Surface circulation and ventilation

Lynne D. Talley
Scripps Institution of Oceanography, UCSD

Plenary White Paper Tuesday, Sept. 22
OceanObs'09 Venice, Italy

Closely associated CWPs (self-identified): Cronin, Dohan, Griffies, Hood, Lagerloef, T. Lee, Mackinnon, Masumoto, Meldrum, Rintoul, Send OceanSITES, Send WBCs

Closely related CWPs (not self-identified): Freeland/Roemmich, Fu, Goni,, Gruber, C. Lee, LeTraon, McPhaden, Meldrum, Shum, Stammer/Kohl

Related CWPs (not self-identified): Feely, Gordon, Kwok, Palmer, Smith

OceanObs'09 committee suggested this very ambitious approach:

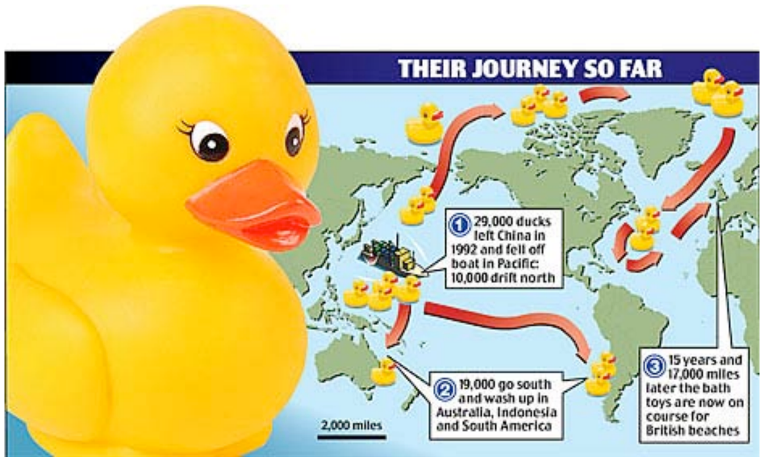
- What was the state of knowledge about 10 years ago?
- What critical new discoveries have been made in the past 10 years?
- What observational and modeling tools were central to the discoveries?
- What in the proposed observing plan will continue the trajectory of discovery?

Plenary white paper task:
Broad participation and authorship invited.
Look for me during meeting – poster session
Email: ltalley@ucsd.edu and please put "white paper" in subject

Ventilation and surface circulation: motivation

Surface circulation: interface of oceans with

- euphotic zone
- coastal regions
- atmosphere via air-sea fluxes
- humanity (shipping, pollutants, search and rescue, etc.)



Upper ocean circulation and overall ventilation:

- sequestration and injection of surface properties (gases, heat, etc)
- upwelling from underlying layers
- volumetrically most significant transports (heat, etc.)

Part 1. Surface and upper ocean circulation

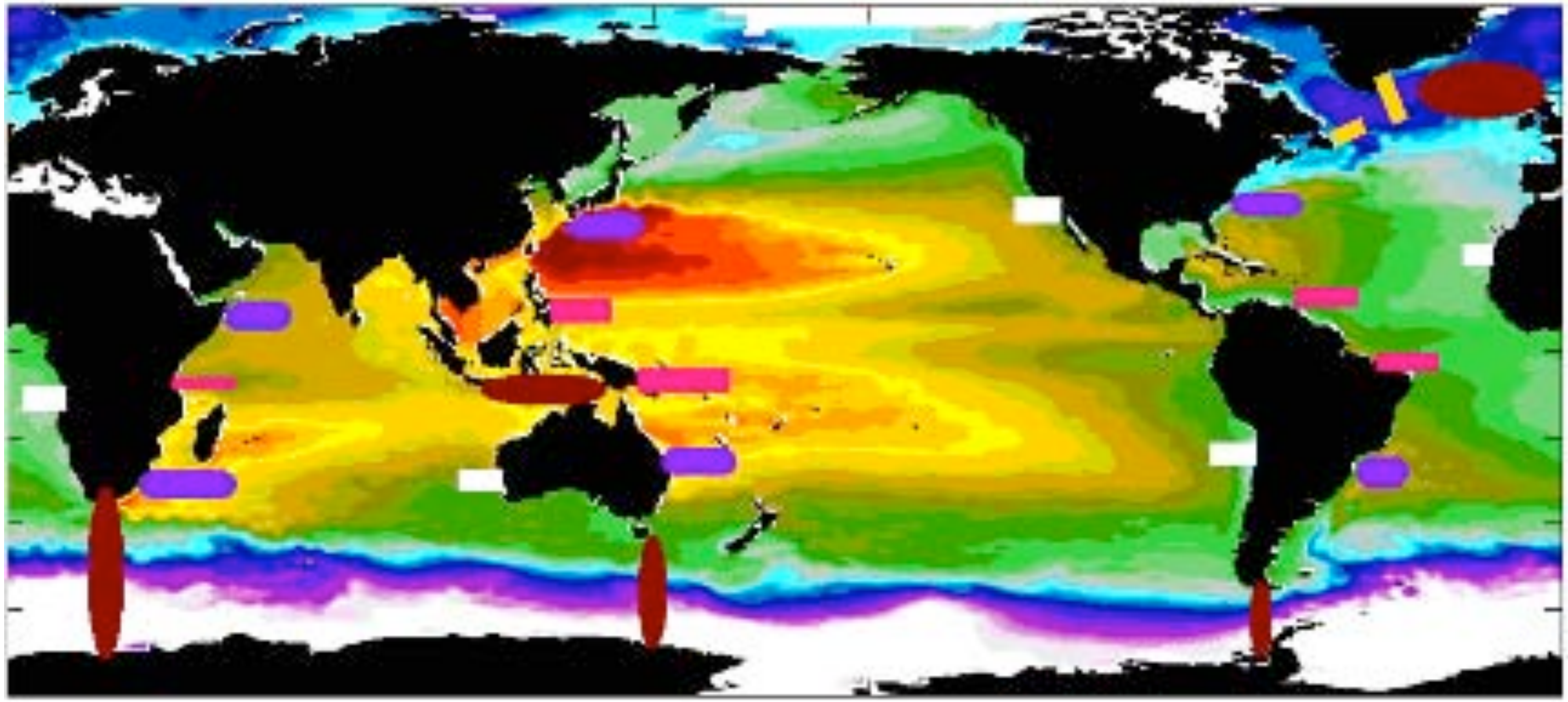
Surface and upper ocean circulation basics

Different regimes, with different sampling requirements

Western boundary currents and WBC extensions: deep, energetic, large transports

Interior non-tropical ocean: broader scale, weaker flow, shallow fronts
Interior tropical ocean: strong zonal flows, typically layered
Interior Southern Ocean: Antarctic Circumpolar Current – deep, energetic

Eastern boundary currents: upwelling regions (ST gyres), shallow, variable, weak



Send CWP, Map from Rio et al., 2007

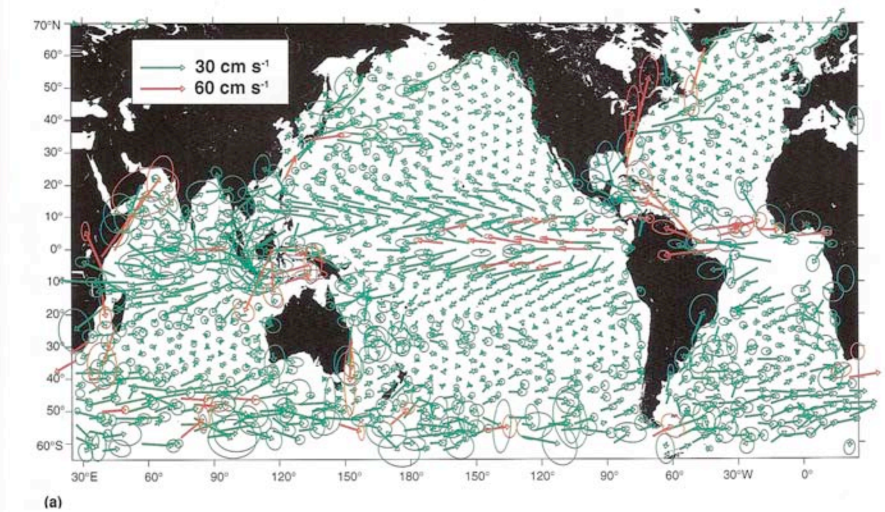
Surface circulation: Insights 1999-2009

Include upper ocean circulation and boundary currents

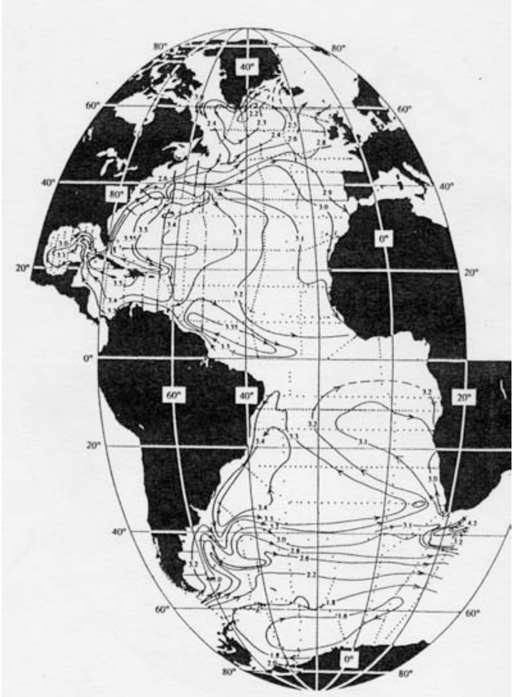
Products	1. High quality, high resolution (mesoscale) global scale mapping 2. High resolution global scale mapping of variability 3. High resolution boundary current mapping and variability
Science Examples	1. Zonality of major ocean current structures in many places 2. Ubiquitous existence of closed eddies (cyclonic and anticyclonic) 3. Strength of near-inertial motions in storm track regions as well as tropics 4. Evolution of currents – dynamical processes and climate timescales 5. Mid-latitude feedback from ocean to atmosphere
Techniques	1. Global surface drifter program 2. Global profiling float program, SOOP (VOS) program 3. Satellite surface height (altimetry) 4. Other satellite observations that are used for blended products: winds, SST, air-sea fluxes 5. Data assimilation 6. High resolution ocean models 7. Local process experiments

What progress has been made in upper ocean circulation?

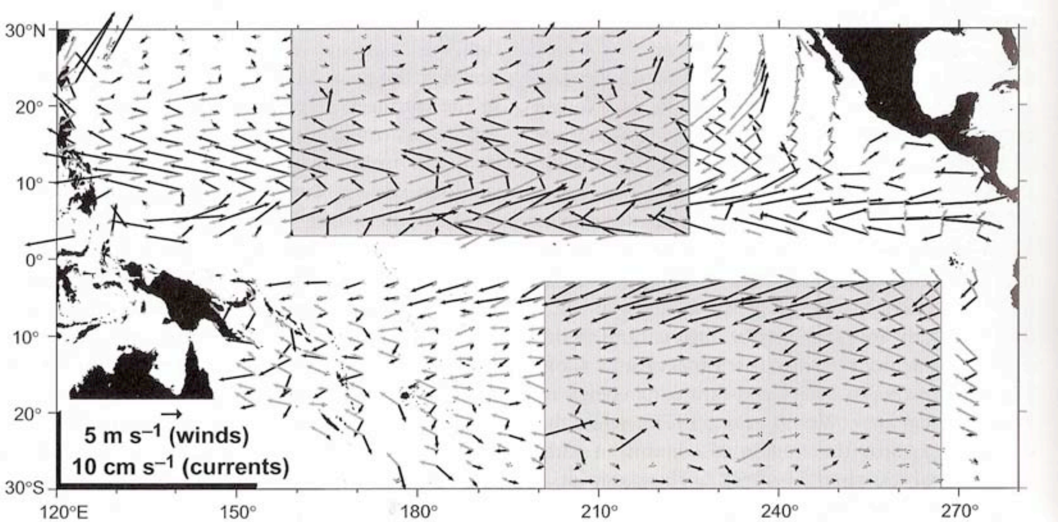
Pre-2000: Global mean 15 m velocity from drifters, 1978-1999, 2°x6° resolution (Niiler, 2001)



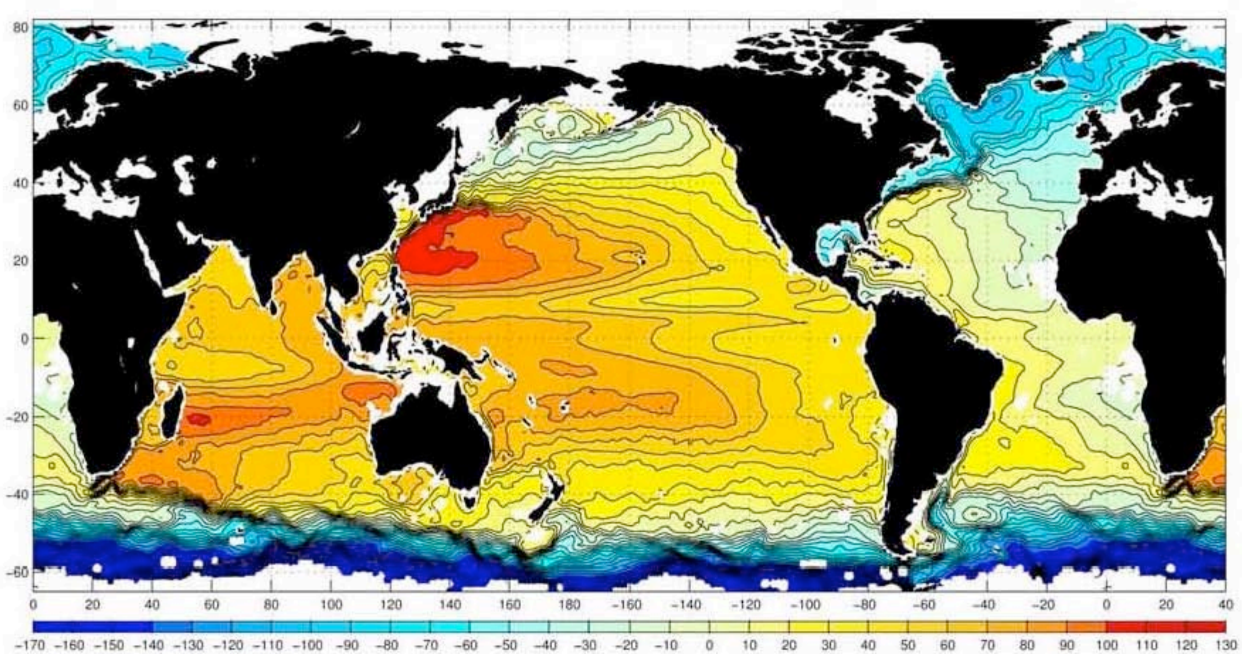
Pre-2000: geostrophic flow from hydrographic data Reid (1994)



Pre-2000: Demonstration of basin-scale Ekman response, using drifters, winds and climatological geostrophic flow (reviewed in Niiler, 2001)

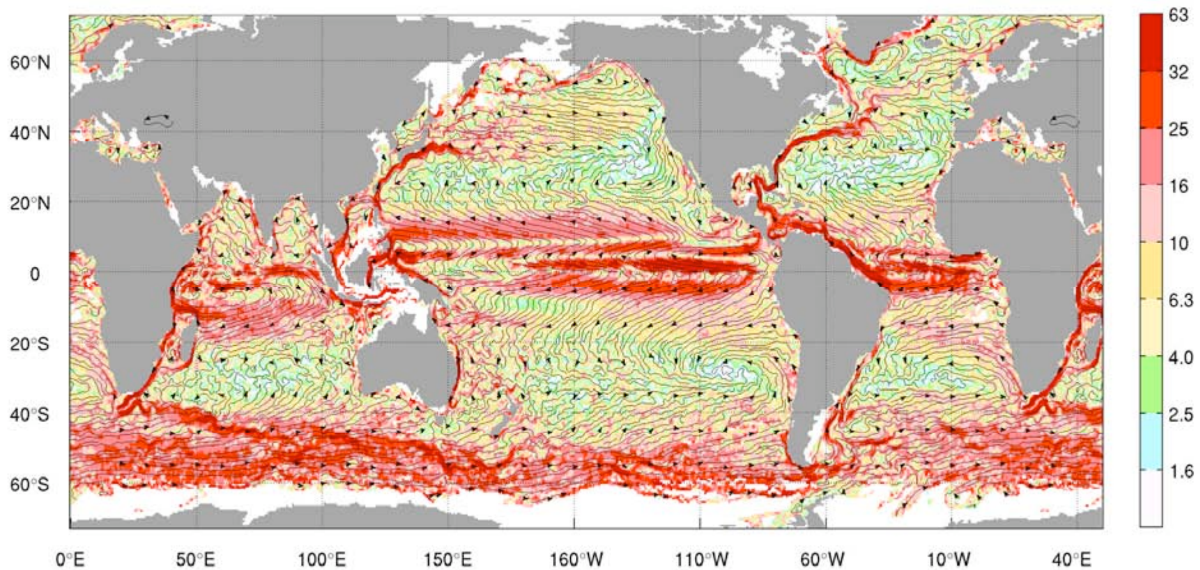


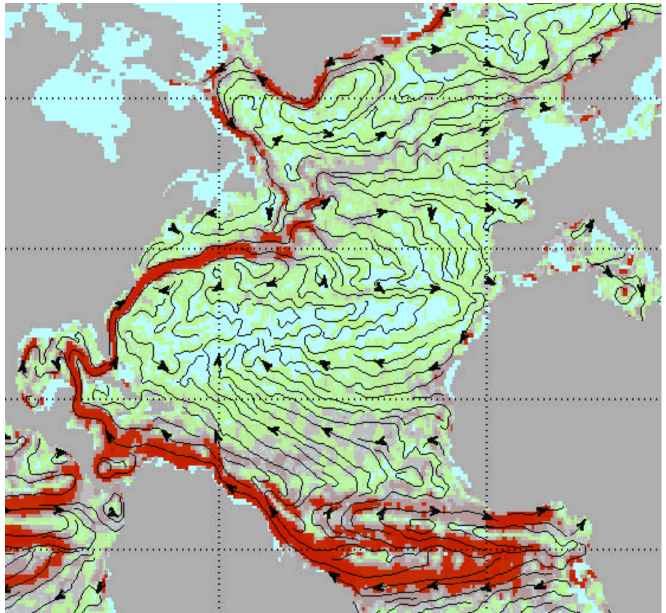
Surface circulation: 1999-2009



From surface drifters (15 m) (Niiler et al., 2003)

From surface drifters (1° resolution) (Maximenko et al., 2009)

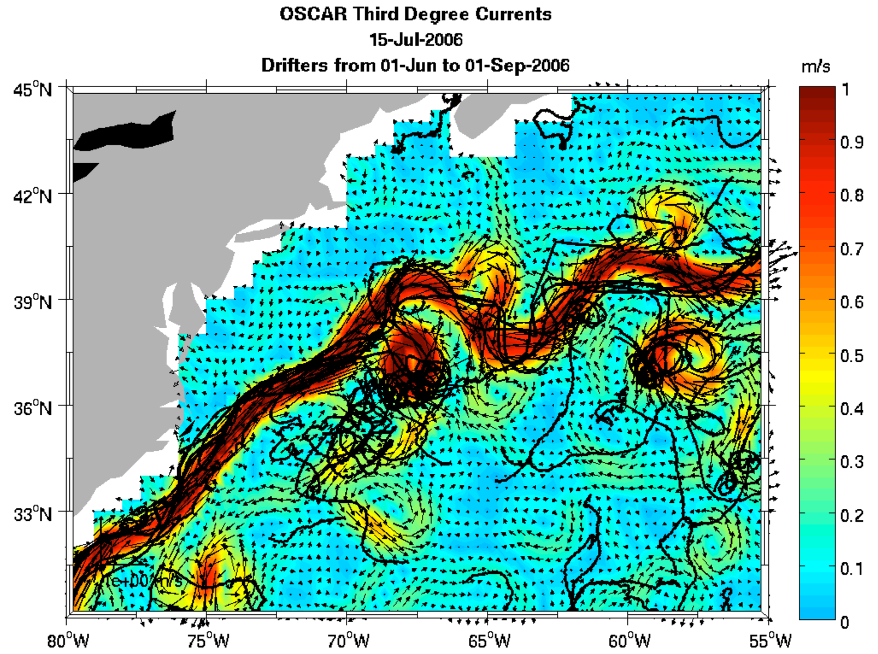


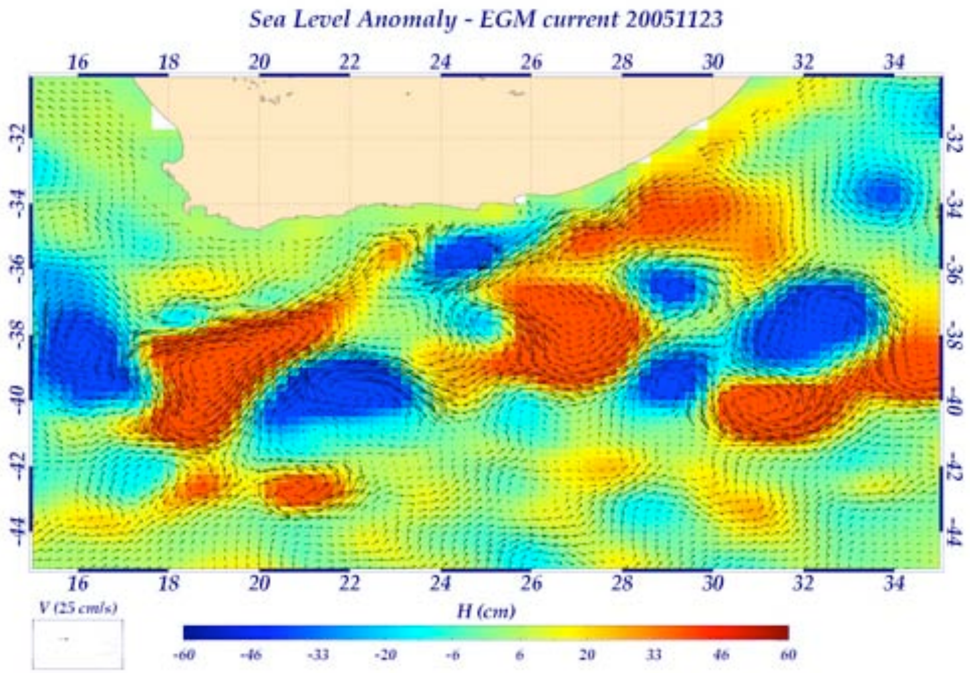


Surface circulation 1999-2009

High resolution surface currents (Dohan CWP, 2009)

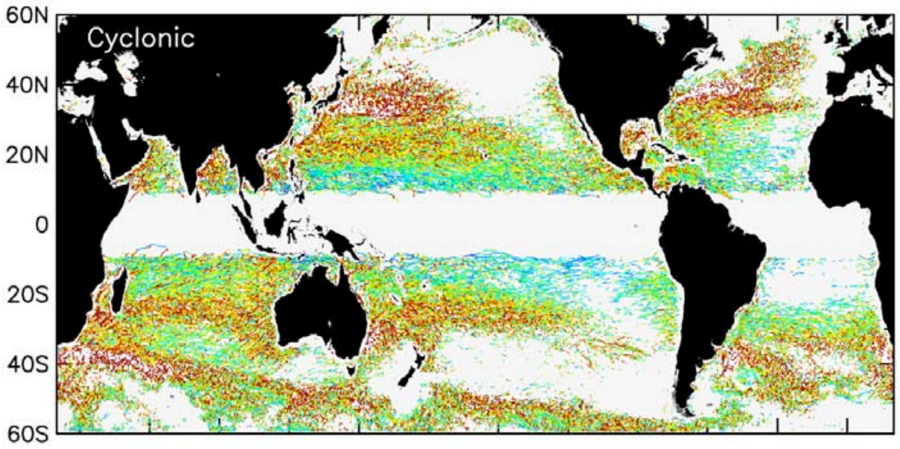
Example 1 from U.S. NOAA: OSCAR (http://www.oscar.noaa.gov)
1/3° mapping of surface velocity
Can therefore watch evolution of mesoscale features.



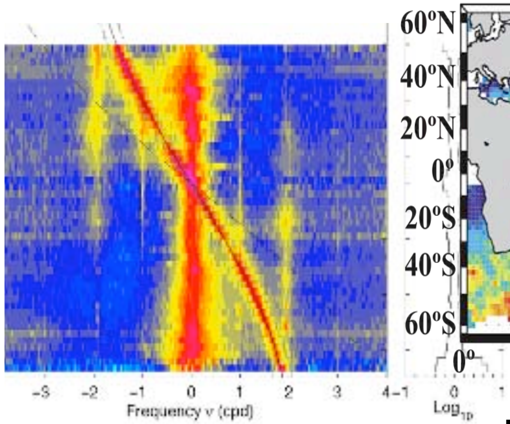


Example 2 from CTOH: ¼°grid every 10 days 1993-2006 using altimetry, scatterometry and climatology
http://www.legos.obs-mip.fr/en/soa/altimetrie/ctoh/SURF_CUR/

Surface circulation 1999-2009

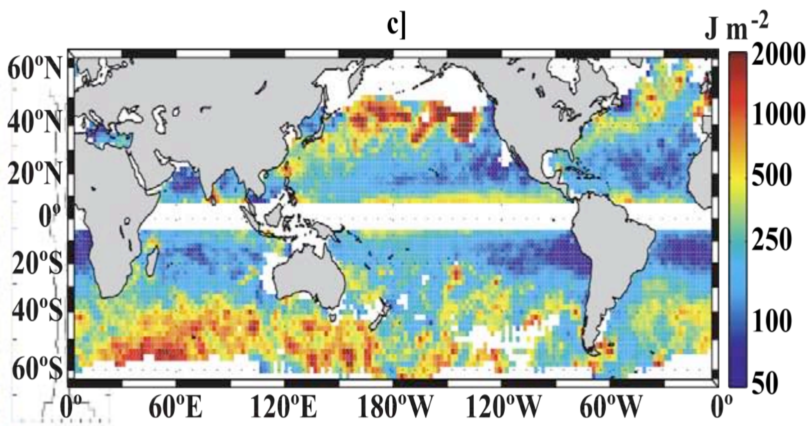


Coherent eddies with lifetimes of more than 4 weeks based on altimetry data (Chelton et al., 2007) (only "cyclonic shown here")



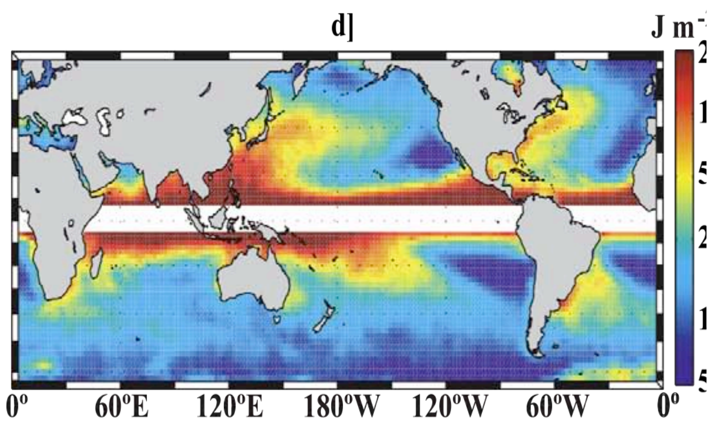
(Elipot and Lumpkin, 2008)

Observed near-inertial energy



Highest observed energy in the storm track regions of both hemispheres.

Modeled inertial energy



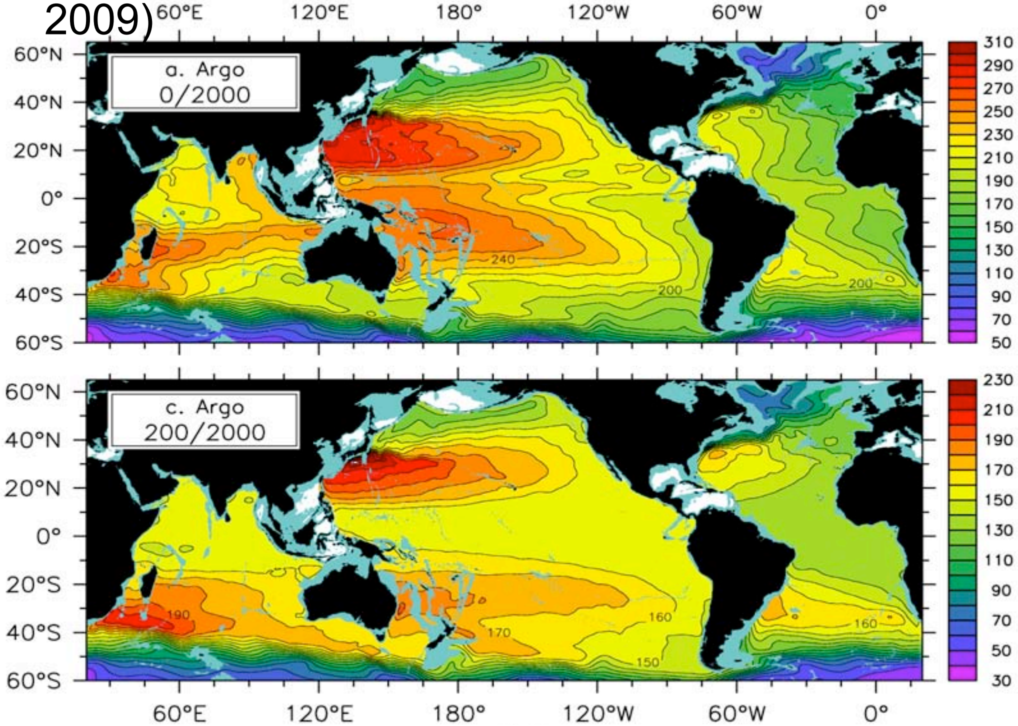
(Chaigneau et al. 2008)

Upper ocean (subsurface) circulation: 1999-2009

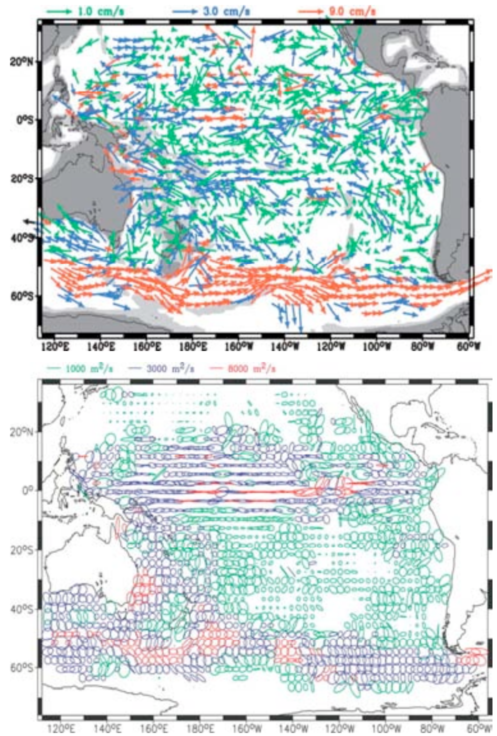
The subsurface circulation differs significantly from the surface circulation, as is well known. Present mapping of subsurface circulation is far less detailed than surface circulation because of absence of high resolution observations.

Progress to be made using in situ profiling, coarse subsurface float deployments, and data assimilation.

Argo profiles: 0 and 200 dbar dynamic height relative to 2000 dbar (Roemmich and Gilson, 2009)

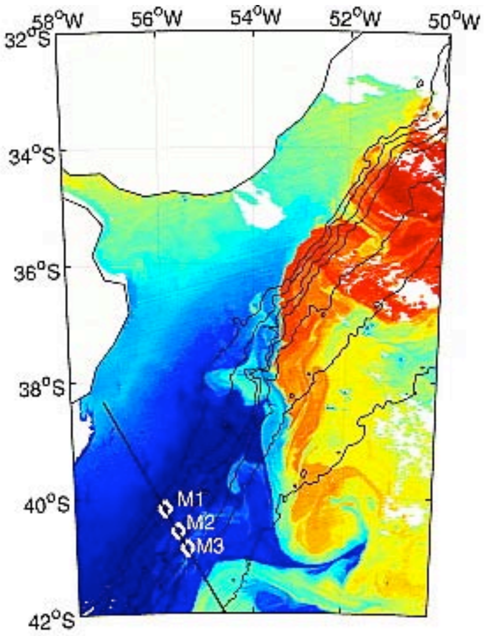


900 m circulation and lateral diffusivity from WOCE profiling floats (Davis, 2005)

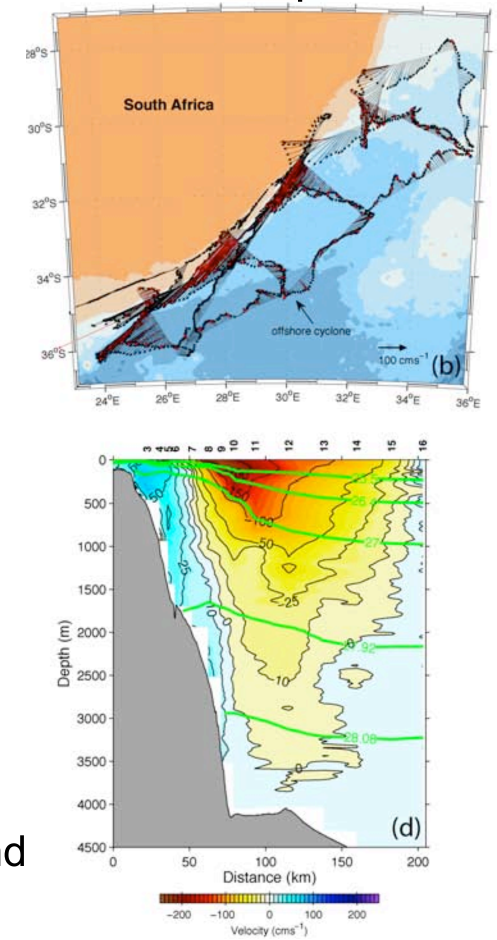


Western boundary currents

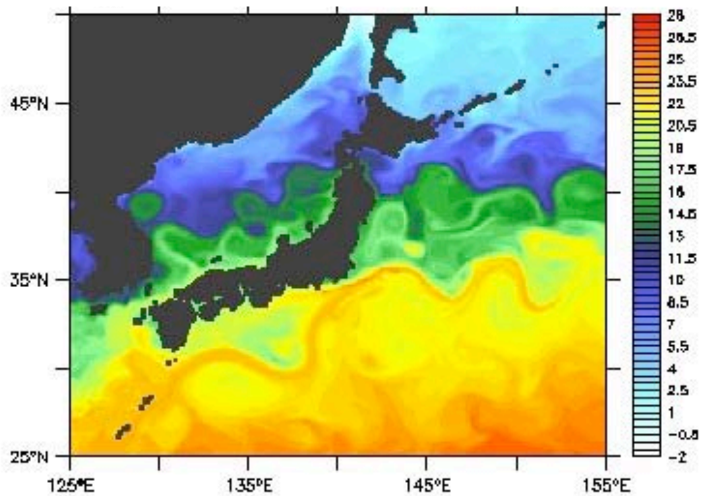
Western boundary currents are energetic, narrow and deep.
They carry large transports.
Appropriate techniques for observing: satellites, dedicated observing systems (moorings, repeat velocity sections, frequent drifter launches)



Brazil Current and Malvinas confluence (1.1 km MODIS on Aqua SST image) (Spadone and Provost, 2009)



Agulhas velocity structure (Beal et al., 2006)

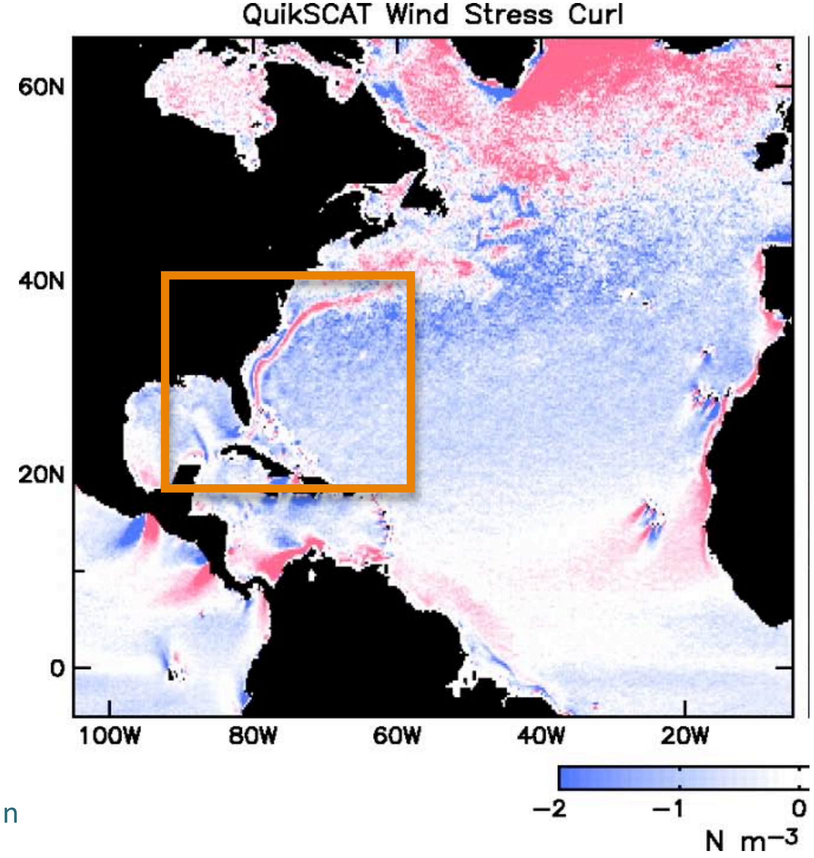


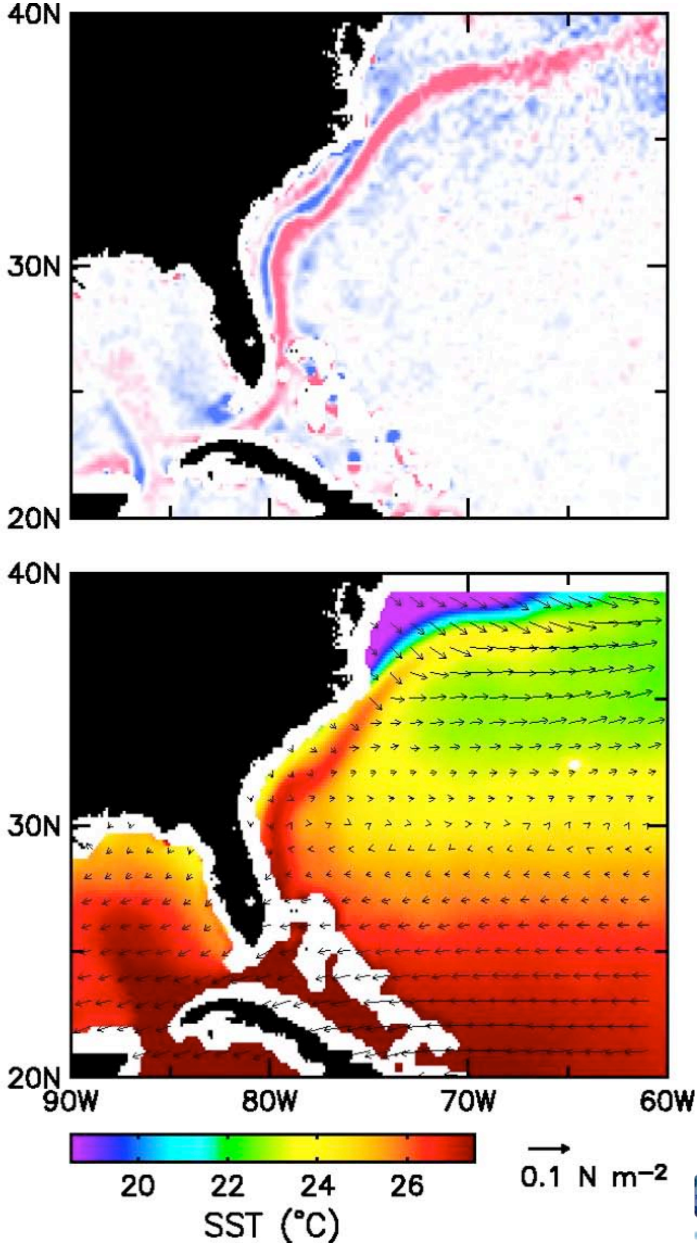
High resolution global ocean modeling (Maltrud and McClean, 2005)

Boundary currents, strong fronts and the atmosphere

Relation of strong ocean frontal features to surface winds, implying feedback on atmosphere in some locations (Chelton et al., 2004).

Appropriate techniques for continued progress: high resolution winds, SST, dedicated western boundary current and WBC extension observations





Surface and upper ocean circulation 1999-2009

Technology and data systems

Mapping upper ocean circulation with much higher temporal and spatial resolution than prior to 2000:

Surface drifter network
Profiling float network
Mooring systems (TAO, PIRATA, RAMA, OceanSITES, etc.)
Satellite altimetry, winds, SST, air-sea fluxes

In situ T-S from ships, VOS, Argo to map subsurface circulation

Modeling and data assimilation

Narrow western boundary current regimes:
Moored arrays of current meters and air-sea flux buoys, repeated cruises, VOS lines

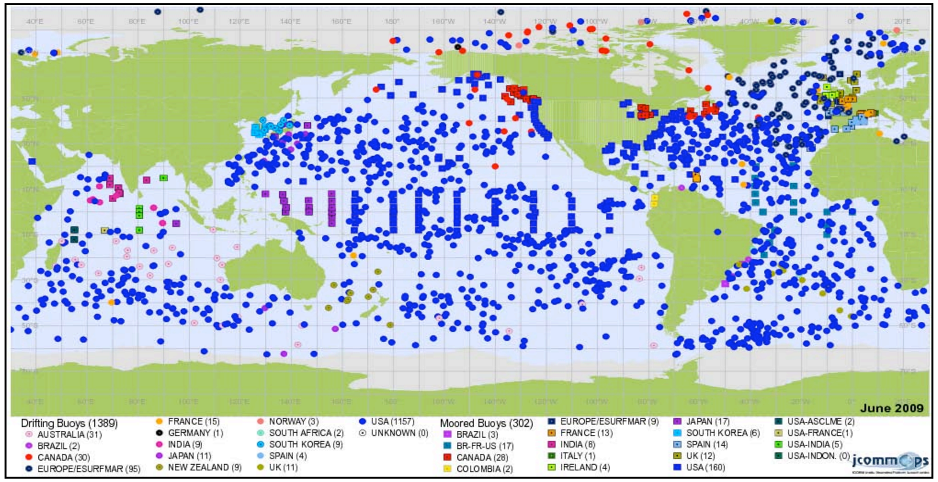
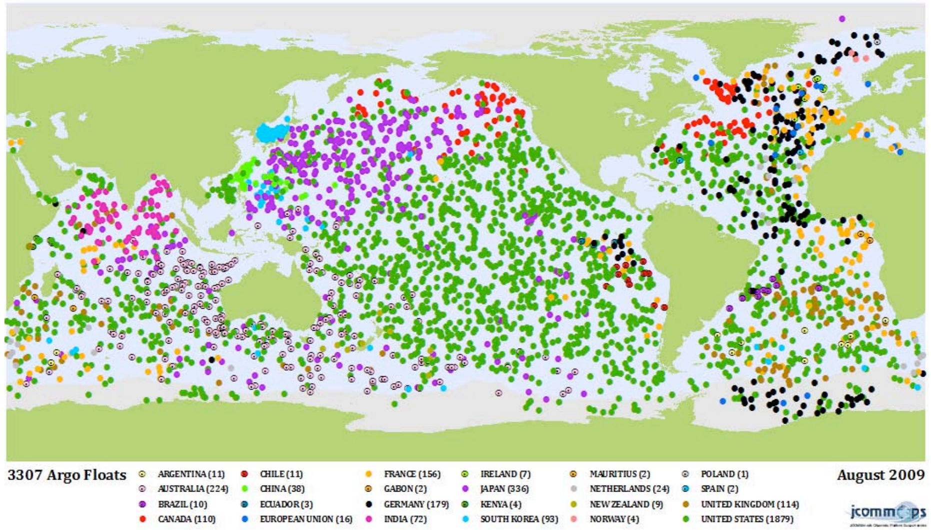


Fig 5. *The global distribution of data buoys reporting via the GTS in June 2009, coloured according to deploying country/agency.*

Data Buoys reporting in 2009 (jcommops)
(Meldrum CWP)



Argo profiling floats (by country)
(Freeland/Roemmich CWP)

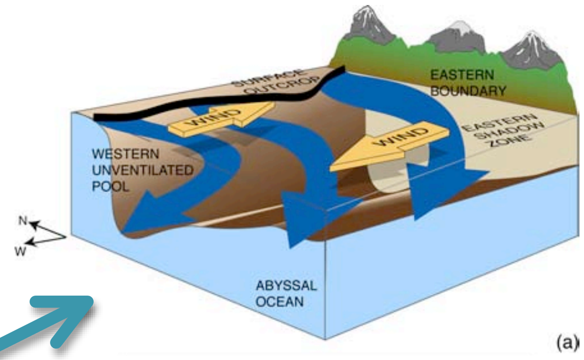
Part 2. Ventilation

Ventilation basics

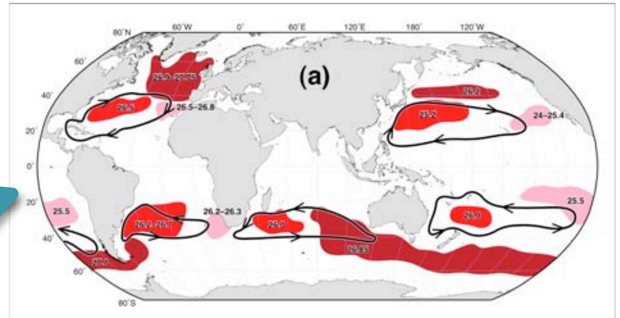
The mixed layer is in contact with the atmosphere.

Connection to the interior causes the interior to be “ventilated”.

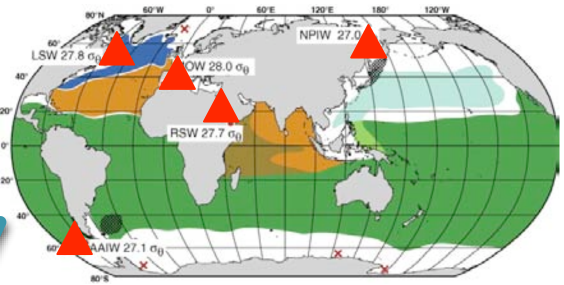
Subduction: Movement of water down along constant density surfaces (upper ocean, subtropical gyres).



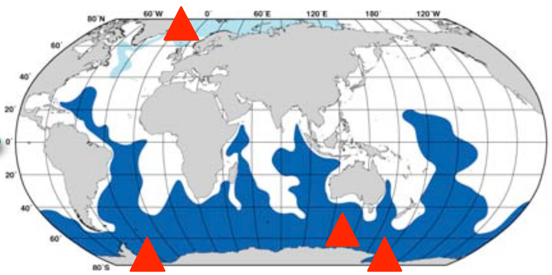
Convection in upper ocean, often involving very strong fronts (Gulf Stream etc.): creation of “Mode Waters”. Monitor using repeat shipboard and moored observations, Argo profiling



Deep convection (> 1000 m): known, isolated locations, but still reachable by Argo profiling



Brine rejection due to sea ice formation: high latitudes, can produce very dense water



Ventilation 1999-2009

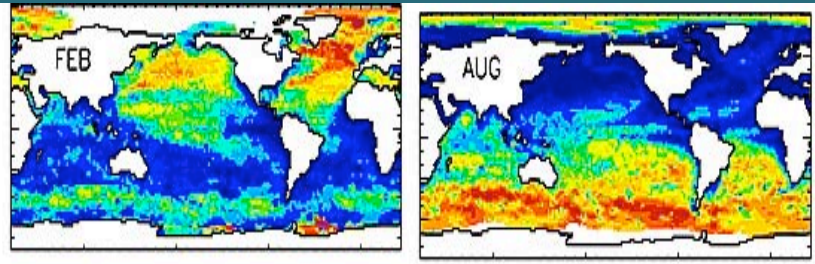
Products	1. Global scale products of ventilation-relevant properties 2. Air-sea flux estimates of ventilation rates (Walin-type) 3. Gyre-scale studies of ventilation, mainly mode water production 4. Local deep convection studies 5. Studies of connection of mixed layer to ocean interior
Science Examples	1. Depth dependence of recently ventilated water column readily recognized and quantified from T/S changes, chemistry 2. Great complexity of processes involved in mode water production near strong fronts 3. Heterogeneity of mixing in the connection from mixed layer to the interior 4. Importance of mesoscale (eddies and major currents) and submesoscale (filaments and fronts) for ventilation
Techniques	1. Global profiling float program and VOS program (historical) 2. Global scale hydrographic observations 3. Local process experiments including seasonal cycles, mixing processes 4. Satellite observations of SSH, SST, winds, air-sea fluxes 5. Reanalysis products yielding air-sea fluxes, winds, etc., and ocean data assimilation products 6. Very high resolution modeling

How have we observed ventilation?

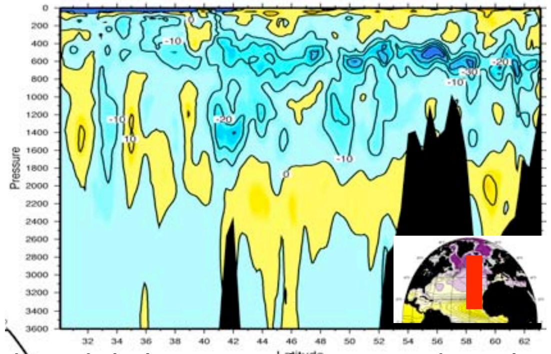
Mixed layer:

Evidence of ventilation:
- temperature and salinity changes (VOS, research ship observations, Argo profiling)
- oxygen content and changes (research ship, possible from Argo if implemented)
- chlorofluorocarbon content (research ship – Repeat Hydrography program)
- anthropogenic carbon content (research ships – Repeat Hydrography program)

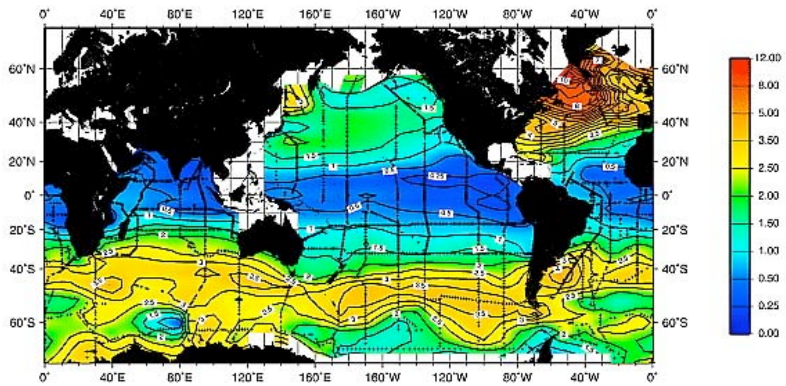
Subduction:
- T/S profiling: explanation of observed structure
- Transient tracers and oxygen
- Process experiments from research ships with velocity, T,S, O_2



ML depth in winter (de Boyer Montegut et al., 2004)



O_2 decadal change: Johnson and Gruber (2005)



CFC column inventory (Willey et al. 2004)

How have we observed ventilation? (slide 2)

Mode Water production near strong fronts: Proving to be very complex mix of processes, no simple answer about formation process

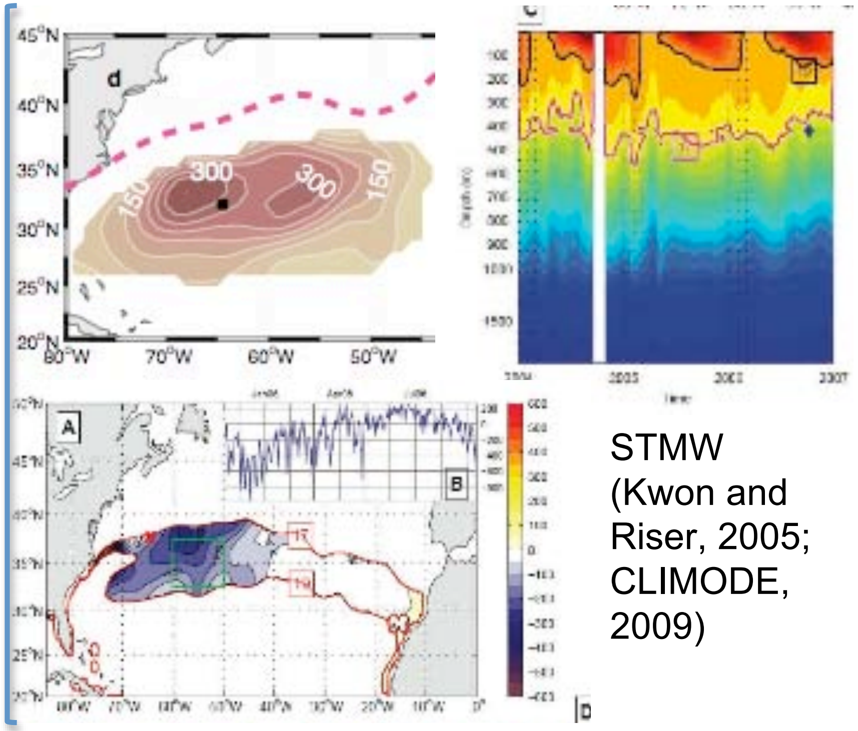
- Repeat shipboard observations
- Argo profiling
- Intensive process experiments

Deep convection:

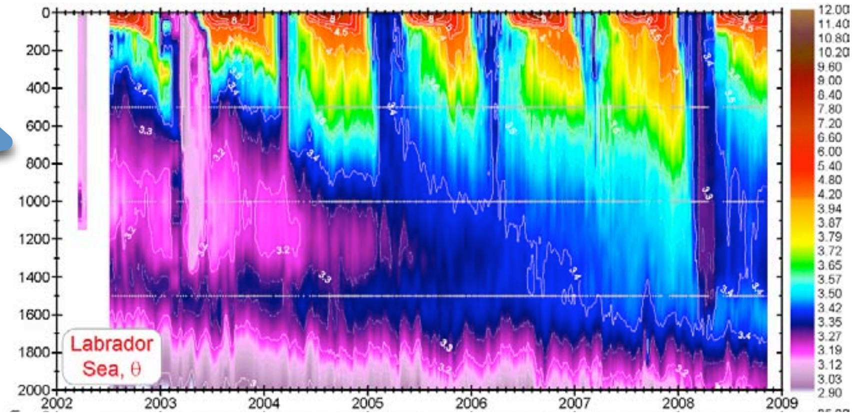
- Routine research ship sampling in the known locations for convection.
- Argo profiling.

Brine rejection:

- Moored observations in the known locations for densest brines
- Shipboard observations, mostly in summer showing evidence for previous winter brine rejection



STMW (Kwon and Riser, 2005; CLIMODE, 2009)



Labrador Sea convection (Yashayaev, from Freeland CWP)

What do we really not understand about ventilation?

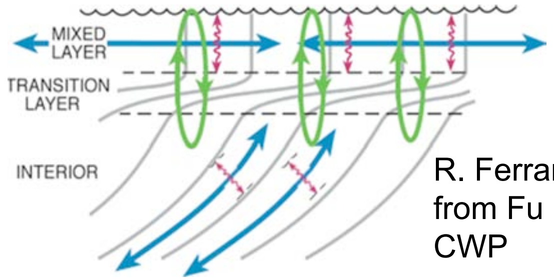
1. The connection between the surface layer and interior.

Emerging evidence for how very small scale variability (submesoscale) and even smaller scale mixing factor into the connection.

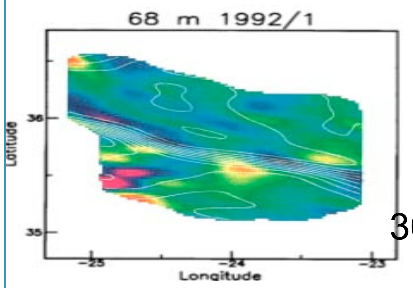
Mixing is very heterogeneous relative to the strong fronts and eddies that are usually found in strong ventilation regions (convection regions)

High resolution sampling (SWOT)
Argo profiling with EM

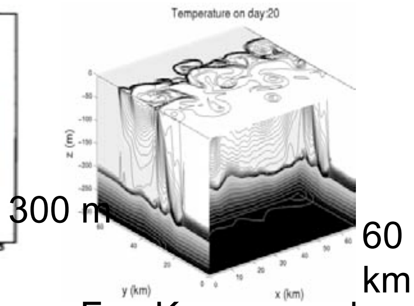
2. Destruction and return of water to surface
Argo profiling with EM and oxygen



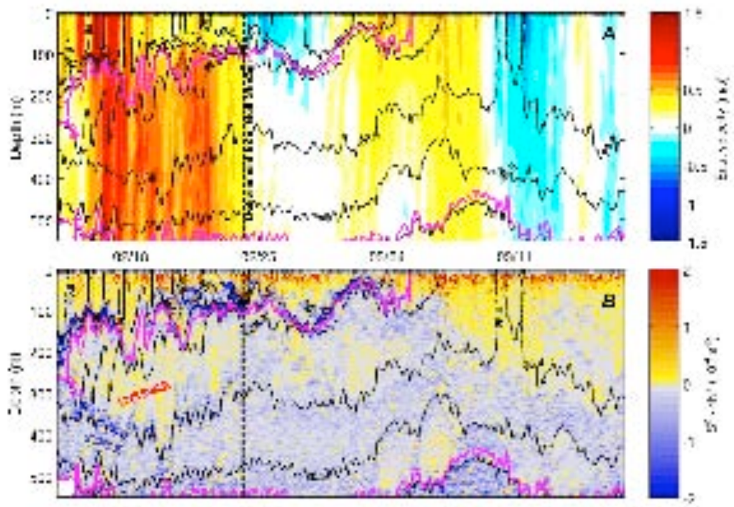
R. Ferrari from Fu CWP



Azores Front obs. Rudnick et al. (1996)



Fox-Kemper and Ferrari, 2008



Gulf Stream observations in CLIMODE (Mackinnon CWP)
Top: velocity (red-eastward)
Bottom: mixing susceptibility (yellow – unstable)

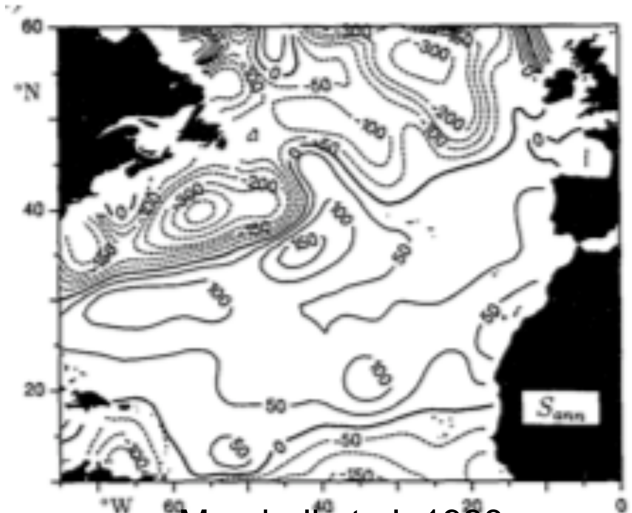
Can we quantify ventilation rates and changes?

Use of air-sea flux observations and matching surface density to calculate formation rates ("Walin approach")

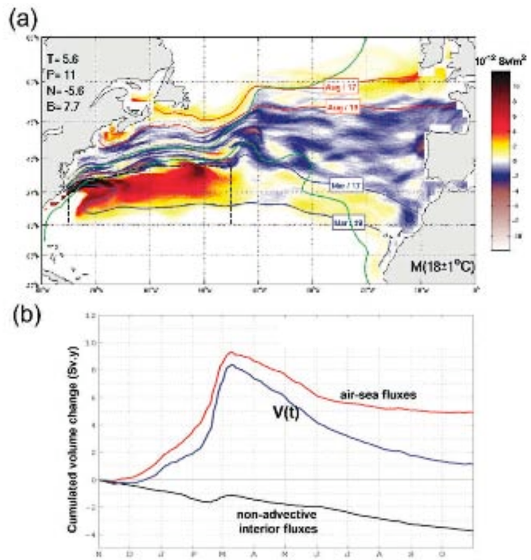
Calculation of subduction rates using winds and in situ density structure

Use of in situ observations to calculate changing volumes: seasonal and interannual resolution required to observe formation and destruction

Use of transient tracers such as chlorofluorocarbons to calculate residence times of reservoirs



Marshall et al. 1993



Forget et al. 2009; CLIMODE 2009

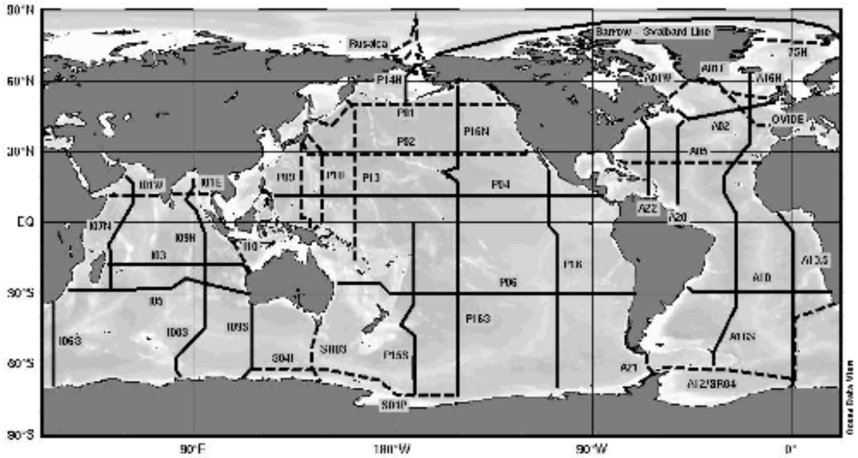
Techniques that contributed to recent knowledge of ventilation

Repeat hydrography (chemistry – oxygen, CFCs and CO2)
VOS, Argo profiling (inventories and changes in column temperature and salinity)

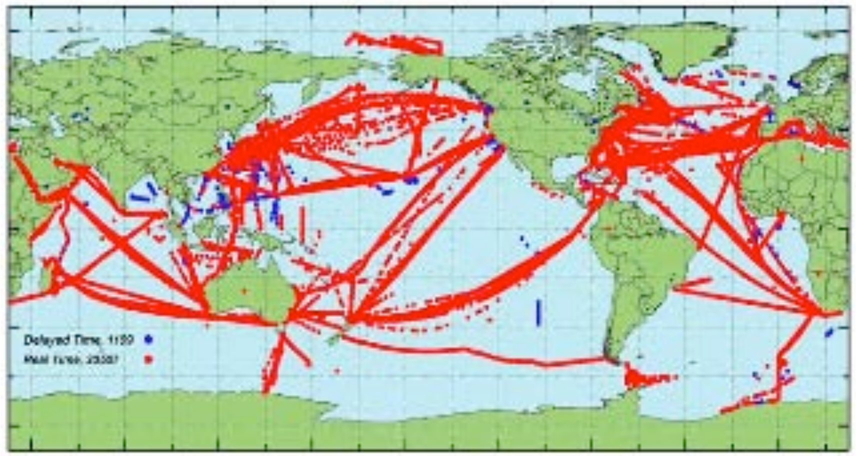
High resolution winds
High resolution surface density
Data assimilation

Process experiments including mixing

Very high resolution modeling



Hood CWP


Goni CWP

Summary: science and products

Surface circulation knowledge is essential for all areas of oceanography.

The upper ocean circulation differs from the surface circulation and is not nearly as well mapped, but is essential for advection of even near-surface waters through the global ocean.

Western boundary regions are important for transports, and possibly also for air-sea interaction (feedback to atmosphere). Eastern boundary regions differ and are important air-sea interaction and productivity.

Ventilation moves waters from the surface into the ocean, essential for sequestration and downstream feedbacks. Understanding the processes is still an area of great ferment, spurred by increasingly small scale observations and modeling, and by major process experiments. A continued variety of approaches is required, from research ships to Argo/SOOP, satellites, local monitoring. Very high quality air-sea fluxes are required for quantitative approaches.

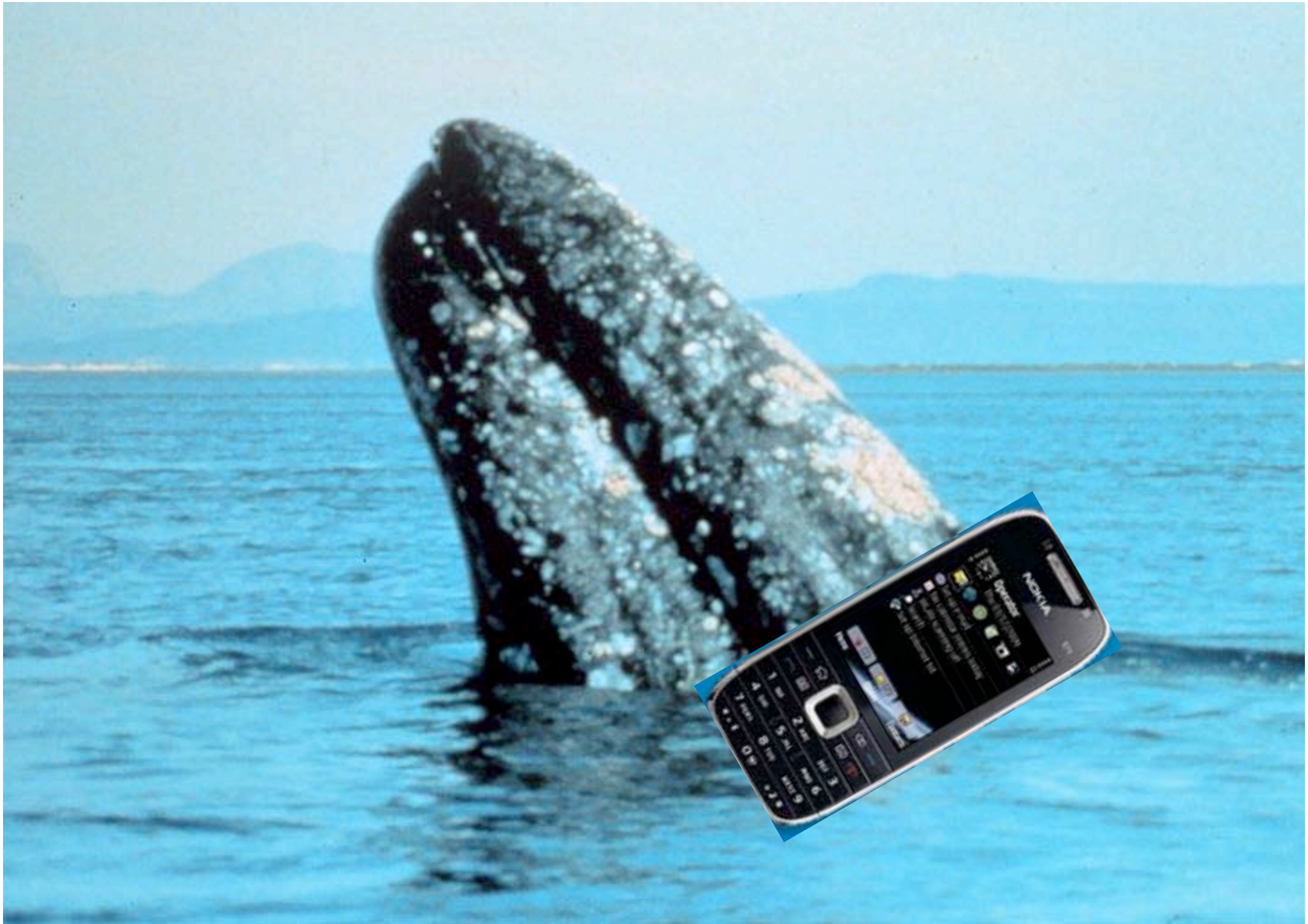
Density depends on salinity as well as temperature. Improvement of salinity products to the level of temperature products is essential for circulation and especially ventilation studies.

Summary: techniques. Where to go from here ?

1. Surface circulation
   1. Keep doing what you're doing with drifters, satellites, Argo
   2. Augment SSH resolution (Fu CWP)
   3. Ensure surface salinity observations associated with SST (Freeland CWP, Lagerloef CWP)
   4. Western boundary current observatories (Send WBC CWP)

2. Subsurface circulation
   1. Get better at it.
   2. Argo and VOS derived products (Freeland, Goni CWPs)
   3. Data assimilation. (LeTraon, Stammer CWPs)
   4. Western boundary current observatories for transports (Send WBC CWP)

3. Ventilation processes
   1. Argo profiling with oxygen, EM, higher sampling in some regions and VOS where operating (Freeland, Goni. Gruber, Mackinnon, Cronin CWPs)
   2. High resolution SSH (SWOT) (Fu CWP)
   3. Western boundary current extension observatories (Cronin CWP)
   4. Air-sea flux observations (Send OceanSITES CWP, reanalyses, assimilation)
   5. High resolution global surface SST and SSH, winds
   6. In situ chemistry from research ships (oxygen, CFCs, carbon, very high accuracy T and S) (Hood CWP)


NOKIA