

The Global Tropical Moored Buoy Array

- ✓ *What it is*
- ✓ *Why we developed it*
- ✓ *What we have learned*
- ✓ *Plans for the future*

*Mike McPhaden
PMEL Lab Review
26-28 August 2008*



A tropical beach scene with palm trees and people. The background shows a clear blue sky, a sandy beach, and turquoise water. In the foreground, there are several palm trees, some leaning over the water. Two people are visible on the beach near some driftwood.

Why the Tropics?

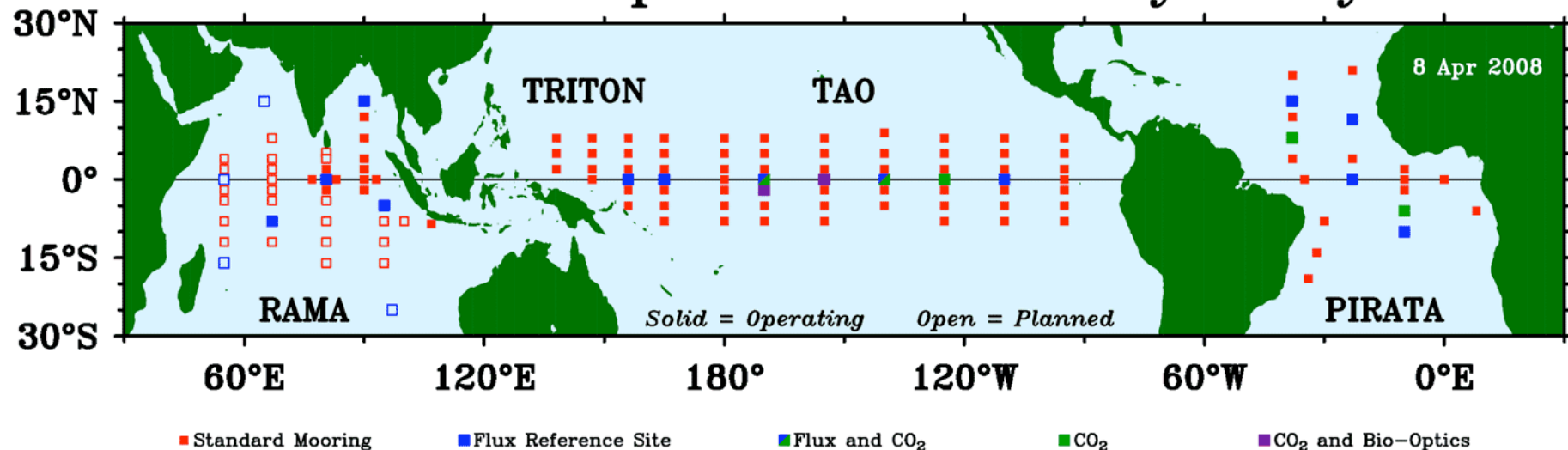
- **A major source of regional and global climate variability (ocean-atmosphere interactions sensitive to SST variations)**
- **Some modes of climate variability originating in the tropics are predictable**
- **Spawning ground for severe tropical storms**
- **Many underdeveloped and climatically vulnerable nations are found in the tropics**

Project Goal: Develop and implement moored buoy observing systems for climate research and forecasting.

NOAA Strategic Plan Goal: Understanding climate variability and change to enhance society's ability to plan and respond.

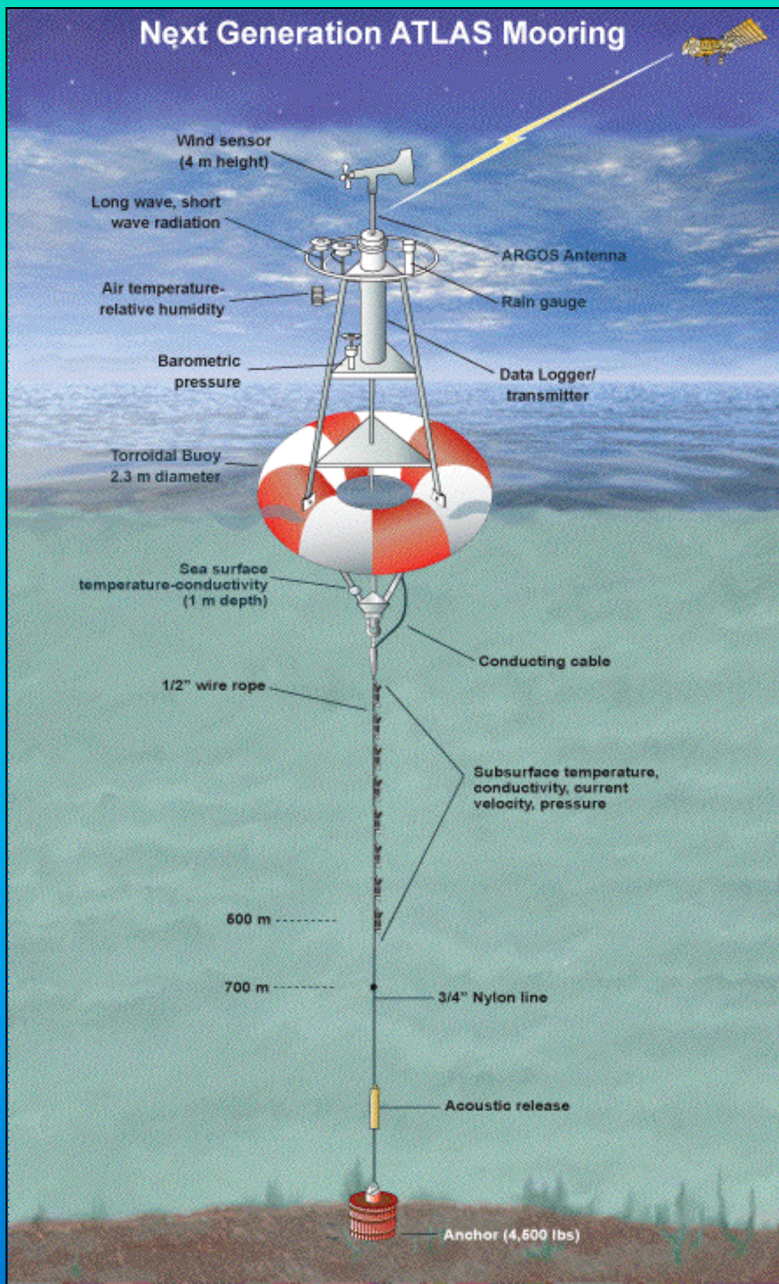


Global Tropical Moored Buoy Array



TAO Project Office, NOAA/PMEL

A contribution to GOOS, GCOS, and GEOSS



Surface Moorings

Advantages

- ✓ Rapid sampling in time so as to resolve rather than alias high frequencies
- ✓ Fixed grid array so time and space are not mixed
- ✓ Multi-variate (ocean, atmosphere, biogeochemical)
- ✓ Real-time data transmission (Service Argos & GTS)

Disadvantages

- ✓ Cost
- ✓ Specialized ships required
- ✓ Subject to vandalism

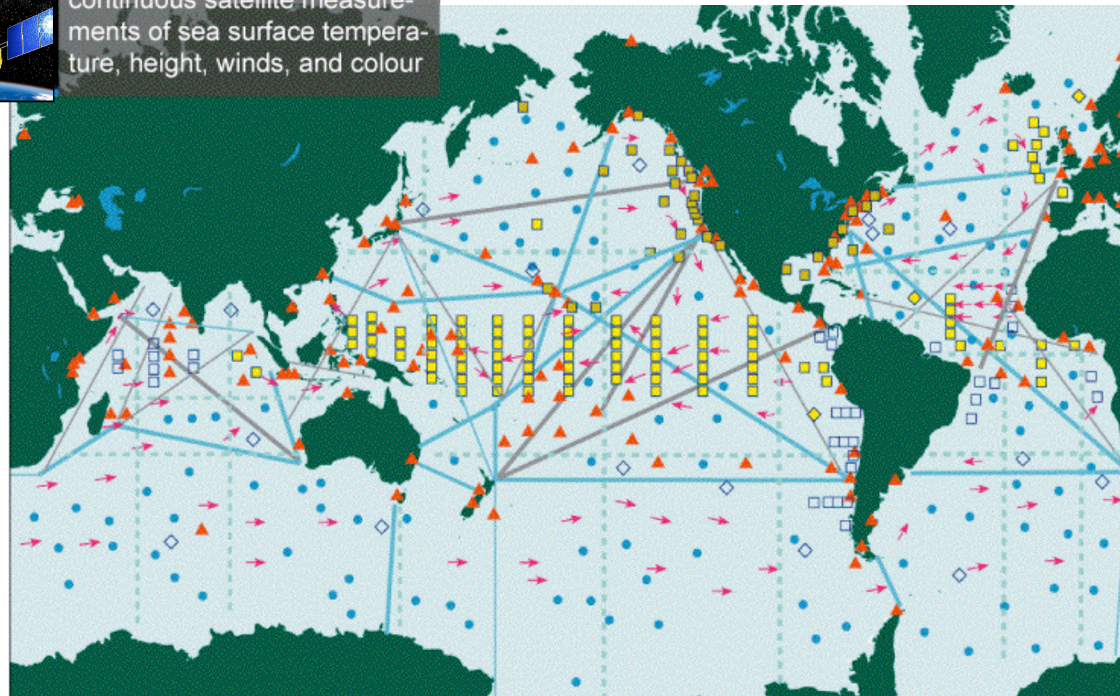
Initial Global Ocean Observing System for Climate

Status against the GCOS Implementation Plan and JCOMM targets

Total *in situ* networks **60%** May 2008



continuous satellite measurements of sea surface temperature, height, winds, and colour



87% Surface measurements from volunteer ships (VOSclim)

200 ships in pilot project



100% Global drifting surface buoy array

5° resolution array: 1250 floats



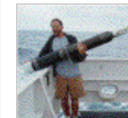
62% Tide gauge network (GCOS subset of GLOSS core network)

170 real-time reporting gauges



81% XBT sub-surface temperature section network

51 lines occupied



100% Profiling float network (Argo)

3° resolution array: 3000 floats



43% Repeat hydrography and carbon inventory

Full ocean survey in 10 years

Reference time series 24%

58 sites



48% Global reference mooring network



29 moorings planned



79% Global tropical moored buoy network



119 moorings planned



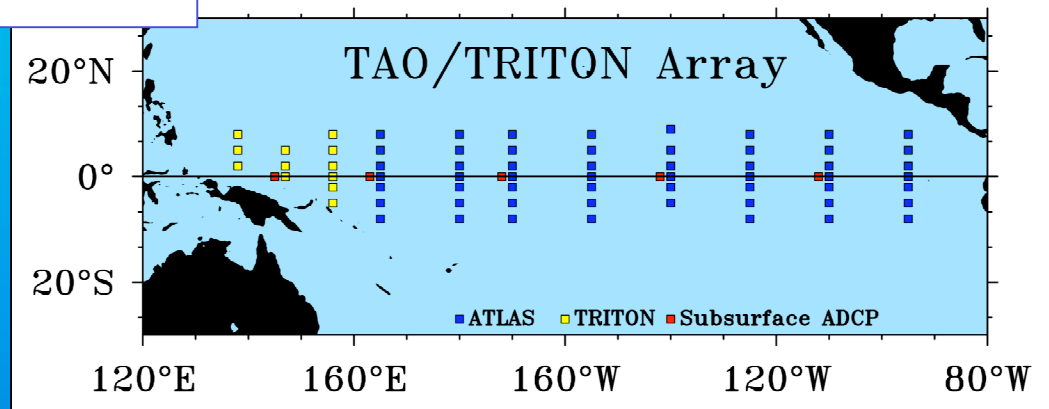
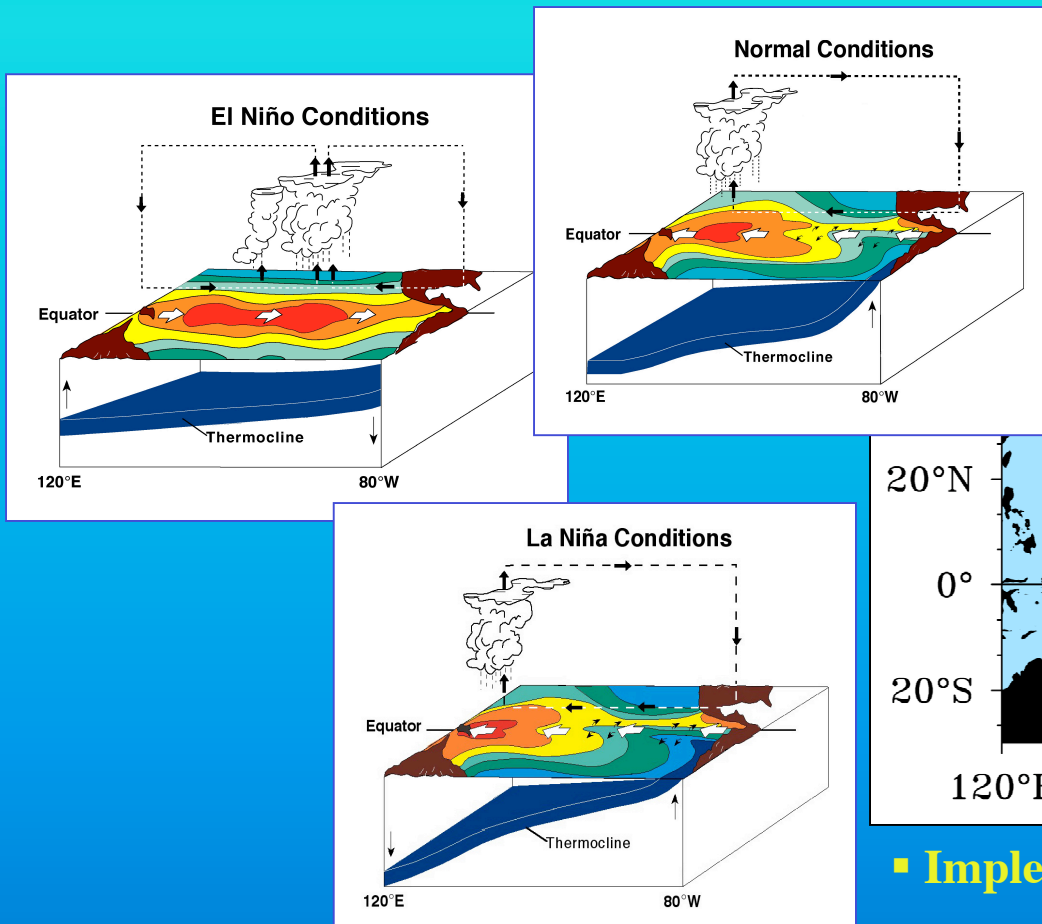
Pacific Ocean
TAO/TRITON



TAO/TRITON Array & the El Niño/Southern Oscillation (ENSO) Cycle

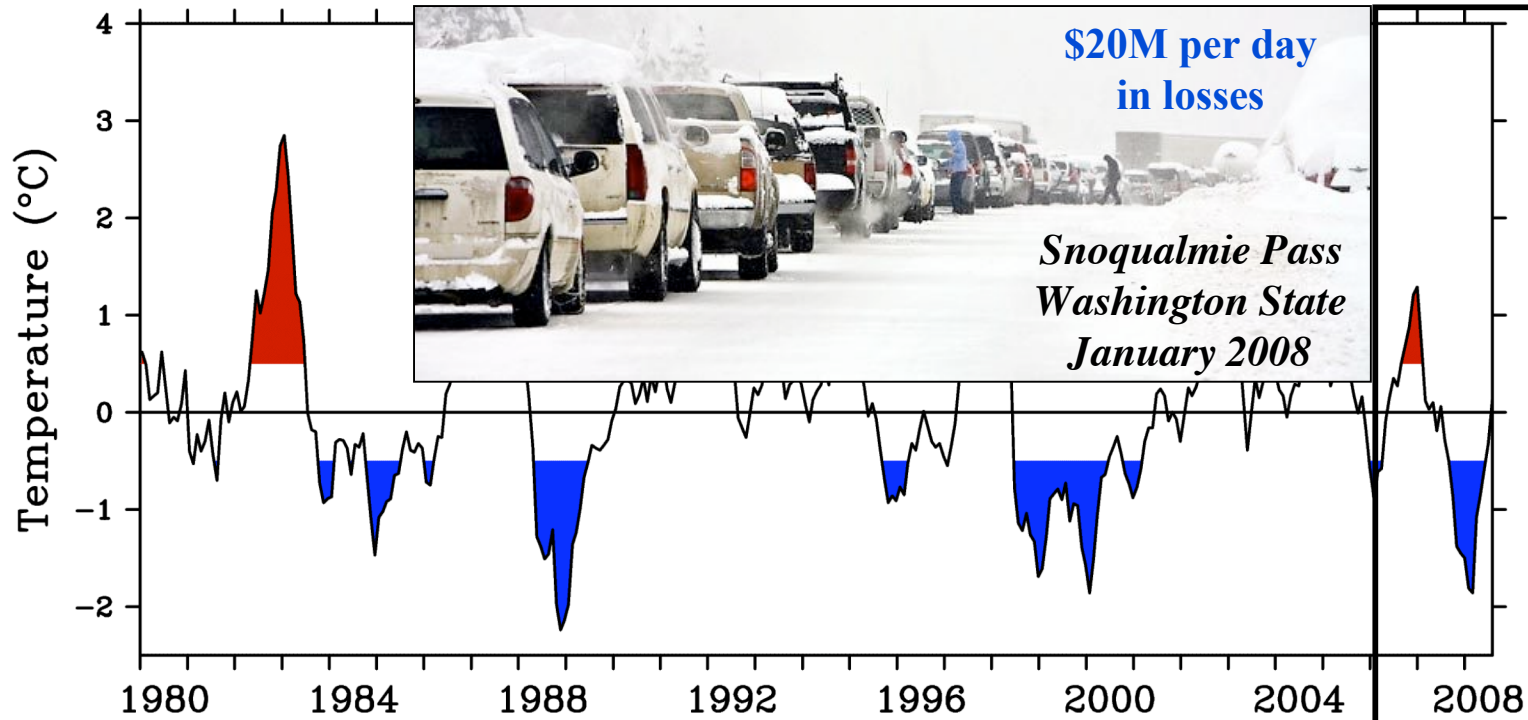
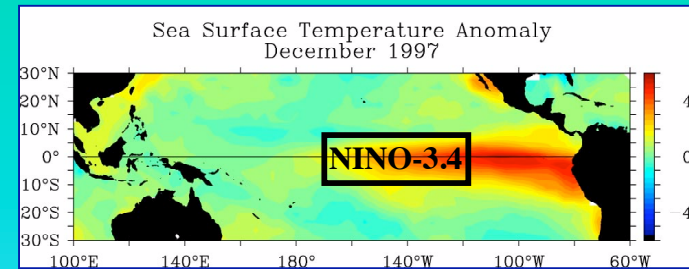
"...the crowning achievement of TOGA was the development of the Tropical Atmosphere/Ocean (TAO) array..."

EOS, Transactions of the AGU
7 January 1997.



- Implemented 1985-94 as part of TOGA
- Presently a U.S./Japan collaboration
- Transition to operations at NDBC underway

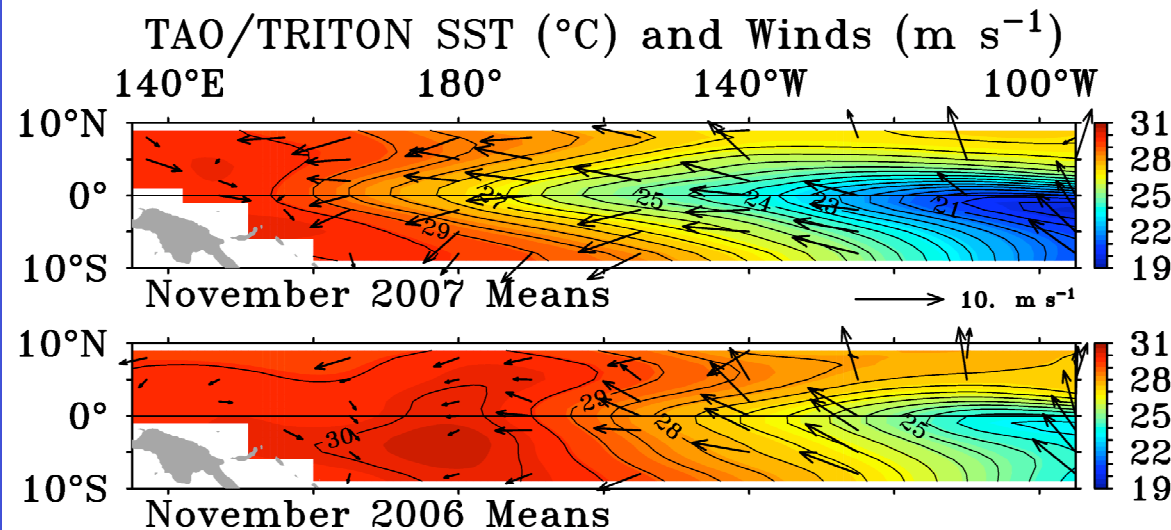
El Niño & La Niña Index



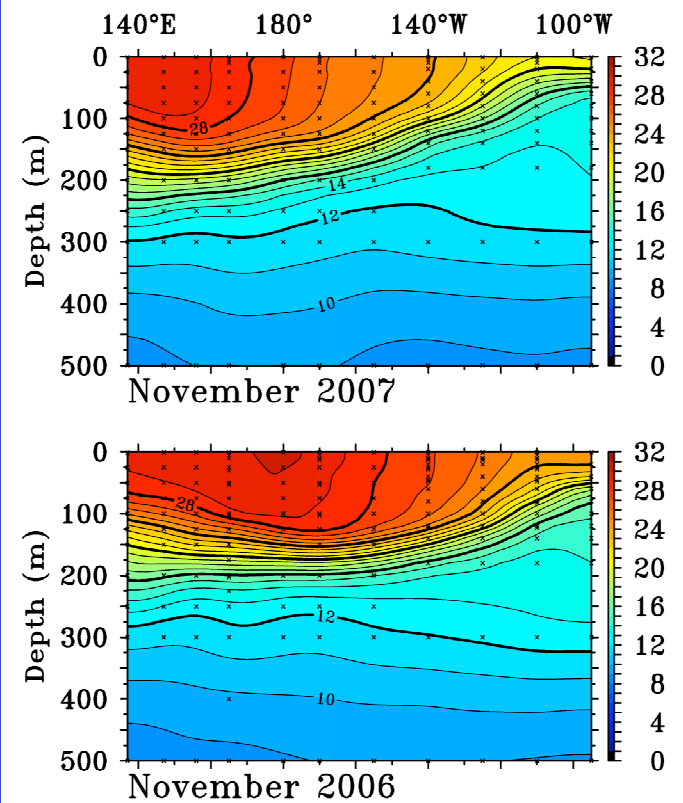
$NINO3.4 \geq 0.5^{\circ}C$ for 5 months = El Niño

$NINO3.4 \leq -0.5^{\circ}C$ for 5 months = La Niña

Contrasting 2006 El Niño and 2007 La Niña Conditions

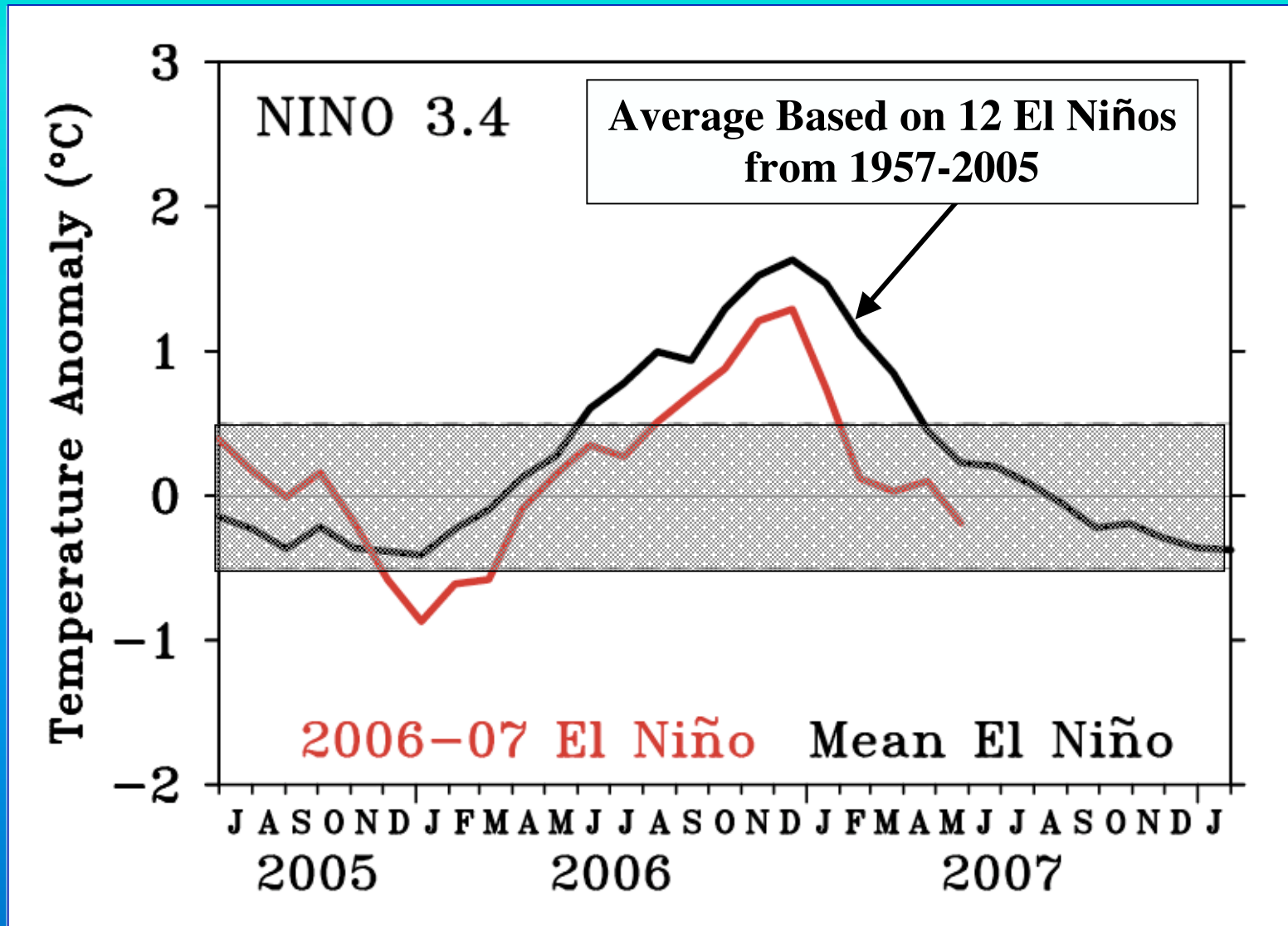


Monthly TAO/TRITON Temperatures ($^{\circ}\text{C}$)
2°S to 2°N Average

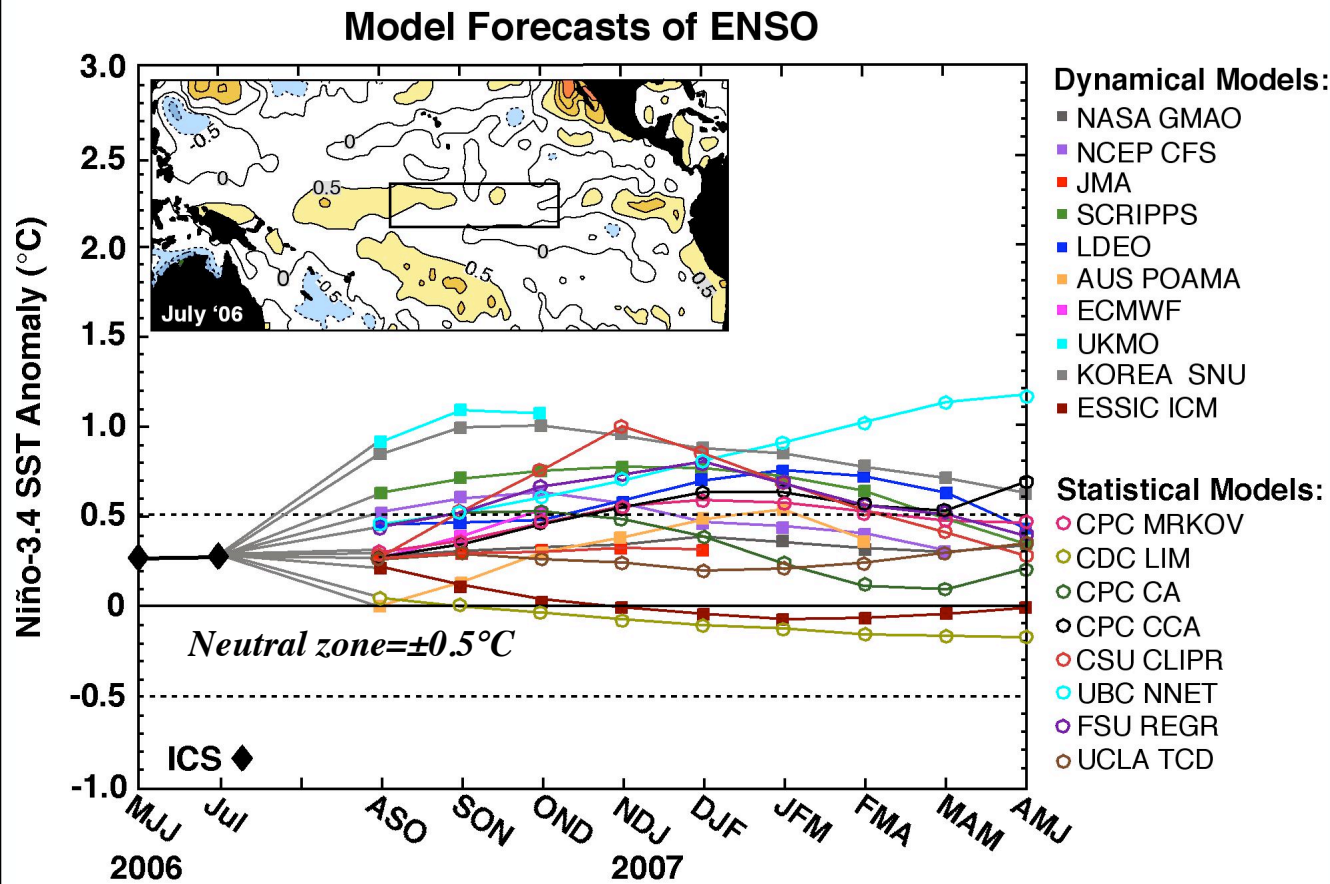


<http://www.pmel.noaa.gov/tao/>

Evolution of 2006-07 El Niño vs “Average” El Niño



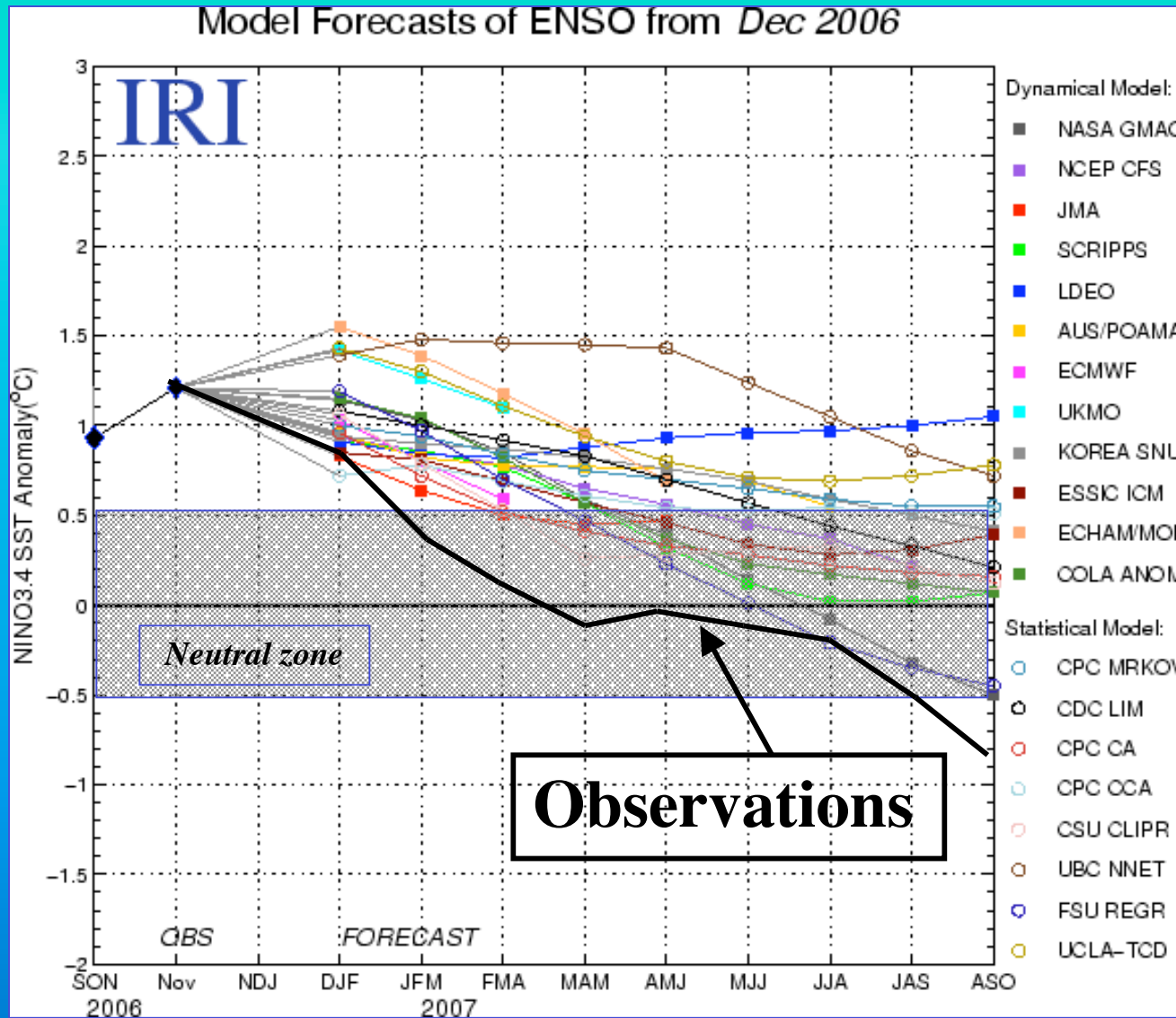
Niño-3.4 Predictions from July 2006



“ENSO-neutral conditions are expected to continue for the next one to three months, with a 50% chance that weak El Niño conditions will develop by the end of 2006.”

NOAA, 10 Aug 2006

Niño-3.4 Predictions From Dec 2006



“El Niño conditions are likely to continue through May 2007.”

NOAA
7 Dec 2006

“Based on the latest observations and forecasts, the probability of maintaining El Niño conditions through the Dec-Feb 2006-07 season is ~95%.”

IRI
20 Dec 2006

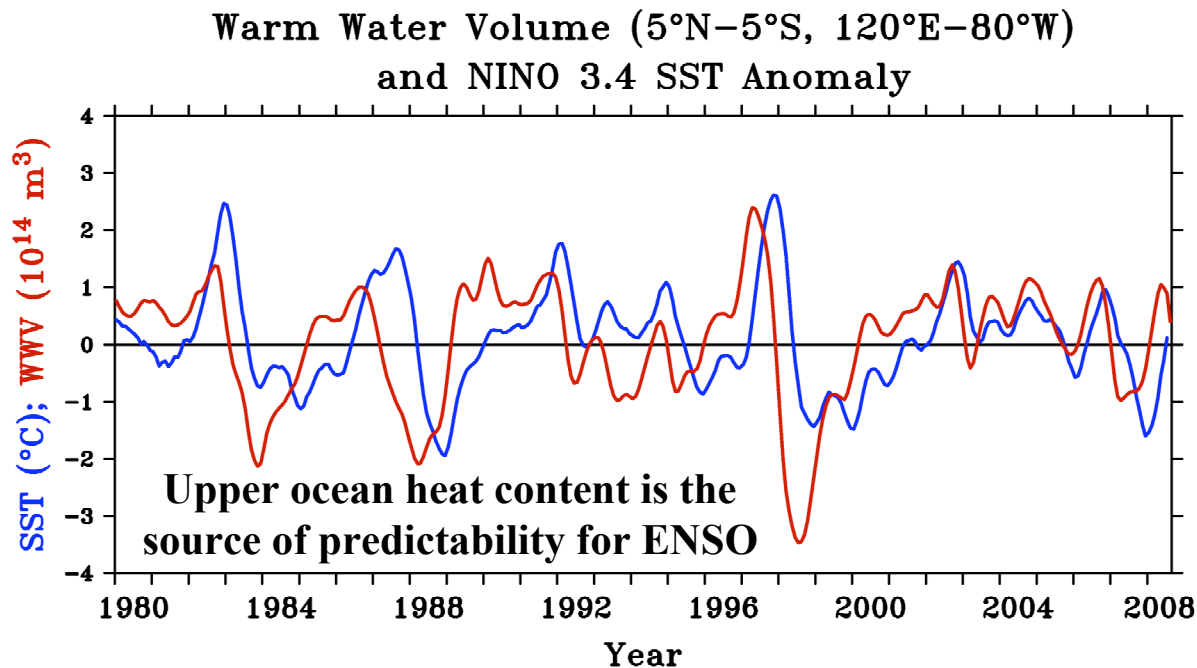
Processes Governing ENSO Evolution

- **Large scale, low frequency deterministic physics (Ocean-atmosphere coupling, oceanic equatorial waves, etc.)**
- **High frequency (days-to-weeks) “stochastic” forcing (wind bursts, Madden-Julian Oscillation, etc.)**
 - ✓ **A source of irregularity**
 - ✓ **Limits predictability**

McPhaden, M.J., 2008: Evolution of the 2006-07 El Niño: The Role of Intraseasonal to Interannual Time Scale Dynamics. Adv. Geosci., 14, 219-230.

Upper Ocean Heat Content

(Based Recharge Oscillator Theory of Jin, 1997)

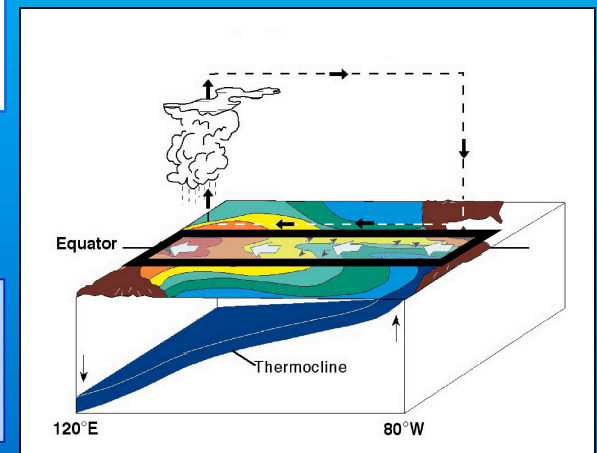


- Build up of excess heat content along equator is a necessary precondition for El Niño to occur.
- El Niño purges excess heat to higher latitudes, which terminates the event.
- The time between El Niños is determined by the time to recharge.

WWV based on BMRC analysis of TAO/TRITON, XBT and Argo data

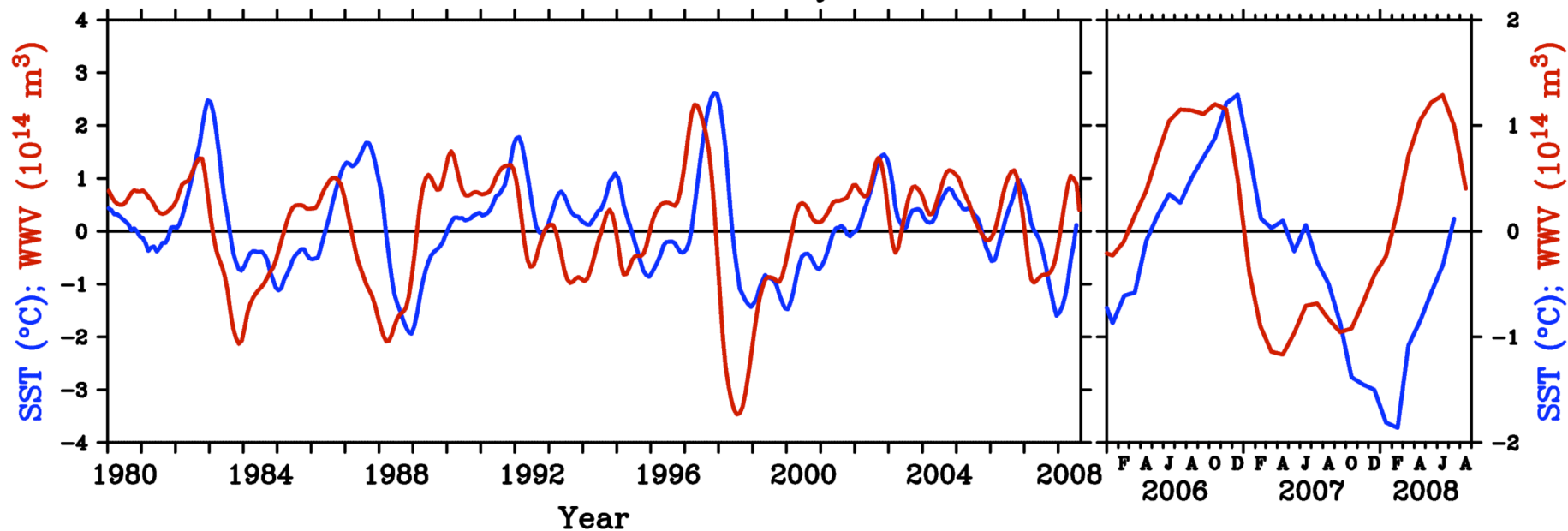
Warm Water Volume (WWV): An Index for Upper Ocean Heat Content

Meinen & McPhaden, 2000



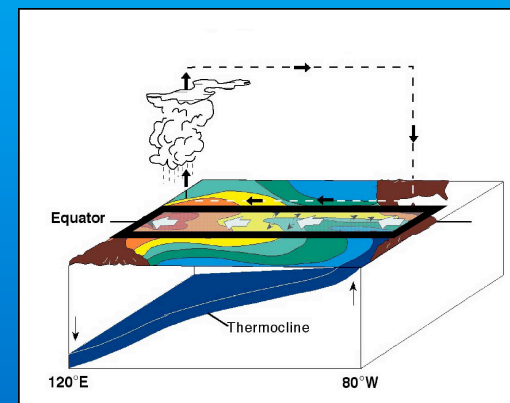
Upper Ocean Heat Content and ENSO

Warm Water Volume (5°N–5°S, 120°E–80°W)
and NINO 3.4 SST Anomaly



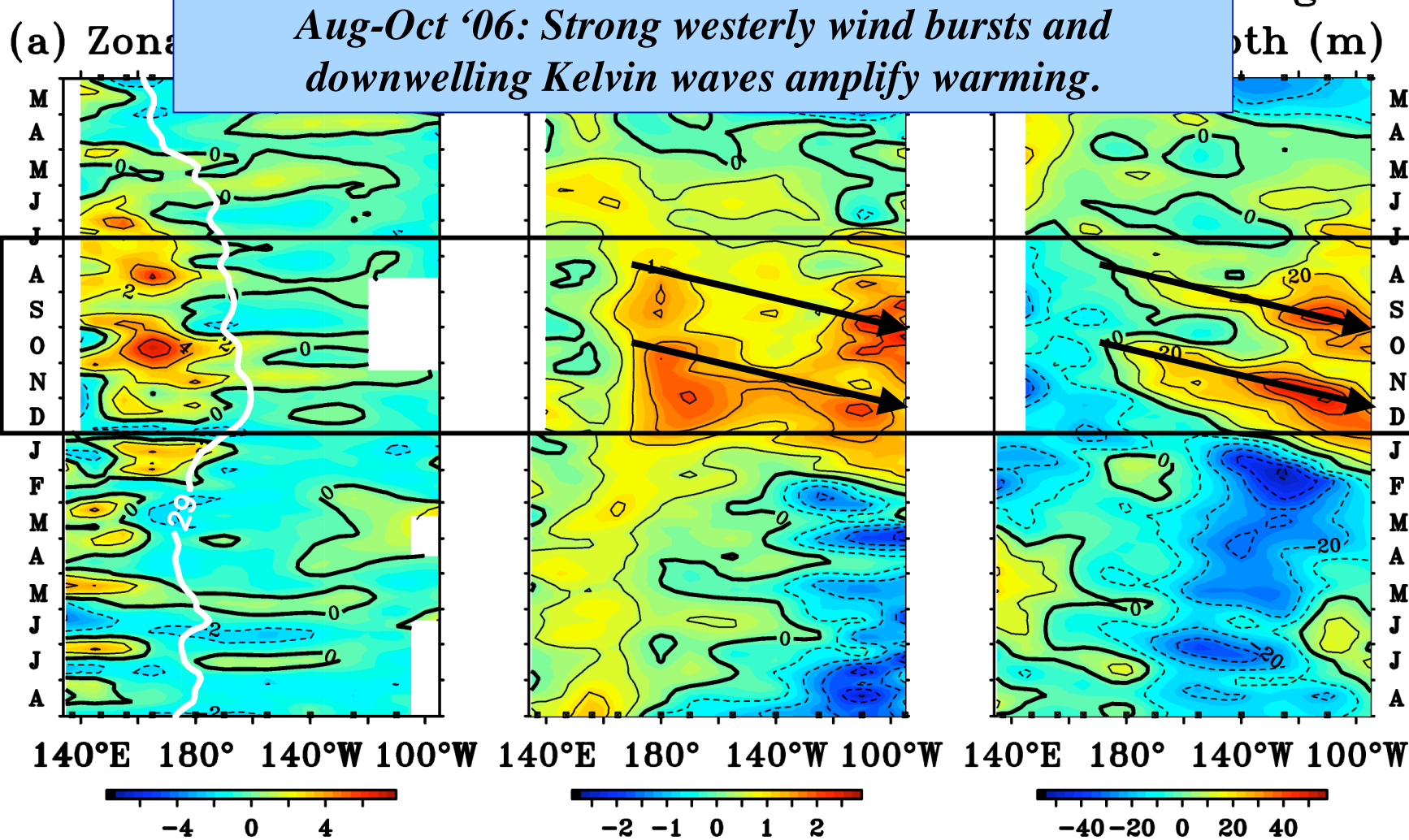
WWV index for heat content based analysis of TAO/TRITON, XBT and Argo data

Upper ocean heat content provides a necessary (but not sufficient) precondition for ENSO cycle variations



March 2006-August 2007

Five Day TAO/TRITON Anomalies 2°S to 2°N Average



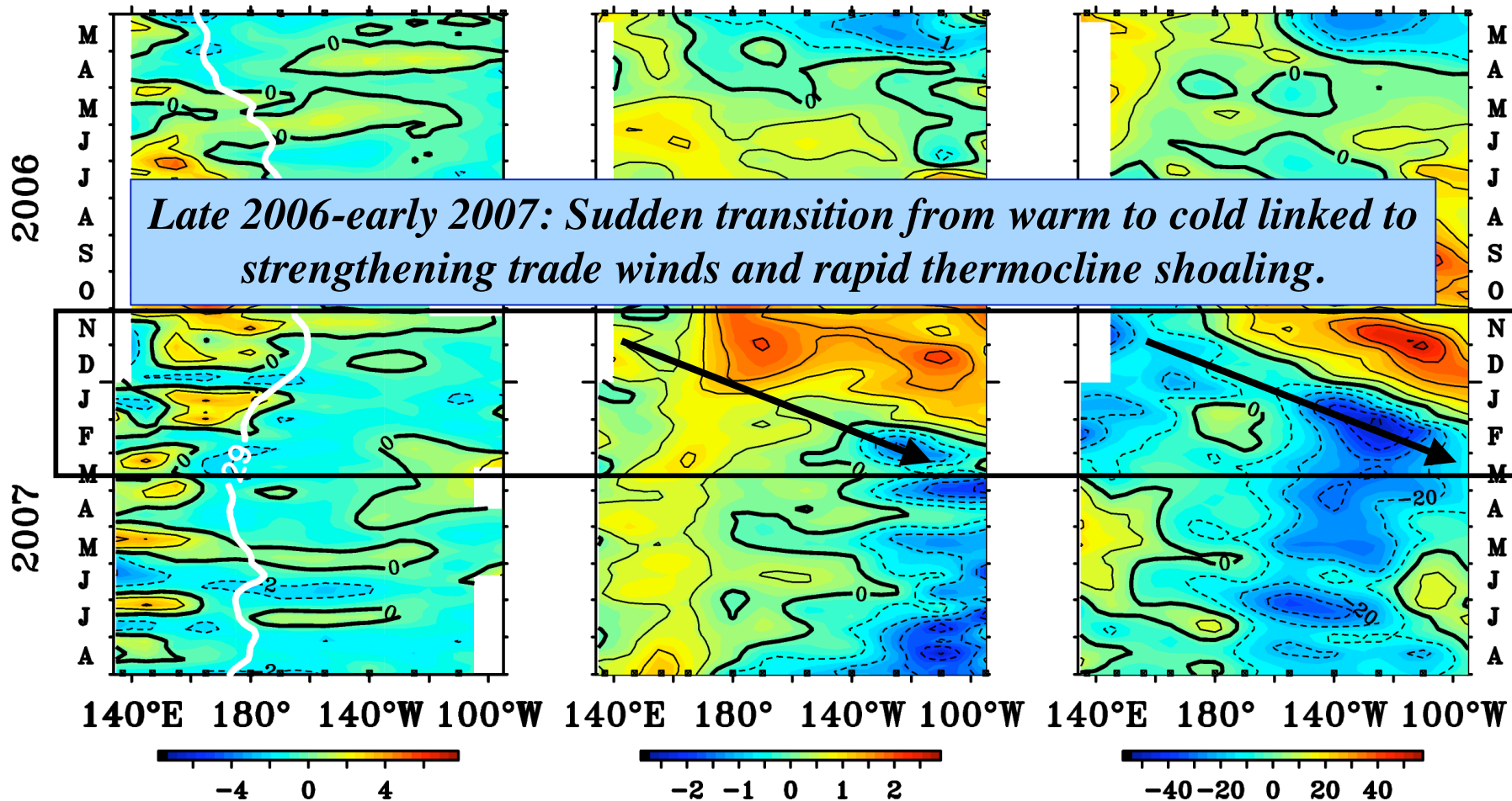
March 2006-August 2007

Five Day TAO/TRITON Anomalies 2°S to 2°N Average

(a) Zonal Wind (m s^{-1})

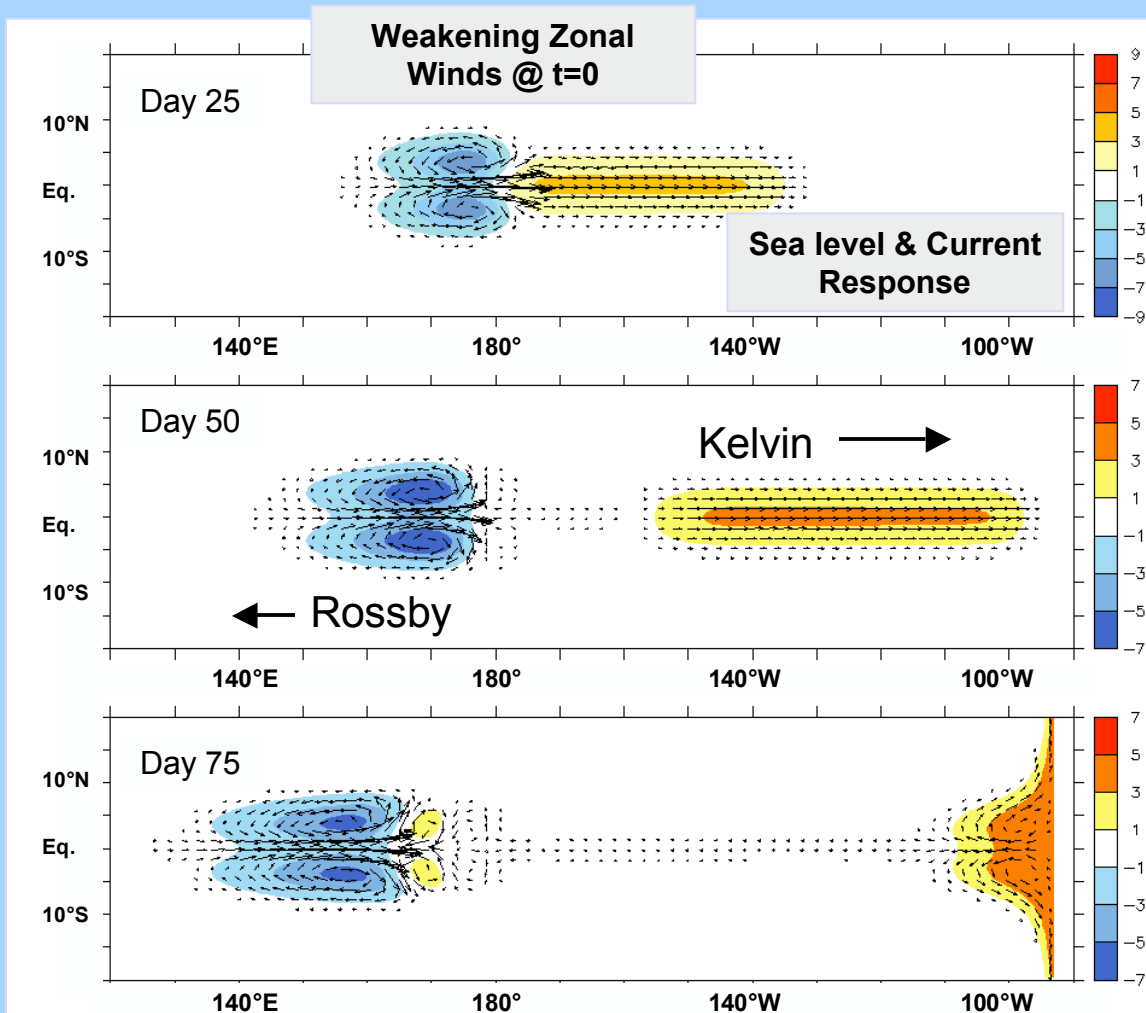
(b) SST ($^{\circ}\text{C}$)

(c) 20°C Depth (m)



Kelvin & Rossby Waves

Key Concepts for Understanding the Ocean's Role in ENSO

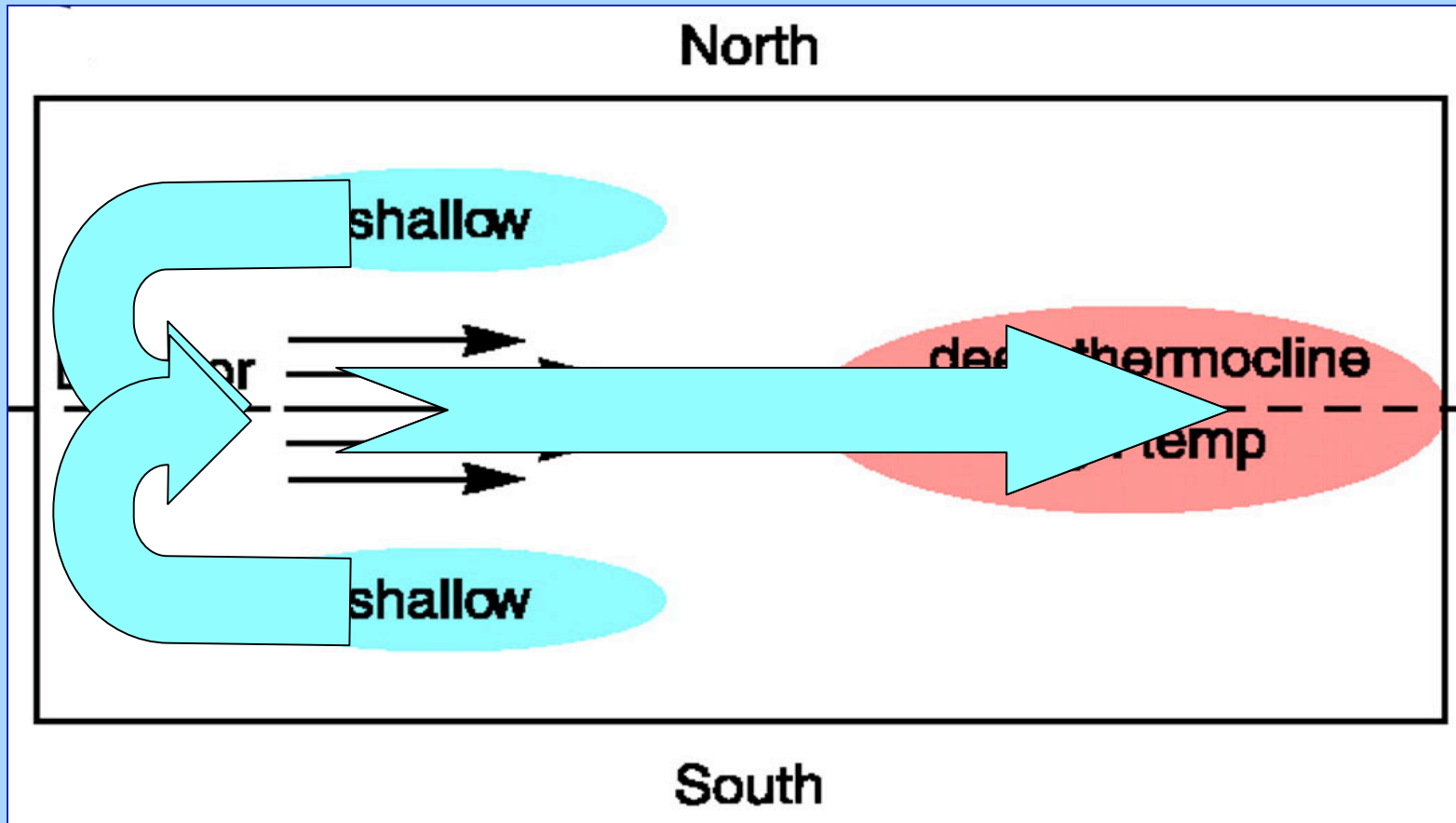


An eastward propagating, non-dispersive, planetary scale wave concentrated in the upper ocean and trapped near the equator.

Sea level response mirrored in thermocline depth (“two layer ocean”)

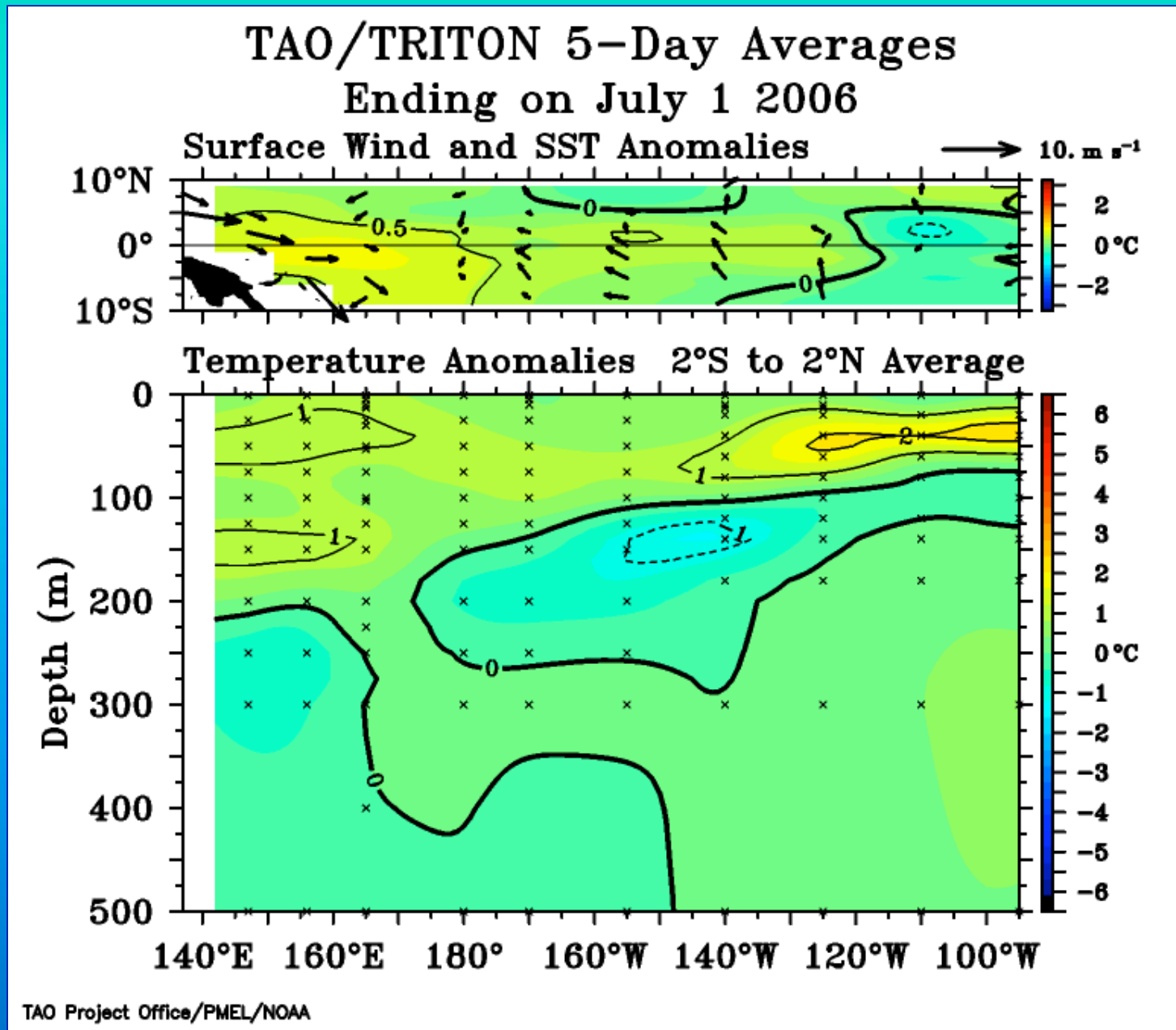
Delayed Oscillator

(Schopf & Suarez, 1988; Battisti & Hirst, 1989)



1. Winds weaken \Rightarrow Downwelling Kelvin wave to the east, upwelling Rossby wave to the west.
2. Upwelling Rossby wave reflects at western boundary as upwelling Kelvin wave.
3. Upwelling Kelvin wave cools the eastern Pacific cold tongue, shutting down El Niño and triggering La Niña.

Evolution: July 2006-March 2007



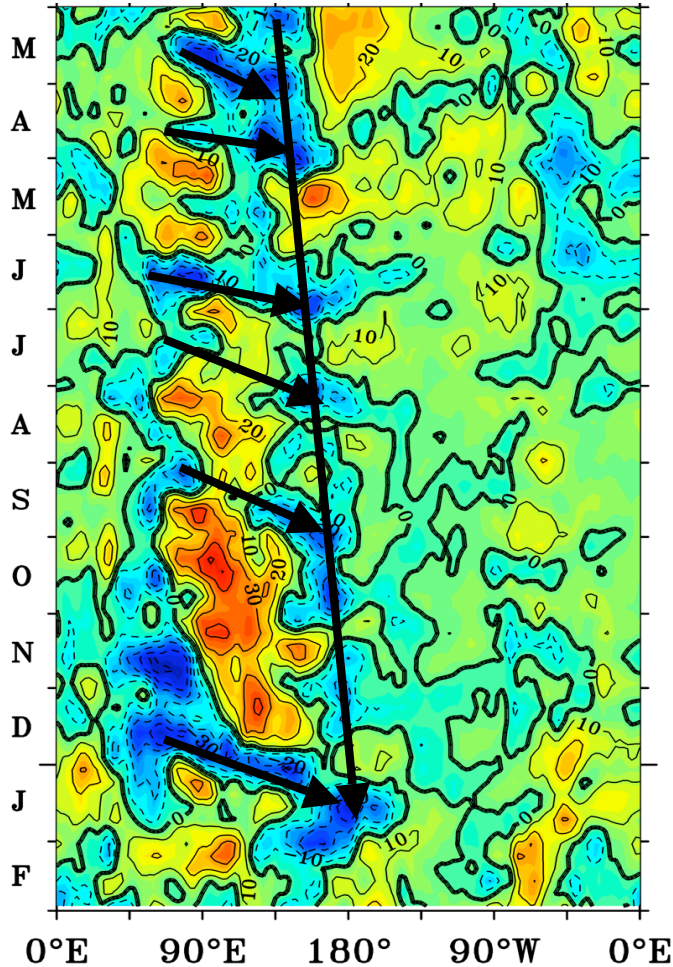
Mar
2006

Feb
2007

2006

Cloudiness & Rainfall

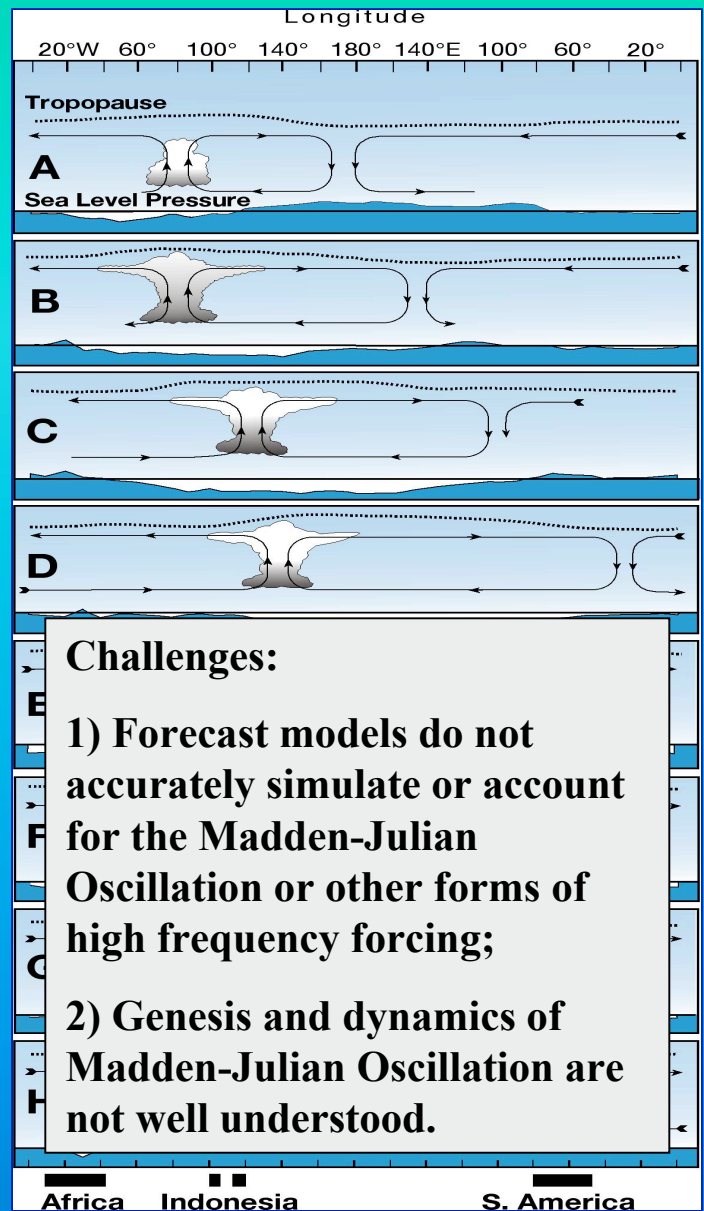
(Outgoing Longwave Radiation, 5°N-5°S)



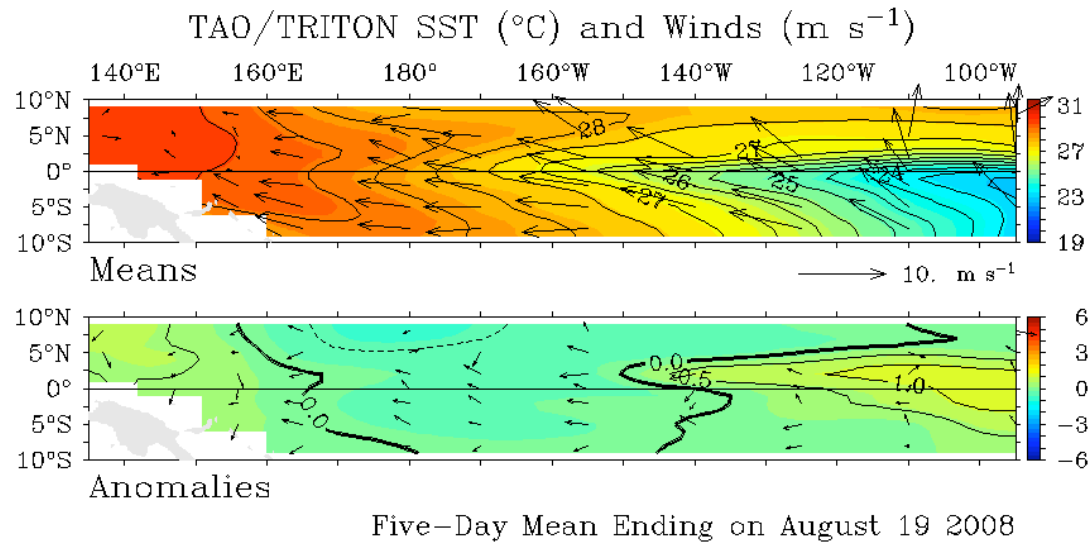
cloudy/wet

clear/dry

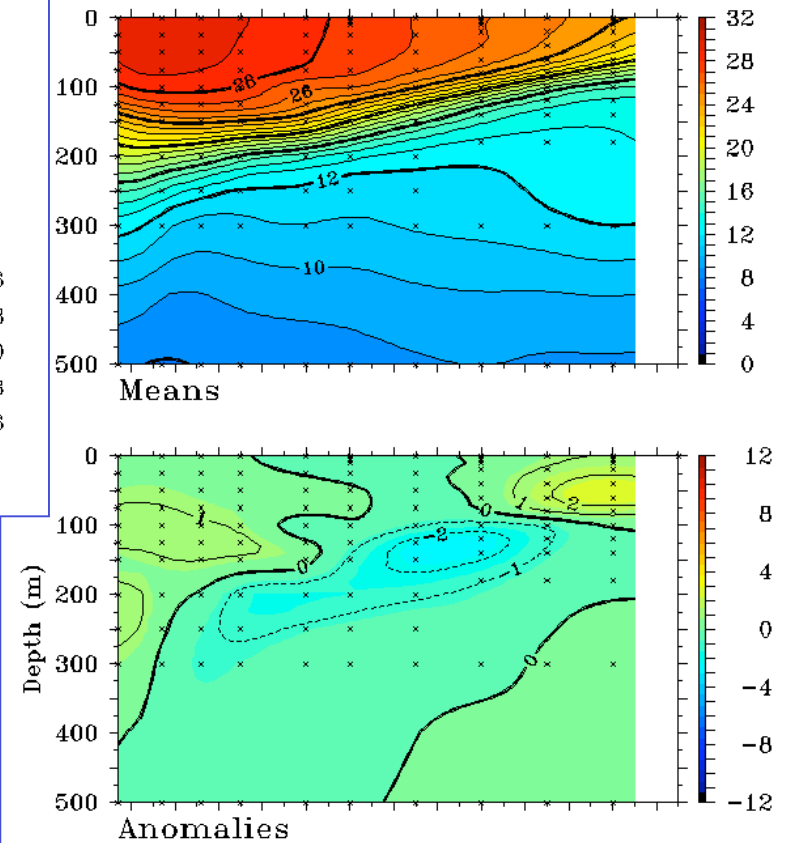
Indian | Pacific | Atlantic



Current Conditions



TAO/TRITON 5-Day Temperature ($^{\circ}\text{C}$)
End Date: August 19 2008 2°S to 2°N Average
140°E 160°E 180° 160°W 140°W 120°W 100°W



<http://www.pmel.noaa.gov/tao/>

***Current ENSO Advisory
NOAA/Climate Prediction Center
7 August 2008***

“ENSO-neutral conditions are expected to continue through the Northern Hemisphere Fall 2008.”

“As is typical with ENSO-neutral conditions, atmospheric and oceanic indicators were mixed, with certain areas...suggesting a lingering influence of La Niña and others reflecting...above-average temperatures...”

“Most of the recent dynamical and statistical SST forecasts for the Niño 3.4 region indicate ENSO-neutral conditions...will continue into the Northern Hemisphere Spring 2009. However...the development of El Niño cannot be ruled out during the later part of the year...”

<http://www.cpc.ncep.noaa.gov/>

Atlantic Ocean
PIRATA



THE PIRATA PROGRAM

History, Accomplishments, and Future Directions*

BY BERNARD BOURLÈS, RICK LUMPKIN, MICHAEL J. McPHADEN, FABRICE HERNANDEZ, PAULO NOBRE, EDMO CAMPOS, LISAN YU, SERGE PLANTON, ANTONIO BUSALACCHI, ANTONIO D. MOURA, JACQUES SERVAIN, AND JANICE TROTTE

A network of deep ocean moored buoys in the tropical Atlantic, developed through a multinational partnership and maintained from 1997, provides unique data for climate research and prediction.

Partners:

- ✓ Brazil (Navy & Space Agency) & France (Inst. for Research & Development, Meteo-France) provide logistic support & most shiptime (228 sea days during 2003-07)
- ✓ USA (NOAA) provides most equipment & data processing

Bull. Am. Met. Soc.,
Cover Story Aug '08

Introduced in Oct '98

Focus: Tropical
Atlantic Climate
Variability
including climatic
conditions in
“hurricane alley”

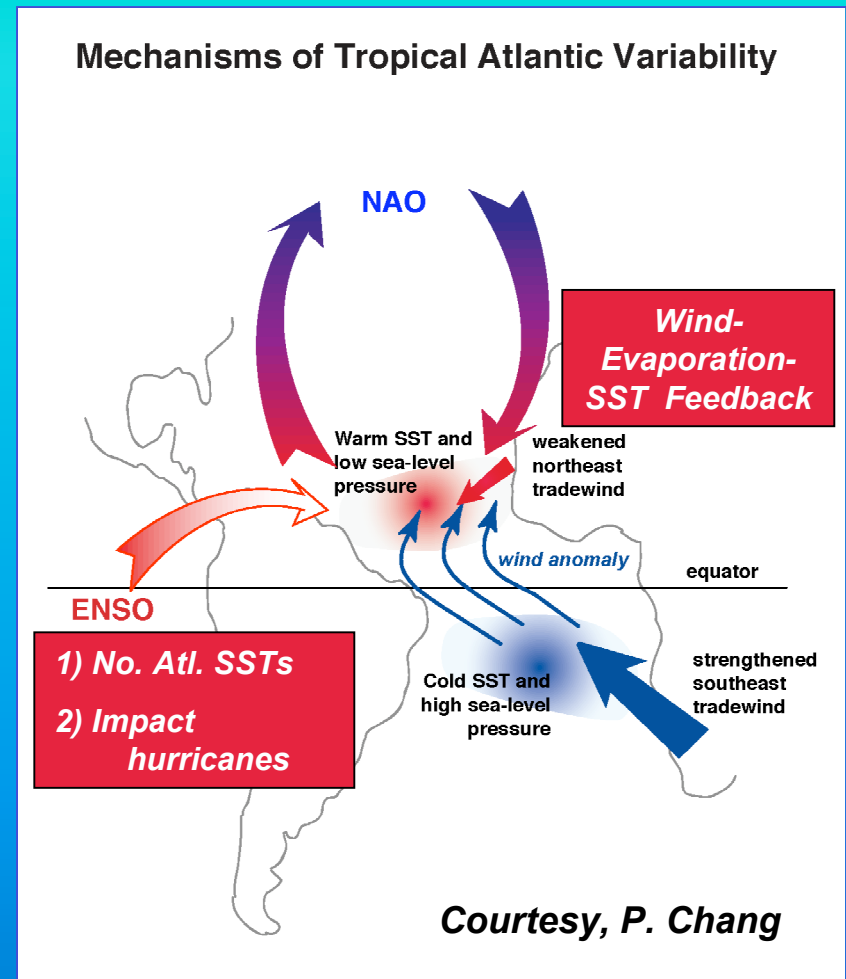
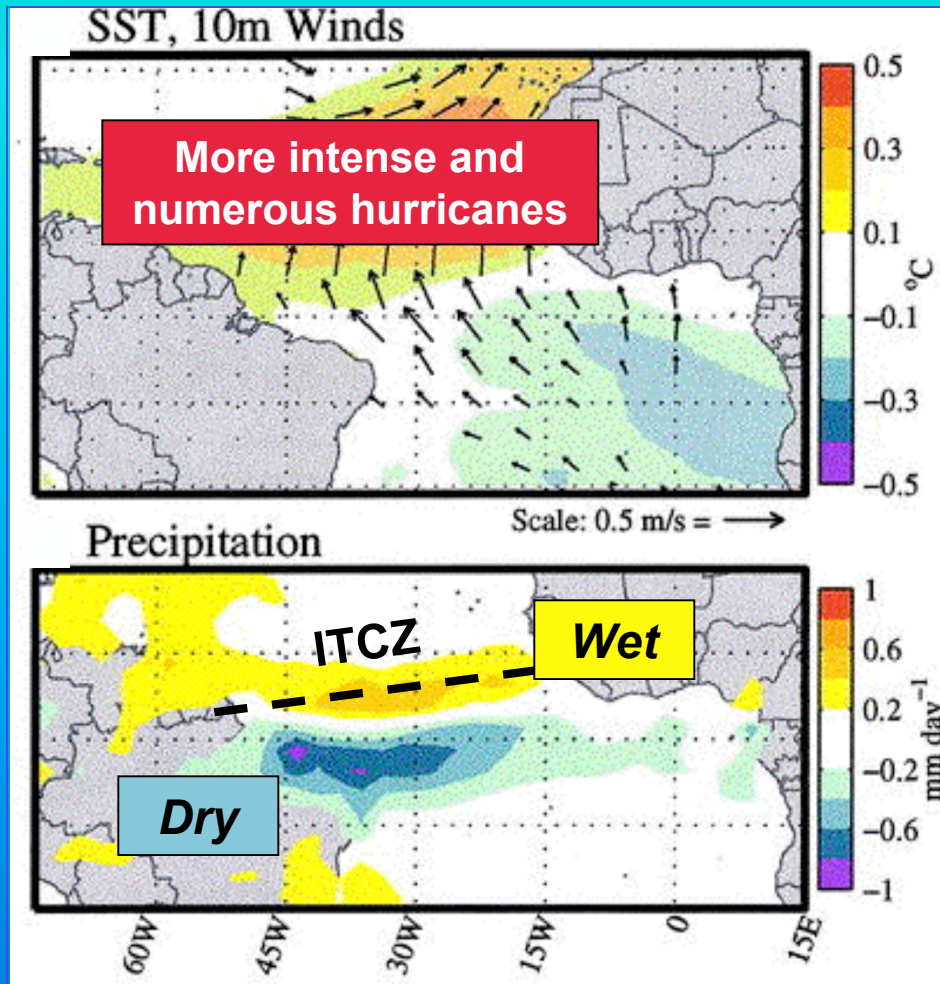


*Pilot Research Moored Array
in the Tropical Atlantic (1998)*

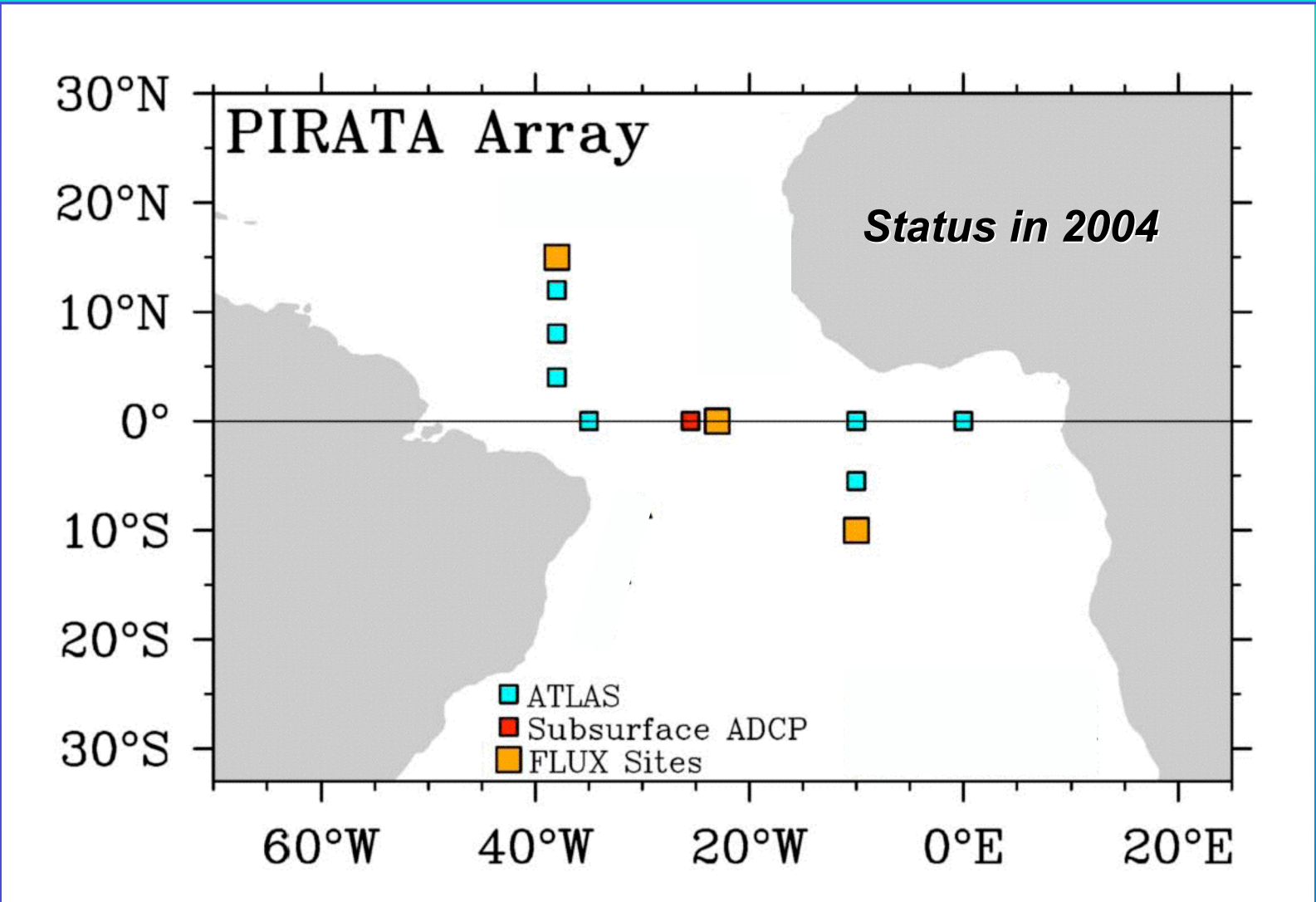
becomes

*Prediction and Research
Moored Array in the Tropical
Atlantic (2008)*

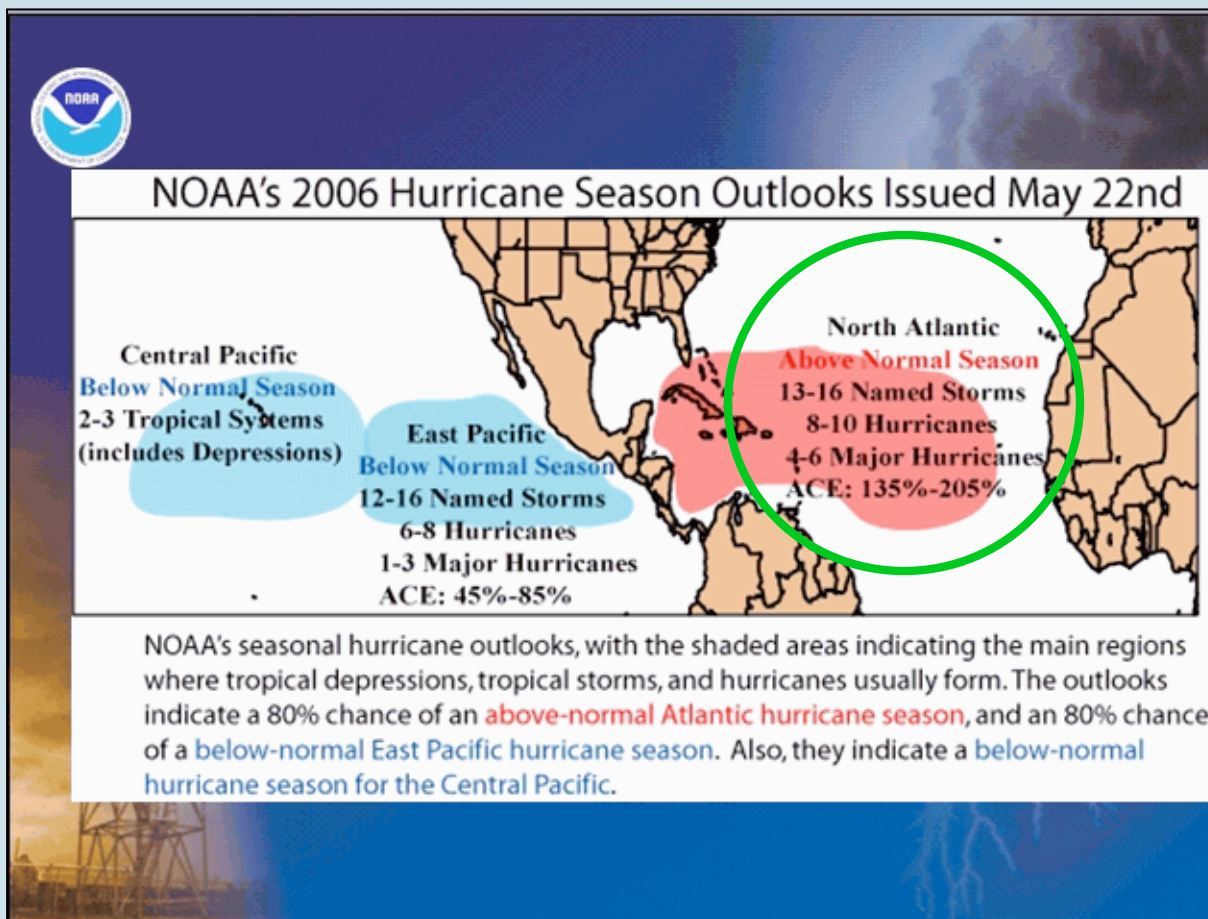
Tropical Atlantic Climate Variability: Atlantic Meridional Mode



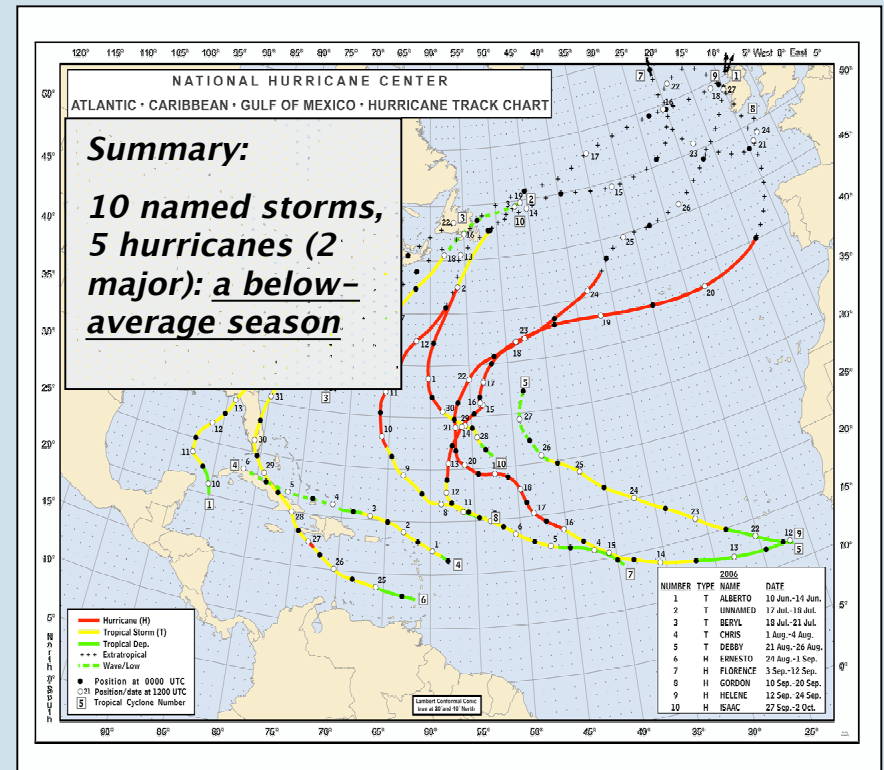
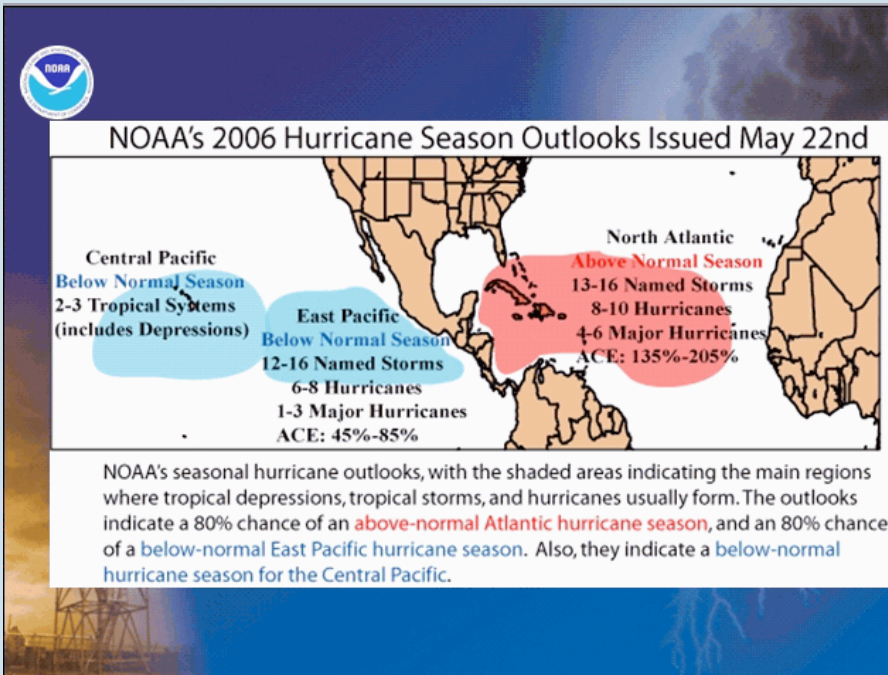
Chiang & Vimont, 2004, J. Climate



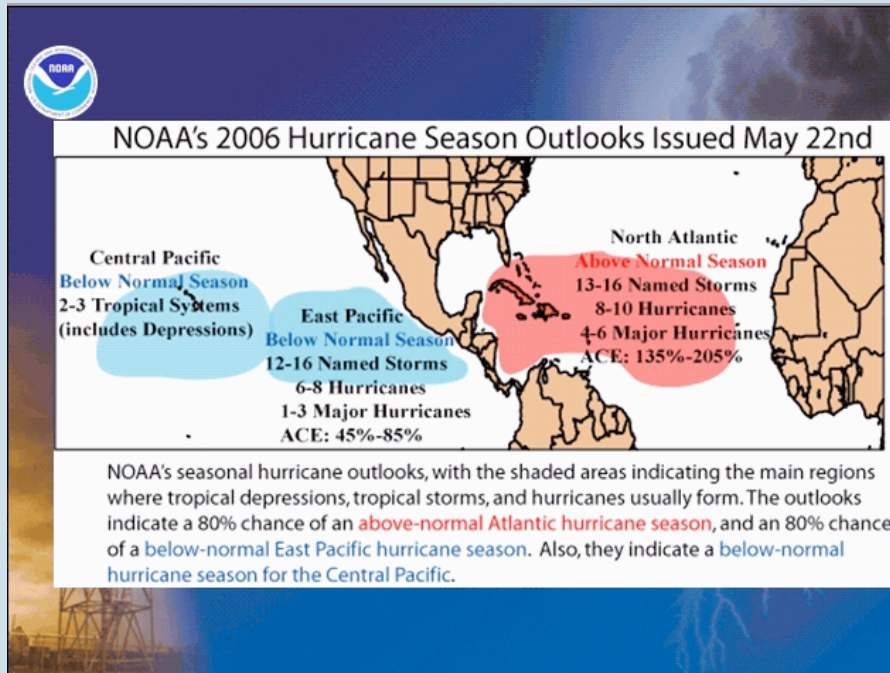
2006 Atlantic Hurricane Season



2006 Atlantic Hurricane Season



2006 Atlantic Hurricane Season



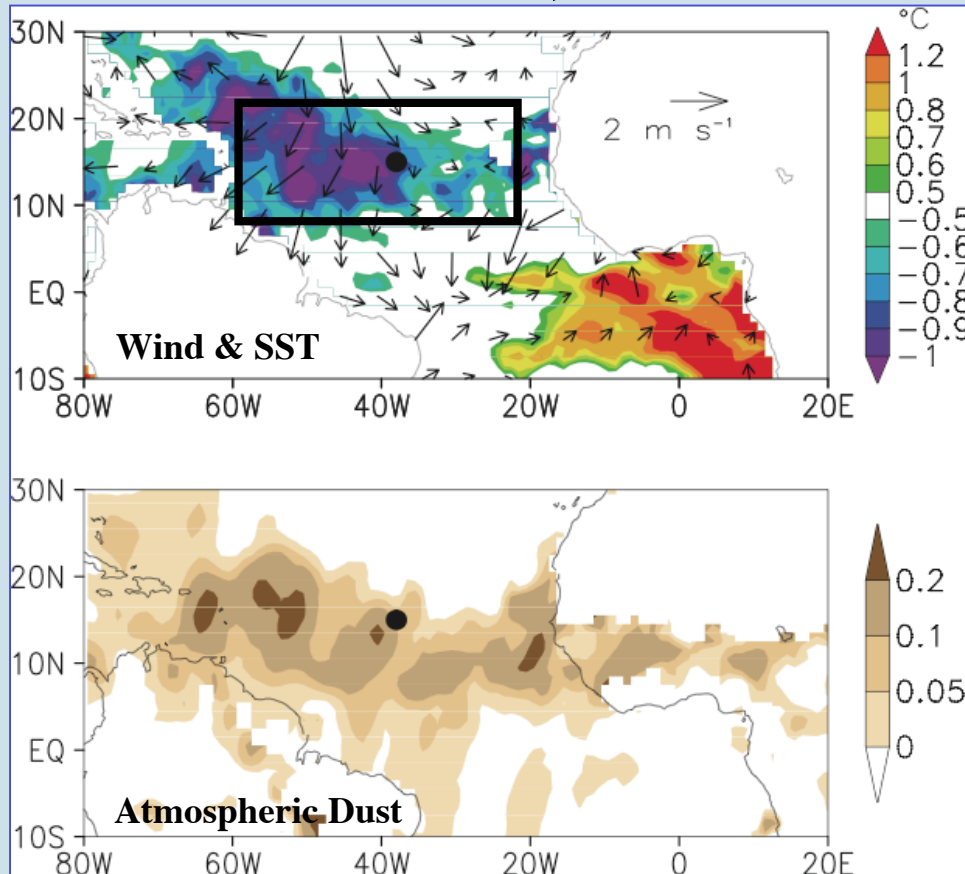
“...the 2006 Atlantic hurricane season activity was lower than expected due to the rapid development of El Niño.”

“El Niño’s rapid development and intensification [was due] to a series of large subsurface ocean waves that affected ocean temperatures during the summer months.”

***NOAA press release
30 Nov 2006***

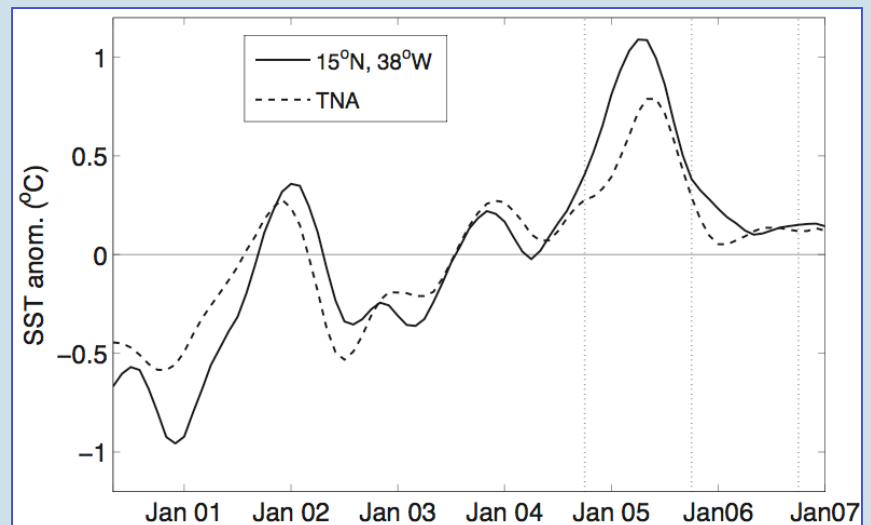
North Atlantic SSTs in 2006

JJA Differences, 2006-2005

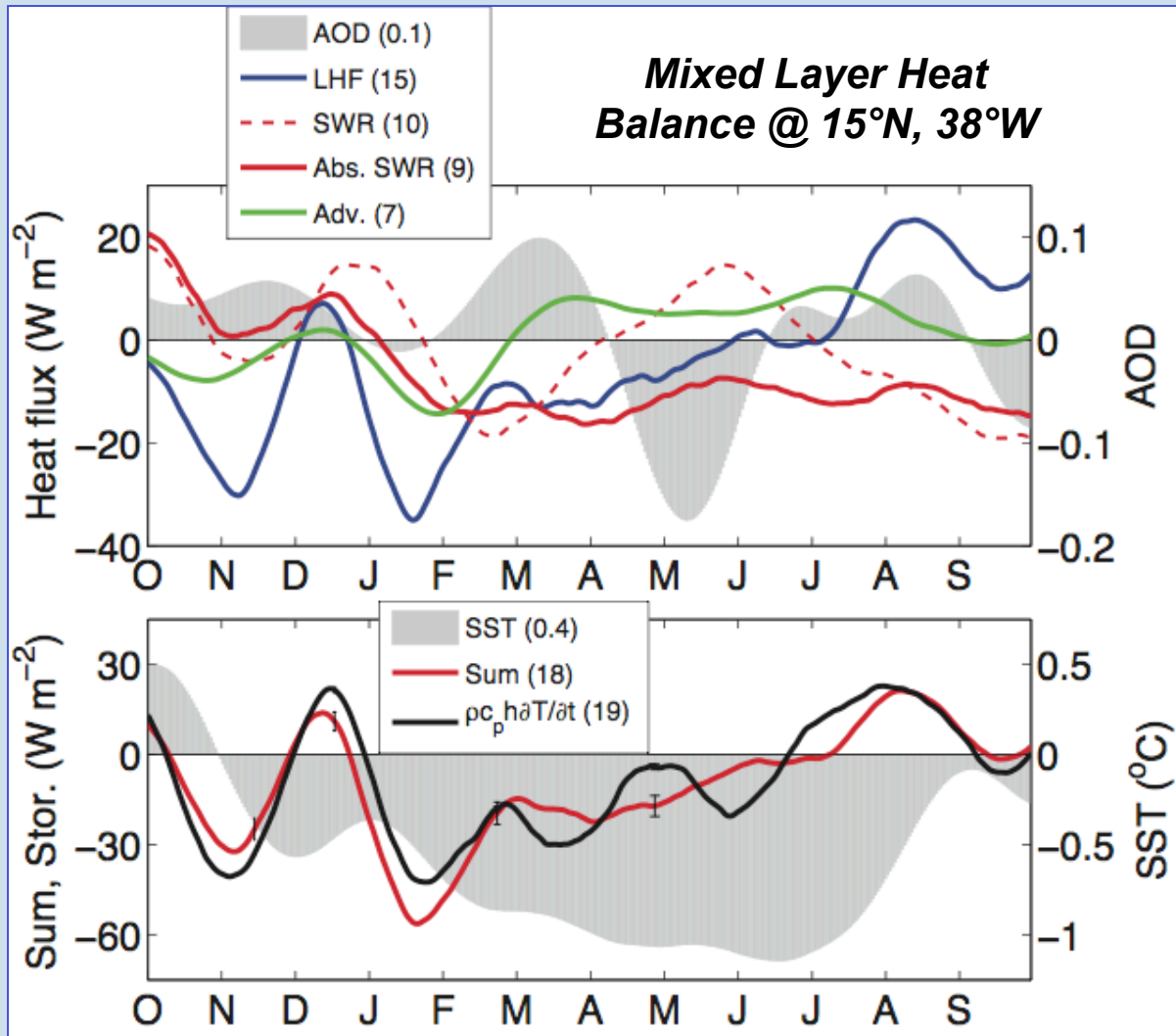


“Increased atmospheric loading of **Saharan dust** over the North Atlantic during the 2006 hurricane season...initiated rapid cooling and suppressed tropical storm and hurricane activity...”

Lau & Kim: How Nature Foiled the 2006 Hurricane Forecast. EOS, 2007.



North Atlantic SSTs in 2006



“...most of the anomalous cooling occurred prior to the period of enhanced dustiness and was driven primarily by wind-induced latent heat loss...dust-induced changes in short wave radiation did not play a major direct role in the cooling that led up to the 2006 Atlantic hurricane season.”

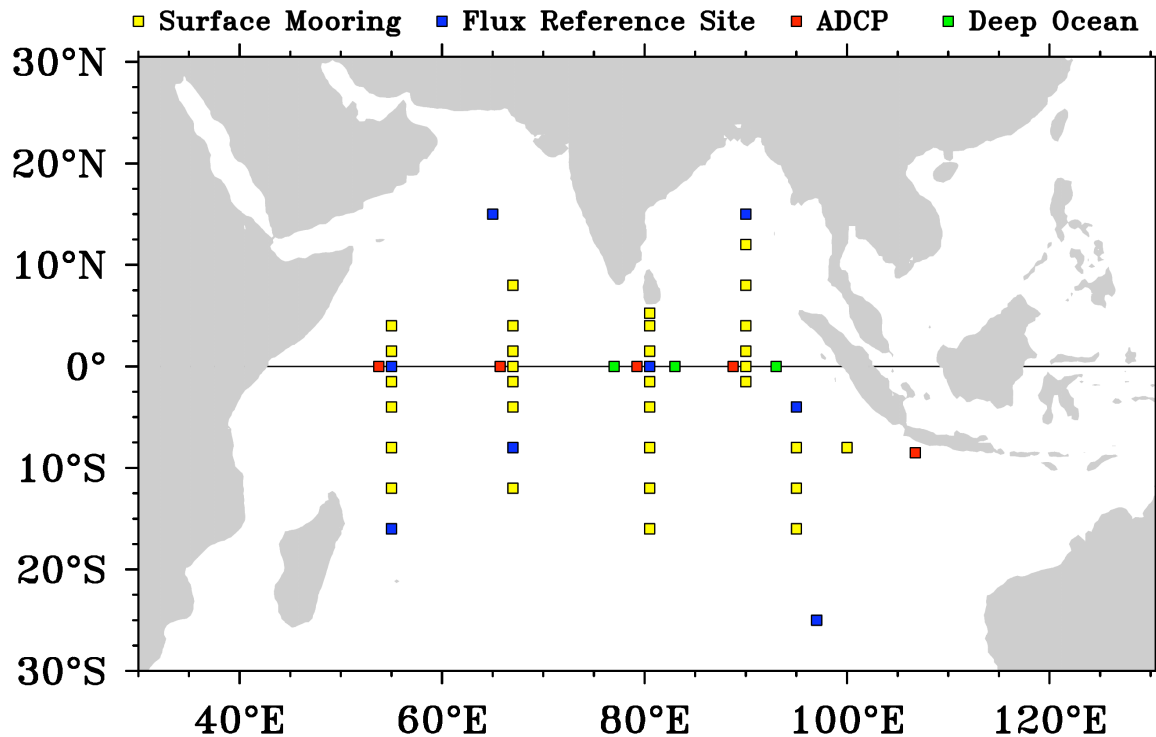
Foltz, G.R., and M.J. McPhaden, 2008: Impact of Saharan dust on tropical North Atlantic SST. *J. Climate*, in press.

*Indian Ocean
RAMA*



RAMA

Research Moored Array for African–Asian–Australian Monsoon Analysis and Prediction (*RAMA*)

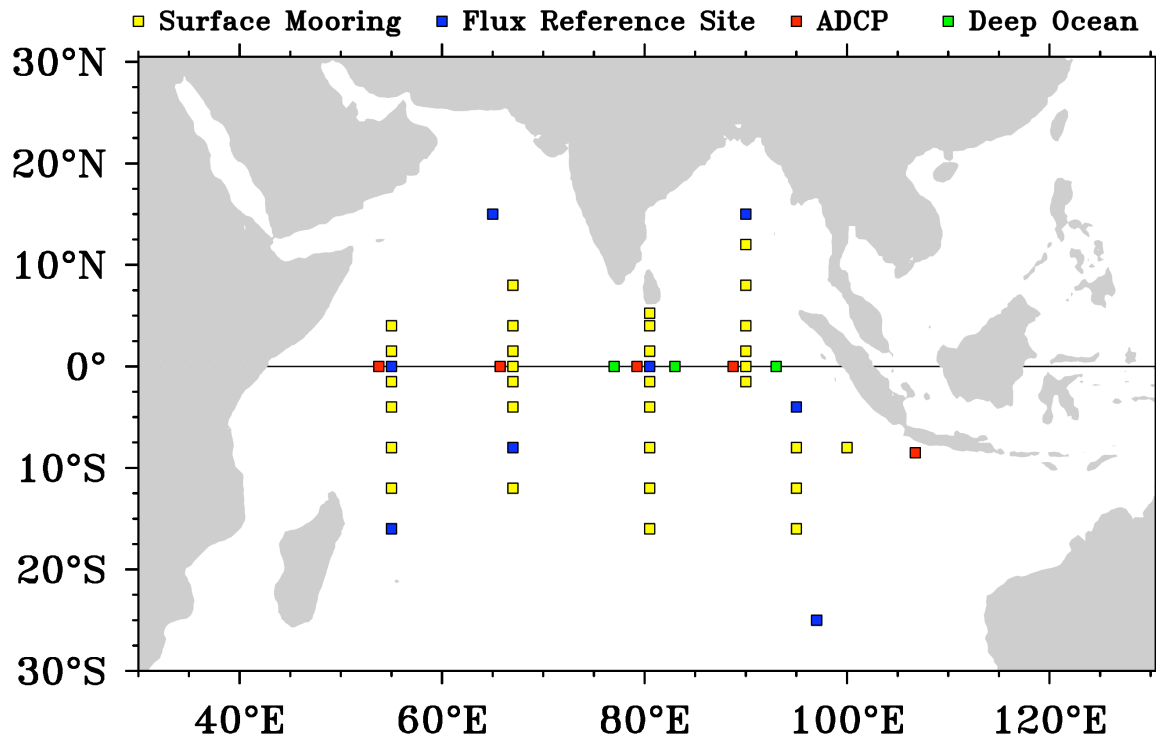


RAMA, 2008: Bull. Am. Meteorol. Soc., accepted.

- Plan developed by the Indian Ocean Panel in 2004.
- Basin scale, upper ocean (~500 m) focus.
- Samples key regions: Arabian Sea, Bay of Bengal, Eq. Waveguide, Thermocline ridge (5°-10°S), subtropical subduction, Java upwelling.
- Design supported by numerical model observing system studies.

RAMA

Research **M**oored **A**rray for African–Asian–Australian
Monsoon **A**nalysis and Prediction (**RAMA**)



RAMA

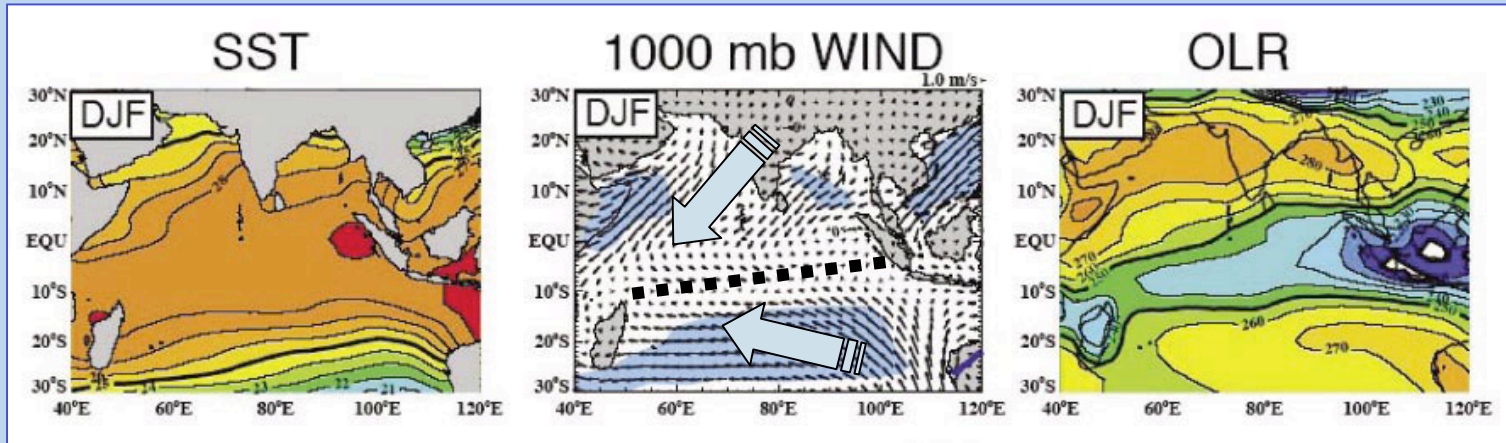


RAMA: Ancient king of India and hero of the epic “Ramayana”.

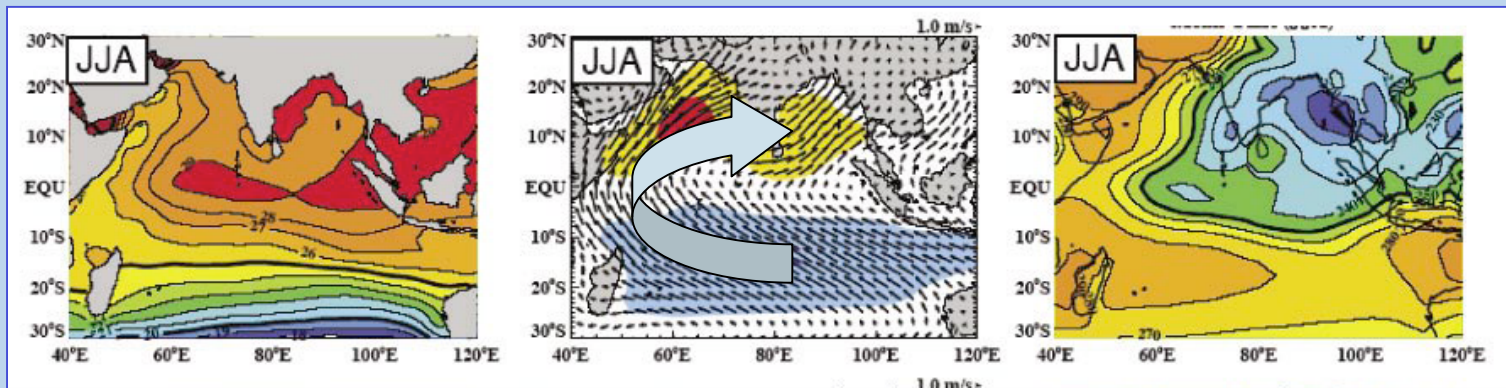
McPhaden et al, 2008: RAMA. Bull. Am. Met. Soc., accepted.

The Monsoon

DJF

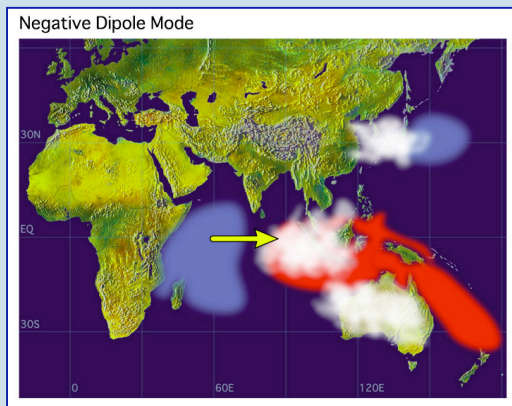
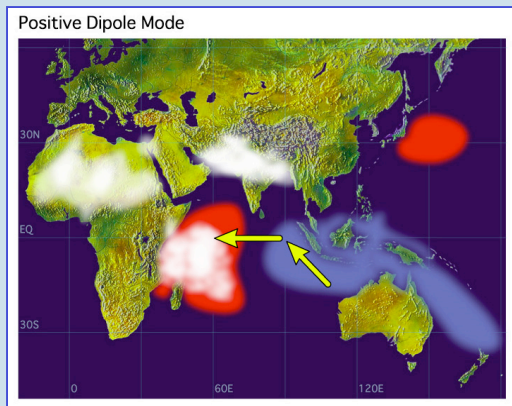


JJA



Half the world's population depends on monsoon rainfall for agriculture

Indian Ocean Climate Science Drivers



Indian Ocean Dipole

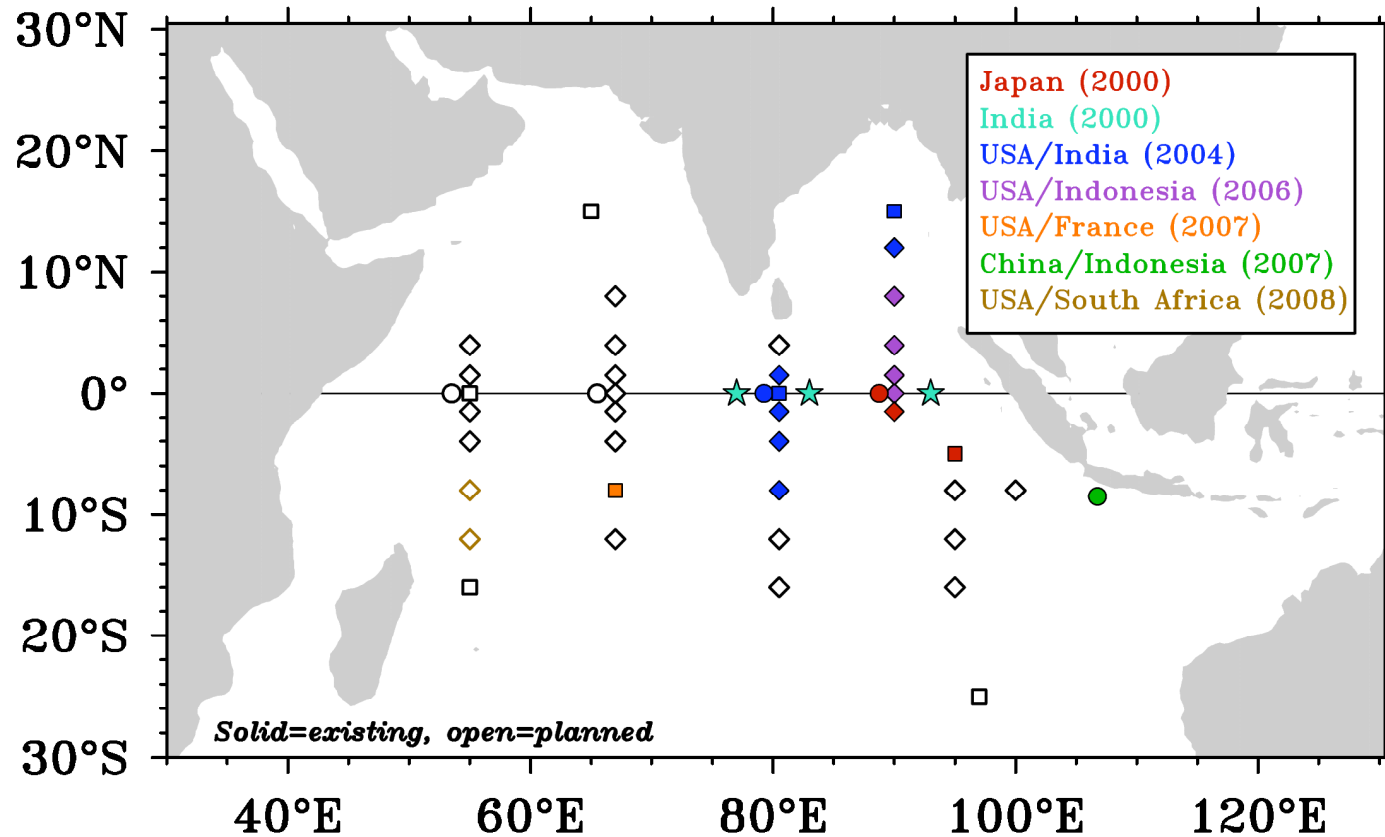
- Seasonal monsoon variability
- Cyclones and synoptic scale events
- Intraseasonal (30-60 day period) Madden Julian Oscillation (\Rightarrow ENSO, west coast US weather, hurricanes)
- Interannual variations: the Indian Ocean Dipole
- Decadal variability
- Warming trends since the 1970s
- Ocean circulation (Indonesian Throughflow, shallow and deep overturning circulation, monsoon currents, etc.)
- Biogeochemical studies



RAMA: Present Status

Research Moored **A**rray for African-Asian-Australian
Monsoon **A**nalysis and Prediction (**RAMA**)

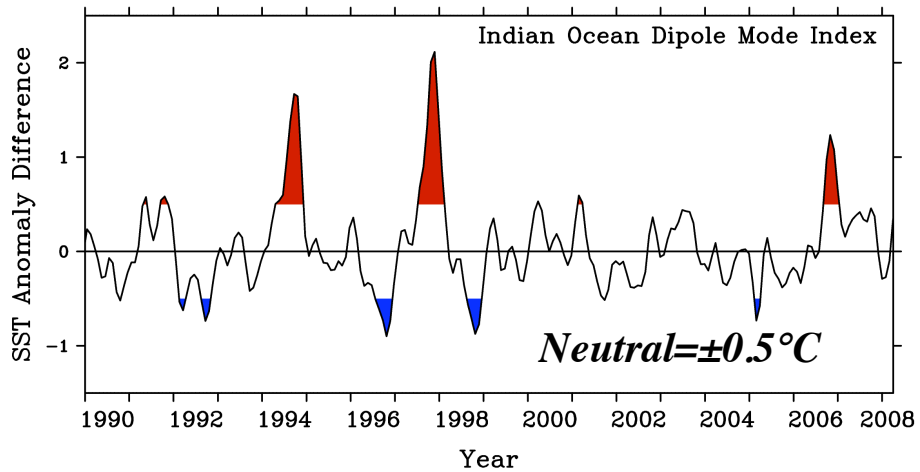
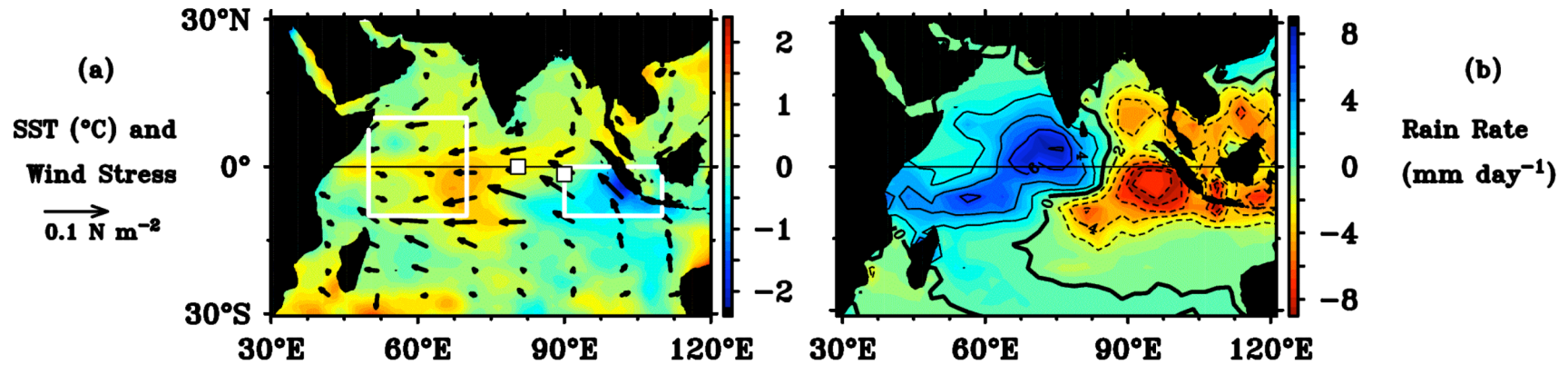
◆ Surface Mooring ■ Flux Reference Site ● ADCP ★ Deep Ocean



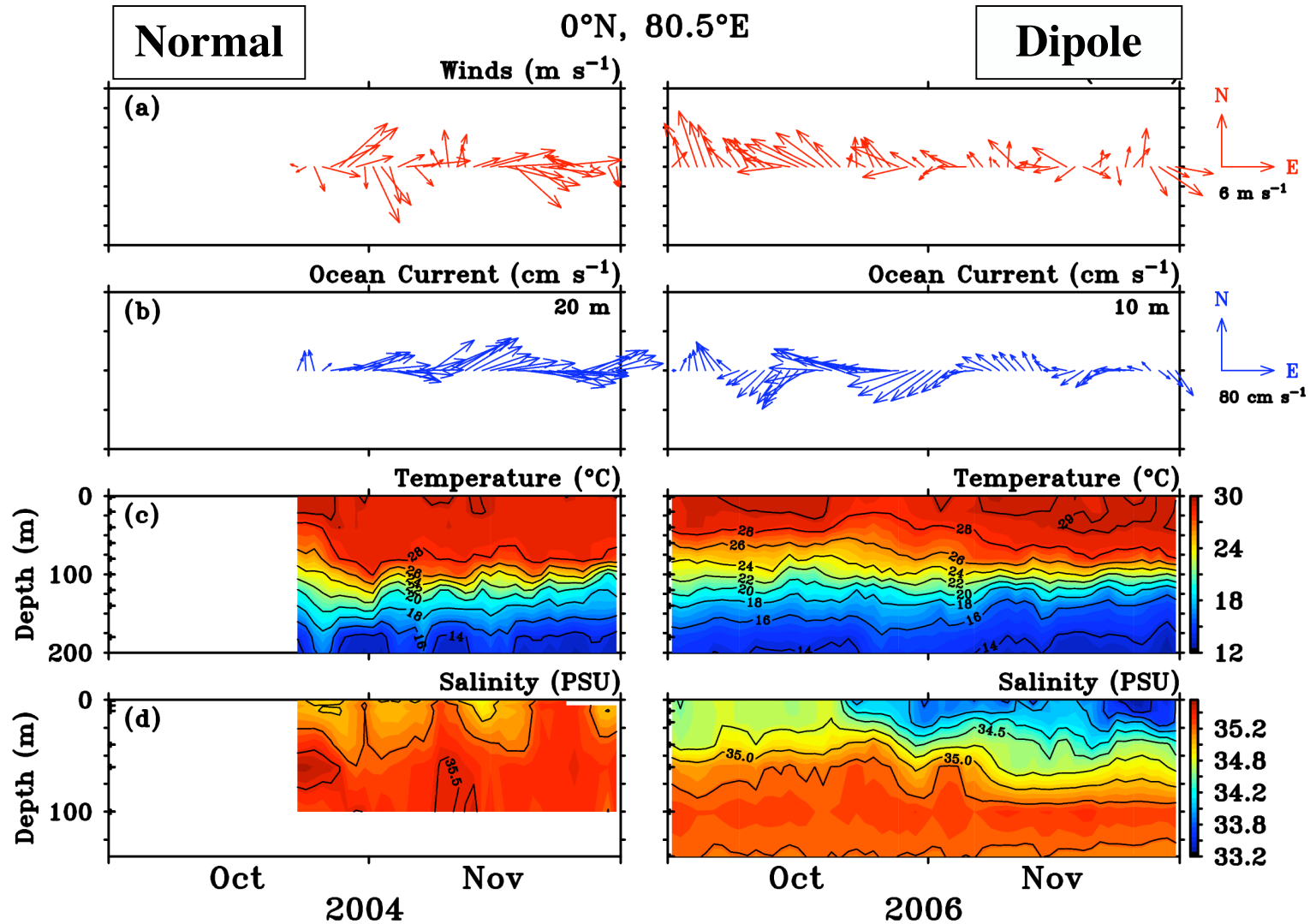
47% of sites occupied by end of 2008 (22 of 46; 15 involve PMEL)

2006 Indian Ocean Dipole

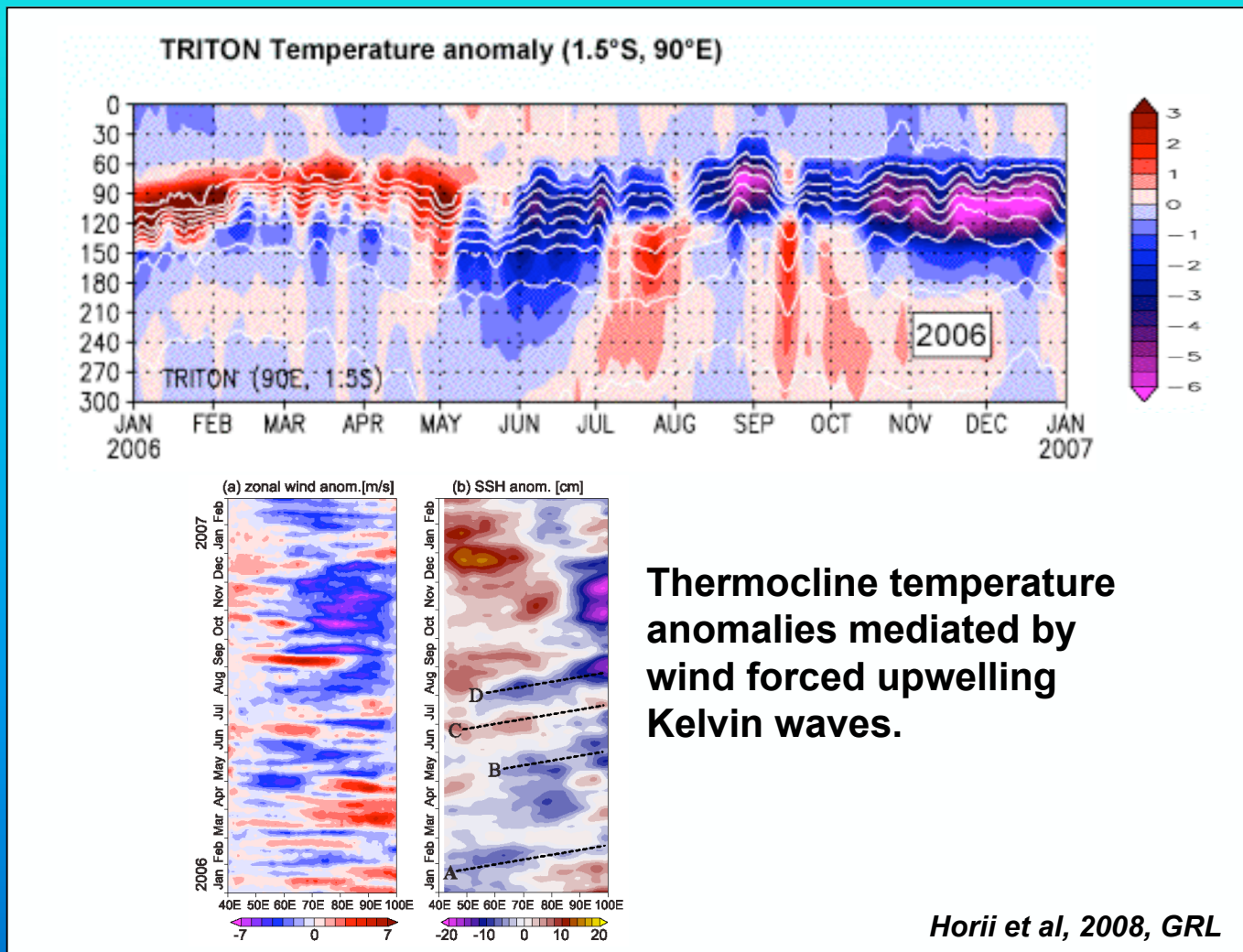
November 2006 Anomalies



Comparison of Oct-Nov 2004 (Normal) & Oct-Nov 2006 (Dipole)

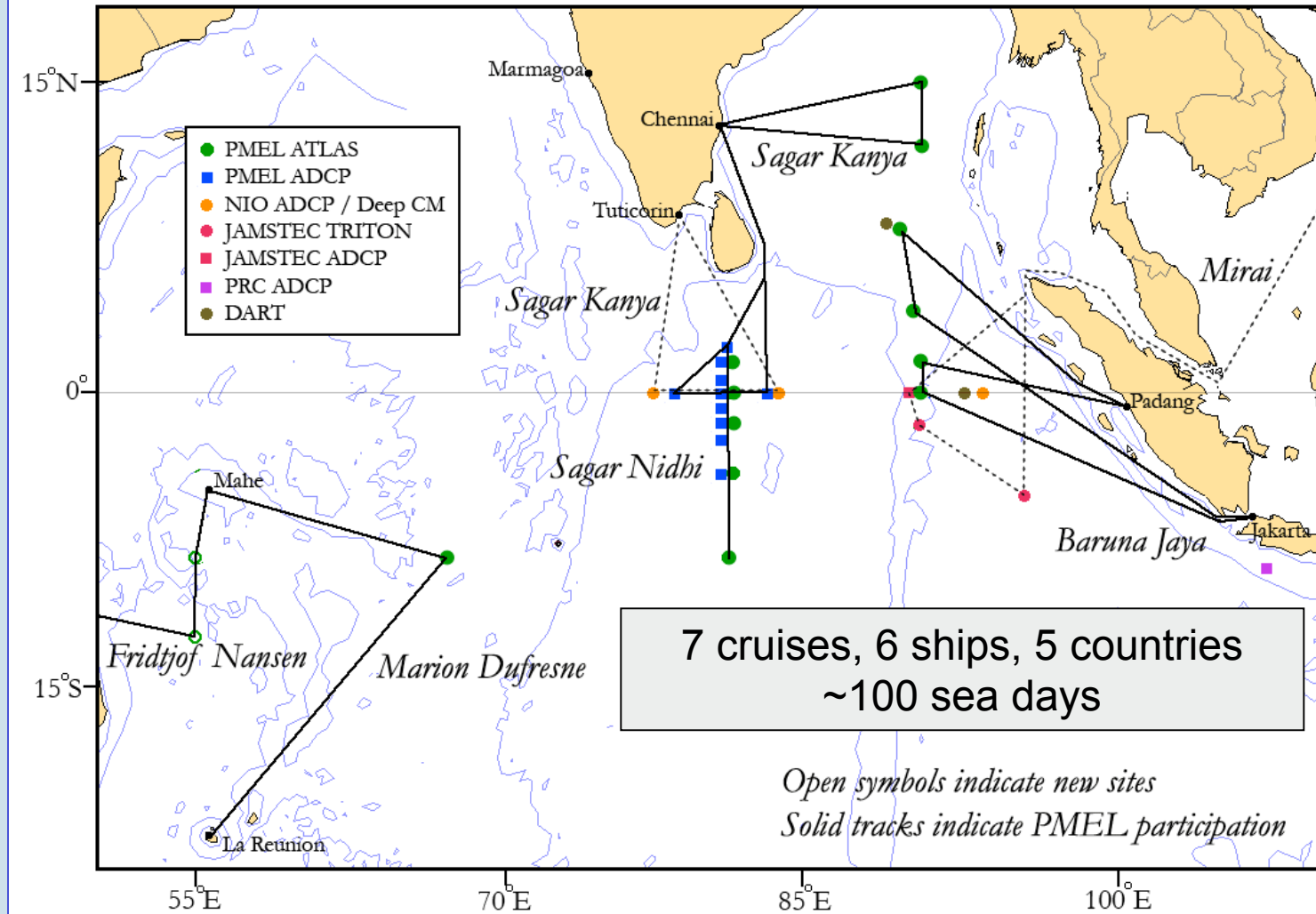


Subsurface Temperature leads SST: A Source of Indian Ocean Dipole Predictability?

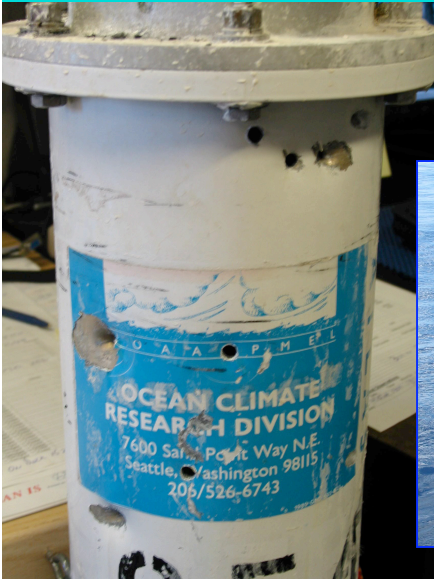


RAMA Plans 2008

RAMA Cruises in 2008



Three Challenges



Funding



Vandalism by Fishermen



Ship time (~200 days per year to maintain full array)

Dealing with Vandalism

- **Outreach and Enforcement**

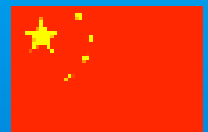
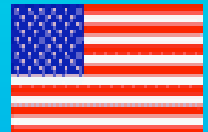
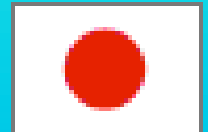
- 1) Outreach to fishermen and national fisheries agencies
- 2) NOAA Enforcement (P. Ortiz)

- **Engineering**

- 1) ATLAS-Make sensors and equipment more difficult to remove by using specialized hardware
- 2) “Conehead” buoys
 - Remove vulnerable sensors
 - Make buoys harder to board
 - Remove buoy attachment points



International Cooperation and Capacity Building for RAMA



- USA (NOAA) and Indonesia (DKP and BPPT) sign MOU in 2007
- USA (NOAA) and Japan (JAMSTEC) sign MOU in 2008
- USA (NOAA) and India (MoES) sign MOU in 2008
- China (SOA) and Indonesia (DKP) sign MOU in 2007
- U. Paris and U. Capetown are committing ship time to expand RAMA into SW Indian Ocean

TAO Project Web Pages

Pacific Marine Environmental Laboratory



Tropical Atmosphere Ocean project

Michael J. McPhaden, Director

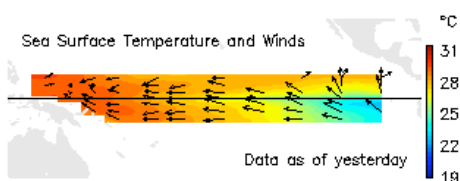
Home | Project overview | Data display | Data delivery | El Niño & La Niña | Site map

Find

Tuesday August 5, 2008 (PDT)



Real-time data from moored ocean buoys for improved detection, understanding and prediction of El Niño and La Niña.



[The TAO Story](#)

NEW! [The Global Tropical Moored Buoy Array](#)

Try our combined [Display and Delivery Page](#) which includes more comprehensive data and features, like the ability to download what you view

Learn about [Warm Water Volume and ENSO](#)



U.S. Department of Commerce Gold Medal in 1997 "For...bringing on line an unparalleled oceanographic and atmospheric observing system of global importance"

Home | [Project overview](#) | [Data display](#) | [Data delivery](#) | [El Niño & La Niña](#) | [Site map](#)

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Tropical Atmosphere Ocean project

Home | Project overview | Data display and delivery | El Niño & La Niña | Site map

TAO Data display and delivery

Find

To select mooring sites, click orange boxes to select lines of sites, click and hold on your mouse to draw a box around sites, or click single sites. Red indicates which sites are selected. Solid squares show where all selected variables are available. Half filled squares show where some are available. Empty squares show where none are available. This page may take a few moments to load on slower networks and computers.

Time Series | Time Section | Lat Lon Map | Depth Section

One Variab One Site Separate Plot Overlay
 SW Rad LW Rad Rain Wspd Uwnd Vwnd Wdir Wnd Ve RH
 Air T SLP SST T(z) SSS S(z) SSD D(z) Heat
 Dyn Ht 20C Ucur Vcur Cur Vec Uadcp Vadcp Long Lat

TAO/TRITON (Pacific) | Monthly

1979 | January | 20 | 2008 | August | 14

files by site | ascii | None

Definitions | Availability | Clear | Deliver | Display

Non-JAVA Version Old Data Display Old Data Delivery Trouble-shooting Comments or Suggestions?
 Mac OS X Users: Safari and Firefox are the recommended browsers.
 Acknowledgment for use of TAO, PIRATA, and RAMA data

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PIRATA (Atlantic) | Monthly

1997 | September | 11 | 2008 | August | 6

files by site | ascii | None

Definitions | Availability | Clear | Deliver | Display

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Time Series | Time Section | Lat Lon Map | Depth Section

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 Air T SLP SST T(z) SSS S(z) SSD D(z) Heat
 Dyn Ht 20C Ucur Vcur Cur Vec Uadcp Vadcp Long Lat

RAMA (Indian) | Monthly

2008 | August | 6

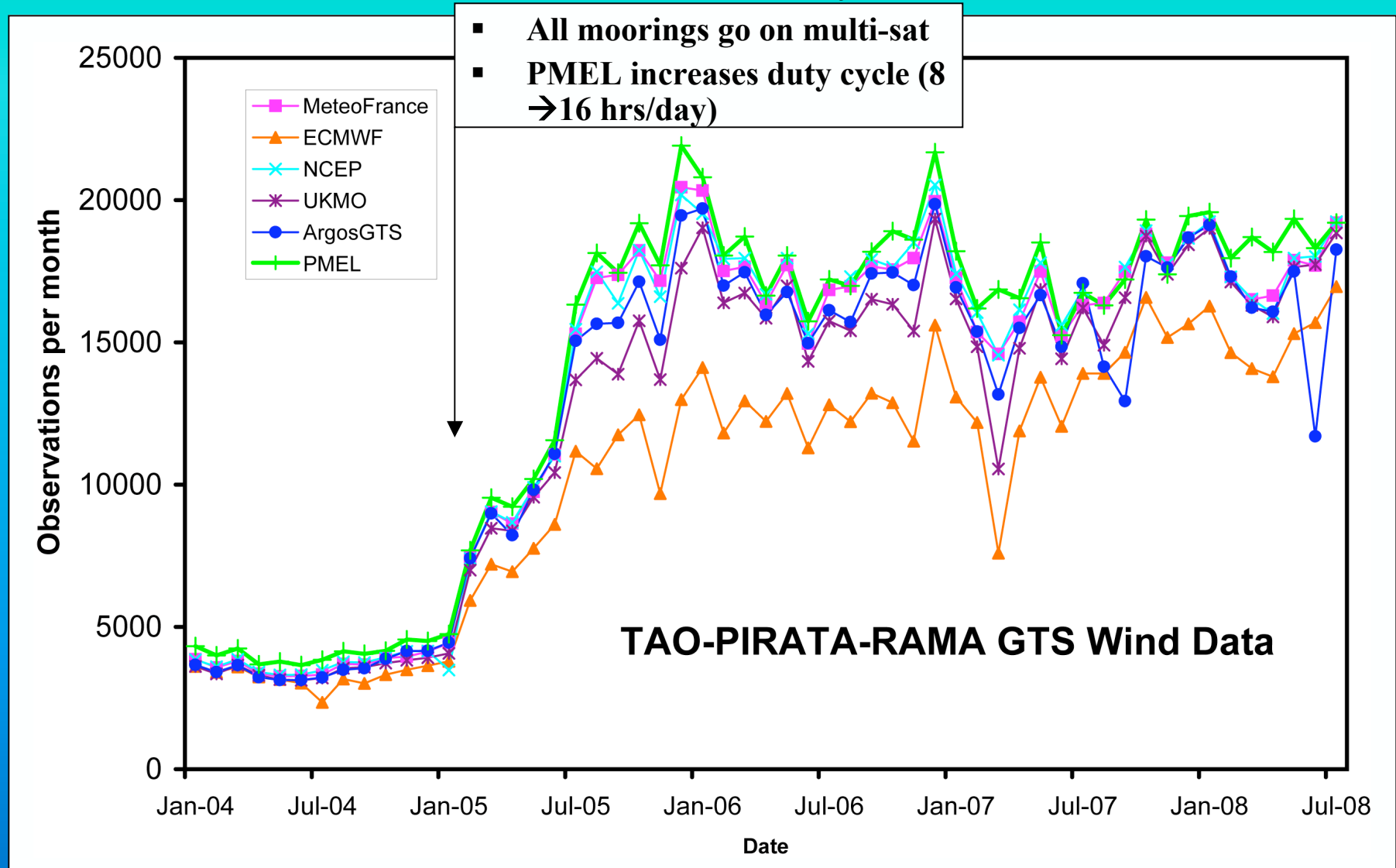
files by site | ascii | None

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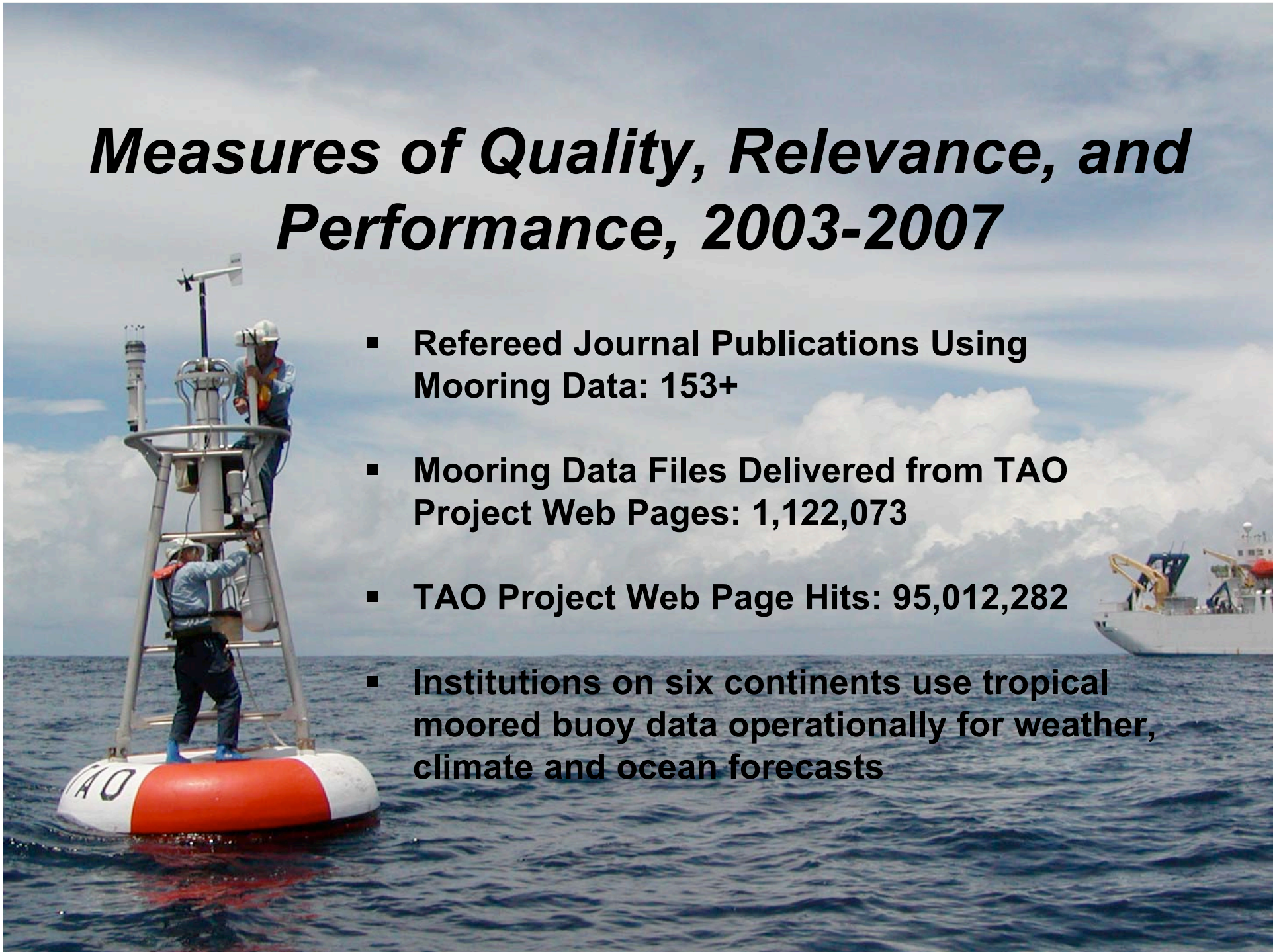
<http://www.pmel.noaa.gov/tao/>

Tropical Moored Array Data on the Global Telecommunications System (GTS)



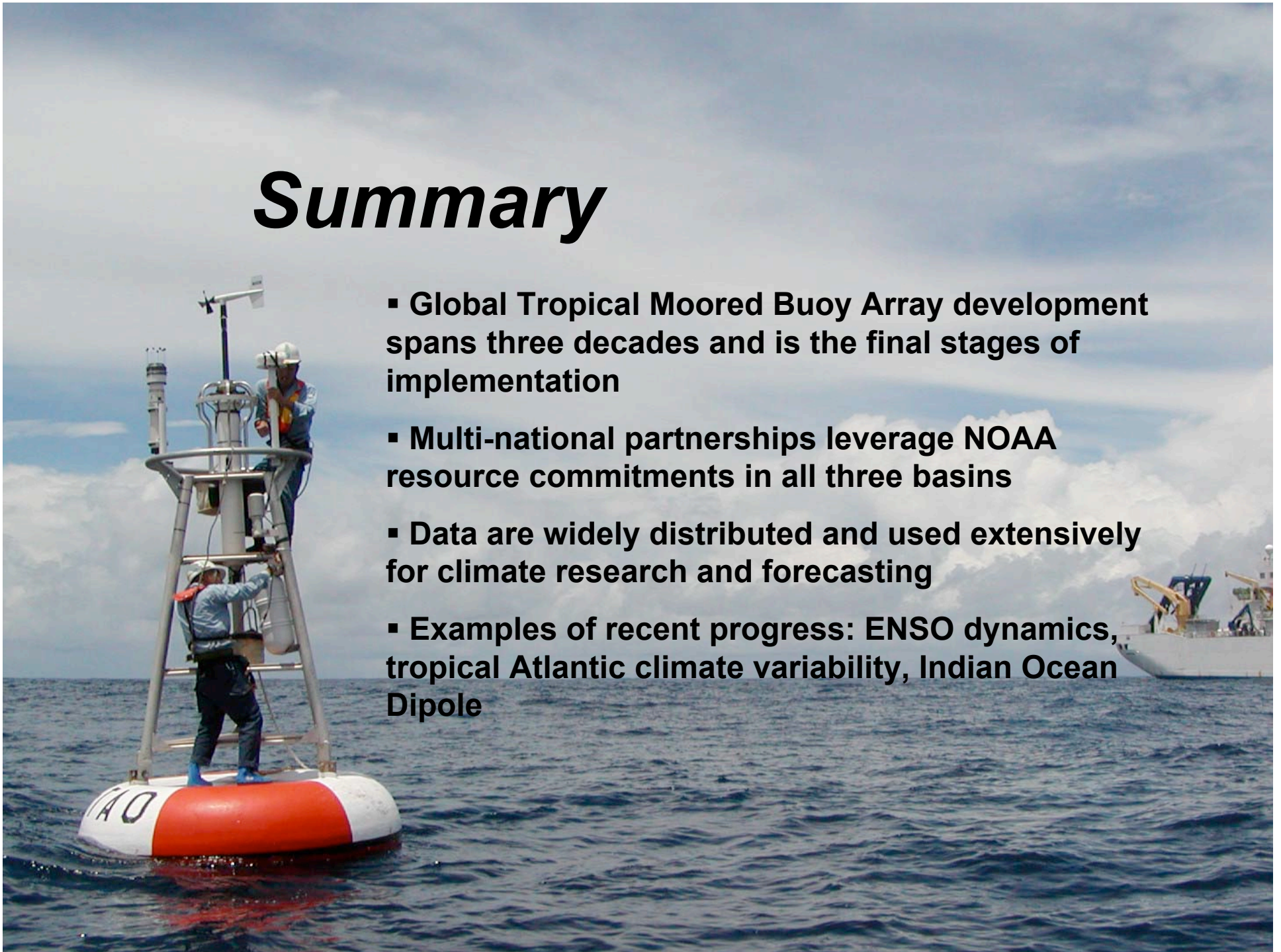
Measures of Quality, Relevance, and Performance, 2003-2007

- **Refereed Journal Publications Using Mooring Data: 153+**
- **Mooring Data Files Delivered from TAO Project Web Pages: 1,122,073**
- **TAO Project Web Page Hits: 95,012,282**
- **Institutions on six continents use tropical moored buoy data operationally for weather, climate and ocean forecasts**



Summary

- Global Tropical Moored Buoy Array development spans three decades and is the final stages of implementation
- Multi-national partnerships leverage NOAA resource commitments in all three basins
- Data are widely distributed and used extensively for climate research and forecasting
- Examples of recent progress: ENSO dynamics, tropical Atlantic climate variability, Indian Ocean Dipole



The Future

- Complete TAO Transition (2005-2013?)
- Demonstrate scientific value of recent PIRATA extensions (~2012)
- Implement RAMA to complete the global tropical moored buoy array (~2013)
- Introduce new technologies to improve efficiency & effectiveness
- Promote use of the data for research & forecasting



Acknowledgments

- NOAA Office for Climate Observation & Climate Program Office for funding
- NOAA partners: Atlantic Oceanographic and Meteorological Laboratory, National Data Buoy Center, Office of Marine and Aviation Operations, Climate Prediction Center
- Joint Institute for the Study of the Atmosphere & Ocean (JISAO) at the University of Washington
- Our many international partners

