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
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

- **Surface measurements** from volunteer ships (VOSclim)
  - 200 ships in pilot project
  - 87%

- **Global drifting surface buoy array**
  - 5° resolution array: 1250 floats
  - 100%

- **Tide gauge network** (GCOS subset of GLOSS core network)
  - 170 real-time reporting gauges
  - 62%

- **XBT sub-surface temperature section network**
  - 81 lines occupied
  - 81%

- **Profiling float network** (Argo)
  - 3° resolution array: 5000 floats
  - 100%

- **Reference time series**
  - 24%
  - 50 sites

- **Global reference mooring network**
  - 48%
  - 20 moorings planned

- **Global tropical moored buoy network**
  - 79%
  - 119 moorings planned

- **Repeat hydrography and carbon inventory**
  - 43%
  - Full ocean survey in 10 years
Pacific Ocean
TAO/TRITON
"...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

$20M$ per day in losses

Snoqualmie Pass
Washington State
January 2008
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

Average Based on 12 El Niños from 1957-2005
“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
Neutral zone

Observations

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

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

**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.

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

*Meinen & McPhaden, 2000*

![Graph showing Warm Water Volume and SST Anomaly](graph.png)
Upper Ocean Heat Content and ENSO

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

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
Aug-Oct ‘06: Strong westerly wind bursts and downwelling Kelvin waves amplify warming.
March 2006-August 2007

Late 2006-early 2007: Sudden transition from warm to cold linked to strengthening trade winds and rapid thermocline shoaling.
**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")
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.
Cloudiness & Rainfall

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

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
THE PIRATA PROGRAM
History, Accomplishments, and Future Directions

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

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)

Introduced in Oct '98
Tropical Atlantic Climate Variability: Atlantic Meridional Mode

More intense and numerous hurricanes

Mechanisms of Tropical Atlantic Variability

1) No. Atl. SSTs
2) Impact hurricanes

NAO

Warm SST and low sea-level pressure
weakened northeast tradewind
wind anomaly
equator

ENSO

Cold SST and high sea-level pressure
strengthened southeast tradewind

Courtesy, P. Chang

Chiang & Vimont, 2004, J. Climate
PIRATA Array

Status in 2004

ATLAS
Subsurface ADCP
FLUX Sites
2006 Atlantic Hurricane Season

NOAA's 2006 Hurricane Season Outlooks Issued May 22nd

Central Pacific
Below Normal Season
2-3 Tropical Systems
(includes Depressions)

East Pacific
Below Normal Season
12-16 Named Storms
6-8 Hurricanes
1-3 Major Hurricanes
ACE: 45%-85%

North Atlantic
Above Normal Season
13-16 Named Storms
8-10 Hurricanes
4-6 Major Hurricanes
ACE: 135%-205%

NOAA's seasonal hurricane outlooks, with the shaded areas indicating the main regions where tropical depressions, tropical storms, and hurricanes usually form. The outlooks indicate a 80% chance of an above-normal Atlantic hurricane season, and an 80% chance of a below-normal East Pacific hurricane season. Also, they indicate a below-normal hurricane season for the Central Pacific.
2006 Atlantic Hurricane Season

Summary:
10 named storms, 5 hurricanes (2 major): a below-average 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

"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..."

“...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.”

Indian Ocean
RAMA
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.

The Monsoon

Half the world’s population depends on monsoon rainfall for agriculture
**Indian Ocean Climate Science Drivers**

- 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

Research Moored Array for African–Asian–Australian Monsoon Analysis 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

(a) SST (°C) and Wind Stress
0.1 N m⁻²
(b) Rain Rate (mm day⁻¹)

Indian Ocean Dipole Mode Index

Neutral=±0.5°C
Comparison of Oct-Nov 2004 (Normal) & Oct-Nov 2006 (Dipole)

(a) Winds (m s⁻¹)
(b) Ocean Current (cm s⁻¹)
(c) Temperature (°C)
(d) Salinity (PSU)
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

7 cruises, 6 ships, 5 countries
~100 sea days

Open symbols indicate new sites
Solid tracks indicate PMEL participation

RAMA Cruises in 2008

Chennai, Sagar Kanya, Sagar Nidhi, Mirai, Baruna Jaya, Padang, Jakarta, Fridtjof Nansen, Marion Dufresne, La Reunion, Marmagao, Tuticorin, Sagar Kanya.
Three Challenges

- Ship time (~200 days per year to maintain full array)
- Funding
- Vandalism by Fishermen
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

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 online an unparalleled oceanographic and atmospheric observing system of global importance"
Tropical Moored Array Data on the Global Telecommunications System (GTS)

- All moorings go on multi-sat
- PMEL increases duty cycle (8 → 16 hrs/day)

- 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 in 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