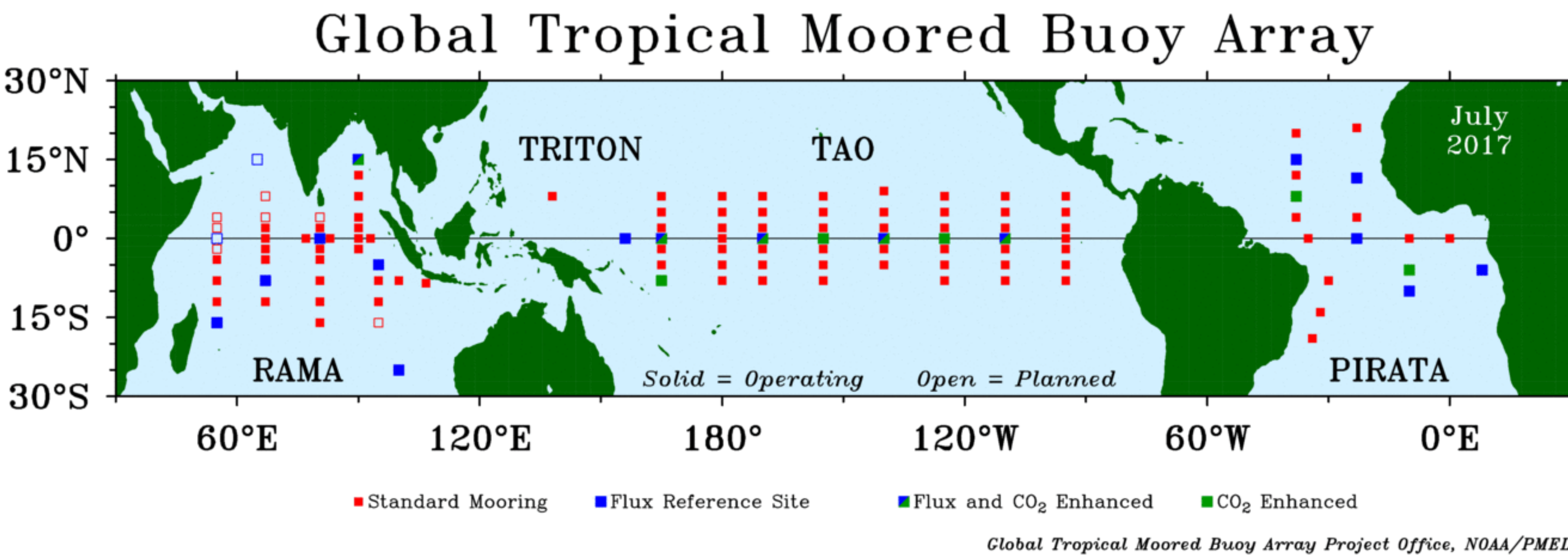
Health of the global observing system: tropical oceans

Renellys C. Perez, UM/CIMAS and NOAA/AOML

w/input from: M. Araujo, B. Bourlès, P. Brandt, K. Connell, K. Drushka, G. Foltz, W. Kessler, R. Lumpkin, M. McPhaden, Y. Serra, J. Sprintall, …



US CLIVAR Summit, August 8-10, 2017

Upcoming international reviews

Tropical Atlantic Observing System (TAOS)

Process will begin during 2017 PIRATA/PREFACE/TAV meeting in Fortaleza, Brazil in November 2017; and an evaluation committee will meet during 2018 Ocean Sciences meeting in February 2018; redraft/ratify new PIRATA MOU in 2019; TAOS white paper review around mid 2019.

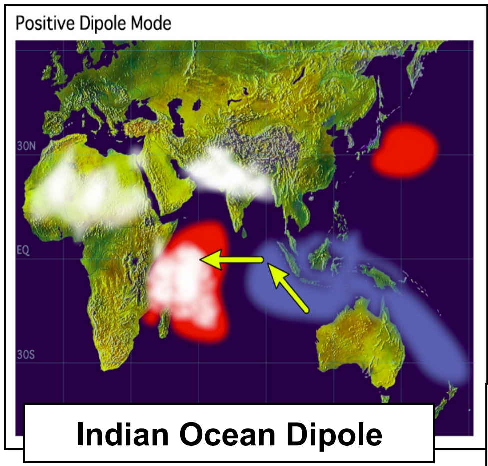
Indian Ocean Observing System (IndOOS)

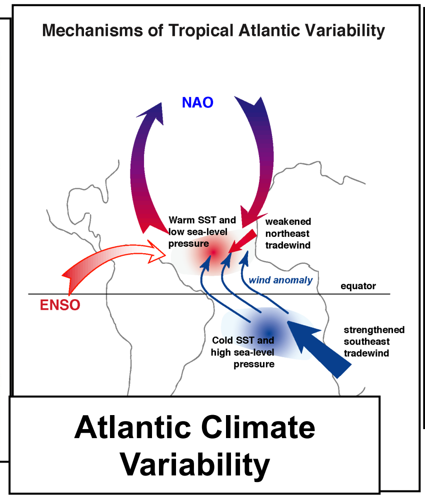
IndOOS Review white paper first draft September 2017; expert panel will meet February 2018.

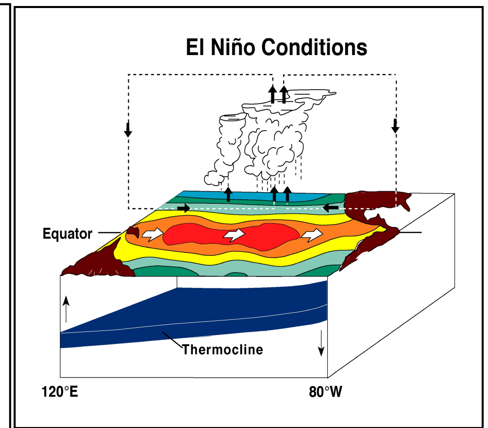
Tropical Pacific Observing System (TPOS)

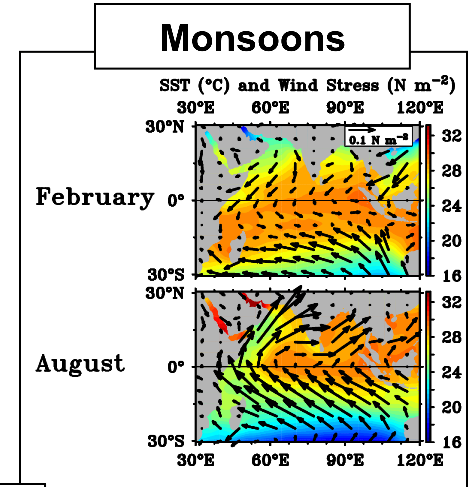
TPOS2020 effort been ongoing for several years; Review of TPOS in January 2014; first interim report issued December 2016 with recommendations for TPOS backbone array and pilot studies; several TPOS pilot studies are underway.

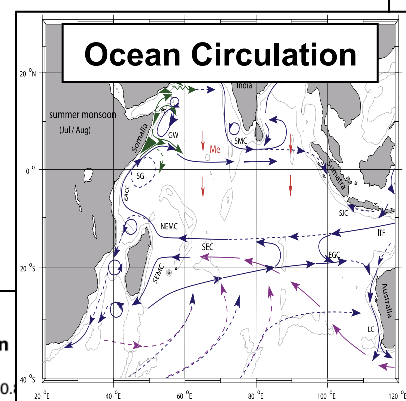
Scientific Drivers: Interacting Variations in Time and Space

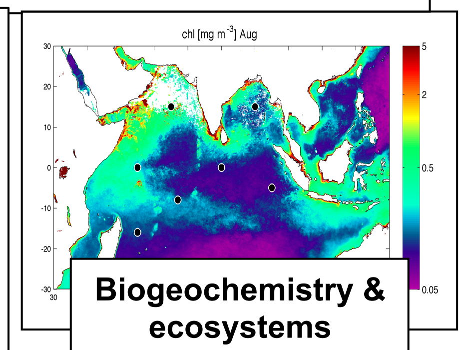


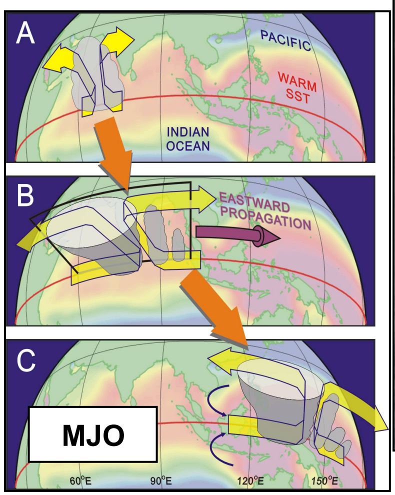


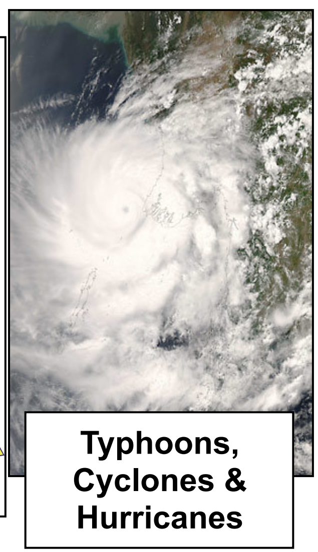


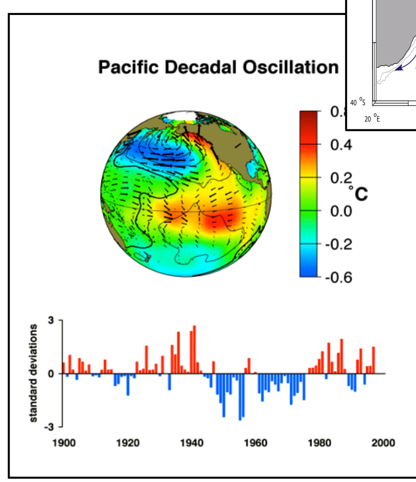


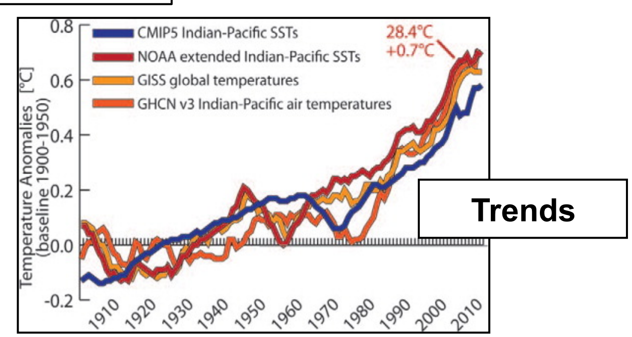












Courtesy of M. McPhaden

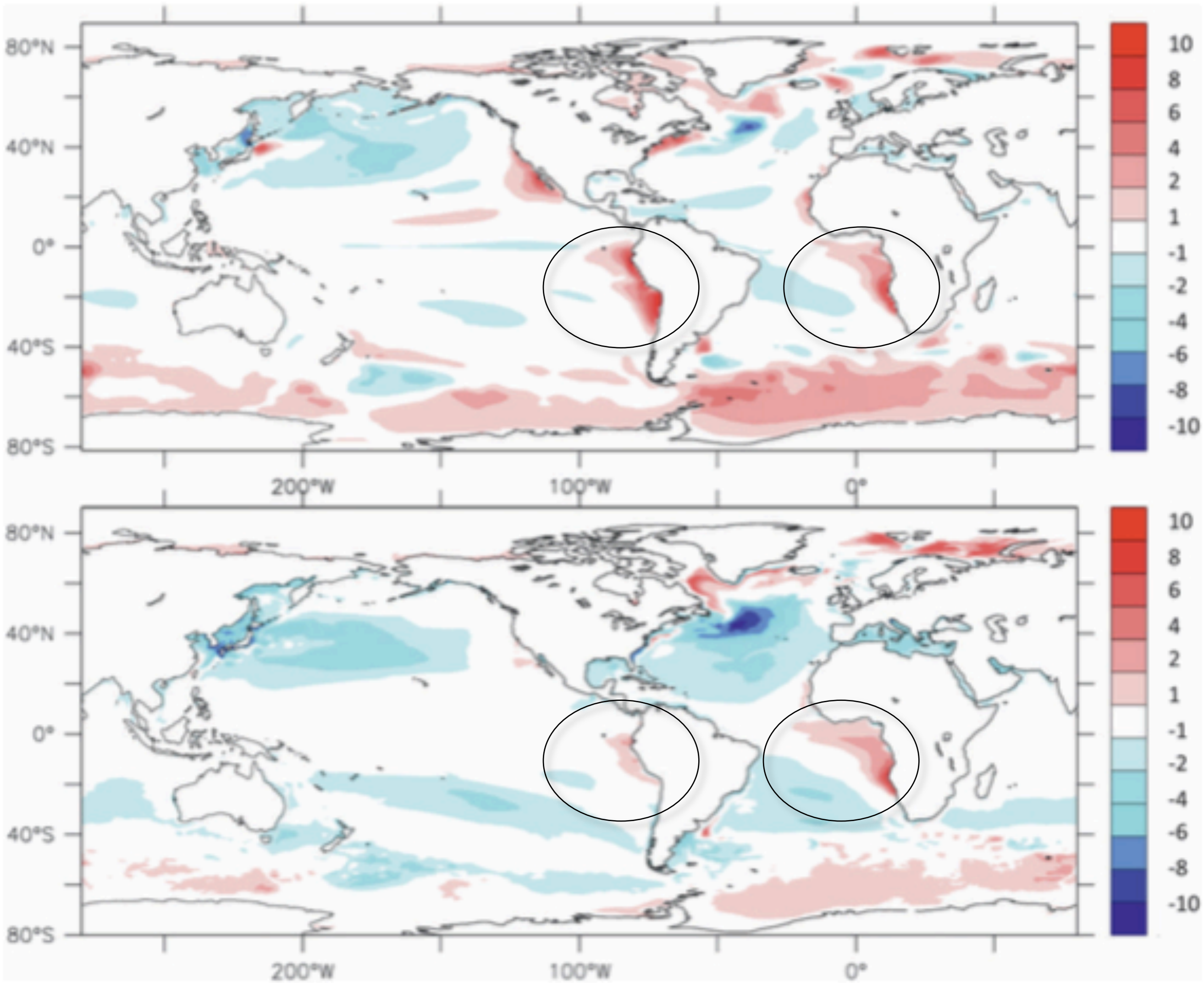
Model SST biases in the tropics

NOAA/GFDL

CM2.1 - Obs

NOAA/GFDL

CM2.5 - Obs



Delworth et al. (2012)

Some models exhibit double ITCZ

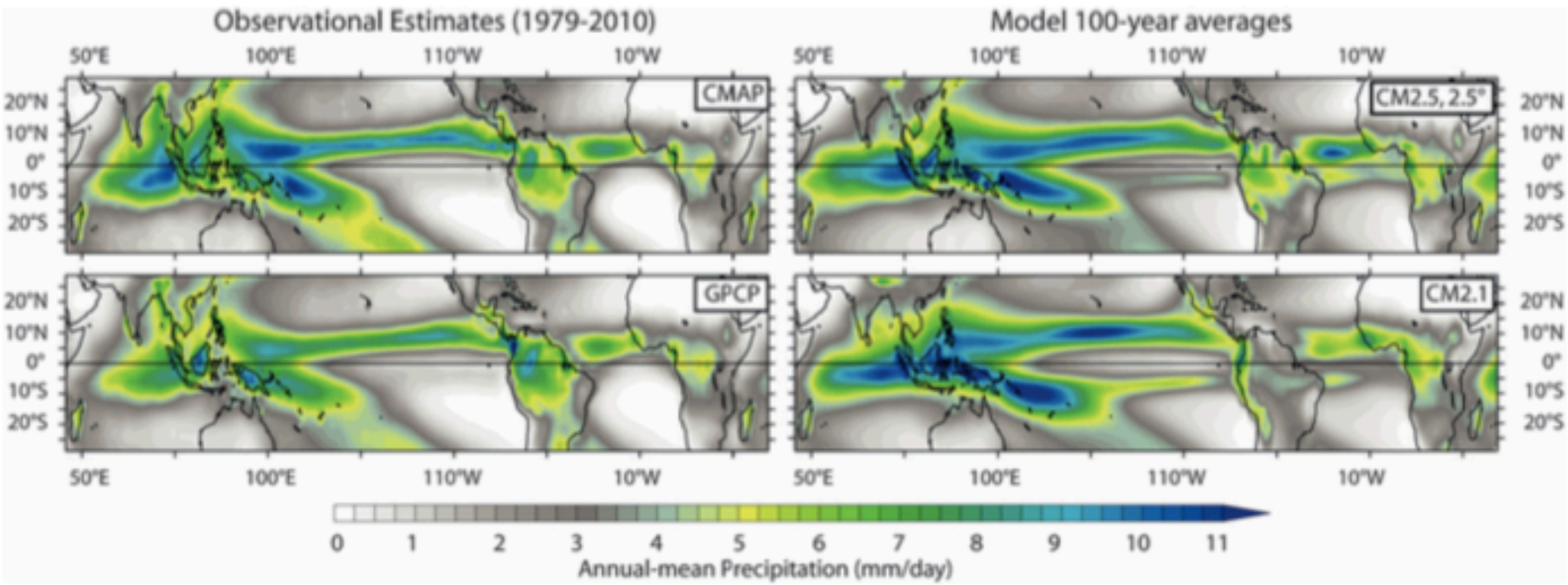
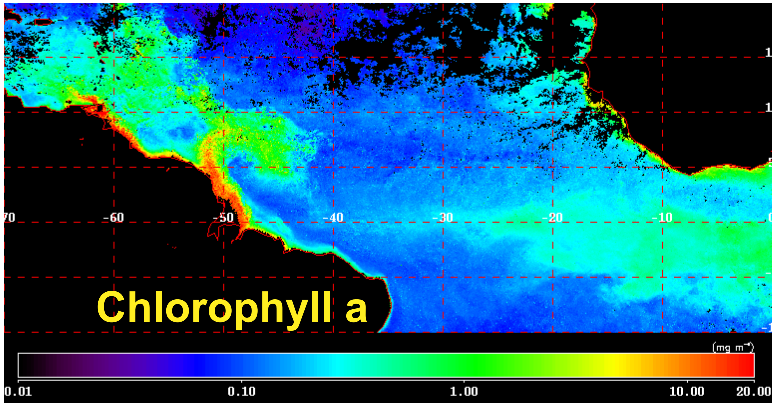


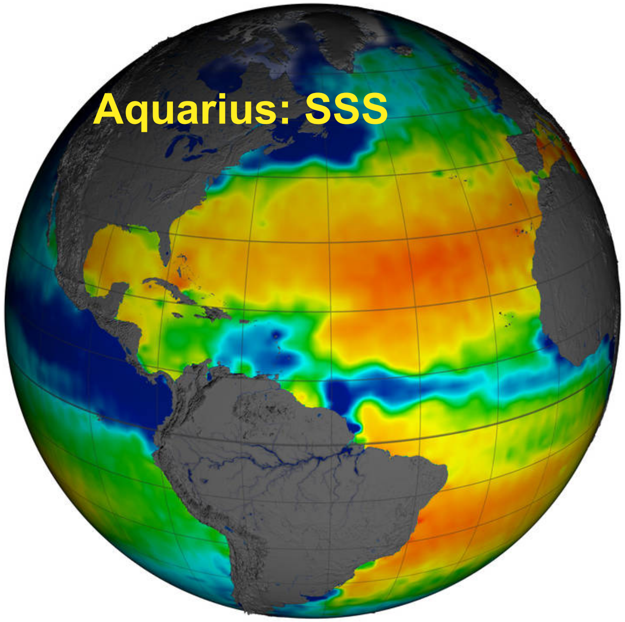
FIG. 9. Annual mean precipitation (mm day^{-1}). (left) Observational estimates with (top) CMAP and (bottom) GPCP. (right) Simulated precipitation with (top) CM2.5 and (bottom) CM2.1. Note that the CM2.5 results are plotted on a grid that is much coarser than its native model grid, but similar to that for CM2.1 and the observations.

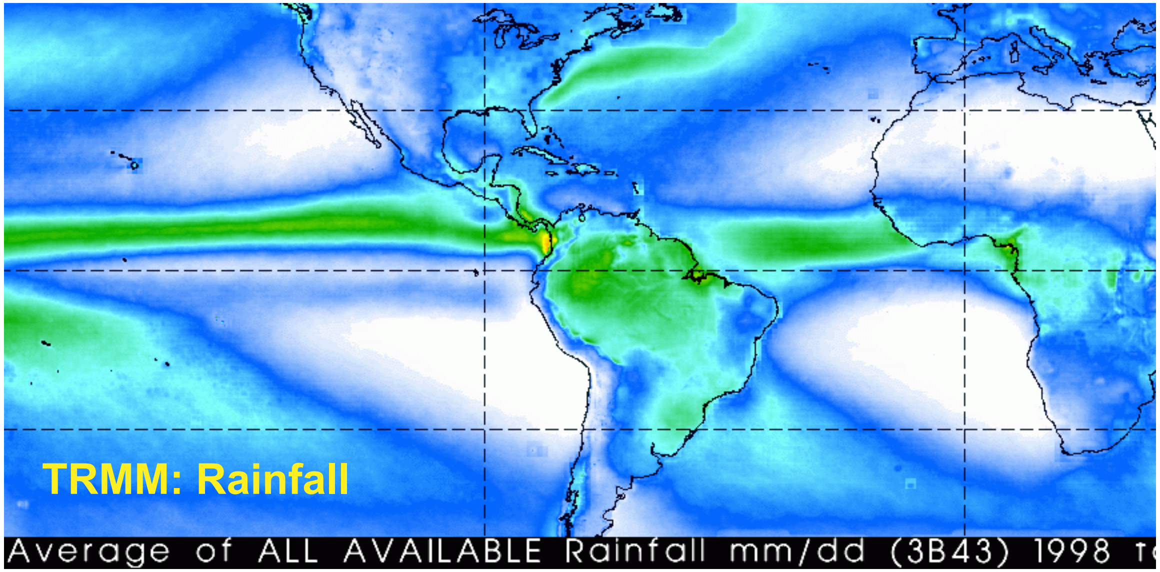
Delworth et al. (2012)

Satellites provide crucial information with global coverage and fine horizontal resolution

Satellites provide:
SSH, SST, SSS, ocean color, rainfall, scalar/vector winds, clouds, optical properties, …

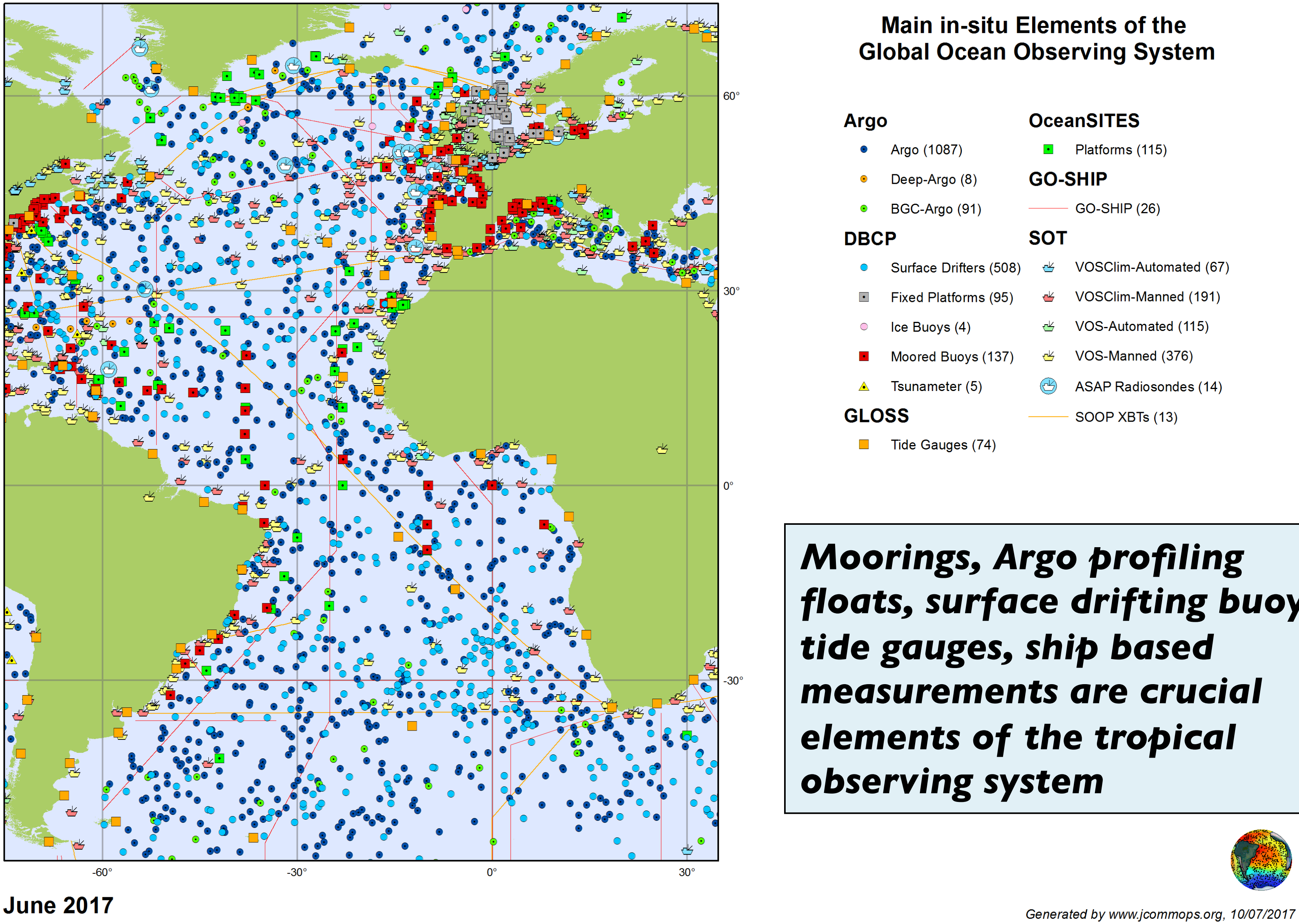






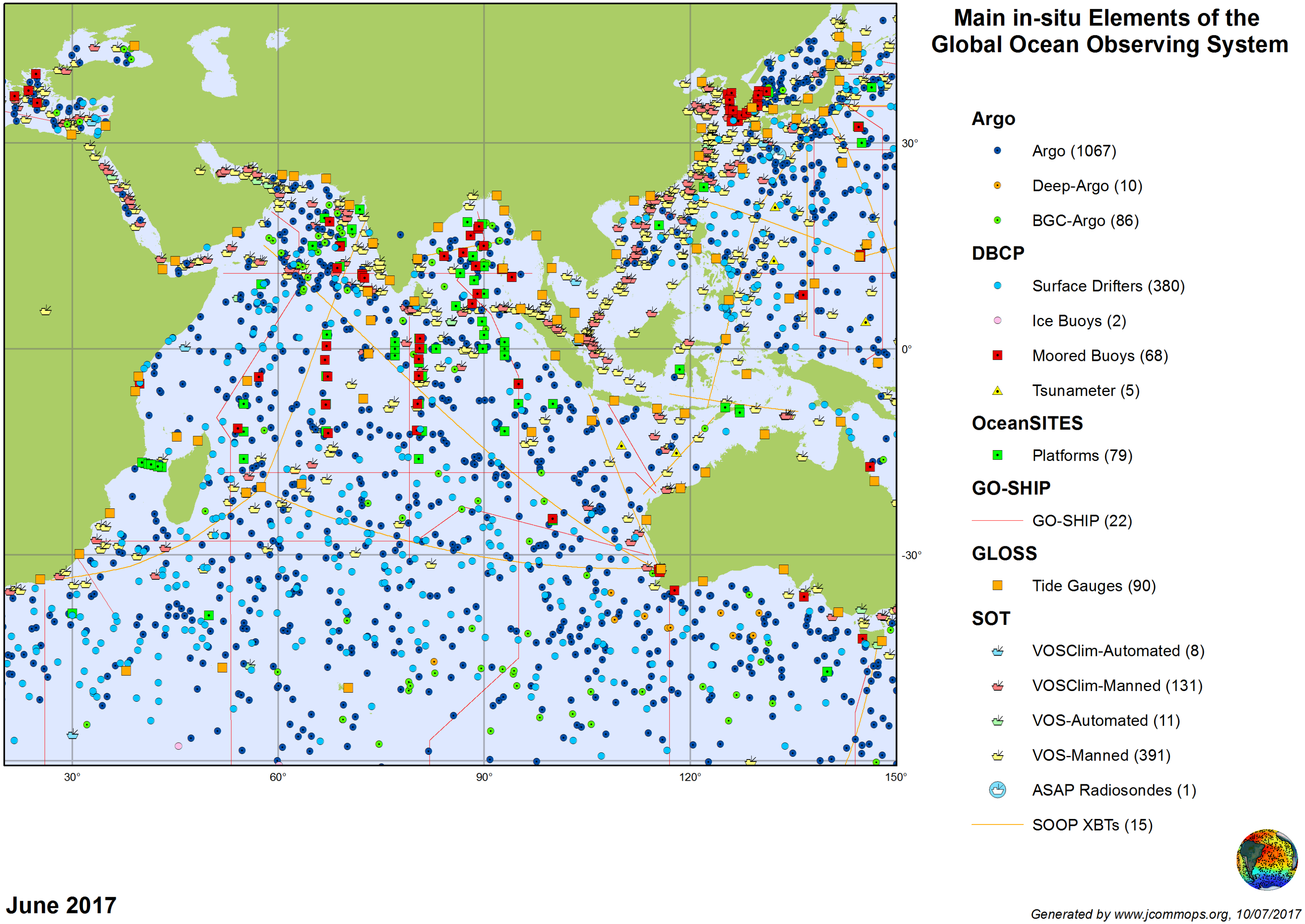
Inherent vulnerability to termination of satellite missions without planned follow-on missions

Global in situ data greatly enhance coverage in the tropical Atlantic Ocean

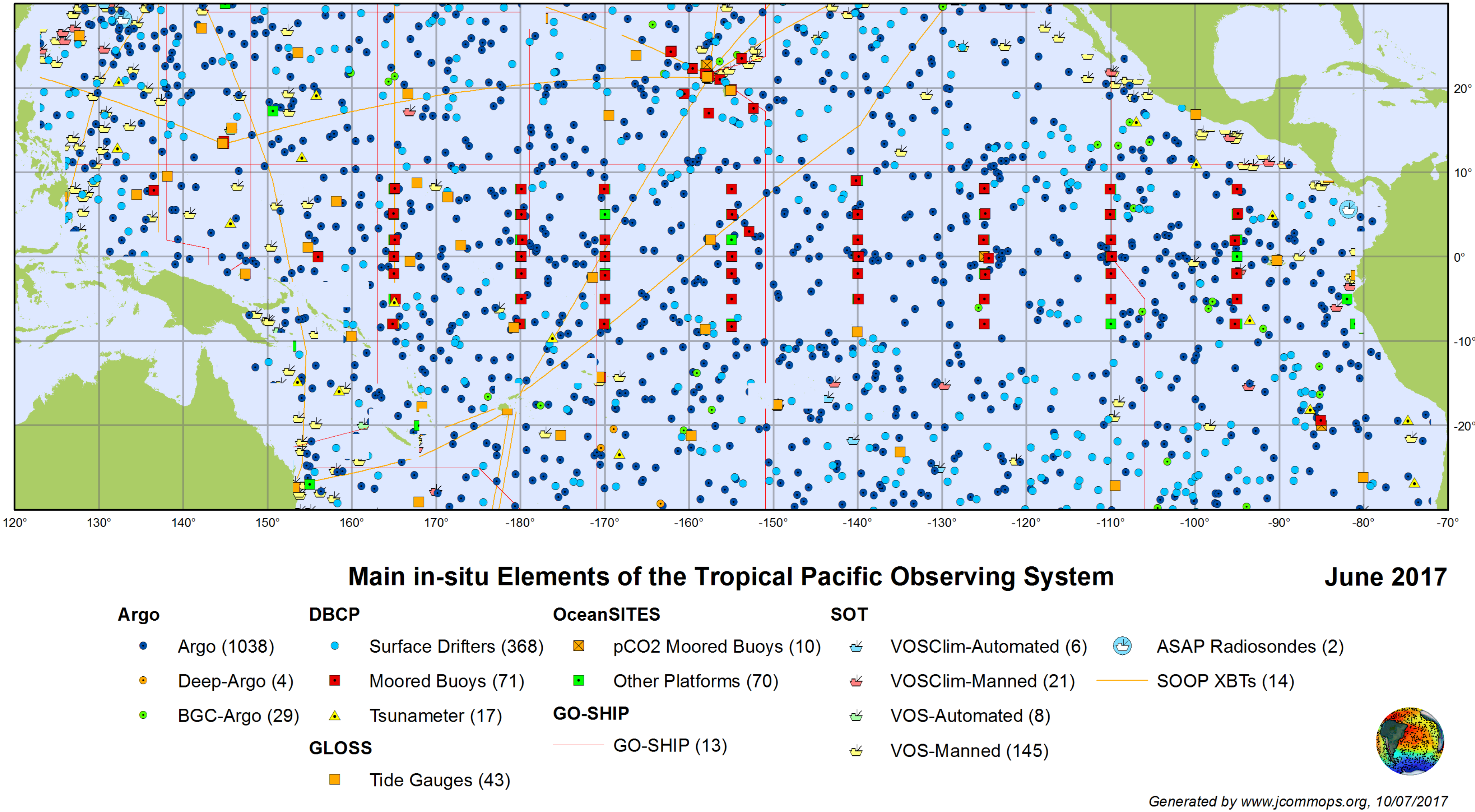


Moorings, Argo profiling floats, surface drifting buoys, tide gauges, ship based measurements are crucial elements of the tropical observing system

Global in situ data greatly enhance coverage in the tropical Indian Ocean

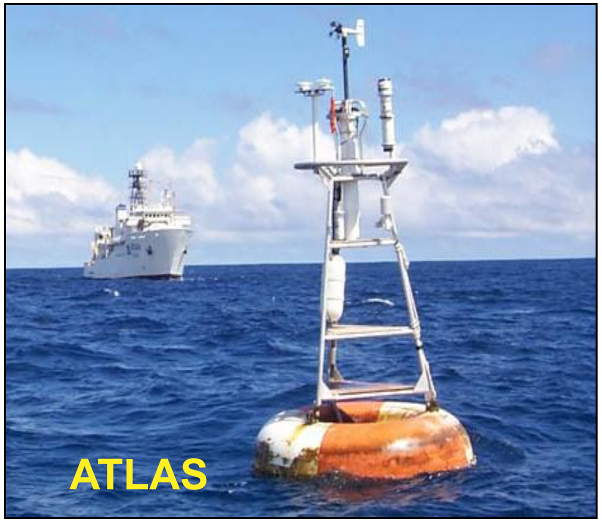


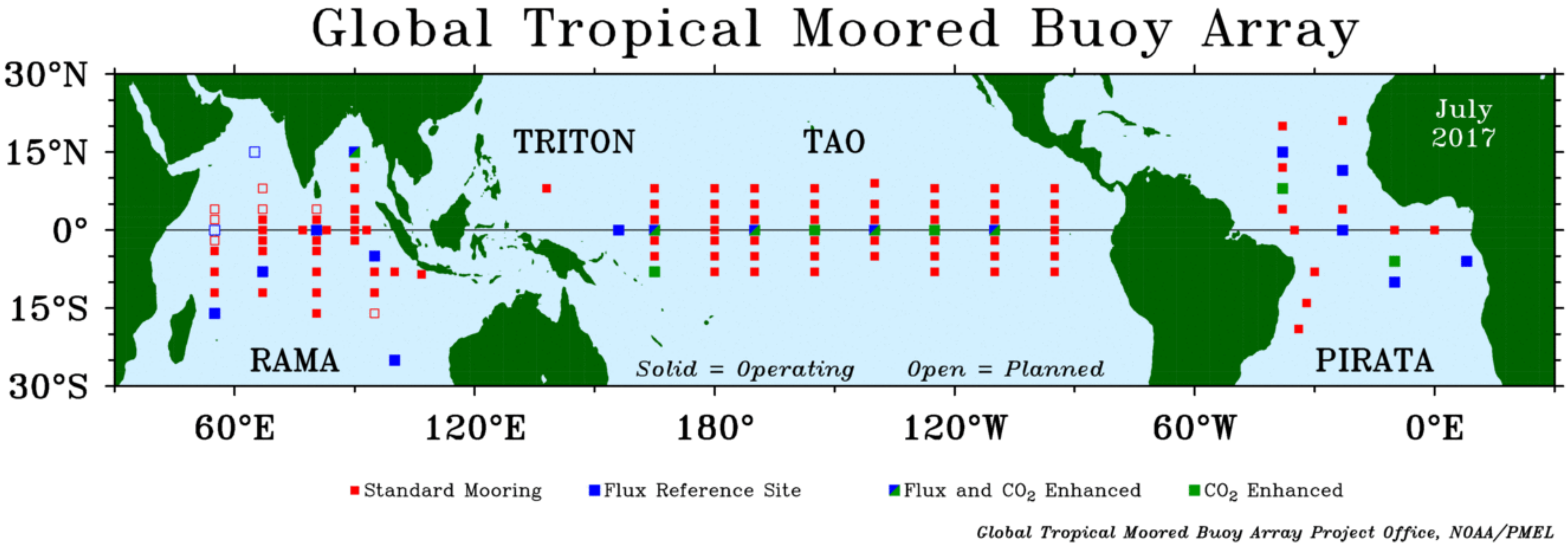
Global in situ data greatly enhance coverage in the tropical Pacific Ocean



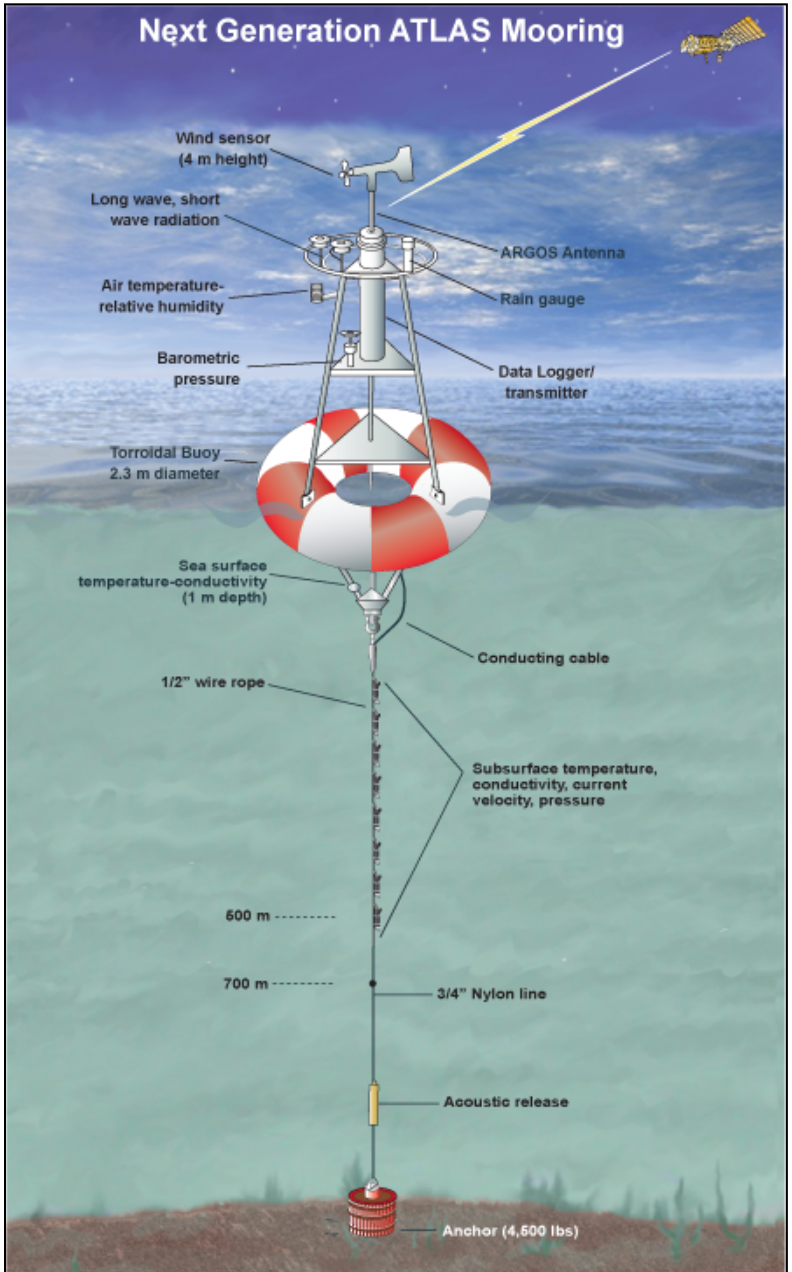
Sustained moored arrays

Global Tropical Moored Buoy Array:
A coordinated, sustained, multi-national effort to develop and implement moored buoy observing systems for climate research and forecasting throughout the global tropics, in support of DOC, NOAA, OAR, PMEL, and COD strategic plans





Courtesy of M. McPhaden



Courtesy of M. McPhaden

ATLAS Mooring:

- ✓ Rapid continuous sampling
- ✓ Real-time data
- ✓ Ocean and atmosphere
- ✓ Platform of opportunity (BCG sensors, chipods, ocean sound sensors…)

Designed and built at NOAA/PMEL

Original ATLAS: 1984

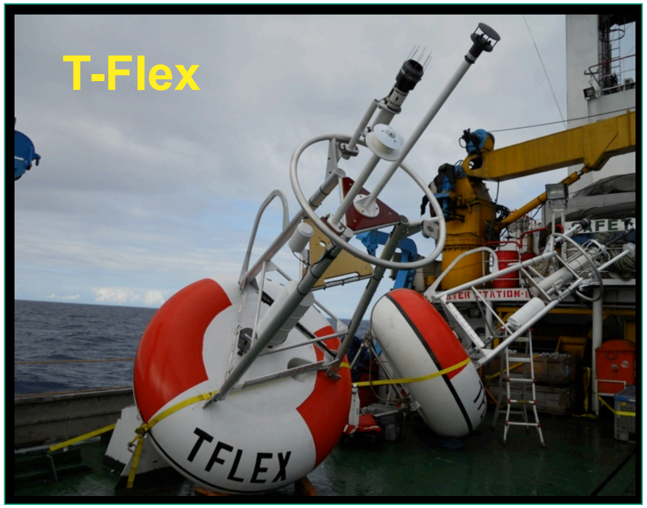
ATLAS-II (Nextgen): 1995

ATLAS-III (T-Flex): 2015

T-Flex: PMEL Designed ATLAS Update

Changeover To
Began in 2015

Side-by-side field
comparisons since 2011



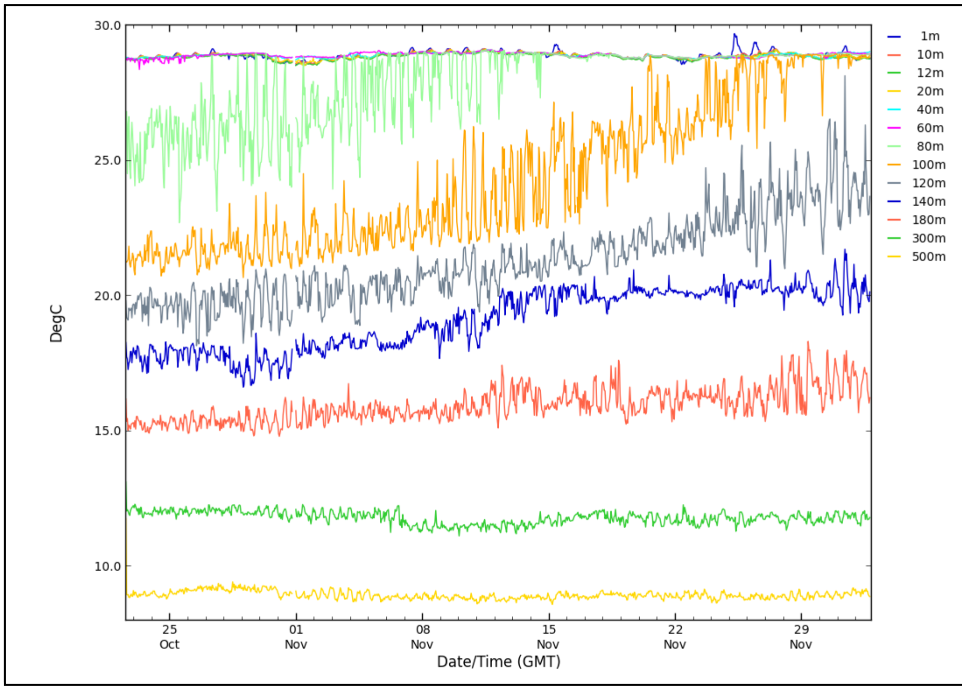
T-Flex Advantages:

- Uses commercially available components
- Increased temporal resolution of telemetered data (Argos→Iridium)
- Includes flexibility to directly incorporate new instrumentation
- Comparable or better data accuracy
- Decreased losses due to vandalism
- Improves GTS data latency for synoptic weather forecasting

Courtesy of M. McPhaden

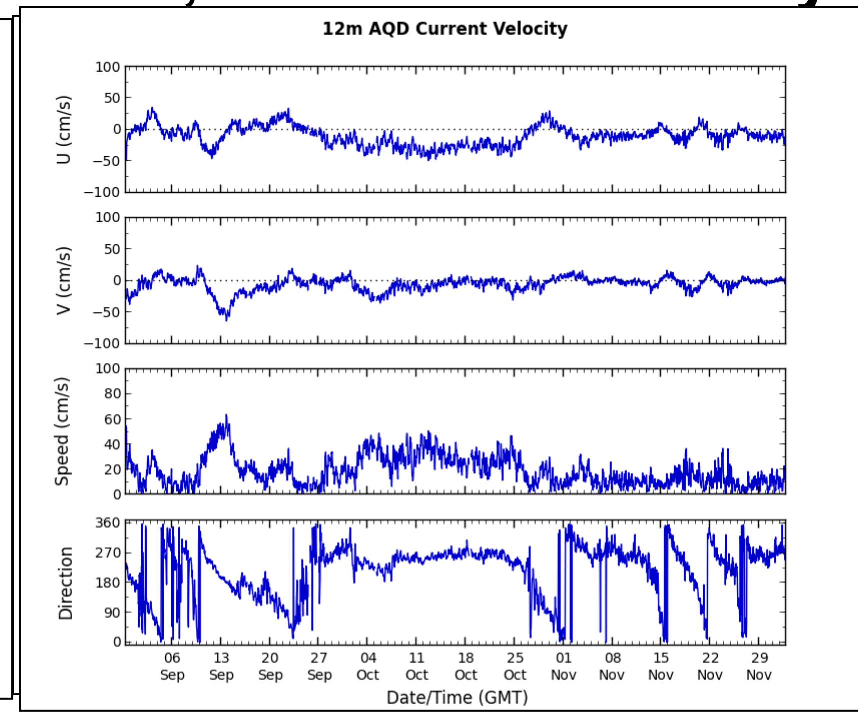
T-Flex Hourly Data in Real Time

12ºS, 80.5ºE Temperature



24-29 Nov 2015

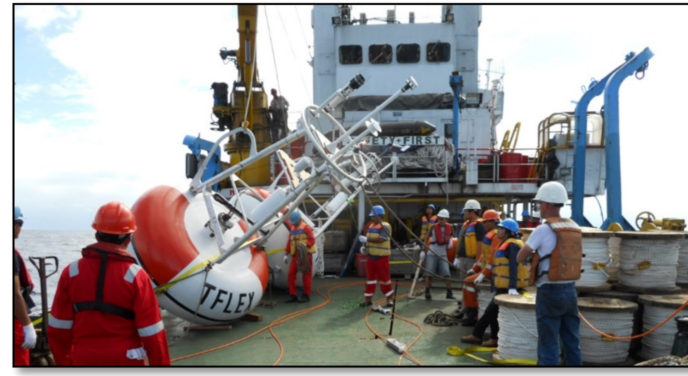
4º S, 80.5ºE 10 m Velocity



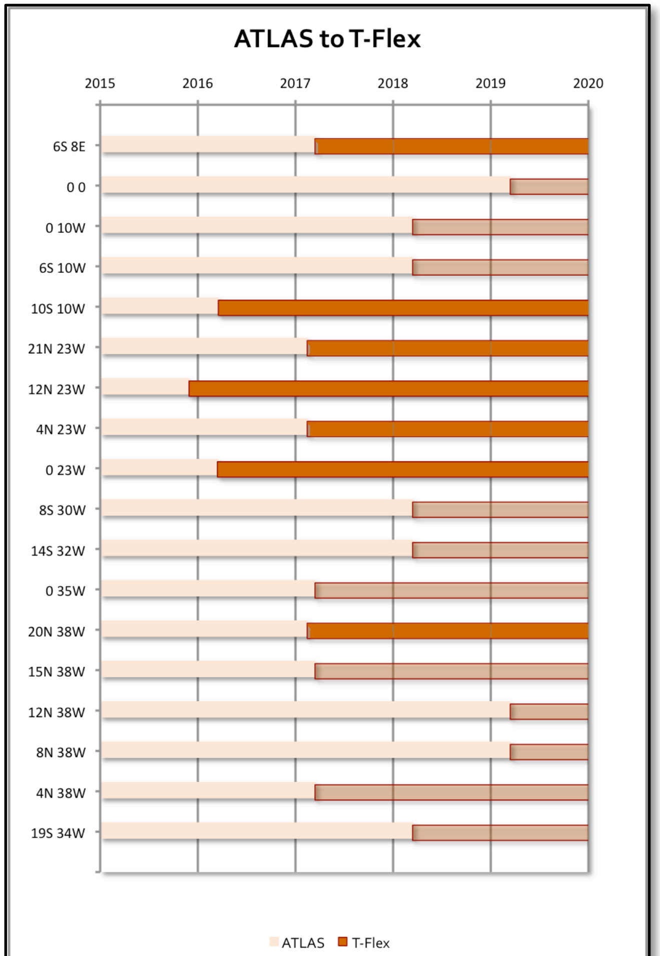
6-29 Sept 2015

Courtesy of M. McPhaden

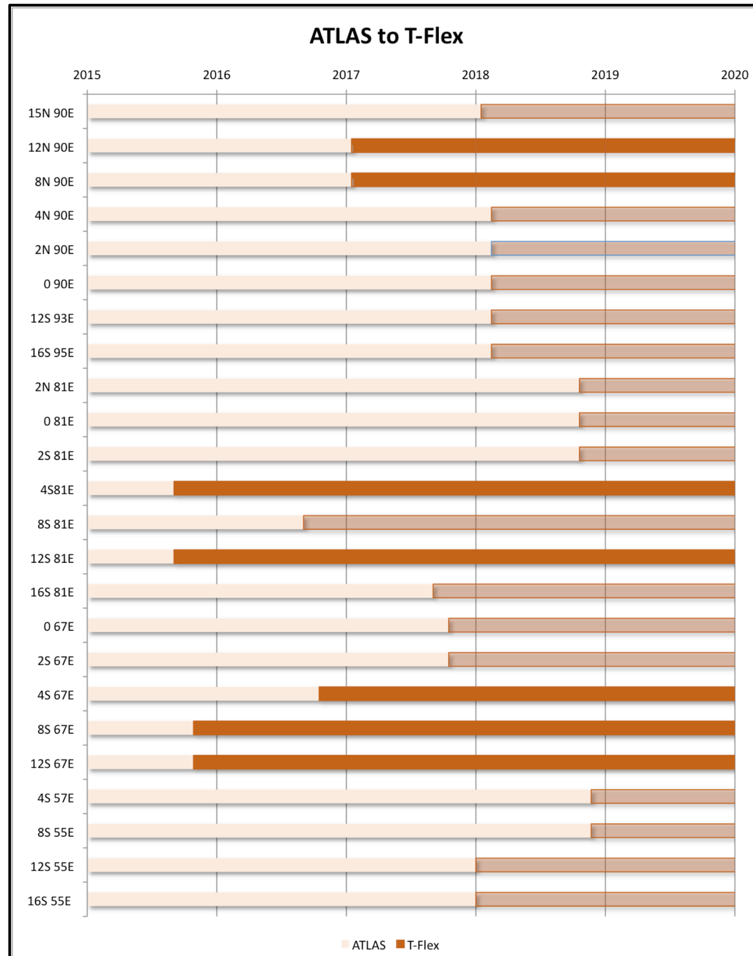
T-Flex transition underway



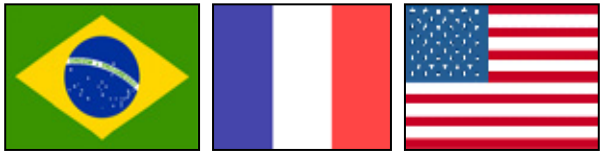
Indian Ocean



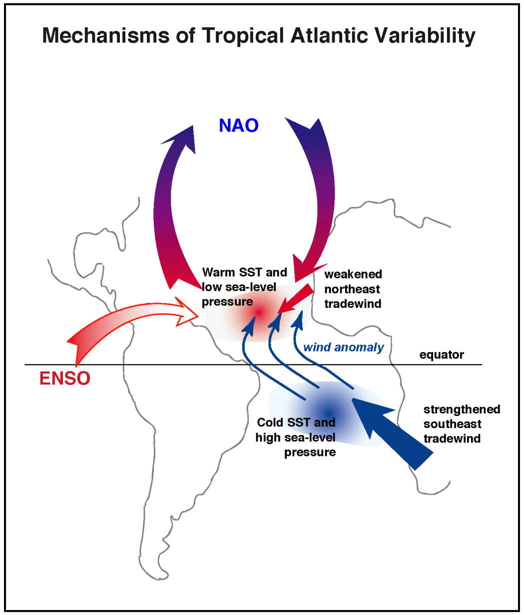
Atlantic Ocean



Tropical Atlantic observing systems



PIRATA: Centerpiece of the Tropical Atlantic Ocean Observing System



<u>Atmosphere:</u>

- wind (direction, speed)
- relative humidity
- air temperature
- precipitation
- incident radiation

<u>Ocean:</u>

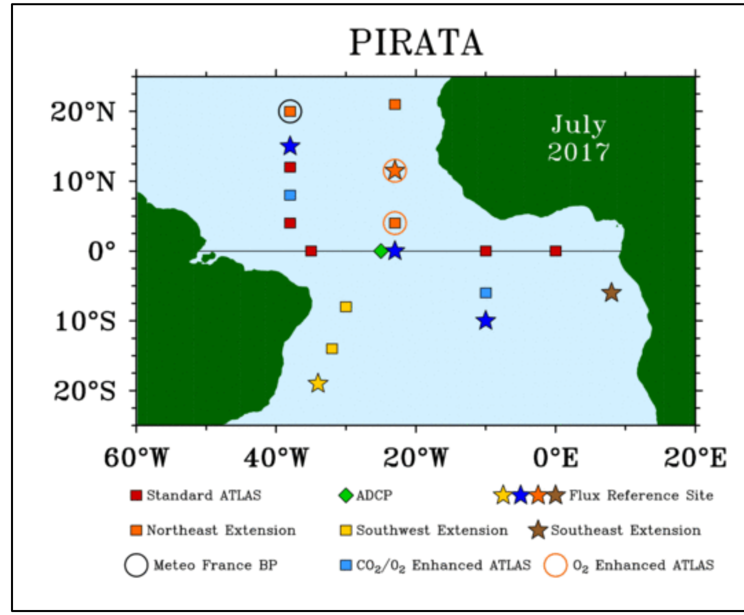
- temperature

(11 levels surface to 500m)

- salinity

(4 to 9 levels surface to 120m)

- pressure (at 300 & 500m)
- surface currents at 4 sites



PIRATA: Prediction and Research Moored Array in the Tropical Atlantic

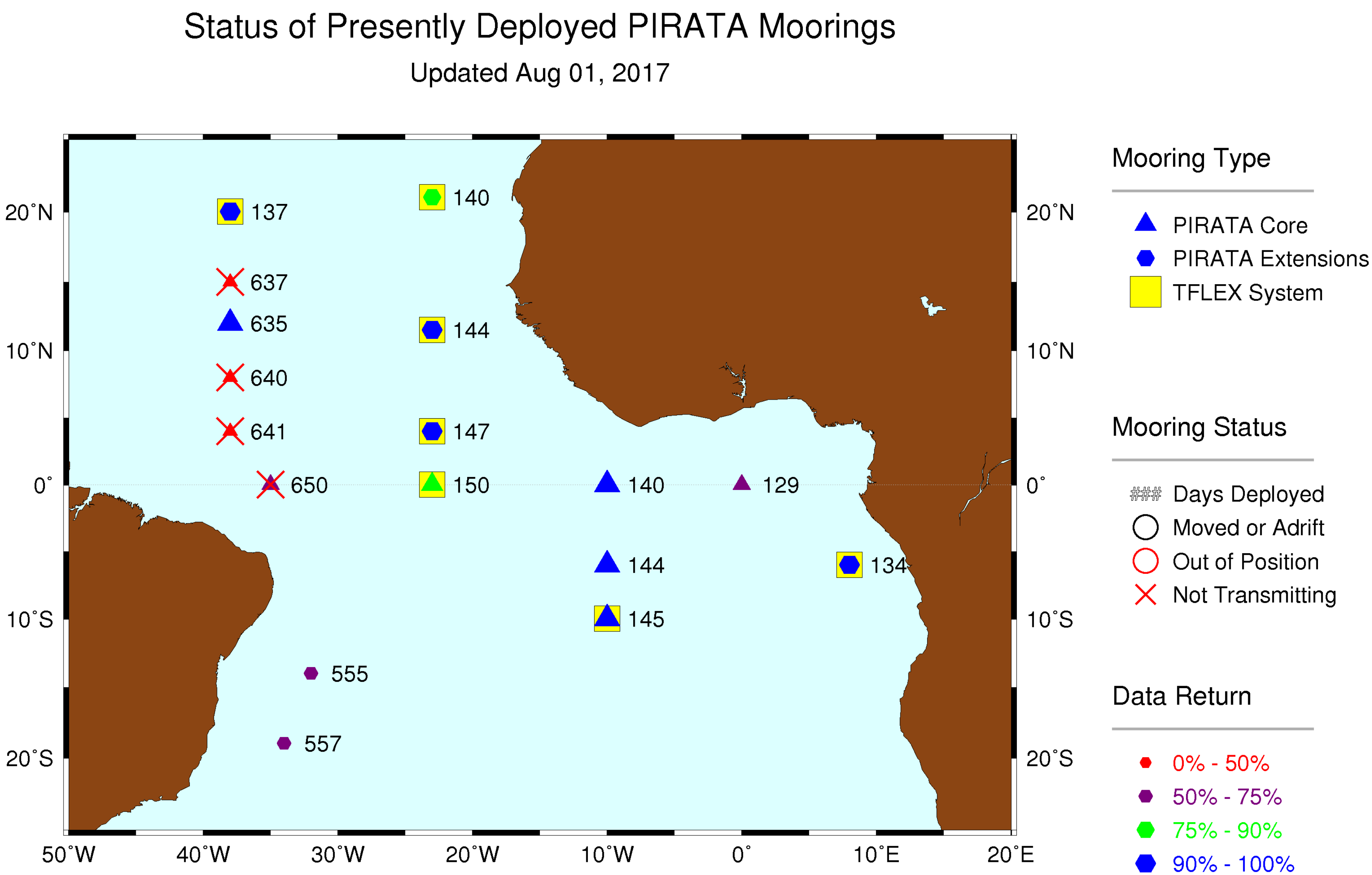
✓ Established in 1997 by France, Brazil and the US (NOAA/PMEL+AOML)

✓ Brazil & France provide logistic support & most ship time

✓ NOAA provides most mooring equipment & data processing

Courtesy of M. McPhaden

PIRATA status



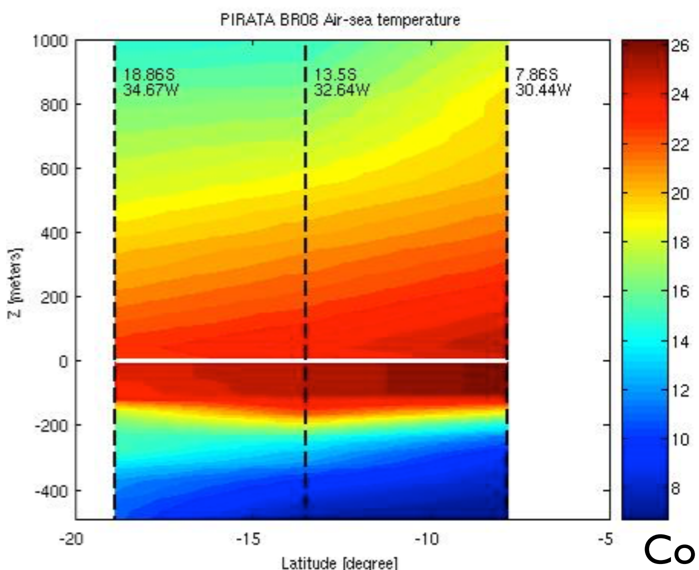
Brazilian: PIRATA-BR XVII

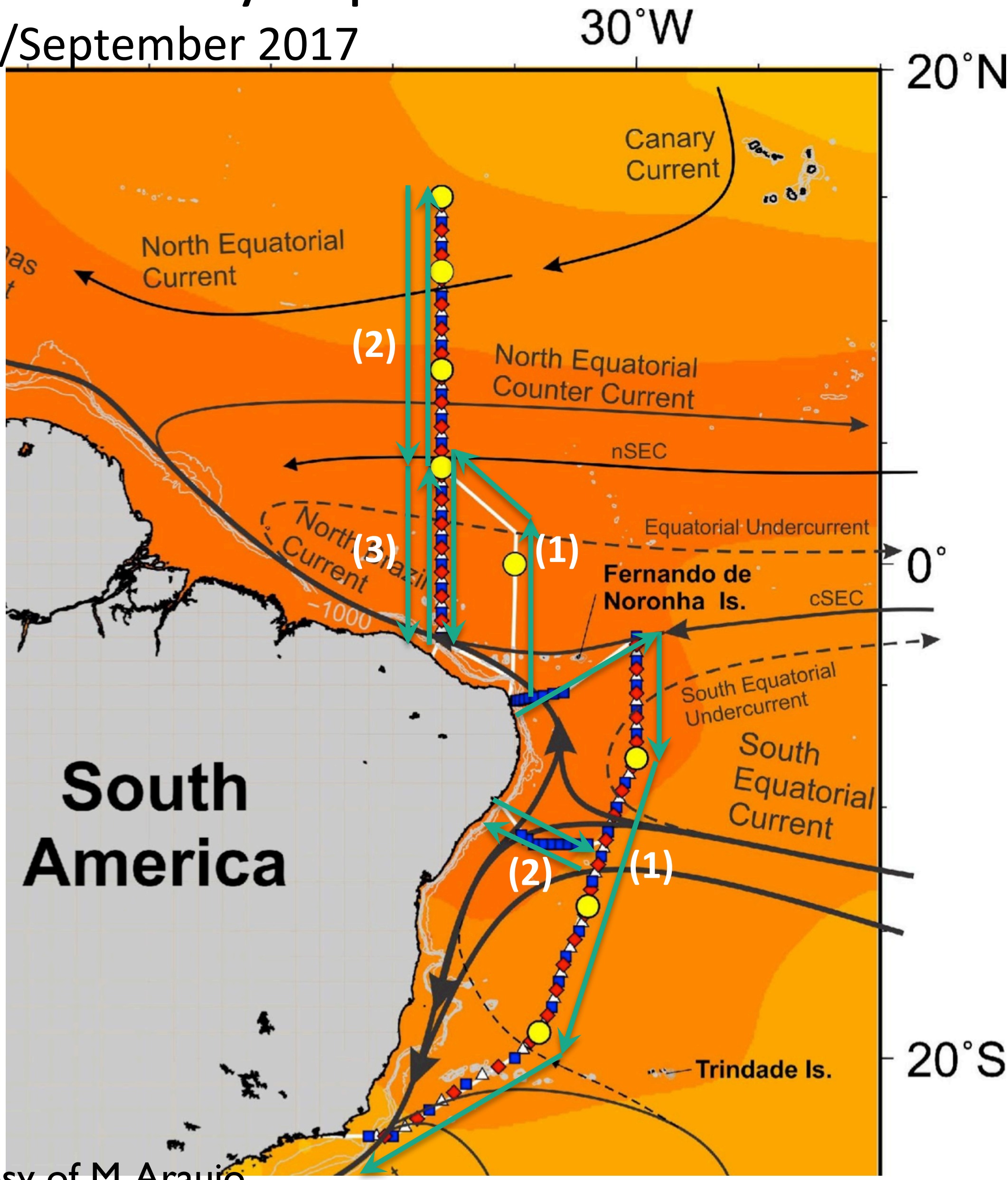
Western Atlantic climate Variability Experiment - WAVEs

21/June – 7/September 2017

Upper Ocean-Atmosphere Repeated Sampling Strategy:

180 T-S profiles
9,000 Km underway: currents, pCO2, atmospheric particles deposition
marine microbiology;
66 daily radiosonding





Courtesy of M.Araujo

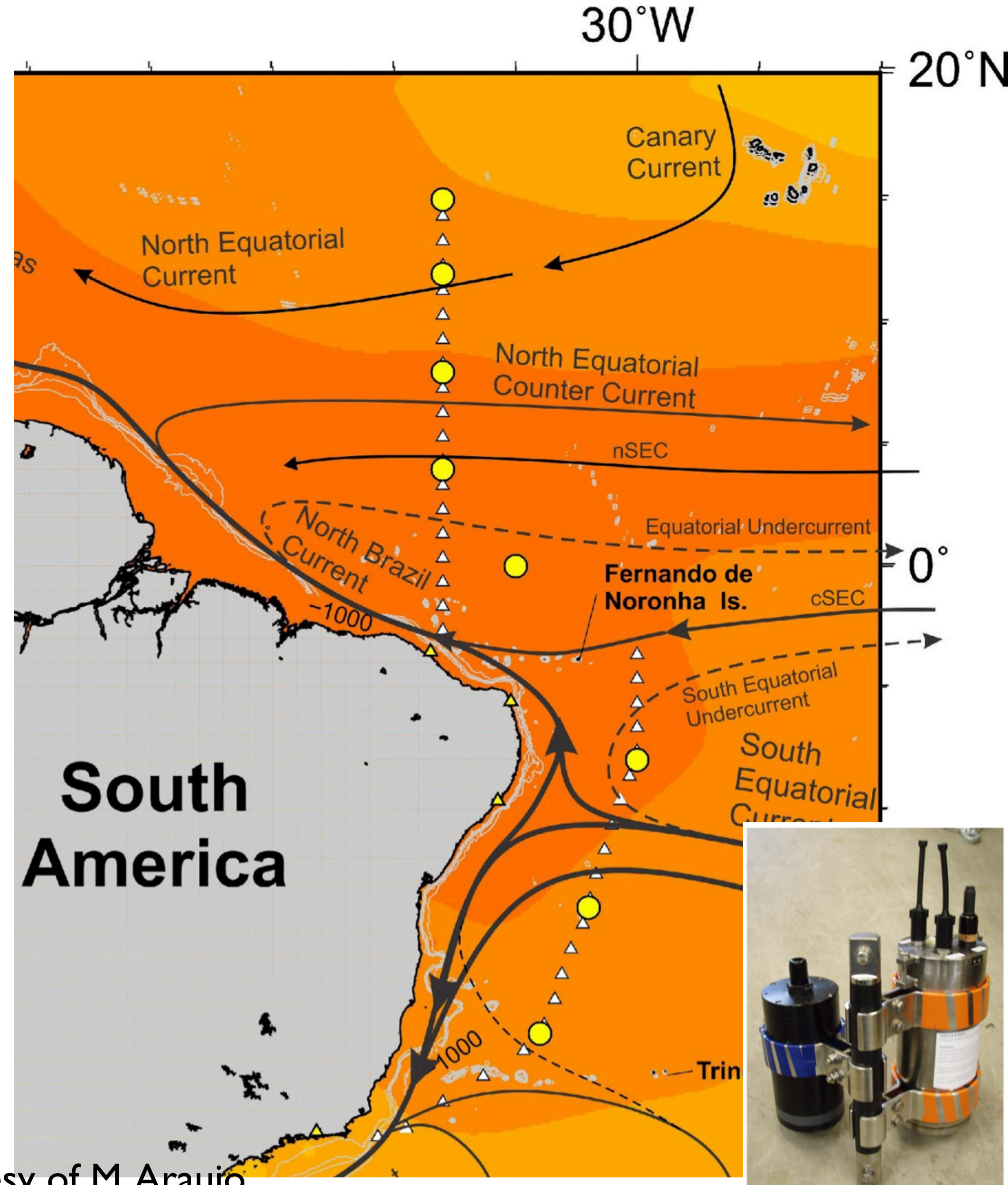
PIRATA-BR XVII Western Tropical Atlantic Experiment

21/June – 7/September 2017

FULL DEPTH OCEAN SAMPLING

60 stations down to 10m of the ocean floor

Currents
Temperature
Salinity
Oxygen
CO_2
Marine Biology
Rare earth elements
Perfluoroalkylated compounds
Bottom mixing layer
...



Courtesy of M.Araujo

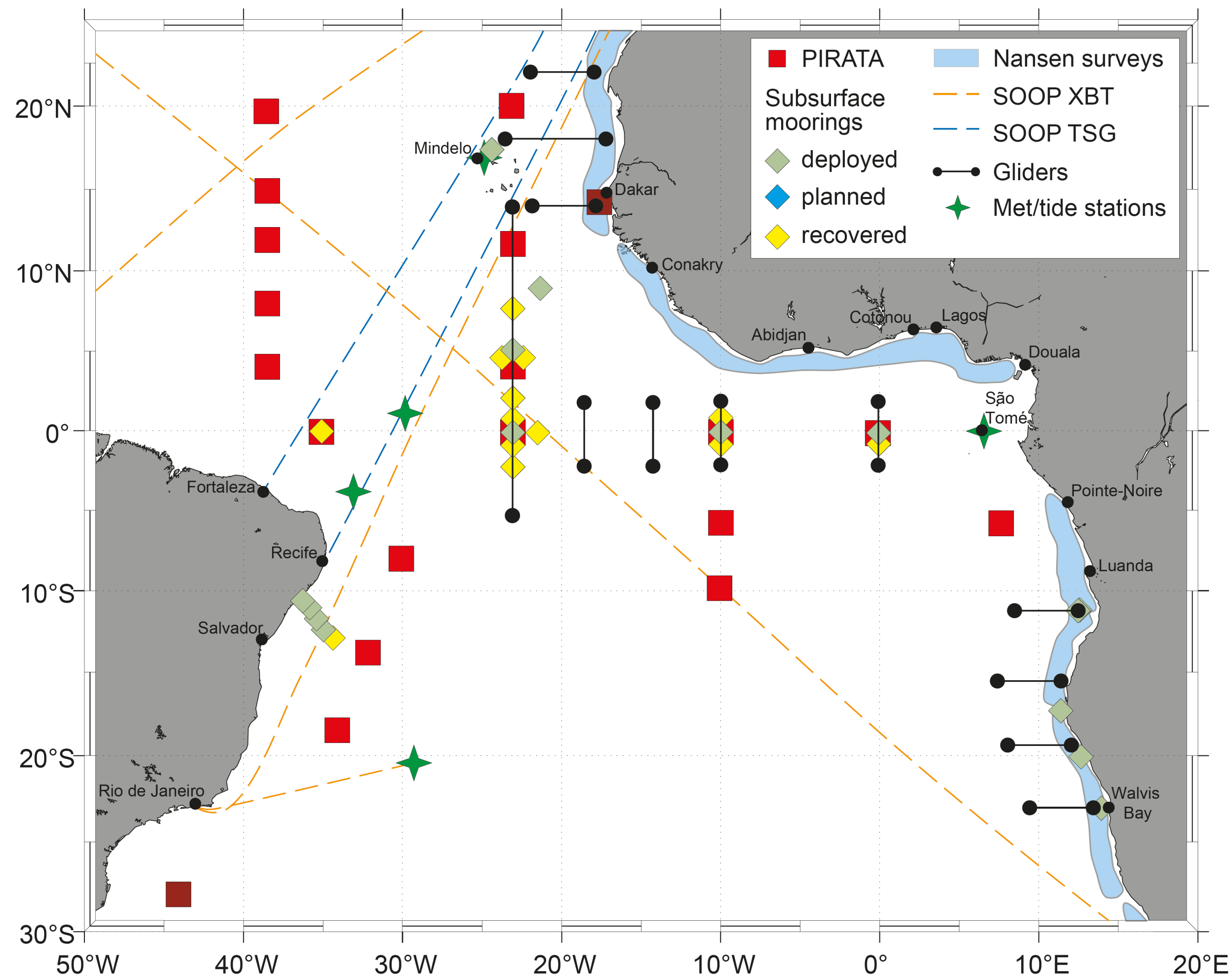
Anchor for process studies, ancillary projects

- Deploy XBTs, drifters, Argo profiling floats, gliders
- 2004+: Nutrients measured during French cruises in eastern tropical Atlantic (IRD-Brest)
- 2006+: Radiosondes and ozonesondes launched during US cruises in northern tropical Atlantic to measure Saharan dust aerosols (Howard University and NOAA/NESDIS)
- 2006+: CARIOCA systems measuring CO_2 parameters at 3 moorings (IRD Paris, AtlantOS)
- 2011+: Measure Chl pigments during French cruises in eastern tropical Atlantic (IRD-Brest)
- 2011+: Sargassum sampling during French cruises in eastern tropical Atlantic
- 2012+: O_2 sensors in the dissolved oxygen minimum zone in NE tropical Atlantic (GEOMAR)
- 2014+: Acoustic retriever units on buoys: contribution to Ocean Tracking Network
- 2014+: Oceanic turbulence measurements (χ-pods) on equatorial moorings (OSU)
- 2017+: Tropical Atlantic Currents Observation Study at 4N, 23W (NOAA/AOML)
- 2017+: Real-time O_2 sensors (GEOMAR, AtlantOS)
- 2017+: Development of enhanced PIRATA synthesis data set (NOAA/AOML)

GEOMAR
Tropical Atlantic Observing System

Activities include:

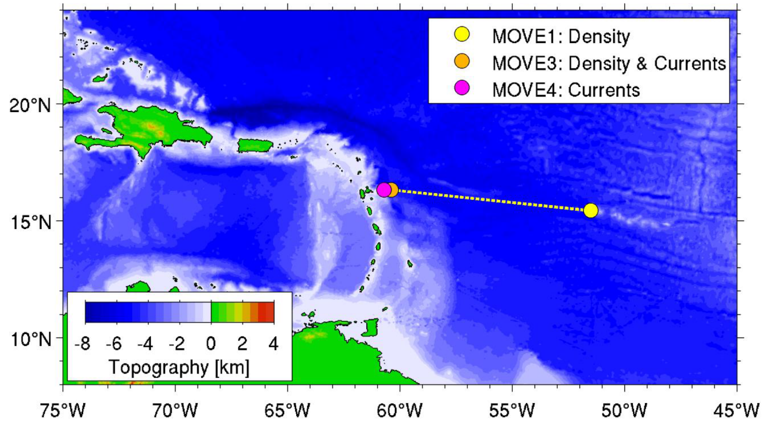
- western boundary current mooring array off Brazil at 11°S
- Angola Current moorings at 11°S
- equatorial mooring at 23°W in cooperation with PIRATA (deep equatorial circulation)
- Cape Verde Ocean Observatory (10+ year total dissolved oxygen record)



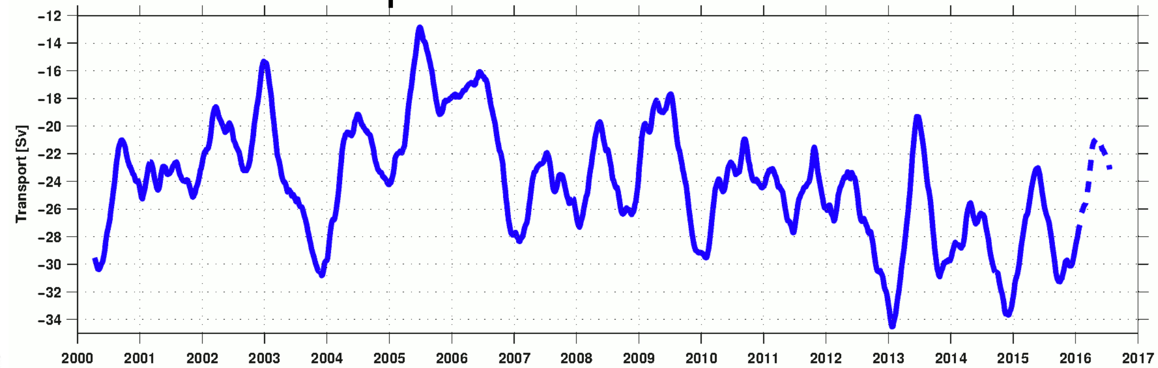
Courtesy of P. Brandt

Tropical Atlantic MOC arrays

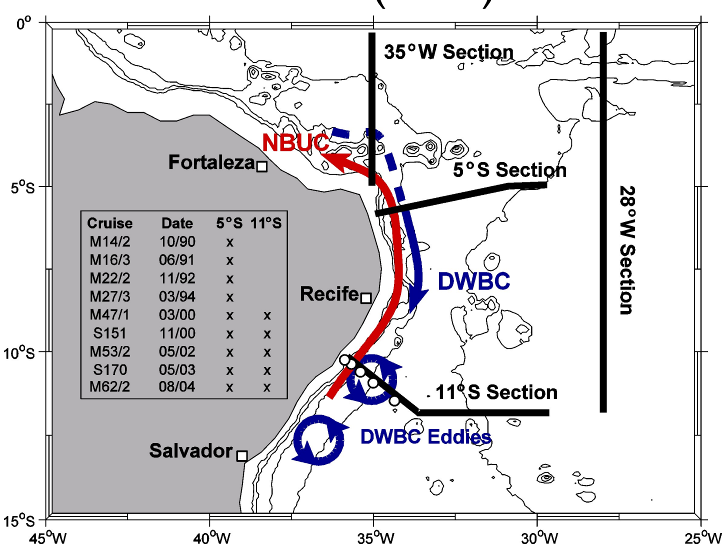
Send et al. (2011)



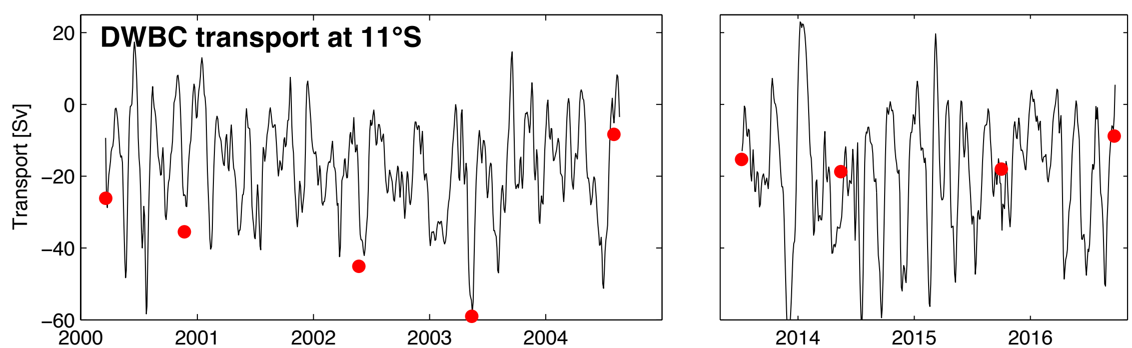
NOAA-funded
Meridional Overturning Variability Experiment:
Deep branch of AMOC at 16N



Hummels et al. (2015)

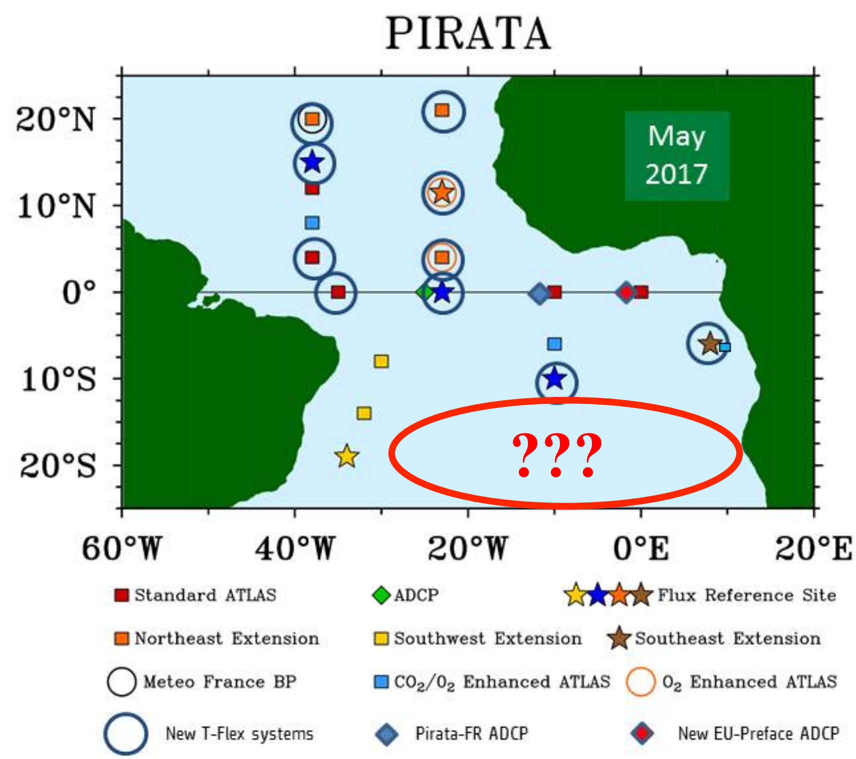


GEOMAR/RACE
Western Boundary Circulation Array at 11S



Tropical Atlantic highlights (a subset)

- 20-year anniversary of the PIRATA backbone array
- Seven TFLEX moorings now, ten after Brazilian PIRATA cruise
- More real-time data (hourly Iridium transmissions)
- Real-time total dissolved oxygen loggers deployed at two sites along 23W
- More sites with 10-m current meters
- CO2 at three moorings
- Many EOVs sampled during cruises
- Microstructure/turbulence measurements
- Interannual-decadal AMOC timeseries
- Decadal CVOO timeseries

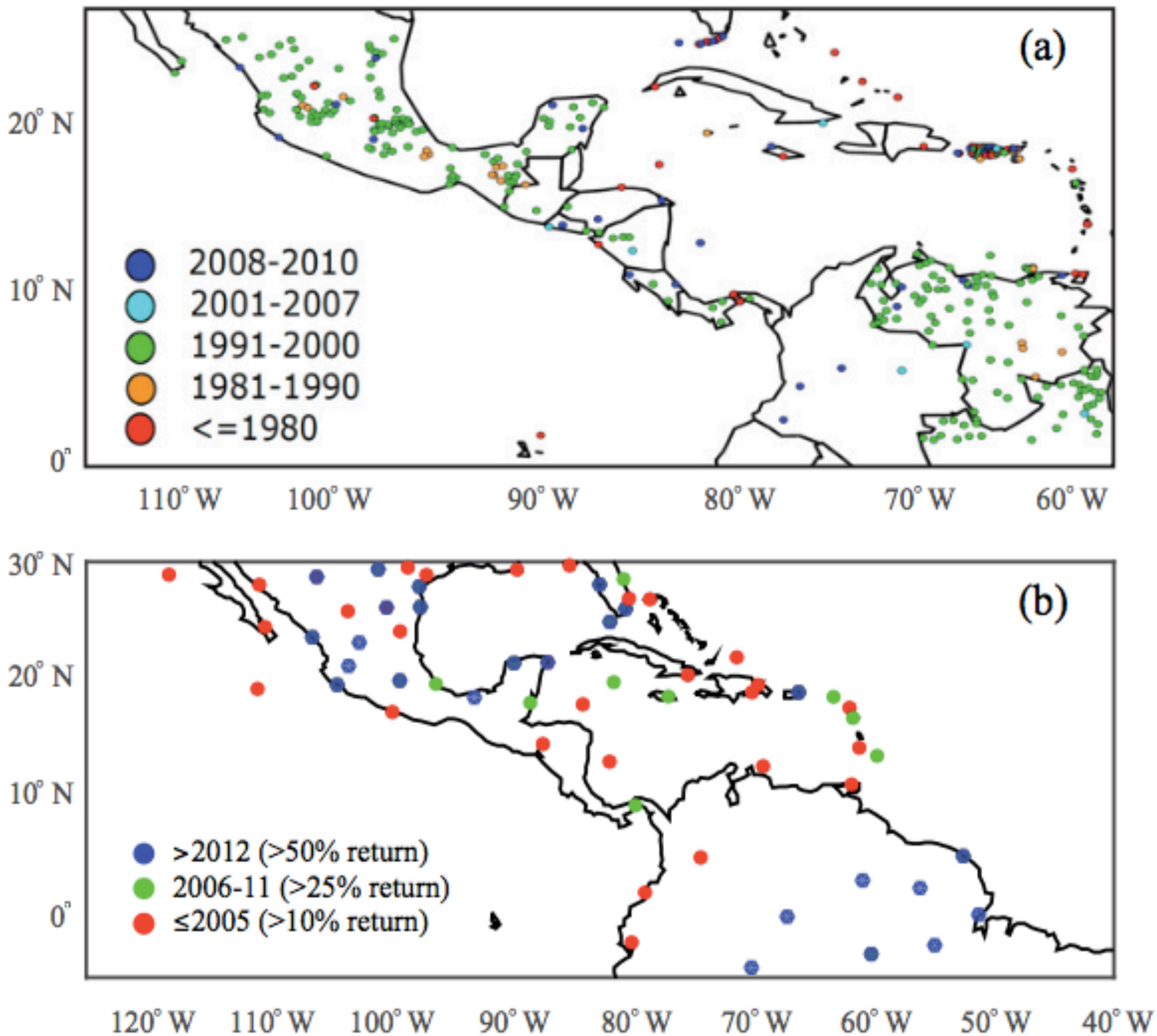


Tropical Atlantic observing system gaps/ concerns/opportunities

- Should POS provide input/engage in the TAOS review effort?
- Lack of time series measurements in the tropical South Atlantic (e.g., in eastern boundary upwelling areas where model biases are large)
- Increasing interest from AtlantOS, CLIVAR, PREFACE to enhance moorings with multidisciplinary sensors (biogeochemistry, aerosols, O_2, CO_2, …)
- Ocean currents and salinity are still undersampled in upper 100 m
- Vertical mixing (microstructure) and turbulence undersampled
- More collaborations needed with South Atlantic community and fishery programs
- More capacity building efforts needed in the African countries bordering the Atlantic Ocean
- PIRATA Memorandum of Understanding needs to be renewed in 2019

Operational networks in IAS region

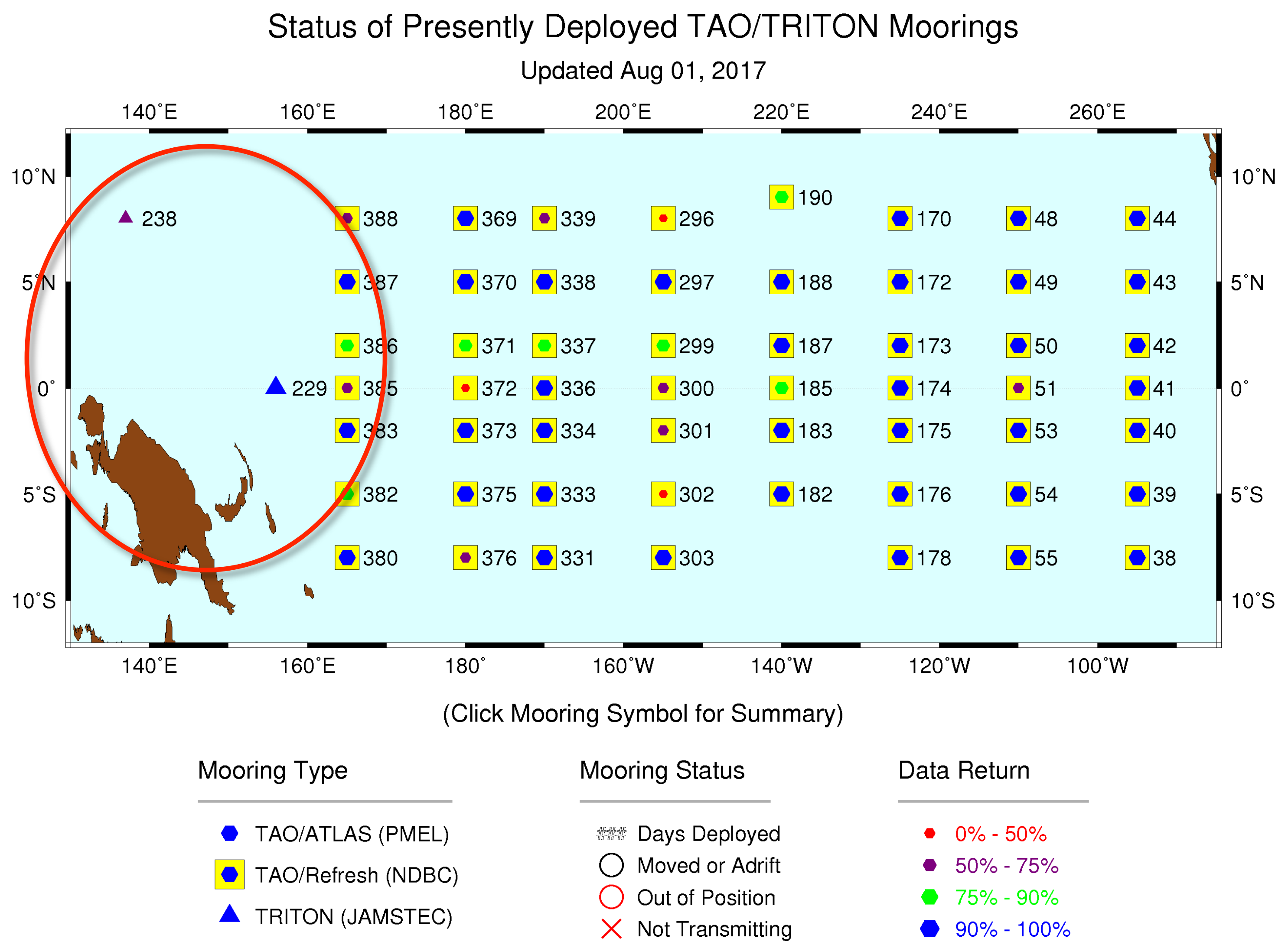
- Several World Meteorological Organization (WMO) radiosonde sites in Central America, but they don't launch regularly (often just during the week, sometimes just once per day) due to lack of resources.
- Over 30 independent countries with different data sharing policies
- Figure shows most recent rainfall measurement



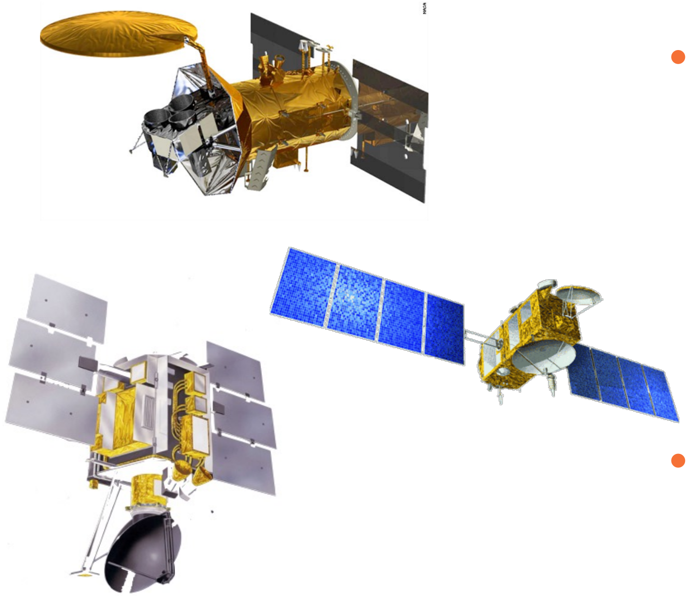
Courtesy of Y. Serra

Tropical Pacific observing systems

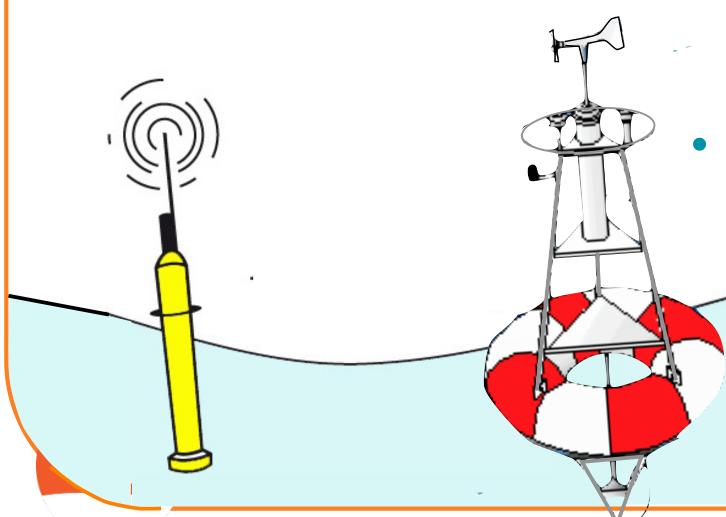
TAO/TRITON status

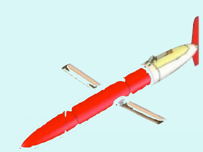


An integrated strategy



- Complementary "backbone" technologies:
  - Satellites give global coverage, fine horizontal detail
  - Argo resolves fine vertical structure, adds salinity, maps subsurface T and S and connects to subtropics
  - Moorings sample across timescales, allow co-located ocean-atmosphere observations, velocity sampling
- How do these pieces fit together?
  - TAO designed in 1980s-90s.
    What is the role of moorings in the coming decade?
  - Where can Argo or other autonomous instruments or satellites supplant moorings?
  - New needs: Expanded biogeochemistry and impacts
- Assimilating models integrate diverse observations
  → Users will increasingly rely on gridded products





Courtesy of W. Kessler

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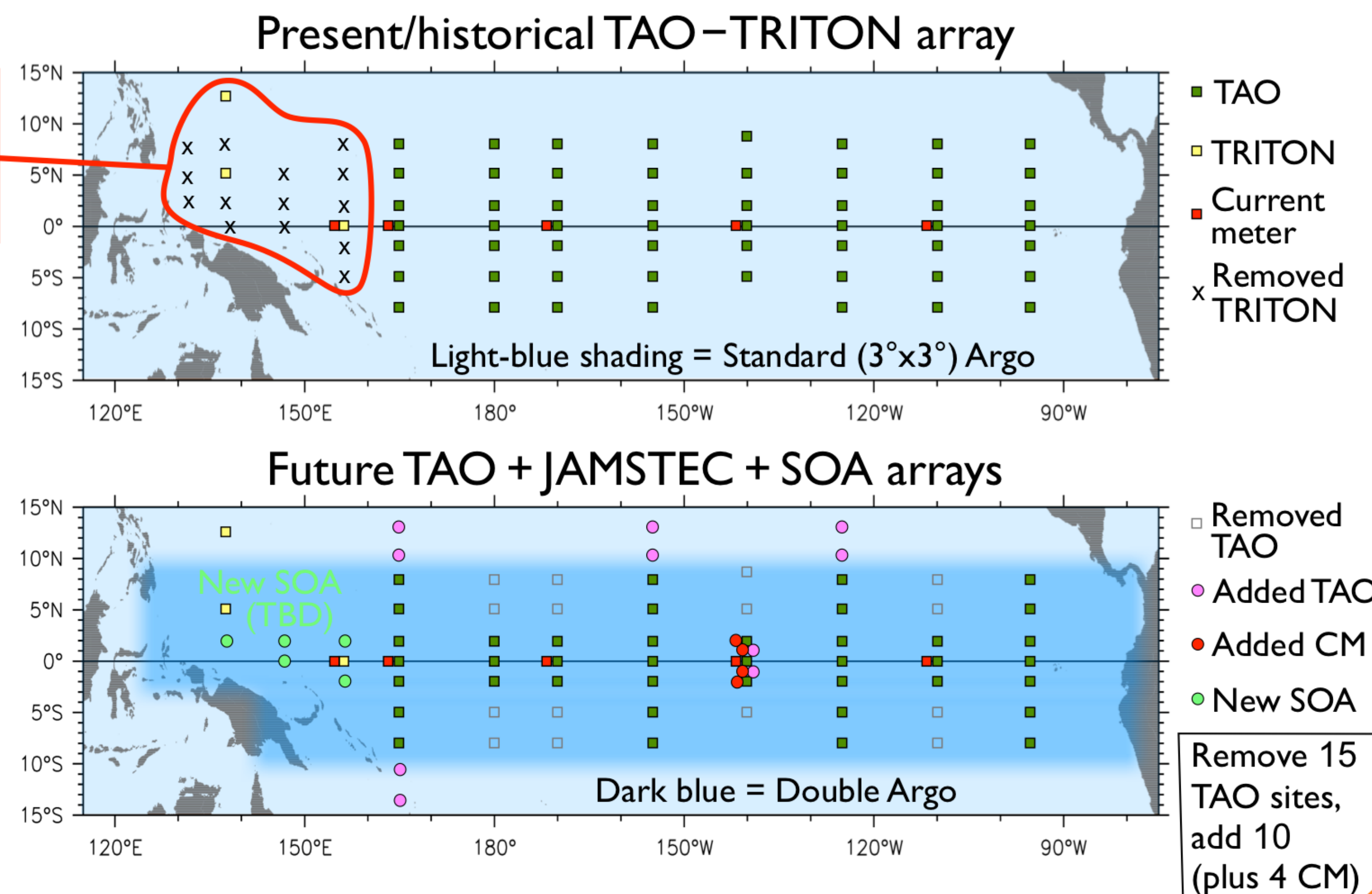
Specific Recommendations: TPOS2020 1st Report

- Reconfigure the moored array

  Use moorings where their special capabilities are needed

- Reducing TAO requires increasing Argo within 10°S-10°N
-

Only 3 of 17 TRITON sites remain



Why change TAO?

- Winds in heavy rain
- Near-equator
- Can remove some "trade-wind" sites

IF: Adequate Argo for subsurface (next slide)

Courtesy of W. Kessler

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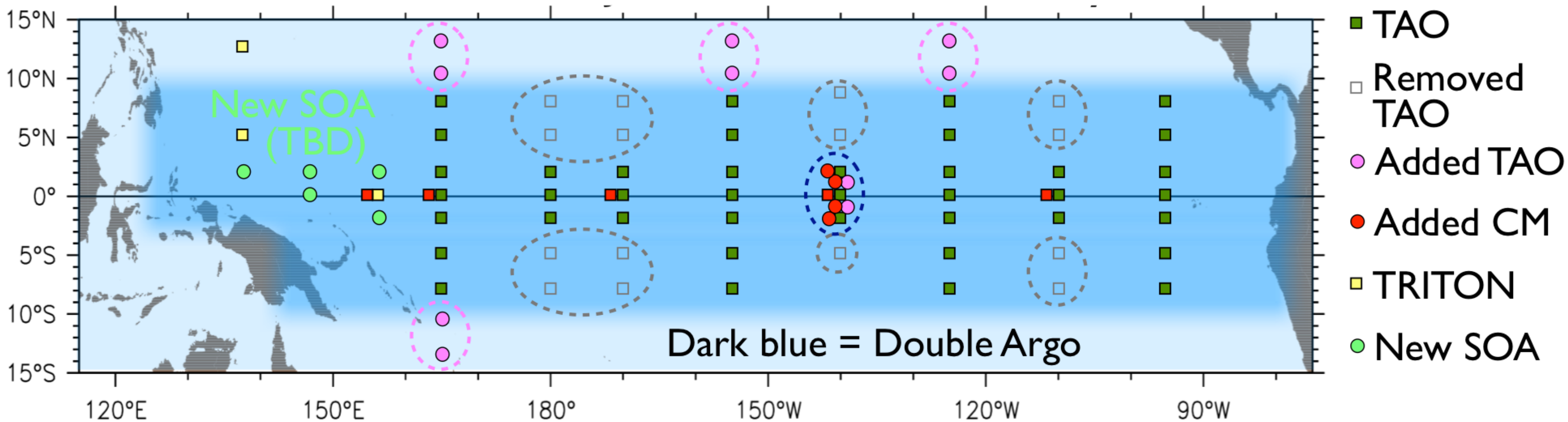
Rationale for reconfiguring TAO

Meeting needs for winds and subsurface temperature



- Scatterometer winds (mostly) meet research and operational needs:
  - still need validation/correction under heavy rain (pink dashes)
  - near-equatorial winds are very sensitive (keep all near-eq sites)

  ⇨ Can remove some TAO sites in the broad tradewind regions (gray),
- Must replace TAO subsurface temperature with adequate Argo
  - Argo spacing and timing can be adjusted to resolve key processes with fewer TAO

  ⇨ Double Argo density (blue shading)
- Near-equator short meridional scales need focused attention

  ⇨ Moorings are (still) the only way to sample this (dark blue dashes)

Courtesy of W. Kessler

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Pilot/process studies now underway:

Autonomous vehicles and platform enhancements: Can we rely on these platforms? What future roles can they fill?

NOAA (OAR/OOMD)
- Autonomous surface vehicles: PBL and surface BGC
- Argo enhancements: rainfall, windspeed and BGC
- Enhanced ocean boundary layer sampling from TAO
- Direct covariance flux measurements from TAO

JAMSTEC
- Autonomous surface vehicles: surface fluxes
- Upgrade 3 TRITON sites to flux Supersites
- Shallow, fast-cycle Argo floats

NASA
- SPURS-2 ITCZ Experiment at 10°N,125°W

Other pilots expected (CHINA):
- -Warm pool array
- -Indonesian Throughflow
- -Western boundary currents

Wave glider

Autonomous surface vehicles have great promise, but need testing in real-world conditions to prove their possibilities and learn their limitations.

New investments advancing these technologies.

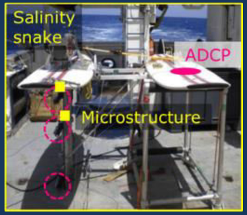
Saildrone

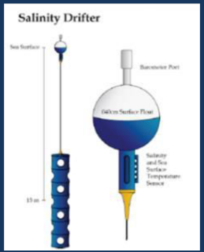
Courtesy of W. Kessler

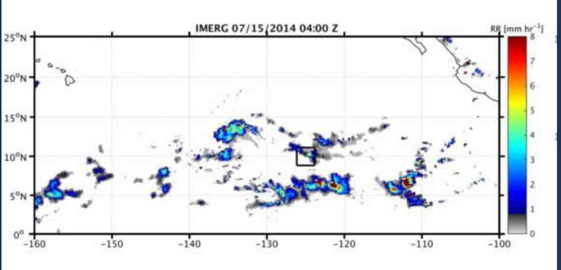
SPURS - 2

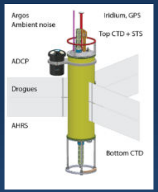
Salinity Processes in the Upper Ocean Regional Study

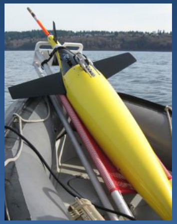
The overall goal of the SPURS-2 field program is to understand the structure and variability of upper- ocean salinity under the ITCZ.

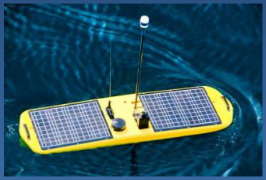












What governs the structure and variability of upper-ocean salinity near the ITCZ?

Where does the fresh water go, and how does the ocean distribute it from the small scales of the input (clouds) to the regional scale of the east Pacific fresh pool?

What local and non-local effect does the freshwater flux have on the ocean?

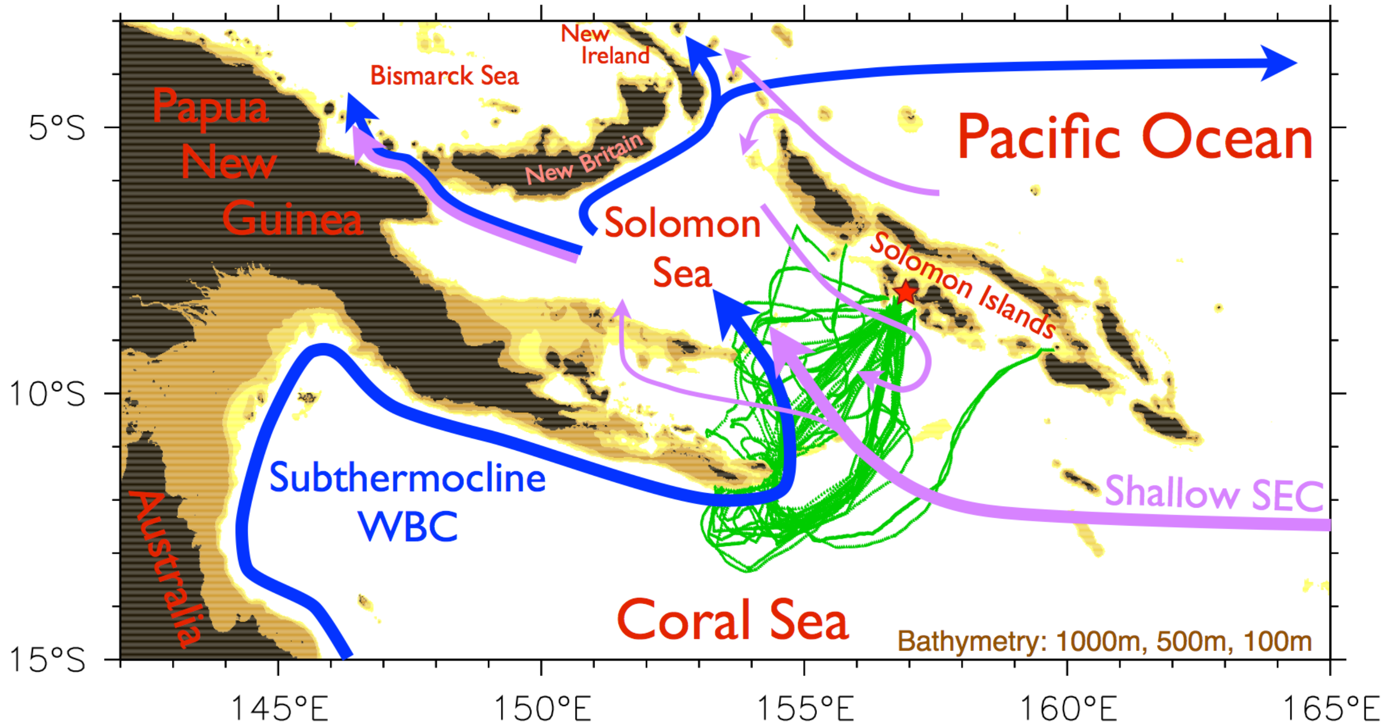
How does ocean salinity feedback on the atmosphere?

Slide from L. Rainville OSM2016 presentation

Gliders in the Solomon Sea (PIs: Kessler, Davis & Send)

Nearly 10 years of glider crossings of the Solomon Sea:

Sustainable sampling of western boundary transport from the South Pacific to the Equator



Two sources of inflow:

- Shallow currents
- Subsurface currents

Green dots show glider dives

54 sections

13000 dives
50,000 km
} About 4km/dive

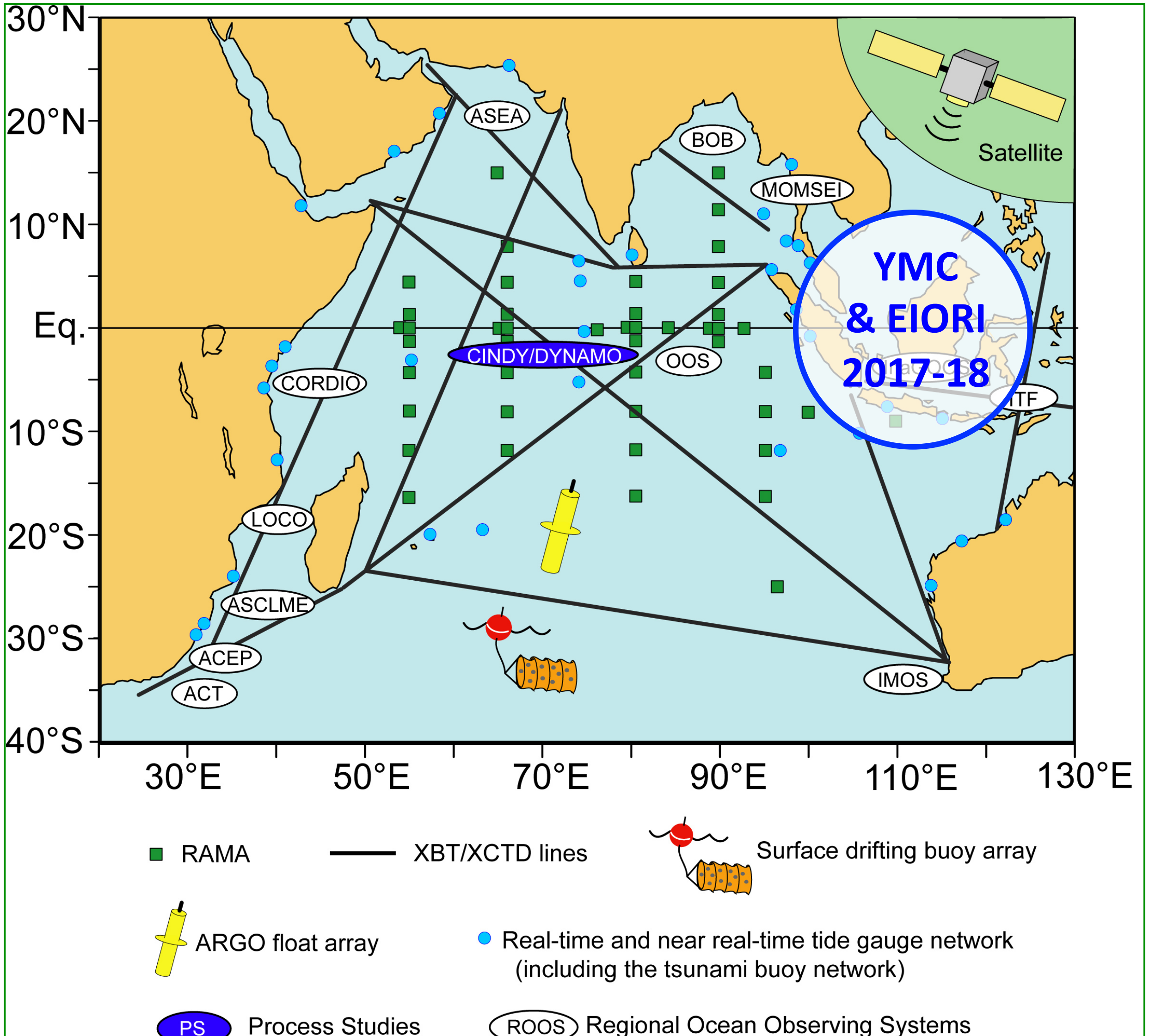
2 people x 2.5 trips/yr

Tropical Pacific observing system gaps/ concerns/opportunities

- TPOS2020 meeting observational needs with fewer more capable TAO moorings
- **Urgent gap** in moored observations exists now in the western equatorial Pacific
- Reducing TAO array relies on satellites and doubling of Argo in equatorial waveguide
- TAO cruises are platforms for ancillary measurements (e.g., underway pCO2 and ADCP sections during TAO cruises) and deployment of drifters and Argo
- Status of TPOS2020 depends on funding outlook
- If we need air-sea flux measurements to capture ENSO precursors – where???
- Need observations to test theories for double ITCZ problem in models (Upcoming OTREC -- Over the far tropical eastern Pacific and western Caribbean - may help understand the vertical structure of convection over the region, but likely global tropical observations of vertical structure of convection along with high quality surface moisture and heat fluxes at the ocean surface are needed to better understand what is going on.)

Tropical Indian observing systems

Indian Ocean Observing System (IndOOS)

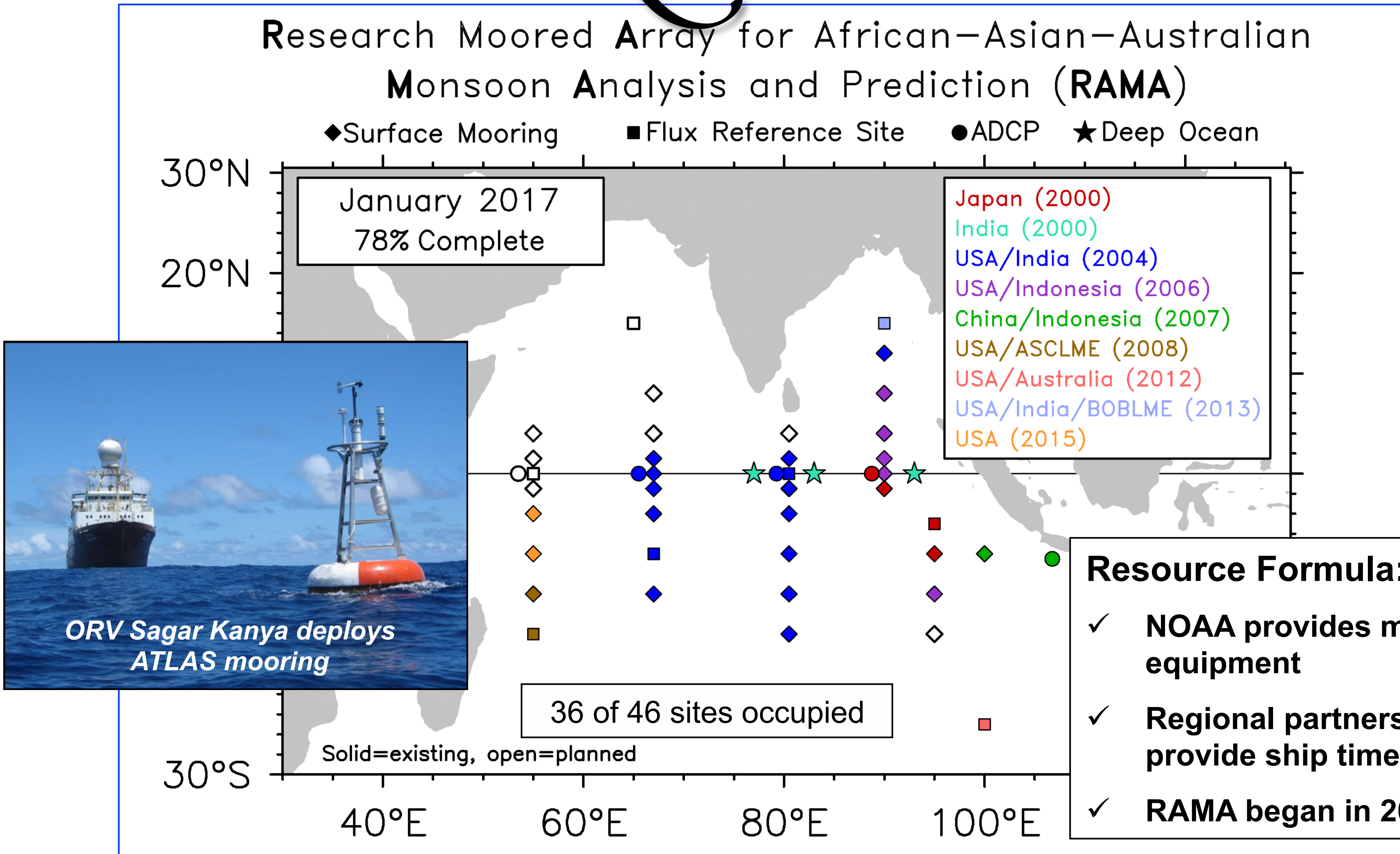


- Planned by CLIVAR/ GOOS Indian Ocean Panel in 2004
- Design supported by numerical model observing system simulation studies
- Basin scale with regional elements
- Supports short term process studies

Courtesy of M. McPhaden

Courtesy of M. McPhaden

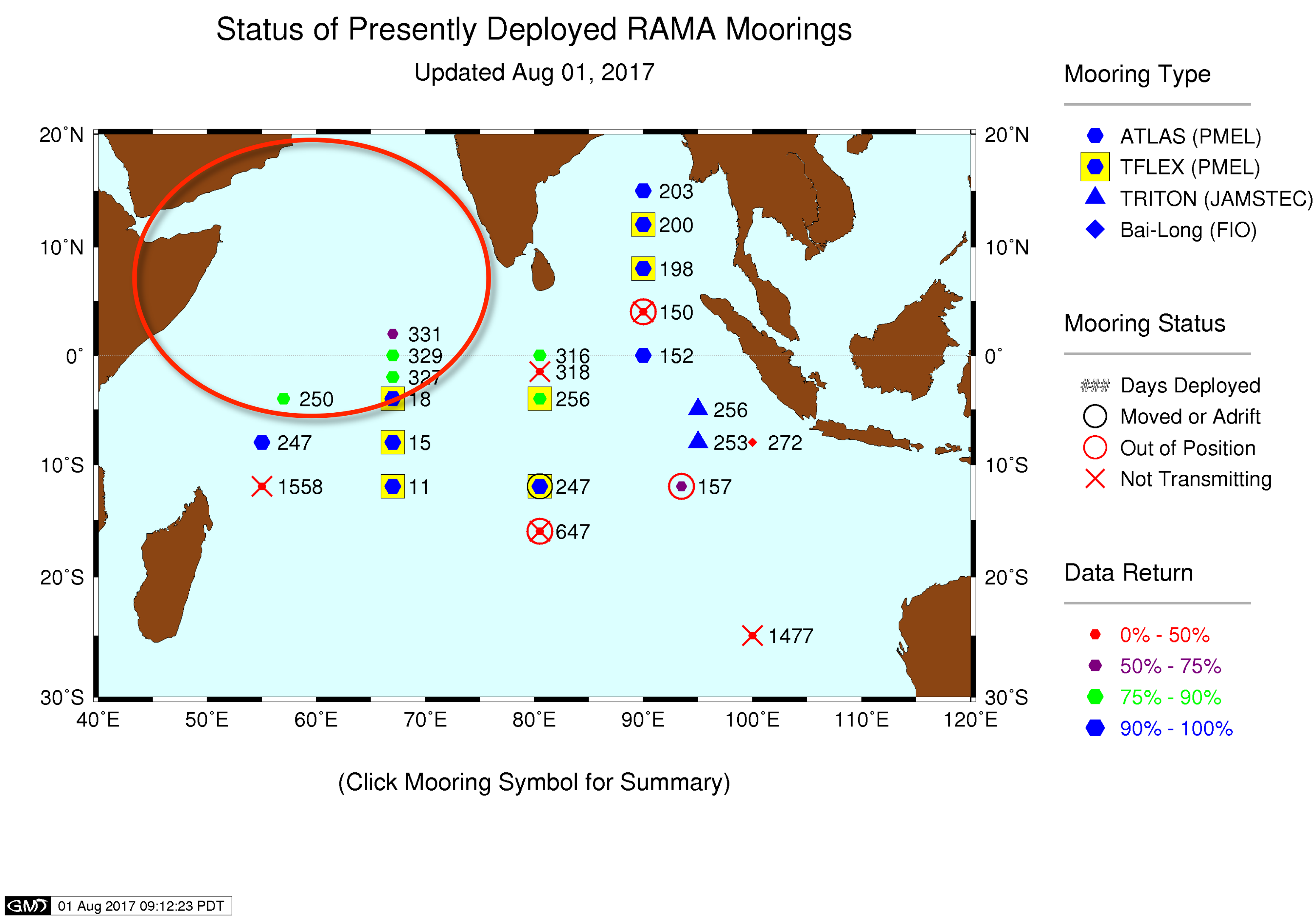
RAMA



Resource Formula:

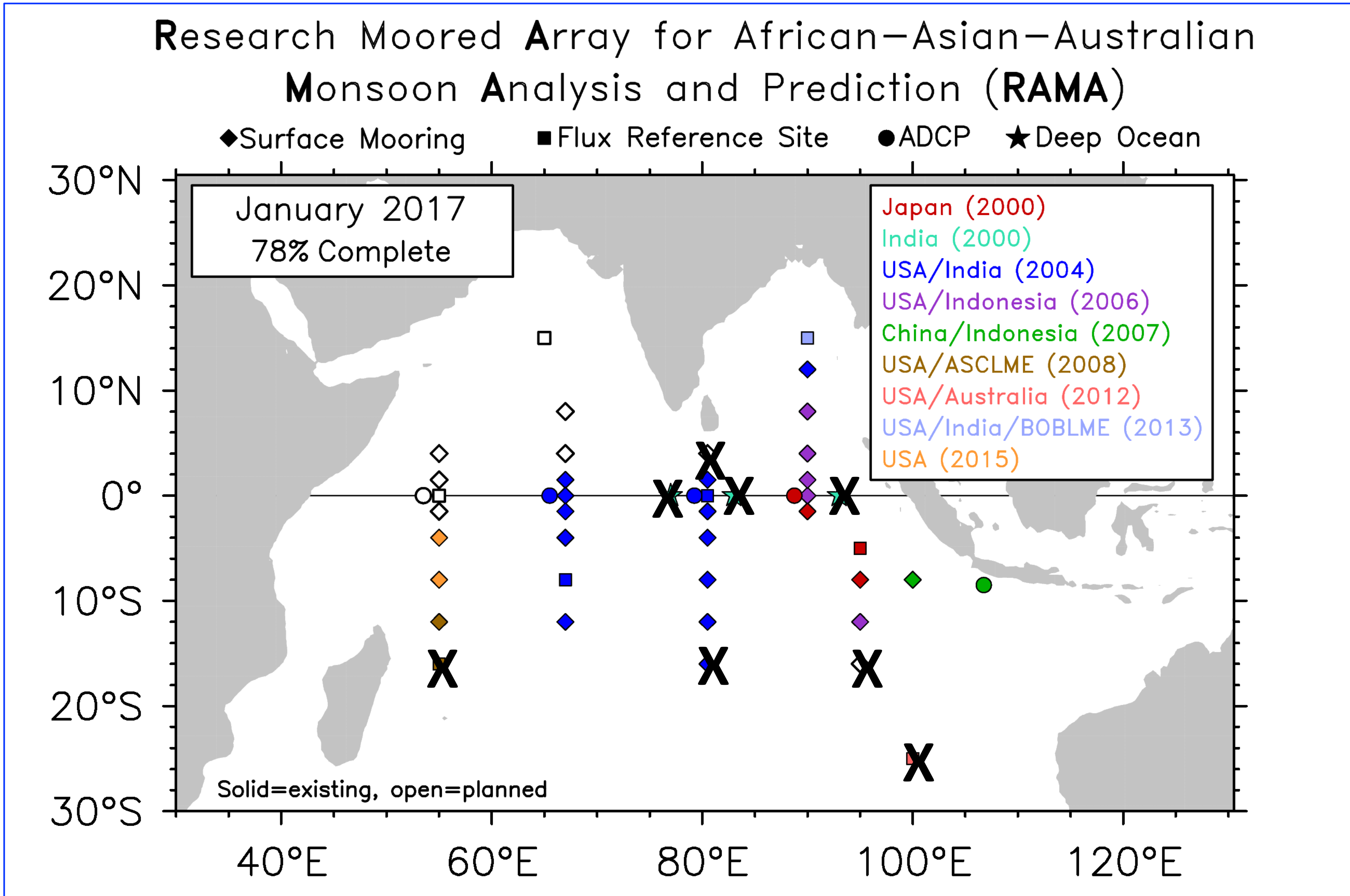
- ✓ **NOAA provides most equipment**
- ✓ **Regional partners provide ship time**
- ✓ **RAMA began in 2003**

RAMA status



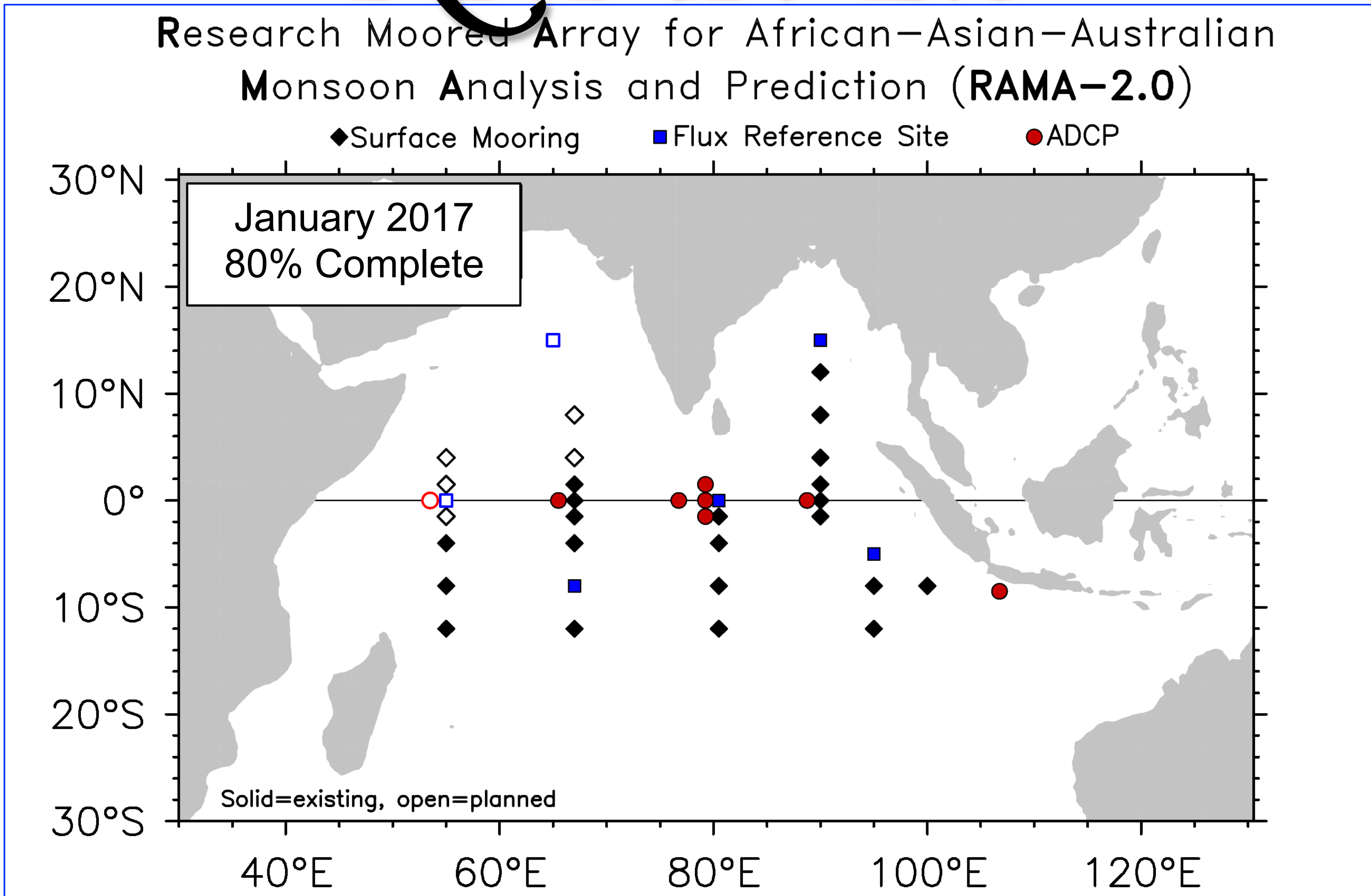
Status of Presently Deployed RAMA Moorings
Updated Aug 01, 2017
20˚N
10˚N
0˚
10˚S
20˚S
30˚S
40˚E
50˚E
60˚E
70˚E
80˚E
90˚E
100˚E
110˚E
120˚E
203
200
198
150
152
331
329
327
18
250
316
318
256
256
253
272
247
15
1558
11
247
157
647
1477
(Click Mooring Symbol for Summary)
Mooring Type
ATLAS (PMEL)
TFLEX (PMEL)
TRITON (JAMSTEC)
Bai-Long (FIO)
Mooring Status
Days Deployed
Moved or Adrift
Out of Position
Not Transmitting
Data Return
0% - 50%
50% - 75%
75% - 90%
90% - 100%
01 Aug 2017 09:12:23 PDT

Adjustments to RAMA



Courtesy of M. McPhaden

RAMA-2.0



80% of sites occupied at present (32 of 40)

Courtesy of M. McPhaden

Anchor for process studies/initiatives

AMIE/DYNAMO -field campaign in the Indian Ocean to study the Madden -Julian Oscillation in the atmosphere to better understand initiation of these events

ASIRI - upper ocean dynamics in the Bay of Bengal, with a focus on submesoscale/ mesoscale, salinity/freshwater

MISO-BOB (ASIRI follow-on) - focused on understanding the dynamics of the monsoon intraseasonal oscillation in the Bay of Bengal.

NASCaR - understand physical processes in the North Arabian Sea / Somali Current System, using only autonomous instruments

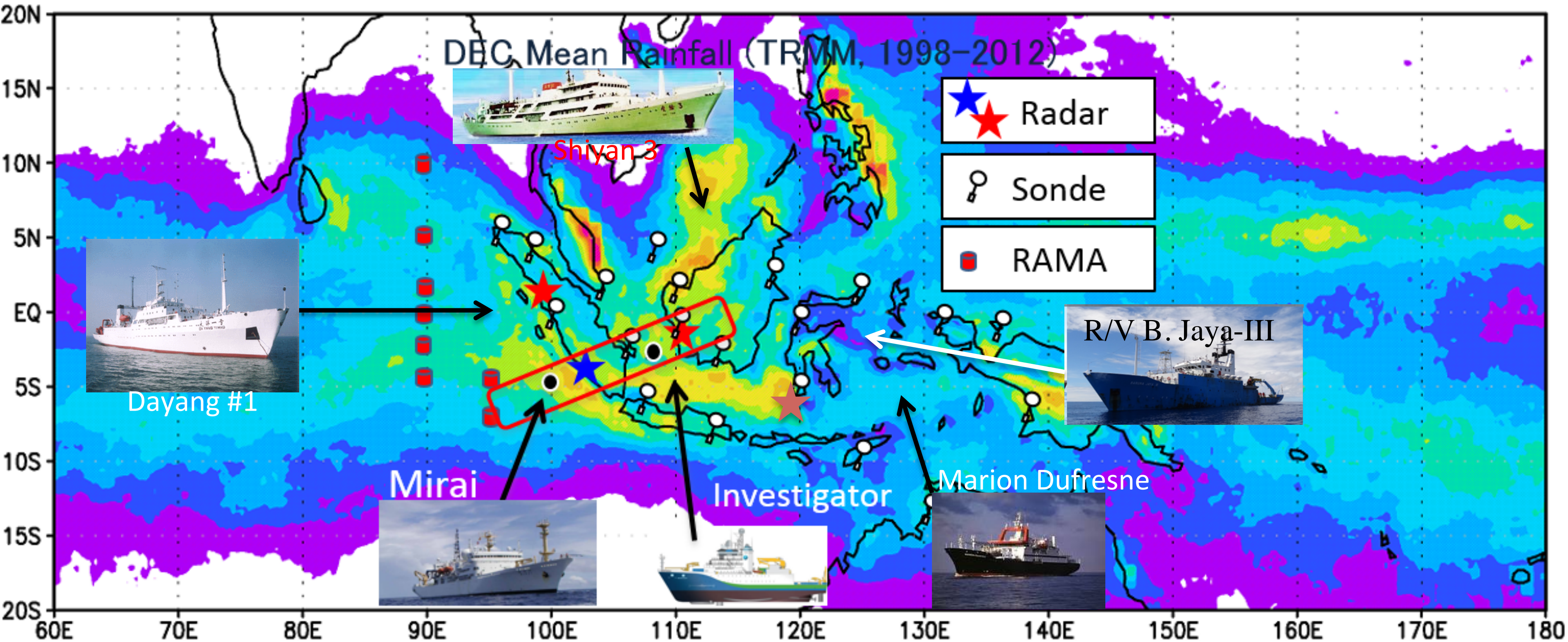
EIOURI – upwelling research initiative in regions that develop seasonally off Java, Sumatra, and northwestern Australia.

WIOURI: upwelling research initiative on the western side of the basin, complementary to EIOURI

YMC: IIOE-2 will coincide with and embrace the Years of the Maritime Continent (YMC) as a major IIOE-2 field campaign in 2017-2018

YMC (2017 – 2018)

A year of field campaign with several IOPs



Observational Targets:

- **Atmospheric convection (diurnal cycle, on-off shore development)**
- **Aerosol from biomass burning and sea spray (physical and chemical properties)**
- **Upper Ocean mixing (tidal, inertial, turbulent mixing, nutrient flux, SST feedback)**
- **Upwelling and through flows**

Courtesy of Chidong Zhang

Tropical Indian highlights (a subset)

- 2010+: Bio-optical measurements by U. Tasmania on ATLAS mooring
- 2013+: BOBLME Ocean Acidification mooring (CO2, pH) deployed @ 15N, 90 E
- 2017+: Ten RAMA sites will have T-Flex moorings
- Piracy has been greatly reduced
- Ship time has improved but it is still a challenge
  - New Korean (KIOST) R/V Isabu serviced three RAMA moorings
  - NOAA R/V Ronald H. Brown will conduct I17N GOSHIP line, RAMA servicing, and YMC sampling in 2018
- A plan for an adjusted RAMA (RAMA 2.0) has been developed
- Tremendous scientific interest in Indian Ocean observations (IIOE-2, YMC, ...)
- IIOE-2 Science workshop in La Jolla, CA (September 2017)

Tropical Indian observing system gaps/ concerns/opportunities

- Should POS panel provide input to the IndOOS Review (or are we already involved)?
- Transition to T-Flex moorings allows for the addition of sensors
- Some suggested measurements (similar to PIRATA list in many ways):
  - Higher vertical resolution (5-10 m) of salinity sensors within the upper 50 m to resolve the mixed layer / barrier layer (currently 1,10,20,40,60,100m)
  - Increase high-resolution (10-min) rain data
  - More velocity/velocity shear estimates in surface mixed layer
  - Multidisciplinary biogeochemical observations (Ocean color, O2, CO2, DIC…)
  - Chipods for turbulent temperature microstructure
- Measurements needed in boundary currents regions
- Fishing vandalism is still a concern (results in low data returns, mooring failures)
- Ship time has improved but is still a challenge

My takeaways

- Rigorous review efforts are already underway for tropical observing system, opportunities for POS panel to engage
- Moored networks in tropics are anchors for process/pilot studies
- T-Flex technology allows for high-resolution real-time data and the addition of multi-disciplinary sensors
- Long records (10+ years) in tropics make it possible to study diverse phenomena with time scales ranging from diurnal to decadal, and interactions between basins
- Ship time continues to be a challenge

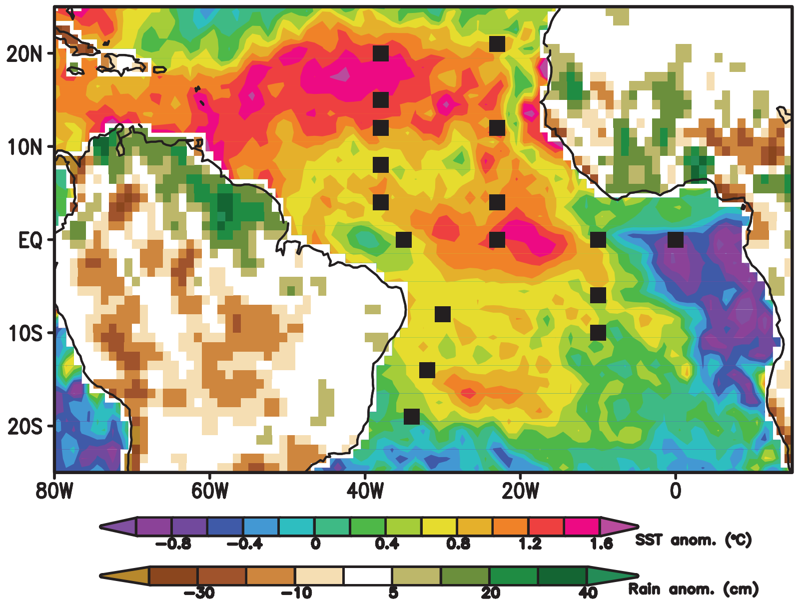
Extra Slides

Guiding questions

- What is the status of the current system?
- What elements are there?
- How robust is in terms of funding and technology?
- Where might it be expanded and what might be gained?
- What are the gaps?
- What are some unobserved key weather/climate processes that could be addressed with an expanded observing system, and what would we need for this?
- What is the status of TPOS2020 and the planning for the expanded tropical Pacific observing system?
- How does the tropical observing system interact with other systems, i.e. mid-latitudes?

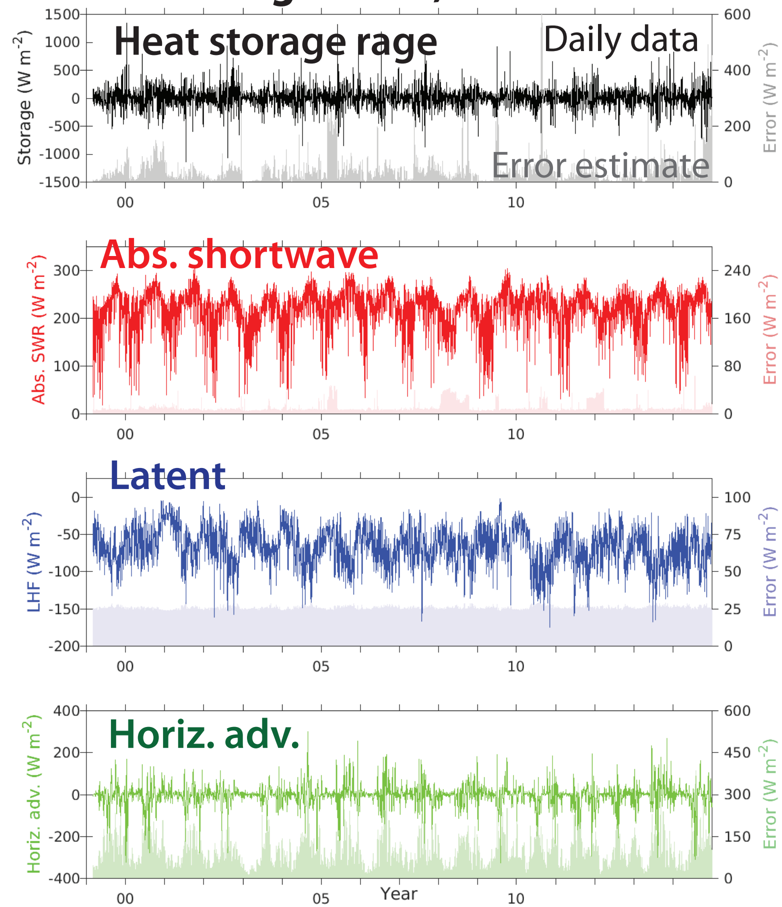
Enhanced PIRATA data set (ePIRATA)

Jun-Sep 2010 SST and rainfall anoms. and locations of PIRATA moorings



Foltz et al., *J. Clim.*, 2017 (in revision)

Heat budget at 0°, 23°W



- Corrects biases, fills gaps in time and depth, provides daily time series of mixed layer heat/temperature budget terms with error bars.

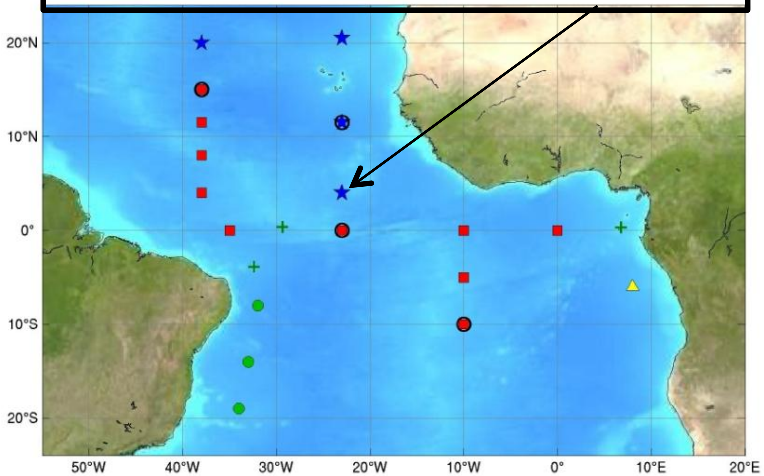
Courtesy of G. Foltz

Data access: http://www.aoml.noaa.gov/phod/epirata/

Developing upper ocean velocity and velocity shear indices as cooling/warming indicators for tropical North Atlantic

Renellys C. Perez

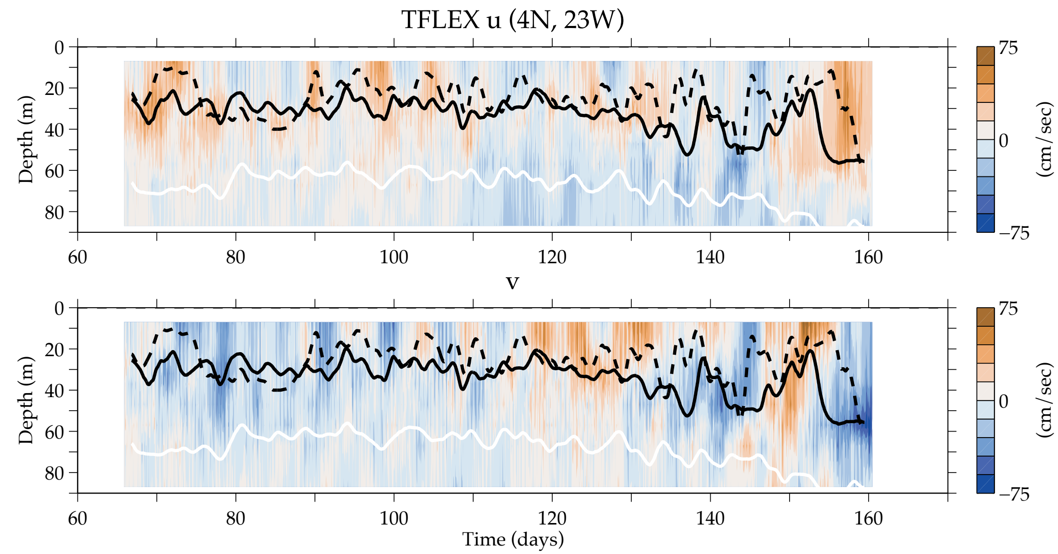
Tropical Atlantic Currents Observations Study (TACOS) began March 2017

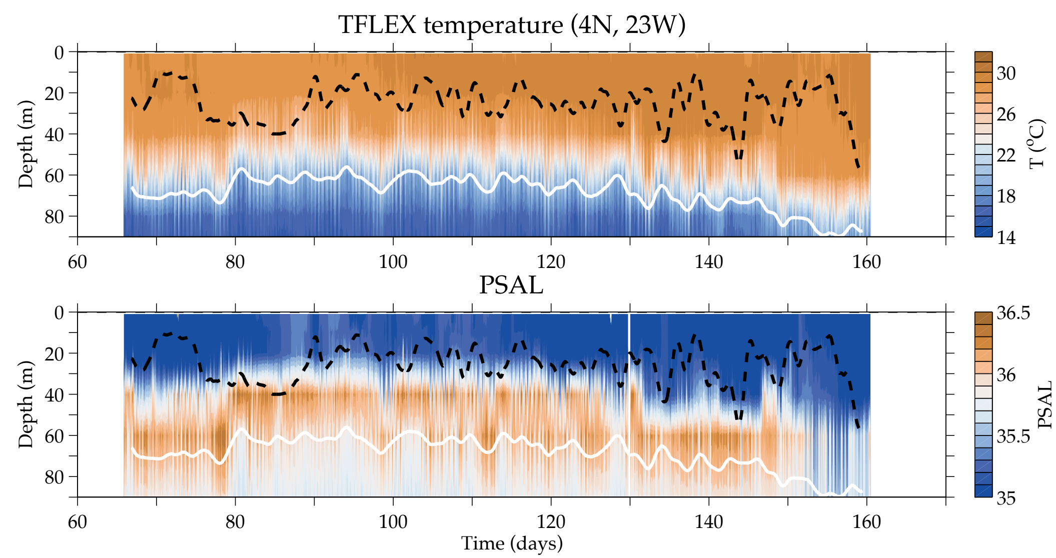


TACOS: 11 current meters in between 7m and 87m at 4N, 23W PIRATA Northeast Extension mooring

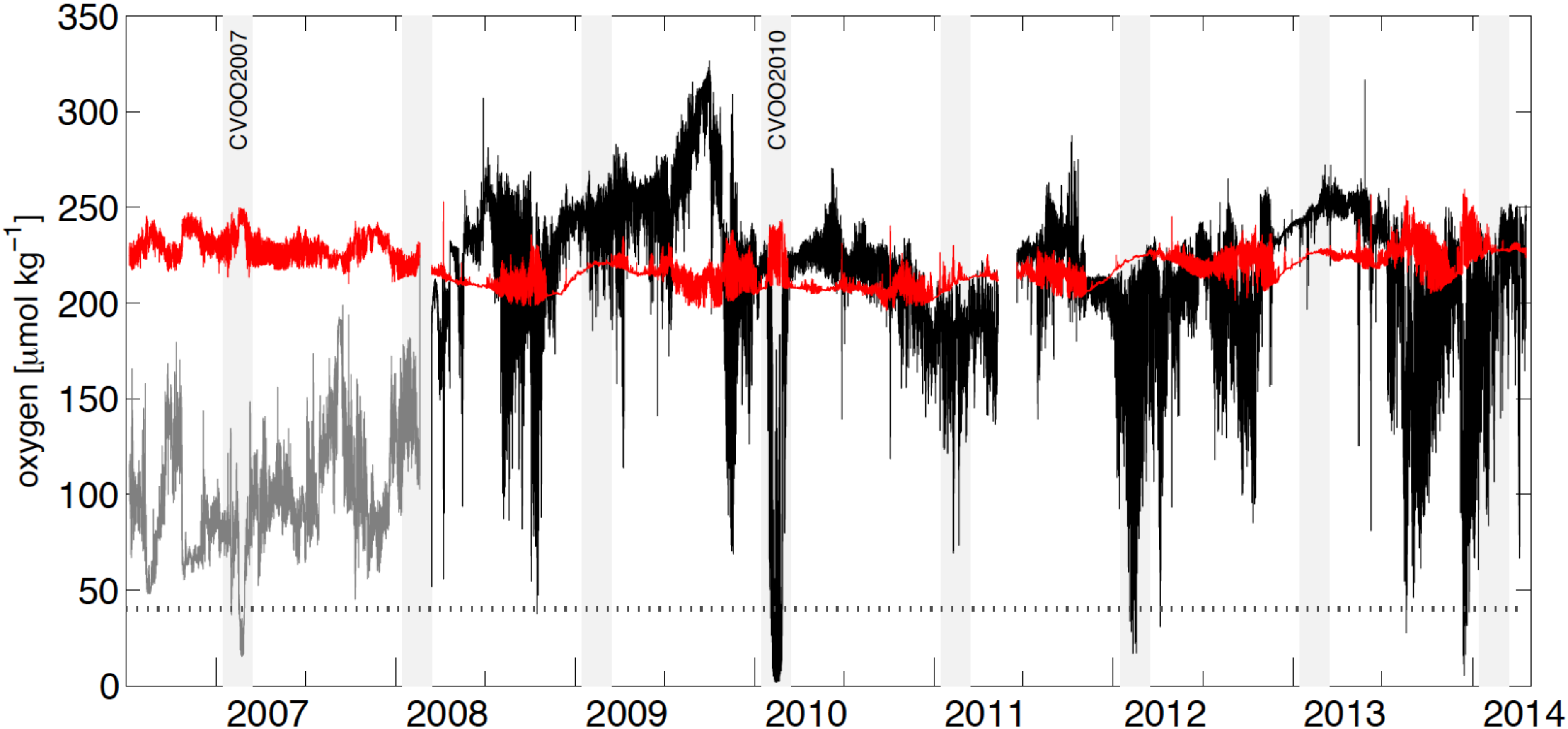
Motivation:

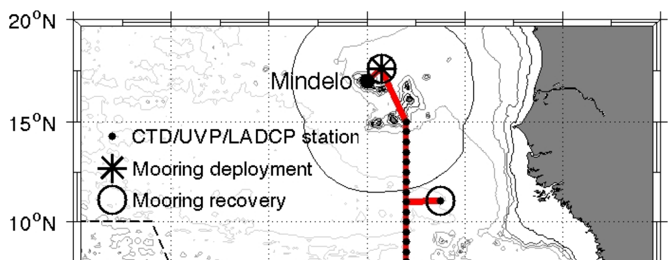
1. Hurricane activity and rainfall over neighboring continents impacted by ocean-atmosphere interactions
2. There are few observations of upper ocean velocity in tropical North Atlantic and these currents can impact temperature, salinity, and air-sea fluxes





Long-term CVOO Mooring, Cape Verde





Oxygen at 40-60m (black), 140m (grey) and oxygen saturation (red)

Karstensen et al., 2015

Courtesy of P. Brandt

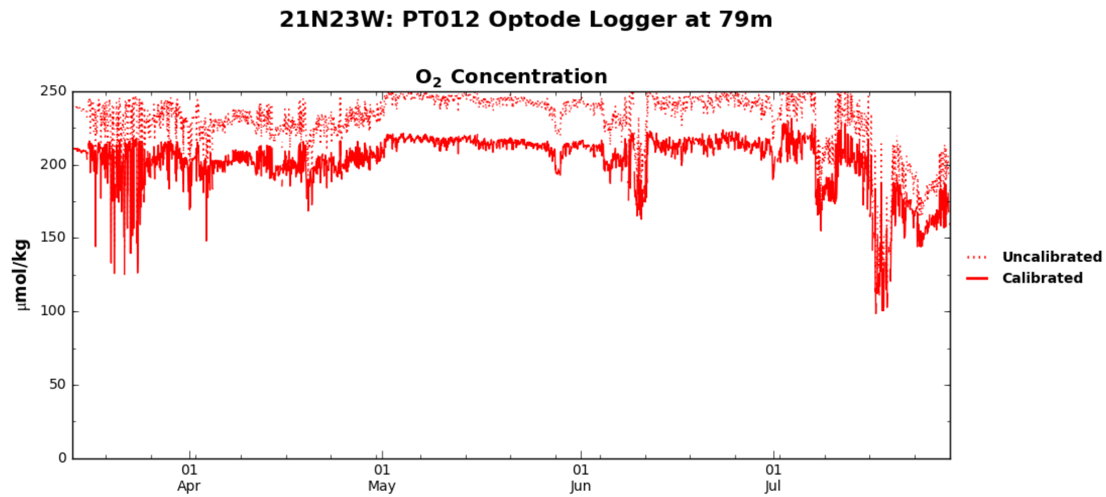
Online oxygen measurements

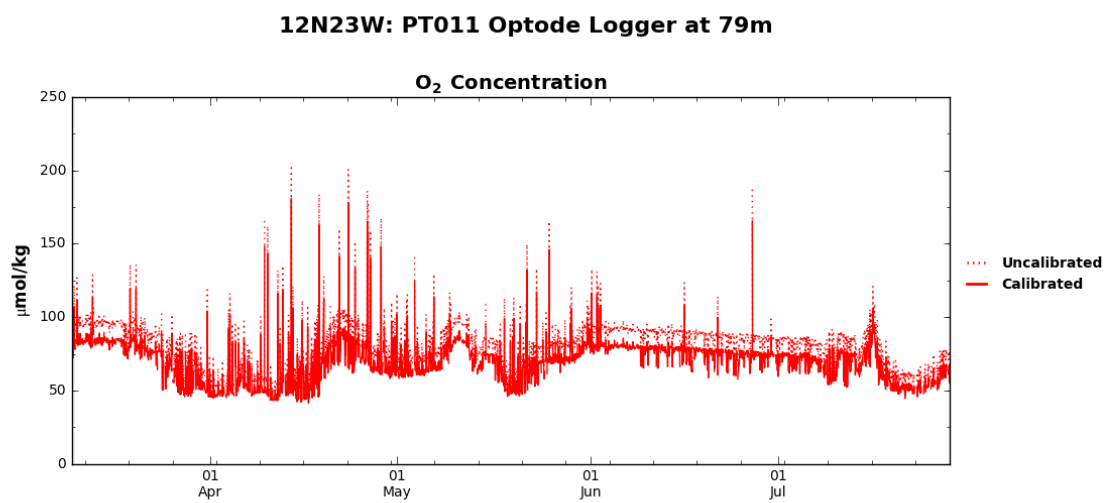
In cooperation with PIRATA programme, oxygen measurements at 23°W, 21°N;

23°W, 12°N;

and 23°W, 4°N.

Data from 21°N and 12°N are online available since March 2017.



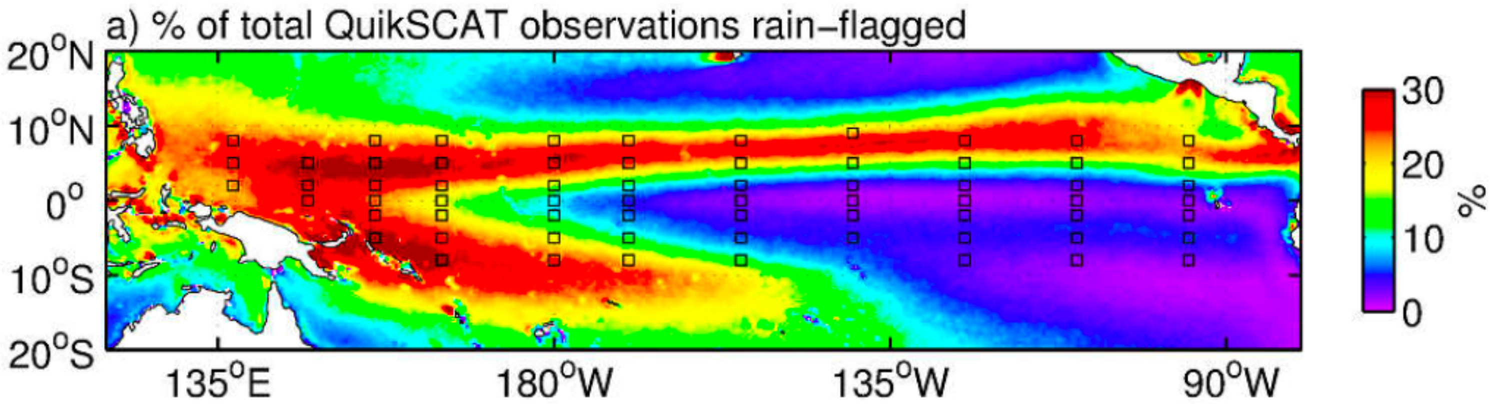


Courtesy of P. Brandt

Requirements for the backbone

What drives our recommendations?

Example: Vector winds



QuikSCAT rain-flag frequency during 1999-2009.
Over much of the Pacific ~25% of QuikSCAT samples are flagged as potentially invalid due to rain.

This does not mean that scatterometer winds are unusable under rain, but they are in question. It is also true that wind products from different centers differ significantly.

The global climate is exquisitely sensitive to the equatorial zonal wind, so we must get this right.

Courtesy of W. Kessler

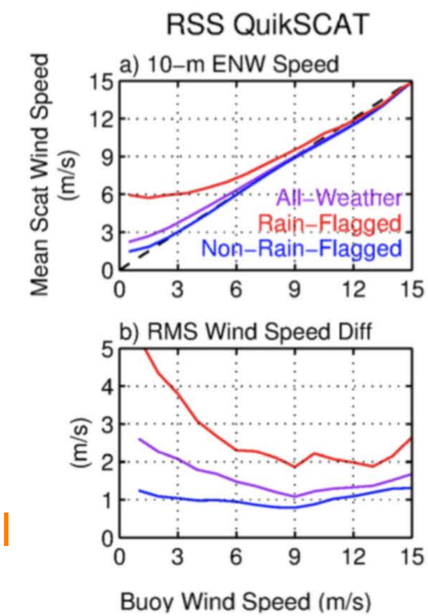
Winds with a reduced moored array

TAO was originally designed to map winds, before scatterometry.

Now we propose to reduce buoy locations, relying more on scatterometer winds.

Two distinct issues:

1) How well do scatterometers measure winds themselves?
2) How well do present analyses produce credible wind fields?



We investigated (1) extensively:

- Only a few ongoing cal/val points are needed in the tropics
- Specific regions need in situ referencing (heavy rain / low winds)
- Equator needs referencing between satellite generations

These considerations were influential in shaping our design:

In situ wind sampling in heavy rain regimes: ITCZ, SPCZ, Warm pool

Maintain full sampling along the equator

The mapping issues (2) are more difficult:

Products from different centers differ considerably! Work is needed!

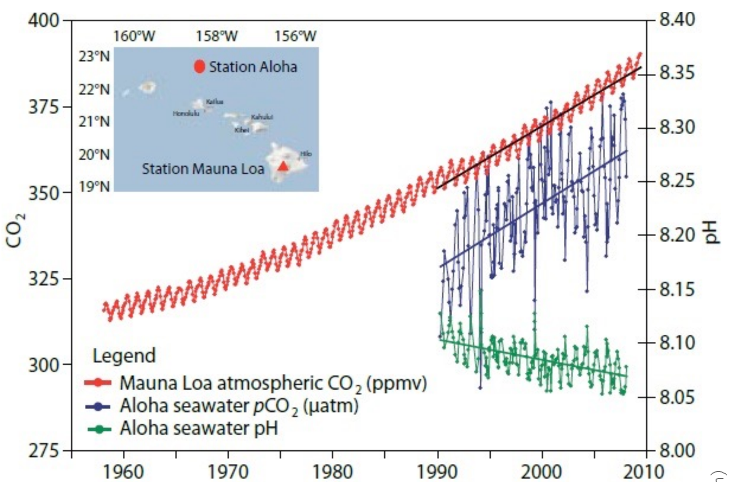
→ TPOS 2020 must provide the in situ observations for adequate referencing of scatterometer winds

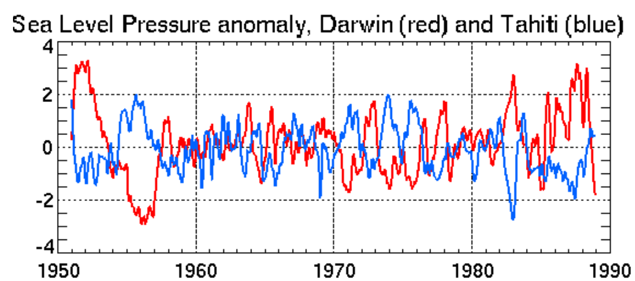
Courtesy of W. Kessler

The climate record in an evolving observing system

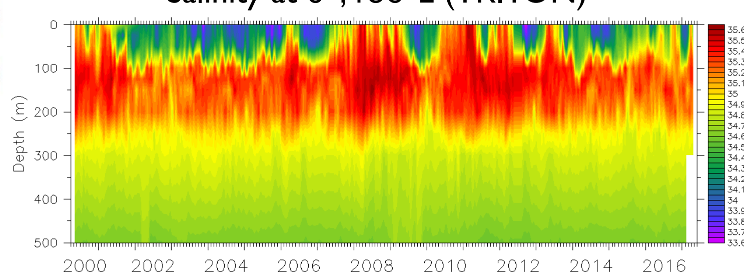
A "climate data record" is a time series at a point (examples).

A "climate record" is a set of measurements that enable detection and accurate description of an element of climate variability in its longterm context.

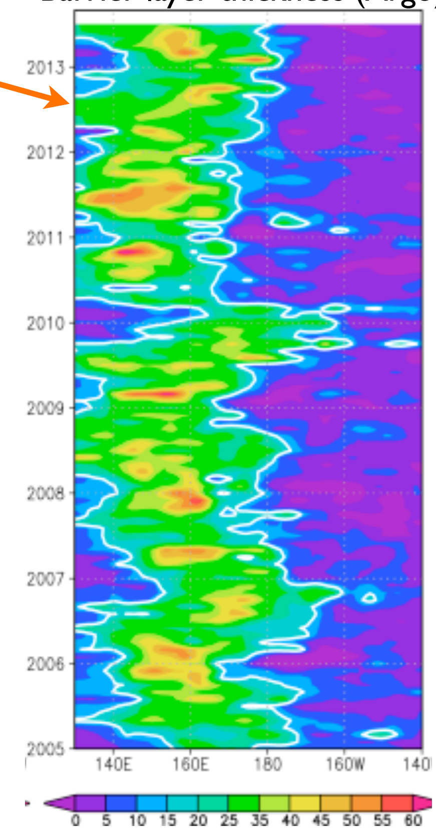




Salinity at 0°,156°E (TRITON)



Barrier layer thickness (Argo)



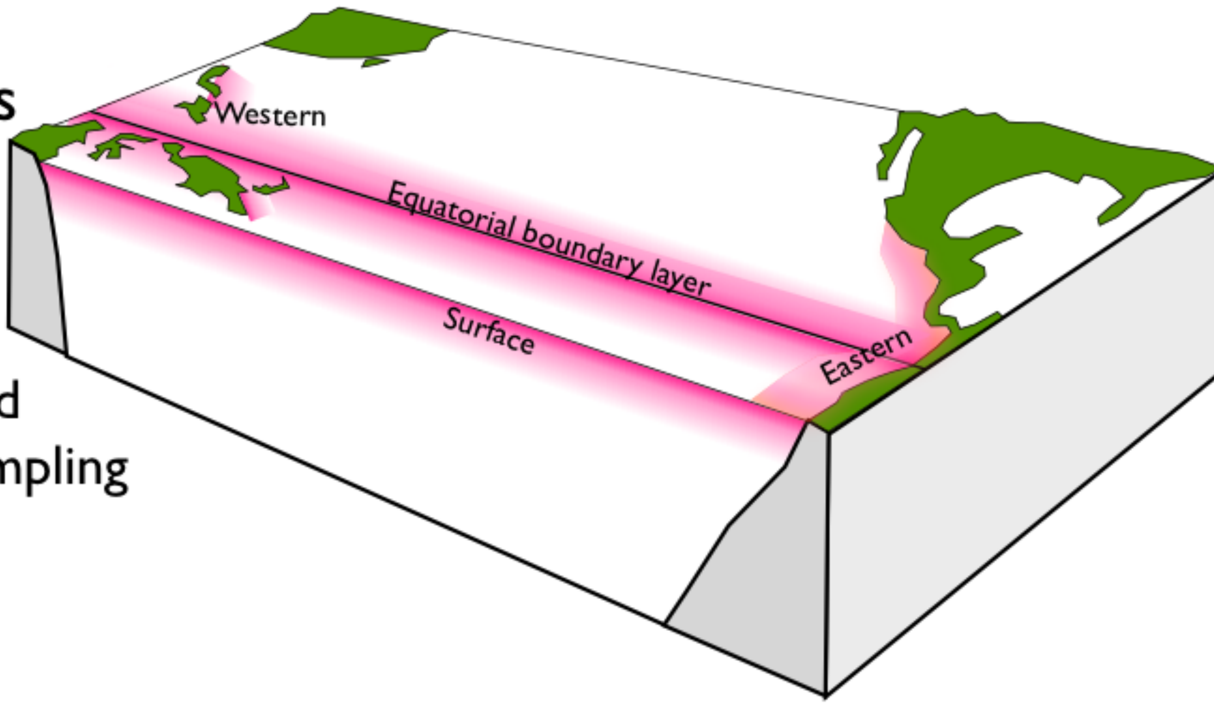
x

We view the tropical Pacific as consisting of a broad interior plus four "boundary layers":

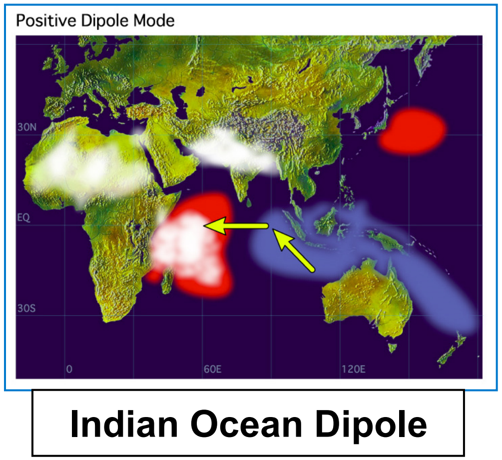
Surface, Equatorial, Eastern and Western

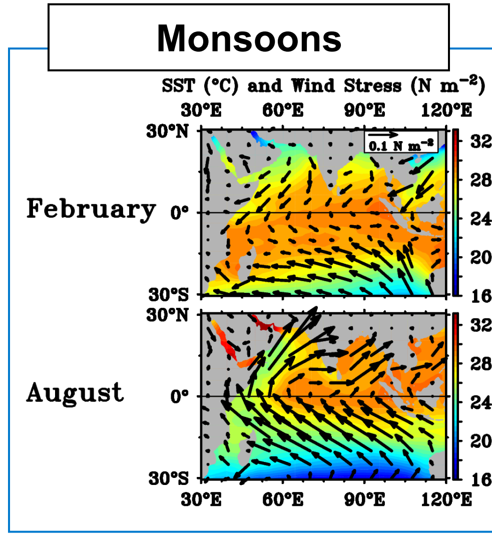
The boundary layers are the hard parts

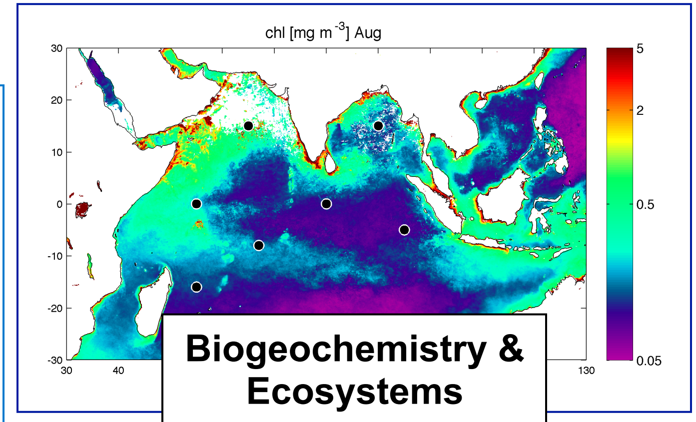
In an integrated system that includes satellites, we are less tied to a grid and can focus in situ sampling on key regimes.

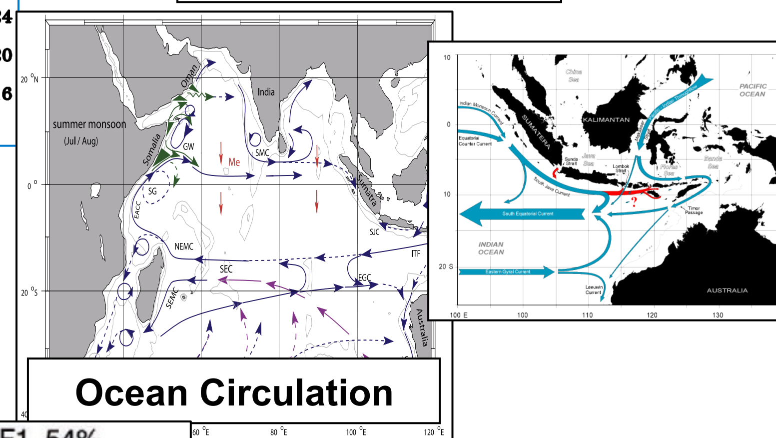


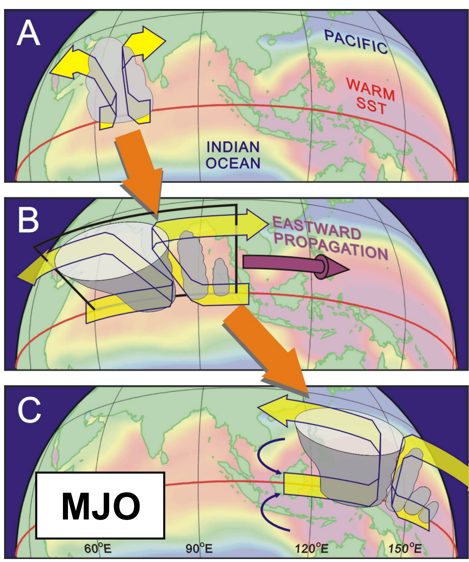
Scientific Drivers

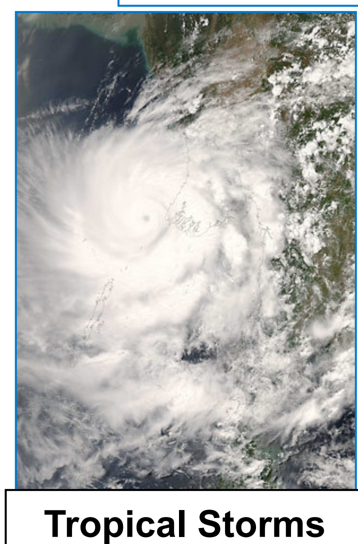


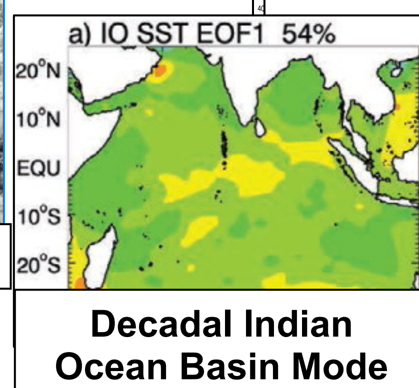


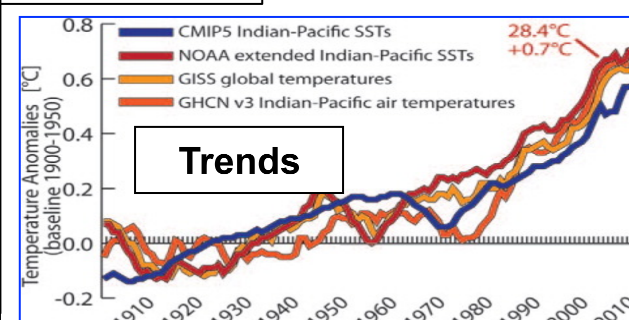












Courtesy of M. McPhaden

Outcomes from IndOOS review workshop

Science and operational drivers

- hydrological/freshwater cycle (P+E+R)
- heat budget (oceanic and surface fluxes) and SST variability and change
- carbon cycle, acidification, and ecological/biological impacts
- monsoon and monsoon onset variability and predictability
- interannual variability and predictability: IOD / ENSO / IOBM / Subtropical Dipole / Ningaloo
- intra-seasonal air-sea coupling (MJO, MISO, eddies)
- Extreme events (cyclones, marine heat waves)
- Oxygen variability / OMZs
- food security: marine productivity variability and predictability
- detection of anthropogenic climate change
- decadal variability and predictability
- boundary currents, interaction of coastal and open ocean, upwelling, and ecosystems
- regional sea level variability and change
- Operation Drivers:
  - development of predictions and predictive models
  - improvement of surface flux products
  - Improvement of ocean reanalyses

Requirements in terms of observing components

- Extreme events (cyclones, marine heat waves/coral bleaching)
  - High temporal resolution;
  - cyclones: BoB & EAS; 10-20°S band;
  - marine heat waves/coral bleaching : Leeuwin current, Maldives, SL
- Intraseasonal (MJO, MISO)
  - Daily resolution needed + potential influence of diurnal cycle; near-surface high-res
  - Key regions: thermocline ridge (maintain), BoB (expand 18°N), AS upwellings, NWAB (develop)
  - Air sea-fluxes, mixing
  - Ocean meso-scale eddies well sampled?
- Seasonal, Interannual
  - maintain components of obs system that have proven useful; expand into AS
  - Indian monsoon!!! Arabian Sea upwellings, Somalia Current(how do we do that?)
- Decadal/climate change
  - Monitor inter basin exchange of properties (ITF piggybacking IX01, 25°S, air-sea interface)
  - Deep measurements, in particular in south
  - Monitor internal redistribution (cross-equatorial, BoB and AS including boundary currents?)
  - Long time series are needed
  - Parameters: air-sea fluxes, heat, freshwater (incl river outflows), nutrients, aerosols?
- Biogeochemistry
  - A. Sea & BoB OMZ (BioArgo)
  - Acidification; carbon fluxes
  - Piggyback on existing system!!!
  - Upwelling systems in A. Sea
- Verified satellite observations; Accurate Air-Sea fluxes; Data assimilation systems; well-validated models
- Pilot studies for innovative observing system strategies
- Additional measurements at the boundaries

Courtesy of M. McPhaden