Ocean Climate Observations from the Tropical Atmosphere Ocean (TAO) Array: Present and Future

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Abstract

The Tropical Atmosphere Ocean (TAO) buoy array is maintained and operated by the U.S. National Oceanic and Atmospheric Administration's (NOAA) National Data Buoy Center (NDBC). The mission of the TAO array is to provide real-time atmospheric and ocean data for improved detection, understanding and prediction of weather and climate, especially El Niño and La Niña. This paper presents the current status and the ongoing technology refresh efforts for the TAO array.

Key word: climate, ocean observation, buoy, mooring, El Niño

1. Introduction

NOAA NDBC operates and maintains fifty-five (55) Tropical Atmosphere Ocean (TAO) buoys and moorings and four (4) Acoustic Doppler Current Profilers (ADCP) along the equatorial Pacific Ocean region extending from 9°N Latitude to 8°S Latitude and 95°W Longitude to 165°E Longitude. The Japan Agency for Marine-Earth Science and Technology (JAMSTEC) operates 13 buoys/mooring west of the 165 East Longitude known as in their design of the TRIangle Trans-Ocean buoy Network (TRITON) Array between 156°E to 138°W, and this combined Array is know as the TAO/TRITON Array. Figure 1 shows the locations of the TAO/TRITON buoys.

The Array's operational significance is for the improved detection, understanding, and prediction of the El Niño and the Southern Oscillation (ENSO) phenomena, which in turn have significant implications for climate predictions. In addition, the observations are used for real-time operational numerical weather prediction and marine weather analysis. The moorings also serve as important and convenient platforms to perform various ocean and atmospheric research projects. TAO is one of the components of the Global Tropical Moored Buoy Network which is one of the subsystems of the Global Climate Observing System (GCOS) and the Global Ocean Observing System (GOOS), which is the oceanographic component of the Global Earth Observing System of Systems (GEOSS). TAO/TRITON has been described as the "crown jewel" of the Global Climate Observation System [1]. TAO provides real-time and post-deployment recovery data to support climate analysis and forecasts for improved detection, understanding, and prediction of El Niño and La Niña.

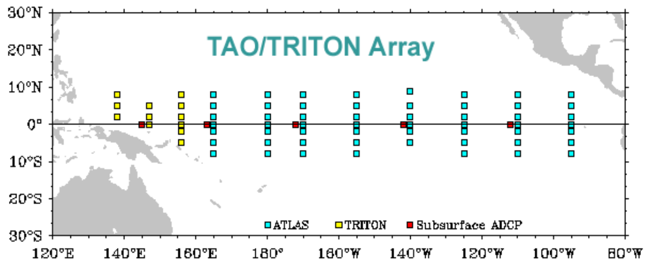


Figure 1 Location map of TAO/TRITON buoys.

The TAO array was developed and completed by NOAA's Pacific Marine Environmental Laboratory (PMEL) in 1994. NDBC assumed responsibility for data management of TAO in 2005 and the at-sea operations in 2007. Because the TAO array was developed and completed many years ago, many of the existing TAO components are obsolete or no longer available or supported by the manufacturers. To ensure the ongoing and long-term TAO operations for collecting valuable climate data, NDBC started to refresh the TAO system (which is called the TAO Refresh system) during the TAO transition.

In this paper, the TAO configurations of TAO buoys/moorings and the current operations are first described. Some examples of TAO data are presented. Then, the ongoing technology refresh efforts and TAO refresh system are discussed. Some results of the inter-comparison between the TAO Legacy and TAO Refresh systems are presented. The goal is to update on current and planned TAO status and to assure the climate community that the TAO array and its operations can meet the rigorous demands of the climate and operational communities in the future.

2. TAO Current Configurations and Status

The current TAO buoy system, which is often referred as Autonomous Temperature Line Acquisition System (ATLAS), was designed in the 1994 and the deployments completed in 2001 by NOAA Pacific Marine Environmental Laboratory. This existing TAO/ATLAS system is termed now the TAO Legacy system. More details of the TAO/ATLAS buoy system can be found in [2].

The TAO/ATLAS surface buoy is a 2.3 m diameter fiberglass-over-foam toroid, with an aluminum tower and a stainless steel bridle. When completely rigged, the system has an air weight of approximately 660 kg, a net buoyancy of nearly 2300 kg, and an overall height of 4.9 m. The electronics tube is approximately 1.5 m long, 0.18 m diameter, and weighs 27 kg. Moorings are deployed in water depths between 1500 and 6000m. TAO buoy and mooring systems collect meteorological, ocean near-surface, and subsurface observations. Non-rotating 0.96 cm diameter 3×19 wire rope is used in the upper 500 m of the mooring for inductive communication between underwater sensors and the data logger in the buoy. Eight-strand plaited nylon line is used for the compliant member of the mooring with an acoustic release above a 2000 kg anchor and a typical mooring scope of 0.98.

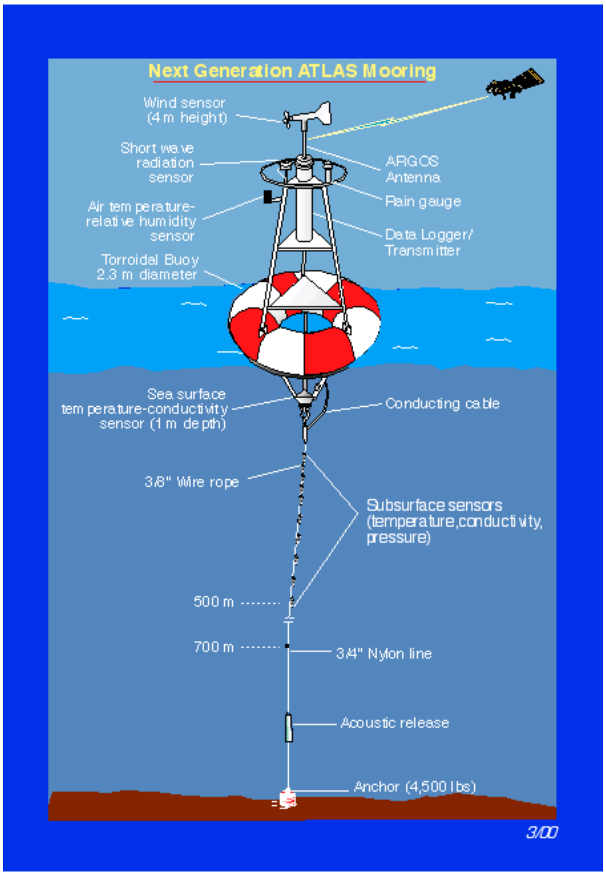


Figure 2 Sketch of standard TAO configuration.

There are two TAO sensor configurations: the standard and flux configurations. The standard configuration TAO buoy consists of one air temperature/relative humidity sensor, one anemometer, one sea surface conductivity/temperature sensor, eight ocean temperature sensors, and two ocean temperature/pressure sensors. Figure 2 shows the standard TAO buoy configuration. Currently, four of the 55 sites (and one of the 13 TRITON sites) at the equator are designated as the flux reference sites and have the flux configuration. In addition to the sensors for the standard configuration, the flux configuration adds one barometer, one shortwave radiation sensor, one rain gauge, up to 5 current meters, and replacement of up to seven ocean temperature sensors with ocean conductivity/temperature sensors. The ADCP mooring configuration consists of one ADCP at an average of 300 meters in depth with an upward looking design and an ocean conductivity, temperature, and depth sensor.

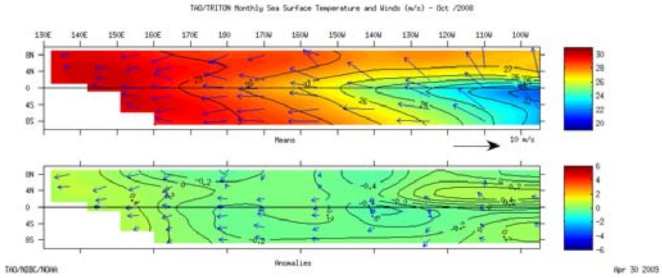
In general, every TAO buoy in the field is serviced twice a year: one service will retrieve and redeploy the buoy and mooring and the other service will only make necessary repair of damaged/failed/problematic sensors or components close to ocean surface. NOAA's research ship, the KA'IMIMOANA, is dedicated to servicing TAO moorings, with an annual operating schedule of 250 days at sea. However, due to limited ship time from the KA'IMIMOANA and some urgent discrepancy responses, other NOAA ships, University-National Oceanographic Laboratory System (UNOLS) research ships, or commercial vessels are used occasionally.

The TAO ATLAS system transmits data via Service Argos that uses Polar Operational Environmental Satellite (POES), which only allows a couple of transmissions during a day. Therefore the ocean temperatures are averaged over 24 hours on board the Atlas buoy and then transmitted on a daily basis. The TAO data are processed daily at NDBC immediately after receipt. The first step in the daily processing is the application of calibration functions. Once the data are converted to engineering units, they are subjected to a series of automated quality control checks. The released data are then pushed to the TAO web data display and data delivery systems for public access.

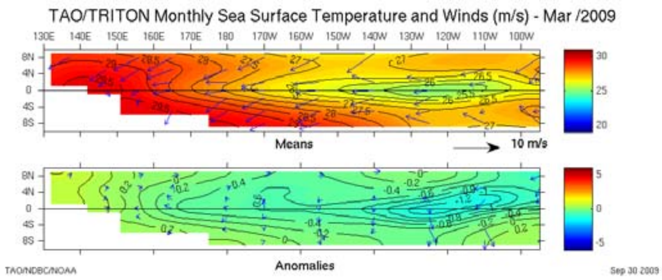
After every mooring recovery, the internally recorded, high-temporal resolution data are subjected to a series of quality checks similar to those for real-time data. Data are de-spiked as necessary, and additional analysis is performed, such as computation of spectra and histograms. In order to compare the high resolution data with the daily means returned in real-time, daily means are re-computed from the high-resolution data. In general, the re-computed daily means from delayed mode data are considered to be of equal or higher quality. If this is the case as determined by data quality analysts, the re-computed daily means replace the ones returned in real-time.

As examples of TAO/TRITON data, Figures 3-(a), 3-(b), and 3-(c) show the latitude-longitude contour plots of monthly sea surface temperature and wind for October, 2008, March 2009 and March 2010, respectively. According to NOAA Climate Prediction Center's ENSO Alert System Status [3], the status was "El Niño Advisory" in March 2010. It is clear from the figures that the sea surface temperatures along the Equator in March 2010 were much warmer than those in March 2009 (which was in the "La Niña Advisory" status) and October 2008 (which was in the "ENSO-neutral conditions" status).

(a) October 2008 (ENSO-neutral conditions)



(b) March 2009 (La Niña Advisory)



(c) March 2010 (El Niño Advisory)

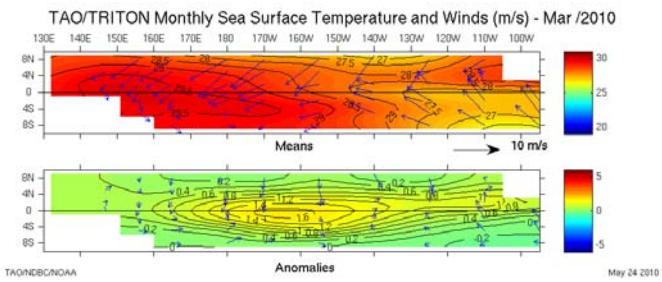


Figure 3 Lat-Lon contour plots of surface temperatures and wind (upper) and temperature and wind anomalies (lower).

3. TAO Technology Refresh

Because the TAO array was developed and completed many years ago, many of the existing TAO components are obsolete or no longer available or supported by the manufacturers. To ensure the ongoing and long-term TAO operations for collecting valuable climate data, NDBC started to refresh the TAO system during the TAO transition. In addition, NDBC takes advantage of advances in the state of the art to meet unfulfilled observing requirements. We will be briefly described the TAO Refresh System. More details of the TAO Refresh system can be found in [4].

The refreshed components for the TAO Refresh System include:

- Newly-designed data logger,
- Commercial off-the-shelf (COTS) underwater temperature/conductivity sensors,
- New compass,
- Some engineering redesign, including new rain gauge and radiometer interface (for the flux configuration), improved TAO tube design, inductive modem coupler and module design, etc.
- Iridium communication,
- Modified and enhanced shore-side data system.

Since the meteorological sensors (including the anemometer and the air temperature/relative humidity sensor) used in the TAO Legacy system are not obsolete, the TAO Refresh system are retains those sensors.

NDBC designed a new, all-purpose data collection system that effectively interfaces between the new sensors and the new communications system. The new data logger/payload is called the Advanced Modular Payload System (AMPS). The AMPS is modular, very low power, and small in size, provides data acquisition, control, processing, and telemetry for the TAO Refresh system. This new data collection system is also being used on NDBC's Weather and Ocean buoys.

To replace the obsolete underwater sensors and inductive modems in the TAO Legacy system, NDBC determined that the most cost-effective approach for sensor replacement was to use the COTS temperature, salinity, and pressure sensors which have been time-tested and proven in the JAMSTEC/TRITON Array. Just like in the case above, where the payload is common with NDBC's other buoy systems, these commercial off-the-shelf oceans sensors are common with NDBC Weather and Ocean systems, as well. Sharing common technology between several systems is very efficient, cost effective, and contributes to the overall maintainability, reliability, and availability of each system.

Since the obsolete compass embedded in the data logger of the TAO Legacy system has been discontinued by the manufacturer, the Refresh system adopted a new internal compass.

Because of the new data logger AMPS used in the TAO Refresh systems, the conditioning and interface electronics for the rain gauge and radiation sensors (used in the flux configuration) are also redesigned.

Engineering redesigns contribute to increased data availability both by reducing the risk of outages and reducing the length of outages. For example, Lithium-ion batteries reduce the weight of the payload/tube and increase the buoy stability. A separate battery enclosure reduces magnetic effects and allows battery replacement at sea. The overall TAO Refresh design was hardened by enclosing all antennas and as much cabling as possible in protective housing lessening the exposure to the marine environment and increasing reliability.

Data measured from the TAO Refresh systems are transmitted and reported in real time via the short burst data (SBD) mode of the Iridium communication system, which allows the TAO Array to meet requirements for hourly resolution time series data and high-frequency weather phenomena, and at the same time keeping the power consumption low. The Iridium satellite coverage means all data is transmitted within an hour of recovering from the sensors. The TAO Legacy system provides high-resolution ocean data collected every two minutes in the "delayed mode" only. This data is made available to researchers only after the buoys are recovered following a year of being deployed. If a TAO Legacy buoy goes adrift, the data are often lost. The TAO Refresh buoy using Iridium communications is capable of delivering the same delayed mode data in "real time", limiting data lost in the event of buoys going adrift.

The temporal resolution requirements in real-time are daily averages (minimum) and hourly averages (optimum). The TAO Legacy presently meets the minimum requirement but not the optimum requirement. Temporal resolution requirements in delayed mode for most variables are hourly resolution (minimum) and 10 minute resolution (optimum). The TAO Refresh system meets the optimum requirements and delivers the same delay mode data in real time.

In order to process and handle the detailed data collected by the TAO Refresh systems and transmitted hourly from the Iridium SBD system, the TAO data system is redesigned from ground up for the much larger data volume in near real time and more frequent data transmission of the TAO Refresh system. The new TAO data system can support both TAO Legacy and Refresh buoys. When high temporal resolution (10-minute and hourly) data from the TAO Refresh systems are delivered to an NDBC communication server hosted at the National Weather Service Telecommunications Gateway (NWSTG), a decoder is used to decode the data and store them in the underlying databases. Hourly or high resolution data quality control checks are performed and the results are integrated into the same daily status report for the legacy moorings. Quality controlled data are then pushed to the TAO web data display and data delivery systems as well as to NWSTG for GTS dissemination. The IT architecture and design follow the NOAA Global Earth Observation – Integrated Data Environment (GEO-IDE) guidance and assist NDBC managements to achieve the TAO array transition rationale, including make operations more cost effective, protect against changes in personnel, and ensure continuity of the data streams. Many new features have been introduced to the TAO data system while existing ones are maintained for backward compatibility. More details on the new data systems for the TAO system can be found in [5].

To maintain the high quality and integrity of the climate data, NDBC conducted a series of lab and field tests for the TAO Refresh system in addition to stringent tests for various components. These tests include:

- Laboratory tests were conducted at NDBC by comparing the TAO Refresh and the TAO Legacy sensors/systems;
- TAO Refresh buoys were deployed in the Gulf of Mexico for field testing; and
- TAO Refresh buoys are deployed in the Pacific Ocean next to TAO Legacy buoys for inter-comparison testing in the field. Figure 4 shows a TAO Refresh buoy at the 5N 140W site (water depth = 4,485m) next to a TAO Legacy buoy in the Pacific Ocean on April 7, 2010 for a side-by-side comparison.

Figure 4 Deployment of a TAO Refresh buoy at the 5N 140W site in the Pacific Ocean.

Numerous analyses on data from these lab and field tests have been conducted at NDBC. Some of results from the lab test and the field tests in Gulf of Mexico were presented in [4]. In addition to providing promising results for the TAO Refresh system, these lab and field tests have greatly helped NDBC to diagnose, improve, and refine the TAO Refresh system. Currently, there are eleven TAO Refresh buoys in the Pacific Ocean next to TAO Legacy buoys. Detailed analyses of data collected from TAO Legacy and Refresh buoys in the Pacific Ocean (using both the transmitted data and delay mode data) are underway. The preliminary results show the comparisons between the

TAO Refresh and Legacy buoys are reasonable with both systems exhibit the same daily characteristics. However, variability in oceanography over small spatial and temporal scales is challenging, but quiescent times indicate similarity in the data.

As an example, Table 1 shows comparisons of 10-min temperature data between the TAO Refresh buoy and the Legacy buoy at 2S140W. Data are from the period from 12 May 2008 to 27 October 2008 at depths 1m, 20m, 40m, 60m, 80m, 100m, 120m, 140m, 180m, 300m, and 500m. At 40m and 100m depths, the TAO Refresh sensors failed to record any good data so they are excluded. The mean and standard deviation values for both Refresh (labeled as Ref in the table) and Legacy (labeled as Leg in the table) are listed in Columns 2 and 3. From the values of the correlation coefficient (R), the data from the two buoys match quite well, despite that the distance between the two stations (they were deployed a few miles away to prevent their moorings from tangling). The correlation coefficients for 80m, 120m, 140m, and 160m are smaller. These high variations may be due to the arrival time differences of the internal waves between the two locations and the variability of ocean thermocline. The correlation coefficients for 80m, 120m, 140m, and 160m improved significantly when we filtered out some data with clear differences in arrival time.

Table 1 Comparison of temperature data between TAO Refresh and Legacy buoys at the 2S 140W site.

Depth (m)	Mean (Ref/Leg)	Standard Dev. (Ref/Leg)	R
1	26.42/26.48	0.766/0.759	0.9986
20	26.36/26.36	0.770/0.763	0.9991
60	26.23/26.27	0.774/0.769	0.9822
80	25.18/25.40	1.536/1.395	0.8360
120	16.31/16.56	1.922/2.045	0.9056
140	14.06/14.20	0.793/0.879	0.8802
180	12.52/12.64	0.418/0.409	0.8952
300	11.07/11.14	0.294/0.287	0.9556
500	8.45/8.56	0.413/0.440	0.9386

4. Summary

The Tropical Atmosphere Ocean (TAO) Array is transitioned from the National Oceanic and Atmospheric Administration's (NOAA) research arm to its operational arm within the National Weather Service at the National Data Buoy Center (NDBC).

NDBC designed, fabricated, integrated, and tested the TAO Refresh buoy system to ensure sustained and smooth operations of the TAO array. The TAO Refresh buoy design meets or exceeds all the National Weather Service Observation Requirements for TAO Mooring for the frequency per day, the maximum delay, and averaging period in addition to meeting the specific minimum requirements for TAO mooring measurements in terms of accuracy, resolution, range, and vertical and temporal sampling.

NDBC has conducted laboratory tests and has successfully deployed several TAO Refresh systems in the Gulf of Mexico and the Pacific TAO array. Currently, eleven TAO Refresh buoys are deployed in the Pacific for in-situ testing with the TAO Legacy buoys. Preliminary evaluations indicate good agreement between the TAO Legacy and TAO Refresh systems.

NDBC plans to continue deploying TAO Refresh buoys next to the TAO Legacy buoys for more side-by-side field comparisons. Upon completion of satisfactory inter-comparisons, the TAO Refresh systems will gradually replace the TAO Legacy systems as funding for replacement hardware allows.

To ensure the continuity and supportability of long-term ocean climate data, the TAO operations and technology refresh efforts follow the ten Climate Monitoring Principals [6], including Management of Network Change, Parallel Testing, Metadata, Data Quality and Continuity, Integrated Environmental Assessment, Historical Significance, Complementary Data, Climate Requirements, Continuity of Purpose, and Data and Metadata Access.

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