7.5 THE TROPICAL ATMOSPHERE OCEAN ARRAY (TAO) REFRESH–NEW CAPABILITIES AND VALUE ADDED

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1. INTRODUCTION

The National Oceanic and Atmospheric Administration's (NOAA) National Data Buoy Center (NDBC) successfully completed the transition from Research to Operations of the Tropical Atmosphere-Ocean Array (TAO) in 2007. TAO consists of 55 buoys and four upward looking Acoustic Doppler Current Profilers (ADCP) moorings that straddle the equatorial Pacific making real-time meteorological and oceanographic observations to monitor climate variability and to improve the detection, understanding, and prediction of the El Niño and Southern Oscillation (ENSO) (Figure 1). TAO Refresh, an initiative to upgrade aging sensors and electronics, inherited from the previous TAO systems and to take advantage of advances in communications, was an integral part of the transition plan the TAO array from research to operations.

1.1 The Development of the TAO Array

Development of the TAO array was motivated by the 1982-1983 El Niño event, the strongest of the century up to that time, which was neither predicted nor detected until nearly at its peak. The event proved the need for real-time *in-situ* data from the tropical Pacific for monitoring, prediction, and improved understanding of El Niño. The success of the TAO array early in the international Tropical Ocean Global Atmosphere (TOGA) Research Programme led to widespread support within the climate research community. The most notable development in TAO was real-time measurements from moored systems, known as the Autonomous Temperature Line Acquisition System (ATLAS) developed by NOAA's Pacific Marine Environmental Laboratory (PMEL) (McPhaden *et al.,* 1998).

The 70-station array was installed over 10 years and was completed as the TOGA Programme was ending in December 1994 (McPhaden, 1995). Installation of the network was accomplished through partnerships of institutions in the United States, Japan, France, Taiwan, and Korea.

The *NOAA Ship KA'IMIMOANA* was commissioned in 1996 to service the array east of 165 East longitude. In 1997, the U.S. Congress authorized long term, sustained support of the TAO array as part of an operational El Niño/Southern Oscillation (ENSO) observing system. By January 1, 2000, moorings west of 165 East longitude were occupied by TRITON (Triangle Trans Ocean Buoy Network) buoys and maintained by the Japan Marine Science and Technology Center (JAMSTEC). In recognition of Japan's contribution, the array was re-named the TAO/TRITON array.

1.2 NOAA Transition

In June 2002, the NOAA Administrator endorsed two recommendations from NOAA's Program Review Team (PRT) regarding the observing systems. He concurred with the PRT Recommendation that stated,

> *NOAA's Office of Oceanic and Atmospheric Research [OAR] often fields and supports research and development (R&D) observing systems that have become, de facto, operational. The PRT supports the development and deployment of R&D systems; however, after NOAA has identified primary operational functions for these systems, the PRT recommends that these systems should migrate to the line offices with the appropriate operational mandate.*

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The NOAA Administrator also concurred with other PRT Recommendations and concluded,

> *Operation and maintenance of marine environmental buoys (weather buoys, Tropical Atmosphere Ocean buoy network (TAO), and Coastal-Marine Automated Network (C-MAN) stations) should be consolidated. I support the ongoing transfer of the Tsunami buoy array from OAR to NWS [National Weather Service]/National Data Buoy Center and request that OAR and NWS develop a transition plan for the TAO array....*

Subsequently, in a memorandum dated August 13, 2002, the Deputy Directors of OAR and NWS requested the Directors of PMEL and NDBC to develop a transition plan for presentation to the NOAA Executive Council by January 15, 2003, to transfer the TAO array to NDBC.

NOAA (2005) defined Operations as:

> *Sustained, systematic, reliable, and robust mission activities with an institutional commitment to deliver appropriate, cost-effective products and services.*

NDBC, PMEL, and the NOAA Office of Global Programs (in October 2005, OGP was incorporated into NOAA's Climate Program Office) established a TAO transition plan in August 2004. This plan describes a "phased approach" to the transition that began in Fiscal Year 2005. The transition plan is based on transition principles to ensure the effective transition of the TAO Array from research to operations. These principles included: laying the groundwork for sustained and successful TAO operation after the transition, maintaining the quality and integrity of the data, and ensuring transparency of the transition to current TAO data users and partners. The transition was only the latest part of a continual process of change and improvement (Table 1).

At the time of initial transition planning, there was within NOAA no precedent for successful transition of an ocean observing system for climate from research to operations (McPhaden, 2005). Transition would be conducted in three phases: Shoreside Data Operations (Bouchard *et al.*, 2007), at-sea Operations, and finally a program of technology refresh to replace obsolete equipment (Moersdorf, 2004).

1.3 The Refresh

During the transition planning, a number of TAO components were identified as becoming obsolescent and not being supported by manufacturers. The then current TAO system, the Next Generation ATLAS (Autonomous Temperature Line Acquisition System) system (Figure 2) had been developed in 1994 (Milburn *et al.,* 1996). Next Generation ATLAS has sometimes been referred to as TAO Legacy when mentioned with TAO Refresh. The components in need of replacement included the compass, the interface for the rain gage and radiation sensors, the central processing unit/datalogger, and the subsurface temperature and salinity sensors (Figure 3). In addition, NDBC, exploiting its expertise gained by use on its other systems, would replace the Service Argos with Iridium communications (Teng et al., 2006). NDBC would use its own Advance Modular Payload System (AMPS) payload for central processing unit/datalogger (Lessing *et al*., 2008).

The subsurface sensors would be replaced by commercial-off-the-shelf (COTS) systems. The COTS approach provided cost-effective sensors that were well-documented and time-tested and well-known to the oceanographic and climate communities.

2. NEW CAPABILITIES AND VALUE-ADDED

The new capabilities and value-added come primarily from the revolution in marine communications of the Iridium satellite system. The new capability reduced the latency of the data and provided the full-resolution dataset in real-time.

2.1 Data Transmissions

Next Generation ATLAS used the Service Argos communications system. Service Argos used the NOAA Polar Orbiting Satellites to acquire data transmissions from the Next Generation ATLAS buoys, download the messages for rudimentary quality control, processing and distribution to the Global Telecommunication System (GTS), and then forward the data once a day to PMEL for quality control. PMEL then would communicate with Service Argos to (a) Stop the release of data, (b) Release new or previously stopped data, or (c) Change the processing coefficients.

The Polar Orbiting Satellites (usually two) had limited bandwidth and did not provide continuous coverage. The limited bandwidth only allowed for daily average measurements from the sensors and a few hourly measurements per day. The full-resolution data would only be available when and if the sensors were recovered – which was about once a year. The daily averages were computed from a minimum number of hourly averages, if the minimum number were not available the daily average was not provided. So users would know that at least the minimum number to form the daily average were used, but did not know if a full set of hourly averages were in the daily average.

TAO Refresh's use of Iridium allows NDBC to transmit the full-resolution data in real-time. Once an hour, six 10-minute measurements (NDBC, 2011) are sent directly to NDBC for quality control and distribution via the GTS increasing the available data and reducing latencies. For example, an intercomparison between co-located TAO Refresh and Next Generation ATLAS from October through December 2009 showed TAO Refresh providing data at each hour of the day and achieving more than 95% data while Next Generation ATLAS provided data at 16 hours a day with 75% data availability (Figure 4).

NDBC no longer produces daily averages, instead users are free to build their own averages and statistics to suit their needs and have complete understanding of the number of degrees of freedom in the compilation of statistics. The real-time transmission of the full-resolution data also reduces the risk of losing the data should the buoy or sensors be lost or the data fail to record.

2.2 Quality Control

By receiving the data directly at NDBC, NDBC can ensure complete end-to-end quality control of the data. Instead of post-release quality control, performed under Next Generation ATLAS, NDBC performs its quality control before the data are released to the GTS. NDBC quality control is a continual process rather than once-day.

Prior to transition, if a TAO buoy broke its mooring and started drifting, the data would only be released if it stayed within a 2° X 10° data grid. Applying its familiarity with drifting buoys and its operational perspective, NDBC saw the utility of releasing data even if a buoy moves out of its data grid. NDBC would assign a station number appropriate for a drifting buoy and release the data (Figure 5). This has resulted in thousands of marine observations in data sparse regions.

2.3 Anti-Vandalism Initiatives

Loss of data due to buoy vessel impacts and vandalism has been a long-standing issue (for example, McPhaden, 1995) for the TAO Array. Vandalism can be deliberate, such as the removal of equipment from a buoy, or inadvertent as a result of fishing activities. The buoys attract fish, and the fish attract fishermen. As the fish aggregate under the buoy, fishermen will pull the buoy and the fish some distance from the mooring anchor and then quickly release the buoy allowing the fishermen to net the slow-responding fish. This activity causes stress to the mooring and can lead to immediate or delayed failure of the mooring. This practice also interferes with accurate collection of subsurface data, as the instruments are suddenly displaced upwards. With Next Generation ATLAS, evidence of vessel impacts and vandalism would often only be data outages.

The high-resolution, real-time subsurface pressure data of TAO Refresh provide sufficient resolution to detect sudden displacements of the mooring that can be indicative of vessel strikes or vandalism (Figures 6a and 6b). However, some ambiguity remained as some displacement can be caused by the effects of currents or wave action on the buoy.

Although not part of the initial TAO Refresh Plan, the Iridium communications allow NDBC to supplement vandalism pressure signatures with real-time camera images (Figures 6a and 6b). The images can corroborate the pressure signatures as vandalism and even allow NDBC to indentify offenders by capturing the vessel's name or profile and document the incidents for further use. Presently the images are limited to daylight hours, but vessels will often use lights at night in their fishing activities and that will provide sufficient illumination for identification.

A combination of the appearance of strong currents in the camera imagery (Figure 7a) and sensor jumps in the high resolution data (Figure 7b) were among the indicators that a buoy had broke its mooring and had healed over enough to submerge electronics. The imagery also provides a value in documenting failures, so that effective maintenance plans can be carried to repair failures, such as distinguishing mechanical failure from electronics failure (Figure 8).

The camera images are an important part of an evolving set of initiates to raise awareness and effectively combat vandalism to keep these vital ocean observations available for improved weather and climate forecasting (Willis and Griesbauer, 2013).

3. CONCLUSION AND PLANS

TAO Technology Refresh provided a comprehensive approach to avoid the impending obsolescence of the Next Generation ATLAS system and preserve the TAO mission to provide real-time atmospheric and ocean data for improved detection, understanding and prediction of weather and climate, especially El Niño and La Niña.

Advances in the state of the art of communications have brought additional capabilities and value-added in the form of reducing data latency, empowering users with the ability to tailor datasets to meet their specific needs, and begin the process of preventing vandalism and loss of data.

The replacement of Next Generation ATLAS moorings with TAO Refresh has slowed in recent years due to budgetary constraints. However, NOAA has committed sufficient resources to complete the replacement of the entire array by the end of 2014.

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Table 1: Timeline of Significant TAO Events

1982-83	The strongest El Niño of 20th Century (at that time) went undetected until peak
1984	Development of the Autonomous Temperature Line Acquisition System (ATLAS) Mooring.
1985-1994	Tropical Ocean-Global Atmosphere (TOGA) program. 70 moorings at conclusion.
1994	Development of the Next Generation ATLAS Mooring.
1995	TAO succeeds TOGA; Part of the Climate Variability and Predictability (CLIVAR) program, the Global Ocean Observing System (GOOS), and the Global Climate Observing System (GCOS)
1997-98	TAO documents "… by some measures, the strongest [El Niño] on record, with major climatic impacts felt around the world." McPhaden (1999)
2002	NOAA Administrator endorses Recommendations of NOAA Program Review Team to transition; NOAA Line offices, OAR and NWS, prepare Transition Plan
2005-2007	Transition from NOAA Research to Operations at NDBC
2007-2010	Development & Testing TAO Technology Refresh
October 5, 2010	TAO Refresh Commissioned for Operational Use
2014	Complete Replacement of Remaining 24 Next Generation ATLAS by TAO Refresh

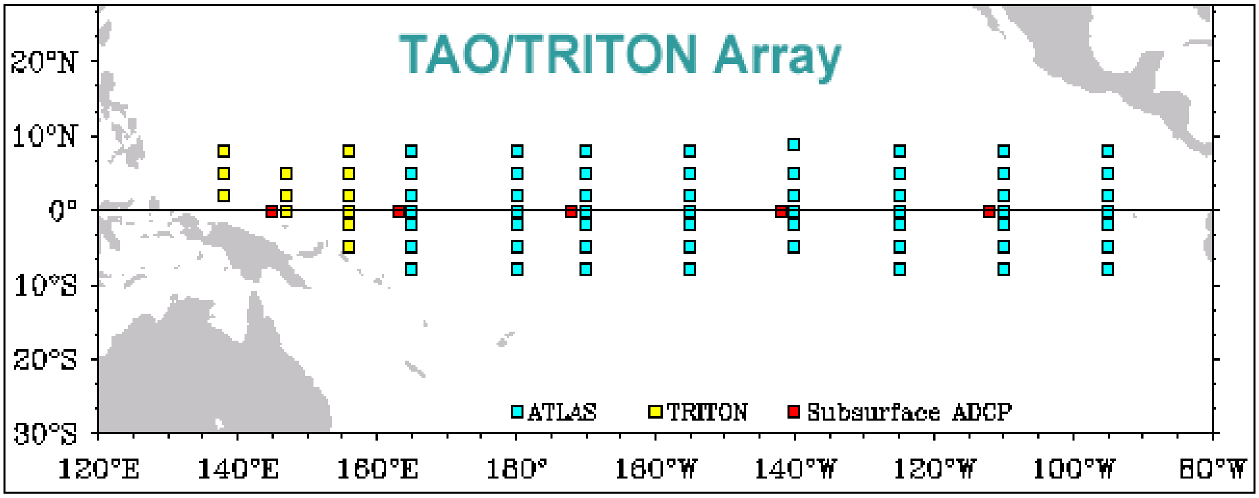

Figure 1: TAO/TRITON Array Buoy Locations

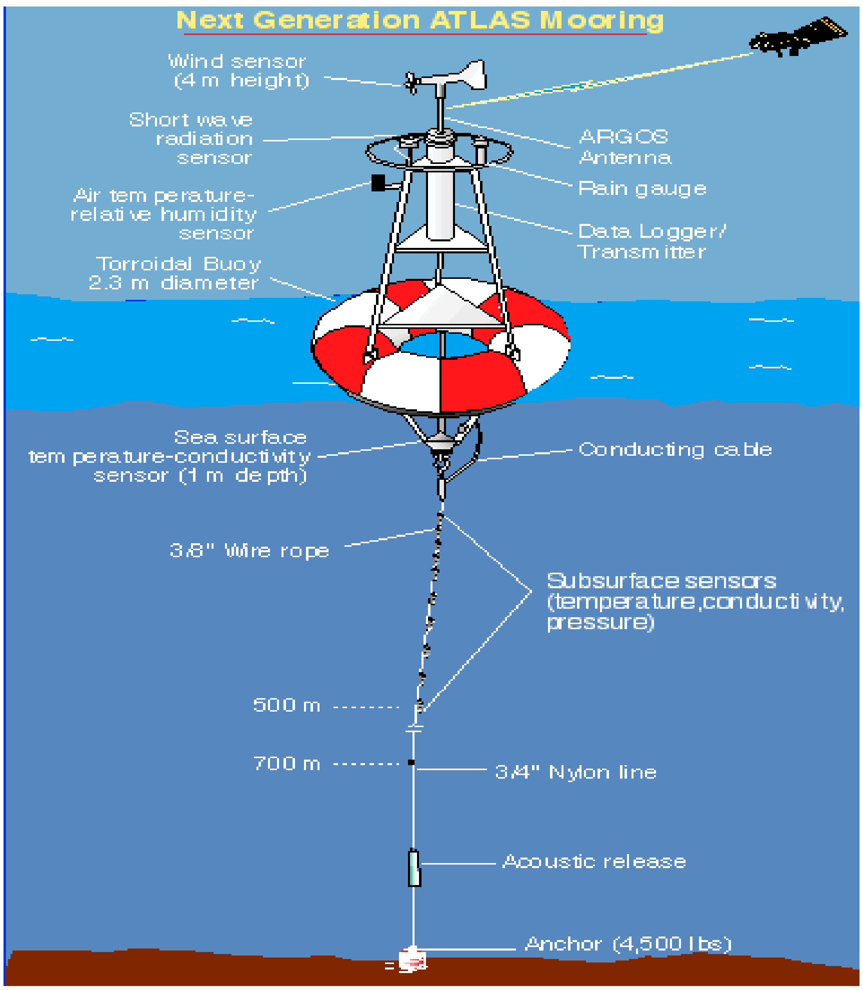

Figure 2: Next Generation ATLAS (circa 1994)

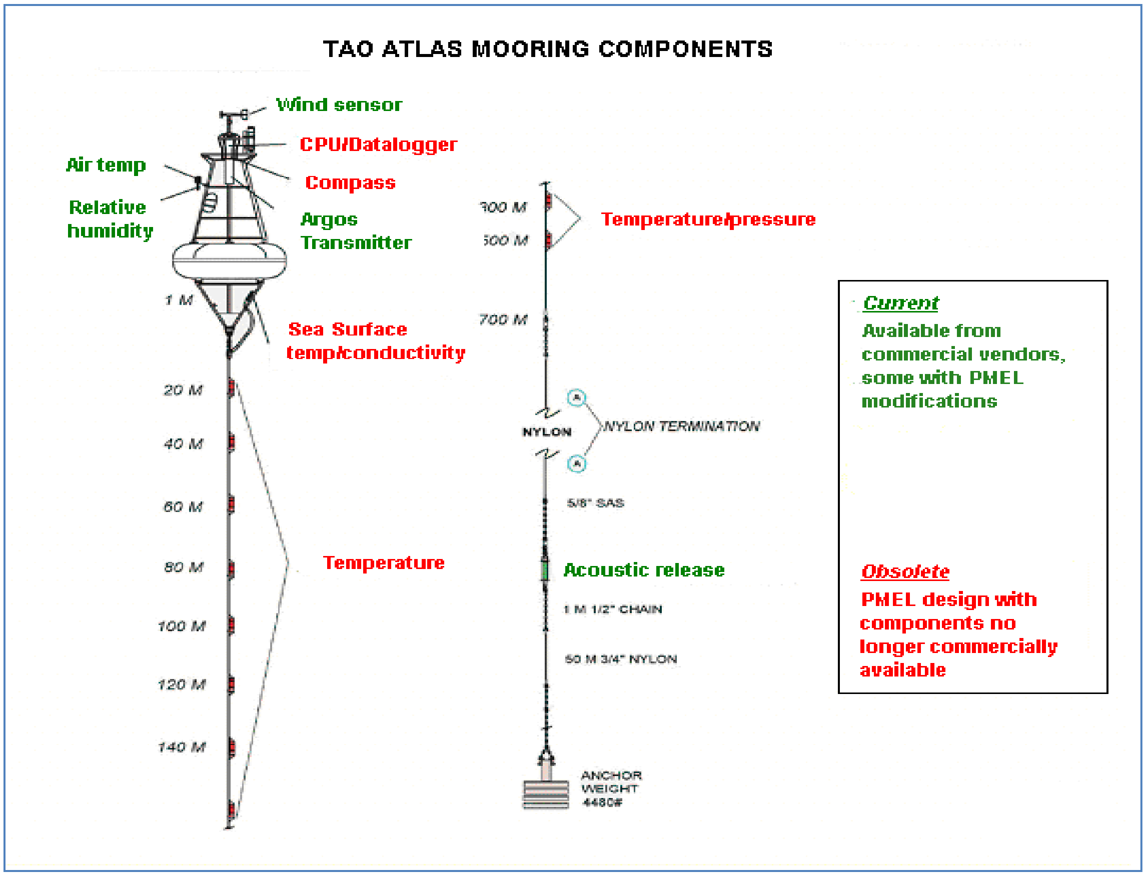

Figure 3: Next Generation ATLAS Components to be Refreshed

Figure 4: Data Availability for Co-located Buoys Oct-Dec 2009

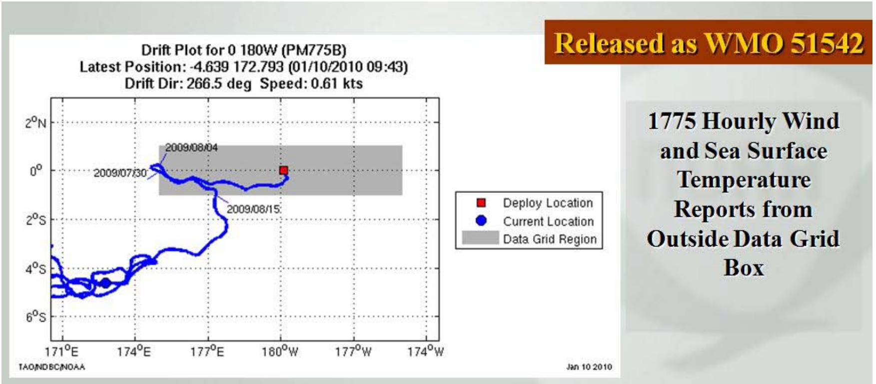

Figure 5: Adrift Buoy Data Released Outside of Data grid

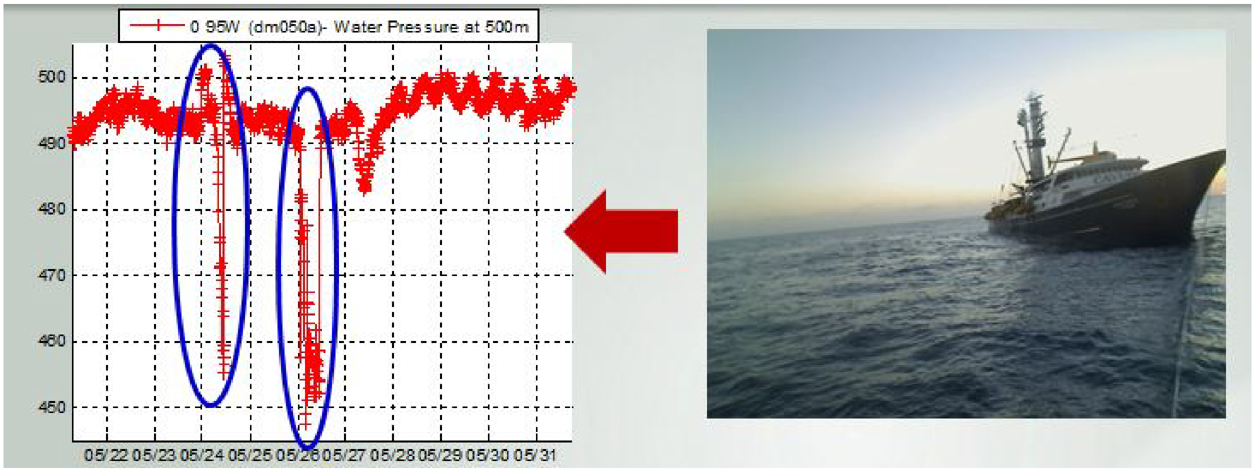

Figure 6a: High-resolution Data (left) Confirms Data Interference by Fishing Vessel Camera Image (right)

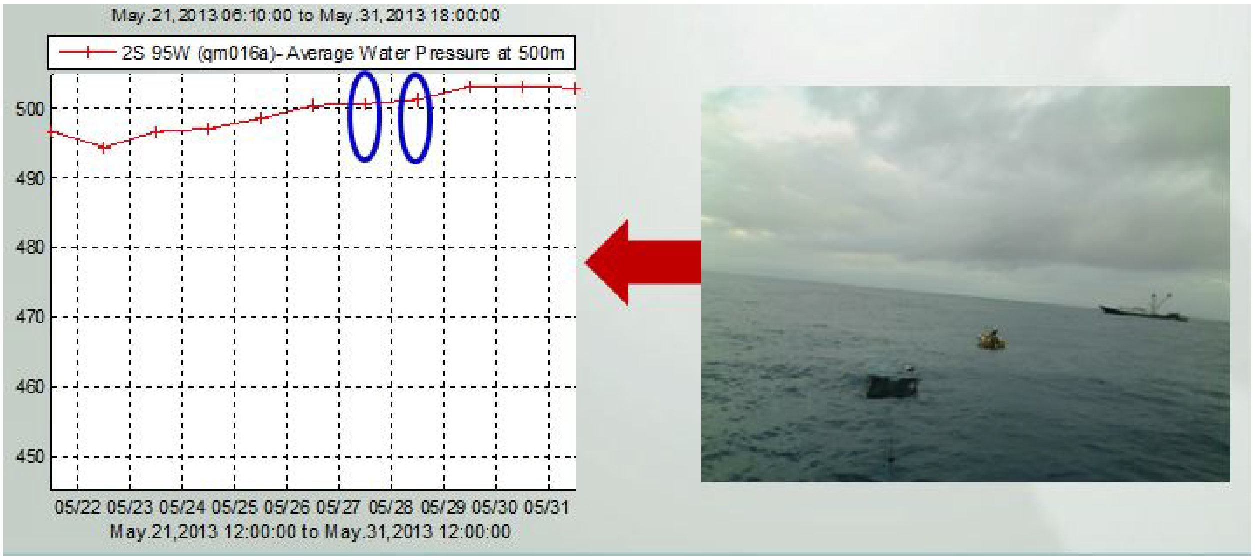

Figure 6b: ATLAS Data too Coarse (left) to Confirm Data Interference as Seen in Camera Image (right)

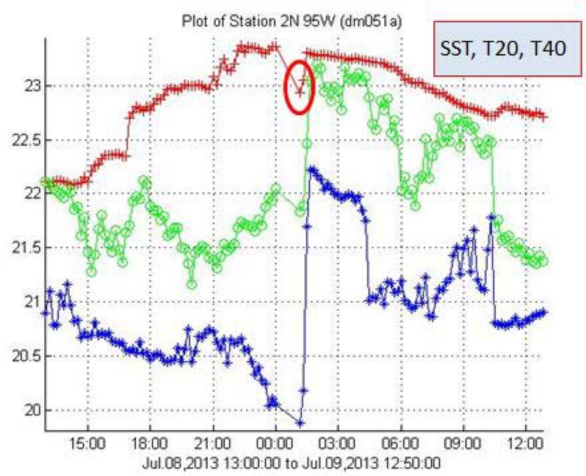

Figure 7b: Temperature jumps in High Resolution Data

Figure 7a: Evidence of Strong Currents in Camera Imagery

Figure 8: Series of images showing the collapse of anemometer stanchion