Progress Report
Global Tropical Moored Buoy Array

Period of Activity: 01 October 2020 – 30 September 2021

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Budget Summary
FY 2021:
PMEL
PIRATA $600,000 (NWS)
GTMBA $3,650,000
AOML
PNE $184,295

Global Tropical Moored Buoy Array

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1. Project Summary

The Global Tropical Moored Buoy Array (GTMBA) project is a sustained multi-national effort to provide high quality time series data in real-time from moored buoys throughout the global tropics for weather and climate research and forecasting. Physical and biogeochemical measurements in the upper ocean (surface to 500 m depth) and near-surface atmosphere are important for improved description, understanding, and prediction of climate variability at seasonal to decadal time scales. The tropics are a key region of Earth's climate system. Solar irradiance is maximum in the tropics, from which heat is exported poleward to moderate climate at higher latitudes. Sea surface temperatures are the highest in the world ocean in the tropics, engendering vigorous ocean-atmosphere interactions that give rise to phenomena such as the El Niño-Southern Oscillation (ENSO), the seasonal monsoons, the Indian Ocean Dipole, and tropical Atlantic climate variability. These phenomena affect patterns of weather variability most immediately in nations within the tropical belt, but their impacts are felt worldwide through oceanic and atmospheric teleconnections. Heat waves, droughts, heavy rains, flooding, tropical storms, and other severe weather events that result from tropical ocean-atmosphere interactions have significant socio-economic ramifications, as well as major impacts on terrestrial and marine ecosystems and fisheries. These consequences warrant sustained ocean observations as the foundation for development and improvement of weather and climate analysis and forecasting tools that may be used for advance warnings of impending natural hazards.

The Global Ocean Monitoring and Observing (GOMO) program provides support for two major moored arrays of the GTMBA project: 1) the Prediction and Research Moored Array in the Tropical Atlantic (PIRATA) and 2) the Research moored Array for African-Asian-Australian Monsoon Analysis and prediction (RAMA). The Tropical Atmosphere Ocean (TAO) array in the Pacific, also part of the GTMBA project, is managed and maintained by the National Data Buoy Center (NDBC) of NOAA's National Weather Service (NWS). International support for the GTMBA is formalized through several Memoranda of Understanding (MOU) and Implementing Arrangements (IA) between NOAA and government agencies in Japan, France, Brazil, India, and Indonesia.

GTMBA data from RAMA, PIRATA, and TAO moorings are available in real-time to operational centers worldwide on the Global Telecommunications System (GTS) and publicly available on the Pacific Marine Environmental Laboratory (PMEL) data display and delivery website: https://www.pmel.noaa.gov/gtmba/data-access/disdel.

2. Scientific and Observing System Accomplishments

This section summarizes the GTMBA project accomplishments in FY 2021. Section 2.1 details the progress on milestones and performance measures for each observing system array in the GTMBA project and describes some of the notable observing achievements accomplished in FY 2021. Section 2.2 describes significant scientific accomplishments during FY 2021 for advancing climate and ocean research. Section 2.3 describes GTMBA data delivery, derived data products, instrumental records of Essential Ocean Variables and Essential Climate Variables, and the GTMBA website. Finally, Section 2.4 presents issues related to funding that affect progress.

2.1. GTMBA Progress, Performance, and Achievements During FY 2021

The GTMBA project supports NOAA's strategic plan goal of "an informed society anticipating and responding to climate and its impacts." It also underpins the international Climate Variability, Predictability and Change (CLIVAR) program's efforts on tropical ocean climate research as well as efforts to develop a sustained Global Ocean Observing System (GOOS). Management of the GTMBA and its program elements is consistent with the "Ten Climate Monitoring Principles." The program is a NOAA contribution to the Global Ocean Observing System (GOOS), the Global Climate Observing System (GCOS), and the Global Earth Observing System of Systems (GEOSS).

GTMBA project deliverables include oceanic and atmospheric time series data, graphical analysis based on the data, scientific publications, and scientific advice to national and international oceanographic and climate related programs. Data are freely available on the Project display and delivery web page: http://www.pmel.noaa.gov/gtmba/data-access/disdel. Flux reference mooring products are available at http://www.pmel.noaa.gov/gtmba/data-access/flux/index.html.

The FY 2021 work plan established a new series of performance measures. The summary of GTMBA project performance measures for FY 2021 are listed in Table 1.

Table 1. Performance Measures (FY 2021)

Performance Measure	**FY 2021 Metrics**
Number of PMEL mooring sites[1] serviced	11 (0^R+11^P)
Data return: Number of EOV days	163,074
Publications authored/co-authored by PIs	23
Publications using data from observing system	127[3]

Notes: R = RAMA; P = PIRATA[2].

1: PMEL mooring sites refer to independent sites (i.e., locations) where PMEL mooring assets are deployed. RAMA sites maintained by Japan and China are not included in the totals. Some mooring sites may include multiple moorings at a single site when both a surface mooring and subsurface ADCP mooring are present, e.g. at 0°, 67°E and 0°, 80.5°E in the Indian Ocean.

2: PIRATA is composed of 18 PIRATA surface mooring sites total: 10 PIRATA core mooring sites that are funded by NWS and 8 PIRATA extension mooring sites that are explicitly funded by GOMO. Of the 7 PIRATA mooring sites serviced in FY 2021, Only 2 mooring sites are PIRATA extension sites and the remaining 5 are core PIRATA sites.

3: According to Web of Science. This count is for calendar year 2021 rather than FY2021 for ease in tracking.

The number of PMEL mooring sites serviced in FY 2021 has been severely impacted by the COVID-19 pandemic. The number of mooring sites serviced was lower than anticipated at the start of FY 2021 because pandemic severely limited scheduling of cruises from the onset of the COVID-19 pandemic in March 2020 to present. In FY 2021 only two PIRATA cruises were completed and zero RAMA cruises were conducted. This resulted in the only metric where we did not meet the target of maintaining 28 PMEL mooring sites. However, during the FY 2021 we were able to service 11 PMEL mooring sites in PIRATA with cruises supported by France and USA (NOAA).

The data return performance measure, EOV days, refers to the total number of days of real-time data returned for each EOV measured, totaled over the course of a fiscal year for the moored buoy array funded by GOMO (i.e., all of PMEL RAMA and PIRATA moorings). Each sensor on each of the moorings is counted in computing EOV days of data. The temporal resolution of the real time data is in many cases hourly, so that there is an order of magnitude more EOV hours of data being telemetered in real time than shown in the table. Also, the EOV days performance measure only considers real-time data return. There are far greater delayed mode EOV data after the moorings are recovered and the 10-minute internally recorded subsurface data is downloaded. In FY 2021, we returned real-time data from sensors that spanned 163,074 EOV days from PMEL moorings. This exceeded our target of 130,000 EOV days.

The number of publications authored or co-authored by GTMBA PIs is the third performance measure identified in the FY 2021 GTMBA Work Plan. GTMBA PIs authored 23 publications plus the AGU book entitled *El Niño Southern Oscillation in a Changing Climate* in FY 2021. This exceeded our target of 6 publications. Finally, GTMBA also tracks a number of publications that explicitly mentions the use of data from the GTMBA moorings. During FY 2021 there were 127 relevant publications identified that use GTMBA data according Clarivate Web of Science. These are the publications we know about and therefore represent a lower bound on papers that have utilized GTMBA data. This exceeded the target of 50 publications that use data from the observing system. These publications are listed in Section 4 of this Progress Report.

In August 2021, representatives from NOAA and the Ministry of Earth Sciences (MoES) of India signed an updated 5-year partnership agreement to advance ocean and atmospheric observations in the Indian Ocean for improved weather and climate prediction. The virtual signing ceremony included a live demonstration of a new joint oceanographic data portal (https://incois.gov.in/portal/datainfo/buoys.jsp) that makes data from the RAMA and OMNI moored buoy arrays in the Indian Ocean publicly available for the benefit of research and forecasting. The renewed partnership also includes additional MoES ship time support for RAMA and a commitment to more closely coordinate the RAMA and OMNI moored buoy programs scientifically and operationally. The new agreement builds on a more than decade-long partnership between NOAA and MoES for Indian Ocean studies and is backed by a broad 10-year NOAA-MoES Science and Technology MOU signed in India in October 2020.

The GTMBA is presently 95% complete (Figure 1 and Table 2). Some mooring sites are occupied by both a surface and a subsurface mooring. NOAA provides the majority of moorings. Non-U.S. mooring contributions are from Japan (two surface moorings and one subsurface mooring in RAMA), France and Germany (two subsurface moorings in PIRATA), and China (one surface mooring and one subsurface mooring in RAMA). In 2012 JAMSTEC began to retire some TRITON sites in the Pacific. At the start of FY 2021, all but 2 of the original 12 TRITON Pacific surface sites had been retired. By the completion of FY 2021, the remaining two TRITON Pacific moorings were retired marking the end of the Pacific TRITON array. The two JAMSTEC sites that were retired in June 2021 are 0°, 156°E (including the co-located subsurface ADCP mooring) and at 8°N, 137°E. The Pacific array currently only consists of the 55 TAO surface mooring sites. Percent completion in Table 2 below is based on the original number of moorings in TAO alone and does not include the TRITON array, which is no longer a "planned" array now that TRITON has been formally decommissioned. Discussions are underway with China to potentially repopulate the western Pacific with new moorings though final design and formal commitment is pending. JAMSTEC has plans to continue to maintain a relatively new TRITON mooring at 13°N, 138°E (north of TAO/TRITON and not a formal TAO/TRITON mooring). This 13°N, 138°E site and the subsurface ADCP mooring at 0°, 156°E are not formally part of the TAO/TRITON array and therefore are not included in the mooring totals listed in Table 2.

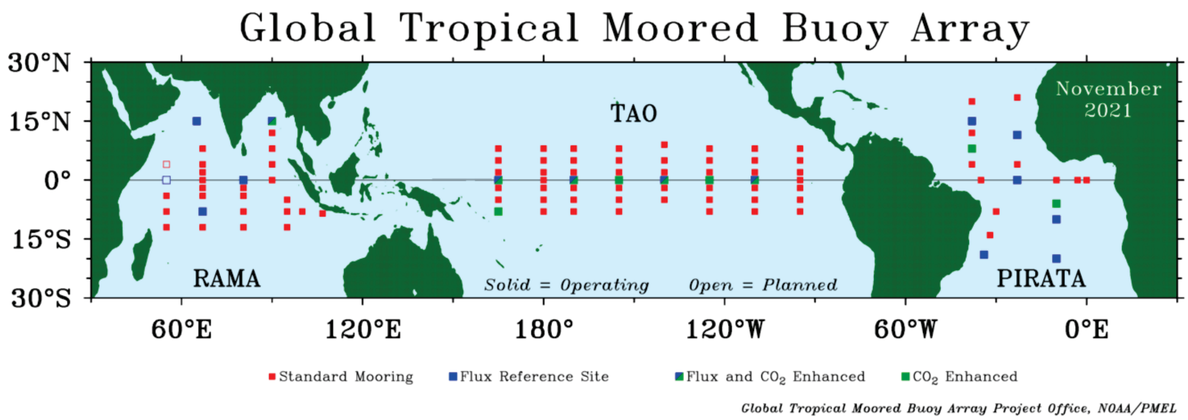

Figure 1. Present status of the GTMBA. Open symbols indicate sites that are planned but not yet operating. Blue and green symbols indicate sites enhanced for surface flux and/or CO2 measurement.

Table 2. The number of NOAA and non-NOAA partner sites and moorings planned and implemented within the GTMBA as of close of FY 2021. Percent Complete is based on number of planned moorings[2].

	TAO	PIRATA	RAMA	GTMBA
Sites[1] Planned	55	18	28	101
Sites[1] Implemented	55	18	23	96
Moorings[2] Planned	59	20	33	112
NOAA Moorings[2] Implemented	59	18	22	99
Partner Moorings[2] Implemented	0	2	5	7
Total Moorings[2] Implemented	59	20	27	106
Percent Complete	100%	100%	82%	95%

Notes:

1: "Mooring sites" refer to independent sites (i.e., locations) where mooring assets are deployed.

2: "Moorings" refers to individual moorings. Some mooring sites may include multiple moorings at a single site when both a surface mooring and subsurface ADCP mooring are present, e.g. at 0°, 67°E and 0°, 80.5°E in the Indian Ocean.

No RAMA cruises were undertaken in FY 2021. PIRATA ship time in FY 2021 was provided by the US and France, with the majority of PIRATA support (56 DAS) from non-U.S. partners. PIRATA field work was accomplished using 97 days of ship time, 56 of which were provided by France. The FY 2021 US PIRATA Northeast Extension cruise was completed in January-February 2021. Brazil was unable to schedule a cruise in FY 2021 due to COVID-19 ship scheduling constraints. The total value of non-US ship time contributions to PIRATA (56 of 97 total days) in FY 2021 is estimated to be $2,800,000 based on a per day cost for a NOAA ship to operate in these ocean areas of $50,000.

2.1.1. PIRATA

The PIRATA Array consists of 18 surface moorings and one subsurface ADCP (Figure 2). Surface moorings had previously all been ATLAS systems, but the Array now consists of 8 ATLAS and 10 T-Flex moorings. The surface mooring array includes a ten (10) mooring PIRATA backbone array configuration (as agreed upon for the 2001-2006 consolidation phase of the program), three (3) "Southwest (SW) Extension" moorings, four (4) "Northeast (NE) Extension" moorings, and one (1) new pilot site at 20°S, 10°W. The "Southeast (SE) Extension" mooring site at 6°S, 8°E was suspended in April 2020 (FY 2020) due to multiple years of repeated equipment losses due to vandalism. Six sites in PIRATA are designated as Flux Reference Sites in support of the Ocean Sustained Interdisciplinary Timeseries Environment observation System (OceanSITES) program: three in the PIRATA core, one in the NE Extension, one in the SW Extension, and one at the new pilot deployment site (Figure 2).

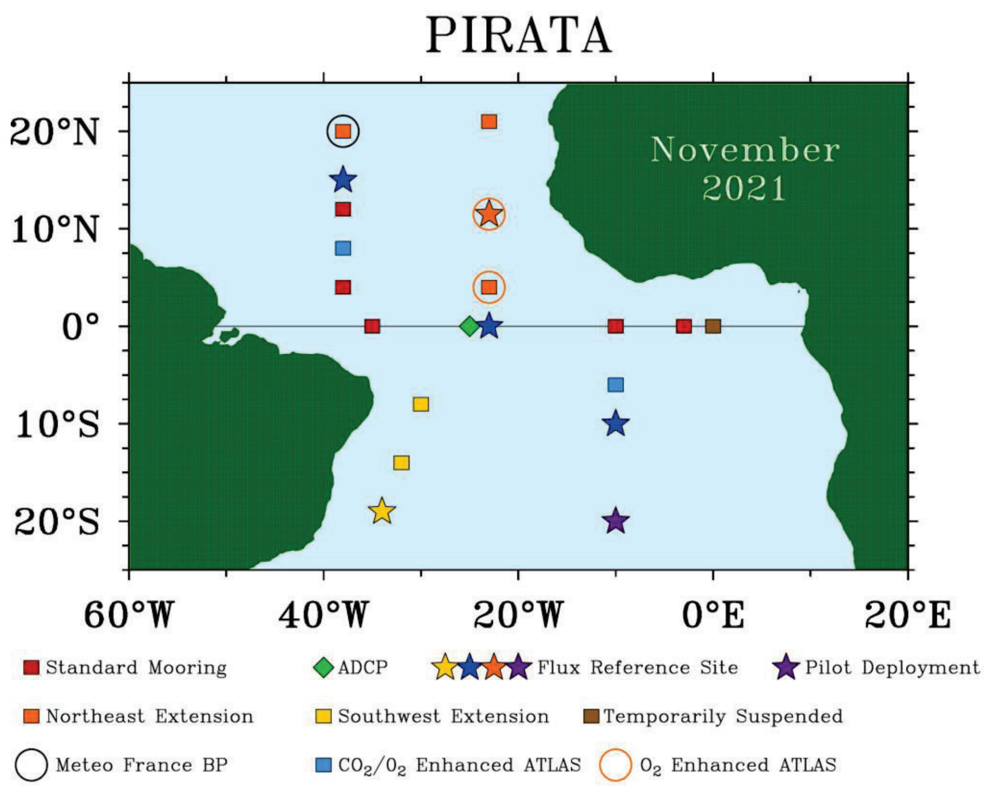

Figure 2. Map of the PIRATA Array.

Primary sensors (those with which all TAO, PIRATA and RAMA moorings are deployed) measure wind speed and direction, air temperature, relative humidity, sea surface temperature, and ocean temperatures at 10 depths down to 500 m. All PIRATA moorings also measure short wave radiation, precipitation, and salinity at the surface and at three subsurface depths down to

120 m. The PIRATA flux reference sites (Sec. 5.1) are enhanced for current, longwave radiation and barometric pressure. The T-Flex moorings also measure currents at 12 m depth and subsurface salinity at one to three additional depths.

NOAA funding of $600K for the 10 PIRATA backbone sites was mistakenly transferred to NWS with TAO funds when TAO was transitioned to NDBC. Since that time, NWS has passed this funding to PMEL, although sometimes with delays. FY 2021 NWS funds were transferred in full to PMEL in the third quarter (April 2021).

PMEL is charged with providing equipment and technical support for surface moorings and instrumentation, support for data processing, dissemination, and display, and at-sea technician support for the NE Extension sites. France and Brazil each provide ship time, shipment of equipment, and at-sea technician support for the backbone array. Brazil also provides these resources for the SW Extension sites and France provides these resources for the new pilot deployment site. NOAA provides ship support for the NE Extension and has also, on occasion, serviced a backbone mooring. France provides ship time and equipment for the subsurface ADCP site and Germany provides the data processing. There were two (2) PIRATA cruises in FY 2021 for a total of 97 sea days (Table 3).

Table 3. FY 2021 PIRATA Cruise Statistics.

Cruise ID	Dates		Work Area	Ship Country	Sea days	PMEL/AOML Staff	Moorings Deployed
PI2-20-RB	15-Jan-2021	24-Feb-2021	0°N - 21°N 23°W - 38°W	Ronald H. Brown USA (NOAA)	41	2	5 T-Flex
PI1-21-TH	22-Feb-2021	18-Apr-2021	Equator - 20°S Meridian - 23°W	Thalassa France	56	0	3 ATLAS 3 T-Flex

Brazil typically provides ship time and technicians to service 8 PIRATA moorings in the western portion of the array near Brazil. The Brazilian PIRATA cruise aboard Vital de Oliveira had originally planned to service all 8 PIRATA moorings. However, as it became uncertain that the Brazil cruise would be scheduled, 1 PIRATA mooring at 15°N, 38°W was deployed during the PNE cruise since this mooring was lost at sea and the PNE cruise was navigating in close proximity to this site. This shifted the plan for Brazil to plan for deploying 7 PIRATA moorings. Unfortunately, this cruise plan never came to fruition during FY 2021.

Five eastern Atlantic PIRATA backbone sites (3 ATLAS + 2 T-Flex) and a new pilot ATLAS site at 20°S, 10°W (6 sites total) were serviced on the 2021 French PIRATA cruise aboard the R/V Thalassa from 22 February 2021 to 18 April 2021 from Brest, France to Brest, France. Unfortunately, due to increased piracy in the Gulf of Guinea, The Thalassa could not deploy moorings at 0°, 0°. Instead, they deployed a surface mooring at 0°, 3°W and did not deploy the ADCP at 0°, 0° this year. Other observations during the cruise included: 78 CTD station casts total with CTD water bottle samples; Lowered Acoustic Doppler Current Profiler (LADCP) profiles; 75 XBT casts; deployment of 12 ARGO floats; deployment of 23 SVP-BS surface drifters; collection of sea surface water samples for diverse biogeochemical and physical parameters; and continuous underway ADCP, TSG, fluorimeter and acoustic measurements. The R/V Thalassa is equipped with a SIMRAD EK60 6-frequency acoustic sensor, from which measurements are of great interest for biotic and abiotic ecosystem components of the PREFACE (Enhancing prediction of Tropical Atlantic climate and its impacts) Project.

The FY 2021 PIRATA Northeast Extension (PNE) cruise was conducted aboard the NOAA Ship *Ronald H. Brown* from 15 January 2021 to 24 February 2021, starting in Miami, FL, USA and ending in Key West, FL, USA. Dr. Gregory Foltz (NOAA/AOML) was the Chief Scientist on the FY 2021 cruise. Due to the COVID-19 pandemic, additional health and safety protocols were implemented, including the requirement to shelter-in-place (SIP) in a hotel near the port of departure for 7 days in advance of the cruise, sending an alternate participant from PMEL to SIP for 7 days in case one of the primary participants tested positive for COVID-19 prior to boarding the ship, during transit to operational stations the ship was required to maintain a maximum distance of 500 nautical miles to the nearest approved hospital (approved hospitals in Miami, San Juan, St. Thomas, and Bridgetown) for the first 7 days at sea (for a combined total 14-day SIP), cruise participants were required to wear additional personal protective equipment (PPE) including face coverings during SIP and for the first 4 weeks of the cruise. These COVID protocols resulted in increased cruise costs covered by the GTMBA project budget. The cruise was successfully executed with no health and safety incidents and all GTMBA cruise objectives were met. The completion of the FY 2021 PNE cruise resulted in new deployments of five moorings. All four PNE T-Flex moorings (20°N, 38°W; 20.5°N, 23°W; 11.5°N, 23°W; and 4°N, 23°W) were recovered and redeployed. In addition, a new mooring was deployed at the 15°N, 38°W Brazilian PIRATA site (the previous buoy had become unmoored and was adrift), and the air temperature and relative humidity sensors were replaced on the French PIRATA mooring at 0°, 23°W. Sixty-one CTD casts were conducted. Twelve Argo profiling floats were deployed, and underway oceanic data was collected (SADCP, TSG, pCO_2). AEROSE measured aerosol optical depth, atmospheric carbon monoxide, ozone, and sulfur dioxide throughout the cruise. A group from Fearless Fund (Dept. of Energy/NOAA-funded project) collected samples of Sargassum and obtained more than 300 water samples from the CTD bottles for post-cruise nutrient analysis. Ten Nortek Aquadopps were recovered at the 4°N, 23°W mooring as part of the PhOD funded Tropical Atlantic Current Observations Study (TACOS).

Several non-NOAA research projects make use of PIRATA mooring platforms for their own observations. Ongoing ancillary observations established in previous years include Oregon State University thermal microstructure instruments (*X*-pods or *Chi*-pods) deployed on the 0°, 23°W and 0°, 10°W moorings. The moorings deployed in FY 2021 have 5 *X*-pods each, at depths between 21 m and 81 m. Also, Dalhousie University Ocean Tracking Network (OTN) acoustic monitors are deployed on all PIRATA surface moorings. PMEL also added barometric pressure instrument provided by Meteo France to a PIRATA mooring (20°N, 38°W). A total of eight

GEOMAR subsurface dissolved oxygen (O2) sensors were deployed and recovered on three moorings in PIRATA in 2021. Three GEOMAR O2 sensors are deployed at 80m, 150m, and 300m on the mooring at 21°N, 23°W; three GEOMAR O2 sensors are deployed at 80m, 300m, and 500m at 12°N, 23°W; and two GEOMAR O2 sensors are deployed at 300m and 500m at 4°N, 23°W in FY 2021. The O2 sensors at two sites (21°N, 23°W and 12°N, 23°W) were deployed with real-time data telemetry for the first time in FY 2017 but the latest deployment is not in real-time to prevent risk to the mooring due to unexpected data telemetry errors and data conflicts during the last two deployments. Two LOCEAN surface Carbon Dioxide (CO2) systems were deployed in FY 2021 at: 0°, 10°W and 6°S, 10°W. Additional temperature and conductivity sensors and a current meter were provided by IRD as funded by EU AtlantOS as enhancements to the 0°, 10°W mooring.

Only 11 of the 18 PIRATA sites were serviced in FY 2021. Ship schedule constraints and cruise cancellations due to the COVID-19 pandemic resulted in the inability for Brazil to conduct a cruise to service 7 PIRATA moorings in FY 2021. These challenges have resulted in data losses and losses of moored buoy assets due to excessive deployment periods well beyond the mooring design lifetime of one year. The number of moorings that are currently non-reporting or have gone adrift in the Atlantic Ocean (PIRATA) is amplified due to the global pandemic shutdown. The PIRATA array currently has 5 moorings not transmitting data. All of these moorings are moorings that are maintained by Brazil along the western edge of the PIRATA array. The long deployments due to inability to secure ship time have translated to loss of data at these sites. Ten (out of 18) PIRATA moorings are reporting less than 70% data return in November 2021. The remainder of the PIRATA array, which has been maintained by France (IRD) and USA (NOAA) remains healthy. However, in late FY2021 two moorings went adrift from 10°S, 10°W and 20°S, 10°W. These moorings were fortunately recovered by the German ship R/V Sonne on 5-7 Sep 2021.

Real-time, primary sensor (wind speed and direction, air temperature, relative humidity, SST and 10 subsurface temperatures) data return was 62% overall for FY 2021 – a 4% decrease from FY 2020. When all sensors are considered, real time data return was 63% (a 1% decrease from FY 2020). Only 11% of the sites (2 of 18) had real-time primary sensor data return above 90%. Only 44% of the sites (8 of 18) had real-time primary sensor data return above 80%. These relatively low data return statistics are evidence of the impacts from deferred maintenance due to COVID-related cruise cancellations.

Real-time PIRATA data return by variable for FY 2021 (and for comparison, FY 2020) is shown in Table 4. Barometric pressure sensors had the best performance of all sensor types in FY 2021. Relative humidity was the poorest performing meteorological sensor. SST showed continued decline with very low data return at 40%. Longwave radiation, Barometric pressure, and salinity were the only sensors to have an increase in data return from FY 2020 to FY 2021.

Table 4. FY 2021 and FY 2020 PIRATA real time data return (in percent).

FY	AT	RH	BP	WIND	RAIN	SWR	LWR	SST	TZ	SAL	CUR	ALL
2021	65	64	88	71	71	74	86	40	63	59	46	62
2020	72	66	87	74	73	80	85	41	67	55	55	64

Key: *AT: air temperature*
RH: relative humidity
BP: barometric pressure
WIND: wind speed and direction
RAIN: precipitation
SWR: short wave radiation
LWR: longwave radiation
SST: sea surface temperature
TZ: ocean temperature at depths to 500 m
SAL: salinity at depths to 120 m
CUR: current

As mentioned earlier, PMEL continues to deliver data to users through both the GTS and through its GTMBA web pages. GTMBA delivered via its web pages a total of 57,441 PIRATA data files from 12,017 separate user requests in FY 2021. These represent an increase of 340% for user requests and an increase of 310% for data files relative to FY 2020 statistics. This three-fold increase was a result of a recent unusual increase in automated (i.e., scripted) data requests from a limited number of users. This recent increase was likely an anomaly this year and we may expect to see a return to a more gradual increase from the average baseline next year, which might manifest as a decrease from these unusual and anomalous FY 2021 data download statistics. An additional 1,347,940 PIRATA data files were delivered via ftp transfer in FY 2021. This represents a 100% increase in PIRATA data files delivered via FTP in FY 2021 when compared to FY 2020. Before this year there had been a consistent trend observed over the past six years with increasing FTP downloads and decreasing web downloads. The total number of PIRATA data files (web + FTP) delivered in FY 2021 was 1,405,381, which represents an increase from FY 2020 of 104%.

In addition to the GTMBA web pages, PMEL hosts a PIRATA web site (www.pmel.noaa.gov/gtmba/pirata) with links to the GTMBA delivery website: https://www.pmel.noaa.gov/gtmba/data-access/disdel. AOML also hosts a PNE-focused PIRATA web site (www.aoml.noaa.gov/phod/pne) with scientific background, technical information, PNE cruise reports, access to PNE data and a bibliography of refereed PIRATA publications. Collection, processing, and dissemination of shipboard CTD and ADCP data are the responsibility of France and Brazil for their cruises, respectively, with AOML taking responsibility for these data collected during the Northeast Extension cruises. Calibrated CTD values of temperature, salinity and oxygen from PNE cruises are available at the PNE web site http://www.aoml.noaa.gov/phod/pne. Uncalibrated CTD and XBT data are distributed during the PNE cruise in near-real time on the GTS. INPE in Brazil has implemented a web page to host CTD data from all PIRATA cruises (http://pirata.ccst.inpe.br/data-2/).

2.1.2. RAMA

The CLIVAR/GOOS Indian Ocean Panel (IOP) developed an implementation plan for a multi-component ocean observing system in 2004, named the Indian Ocean Observing System (IndOOS). A key element of IndOOS is the Research moored Array for African-Asian-Australian Monsoon Analysis and prediction (RAMA). Elements of the array were established prior to IndOOS by Japan in 2000-2001 and by India in 2000-2002. PMEL and India's National Institute of Oceanography (NIO) deployed the first ATLAS moorings in 2004. Nations currently supporting RAMA include the United States, Japan, India, Indonesia, and China. Previously, Australia supported implementation and maintenance of 1 site in 2012 and 2013. Likewise, the Agulhas and Somali Current Large Marine Ecosystems (ASCLME) Project, a consortium of 9 African nations (Comoros, Kenya, Madagascar, Mauritius, Mozambique, Seychelles, Somalia, South Africa and Tanzania) supported 3 sites from 2008 to 2013. Meteo France supports barometric pressure observations at 5 RAMA sites (and 1 PIRATA site). The Bay of Bengal Large Marine Ecosystem Project (BoBLME) supports CO2 and ocean acidification observations at 1 RAMA site. In FY 2021, NOAA and the Ministry of Earth Sciences (MoES) of India signed an updated 5-year partnership agreement to advance ocean and atmospheric observations in the Indian Ocean for improved weather and climate prediction. The renewed partnership includes additional MoES ship time support for RAMA and a new joint oceanographic data portal (https://incois.gov.in/portal/datainfo/buoys.jsp) that makes data from the RAMA and OMNI moored buoy arrays in the Indian Ocean publicly available for the benefit of research and forecasting.

RAMA principal investigators in the U.S., China, India, and Japan proposed a revised array design, referred to as RAMA-2.0, in the context of the 2017-19 IndOOS review. This re-design is intended to make the array more robust, cost-effective and less dependent on ship time, which is the most limiting resource for sustaining the array. RAMA-2.0 has fewer moorings than the original design and eliminates moorings in regions prone to heavy fishing vandalism or where it has not been possible to find reliable ship support. The RAMA-2.0 plan received final endorsement by the IndOOS review community and is now published IndOOS-2: A roadmap to sustained observations of the Indian Ocean for 2020-2030 (Beal, et al., 2019).

Vandalism has presented a significant burden on the GTMBA project in recent years. The COVID-19 global pandemic has further contributed to the loss of additional GTMBA mooring assets due to extended deployments well beyond the one-year design life of the moorings. These extended deployments result in degradation of hardware components, which facilitates vandalism and mechanical failures. Furthermore, the inability to send ships to attempt to recover drifting moorings in a timely manner results in additional lost equipment at sea as distances increase and eventually all position transmissions fail after power loss or electronics corrosion. Mooring losses in FY 2020 and FY 2021 far exceeded any single year in recent memory. At the close of FY 2021, RAMA was at critically low data return with only three RAMA moorings transmitting data and 16 moorings lost (9 confirmed lost at sea; 7 not transmitting and presumed lost at sea). All of these were PMEL owned (and GOMO funded) assets.

To address these funding shortfalls and associated loss of assets, we proposed in FY 2021 to eliminate 3 moorings in RAMA. The proposed changes in RAMA include the elimination of 1) all moorings along longitude 55°E; and 2) replacing the surface mooring at 0°, 90°E with a subsurface ADCP mooring at 0°, 90°E. This newly proposed RAMA configuration is named "RAMA-3.0" and will be implemented in the FY2022 field season.

All PMEL surface moorings deployed in the Indian Ocean have the PIRATA suite of instrumentation, plus one additional subsurface temperature sensor, 2 additional salinity subsurface sensors and one near surface current meter. Presently, five of the PMEL sites are enhanced for flux reference measurements with addition of salinity, LWR, and BP sensors (Sec.5.1).

In FY 2018 GTMBA received funding in the amount of $96K to instrument two existing RAMA Flux Reference Site moorings with enhanced measurements in the mixed layer. These enhancements were proposed to address the IndOOS recommendations of higher vertical resolution measurements in the mixed layer to better understand the diurnal cycle and how it affects intraseasonal variability associated with the Madden-Julian Oscillation (MJO) and monsoon intraseasonal oscillations (MISOs). These enhanced sites are at 8°S, 67°E in the Seychelles Chagos Thermocline Ridge (SCTR) region and 15°N, 90°E in the northern Bay of Bengal. Cruise cancellations/delays prevented the first set of enhanced sensors to be deployed in FY 2019, but the enhancements at 15°N, 90°E were deployed in early FY 2020 (December 2019) on an Indonesian InaPRIMA cruise. Cruise cancellations in FY 2021 due to COVID-19 pandemic prevented deployment of the second set of enhancements at 8°S, 67°E, but we anticipate the enhancements at 8°S, 67°E will be deployed in FY 2022.

Several non-NOAA research projects make use of RAMA moorings for ancillary observations. Dalhousie University Ocean Tracking Network acoustic monitors are deployed on all RAMA surface moorings. However, as none of these moorings were maintained in FY 2021 due to the COVID-19 pandemic. In FY 2020, PMEL also added barometric pressure sensors purchased by Meteo France to two RAMA moorings: 12°S, 67°E and at 8°S, 55°E. The pressure sensor at 8°S, 55°E was purchased by Meteo France in late FY 2019 and the FY 2020 deployment was the first time it was deployed at 8°S, 55°E. Finally, a CO2 and ocean acidification sensor package (PMEL MAPCO2) is deployed at 15°N, 90°E in the Bay of Bengal. Some of these ancillary partner instruments have been lost as RAMA moorings are lost due to deferred cruises.

The RAMA-2.0 plan includes a total of 33 moorings. As of the close of FY 2021, 30 (91%) of the planned 33 RAMA-2.0 moorings had been implemented (Figure 3). However, due to ongoing ship scheduling constraints and travel restrictions due to COVID-19, repeated vandalism losses, and resulting impacts to the GTMBA budget, three of RAMA sites have been suspended in FY 2020. These three suspended mooring sites are: 12°S, 55°E; 12°S, 93°E; and 4°N, 90°E. An additional three RAMA moorings have been suspended in FY 2021: 4°S, 57°E; 8°S, 55°E; and the surface mooring at 0°, 90°E. PMEL will maintain the subsurface ADCP mooring at 0°, 90°E after JAMSTEC withdraws from this site in 2022. Excluding the six suspended moorings (at five sites) from the number of established RAMA moorings, the number of NOAA moorings drops to 25 out of a total of 33 in the RAMA 2.0 design (Table 2). As previously mentioned, zero moorings were serviced in FY 2021 because of ship scheduling restrictions and travel restrictions due to COVID-19.

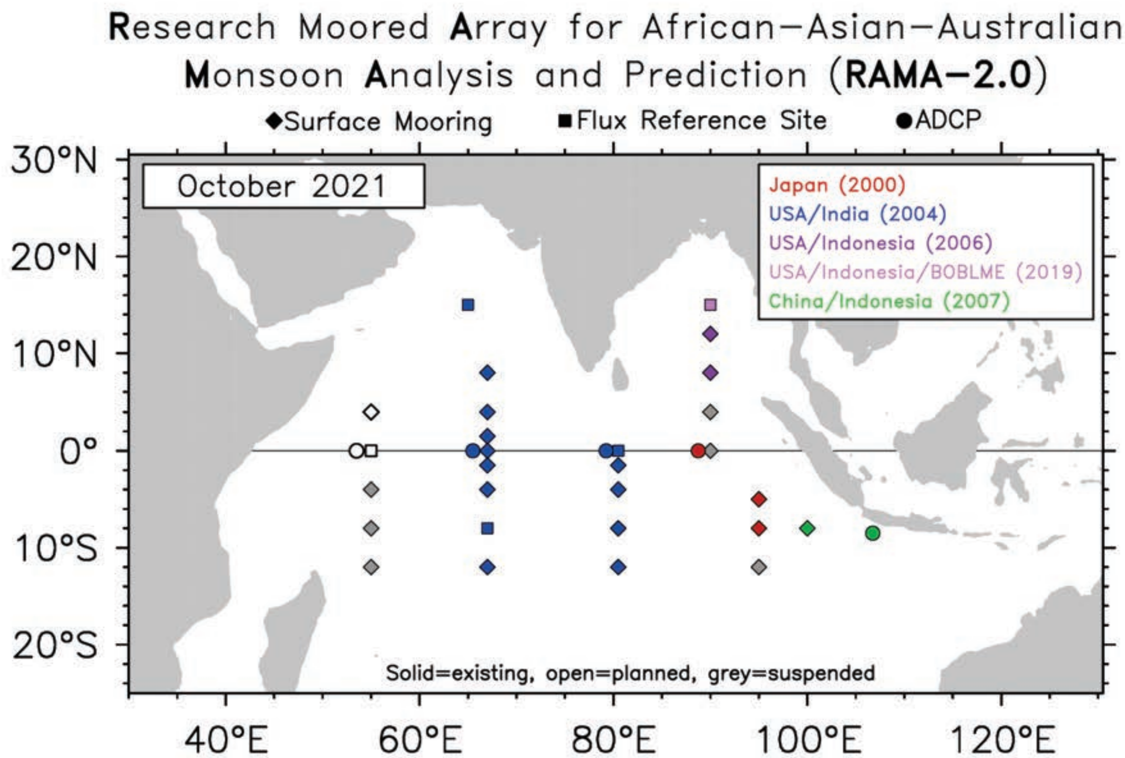

Figure 3. RAMA moorings.

A RAMA web site (http://www.pmel.noaa.gov/gtmba/rama) provides scientific background, technical information, access to RAMA data and displays, status of the array, a bibliography of refereed publications, history of cruises, and additional information. RAMA data are available from the web at https://www.pmel.noaa.gov/gtmba/data-access/disdel. For FY 2021, a total of 13,007user requests delivered 60,327 RAMA data files. An additional 890,633 RAMA data files were delivered via public and password protected ftp sites. The total number of RAMA data files (web + FTP) delivered in FY 2020 was 950,960, which represents an increase from FY 2020 of 3%.

2.1.3. TAO/TRITON

Management of the TAO array, which is the U.S. contribution to TAO/TRITON, is the responsibility of the National Data Buoy Center (NDBC) in Stennis, Mississippi. Though not an activity funded directly by GOMO, TAO/TRITON is mentioned here since it is a major component of the GTMBA and is linked with Tropical Moored Buoy Implementation Panel (TIP) activities. Also, while no longer responsible for operation of the TAO Array, PMEL monitors, distributes, and archives TAO/TRITON data, produces and disseminates TAO/TRITON data products, and contributes to planning for future tropical Pacific Ocean observing system goals.

2.2. Scientific Accomplishments Advancing Climate and Ocean Research

The PIs and their colleagues have published several papers in the past year using data collected in, or inspired by, RAMA, PIRATA, TAO/TRITON (see Section 4). Here, we highlight a few examples of scientific progress enabled by GTMBA efforts in FY 2021:

Jin, Y., Z. Liu, and M.J. McPhaden, 2021: A Theory of the Spring Persistence Barrier on ENSO. Part III: The Role of Tropical Pacific Ocean Heat Content, *J. Climate*, *34,* 8567-8577. https://doi.org/10.1175/JCLI-D-21-0070.1

This paper describes an analytical theory for decadal variations in the relationship between upper heat content and SST on interannual time scales in the equatorial Pacific Ocean.

McPhaden, M. J., A. Santoso, and W. Cai, 2020: El Niño Southern Oscillation in a Changing Climate. AGU Monograph. Washington DC, doi: 10.1002/9781119548164

This AGU monograph is the most comprehensive assessment of ENSO dynamics, predictability and impacts in a warming world. Nearly 100 authors from 58 institutions in 16 countries contributed to the book.

Nagura, M. and M.J. McPhaden, 2021: Interannual variability in sea surface height at southern mid-latitudes of the Indian Ocean. *J. Phys. Oceanogr., 51*, 1595-1609. https://doi.org/10.1175/JPO-D-20-0279.1.

This study examines interannual variability in sea surface height at southern midlatitudes of the Indian Ocean using satellite altimetry measurements, an atmospheric reanalysis, and a one-dimensional long wave ocean model. The analysis suggests that sea surface height variability along the west coast of Australia originates from remote wind forcing in the tropical Pacific associated with ENSO after which the signal propagates into the interior Indian Ocean via Rossby waves.

Planton, Y.Y., and co-authors, 2021: Evaluating climate models with the CLIVAR 2020 ENSO metrics package. *Bull. Amer. Meteor. Soc., 102*, E193-E217. https://doi.org/10.1175/BAMS-D-19-0337.1.

This paper describes a community-wide effort to evaluate the simulation of ENSO variability, teleconnections, and processes in climate models using a specially designed metrics package to 1) highlight aspects that need improvement; 2) monitor progress across model generations; 3) help in selecting models that are well suited for particular analyses; 4) reveal links between various model biases; and to 5) advance ENSO literacy.

Pujiana, K., M.J. McPhaden, 2021: Biweekly mixed Rossby-gravity waves in the equatorial Indian Ocean., *J. Geophys. Res.*, 126, e2020JC016840. https://doi.org/10.1029/2020JC016840.
This study provides the most comprehensive description of ubiquitous and highly energetic biweekly (defined as periods between 10 and 15 days) variability in the upper layers of the Indian Ocean in relation to equatorial wave theory using a comprehensive set of moored RAMA ocean current velocities as well as satellite-retrieved oceanic and atmospheric parameters.

Christophersen, J. A., G. Foltz, and R. C. Perez, 2020: Surface expressions of atmospheric thermal tides in the tropical Atlantic and their impact on open-ocean precipitation. *J. Geophys. Res. Atmos*., 125, e2019JD031997, https://doi.org/10.1029/2019JD031997.
Christophersen et al. (2020) used data from PIRATA buoys and an atmospheric reanalysis to quantify the surface atmospheric pressure and wind signals associated with diurnal and semidiurnal thermal tides (TTs) in the tropical Atlantic. TTs are driven by solar heating of the atmosphere and differential heating of the land and ocean surfaces. Christophersen et al. also showed a westward-propagating diurnal cycle of winds that originates in Africa and helps to explain the morning peak of rainfall over the open ocean. These results help to advance understanding of tropical deep convection and rainfall, which many climate models have difficulty simulating realistically.

2.3. GTMBA Website and Delivery of Societally Relevant Services

The GTMBA Project continues to update the content and functionality of its web site (http://www.pmel.noaa.gov/gtmba). The GTMBA website provides easy access to PIRATA, RAMA, and TAO/TRITON data sets, as well as updated technical information on buoy systems, sensor accuracies, sampling characteristics, and graphical displays.

Data from all three tropical ocean basins are available from PMEL's GTMBA data display and delivery web page, http://www.pmel.noaa.gov/gtmba/data-access/disdel, as well as from other PMEL sites and from sites maintained by other organizations.

In FY 2021, as part of the updated 5-year partnership agreement between NOAA and the Ministry of Earth Sciences (MoES), a new joint oceanographic data portal was developed to make data from the RAMA and OMNI moored buoy array data publicly available (https://incois.gov.in/portal/datainfo/buoys.jsp).

In late FY 2019, a new data display and delivery web site was added to disseminate *X*-pod (i.e., *Chi*-pod) data processed by Oregon State University (OSU), which were deployed on several GTMBA mooring platforms in TAO, PIRATA, and RAMA. This *X*-pod new website gives users the capability to access, download, plot time-series figures for *X*-pod temperature, vertical temperature gradient, squared buoyancy frequency, turbulent diffusivity of temperature, Dissipation of temperature variance, turbulent dissipation rate, and turbulent heat flux at each *X*-pod site. The *X*-pod data website is accessible at: https://www.pmel.noaa.gov/gtmba/data-access/chipod.

The GTMBA program is a major contribution to the data collection and dissemination of instrumental records of GOOS Essential Ocean Variables (EOVs) identified by the GOOS Expert Panels based on relevance, feasibility, and cost effectiveness. Further information regarding EOVs is available at the GOOS website: http://www.goosocean.org/index.php?option=com_content&view=article&id=14&Itemid=114.

EOVs collected by GTMBA moorings and distributed as part of the GTMBA project include:

- Ocean surface stress
- Sea surface height
- Sea surface temperature
- Subsurface temperature
- Sea surface salinity
- Subsurface salinity
- Surface currents
- Subsurface currents
- Ocean surface heat flux
- Dissolved Oxygen
- Fish abundance and distribution (via OTN)
- Marine turtles and mammals abundance and distribution (via OTN)

The GTMBA program is also a major contribution to the data collection and dissemination of instrumental records of GCOS Essential Climate Variables (ECVs), which are “physical, chemical or biological variable or a group of linked variables that critically contributes to the characterization of Earth’ s climate.” Further information regarding ECVs is available at the following websites:

- https://www.ncdc.noaa.gov/gosic/gcos-essential-climate-variable-ecv-data-access-matrix
- https://public.wmo.int/en/programmes/global-climate-observing-system/essential-climate-variables

ECVs collected by GTMBA moorings and distributed as part of the GTMBA project include:

- Precipitation
- Pressure
- Surface radiation budget
- Surface wind speed and direction
- Air temperature
- Water vapour (relative humidity)
- Carbon dioxide
- Ocean surface heat flux
- Sea surface temperature
- Subsurface temperature
- Sea surface salinity
- Subsurface salinity
- Surface currents
- Subsurface currents
- Dissolved Oxygen

Additional details and statistics on GTMBA web pages and data management are presented in Section 5.2 and 5.3.

2.4. Funding Issues and Barriers to Progress

Other issues and activities which are common to more than one of the basin-scale arrays include funding limitations (Sec. 2.4.1), fishing vandalism (Sec. 2.4.2), development of new mooring systems (Sec. 2.4.3).

2.4.1. Funding limitations

GTMBA increasingly encounters new funding constraints limiting our capability to maintain a sustained tropical observation system network. The GTMBA project has struggled to keep up with increasing demands, particularly dealing with an expanding RAMA array, obsolescence of legacy technologies, loss of equipment due to vandalism, inflation, and new corporate taxes as detailed in paragraphs below. While costs have increased, budgets have remained essentially flat for 10 years for RAMA and PIRATA Extensions and nearly 20 years for the core 10 moorings of PIRATA.

FY 2021 was a devastating year with respect to mooring losses. The inability to schedule RAMA cruises in the Indian Ocean has resulted in massive loss of data and equipment. There have been significant losses in PIRATA as well, particularly on the west side of the Array. This is also linked to excessively long deployments due to inability for Brazil to secure ship time needed to service the moorings in Western PIRATA. The conversion to new instrumentation associated with T-Flex moorings has been a significant cost burden particularly for Sea-Bird instruments. A new T-Flex mooring system, designed to replace the obsolescent ATLAS system, costs typically $165K (and $200K for a flux site) in early FY 2021, which is $63K more than an equivalent ATLAS mooring on average. The difference is mainly due to the cost of commercial water temperature and salinity instrumentation. T-Flex moorings transmit through Iridium rather than Service Argos, so telemetry costs must be borne directly by the project in contrast that Argos costs that were covered directly by OAR. New taxes have also been imposed on GOMO budgets by NOAA cooperative institutes, by PMEL for rent, and by NOAA administration for procurement contracts. The sum of all these unsupported cost increases in FY2021, estimated at approximately $300K, puts additional burdens on the GTMBA budget. Details of these tax levies follow.

Cooperative Institute Task 1 funding was included in our FY 2021 budget. Historically Task 1 funding was provided by PMEL base funding. A new formula for funding Task 1 was implemented in FY 2015, which places additional burden on Project funding. For FY 2021, the Task 1 fee is 2.8% of Cooperative Institute salaries (after inclusion of benefits and overhead). Based on estimated GTMBA funding to be transferred to CICOES in FY 2021, the amount required for Task 1 was $51K. This additional cost to the project further limits our ability to achieve our goals of RAMA implementation, PIRATA maintenance, and technological advancement.

Beginning in FY 2017, NOAA added a service fee on all contract actions, including purchases orders on new contracts as well as charges against existing contracts. The NOAA Executive Panel (NEP) approved a plan that replaces the funding provided to the Acquisition and Grants Office (AGO) through the Direct Bill process with funding generated by the assessment of a fee on all acquisition actions processed by AGO. The fees are charged as a percentage based on dollars obligated for each contract action. The fees charged for Simplified Acquisition Procedures (SAP) up to $150K are 7% of the obligated dollar amount and the fees charged for all other contract actions are 3% of the obligated dollar amount. No fees are assessed on contract actions obligated by a Field Delegate. PMEL has access to a Field Delegate who can process SAP contract actions up to $150K and therefore we typically would not be charged the 7% fee on low cost (<$150K) contract actions. However, all future obligations on contracts greater than $150K will be charged a 3% fee. The impact of this fee to the FY 2021 budget is estimated to be $20K.

In FY 2018 PMEL was notified of a significant rent and maintenance fee increase to cover deferred maintenance, change in maintenance contract and an earlier decision to move the responsibility of covering these costs to the NOAA Western Regional Center (WRC) campus. PMEL is currently evaluating options to close a facilities rental and maintenance fee gap on PMEL’s portion of the facilities rental at NOAA’s WRC. The facilities rental fee gap that needed to be recovered in FY 2021 was approximately $1.1M, with the possibility that this amount may increase in subsequent years. This facilities fee gap resulted in a significant tax increase to PMEL projects starting in FY 2019 resulting in $258K in overhead in FY 2019 ($116K more than in FY 2018). The GTMBA project had to pay $266K ($124K more than in FY 2018) in FY

2021 because of this assessment. GTMBA expects to be required to pay even more in FY 2022 (estimated at $403K, or $261K more than in FY 2018) after a recent doubling of the PMEL overhead tax rate again to cover cost increases to the OAR laboratories.

GTMBA continues to run a deficit in light of these expanding budget demands. At the close of FY 2021, the GTMBA deficit was at $469K. Our plan to eliminate this deficit over the next three years (FY 2021 – FY 2023) focuses on suspension of planned T-Flex implementation, freezing T-Flex component inventory at current levels, and replacing T-Flex with older ATLAS moorings at two sites. Furthermore, as a cost-savings strategy we have suspended deployments at three sites in RAMA and one site in PIRATA in the face of increased vandalism (4°N, 90°E and 6°S, 8°E) and inability to obtain adequate ship time (12°S, 55°E and 12°S, 93°E).

This deficit elimination plan assumed that there would be no anomalously high losses of equipment due to either vandalism or mooring failures. However, with the impacts that the COVID-19 pandemic has had on the GTMBA program, it is clear that without additional funding support to recover the costs of these lost assets, additional cost reduction measures will need to be implemented or the deficit will increase again. Delays in servicing moorings that have been out now in some cases over a year will translate into deployment periods well beyond the 1-year design lifetime of the moorings. Thus, there is increased risk of mooring losses due to prolonged exposure to vandalism and increased wear and tear.

Finally, obsolescence of ATLAS mooring components poses a significant long-term risk to the GTMBA program. By suspending the transition from ATLAS to T-Flex mooring technologies, and in some cases rolling back already established T-Flex sites, we are in fact prolonging the transition away from obsolete ATLAS moorings. Many ATLAS components are no longer available on the market and GTMBA has resorted to cannibalizing components from retired ATLAS systems for replacement parts. There is limited ATLAS inventory to draw from for this purpose, so that eventually the heavy reliance on ATLAS may force us to decommission some existing mooring sites in RAMA and/or PIRATA.

2.4.2. Fishing vandalism and deferred maintenance

FY 2021 ended with the most moored buoy losses in the history of the GTMBA project. Without evaluating the mooring for forensic evidence, it is difficult to determine whether the moored buoys lost at sea were a result of fishing vandalism or hardware failure. However, the end result is the same. Increased exposure to extended periods of environmental forces or to fishing vandalism or to both increases risk of losing equipment and data. The significant reduction of cruises in FY 2021 has resulted in greater exposure to risk due to extended deployments well beyond the mooring design life. Repetitive environmental forces cause wear and tear on equipment and fishing vandalism causes wear and tear on equipment. Greater exposure to these forces increases the risk of catastrophic failure. Since the start of the COVID-19 pandemic, 2 moorings were confirmed lost at sea in PIRATA and 9 moorings were confirmed lost at sea in RAMA. Furthermore, 10 moorings (3 in PIRATA and 7 in RAMA) stopped transmitting data and positions by the end of FY2021 and are presumed lost at sea. This is an expected loss of 21 moorings (16 RAMA moorings and 5 PIRATA moorings) since the start of the pandemic in March 2020. The replacement costs for those five moorings lost is over $3-Million if we are to replace all with T-Flex moorings.

Intentional and unintentional damage to moorings is a major source of data and equipment loss as has been noted by several international bodies. PMEL's GTMBA project has contributed to the formulation of several international resolutions intended to mitigate the effects of this vandalism. In 2011 the DBCP released TD 41, Ocean Data Buoy Vandalism – Incidence, Impact and Response, (http://www.jcommops.org/doc/DBCP/DBCP41-Buoy-Vandalism-v1.20.pdf). NOAA's General Council web pages (http://www.gc.noaa.gov/gcil_buoys.html) provide information on recent international resolutions by the WMO, IOC, Western and Central Pacific Fisheries Commission (WCPFC), Inter-American Tropical Tuna Commission (IATTC) and Indian Ocean Tuna Commission (IOTC), and presentations made to the UN General Assembly.

These resolutions are valuable in that they raise awareness and visibility of the problem in international organizations. However, these resolutions lack efficacy based on our experience in maintaining the GTMBA. Therefore, PMEL continues to pursue engineering solutions. For example, RAMA moorings are equipped with hardware that inhibits the removal of sensors and the buoy towers, but theft of sensors remains a problem as described above. T-Flex moorings feature added protection to the system CPU, batteries, and satellite antenna by placing these lower on or within the buoy, where they are less accessible and less susceptible to damage. But T-Flex moorings are also more expensive than ATLAS, so their loss to vandalism is felt even more acutely.

2.4.3. Technology Obsolescence and Need for Engineering Development

The majority of PIRATA and RAMA moorings use PMEL's ATLAS mooring electronics, which were developed in the mid-1990's before ocean instrumentation capable of subsurface telemetry was widely commercially available. As the ATLAS system ages, several key components have gone out of production and replacements have been difficult to locate. At the same time, new and improved sensors have become commercially available. PMEL has developed a new instrument system, dubbed Tropical Flex, or T-Flex, for use with ATLAS mooring hardware (Freitag et al., 2018; https://doi.org/10.25923/h4vn-a328). T-Flex integrates new or updated sensors, replaces some PMEL produced sensors with those commercially available, and uses Iridium for telemetry of higher temporal resolution data. The current meter chosen for use in the T-Flex system features an integrated inductive modem, which should prove superior for real time data telemetry to that used in ATLAS systems.

The T-Flex system is robust with a design lifetime of at least one year, comparable to the ATLAS system. Battery capacity of the T-Flex system has been shown to be well beyond a year, reducing potential data loss when maintenance delays result in deployments exceeding the design lifetime. Analysis of the T-Flex data indicated that the system performed as per our design requirements, with high levels of hourly data throughput. Comparison of data with nearby

ATLAS moorings confirmed that differences are sufficiently small so that the data streams can be considered interchangeable.

The first standalone T-Flex system was deployed in RAMA in August 2015. Currently there are 18 T-Flex systems deployed in RAMA and PIRATA combined, with 8 T-Flex systems deployed in RAMA and 10 T-Flex systems deployed in PIRATA.

3. Outreach and Education

GTMBA PIs and staff frequently engage in activities to inform the scientific community and the public of research and operations conducted by the GTMBA project. GTMBA staff also engage with the public and visitors to the lab to educate the next generation of scientists to understand and appreciate ocean climate science. Some of these activities in FY 2021 included:

- Dr. Mike McPhaden, the TAO Principal Investigator:
    - Chair of the Tropical Moored Buoy Implementation Panel (TIP)
    - Serves on the PIRATA Scientific Steering Committee (SSC), the OceanSITES Science Team, the CLIVAR/GOOS Indian Ocean Regional Panel, the CLIVAR Pacific Regional Panel
    - Serves on the program advisory committee for the US(NSF)-UK (NERC) “Changing North Atlantic” program.
    - Oceanography Editor for the Bulletin of the American Meteorological Society
    - Supervised and supported 3 NRC postdocs, advised two graduate students (one each at University of Washington and Utah State University), and mentored one undergraduate LaPenta scholar
    - Numerous media interviews and news articles summarizing research publications
    - Convenor or Steering Committee member of two international conferences
    - Chief Editor of Wiley book *El Niño Southern Oscillation in a Changing Climate*, published in November 2020.
- Dr. Greg Foltz, Co-Principal Investigator at AOML:
    - Organized and executed the 24th PIRATA and Tropical Atlantic Variability meeting with Dr. Perez May 10-14, 2021.
    - Served on the PIRATA SSG with Dr. McPhaden.
    - Is a member of CLIVAR's Atlantic Region Panel.
    - Has been an editor of the *Journal of Physical Oceanography* since 2015.
    - Is supporting two postdoctoral researchers, who are investigating interannual variations of the Amazon-Orinoco River plume and hurricane-induced changes in ocean salinity.
    - Co-advisor (with G. Chirokova, Colorado St. Univ.) of a postdoctoral researcher who is using coupled model output to create an improved empirical model to predict hurricane-induced ocean cooling.
    - Is advising a research associate, who is creating a database of Atlantic hurricane ocean observations.

    - Advises a third-year Ph.D. student at the University of Miami, who is researching the impact of ocean stratification on tropical cyclone intensification.
    - Co-advised (With Dr. Renellys Perez) a graduate student Lapenta intern during summer 2021. The intern quantified tropical cyclone-induced changes in the ocean and near-surface atmosphere using PIRATA data.
    - Gives annual “career day” presentations on PIRATA and the tropical Atlantic to students at a local elementary school.
    - Served as Chief Scientist of the FY21 PNE cruise.
- Dr. Renellys Perez, Co-Principal Investigator at AOML:
    - Organized and executed the 24th PIRATA and Tropical Atlantic Variability meeting with Dr. Foltz May 10-14, 2021.
    - Gave a presention at the GOMO Community Virtual Workshop in July 2021 on “Developing a diverse and inclusive ocean observing workforce”
    - Collaborated with Dr. Foltz and Dr. McPhaden to organize the 24th PIRATA and Tropical Atlantic Variability meeting, on May 10-14, 2021. This meeting was held virtually due to the COVID19 pandemic.
    - Became a member of the South Atlantic Meridional Overturning Circulation (SAMOC) Executive Committee in March 2020.
    - Became a member of the U.S. National Committee for Geodesy and Geophysics in April 15, 2020.
    - Supported a postdoc working on an NSF-funded project to study ENSO mechanisms using idealized numerical modeling experiments, and a postdoc working on a NOAA-funded project to study the South Atlantic meridional overturning circulation using moored data.
    - Collaborated with a research associate working with Dr. Greg Foltz, who is investigating upper-ocean diurnal variability and wind-forced current shear using measurements from the 4°N, 23°W PIRATA mooring.
    - Advised (With Dr. Gregory Foltz) a graduate student Lapenta intern during summer 2021. The intern quantified tropical cyclone-induced changes in the ocean and near-surface atmosphere using PIRATA data.
    - Regularly participates in AOML Open House, K-12 outreach events, diversity and inclusion activities, and during the COVID19 pandemic gave several virtual talks to K-12 and undergraduate university students.
    - Worked with the communications team and Dr. Gregory Foltz to update the AOML PNE webpage (https://www.aoml.noaa.gov/pirata-northeast-extension/) and develop a new TACOS page (https://www.aoml.noaa.gov/tropical-atlantic-variability/).
- Mr. Ken Connell, GTMBA Project Manager:
    - Serves as coordinator for the Tropical Moored Buoy Implementation Panel (TIP)
    - Serves as chair of the DBCP Task Team on Moored Buoys
    - Serves as a member of the WMO Expert Team-Editorial Board (EdBd) of the Standing Committee on Measurements, Instrumentation and Traceability (SC-MINT) a subgroup of the WMO Commission for Observation, Infrastructures and Information Systems (INFCOM).

4. Publications and Reports

4.1. Publications by Principal Investigators

GTMBA publications by Principal Investigators have satisfied the NOAA Public Access to Research Results (PARR) requirements for publications.

4.1.1. Published

Alvera-Azcarate, A., C. Troupin, H. Goosse, M.J. McPhaden, and J.-M. Beckers, 2020: Editorial to the Liege Colloquium Special Issue: Long-term studies in oceanography – a celebration of 50 years of science at the Liege Colloquium (1969-2018). *Ocean Dyn.* https://doi.org/10.1007/s10236-020-01421-0.

Beal, L.M., J. Vialard, M.K. Roxy, J. Li, M. Andres, H. Annamalai, M. Feng, W. Han, R. Hood, T. Lee, M. Lengaigne, R. Lumpkin, Y. Masumoto, M.J. McPhaden, M. Ravichandran, T. Shinoda, B.M. Sloyan, P.G. Strutton, A.C. Subramanian, T. Tozuka, C.C. Ummenhofer, A.S. Unnikrishnan, J. Wiggert, L. Yu, L. Cheng, D.G. Desbruyères, and V. Parvathi, 2020: A roadmap to IndOOs-2: Better observations of the rapidly-warming Indian Ocean. *Bull. Am. Meteorol. Soc., 101*. E1891-E1913. doi: https://doi.org/10.1175/BAMS-D-19-0209.1.

Cai, W., B. Ng, T. Geng, L. Wu, A. Santoso, and M.J. McPhaden, 2021: Addendum: Butterfly effect and a self-modulating El Niño response to global warming. *Nature. 126*, e2020JC016840. https://doi.org/10.1038/s41586-021-03261-4.

Cai, W., A. Santoso, M. Collins, et al., 2021: Changing El Niño Southern Oscillation in a warming climate. *Nat. Rev. Earth Environ.* https://doi.org/10.1038/s43017-021-00199-z.

Chakravorty, S., R. C. Perez, B.T. Anderson, S. M. Larson, and B. S. Giese, 2021: Ocean dynamics are key to extratropical forcing of El Niño. *J. Clim*., https://doi.org/10.1175/JCLI-D-20-0933.1.

Christophersen, J. A., G. Foltz, and R. C. Perez, 2020: Surface expressions of atmospheric thermal tides in the tropical Atlantic and their impact on open-ocean precipitation. *J. Geophys. Res. Atmos*., 125, e2019JD031997, https://doi.org/10.1029/2019JD031997.

Da, N. D., G. R. Foltz, and K. Balaguru, 2021: Observed global increases in tropical cyclone-induced ocean cooling and primary production. *Geophys. Res. Lett*., 48, e2021GL092574, https://doi.org/10.1029/2021GL092574

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4.1.2. In press

None

4.1.3. Proceedings from conferences (if peer-reviewed)

None

4.1.4. Technical reports

None

4.1.5. Data reports

None

4.2. Other Relevant Publications

See the RAMA (https://www.pmel.noaa.gov/gtmba/rama-journal-publications), PIRATA(https://www.aoml.noaa.gov/phod/pne/publications.php), and TAO bibliographies (https://www.pmel.noaa.gov/gtmba/tao-journal-publications) for more detail. According to Web of Science, there are a total of 127 publications that have used GTMBA data, a selection of which are listed below. These are the publications we know about and therefore represent a lower bound on papers that have utilized GTMBA data.

4.2.1. Published

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Foli, B. A. K., K. A. Addo, J. K. Ansong, and G. Wiafe, 2021: Evaluation of ECMWF and NCEP reanalysis wind fields for long-term historical analysis and ocean wave modelling in West Africa, *Remote Sen. Earth Sys. Sci.*, https://doi.org/10.1007/s41976-021-00052-3

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4.2.2. In press

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Zeng, L., et al., 2021: A Decade of Eastern Tropical Indian Ocean Observation Network (TIOON), *Bull. Am. Meteorol. Soc*., E2034–E2052. https://doi.org/10.1175/BAMS-D-19-0234.1.

4.2.3. Proceedings from conferences (if peer-reviewed)

None

4.2.4. Technical reports

None

4.2.5. Data reports

None

5. Data and Publication Sharing

As part of NOAA's Public Access to Research Results (PARR) plan (https://repository.library.noaa.gov/view/noaa/10169) new requirements (https://nosc.noaa.gov/EDMC/PD.DSP.php) have been implemented to ensure that all NOAA and NOAA-funded data are well-documented, publicly accessible, and preserved. PMEL's GTMBA data and publications are all publicly distributed and served via the GTMBA website in real-time and delayed mode (following recovery of instruments deployed on moorings at sea).

The GTMBA project has had a long established data management plan in place. All GTMBA data are available in real-time to operational centers worldwide on the GTS and publicly available on the PMEL data display and delivery website. GTMBA data publication and sharing activities are detailed in the following sections for Flux Reference Stations (Sec. 5.1) in PIRATA and RAMA, data delivery in Section 5.2, and data management in Section 5.3.

5.1. Flux Reference Sites

The OceanSITES program is built around a worldwide network of long-term, deepwater reference stations measuring many oceanographic and meteorological variables of relevance to climate and biogeochemical cycles and is a contribution to the Global Ocean Observing System and international research programs. PMEL is a major contributor to OceanSITES: RAMA and PIRATA in totality are a major components of OceanSITES. In addition, embedded in RAMA are 5 flux sites. PMEL currently maintains 4 of these flux sites while the fifth flux site at 0°, 55°E is not yet implemented. There are 6 flux sites embedded in PIRATA, all of which PMEL maintains. Four (4) equatorial Pacific mooring flux sites in the TAO/TRITON Array (4 ATLAS Refresh) are maintained by NDBC.

Enhancements to the primary measurements in each array provide the functionality for all flux reference moorings to measure shortwave and longwave radiation, precipitation, sea level pressure, water temperature with higher vertical resolution, surface and subsurface salinity at 8 depths, and current velocity at one or more depths. PMEL's contributions to OceanSITES are highlighted on the PMEL web site http://www.pmel.noaa.gov/gtmba/oceansites. Heat, moisture, buoyancy, and momentum flux are available from a data display and delivery (http://www.pmel.noaa.gov/gtmba/data-access/flux).

5.2. Web Pages and Data Services

The PMEL's GTMBA web pages (http://www.pmel.noaa.gov/gtmba) continue to provide data, products and information about the arrays in all three tropical basins to a wide range of users. These users include: the oceanic, atmospheric, and climate research communities; operational weather, climate, and ocean forecasting centers; the satellite community for sensor validation;

educators developing classroom and curriculum materials; students in elementary, high school, undergraduate, and graduate education programs; and the general public.

In January 2017 the GTMBA went public with a new website (i.e., complete series of web pages) to replace the legacy PMEL TAO web pages. The new website was developed on the Drupal™ open-source content management framework and will improve integration with other PMEL and NOAA websites to improve content, visualization, and user-experience.

In FY 2021 PMEL's GTMBA web pages received 14,124,388 hits, an increase of 6% over FY 2020. Data from all three tropical ocean basins are available from PMEL's GTMBA data and delivery web page, http://www.pmel.noaa.gov/gtmba/data-access/disdel, as well as from other PMEL sites and from sites maintained by other organizations. In FY 2021 PMEL's data delivery pages served 72,610 user requests for 490,709 data files, an increase of 109% and 52%, respectively from FY 2020. PMEL also tracks the volume of FTP access and finds files delivered to be steadily increasing, exceeding web usage every year since FY 2010 (Table 7). The total FTP delivery in FY 2021 was 5,385,744 data files, a 45% increase from FY 2020.

Table 7. Number of GTMBA data files delivered via the Web and FTP for Fiscal Years 2012 to 2021.

	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021
Web	311,518	439,847	461,934	377,164	394,232	377,057	1,806,364	241,278	322,092	490,709
FTP	1,226,838	1,585,698	1,651,558	2,305,732	3,230,215	3,485,285	3,587,700	4,165,632	3,724,363	5,385,744

Since 2011 PMEL has provided all available daily TAO/TRITON, PIRATA, and RAMA data, and 5-day, monthly, and quarterly averages, to the Southwest Fisheries Science Center (SWFSC) in La Jolla, California, at their request. These downloads constitute such a large percentage of our overall activity that we have excluded them from the statistics above. SWFSC provides all of these data through their ERDDAP system, which also includes many other data sets. TAO/TRITON, PIRATA, and RAMA, are available from SWFC at: http://coastwatch.pfeg.noaa.gov/erddap/search/index.html?searchFor=tao%2Ftriton+rama+pirata

5.3. Data Management

GTMBA data are freely available to all. Real-time data are accessible from PMEL's Data Display and Delivery pages, http://www.pmel.noaa.gov/gtmba/data-access/disdel on the day of reception. Delayed-mode data are made available from the same web site after a mooring is recovered, generally within six months. In addition to distribution from PMEL's web pages, data are distributed in real-time via the GTS to centers such as National Centers for Environmental Prediction (NCEP), The European Centre for Medium-Range Weather Forecasts (ECMWF), and Meteo-France where they are used for operational weather, climate, and ocean forecasting and analyses. Data placed on the GTS include hourly values of wind speed and direction, air temperature, relative humidity, and sea surface temperature. Daily File Transfer Protocol (FTP) transfers are made from PMEL to the CORIOLIS operational oceanography program in France. The MERCATOR program in France makes use of the CORIOLIS data base to generate operational ocean model-based data assimilation products. GTMBA data are also available on the GODAE server in Monterrey, California.

GTMBA data are archived and available for distribution at the NOAA National Centers for Environmental Information (NCEI). GTMBA data and metadata are accessible from data.gov, the US Government open data site managed and hosted by U.S. General Services Administration. PIRATA and RAMA data are also available from OceanSITES data archives and RAMA data are available via the new joint RAMA-OMNI data portal hosted by INCOIS (https://incois.gov.in/portal/datainfo/buoys.jsp).

GTMBA data are available as web services via the OPeNDAP data standard for automated consumption of up-to-date data from authoritative sources through multiple the ERDDAP data servers. The ERDDAP servers promote data discoverability and interoperability with machine-to-machine access and follow FAIR (Findable, Accessible, Interoperable, and Reusable) Guiding Principles for scientific data management and stewardship. GTMBA data are hosted on the following ERDDAP servers:

- http://coastwatch.pfeg.noaa.gov/erddap
- https://comet.nefsc.noaa.gov/erddap/index.html
- https://upwell.pfeg.noaa.gov/erddap/index.html
- https://ferret.pmel.noaa.gov/pmel/erddap/index.html
- http://osmc.noaa.gov/erddap/index.html

Details on GTMBA data telemetry, processing and quality control are available on web sites at:

- https://www.pmel.noaa.gov/gtmba/data-telemetry
- https://www.pmel.noaa.gov/gtmba/sampling
- https://www.pmel.noaa.gov/gtmba/data-quality-control
- https://www.pmel.noaa.gov/gtmba/gts-data-distribution

Data management documentation based on the NOAA Environmental Data Management Committee Data Management Planning Procedural Directive is under development.

6. Project Highlight Slides

Please refer to attached two slides, which highlight the GTMBA FY 2021 progress. We anticipate that information shared on slides may be shared with agency leadership, in interagency discussions, and occasional briefings in public settings.