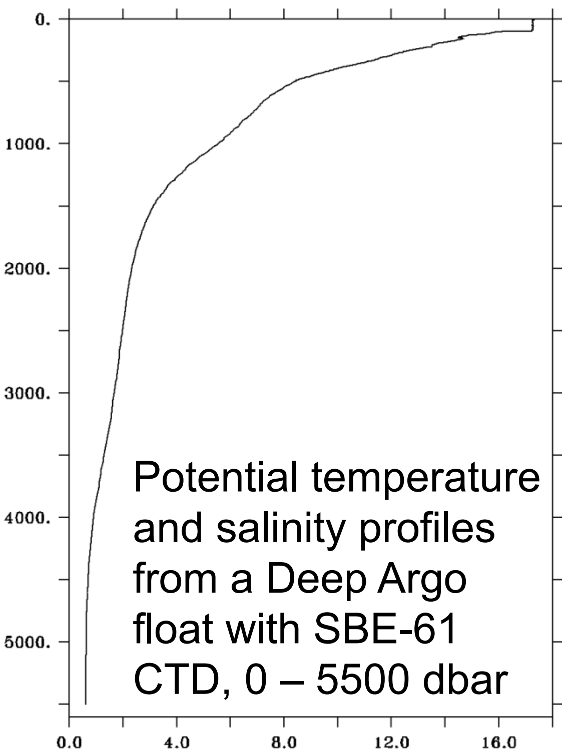




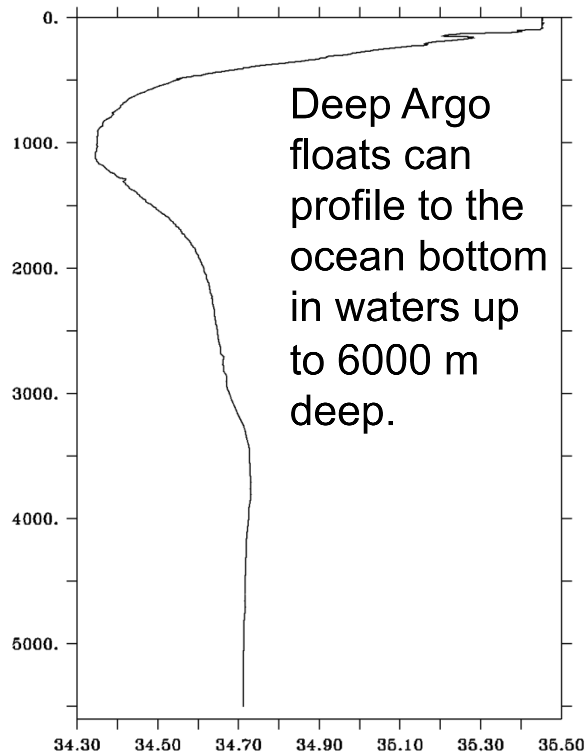
Bottom Water warming from 1990's to 2000's
Purkey and Johnson (2010)

Deep Argo deployment and validation cruise: RV Tangaroa June 2014

A collaborative activity of Argo N.Z., U.S., and Australia



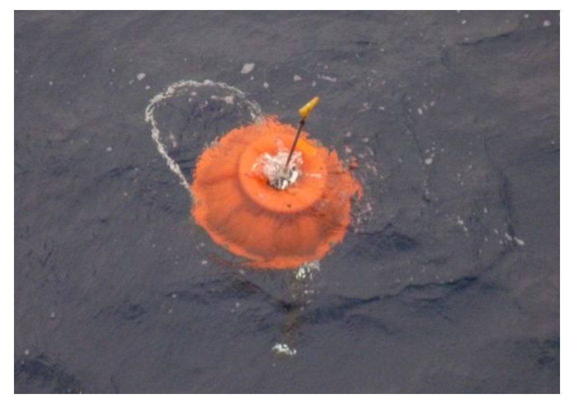
Potential temperature and salinity profiles from a Deep Argo float with SBE-61 CTD, 0 – 5500 dbar



Deep Argo floats can profile to the ocean bottom in waters up to 6000 m deep.

Two prototype Deep (SOLO) Argo floats were deployed at 36°S 177°W and will profile rapidly for 1 year (> 120 cycles) before recovery. Photos: LEARNZ

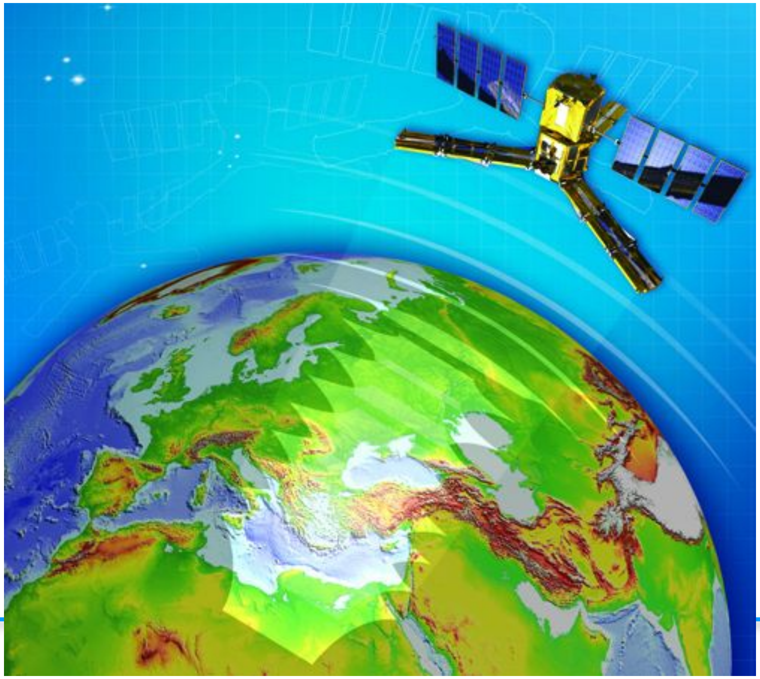
The shipboard rosette included a dual sensor SBE-911plus CTD system (as a standard) and 4 SBE-61 Deep Argo CTDs for testing and validation. The SBE-61 was specially developed with high accuracy and stability for Deep Argo. Photo: LEARNZ



Dean Roemmich

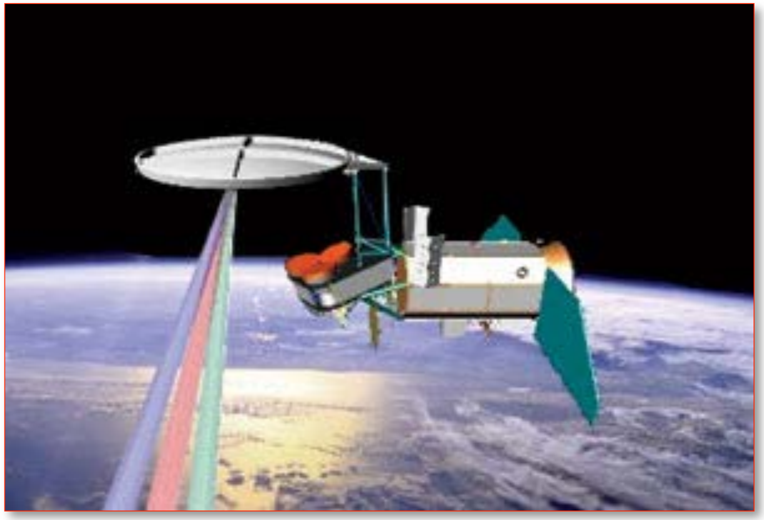
Soil Moisture and Ocean Surface Salinity

- Launched on 2 November 2009
- Soil moisture (SM) and ocean salinity (OS)
- Resolution : 1-3 days & 45 km
- Accuracy of 0.1 psu/ 30 days/200 km

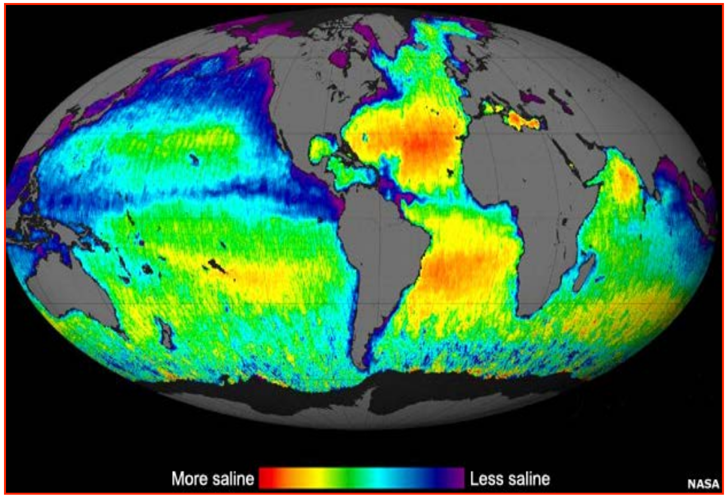


Aquarius

- NASA & CONAE; launched on 10 June 2011
- MWR-ocean wind & direction, rain, sea ice
- NIRST – SST; 3 bands
- Resolution: 7 days & 150 km
- Accuracy: 0.2 psu/30 days/150 km

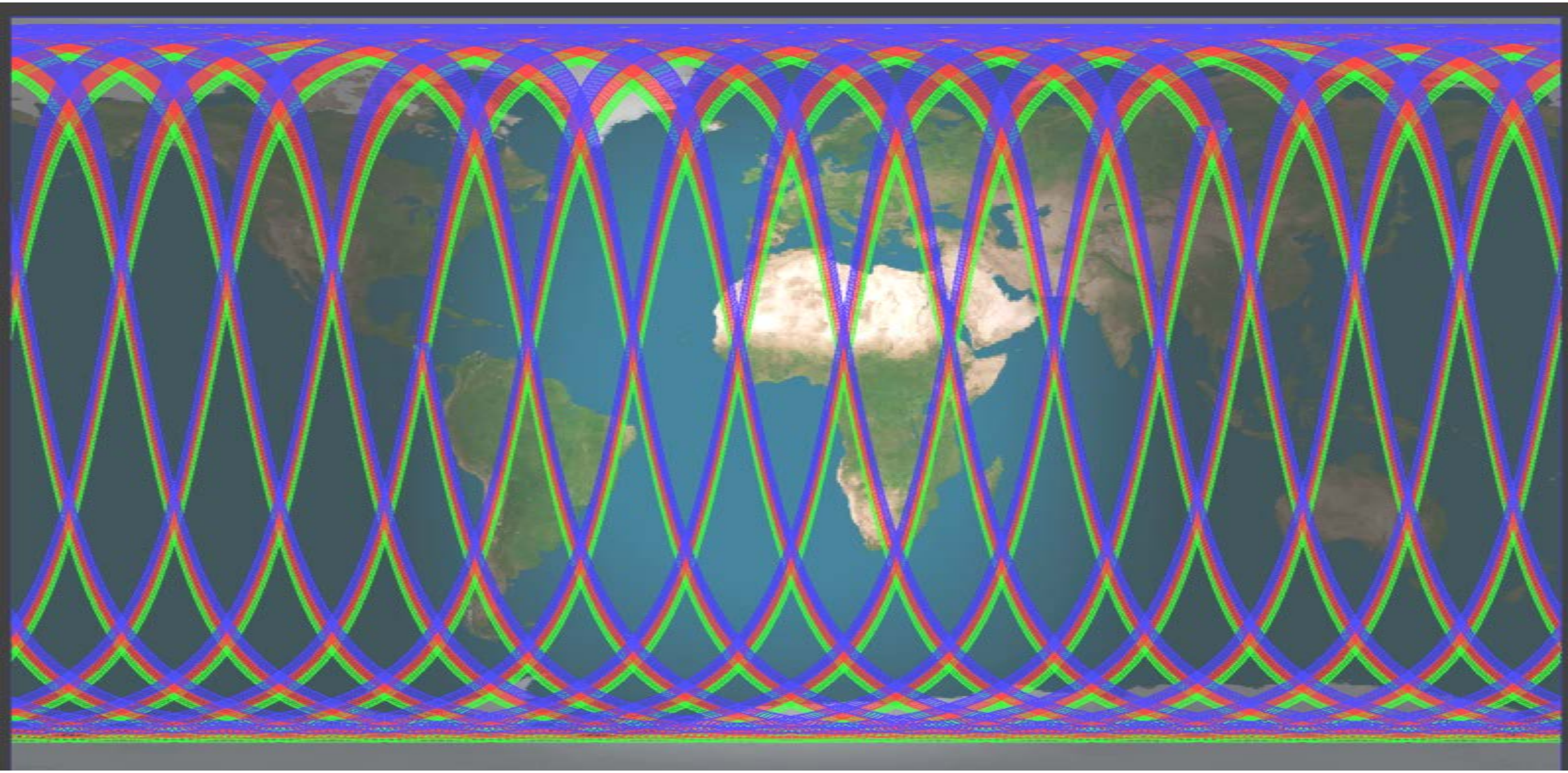


Aquarius satellite in orbit



Aquarius global mean SSS

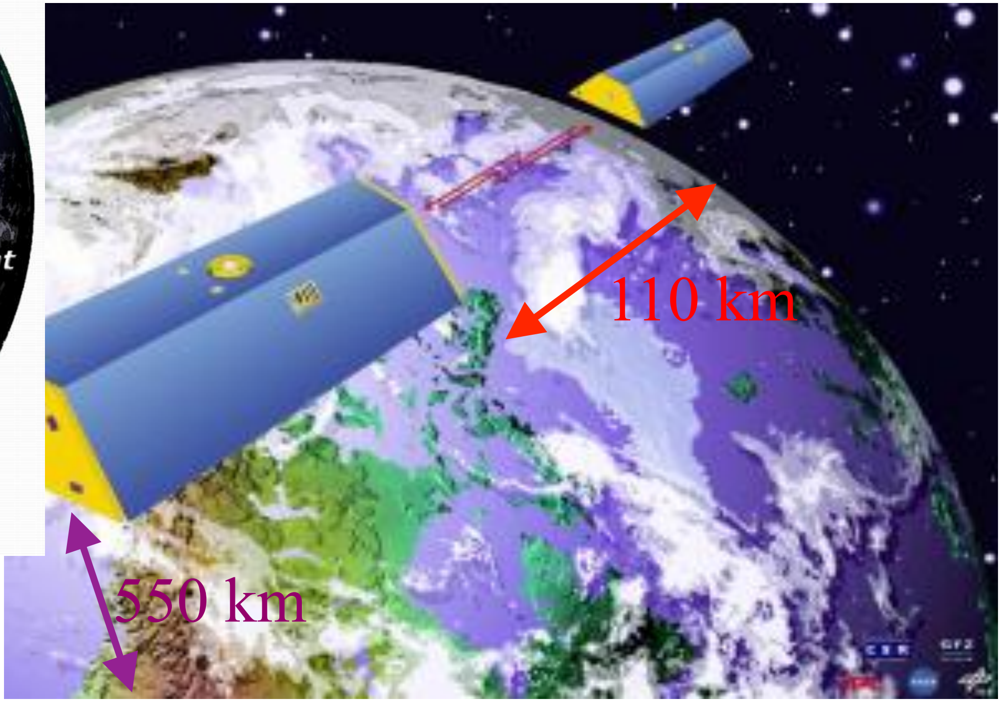
A single day orbit swath pattern of Aquarius



Source: Gary Lagerloef

Gravity Recovery and Climate Experiment

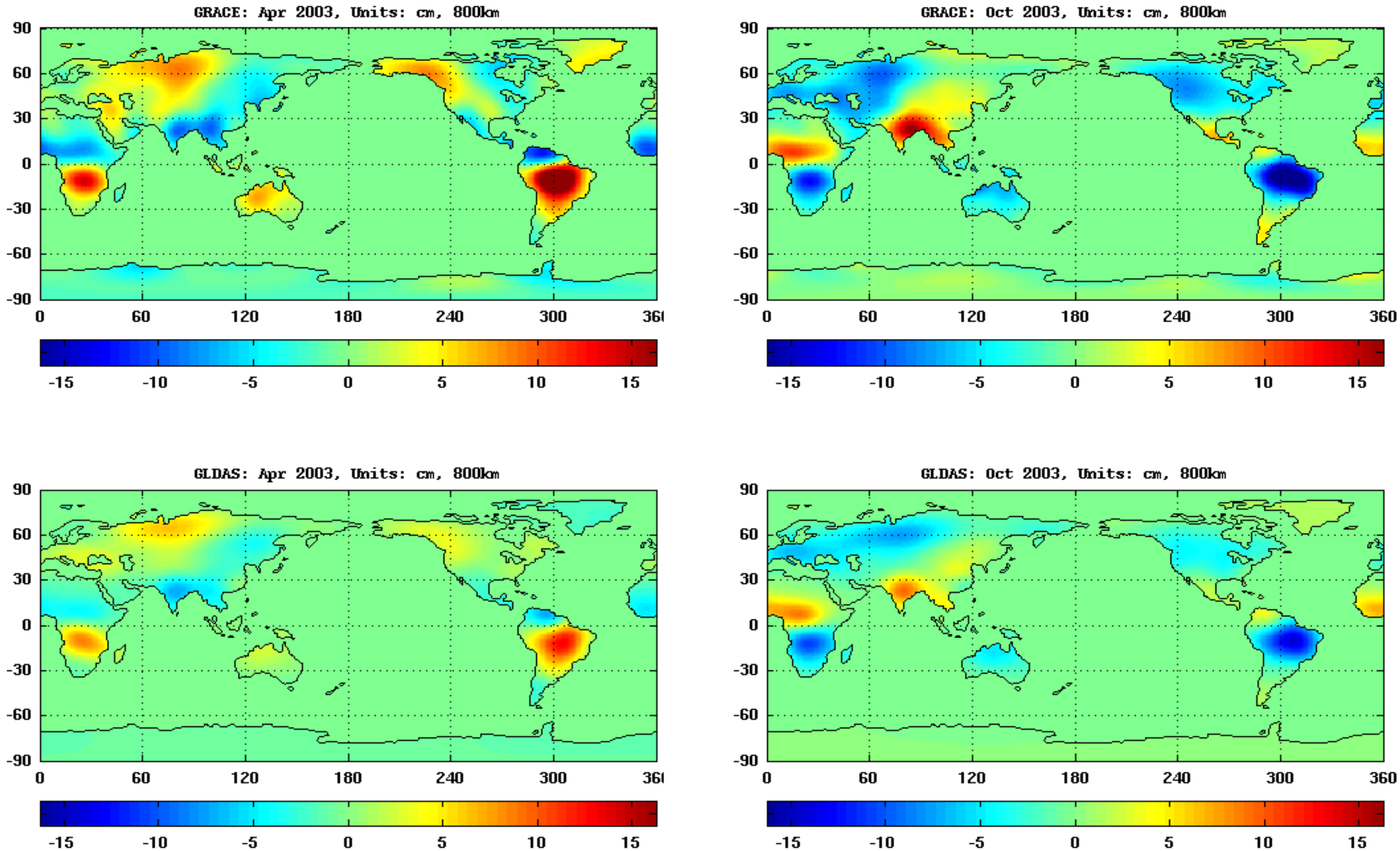
Grace



GRACE Geophysical Applications

- HYDROLOGY
  - LAND WATER STORAGE
  - GROUND WATER
  - EVAPOTRANSPIRATION
  - RUNOFF
- OCEANOGRAPHY
  - NON-STERIC SEA LEVEL CHANGE
  - OCEAN BOTTOM PRESSURE
  - HEAT CONTENT
  - OCEAN TIDES
- GLACIOLOGY
  - POLAR ICE SHEETS MASS BALANCE
  - MOUNTAIN GLACIERS MASS BALANCE

Global Water Storage from GRACE



Arctic Fresh Water Budget

Ocean: 60,000 km^3
Ice : 30,000 km^3

Runoff: 2500 km^3/year

Sea Ice
Export: 2500 km3/year

Liquid
Export: 2000 km3/year

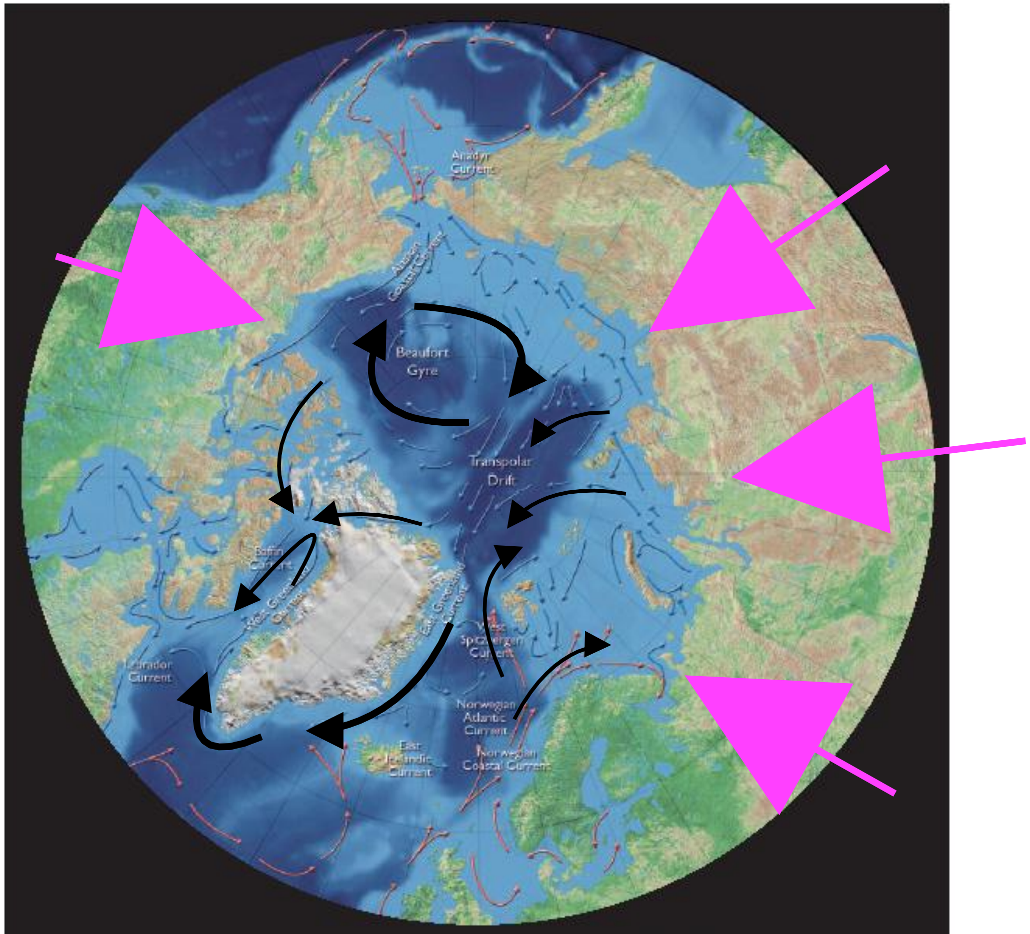
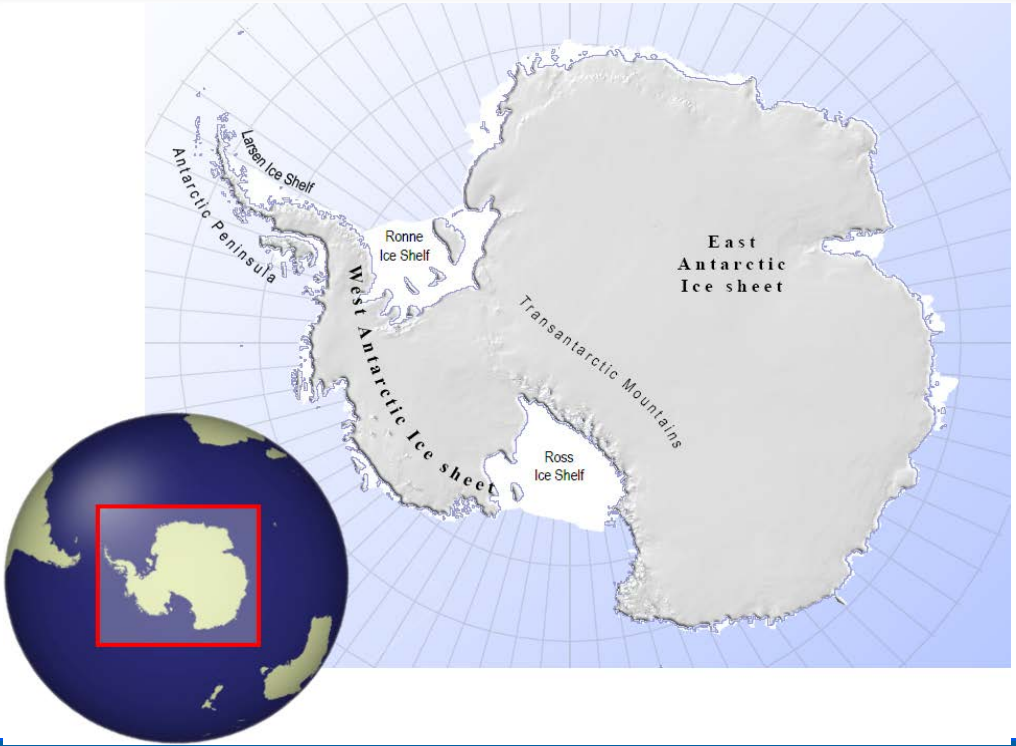


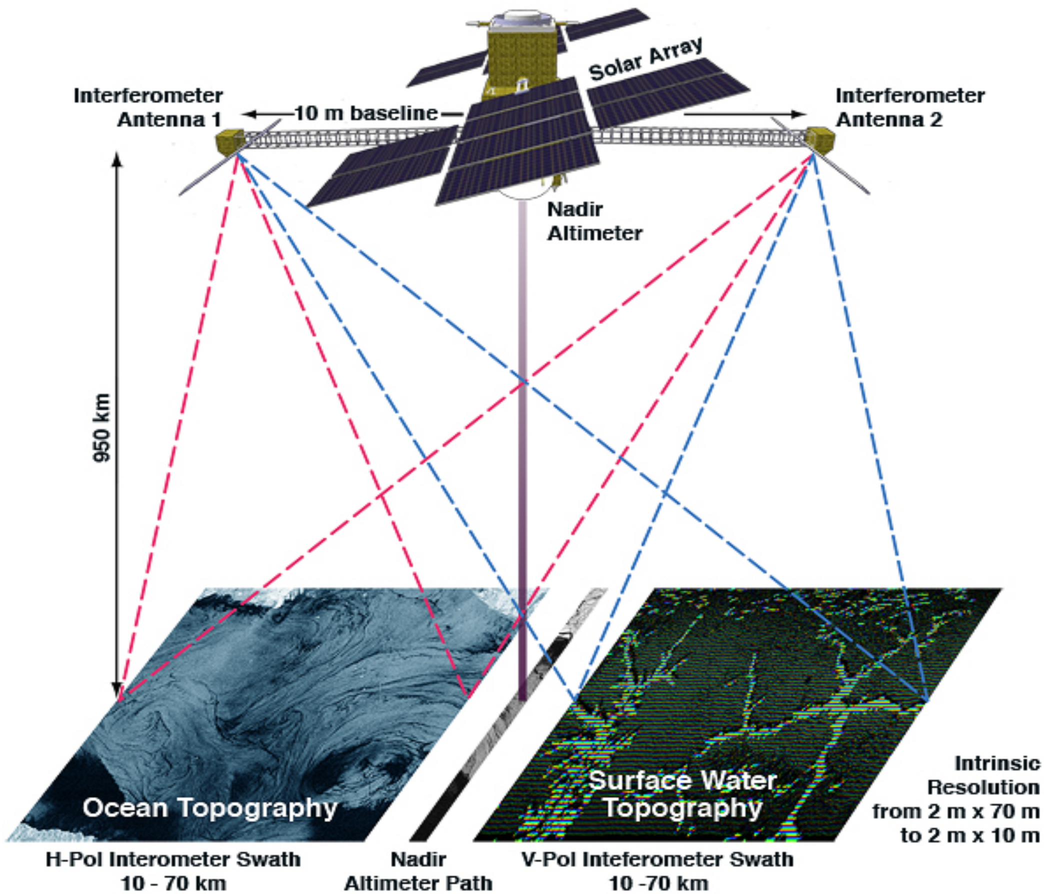
Fig. 2.5. Surface currents in the Arctic, with warm water flows shown in red (based on AMAP, 1998).

Antarctic Ice Sheet



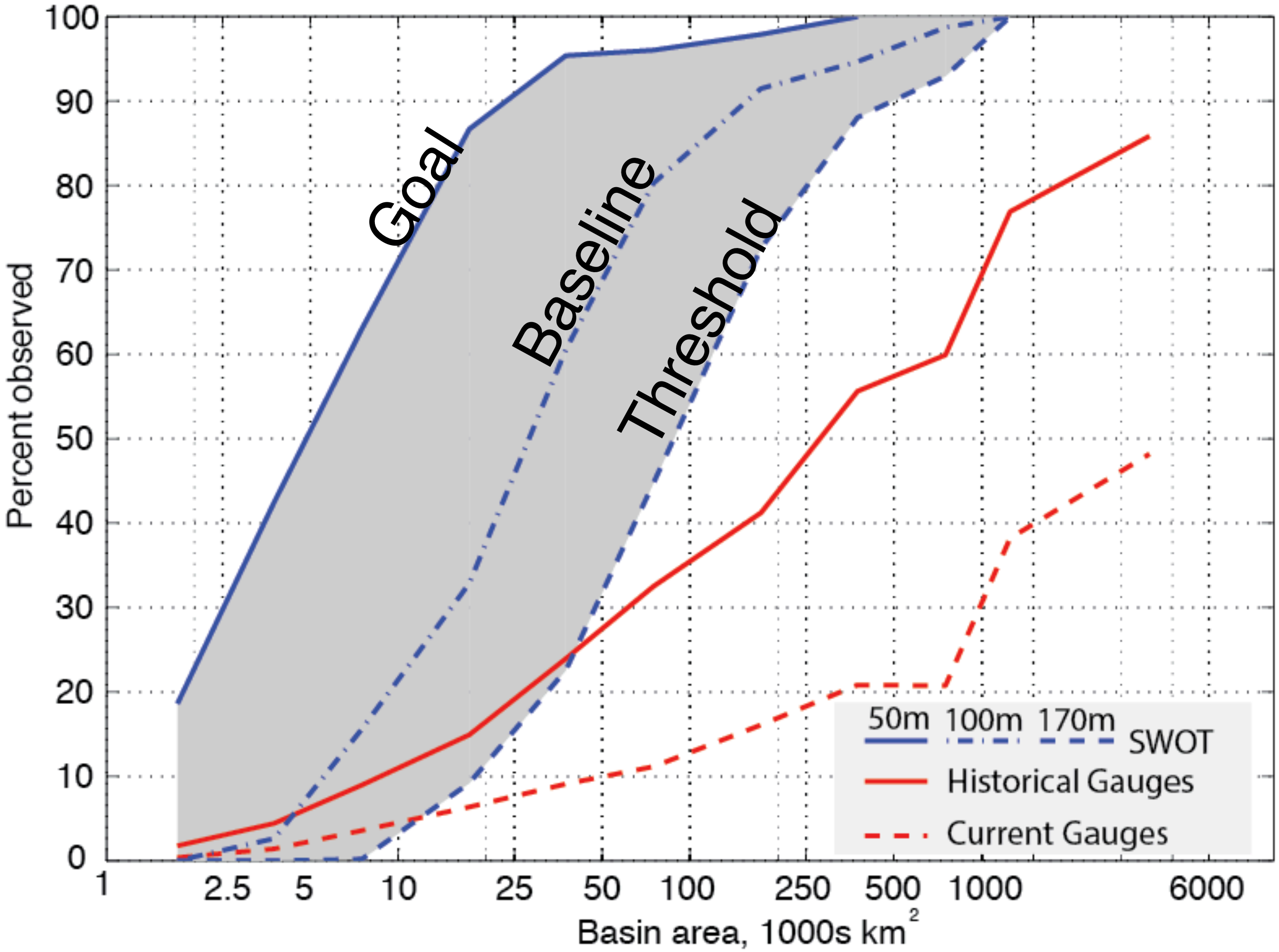
The Antarctic ice sheet has a total area of ~ 14,000,000 km^2 and averaged ice sheet thickness of ~ 2.16 km, accounts for 90% of the world's ice and 75% of the world's fresh water resources, and has the potential to raise the global sea level by over 70 meters if completely melt.

Surface Water Ocean Topography (SWOT) Mission Goals



- SWOT is a NASA decadal review mission that will provide a quantum improvement for oceanography and hydrology
- Oceanography: First global determination of the ocean circulation, kinetic energy and dissipation at high resolution
- Hydrology: First global inventory of fresh water storage and its change on a global basis

SWOT Performance Requirements: Rivers



Width to drainage area translation:

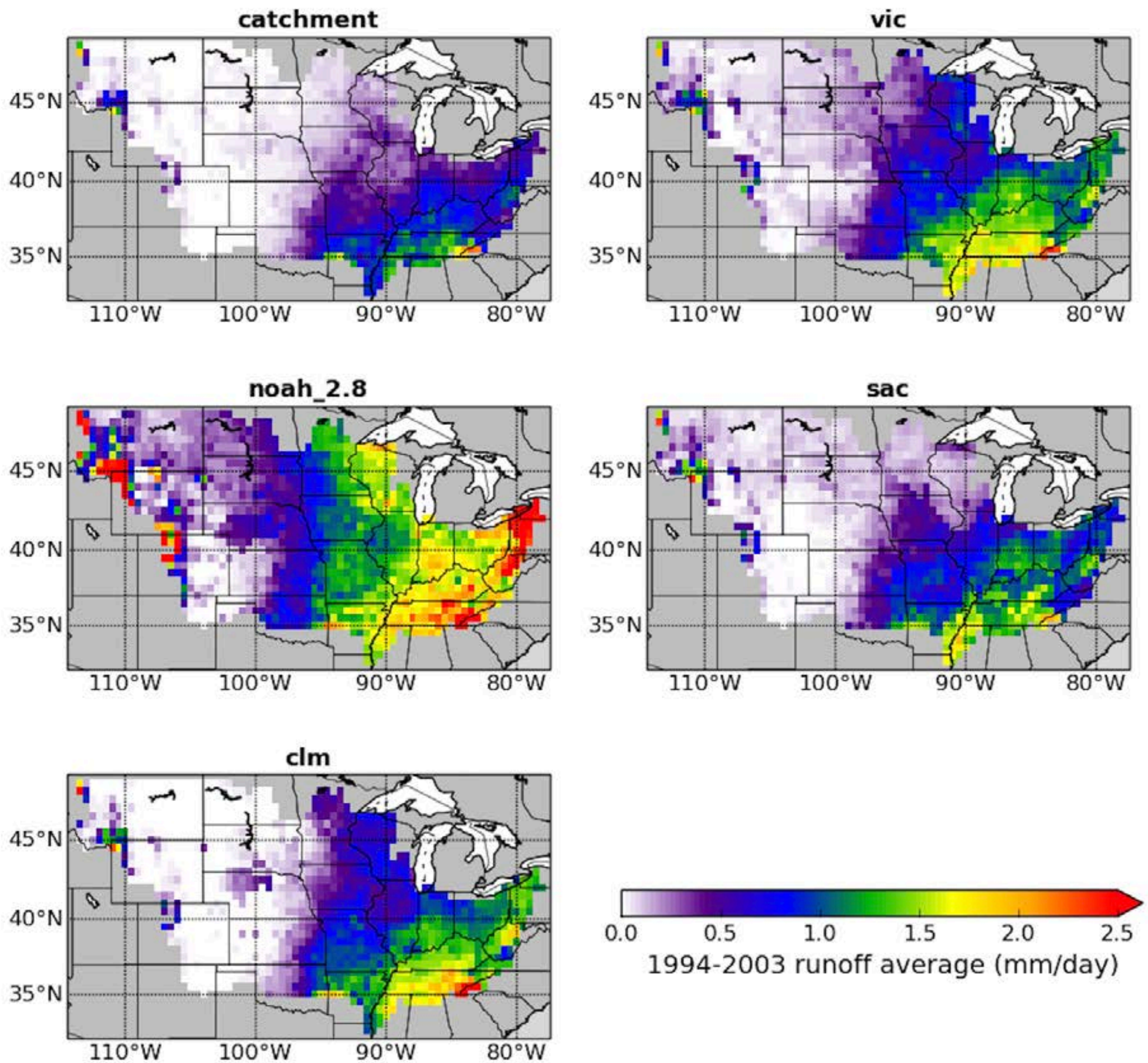
50 m ~ 10,000 km^2
100 m ~ 50,000 km^2
170 m ~ 150,000 km^2

SWOT will give us globally consistent observations of river height and discharge and these spatial scales for the first time.

Tamlin Pavelsky

from Pavelsky et al., in review, J. Hydrology

Understanding the Water Cycle

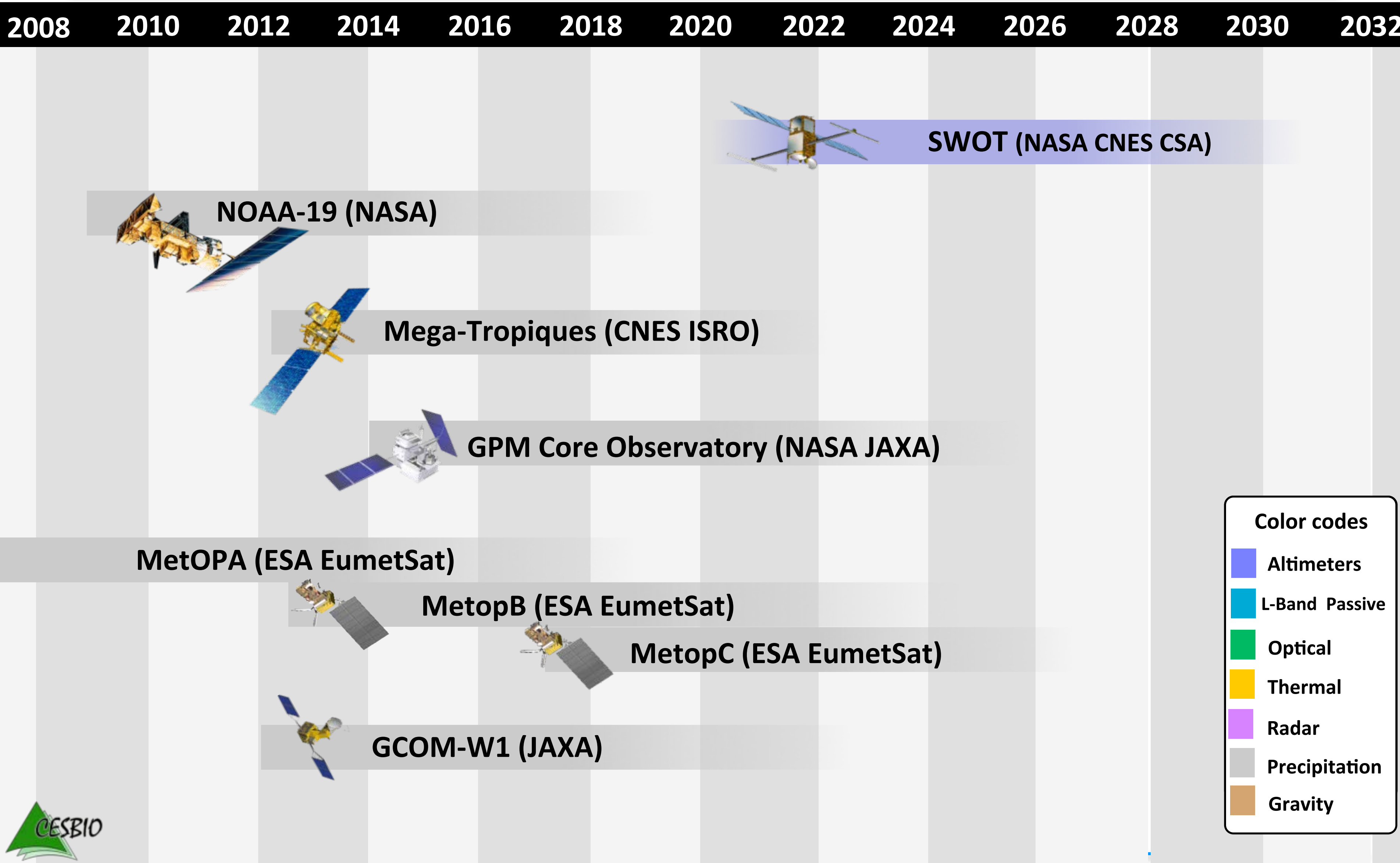


- To understand how climate change will affect the water cycle (both average and extreme events), we need to understand how precipitation is partitioned into evapotranspiration and runoff.
- Our ability to accurately partition precipitation is limited, in part because we lack globally consistent runoff data to constrain models.
- SWOT must provide runoff data at sufficiently fine spatial scales to constrain regional patterns.

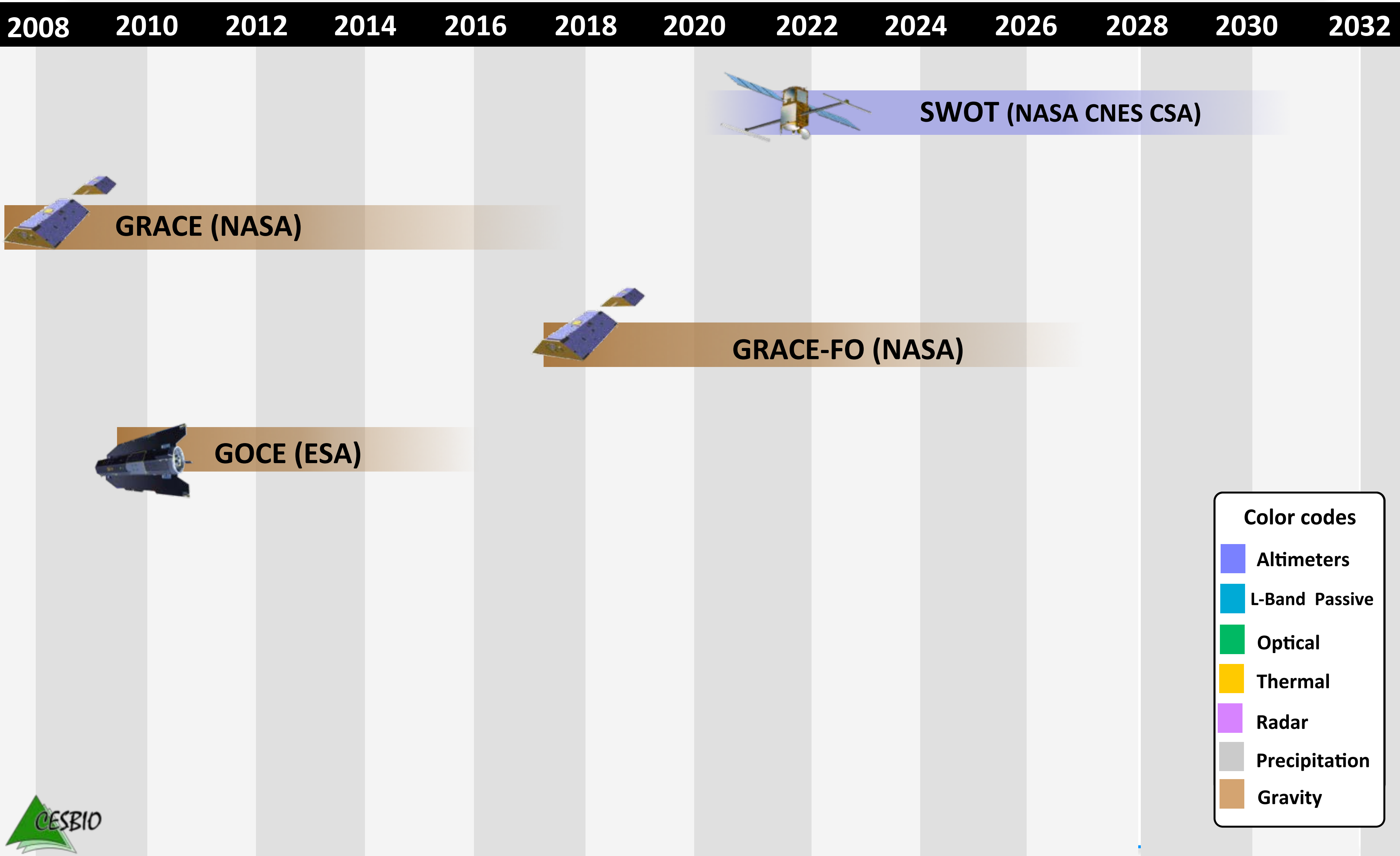
Current models simulate very different patterns of runoff

From D. Lettenmaier

SWOT Precipitation Missions



SWOT & Gravity mIssions



What we need?

- Better monitoring of the ocean Salinity field (ARGO, Aquarius, TSGs on VOS, etc) to assess change in the global water cycle. Need Aquarius salinity mission follow-on.
- Process studies to understand the ocean's response to freshwater forcing, both precipitation and evaporation.
- Better measurements of rainfall over the ocean.
- Argo floats: high vertical resolution in the surface layer, sampling closer to the sea surface, and burst (high frequency) sampling of the surface layer for diurnal and event-scale. Urgent need for Deep-Argo floats.

  Deep Argo also will (eventually) be valuable for estimating the dilution of the oceans due to melting ice. However, this signal is quite small in the volume-averaged salinity of the ocean, and likely will take decades to detect.
- No long-term rain gauge net work of meteorological stations with century-long records.

SUMMARY: Oceans and Global Water Cycle

- Most of the GWC is over the oceans
- Changes in the water cycle have impact on salinity and seawater density, and thus modulate oceanic mixing and the uptake of heat and CO2
- Trends in ocean salinity are very similar to the mean salinity distribution, supporting an intensification of the water cycle well above that predicted by models.

SUMMARY: Oceans and Global Water Cycle

- These salinity changes are due largely to trends in evaporation and precipitation over the ocean; rivers and glacial melt play only a minor role.

- Ocean advection and mixing processes must be understood to calibrate the SSS - E-P relationship.

- In future SWOT mission will improve our understanding of fresh water storage (rivers, lakes).