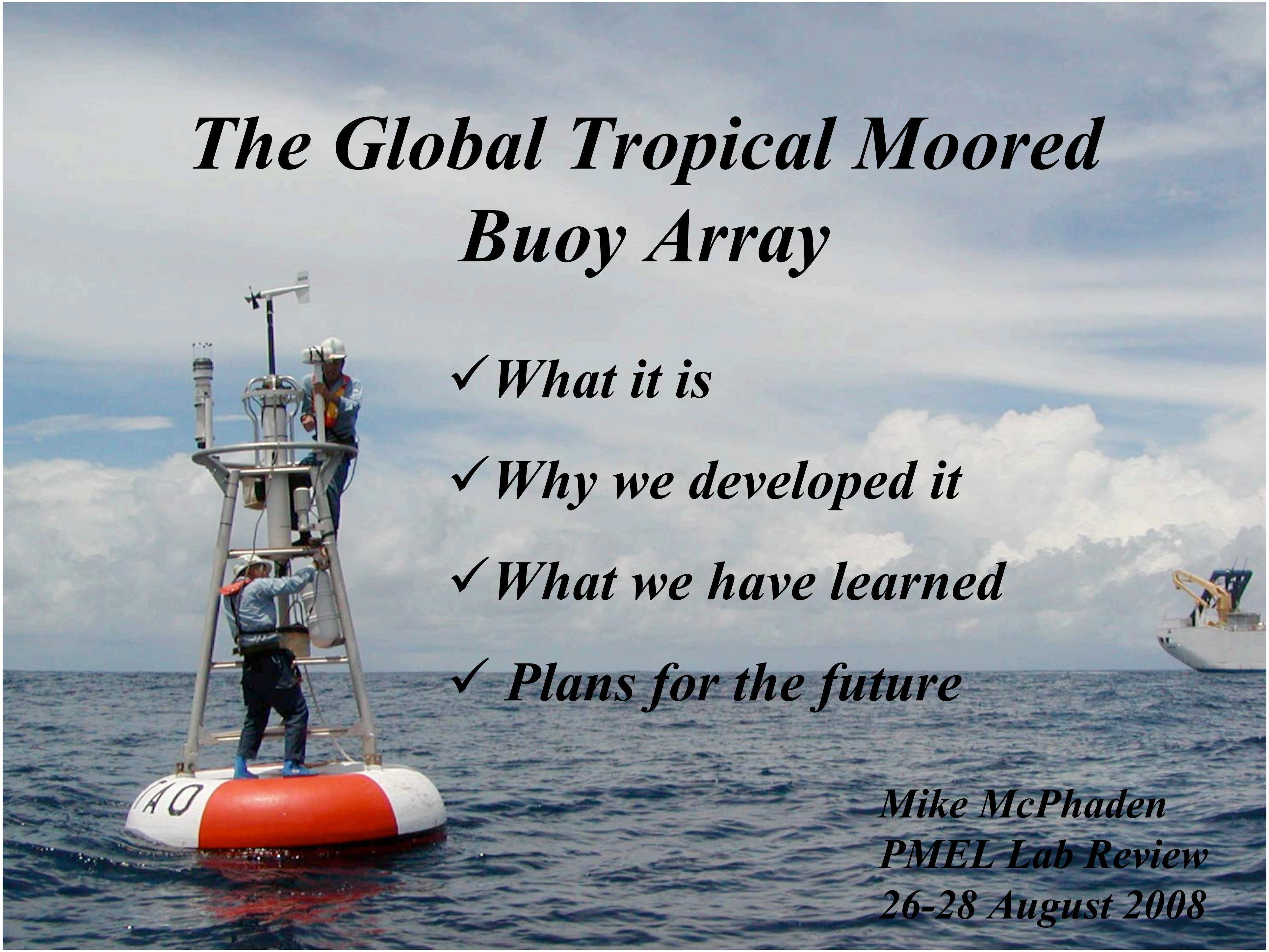
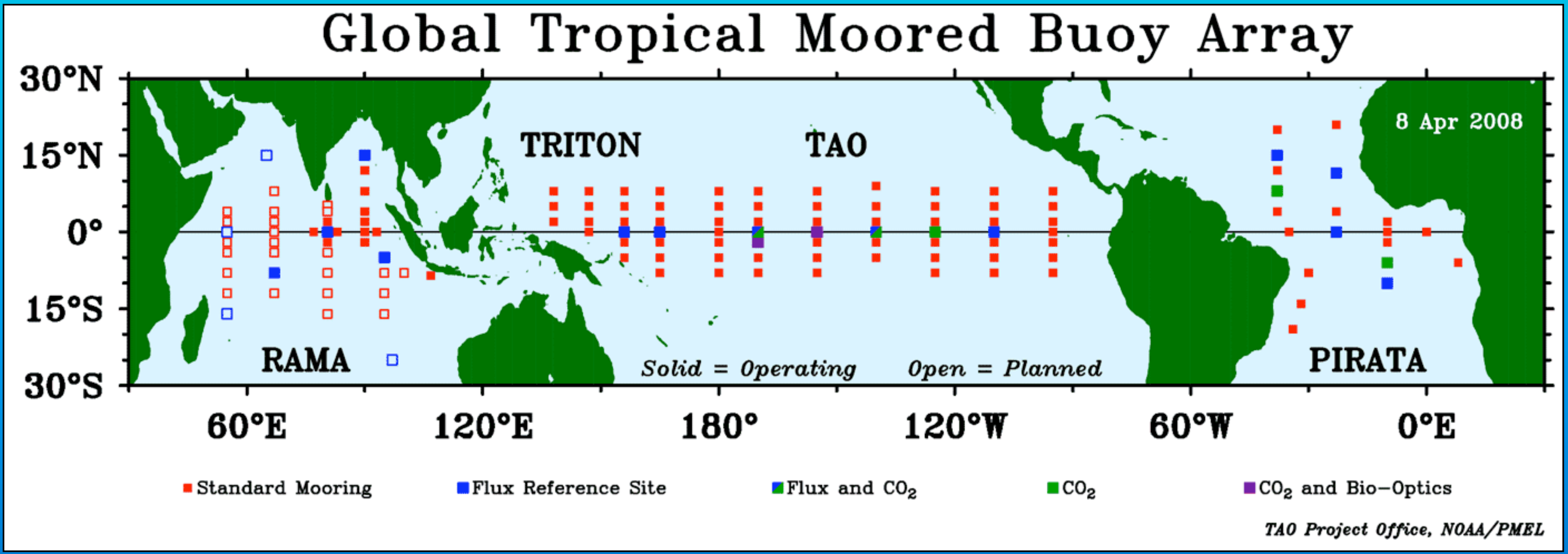

The Global Tropical Moored Buoy Array
✓What it is
✓Why we developed it
✓What we have learned
✓ Plans for the future
Mike McPhaden
PMEL Lab Review
26-28 August 2008
TAO

Why the Tropics?

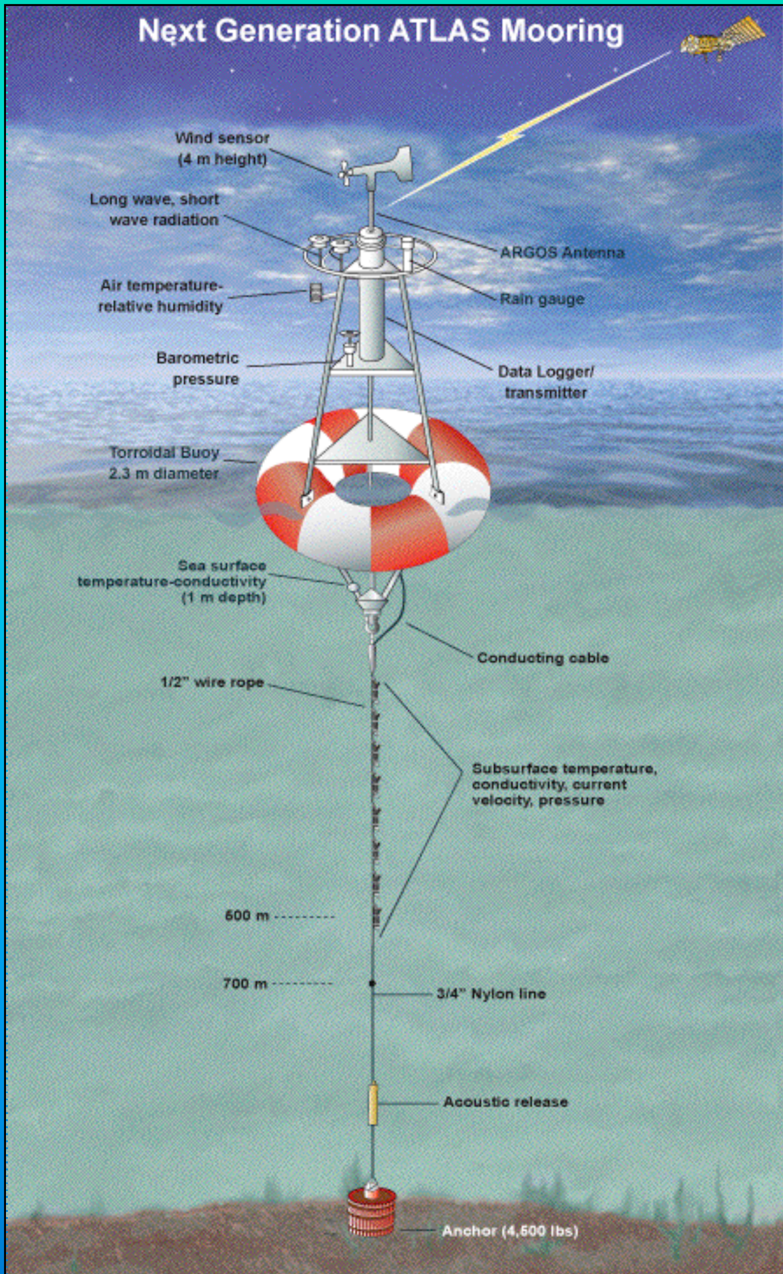
- A major source of regional and global climate variability (ocean-atmosphere interactions sensitive to SST variations)
- Some modes of climate variability originating in the tropics are predictable
- Spawning ground for severe tropical storms
- Many underdeveloped and climatically vulnerable nations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



A contribution to GOOS, GCOS, and GEOSS



Surface Moorings

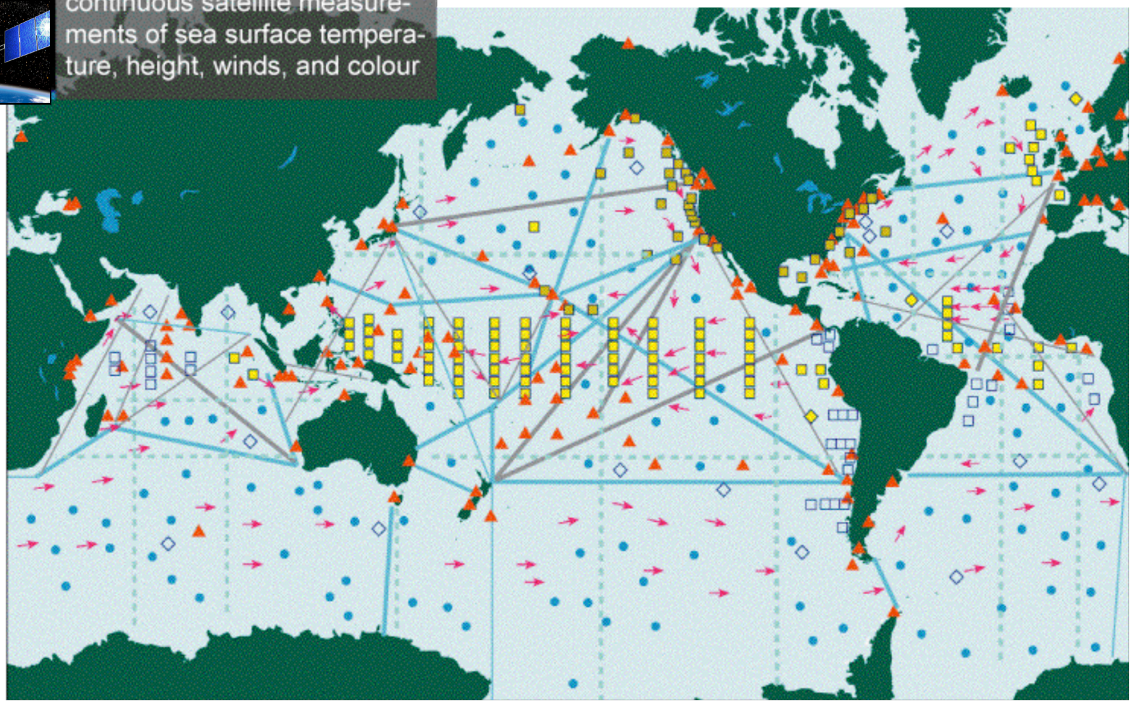
- **Advantages**
  - ✓**Rapid sampling in time so as to resolve rather than alias high frequencies**
  - ✓**Fixed grid array so time and space are not mixed**
  - ✓**Multi-variate (ocean, atmosphere, biogeochemical)**
  - ✓**Real-time data transmission (Service Argos & GTS)**
- **Disadvantages**
  -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

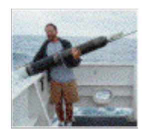
5° resolution array: 1250 floats

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

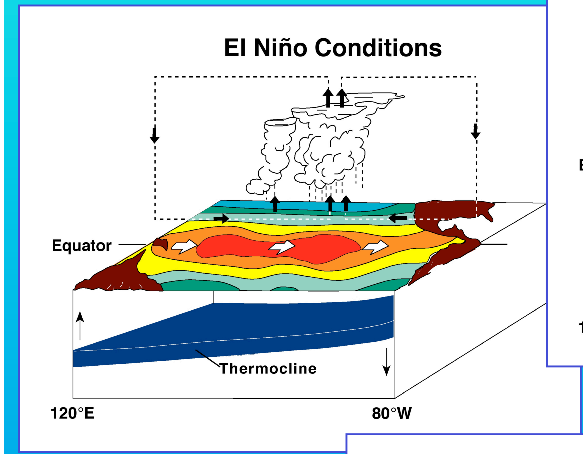
79% Global tropical **moored buoy** network

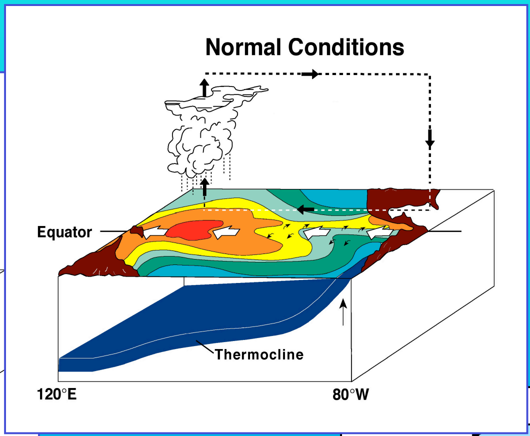
119 moorings planned

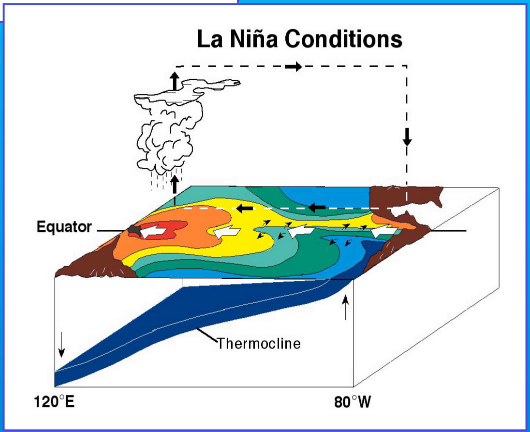
GCOS GOOS jcomm


Pacific Ocean
TAO/TRITON
TAO

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

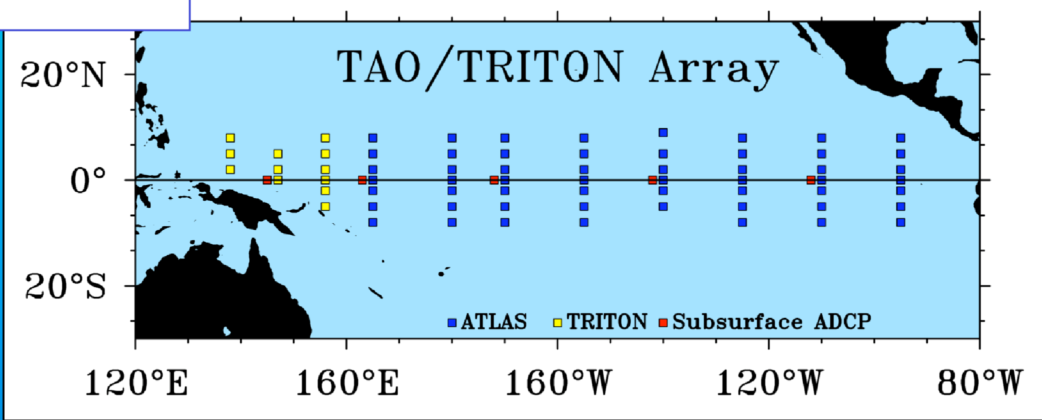






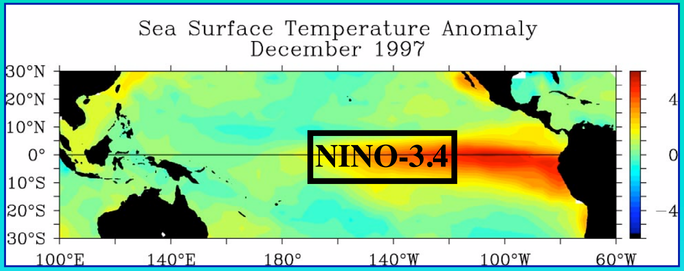
"...the crowning achievement of TOGA was the development of the Tropical Atmosphere/Ocean (TAO) array..."

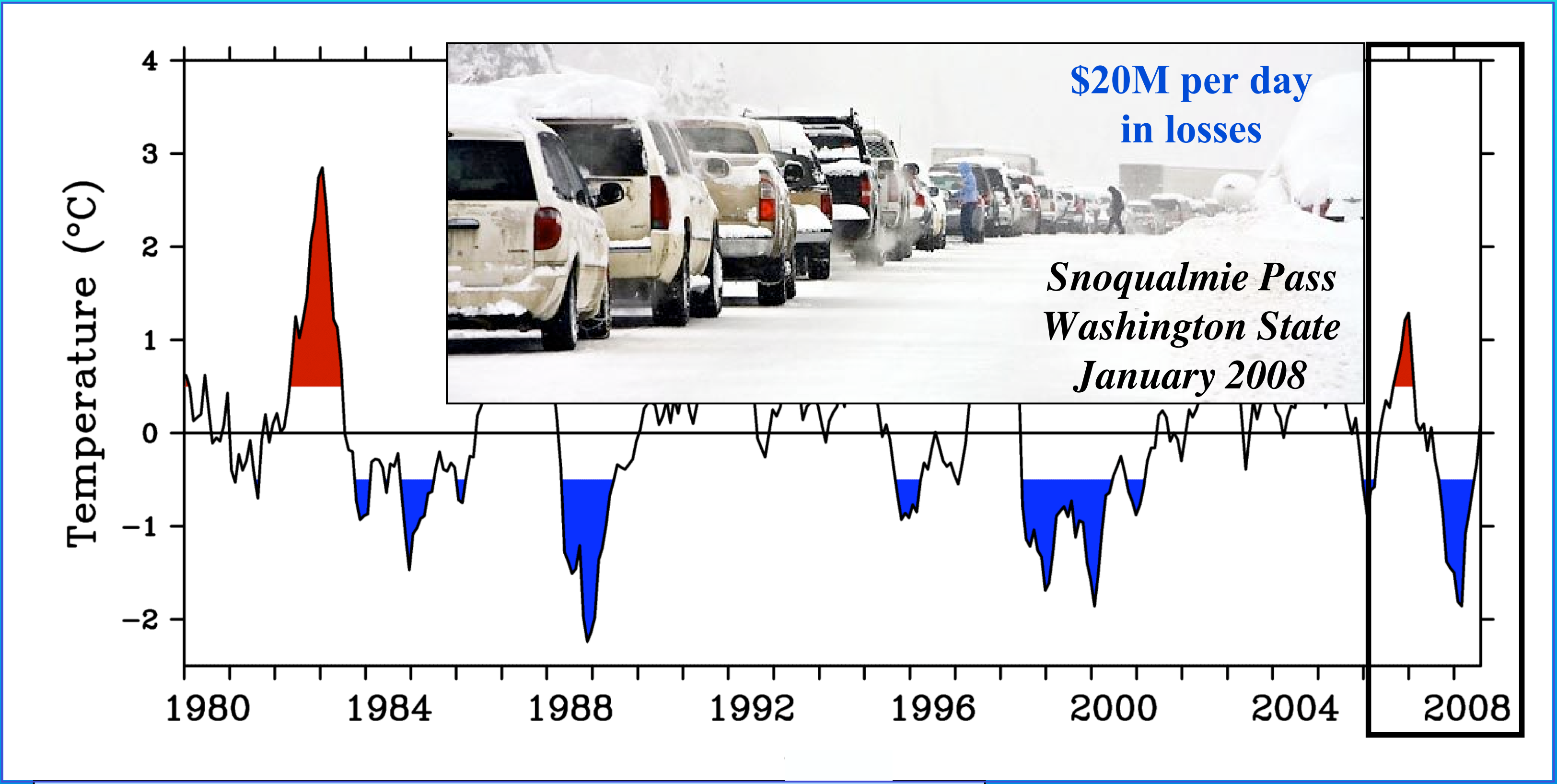
EOS, Transactions of the AGU
7 January 1997.



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

El Niño & La Niña Index

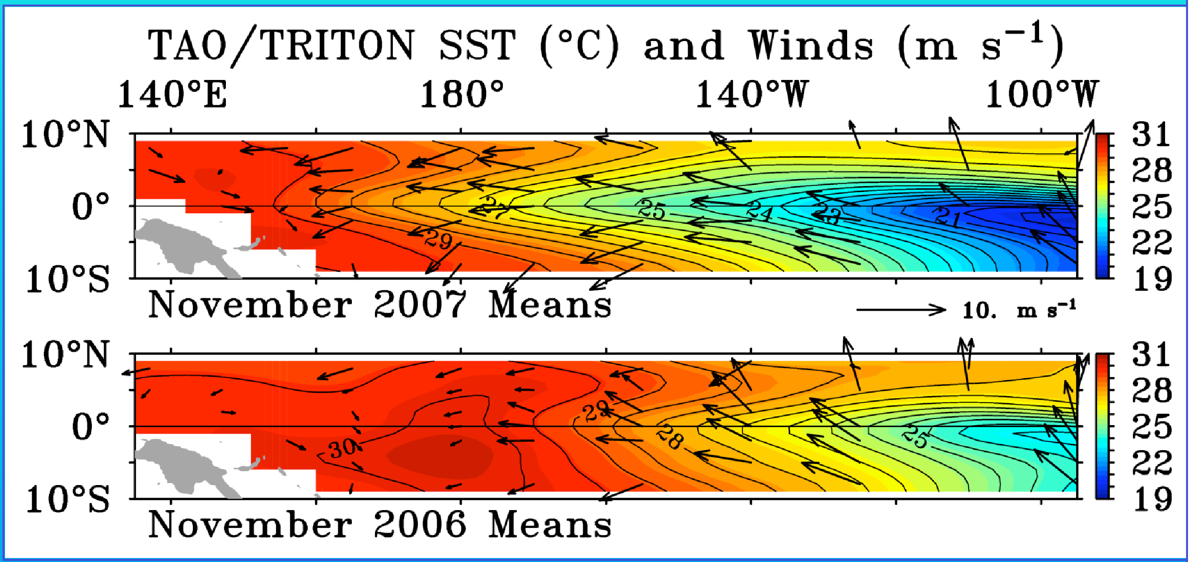


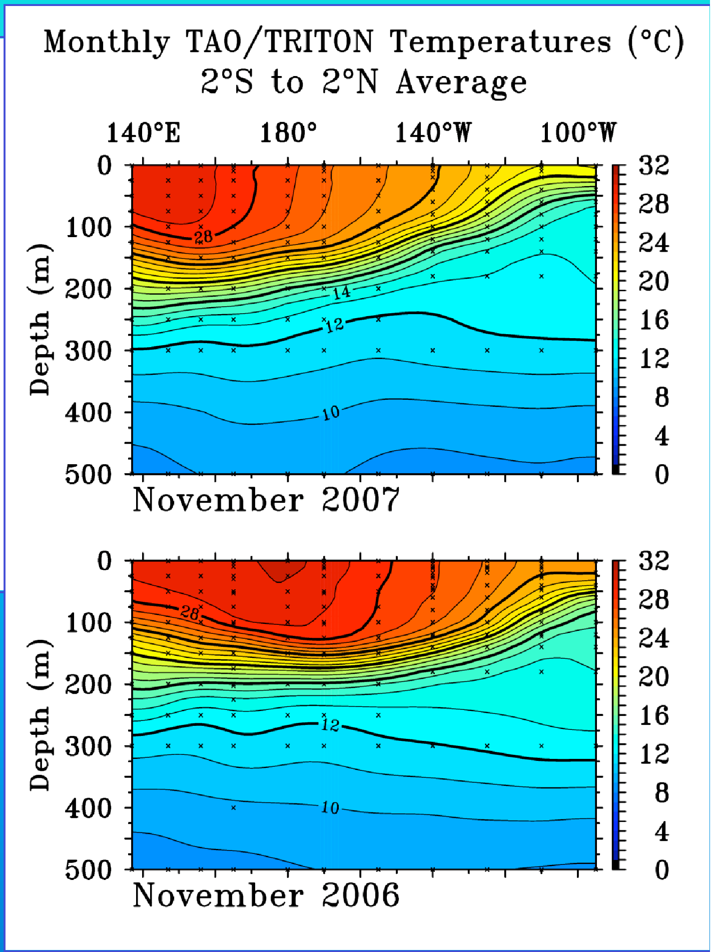


NINO3.4 ≥ 0.5°C for 5 months= El Niño

NINO3.4 ≤ -0.5°C for 5 months= La Niña

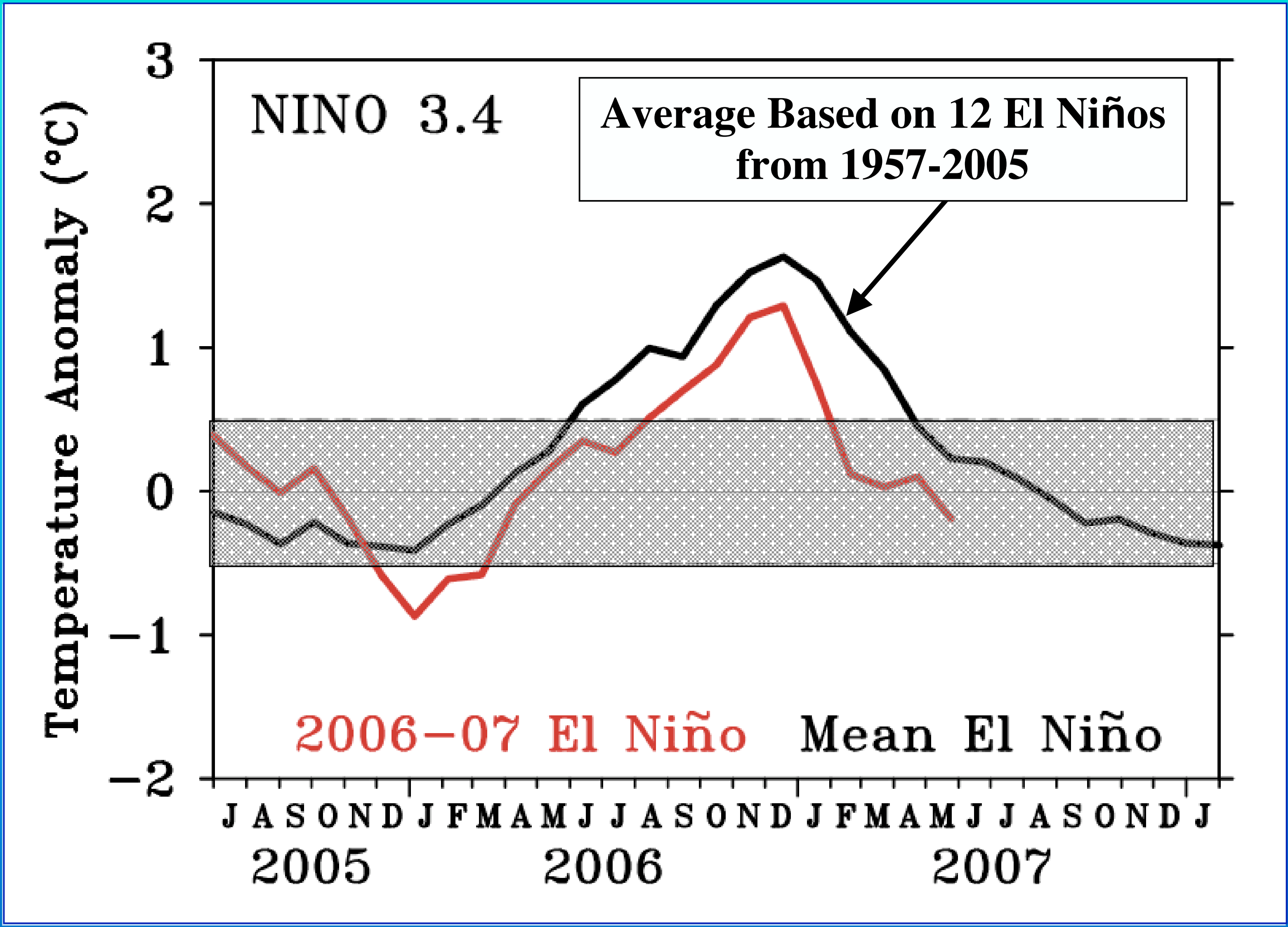
Contrasting 2006 El Niño and 2007 La Niña Conditions



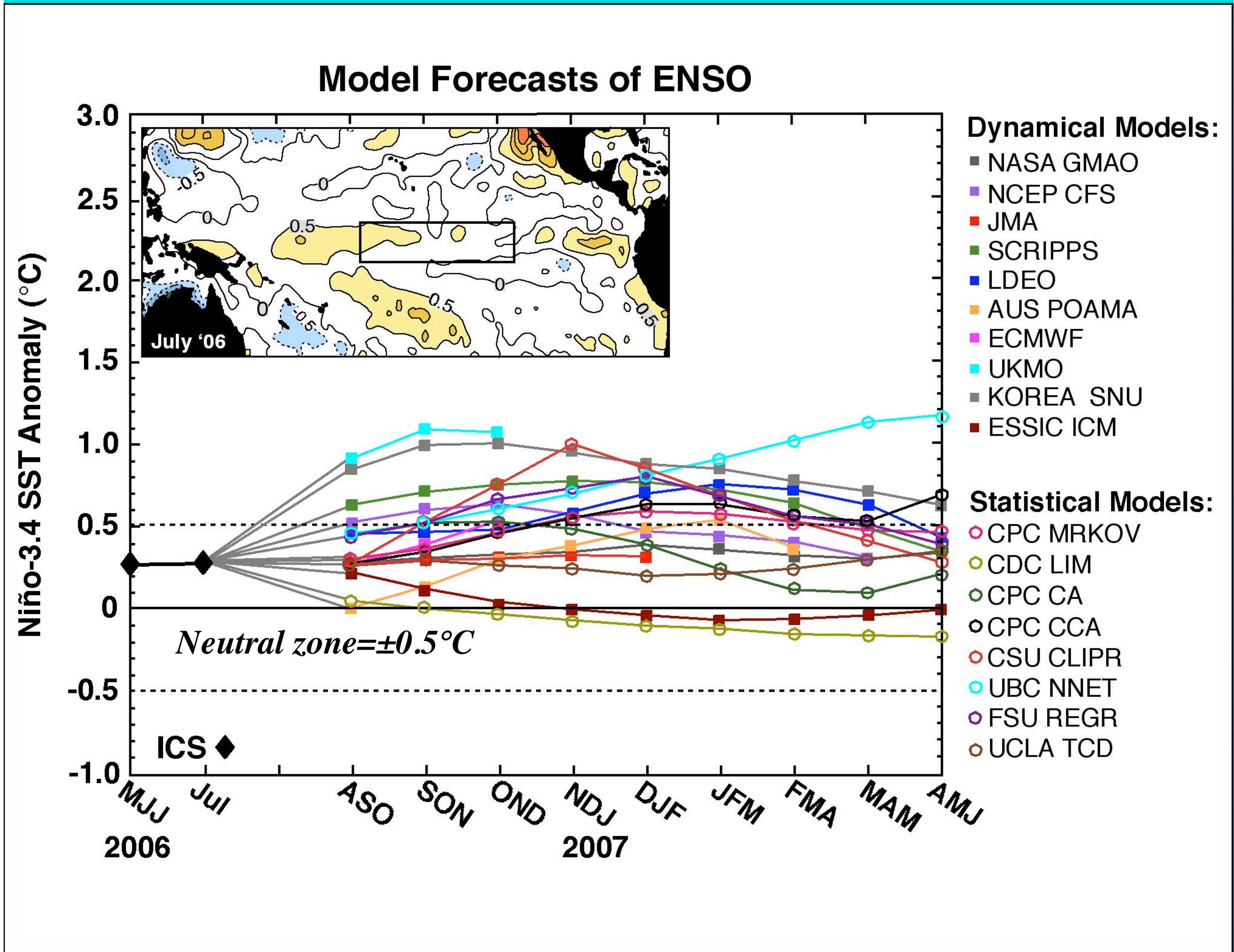


http://www.pmel.noaa.gov/tao/

Evolution of 2006-07 El Niño vs "Average" El Niño



Niño-3.4 Predictions from July 2006

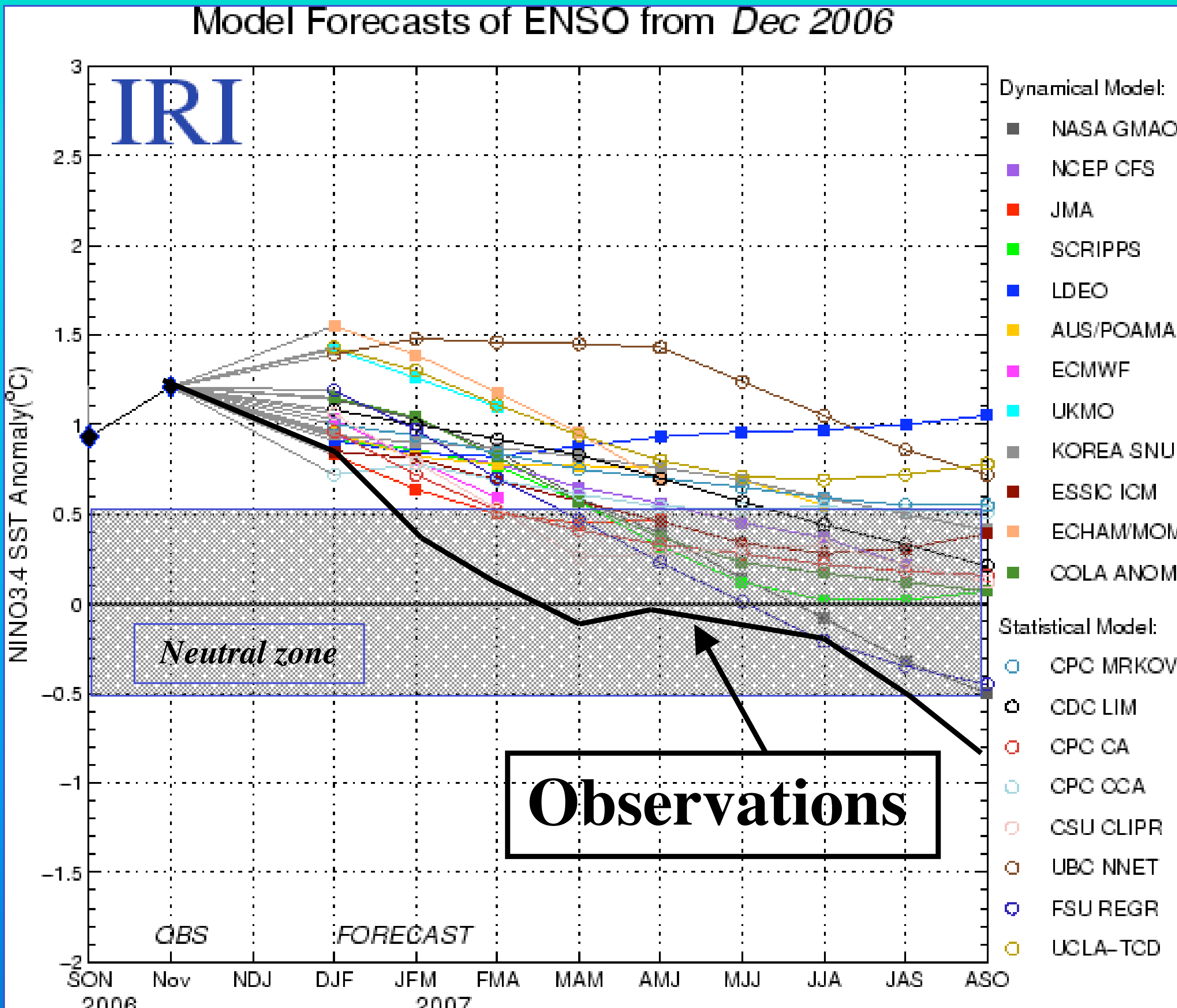


"ENSO-neutral conditions are expected to continue for the next one to three months, with a 50% chance that weak El Niño conditions will develop by the end of 2006."

NOAA, 10 Aug 2006

Compiled by the International Research Institute for Climate and Society (IRI)

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 El Niño maintaining El Niño conditions through the Dec-Feb 2006-07 season is ~95%."

IRI
20 Dec 2006

Compiled by the International Research Institute for Climate and Society (IRI)

Processes Governing ENSO Evolution

- **Large scale, low frequency deterministic physics (Ocean-atmosphere coupling, oceanic equatorial waves, etc.)**

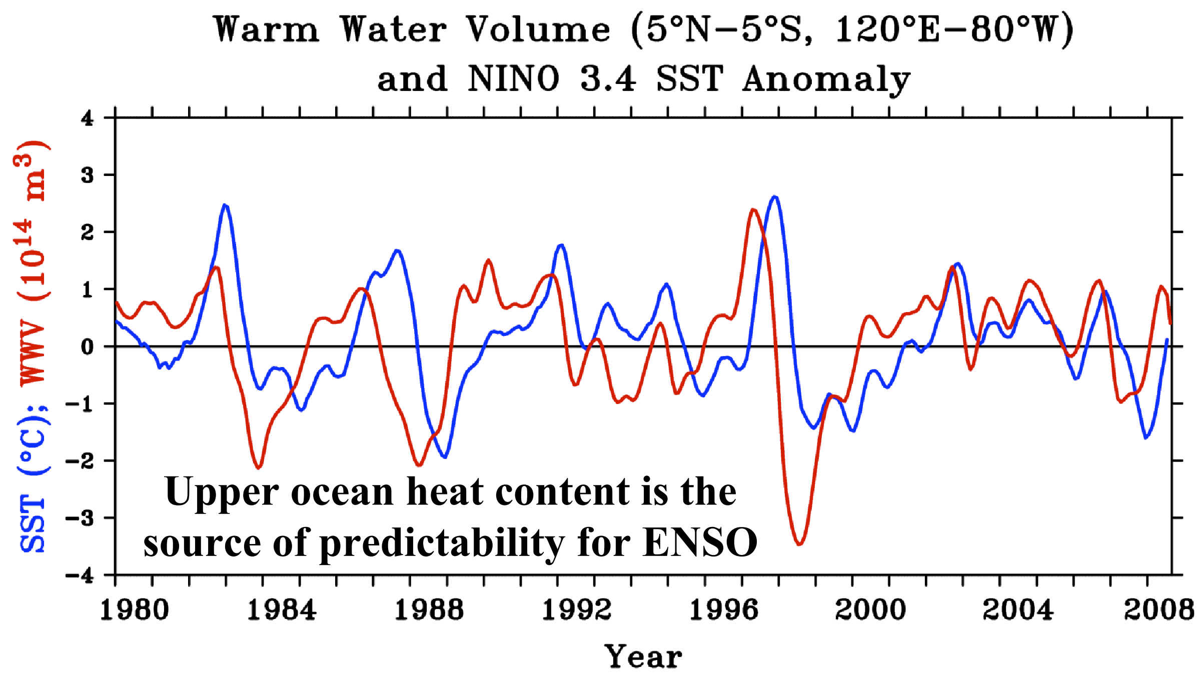
- **High frequency (days-to-weeks) "stochastic" forcing (wind bursts, Madden-Julian Oscillation, etc.)**

  - ✓ **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.

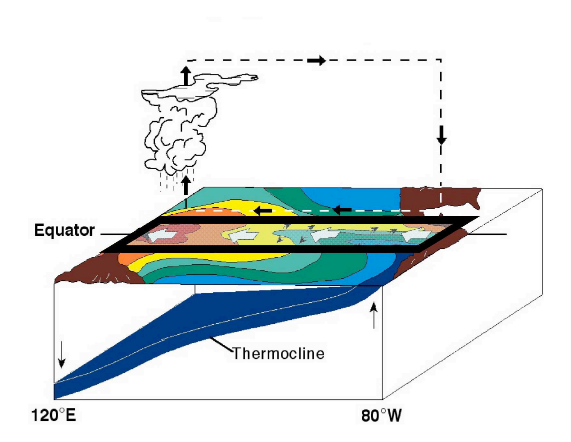
Upper Ocean Heat Content

(Based Recharge Oscillator Theory of Jin, 1997)



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

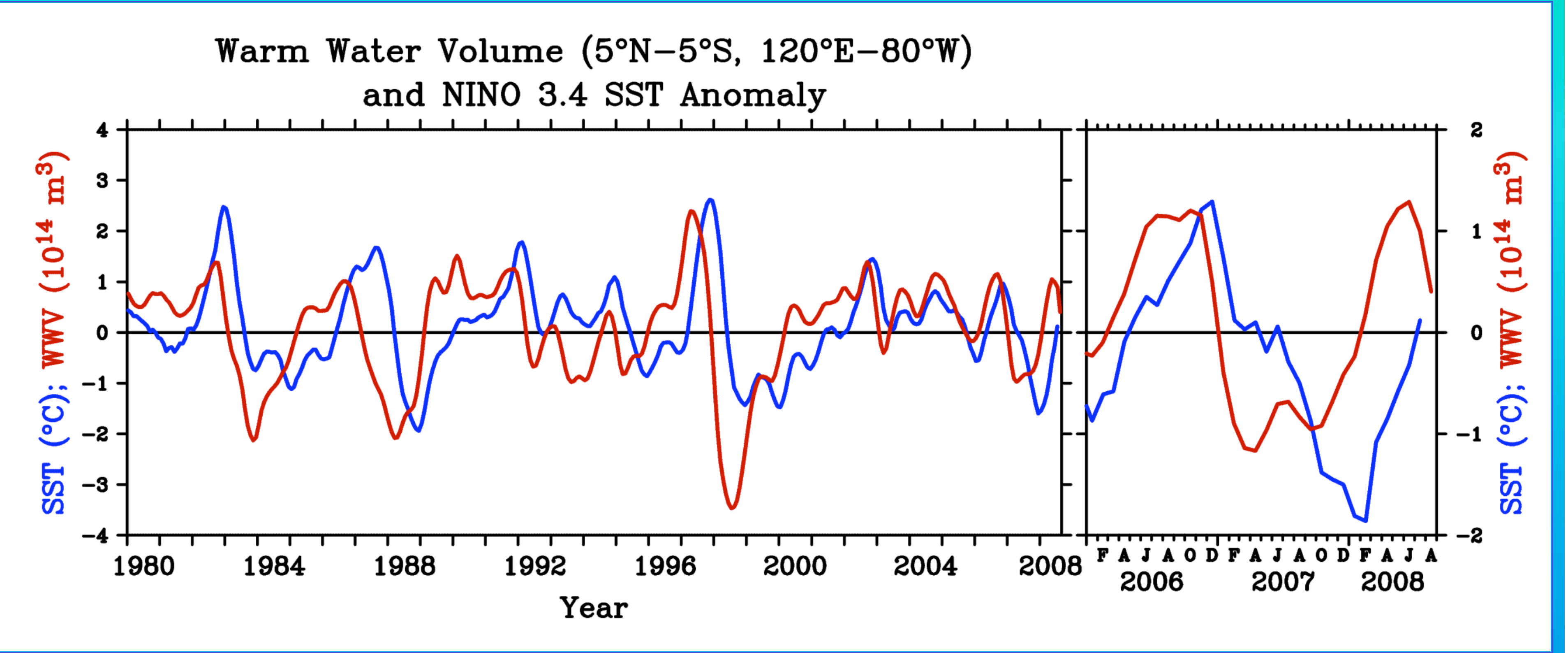
- **Build up of excess heat content along equator is a necessary precondition for El Niño to occur.**
- **El Niño purges excess heat to higher latitudes, which terminates the event.**
- **The time between El Niños is determined by the time to recharge.**



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

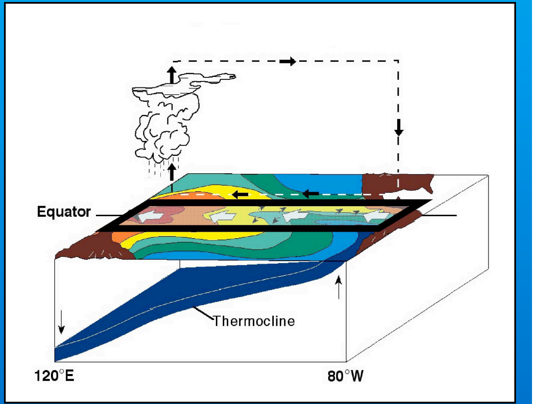
Meinen & McPhaden, 2000

Upper Ocean Heat Content and ENSO

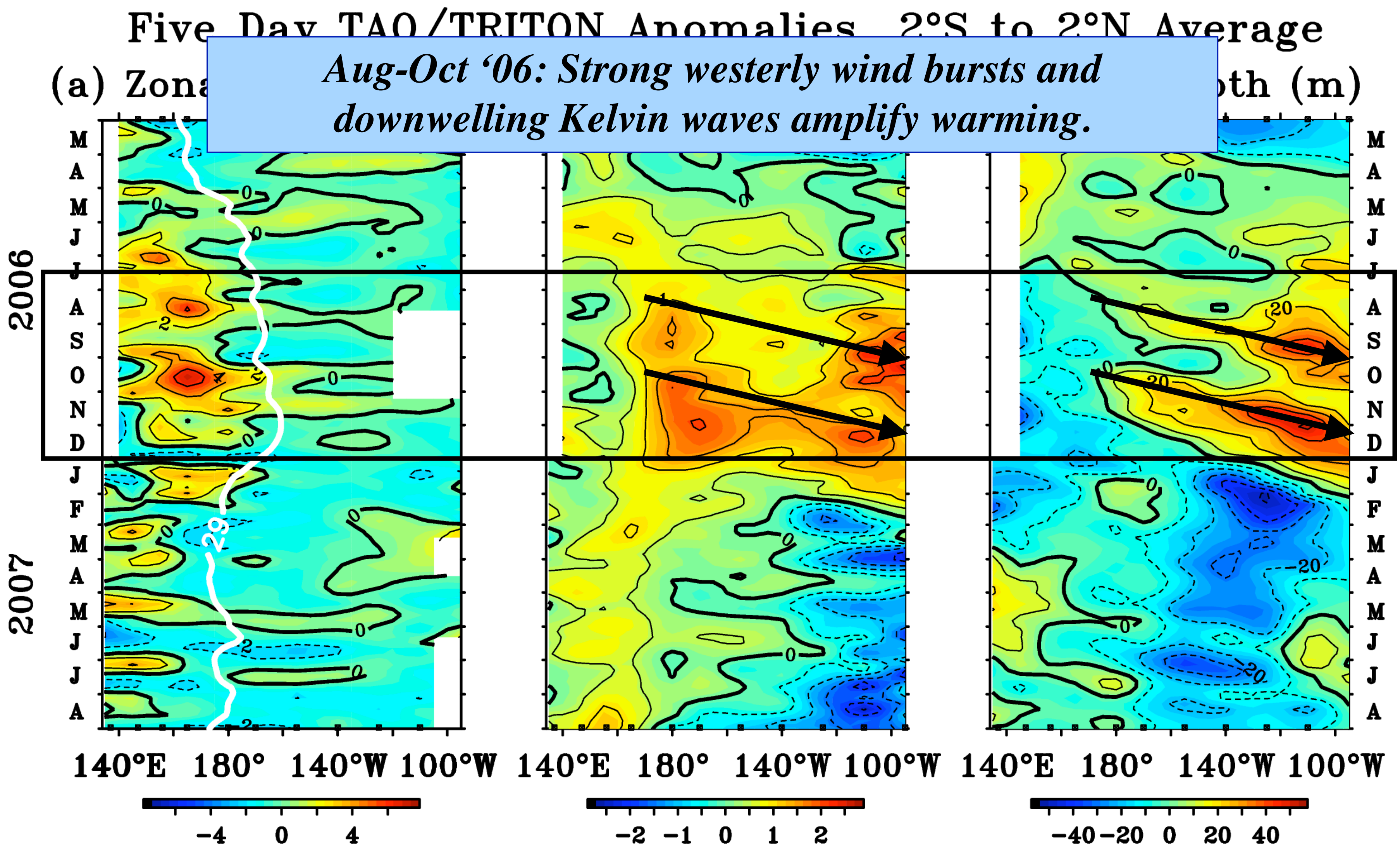


WWV index for heat content based analysis of TAO/TRITON, XBT and Argo data

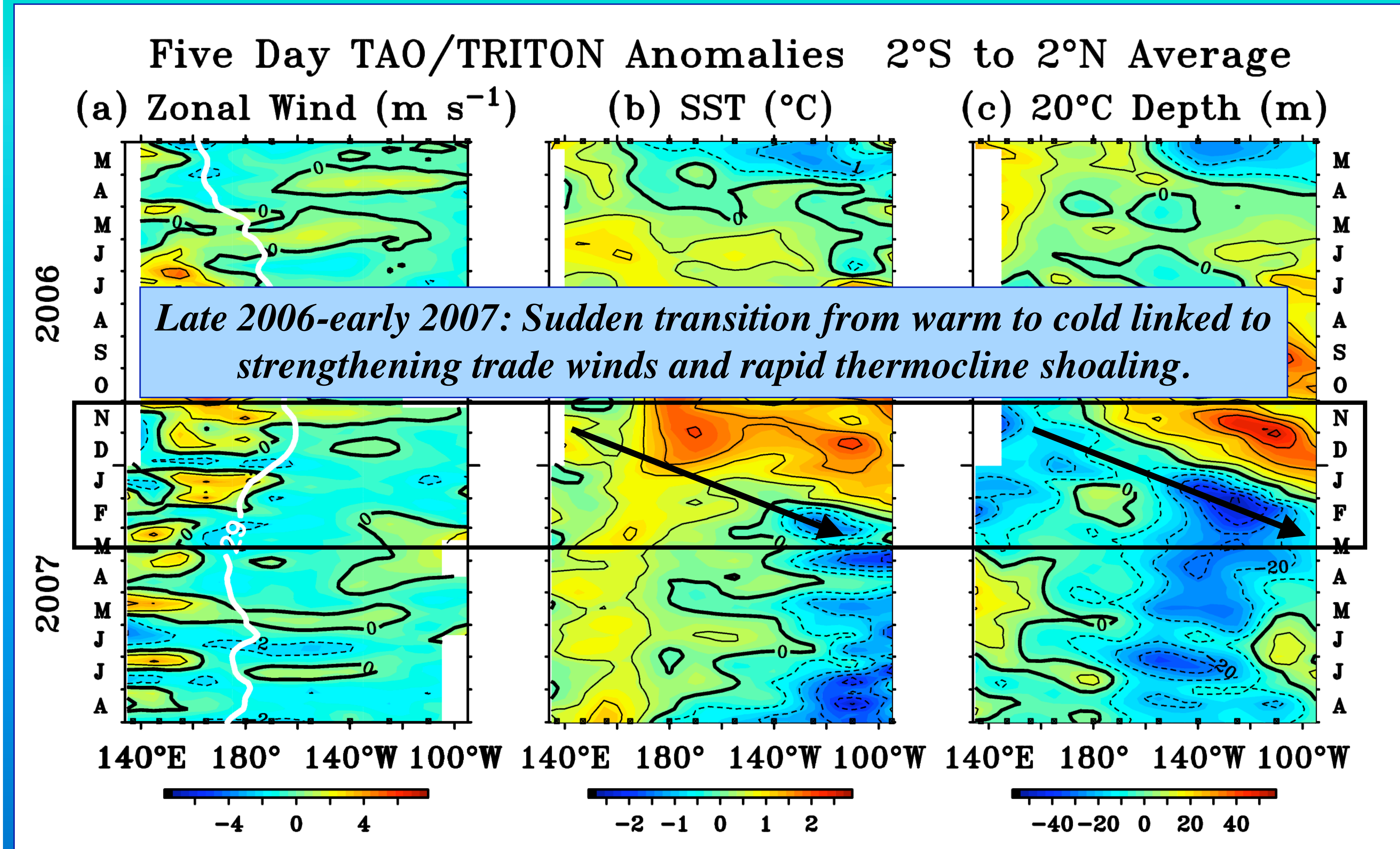
Upper ocean heat content provides a necessary (but not sufficient) precondition for ENSO cycle variations



March 2006-August 2007

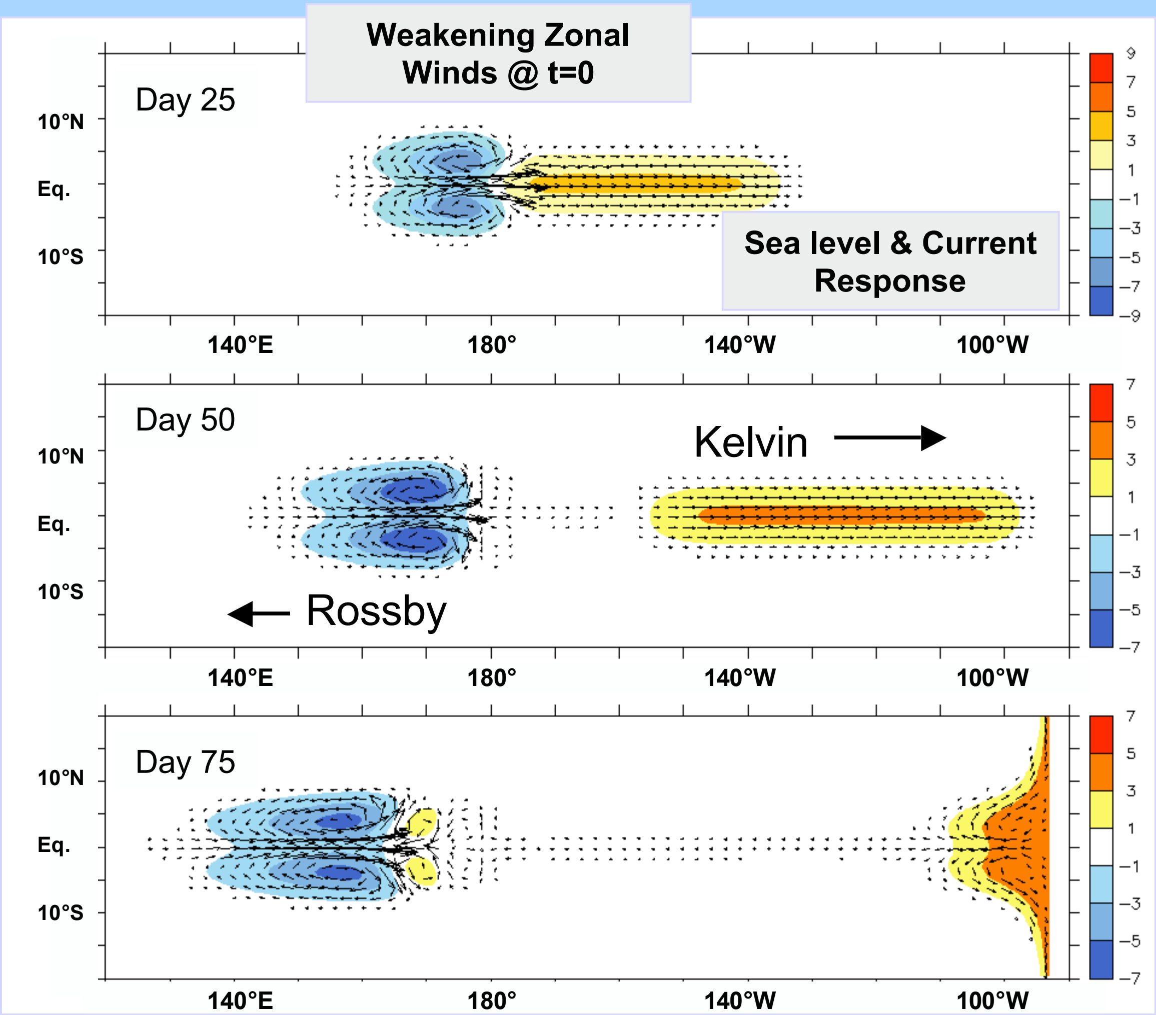


March 2006-August 2007



Kelvin & Rossby Waves

Key Concepts for Understanding the Ocean's Role in ENSO

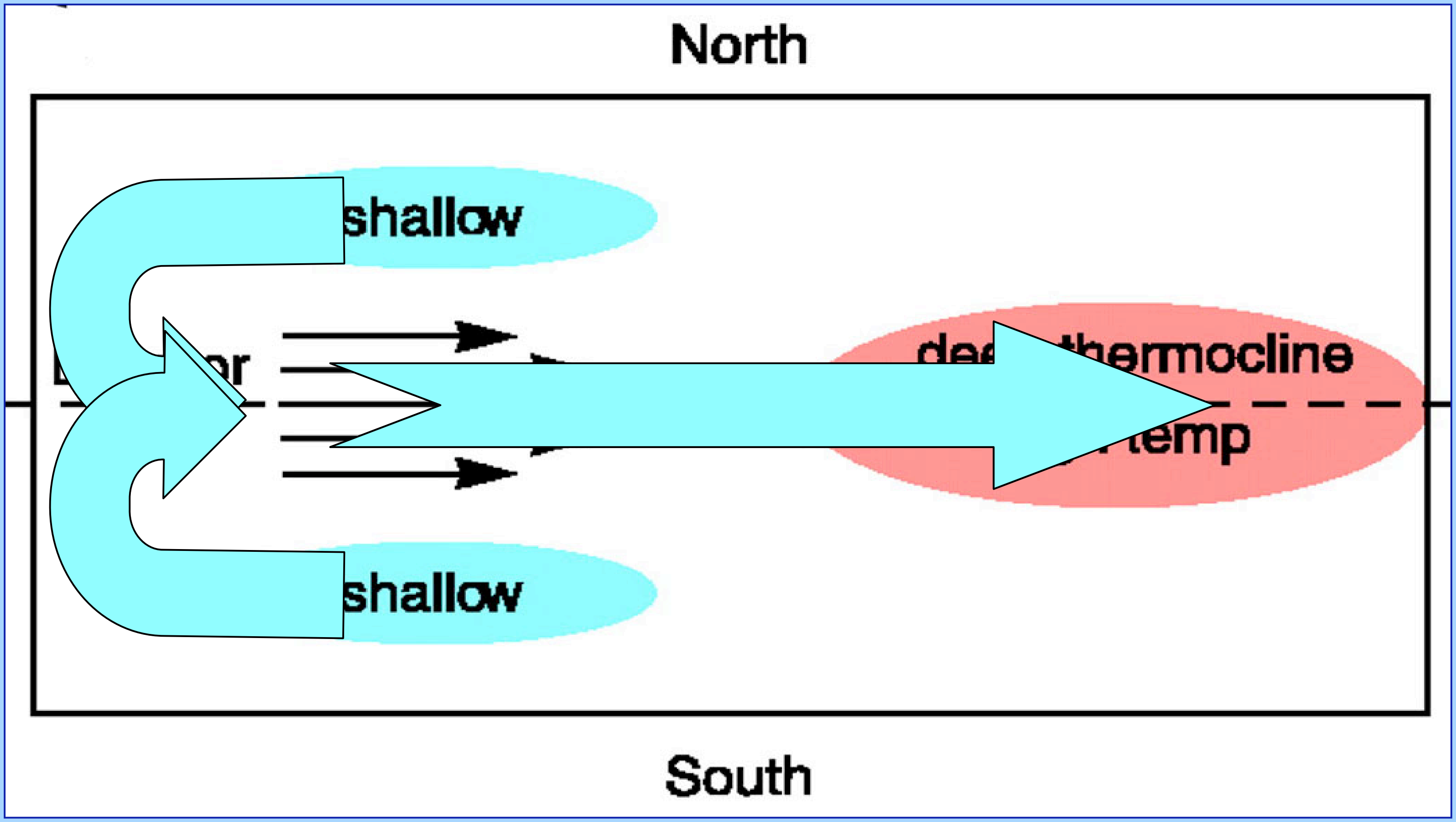


An eastward propagating, non-dispersive, planetary scale wave concentrated in the upper ocean and trapped near the equator.

Sea level response mirrored in thermo-cline depth ("two layer ocean")

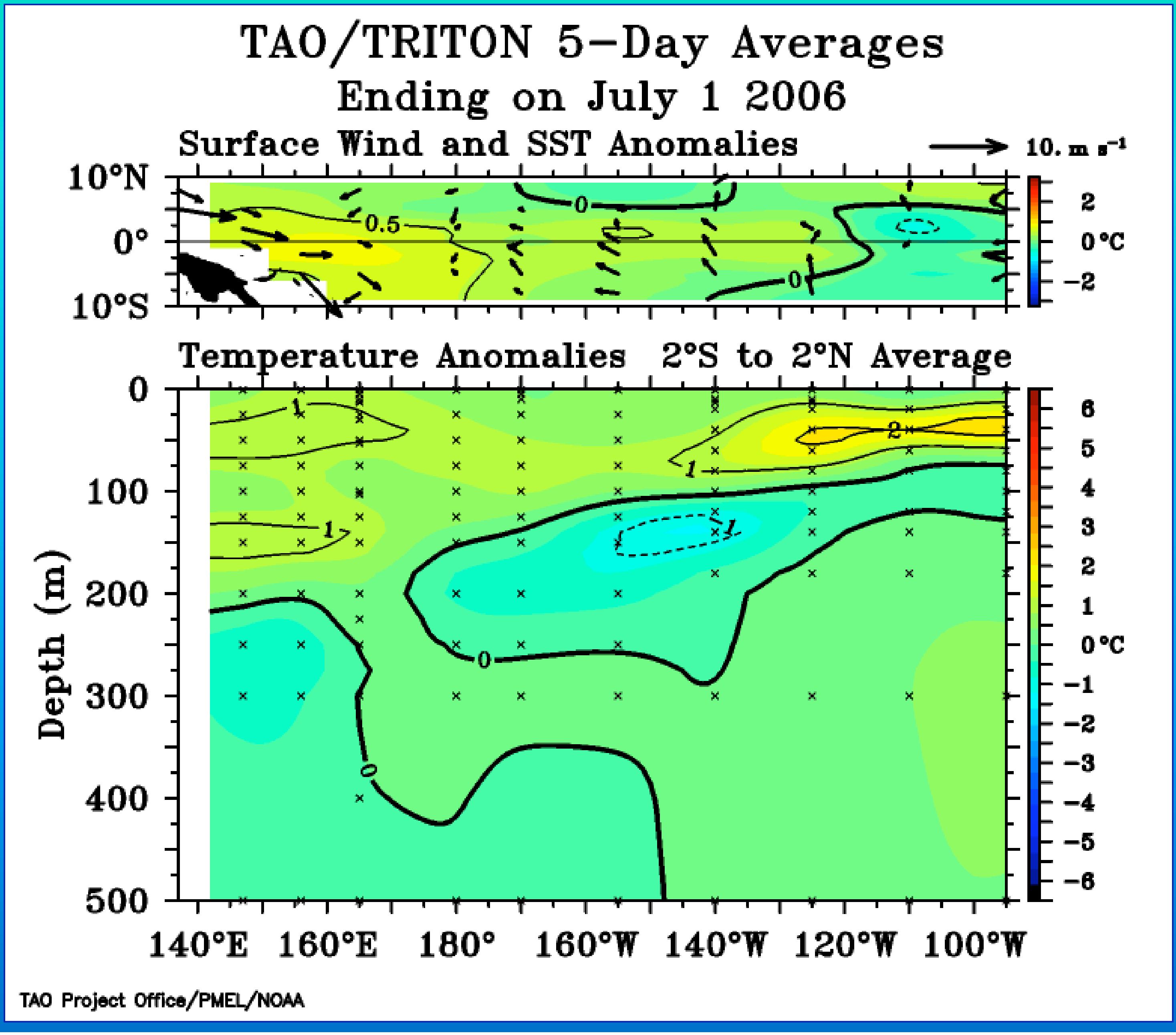
Delayed Oscillator

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



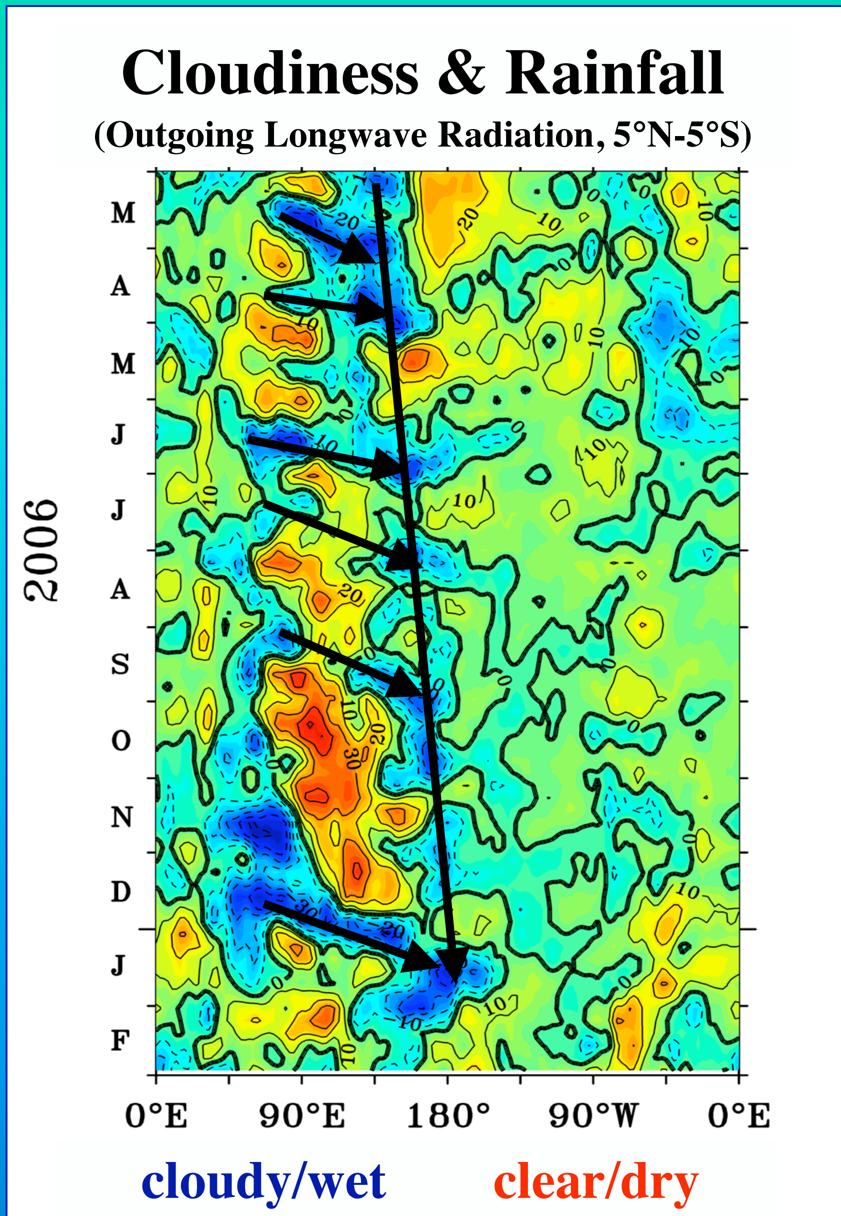
1. Winds weaken ⇒ Downwelling Kelvin wave to the east, upwelling Rossby wave to the west.
2. Upwelling Rossby wave reflects at western boundary as upwelling Kelvin wave.
3. Upwelling Kelvin wave cools the eastern Pacific cold tongue, shutting down El Niño and triggering La Niña.

Evolution: July 2006-March 2007

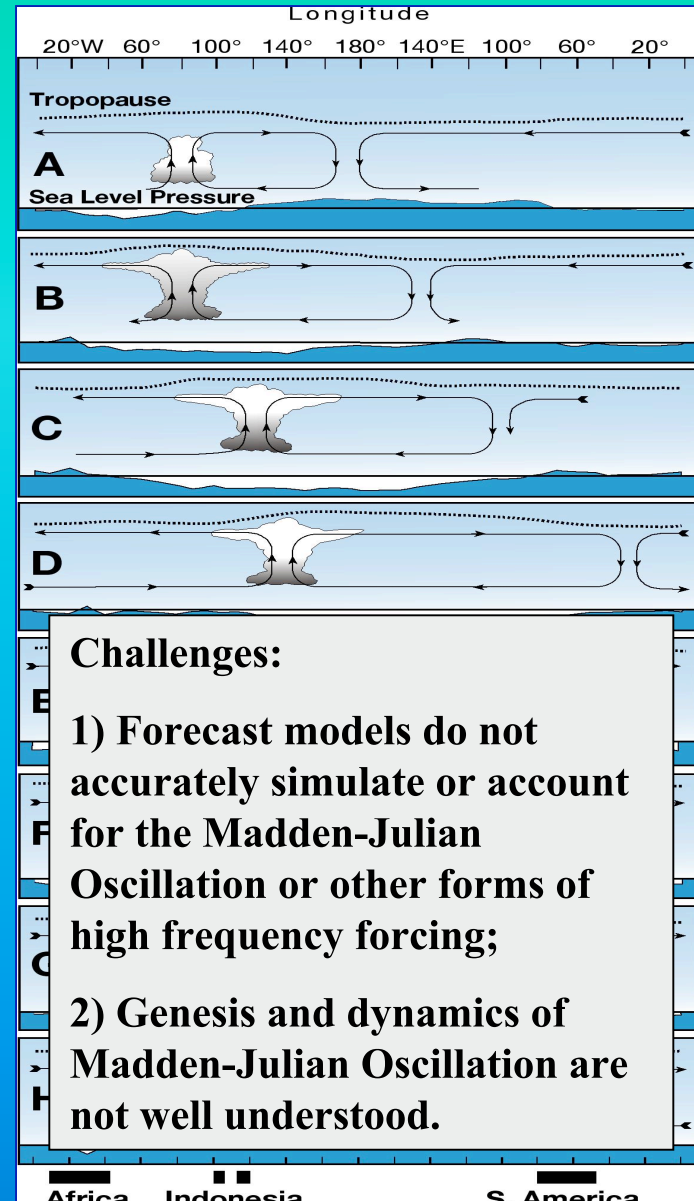


Mar
2006

Feb
2007



Indian | Pacific | Atlantic

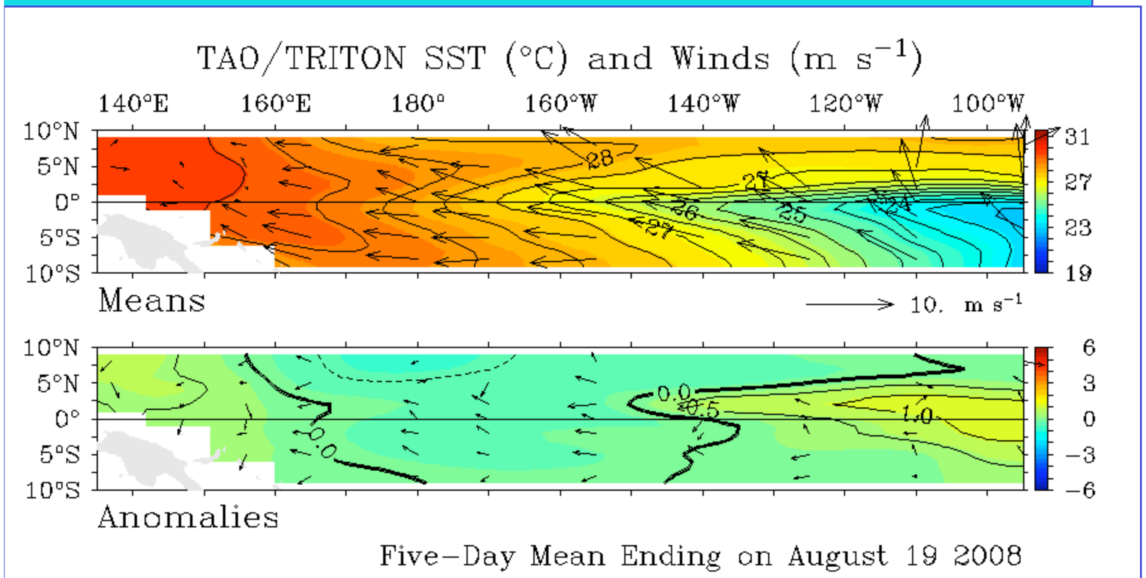


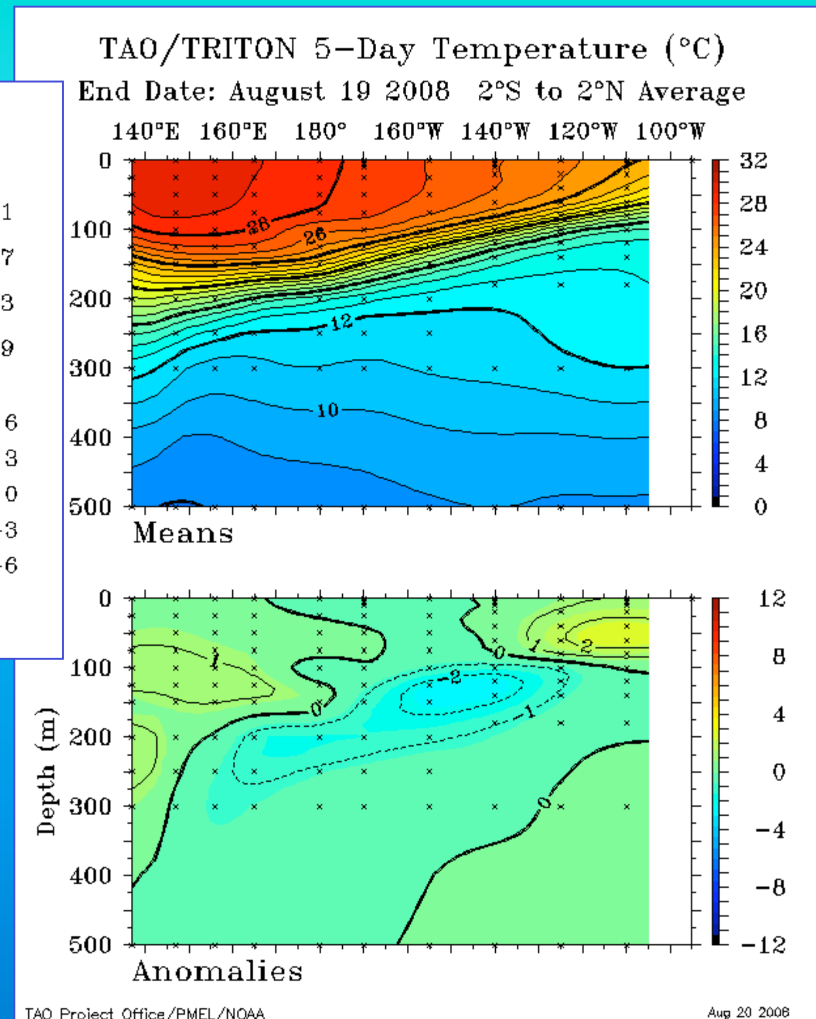
Challenges:

1) Forecast models do not accurately simulate or account for the Madden-Julian Oscillation or other forms of high frequency forcing;

2) Genesis and dynamics of Madden-Julian Oscillation are not well understood.

Current Conditions





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...*"*

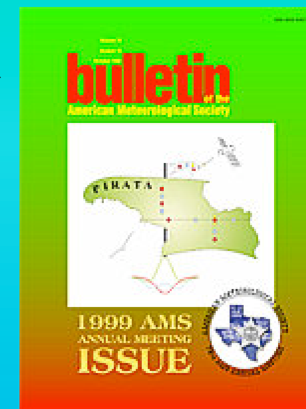
"Most of the recent dynamical and statistical SST forecasts for the Niño 3.4 region indicate ENSO-neutral conditions…will continue into the Northern Hemisphere Spring 2009. However…the development of El Niño cannot be ruled out during the later part of the year…"

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


Atlantic Ocean
PIRATA

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

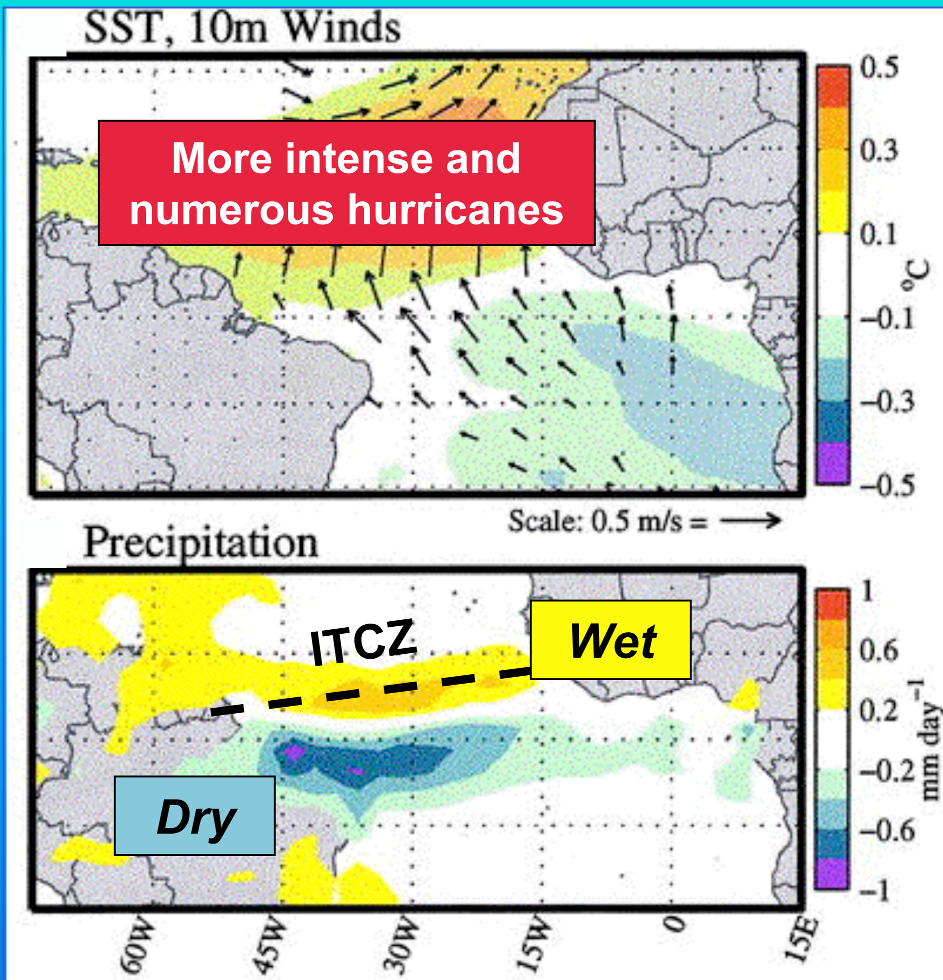
Prediction and Research Moored Array in the Tropical Atlantic (2008)

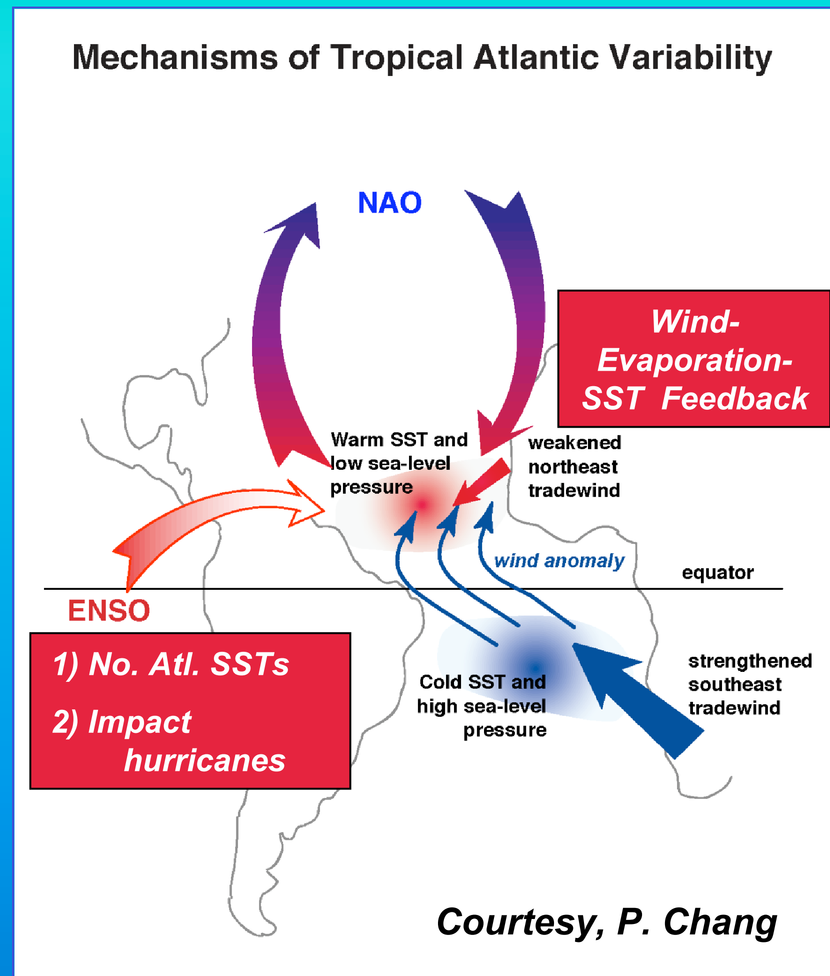
Partners:

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

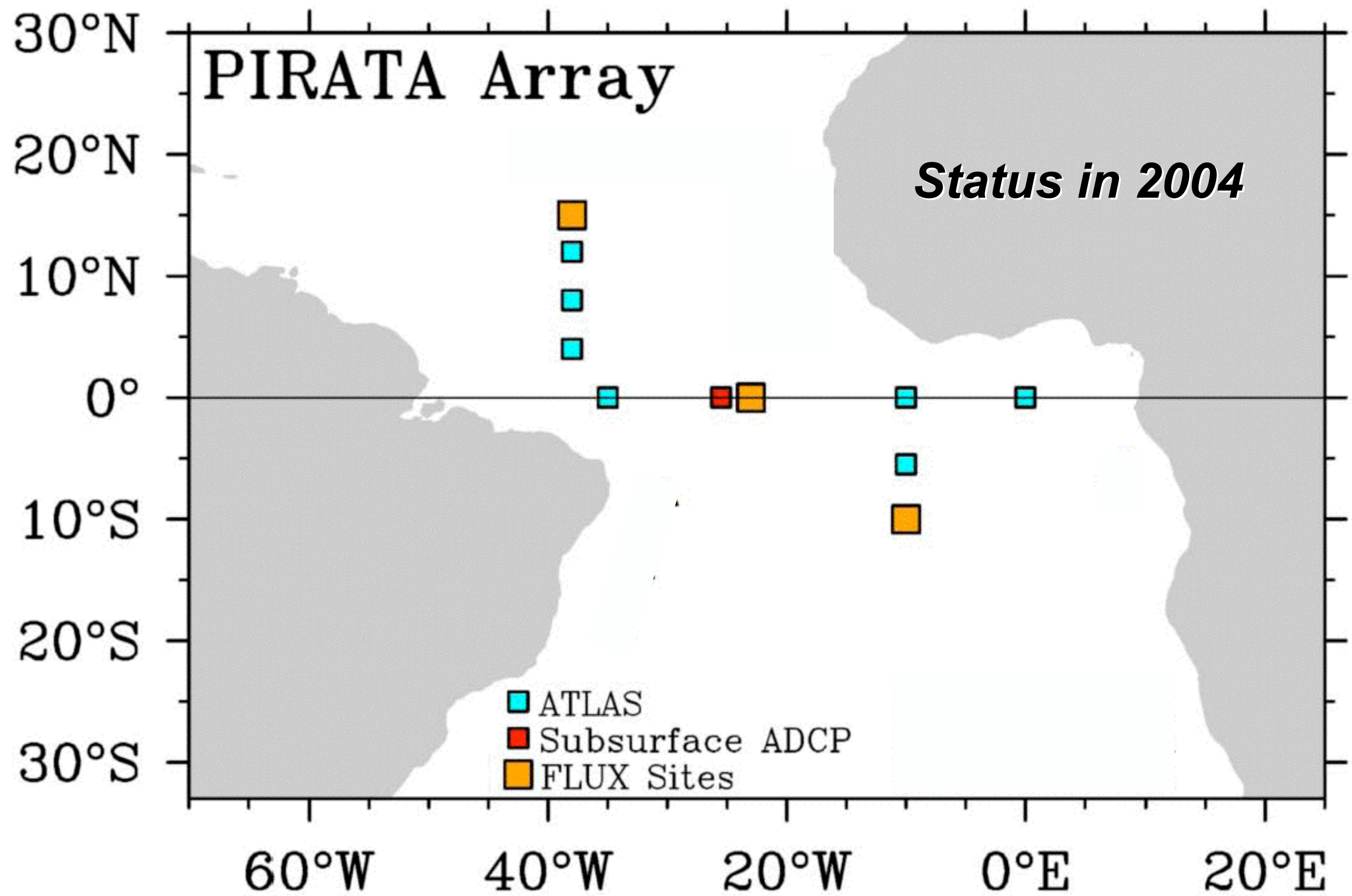
✓USA (NOAA) provides most equipment & data processing

Tropical Atlantic Climate Variability: Atlantic Meridional Mode

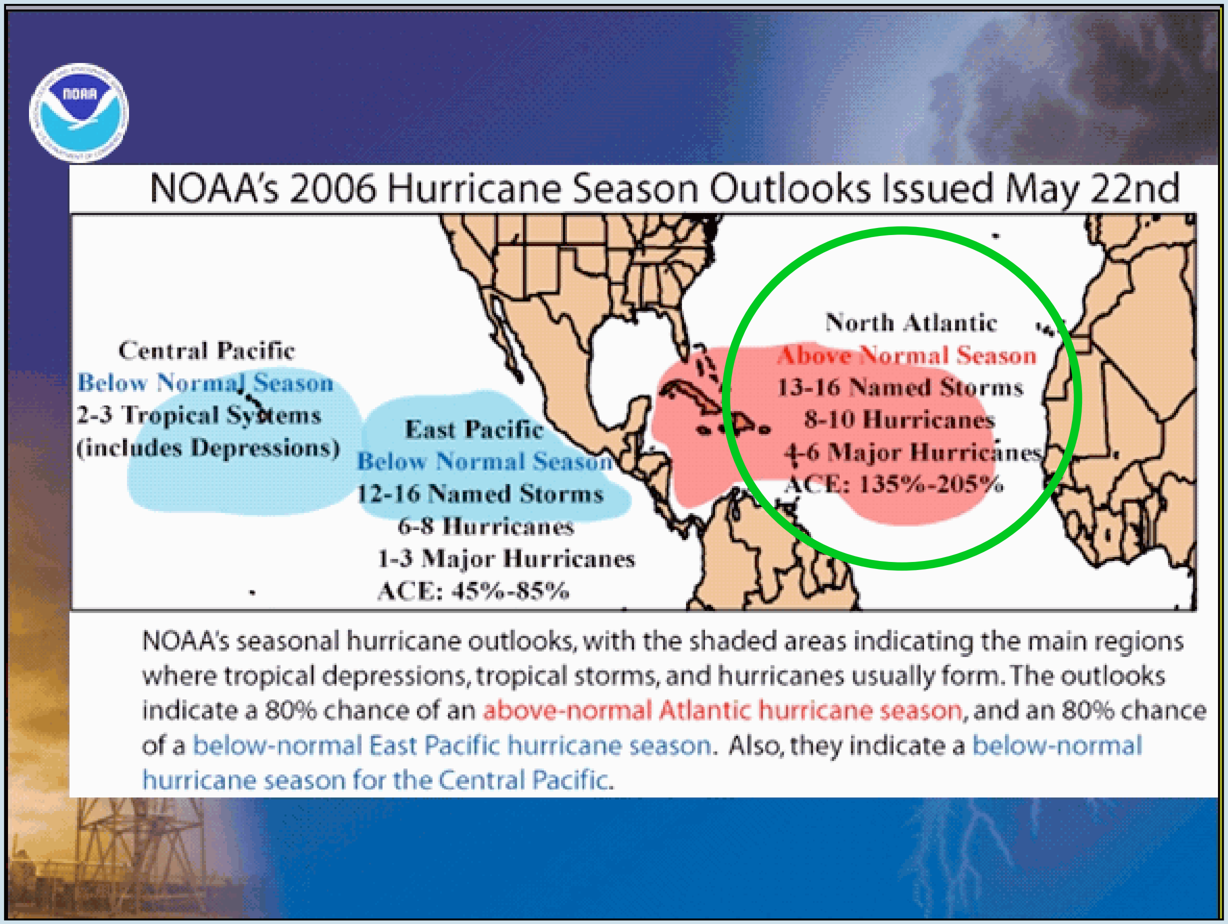




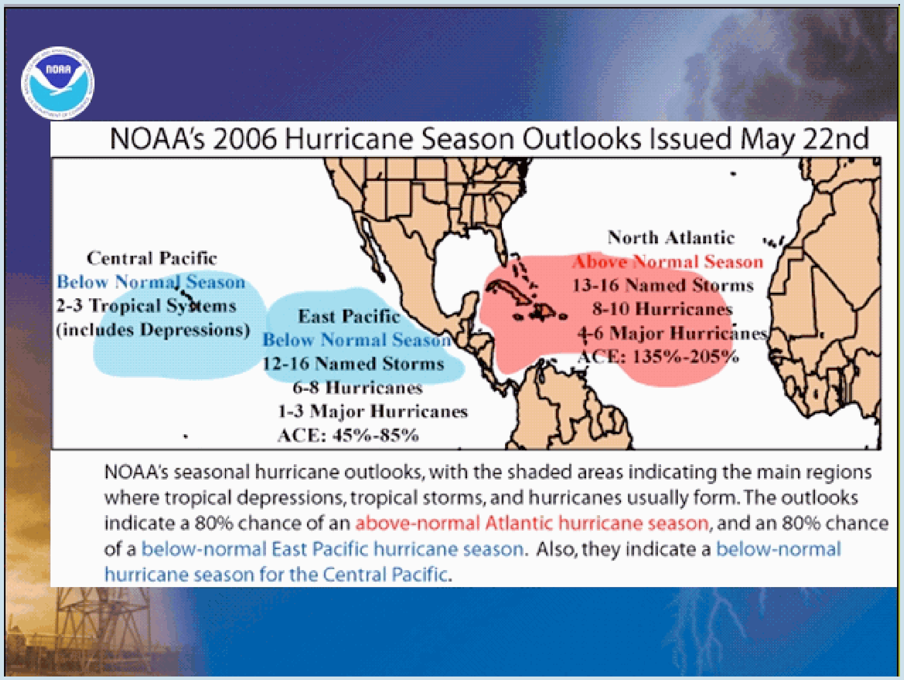
Chiang & Vimont, 2004, J. Climate

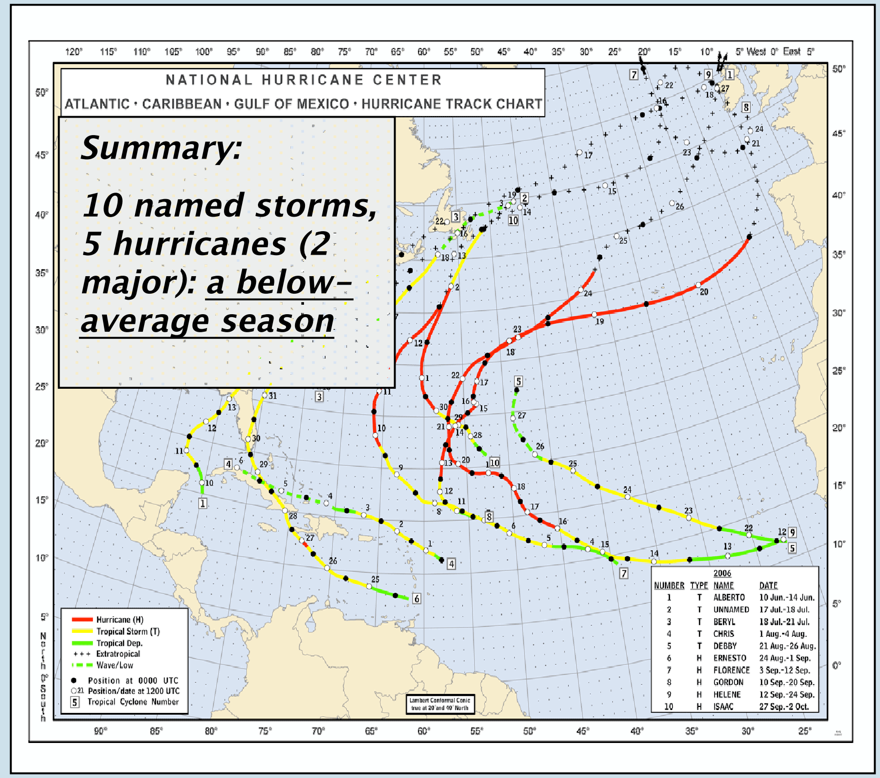

PIRATA Array
Status in 2004
30°N
20°N
10°N
0°
10°S
20°S
30°S
60°W
40°W
20°W
0°E
20°E
ATLAS
Subsurface ADCP
FLUX Sites

2006 Atlantic Hurricane Season

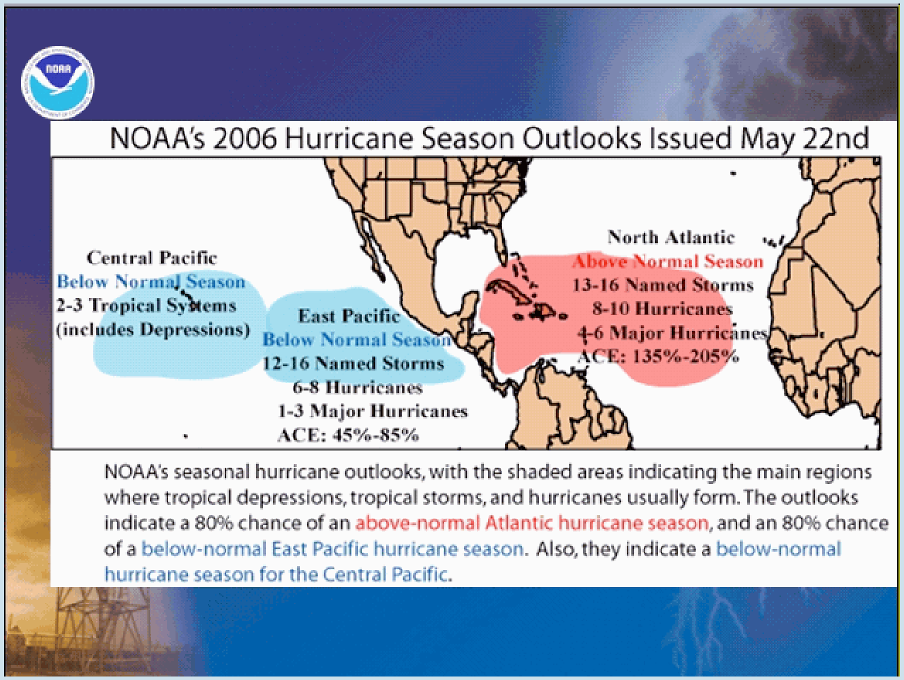


2006 Atlantic Hurricane Season





2006 Atlantic Hurricane Season



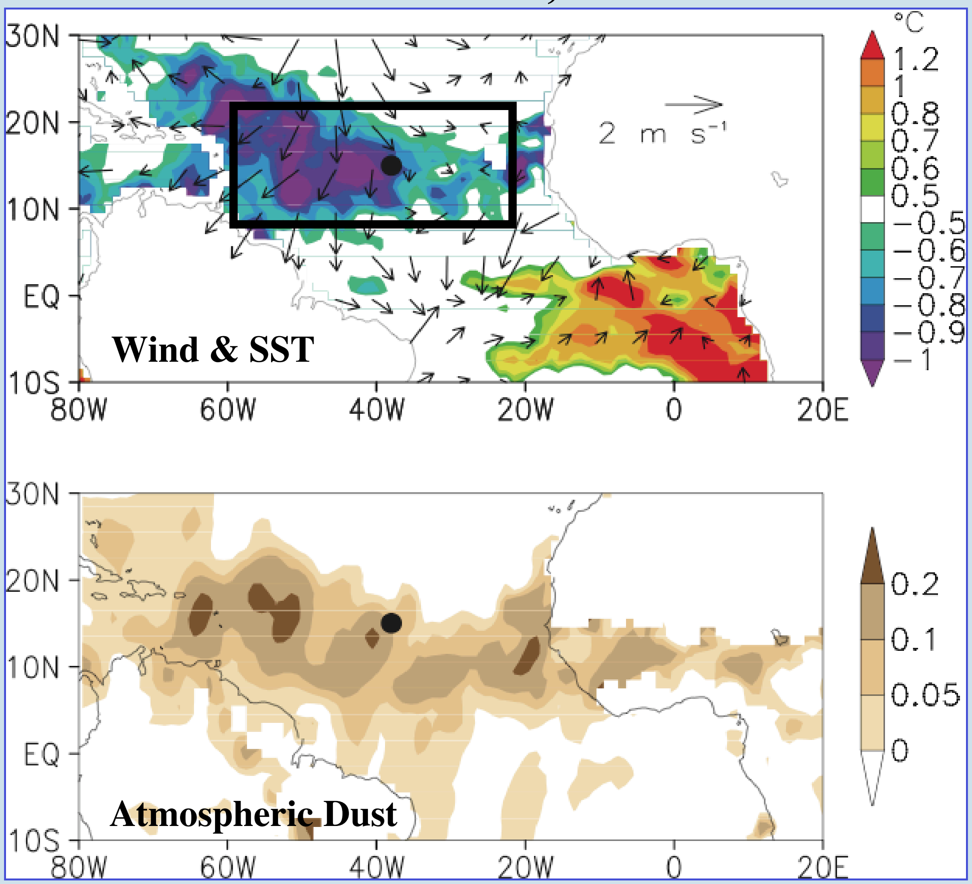
"…the 2006 Atlantic hurricane season activity was lower than expected due to the rapid development of El Niño."

"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

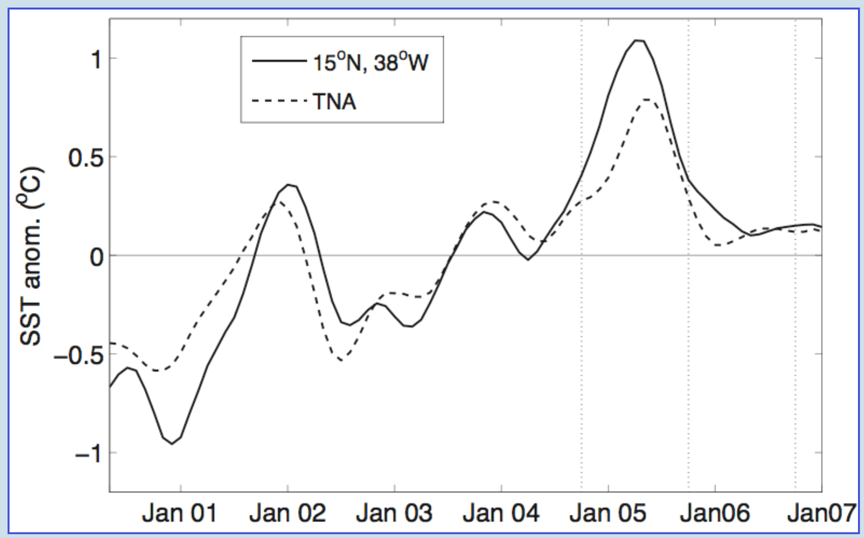
North Atlantic SSTs in 2006

JJA Differences, 2006-2005

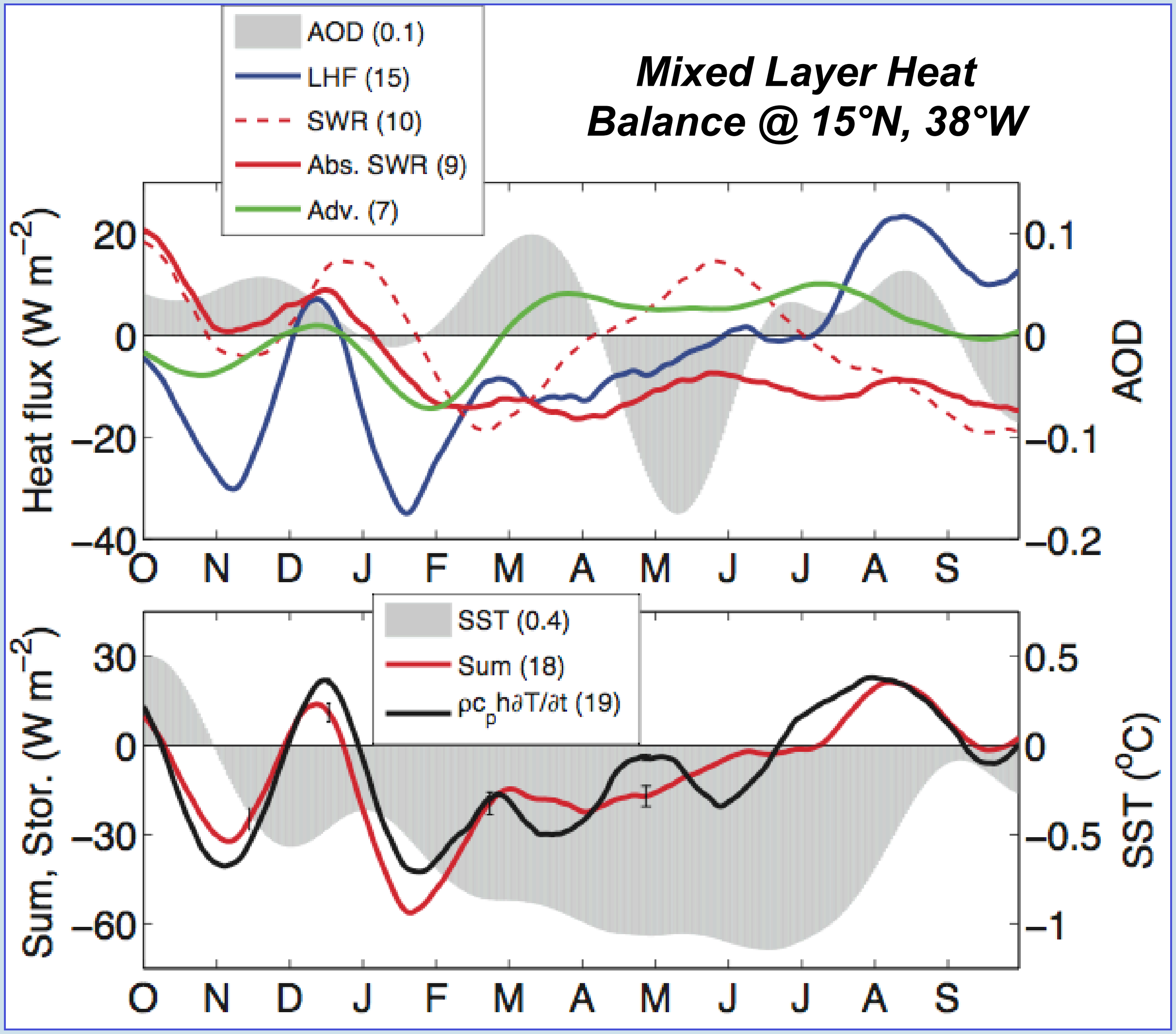


"Increased atmospheric loading of **Saharan dust** over the North Atlantic during the 2006 hurricane season…**initiated rapid cooling** and suppressed tropical storm and hurricane activity…"

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



North Atlantic SSTs in 2006

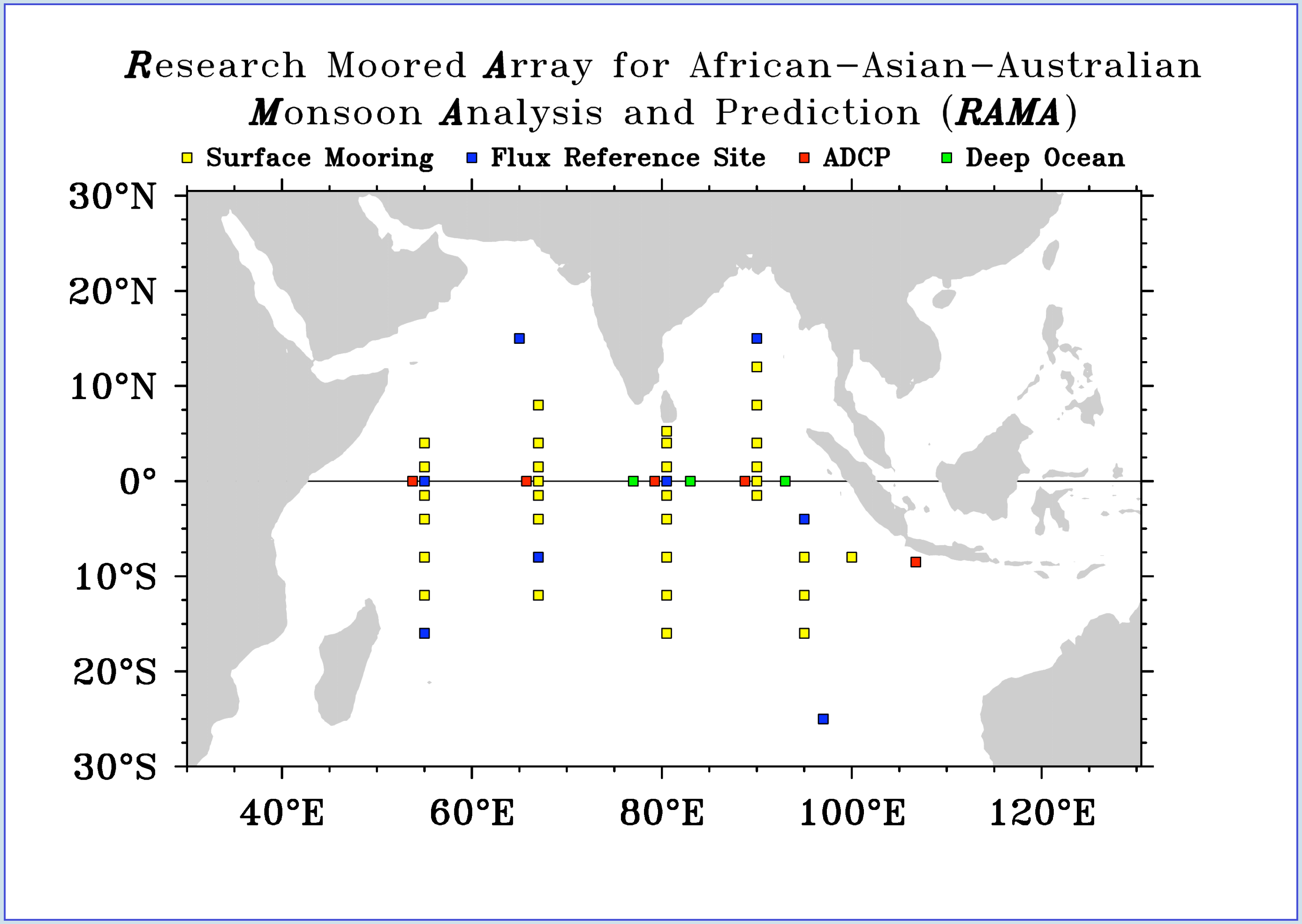


"…most of the anomalous cooling occurred prior to the period of enhanced dustiness and was driven primarily by wind-induced latent heat loss…dust-induced changes in short wave radiation did not play a major direct role in the cooling that led up to the 2006 Atlantic hurricane season."

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


Indian Ocean
RAMA
TAO

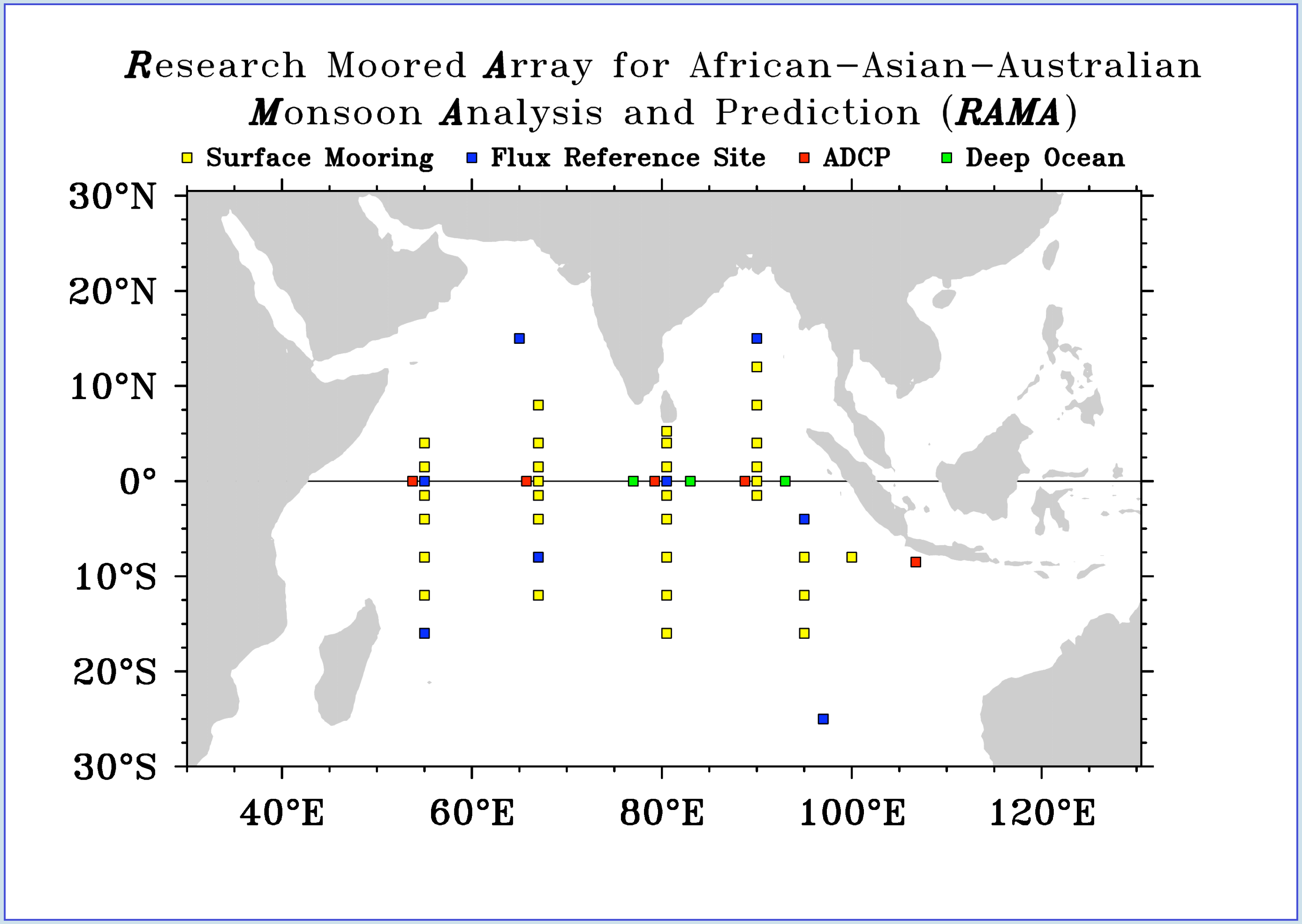
RAMA



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



RAMA

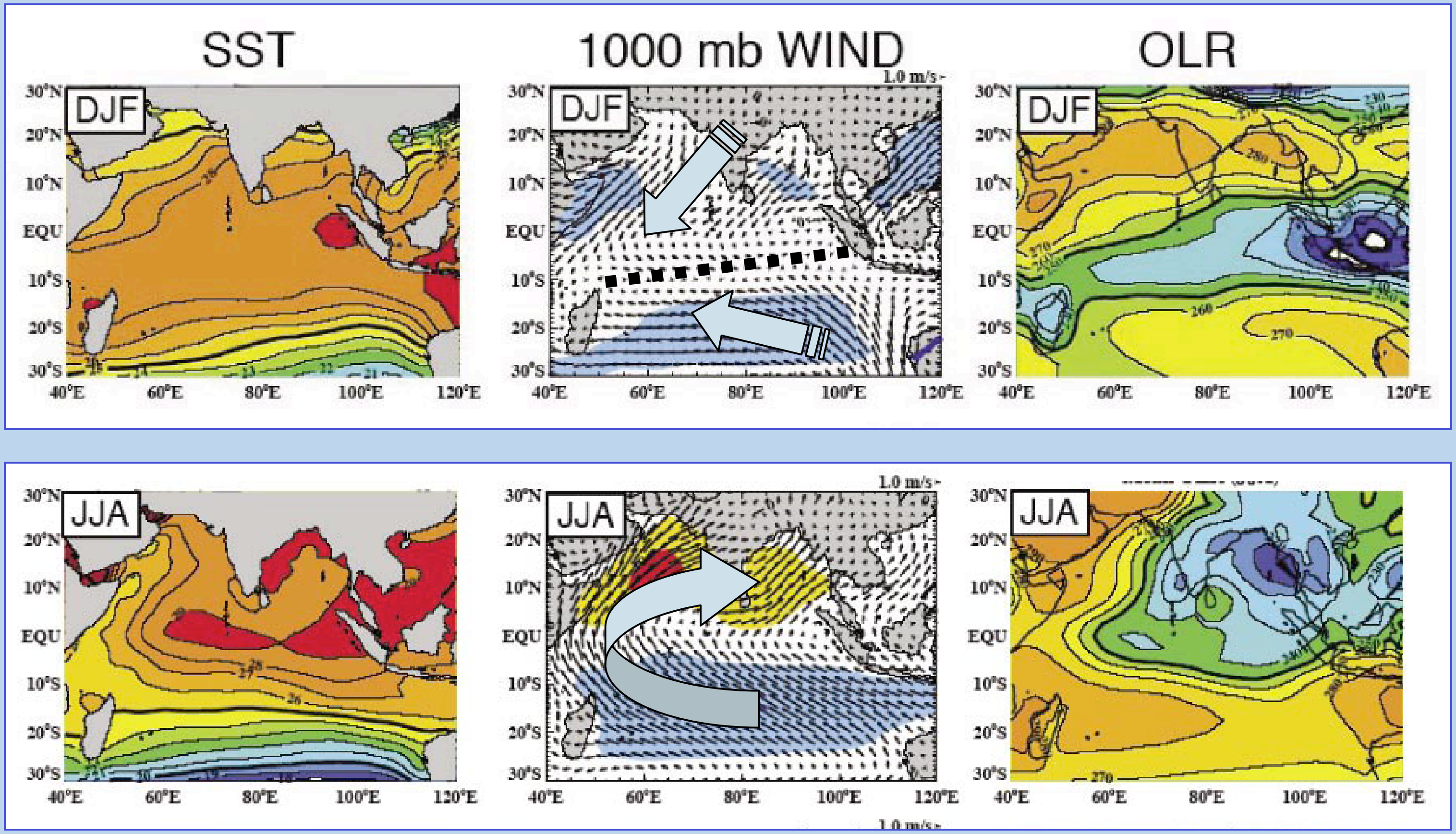
RAMA: Ancient king of India and hero of the epic "Ramayana".

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

The Monsoon

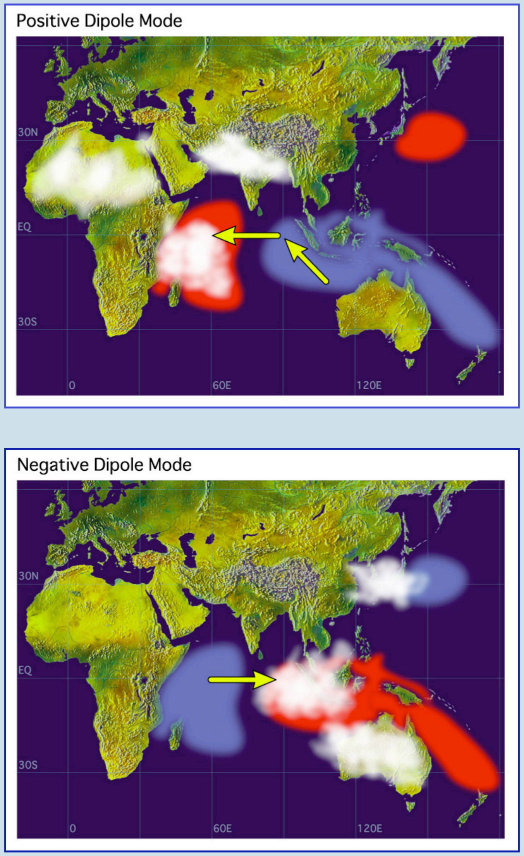
DJF

JJA



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

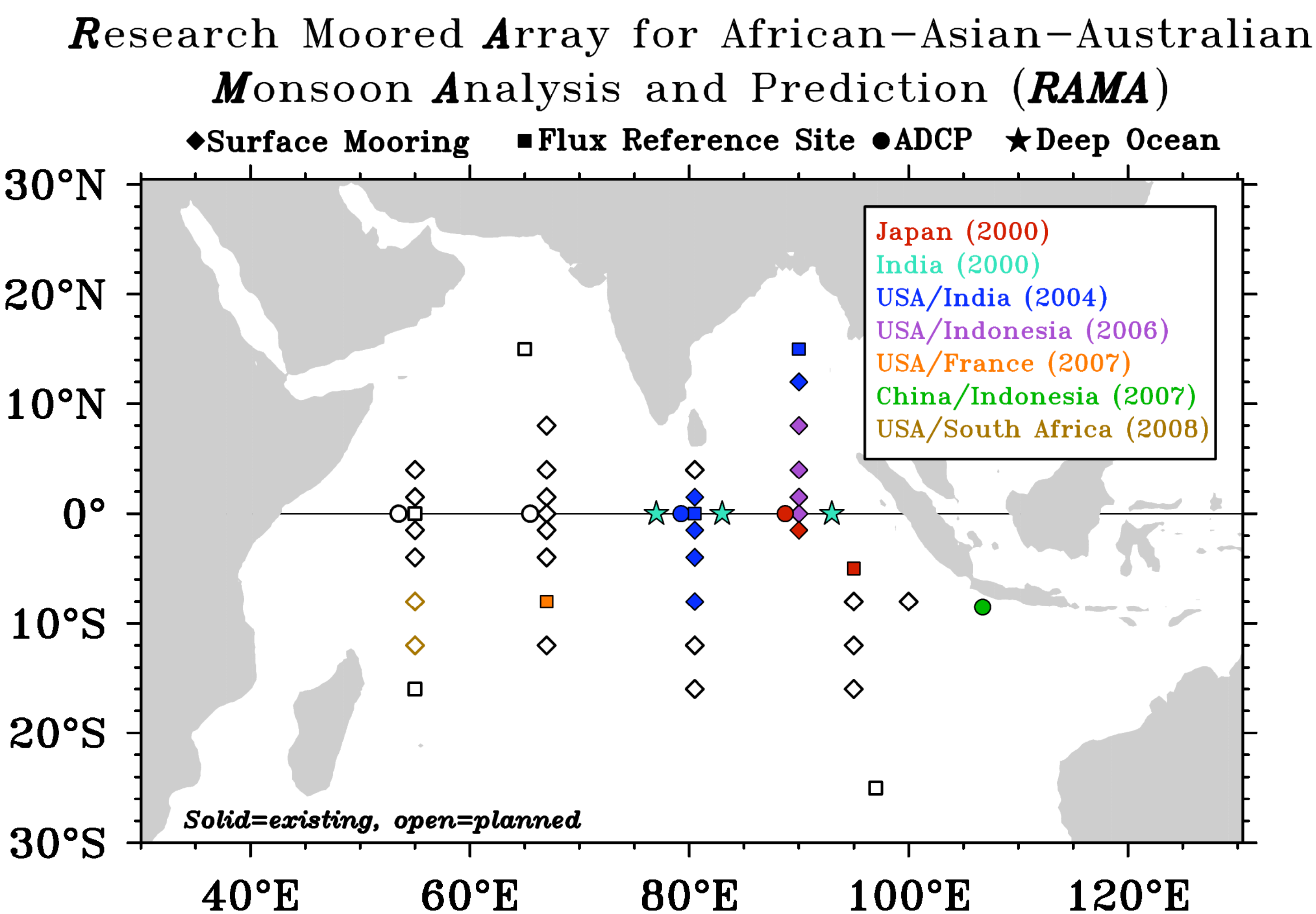
Indian Ocean Climate Science Drivers



Indian Ocean Dipole

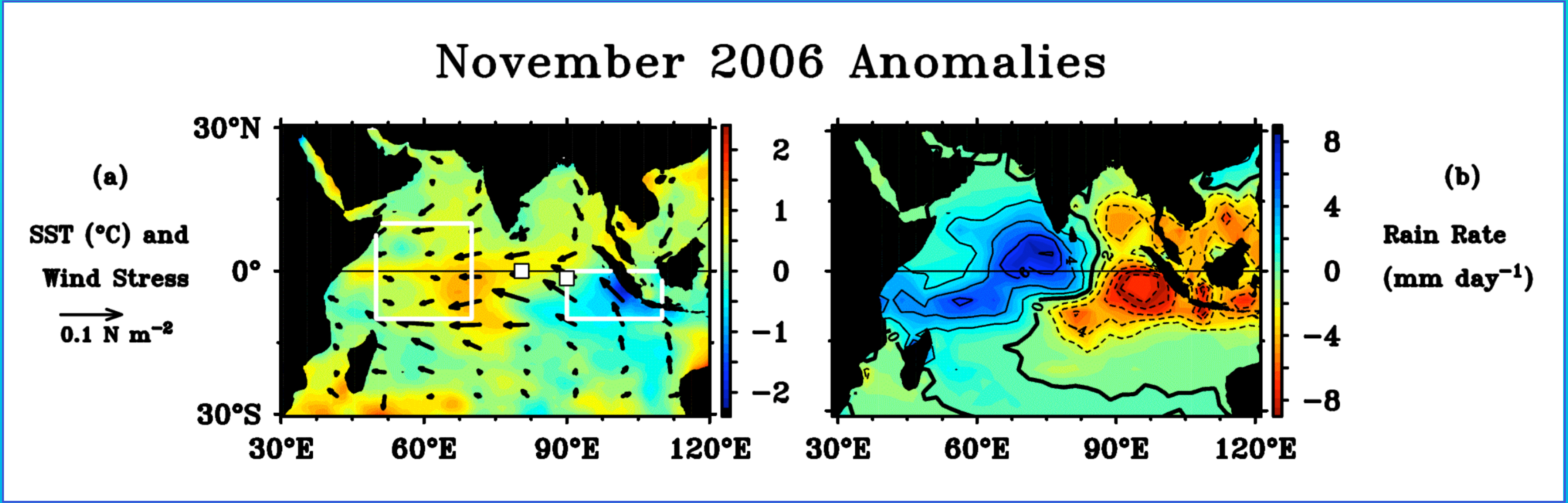
- **Seasonal monsoon variability**
- **Cyclones and synoptic scale events**
- **Intraseasonal (30-60 day period) Madden Julian Oscillation (⇒ ENSO, west coast US weather, hurricanes)**
- **Interannual variations: the Indian Ocean Dipole**
- **Decadal variability**
- **Warming trends since the 1970s**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

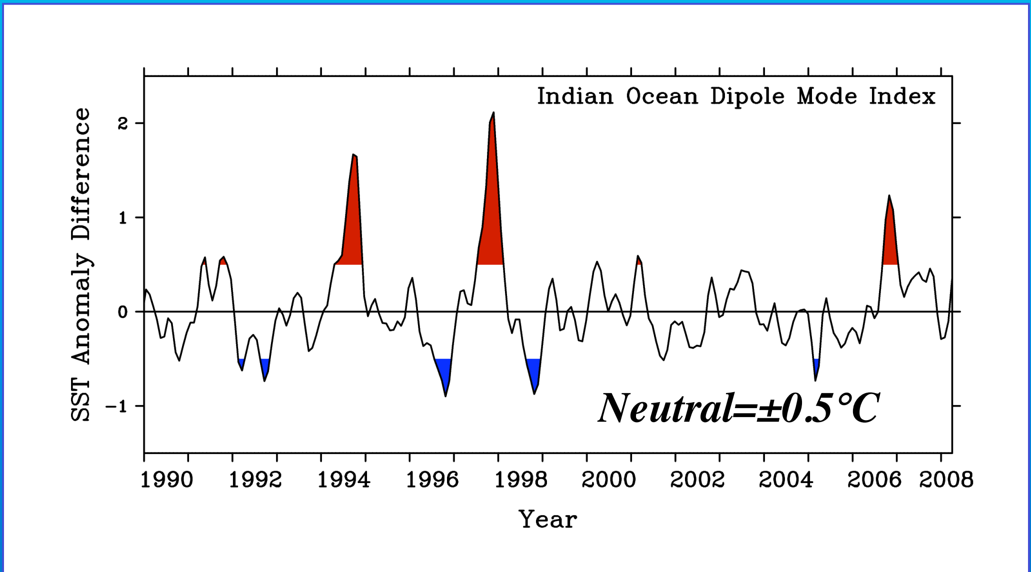
RAMA: Present Status



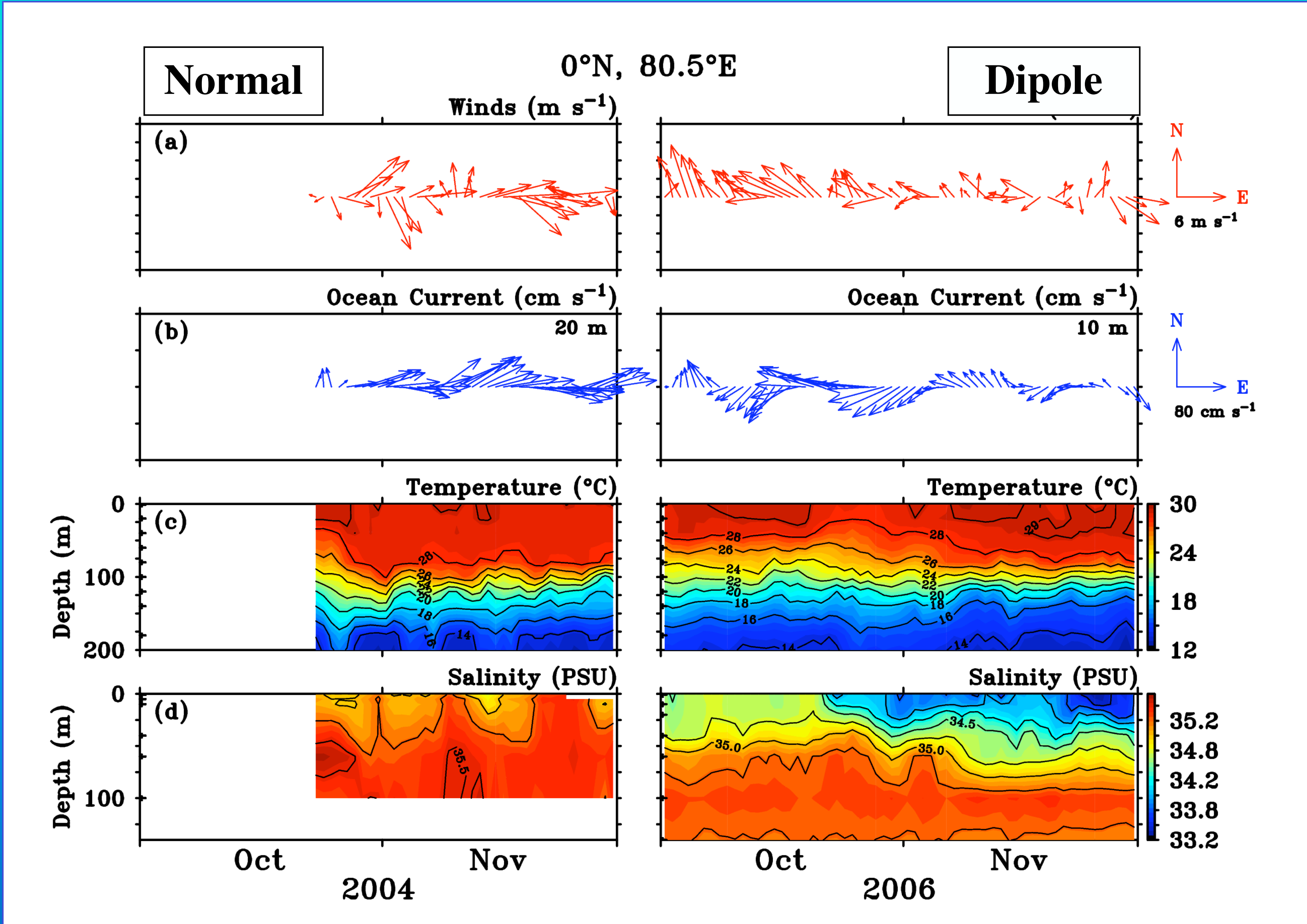
47% of sites occupied by end of 2008 (22 of 46; 15 involve PMEL)

2006 Indian Ocean Dipole

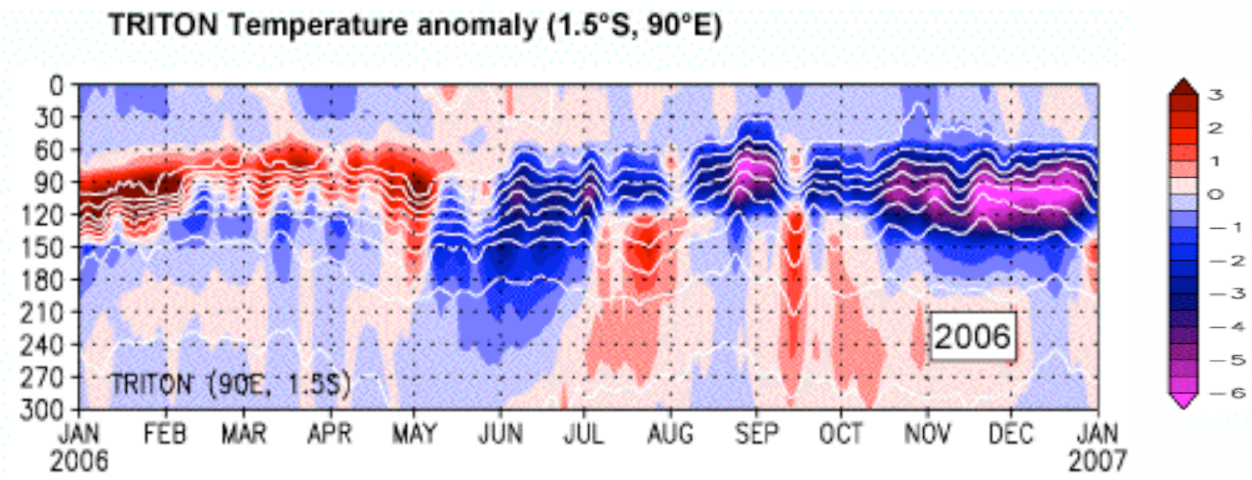


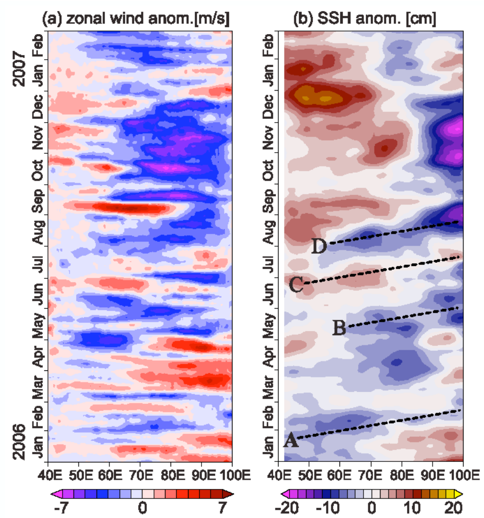


Comparison of Oct-Nov 2004 (Normal) & Oct-Nov 2006 (Dipole)



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

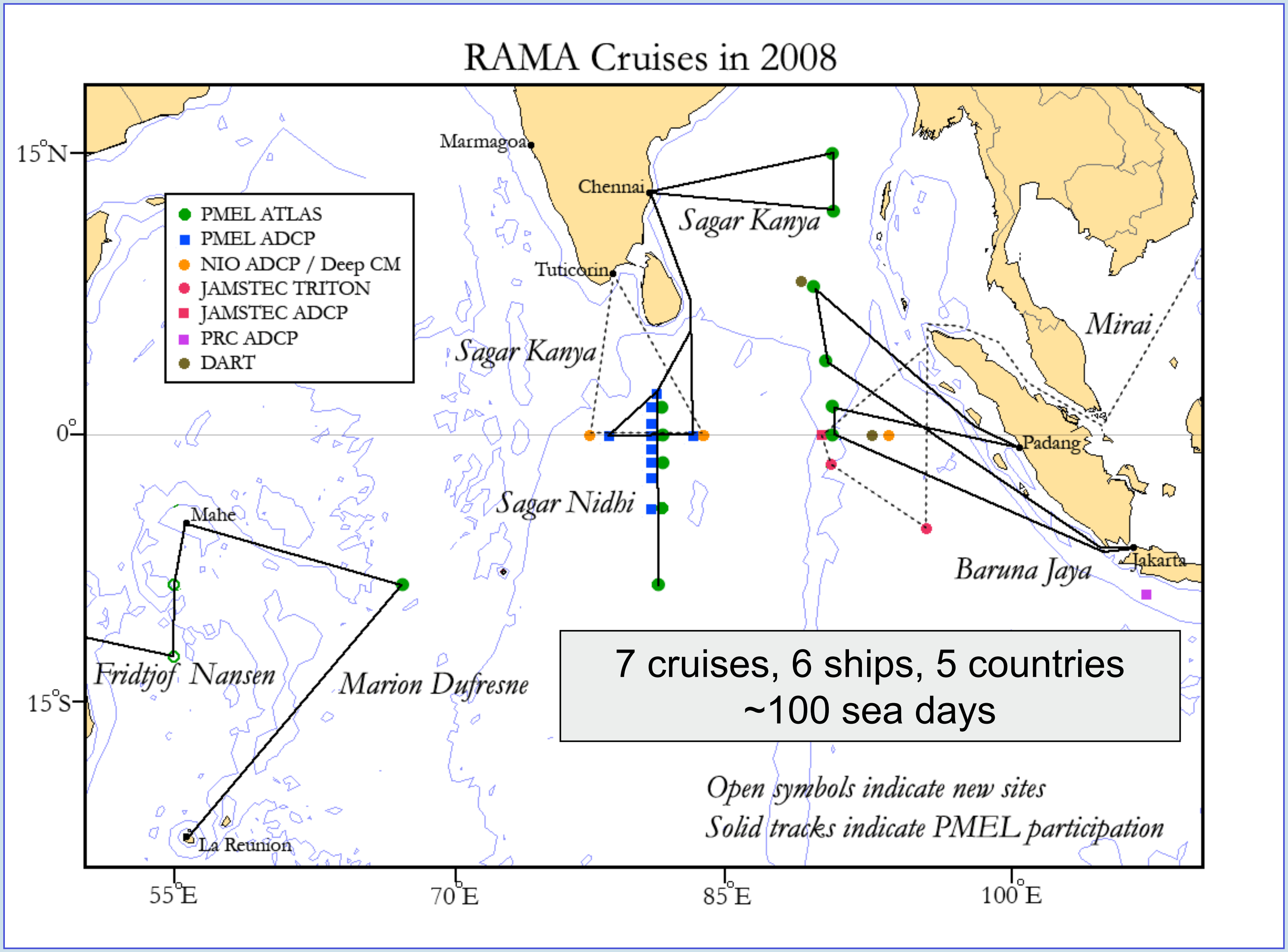




Thermocline temperature anomalies mediated by wind forced upwelling Kelvin waves.

Horii et al, 2008, GRL

RAMA Plans 2008



Three Challenges

Vandalism by Fishermen

Funding

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

Dealing with Vandalism

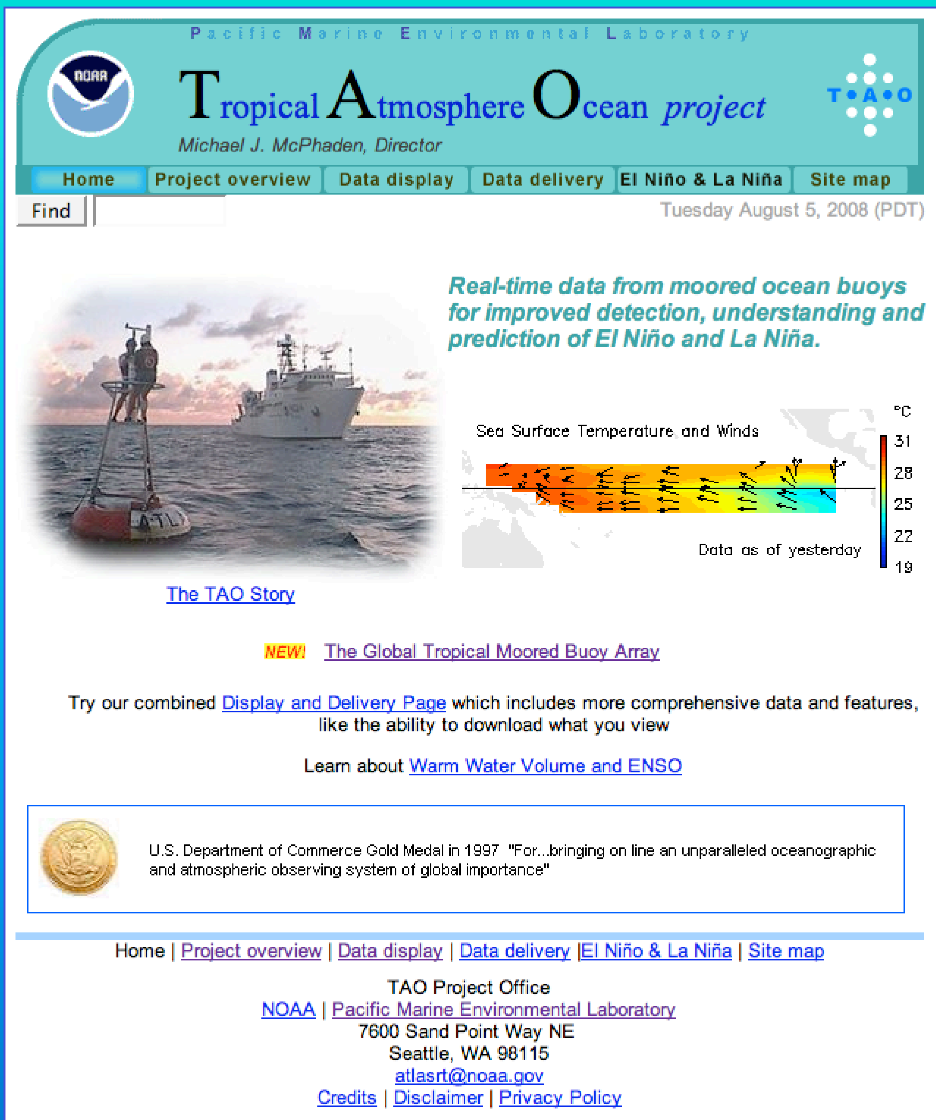
- **Outreach and Enforcement**
  1) **Outreach to fishermen and national fisheries agencies**
  2) **NOAA Enforcement (P. Ortiz)**
- **Engineering**
  1) **ATLAS-Make sensors and equipment more difficult to remove by using specialized hardware**
  2) **"Conehead" buoys**
     - **Remove vulnerable sensors**
     - **Make buoys harder to board**
     - **Remove buoy attachment points**

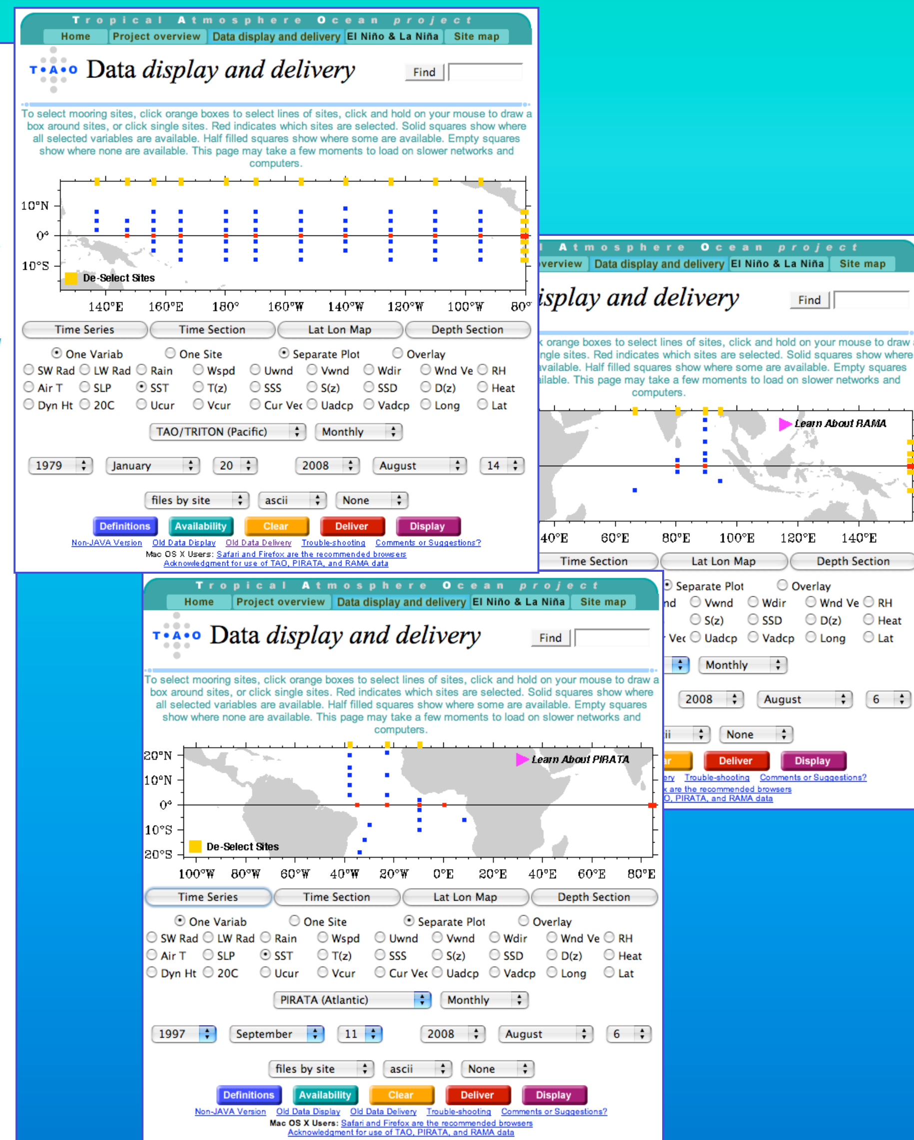
International Cooperation and Capacity Building for RAMA

Tsunami/RAMA cruise
RV Baruna Jaya III
Sept 2007

- **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**

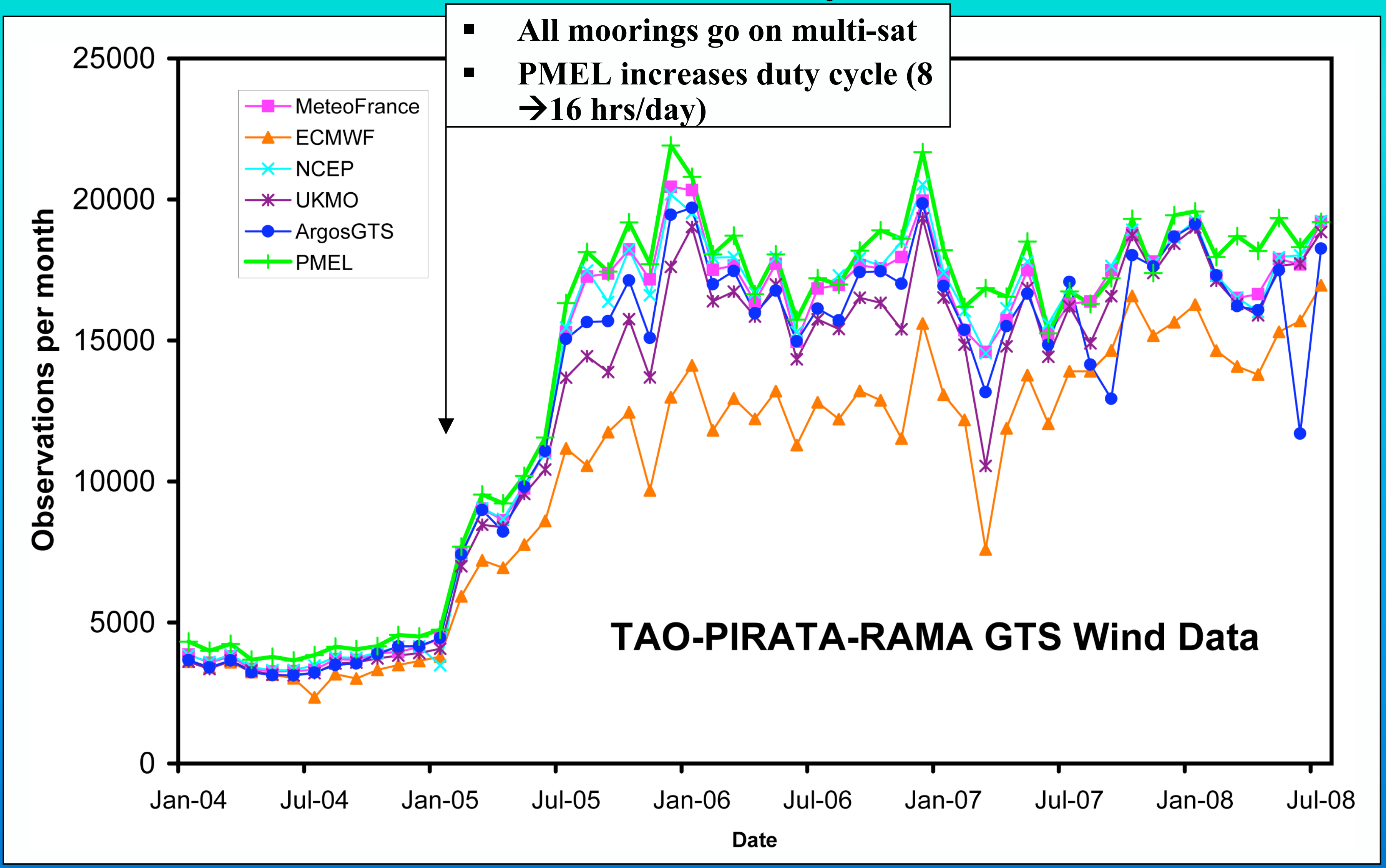
TAO Project Web Pages





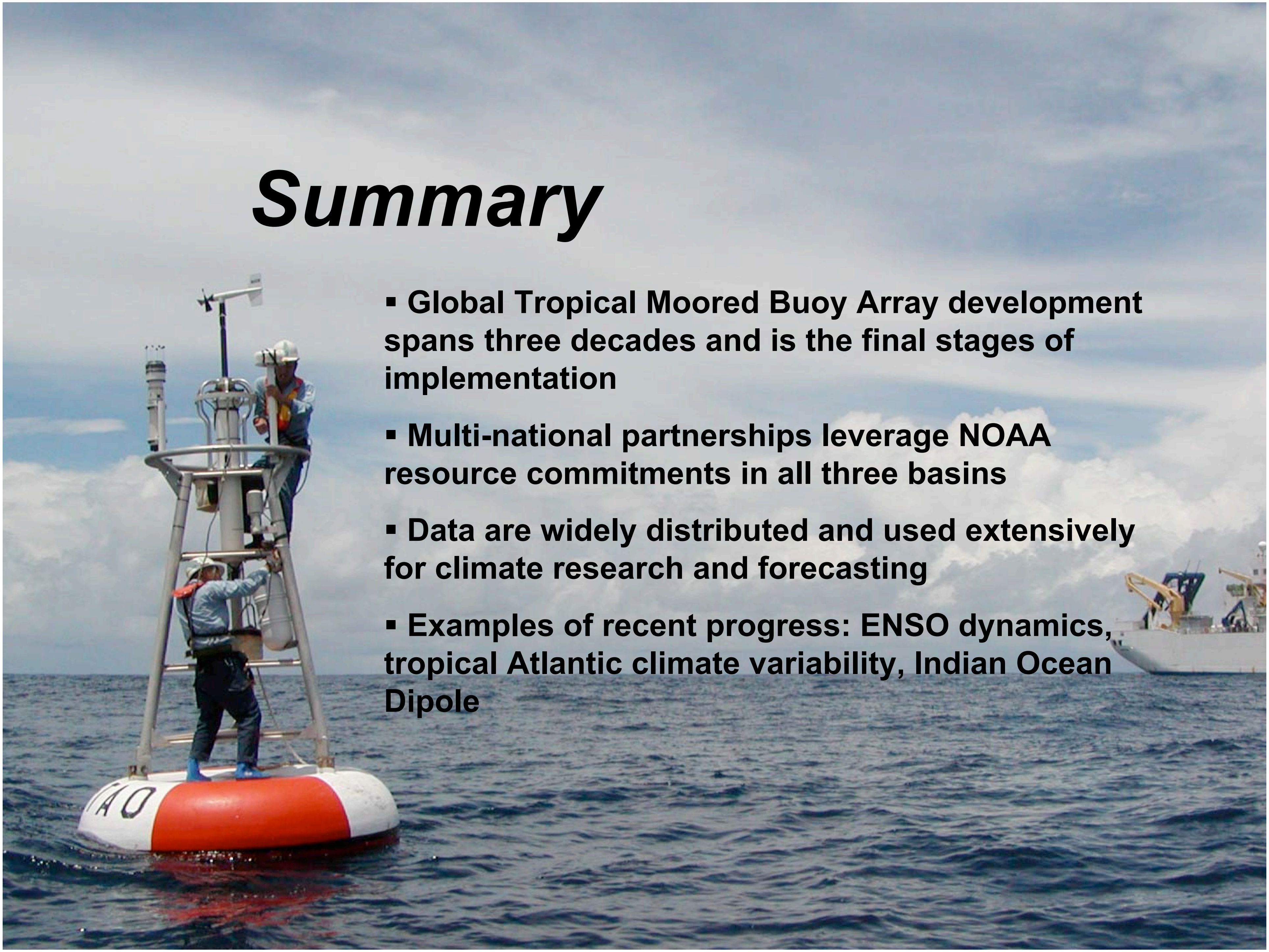
http://www.pmel.noaa.gov/tao/

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

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- Joint Institute for the Study of the Atmosphere & Ocean (JISAO) at the University of Washington
- Our many international partners