Eastern boundary current observing systems – current status and observational gaps

Frederick Bingham and Carol Anne Clayson

With much help from R. Perez

Why observe eastern BCs (EBCs)?

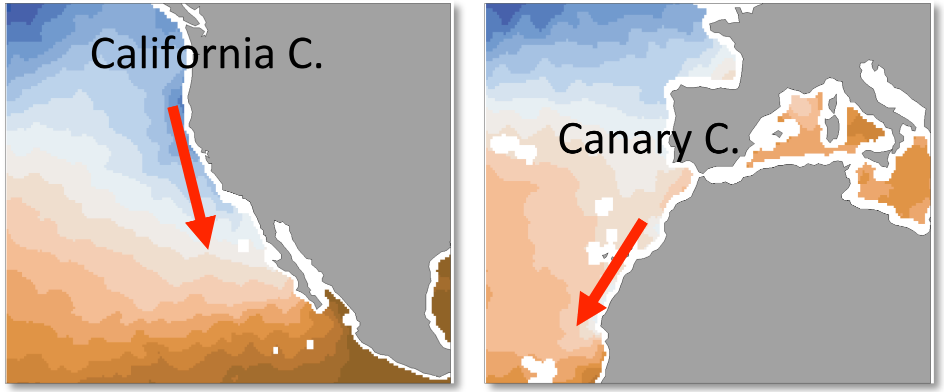
Societally relevant effects of climate

Upwelling, cross-shore exchange (nutrients, carbon)

Ecological hotspots

Equatorial interactions (ENSO-blob)

Oxygen minimum zones (OMZs)



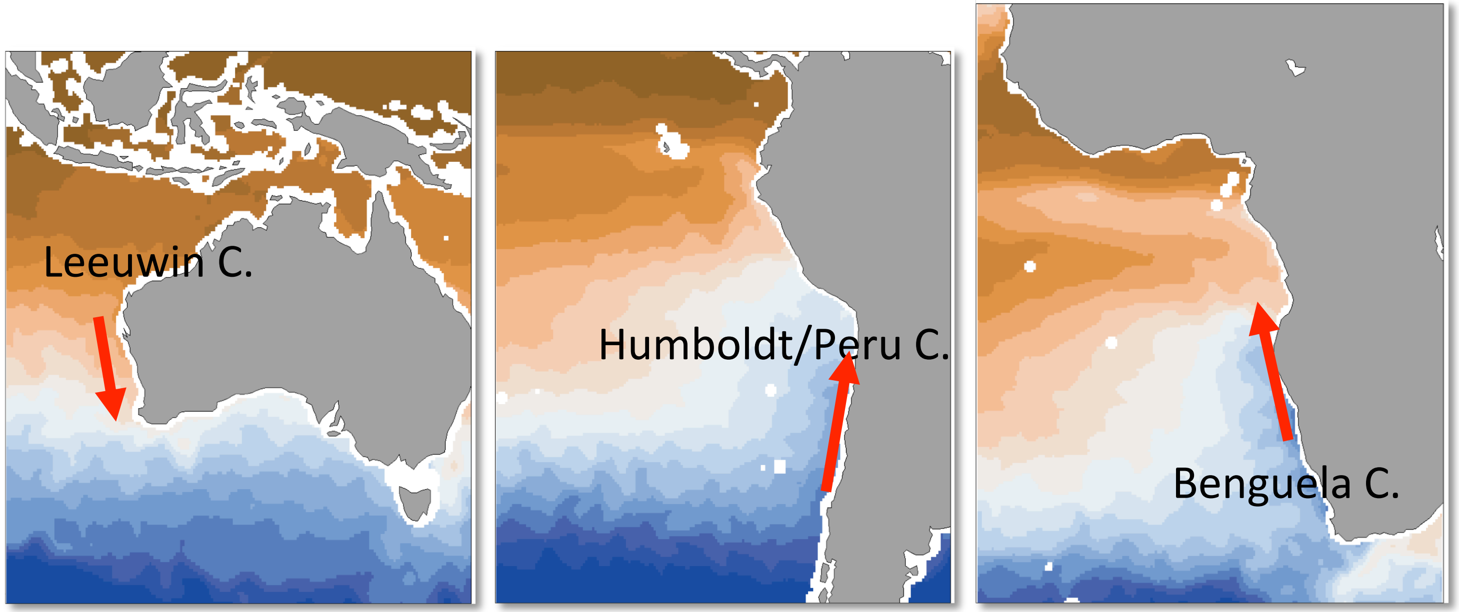


***Figure**: Surface temperatures from RSS Combined Microwave for June-August 2015. Blue = cold SSTs, brown = warm SSTs.*

Why observe EBC's?

DiLorenzo 2015 & Diffenbaugh and Field 2013

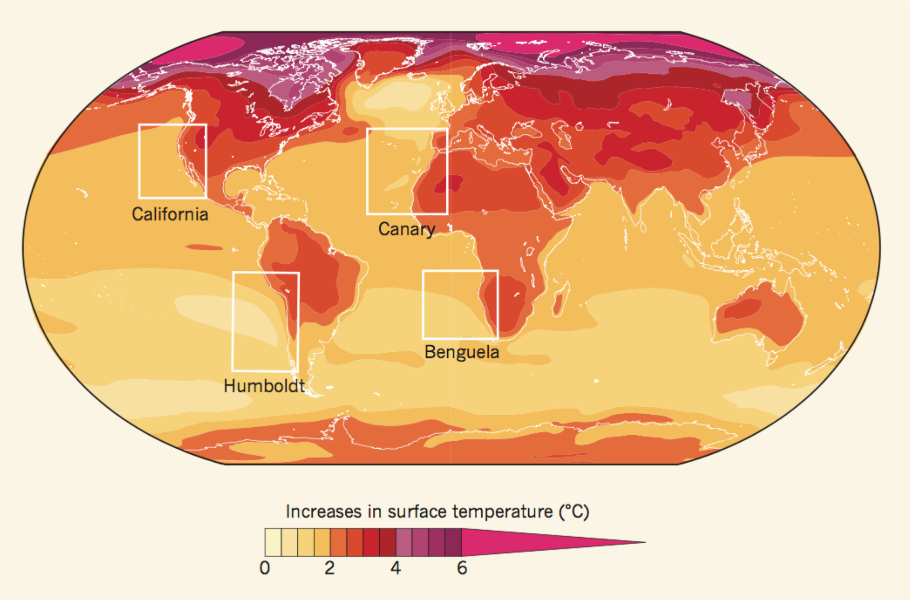
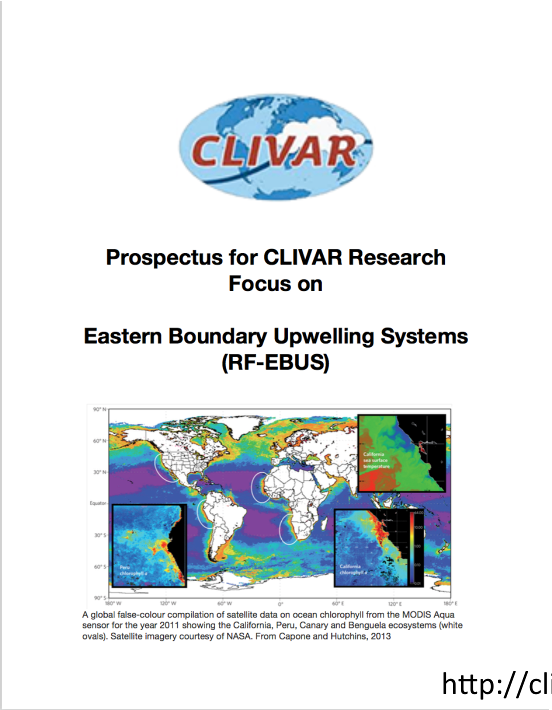


Figure 1 | Predicted changes in Earth's surface temperature. The map depicts differences in surface temperature between now and 2050, based on predictions from 27 climate models. The land heats up more than the ocean along major Eastern Boundary Upwelling Systems of the ocean (such as the California, Humboldt, Canary and Benguela systems). The resulting ocean–land temperature gradients

Increased land-ocean temperature contrasts on a warmer planet have led to stronger longshore winds and increased upwelling

⇒ Increased degassing of CO2
⇒ Larger productivity leading to more hypoxia



CLIVAR

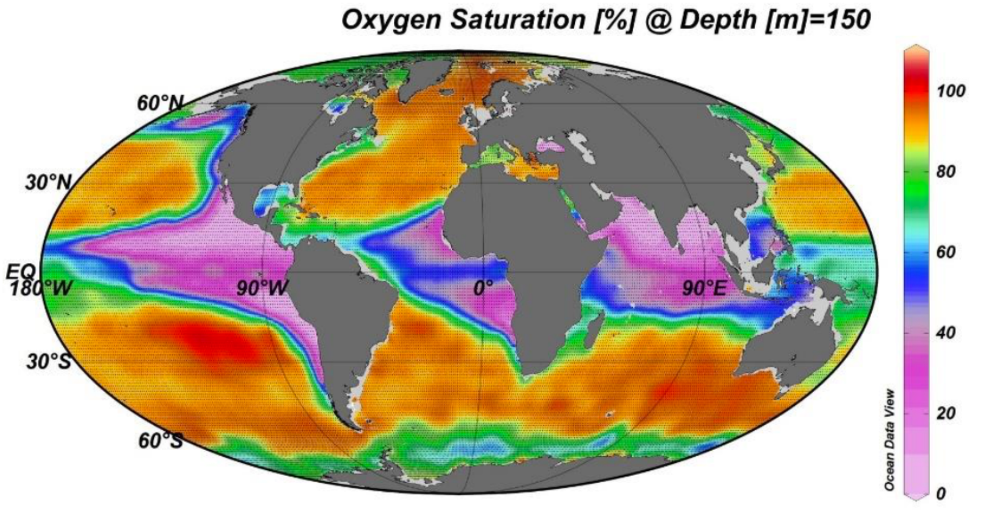
Prospectus for CLIVAR Research Focus on

Eastern Boundary Upwelling Systems (RF-EBUS)

A global false-colour compilation of satellite data on ocean chlorophyll from the MODIS Aqua sensor for the year 2011 showing the California, Peru, Canary and Benguela ecosystems (white ovals). Satellite imagery courtesy of NASA. From Capone and Hutchins, 2013

http://clivar.org/sites/default/files/EBUS-Prospectus.pdf

Why observe EBC's?



ıre 4. Global view of the oxygen saturation state at the 150 m depth. Pink areas point at locations of mos

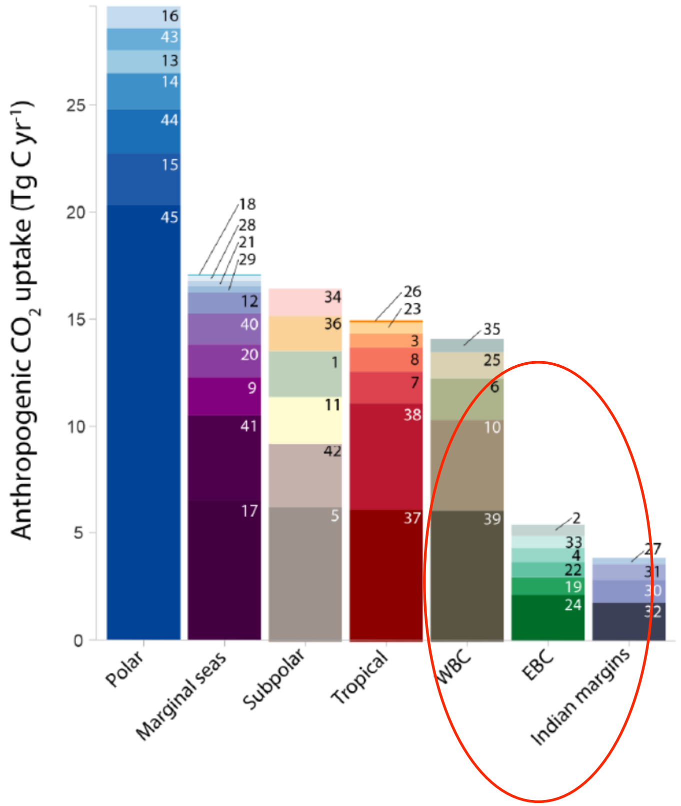


Figure 6. MARCATS regions: Anthropogenic carbon uptake: WBC, Western B
Boundary Currents (see Bourgeois et al. (2016) for details.

Oxygen minimum zones emanate from the eastern boundary

EBC's participate in the uptake of anthropogenic carbon

Why observe EBC's?

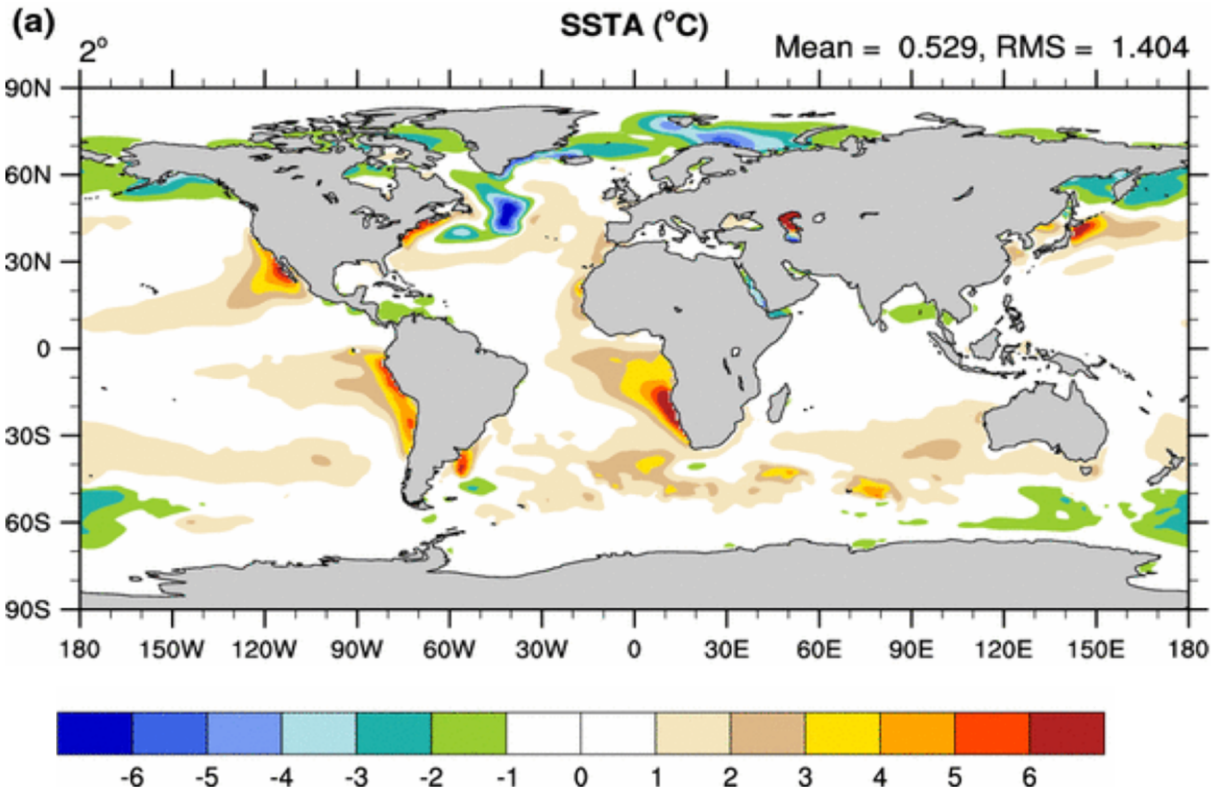


Figure 1: Sea surface temperature anomalies between an NCAR-CESM simulation and WOA data.

EBC regions are some of the most uncertain with regards to predicted changes in SST

Technology (*multidisciplinary)

Moored buoys (T, S, current meters, ADCPs, PIES, O2*, Carbon*, …)

Research vessels*

Ship of opportunity program (XBTs, XCTDs, ADCPs)

Underwater autonomous gliders*

Argo profiling floats*

Surface drifting buoys

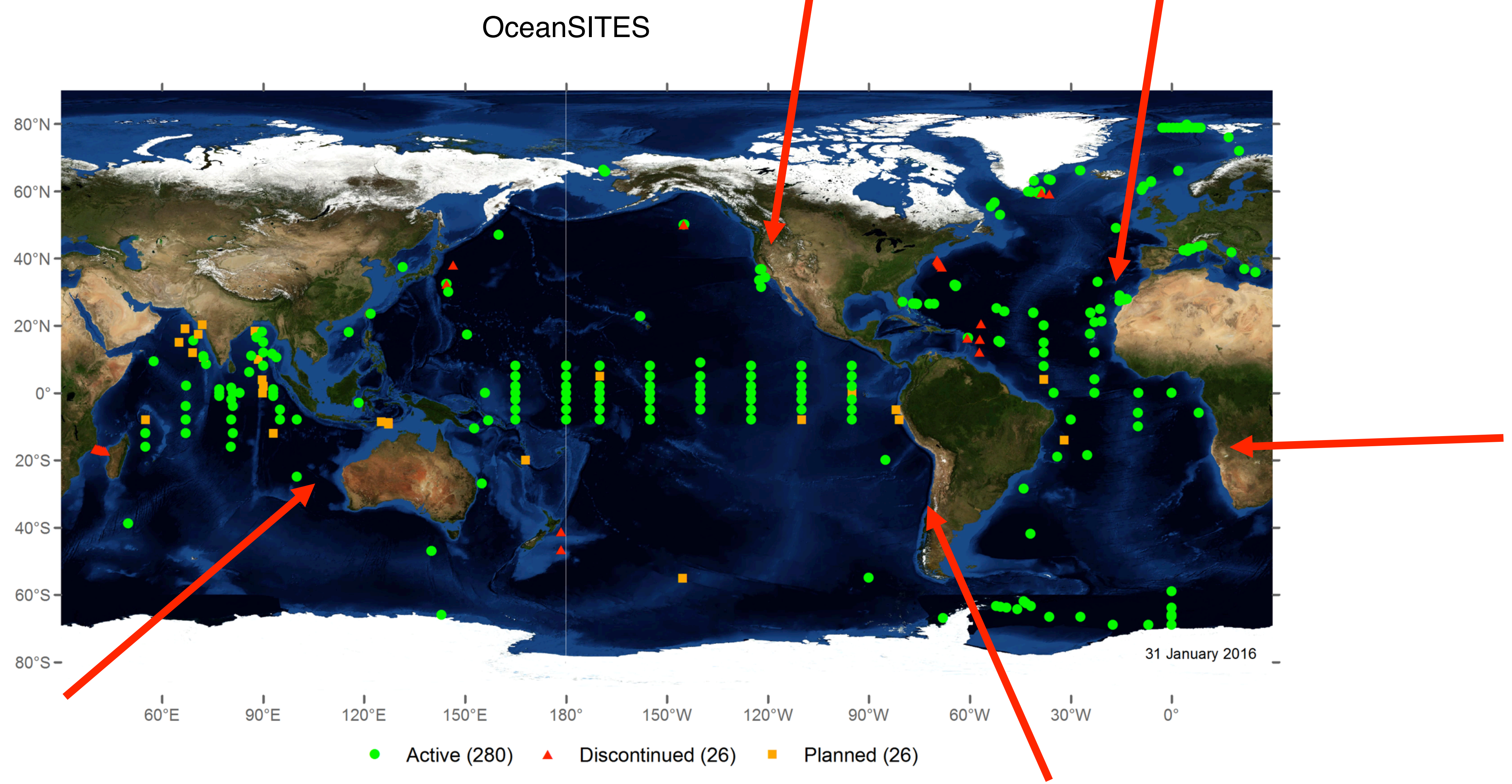
Sail drones*

Coastal HF-Radar

Satellites*

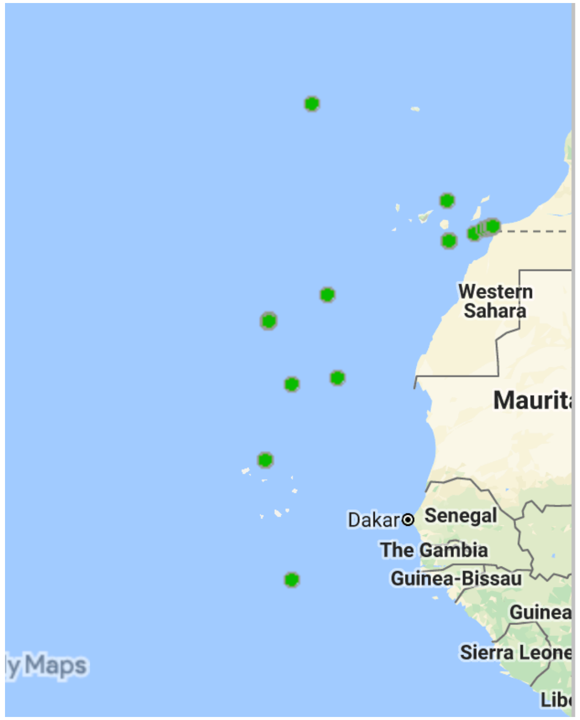
Blended *in situ*-satellite products

Moored buoys



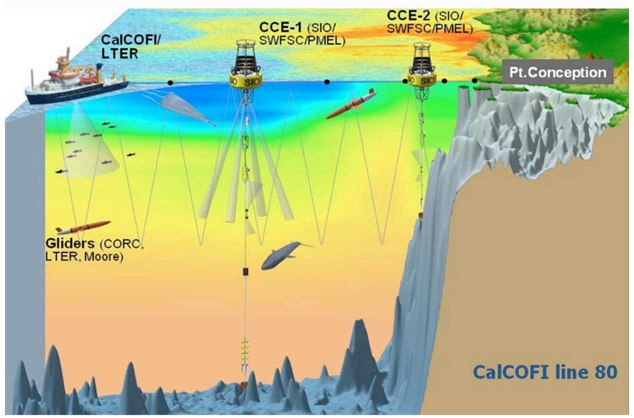
Integrated observational networks

RAPID/MOCHA and PIRATA moorings in the eastern North Atlantic

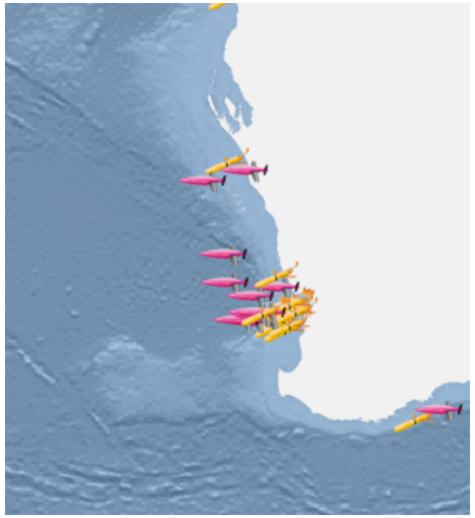


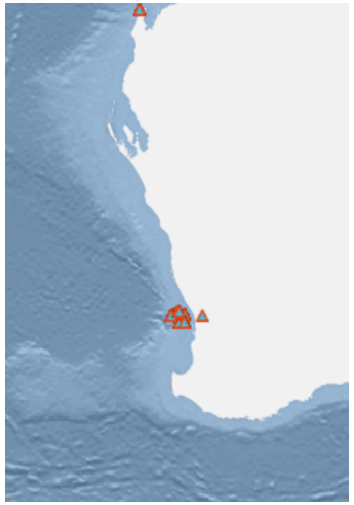
http://www.oceansites.org/network/index.html

Moored Climate, Carbon, BGC, and Ecosystem, South California Current



Integrated Marine Observing System

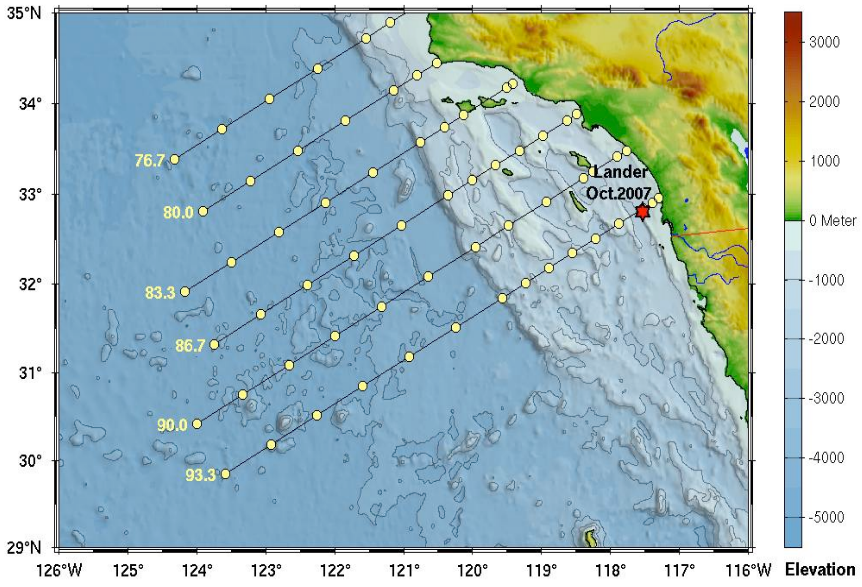




https://portal.aodn.org.au/search

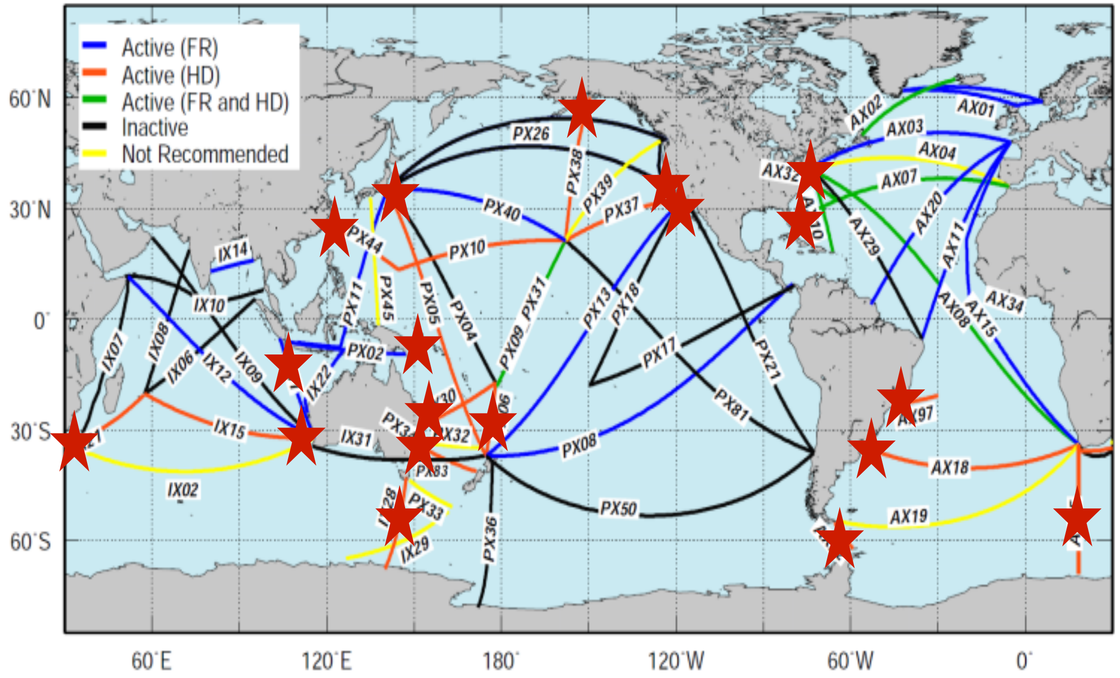
Research vessels, SOOP

CalCOFI (hydrography, biology)



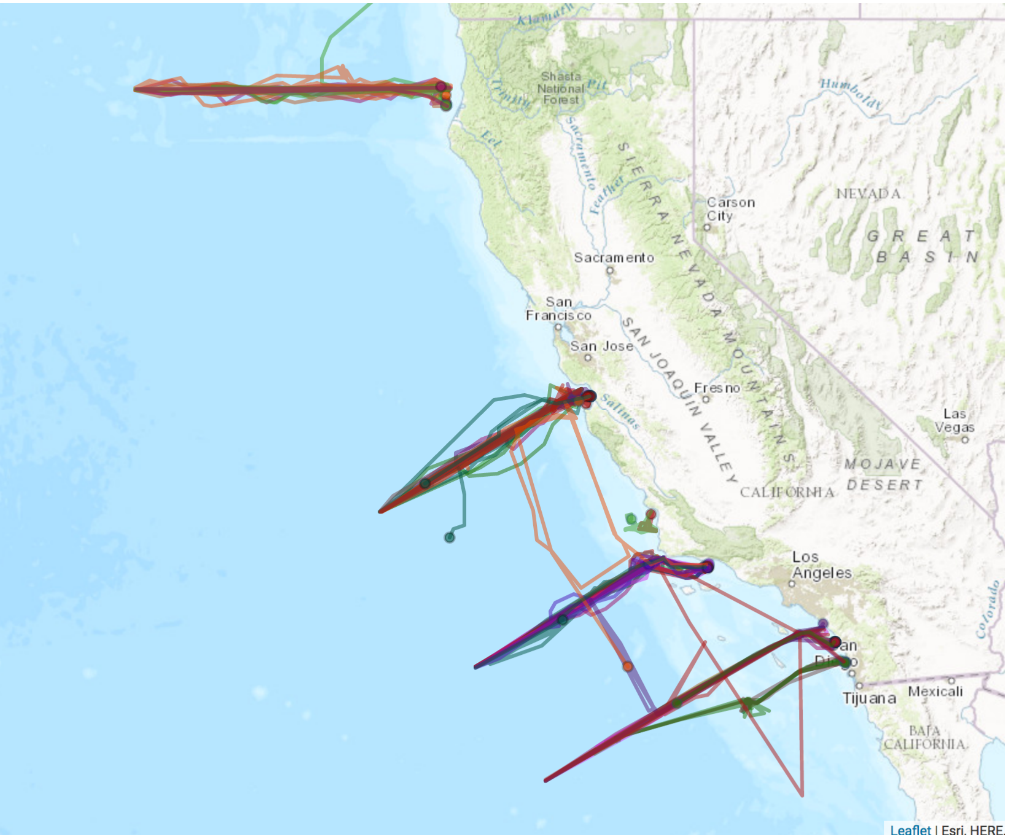
XBT network

: Boundary currents sampled by the HRX Network



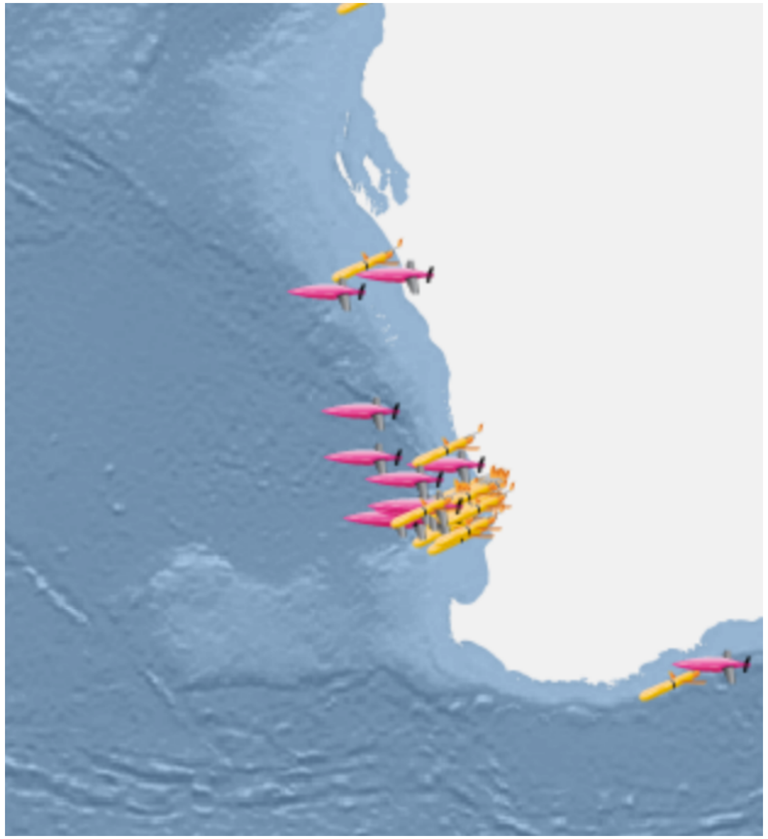
Gliders

California Current



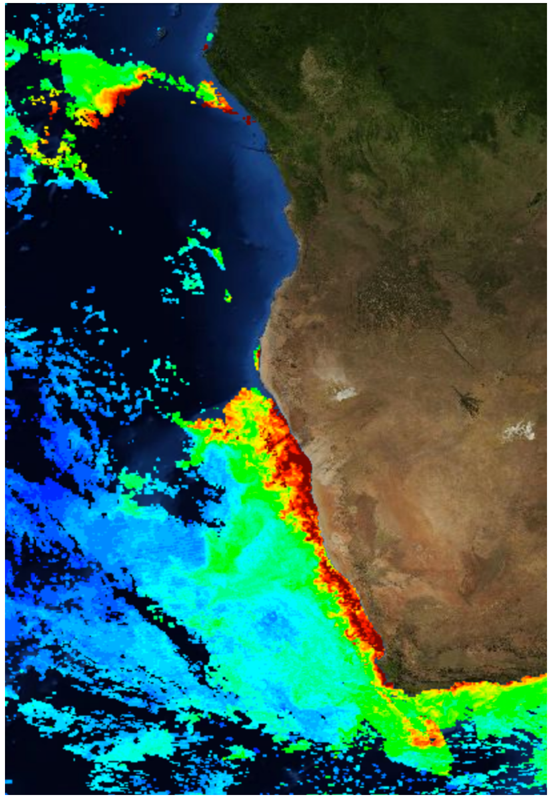
https://gliders.ioos.us/map/

Leeuwin Current

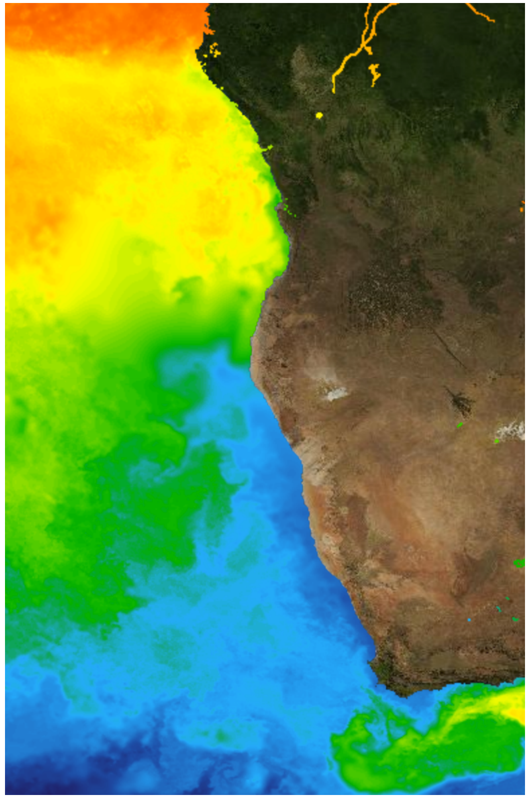


Satellite

Models



Ocean color



SST

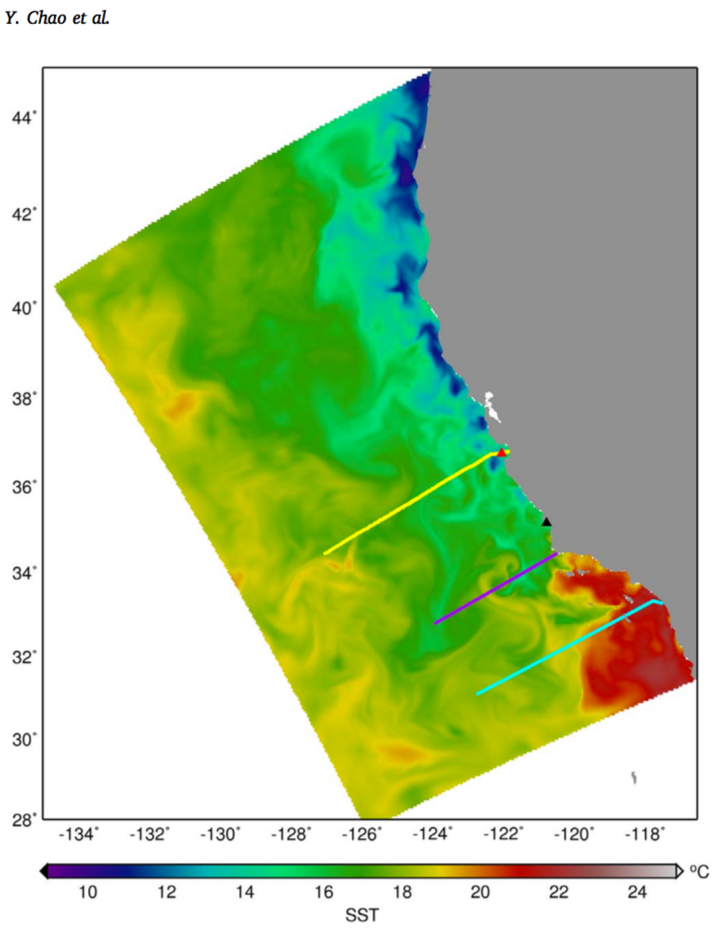
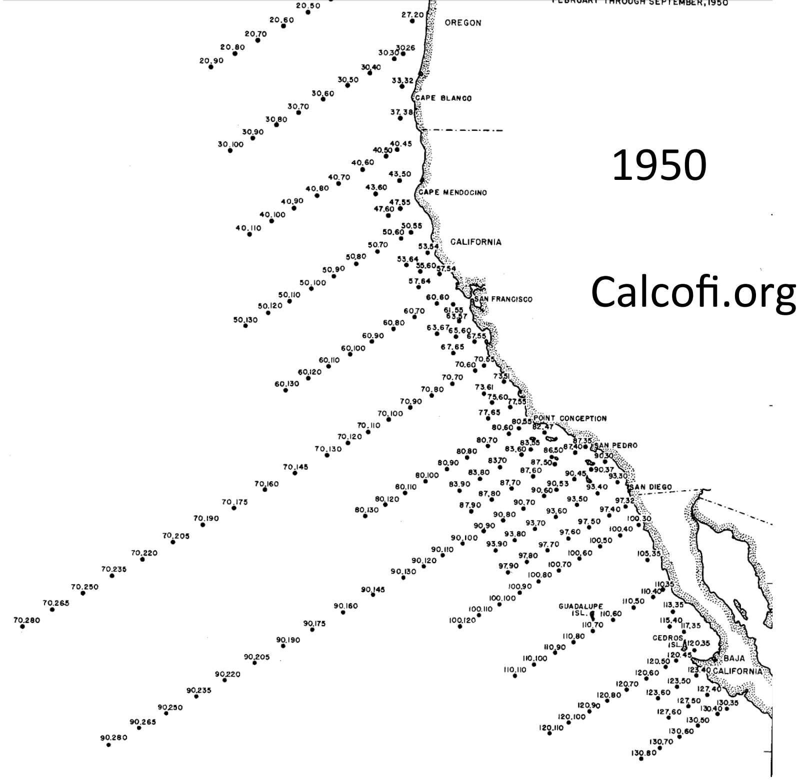
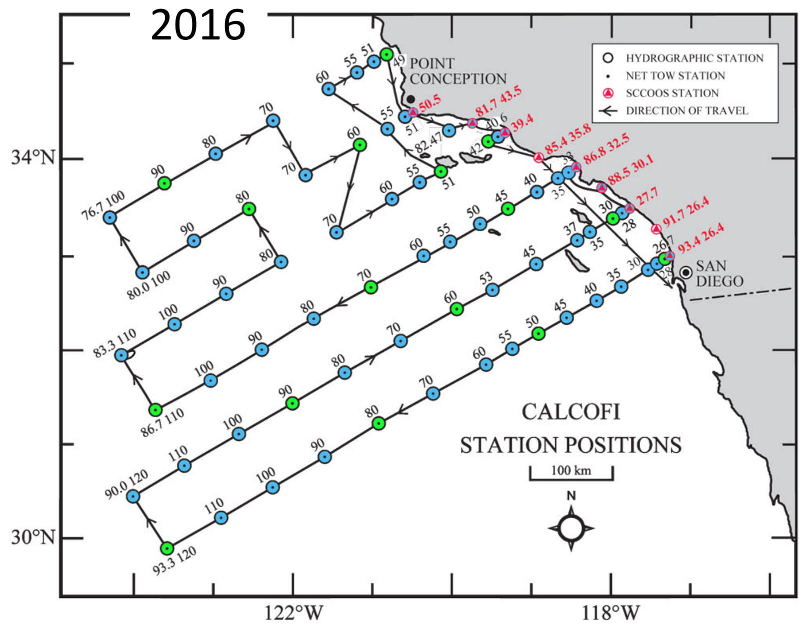


Fig. 1. Daily mean ROMS sea surface temperatures for 28 September 2012 on the ROMS CA-3km model domain (colored region). The yellow, purple and cyan lines show the

Conclusions

- EBC observing systems are very inconsistent
- They are mostly non-existent in the southeastern Atlantic and Pacific basins
- The US Pacific coast system is the most developed and might serve as a model for other systems
- Monitoring biological variables (e.g. productivity) is more important for EBCs than other ocean areas
- Integration with coastal observing systems is important as is understanding of shelf-edge exchange of nutrients, oxygen, heat, carbon, etc.
- More intensive monitoring of EBCs could help quantify their role as a carbon source/sink or oxygen sink.





Western boundary currents – current status and observational gaps

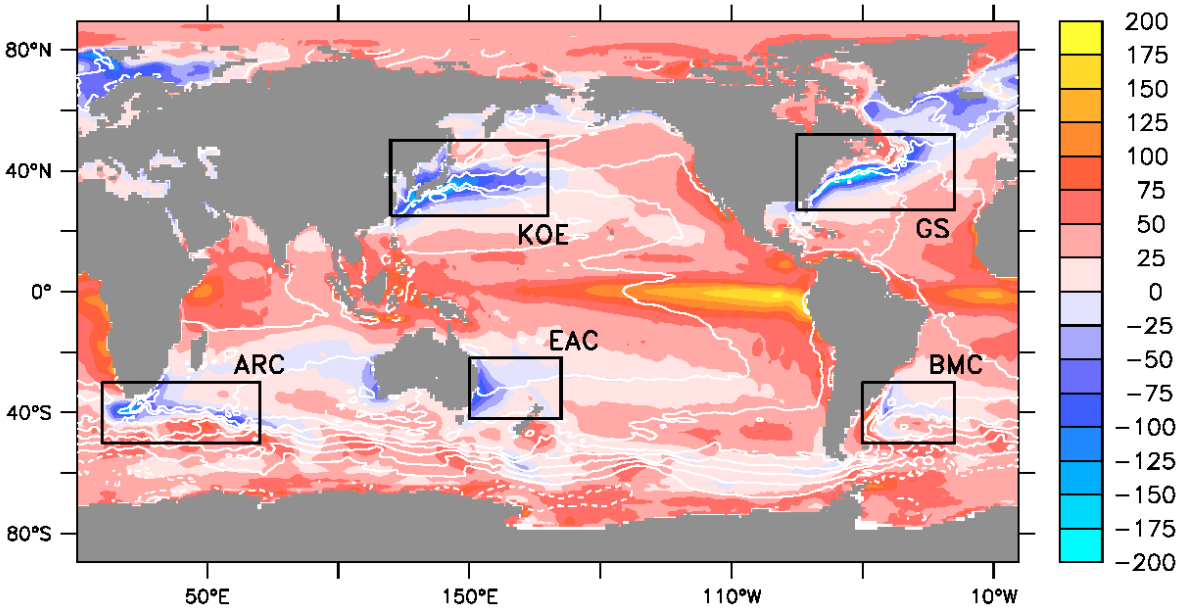
Carol Anne Clayson and Frederick Bingham

With input from Robert Todd, Meghan Cronin, and Susan Wijffels

From Meghan Cronin

Why a focus on WBCs?

- BCs nexus of societal use of ocean for fisheries, transportation, and recreation.
- WBC regions of the most intense currents in the ocean → key to transport of mass, heat, salt, biogeochemical variables and plankton.
- WBCs dominate the poleward transport of warm water or equatorward transport of cold water and are major drivers of climate variability.
- Major transport of heat between ocean and atmosphere in mid-latitudes occurs at the WBCs: affects locations/ strength of storm tracks, transient and intraseasonal eddies
- Deep boundary currents essential contributor to thermohaline circulation
- BCs are major means of exchange between coast and open ocean and impact ecosystems, flood levels, erosion and commercial activity.
- Major carbon cycle/budget impact
- Seismic and tsunami prediction
- Commerce, safety at sea, defense
- Sea level, inundation



Mean Net Surface Heat Flux (Wm^{-2})

Global WBCE Systems

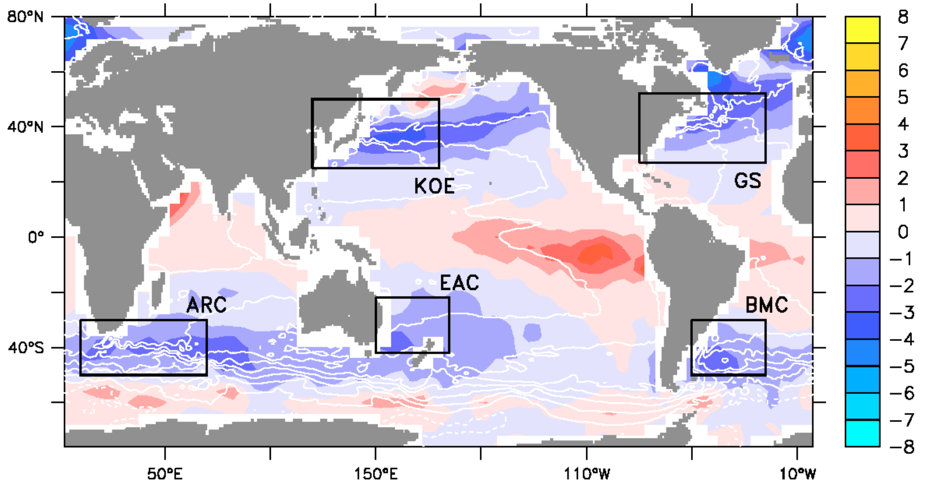
Kuroshio–Oyashio Extension

Gulf Stream

Agulhas Return Current

East Australian Current

Brazil-Malvinas Confluence

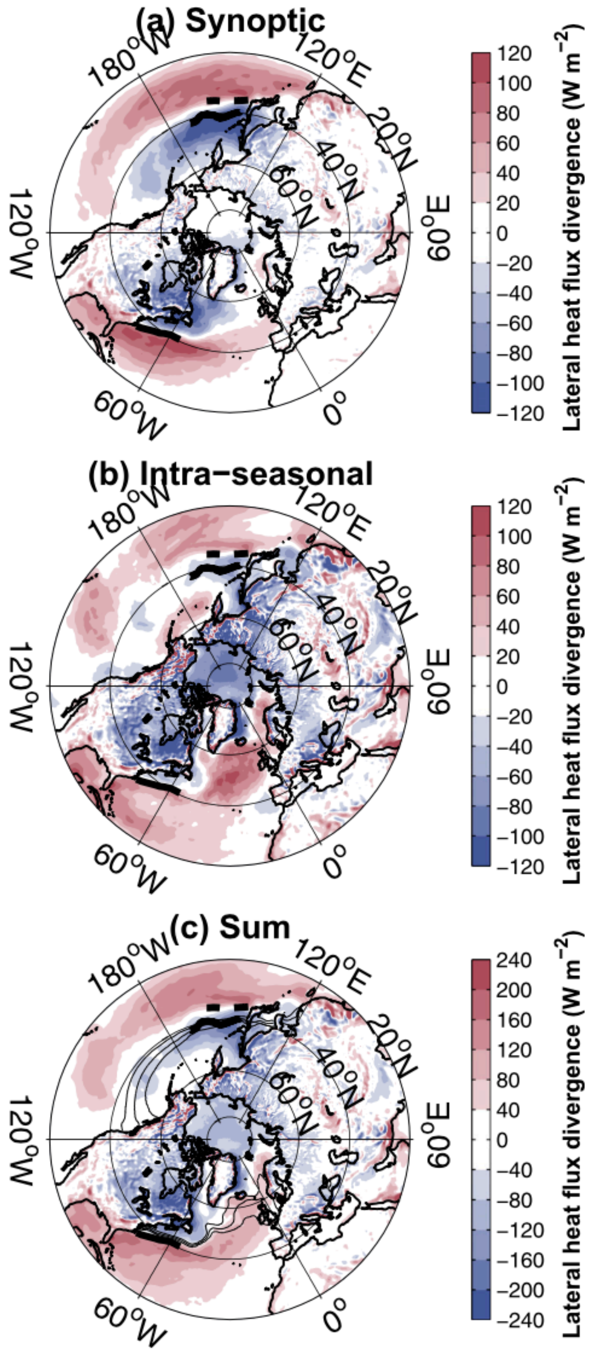


Mean CO_2 flux (moles m^{-2} yr^{-1})

WBCs affect atmospheric transfer of heat through stratosphere

- Need information on transport, location of frontal gradients and ocean heat content
- Need air-sea fluxes, lower atmospheric properties

31 year winter mean



Kwon and Joyce, 2013

IMSOO identified these issues for BCs:

- 1. Inter-annual variability of currents and water properties has fundamental effects on ecosystem structure/dynamics in all coastal and boundary current systems
- 2. Cross-shore overturning is key exchange between shelf and deep ocean
- 3. Episodic events (e.g., upwelling) are key, as are sub-mesoscale processes, and ecological hotspots
- 4. Land-deep ocean connectivity

From: **IMPLEMENTATION OF MULTI-DISCIPLINARY SUSTAINED OCEAN OBSERVATIONS (IMSOO), Miami, FL, USA , 8 -10 February 2017, FINAL WORKSHOP REPORT, GOOS Report No. 223**

What needs to be observed?

- Transport of mass, heat, and fresh water to complement broad-scale observations and define basin-wide transports
- Time series of both integral of transports through trans-basin sections and structure of temperature, salinity and velocity fields are needed to:
  - Establish mean and seasonal cycles of mass, heat, and freshwater transports → key for understanding global circulation, heat engine, and water cycle AND validating representation of these processes in dynamical models
  - define interannual climate variability in order to (a) identify key processes linking ocean and atmosphere and connecting different regions, (b) characterize physical environment affecting ecosystem management, and (c) define the temporal sequences of change to validate models used to forecasting climate variability;
  - describe, in real-time, structure of non-seasonal variability to assist, through data assimilation, initialization of models used to forecast weather and climate for operational purposes
- Also need observations for:
  - impact of eddies
  - changes in potential vorticity
  - air-sea interaction
  - ecosystem dynamics

Challenges observing WBCs

- Small scales: can't be adequately sampled with Argo floats and satellite altimetry
- Other Argo issues:
    - Sparsity (can't resolve eddies, for instance)
    - Inability to detect across WBC unless separated (shallow water issues)
- Boundary currents produce turbulence on multiple scales in response to coastline, bathymetric irregularities, and flow instabilities.
- Speed of WBC flows:
    - inherently nonlinear, producing internally-generated variability that can be the dominant term in the momentum and vorticity balances, and which demands sustained sampling.
    - Operation of of various platforms untenable in some regions due to flows.
- WBCs often have large vertical extent, which can require full-depth profiling and cause assumptions about reference levels to be especially unrealistic.
- Intense fishing activity close to coasts poses problems of vandalism, while the need to work within EEZ zones can lead to political complications.

Tools for measuring WBCs

- Mooring arrays. Pros/cons:
  - Significant design considerations
  - Endurance limits
  - Costs associated with building, deploying and recovering
  - But: no capability presently able to return equivalent high temporal- and spatial-resolution and accuracy of volume, water-property transport estimates, and meteorological measurements
- Ships of opportunity. Pros/cons:
  - Available only on stable commercial shipping routes,
  - Measurements are limited to the upper ocean and atmosphere, but atmospheric measurements have significant accuracy issues.
  - ADCP measurements require substantial effort for installation, but the direct observations of boundary current velocity are uniquely valuable

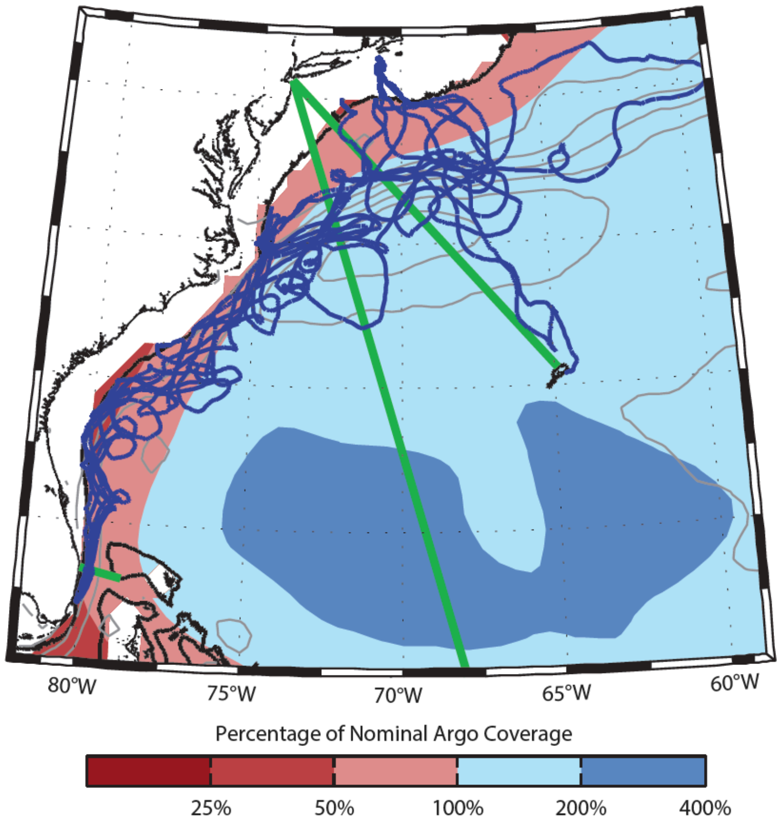
More tools for measuring

- Gliders. Pros/cons:
  - Moderate cost (unless long travel for deployment/recovery)
  - High spatial resolution (mid-depth of 1000m profiles only 2 − 3 km apart)
  - Low operating cost and loss rate
  - Can be equipped with CTDs, ADCPs, chlorophyll florescence, acoustic backscatter, optical backscatter and CDOM, oxygen: limited by available energy
  - Can complement satellite measurements of SST, ocean color, and SSH, although at only at a few points.
  - Can sample close to shore (unlike satellite SSH)
  - Can sample across the continental slope and into shallow inshore water
  - Slow speed compared to current velocities
- Electromagnetic ocean transport observations (e.g., telephone cable). Pros/cons:
  - Provides true vertical and horizontal integration of the transport instantaneously
  - Necessary to make regular calibration checks on the cable using in situ transport observations
  - Extremely cost effective and produces highly accurate near-real-time data
- Satellite Altimetry. Pros/cons:
  - Used extensively in monitoring flow field of boundary currents; only temporal variation at present
  - Distance between tracks large, can't resolve eddies, narrow WBCs
  - Issues near coast

Gulf Stream observations

- Gulf Stream is most likely the best-observed of the WBCs, and yet, observations are sparse

- Mean SSH contours (gray)
- Percentage of nominal Argo coverage (one float per 3° x 3° box) during 2008–2014 (shaded)
- Locations of sustained subsurface observations (green lines):
  - Florida Strait
  - AX10 XBT line (a high-density repeat XBT transect run by NOAA)
  - M/V Oleander line.
- Trajectories of 11 Spray glider missions through May 2017 (blue lines)
- 200 m isobath (black line)



Glider Surveillance of the Gulf Stream

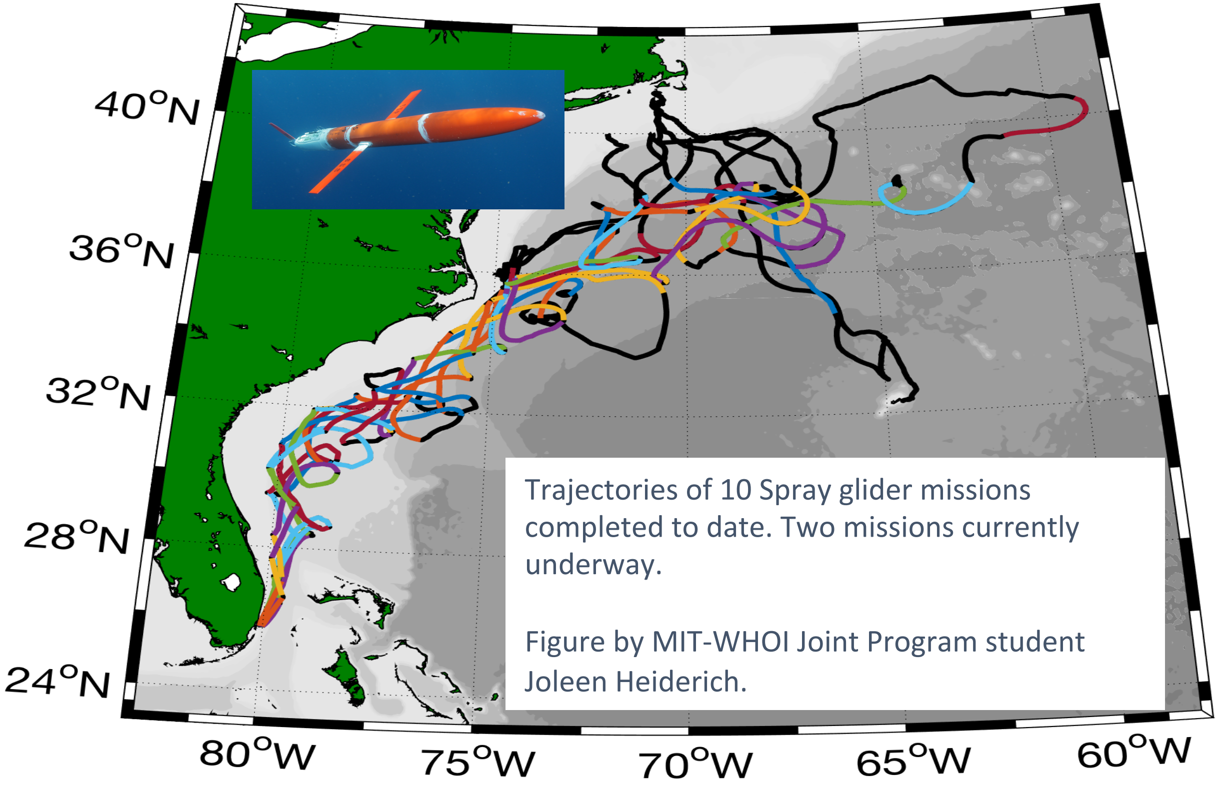
Robert E. Todd, Woods Hole Oceanographic Institution

Mission Plan:

- Deploy off Miami
- Zig-zag downstream
- Recover on New England shelf
- Endurance: 110 days
- Provide real-time data via GTS

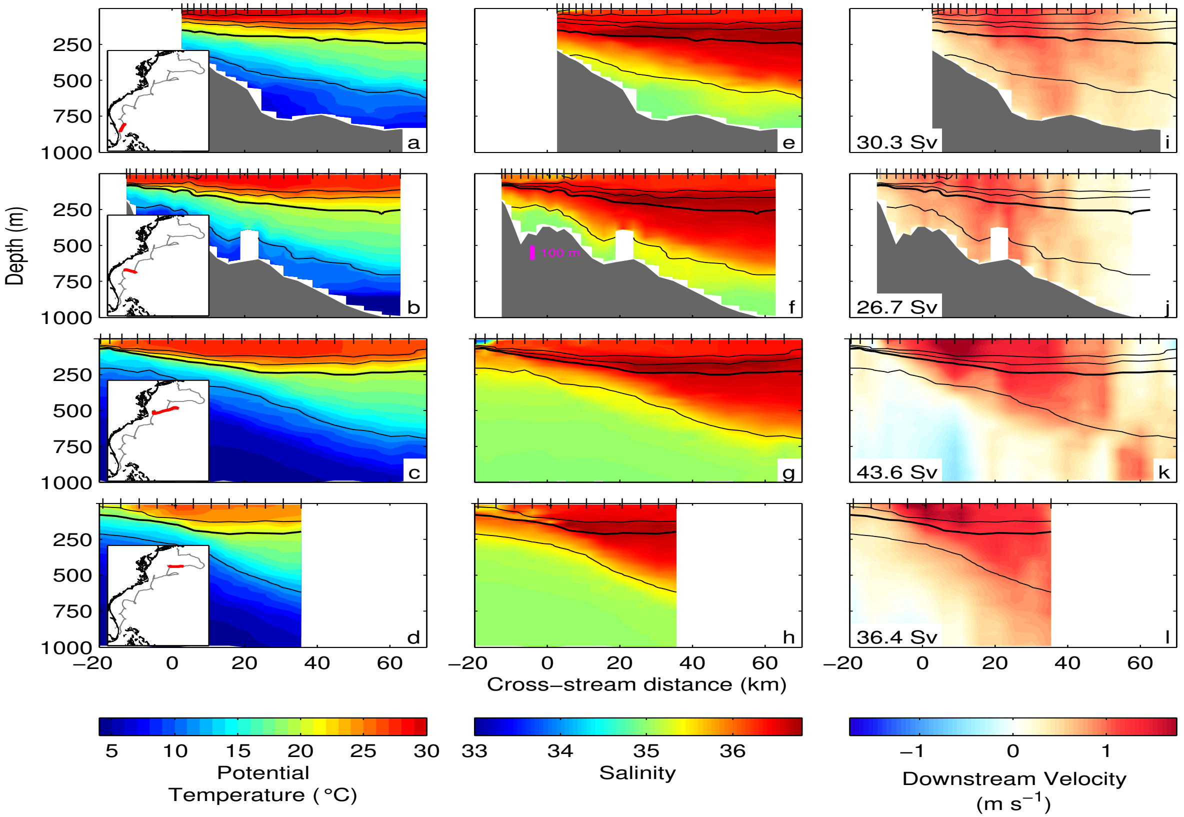
High-resolution, cross-Gulf Stream transects of:

- Temperature
- Salinity
- Velocity
- Chlorophyll a (phytoplankton)
- Acoustic Backscatter (zooplankton)



Trajectories of 10 Spray glider missions completed to date. Two missions currently underway.

Figure by MIT-WHOI Joint Program student Joleen Heiderich.



[Todd, 2017, *Geophys. Res. Lett.*]

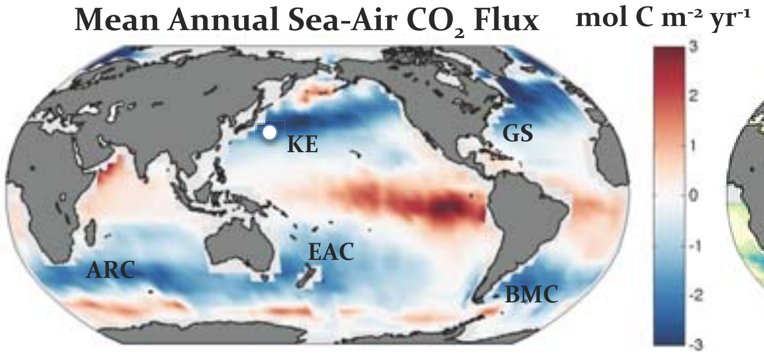
Thoughts on Gulf Stream observations

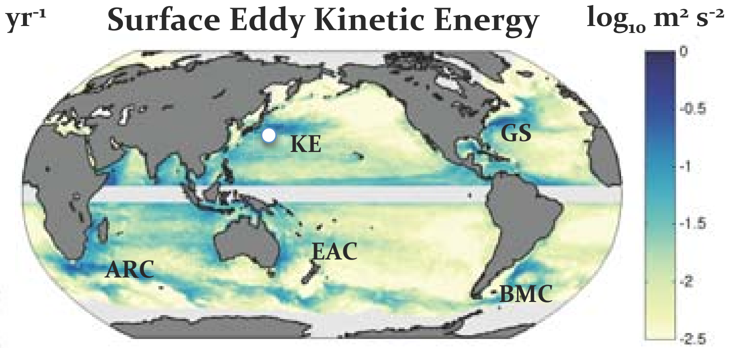
- Sustained observations: Western Boundary Current Timeseries in the Florida Strait and the Oleander Line between NJ and Bermuda
  - WBTS: Volume transport from cable
  - Regular hydrographic cruises at 27N
  - Oleander line: XBT (only upper 800m, no salinity), ADCP (only upper 400 m), thermosalinograph every two weeks (some funding pressure also) (http://po.msrc.sunysb.edu/Oleander)
- Glider observations: funding for another 18 months
  - CTD, ADCP, chlorophyll flurometer
  - Limited to upper 1000m; no exact repeat transects, very high spatial resolution, persistent presence at sea
- Occasionally entrained Argo floats
- HF radar along NC Outer Banks captures surface current expression near separation point
- Air-sea related measurements lacking (except from satellite) throughout. Also needed: full depth measurements (when bottom deeper than 1000m)
- ***MISSING***: air-sea interactions; seasonal and shorter scale variability is not characterized; unknown physics because we're not observing them, like the recently identified large amplitude lee waves and thick bottom layers as Gulf Stream flows over Blake Plateau

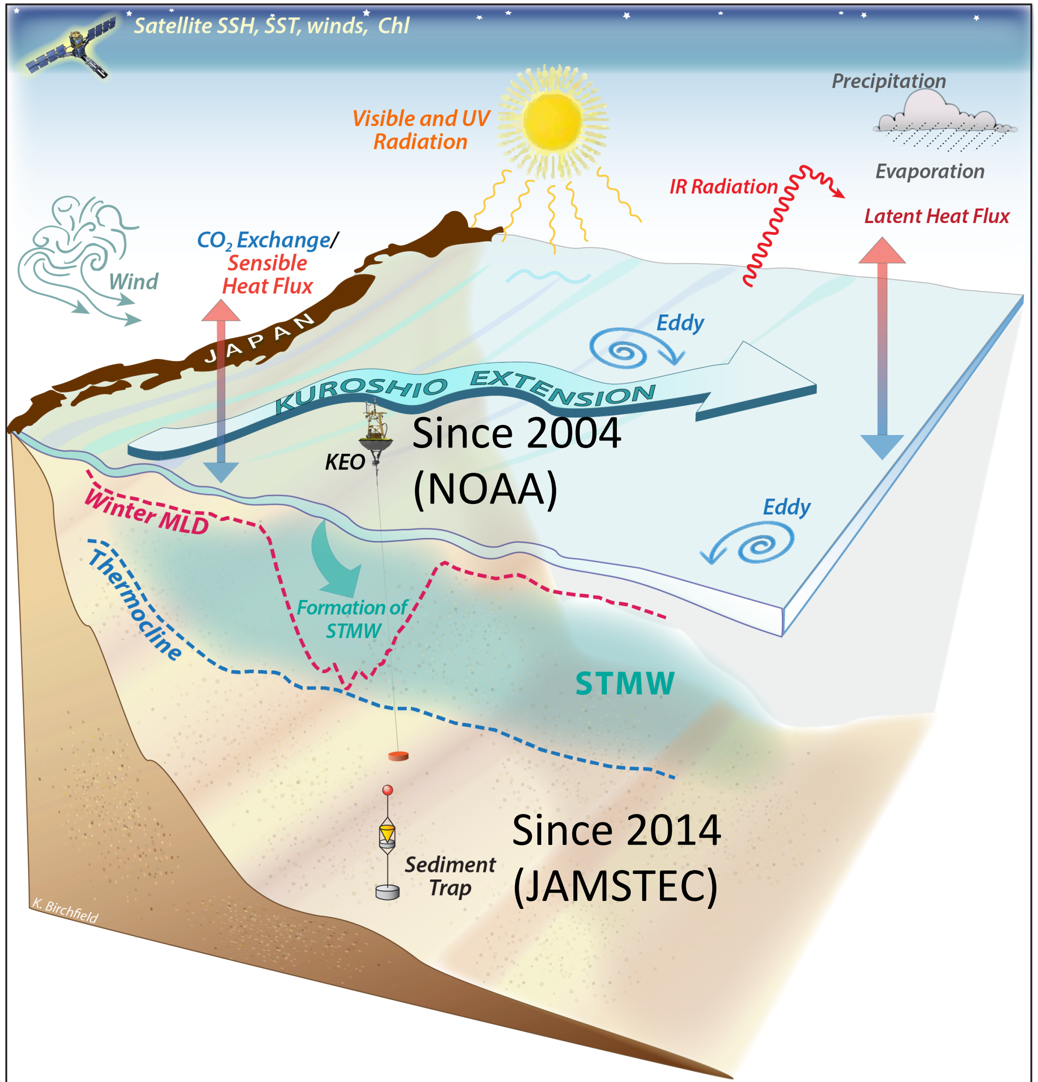
Kuroshio Extension Observatory (KEO)

NOAA Surface Mooring & JAMSTEC Sediment Trap

From Meghan Cronin







The KEO station has the NOAA surface mooring, initiated in 2004, and JAMSTEC subsurface sediment trap, which was moved here in 2014. KEO is located in the highly dynamic recirculation gyre south of the Kuroshio Extension.

Recent study by Andrea Fassbender estimated annual net community production at KEO. But a major caveat to her analysis is that she had to *rely upon climatology to determine spatial gradients* and therefore her analysis is missing productivity due to *eddies*, which potentially could be significant.

Further details on KEO

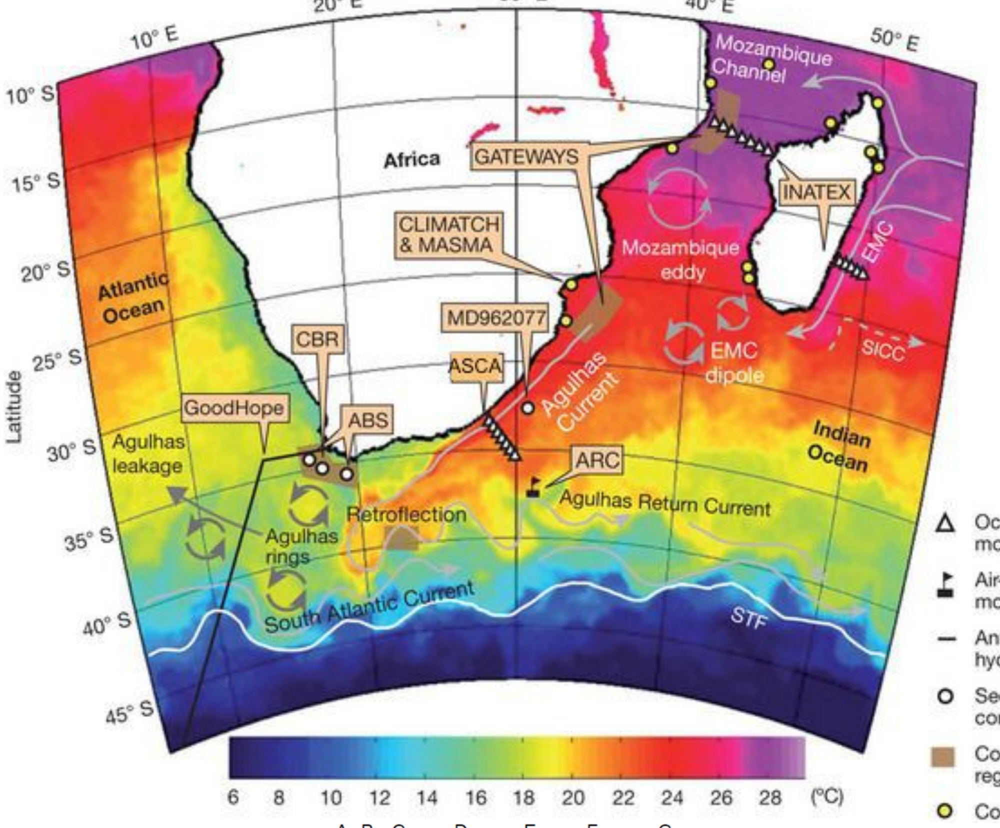
- KEO surface mooring:
  - bulk fluxes of heat, freshwater, momentum, and CO_2.
  - suite of ocean acidification sensors
  - upper ocean (1 m-525m) T&S&P
  - near surface currents (15 m and 35 m).
  - New this year, upward looking ADCP at 85 m to monitor near surface current profiles
  - T&S&P "microcat" sensor on its anchor release to measure bottom water temperature and salinity
- Concerns (from Meghan Cronin):
  - In the past, JAMSTEC had a very active western North Pacific observing system, with several moorings in the Kuroshio Extension region (e.g. JKEO to the north of the KE, and the biogeochemical S1 mooring SE of KEO). They have since discontinued these sites and moved the former S1 sediment trap mooring to be next to the KEO NOAA surface mooring.
  - Present data logger/telemetry system approaching obsolescence. Nobody wants to pay for that kind of engineering, yet this is the brain and heart for the system. Without it, we do not have any meteorological data and no realtime data.

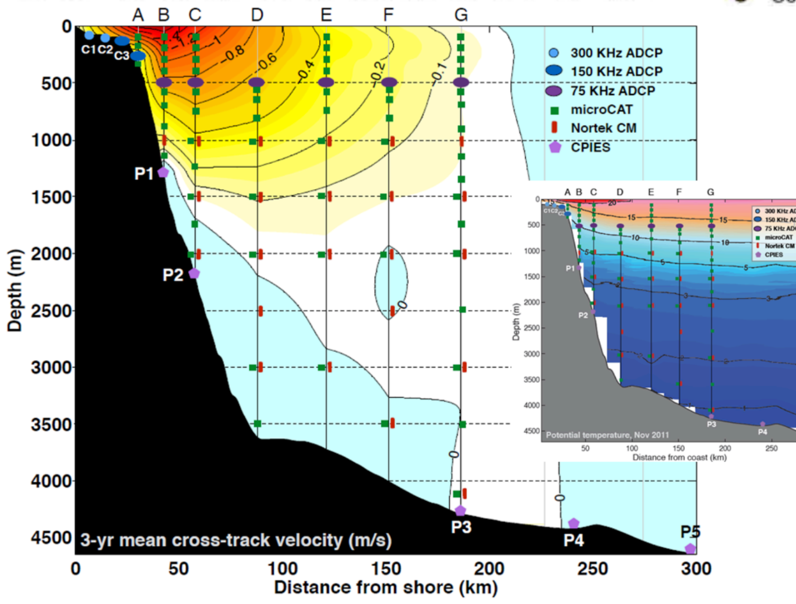
Gliders in KOE

- Repeated sections across the Kuroshio, off Taiwan and Luzon, were occupied continuously from 2011-2013 to document variability and water mass modification immediately downstream of its formation region.
- Measurements will resume in 2017, with plans for sustained occupation of a line east of Taiwan.

Agulhas System Climate Array

- Begun in 2015; funded by South Africa, Netherlands, and NSF.
- 2 shelf and 7 full-depth tall moorings, interspersed 5 CPIES
  - Measuring pressure, current velocities, temperatures and salinities.
- ASCA shelf and tall moorings will extend 200 km offshore through the core of the Agulhas Current, with CPIES measurements extending the array to 300 km offshore.
- Follow up to 2015 Shelf Agulhas Glider Experiment (SAGE) proposed. Will supplement observations from the Agulhas System Climate Array (ASCA) and coastal monitoring efforts near 34°S
- No surface/met measurements
- http://asca.dirisa.org





East Australian Current

Also: gliders doing repeated sections in the East Australian Current (EAC) using the Australian Integrated Marine Observing System (IMOS) assets will conduct experiment during 2017-19 in conjunction with the IMOS EAC mooring array.

The objective is to understand what role gliders can play along with other technologies in cost effective monitoring of this western boundary current.

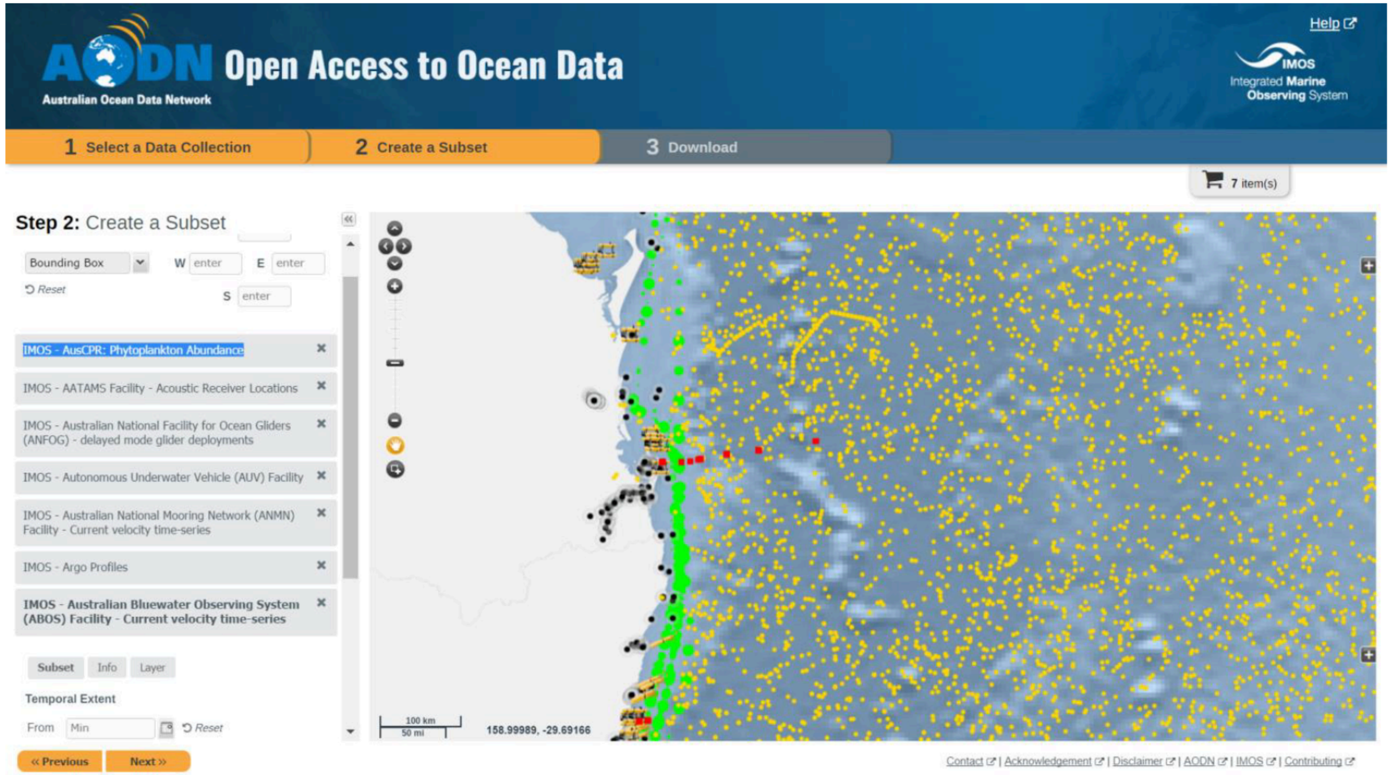


Figure 16a. A view of ocean observing assets in the East Australian Current as part of the Integrated Marine Observing System.

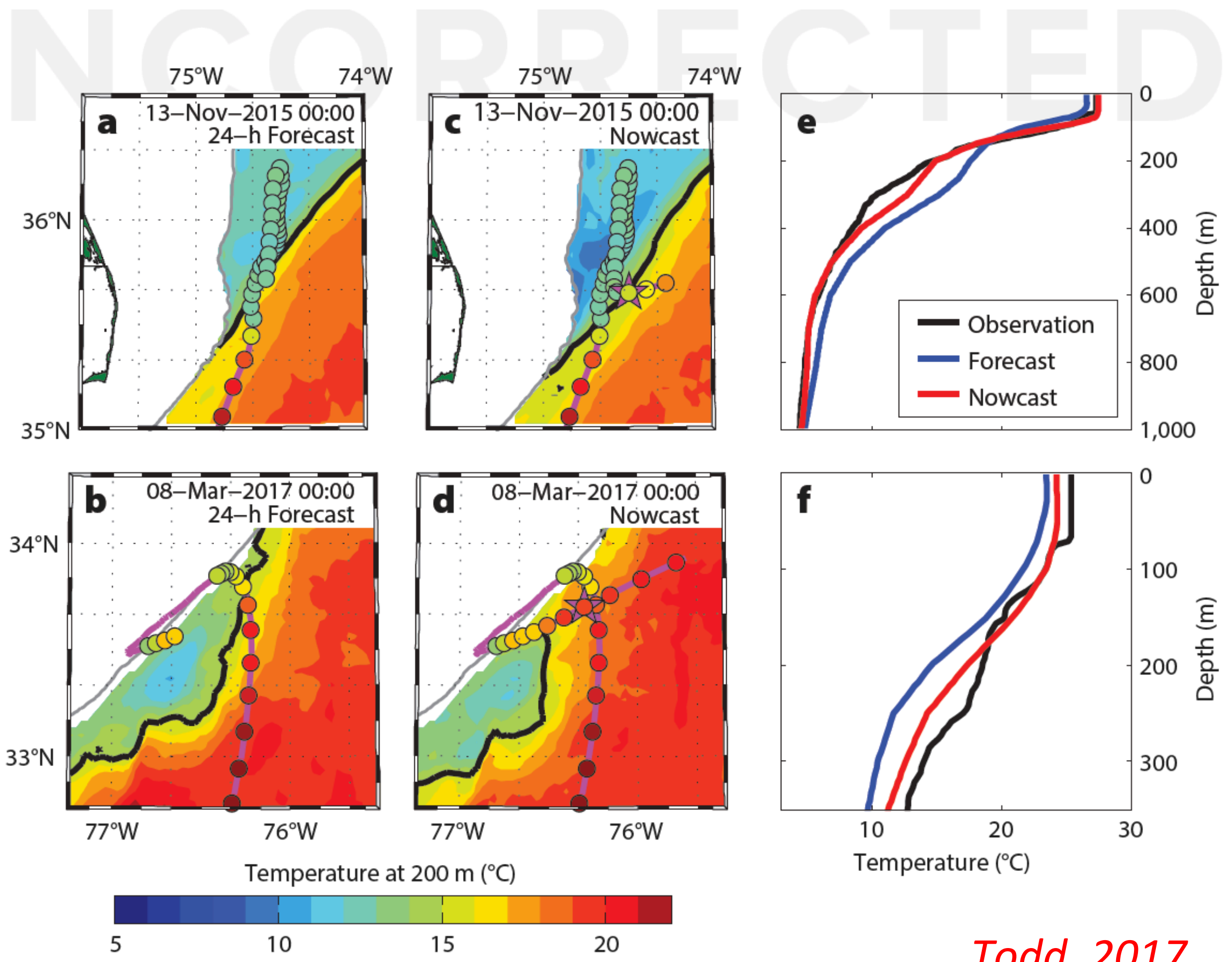
New glider observing network

- OceanGliders Boundary Ocean Observing Network (BOON)
  - provide coordination and linkage for a global observing program
- Issues: BCs invariably reside in EEZs: observation must depend on regional efforts respectful of coastal countries.
- Regional networks comprising BOON intend observations be sustained year-round. Will publish data in near-real time on the GTS and in CF compliant formats to a central data assembly center.
- Benefits: Improved and sustained quality control of glider data. A global network of regional networks that monitor boundary current variability across international borders.

Conclusions

- WBC systems are not well represented by current observational system, even for oceanographic, let alone met, data
- Opportunities exist for buoys to be used with more site-based process studies
- Hybrid, coordinated, individualized regional approaches needed for each WBC
- Gliders are a new help to sample WBCs
- What new measurements do we need?
  - Most likely we need a 5 knot glider to really investigate WBCs
  - We also need a Doppler altimeter
- We also need much better ocean models to help us determine what the improvements by adding certain data types/resolutions will be
  - Present models strongly drift; observations are mainly “tugging them back into line”, and most likely can’t give quantitative information about usefulness of various new data

NAVO predictions without glider data (left panels) and with glider data (middle panels)



Todd, 2017