The in-situ Tropical Pacific Ocean Operational Observing System

Elizabeth J. Thompson (1), Kyla Drushka (2), Brandon Wolding (1, 3)
1) NOAA Physical Sciences Lab, Boulder, CO
2) Applied Physics Laboratory, University of Washington, Seattle, WA
3) Cooperative Institute for Research In Environmental Sciences, NOAA Physical Sciences Lab / University of Colorado Boulder, Boulder, CO

1. Introduction:

This article summarizes the tropical Pacific Ocean operational observing system in terms of routine, operational, and/or long-time series records (Table 1, Fig 1). We discuss physical oceanographic, meteorological, and air-sea interface data types. These are summarized in Fig. 1, Table 1, and discussed in Sec. 2.

Ocean vertical profiles	**Surface data: ocean, atmosphere, interface**	**Atmosphere vertical profiles**
Argo profiling floats	Meteorology and near-surface oceanographic measurements from research vessels and voluntary observing ships. SAMOS repository for all ship data	NOAA Integrated Global Radiosonde Archive
XBTs launched from ships along repeat transects	AOML global surface drifter program	dropsondes
AXBTs launched from aircraft	CDIP surface buoys	
TRITON/TAO moorings	Ocean Reference Station (OceanSITES) moorings	
Ocean Reference Station (Ocean SITES) moorings	Tide gauge networks	
GO-SHIP	Moorings or buoys with surface data also served through NDBC	
Repeat Glider transects	Saildrones	

Table 1. Summary of operational in-situ measurements in the tropical Pacific Ocean

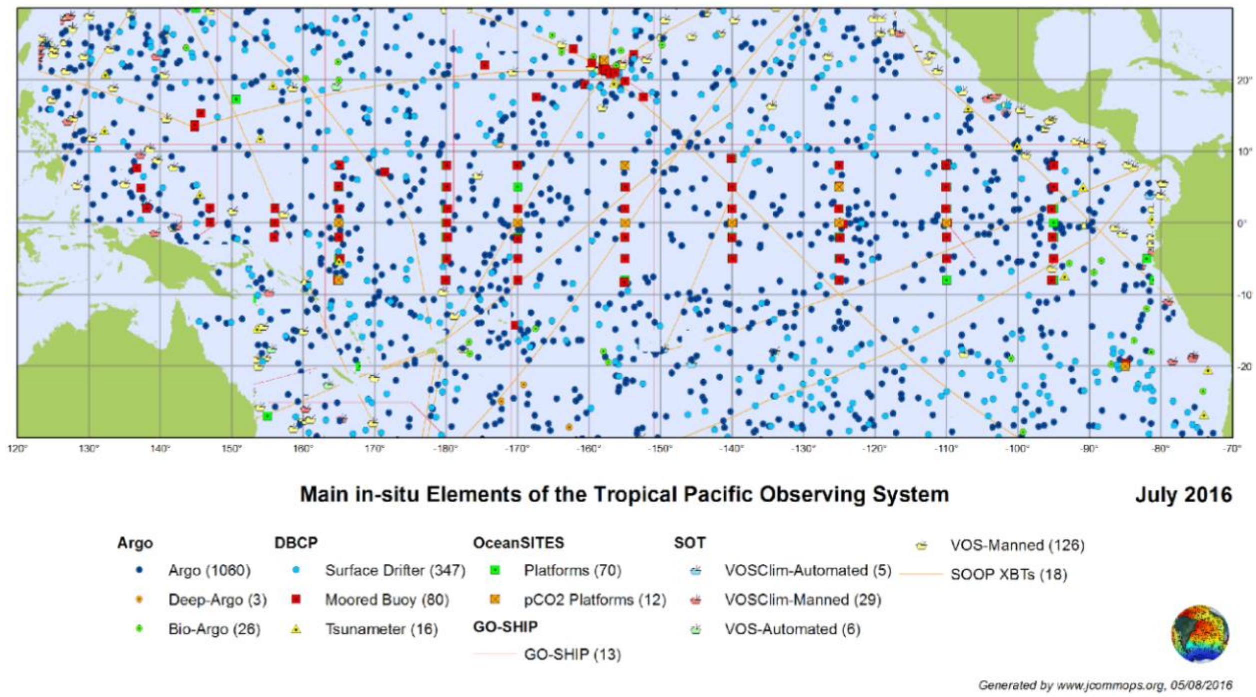


Figure 1: Tropical Pacific in-situ Observing System from TPOS 2020 first report: https://tropicalpacific.org/tpos2020-project-archive/reports/

Field campaign data taken in the tropical Pacific Ocean from ship, aircraft, and autonomous platforms collect valuable data of all these types during intensive operations periods. However, data archive location and availability vary from experiment to experiment. Field campaign data are not discussed here.

2. Operational Datasets:

Argo profiling floats

The international global Argo profiling float array is the largest source of global ocean data in terms of vertical profiles (Fig. 2). The University of California San Diego runs the Argo Program Office (https://argo.ucsd.edu), and Argo data are served by Global Data Assembly Centers (GDACS) in France and in the US. Argo floats transmit data when they surface, make a downward vertical profile of temperature, salinity (conductivity), and depth (and additional biogeochemical properties, for some floats) between the surface and about 1000 m, drift freely with 1000 m ocean currents for approximately 9 days, descend to 2000 m, make an upward vertical profile of the ocean of the same variables, then start the cycle over at the surface. The goal is for an Argo float to visit every 1000 x 1000 km box every 3 months. Some areas are covered more densely than others due to natural convergence or sheltering by coastlines and currents. For instance, the equatorial region requires a constant resupplying of drifters to maintain consistent Argo data coverage. There is also a notable lack of Argo vertical profiles within the seas of the Maritime Continent, where virtually no Argo data have been collected.

Although most of the Argo float network samples only to 2000 m, a number floats from Deep Argo mission collect profiles down to 6,000 m depth. The current and future capabilities of the Argo array are discussed by Roemmich et al. (2019).

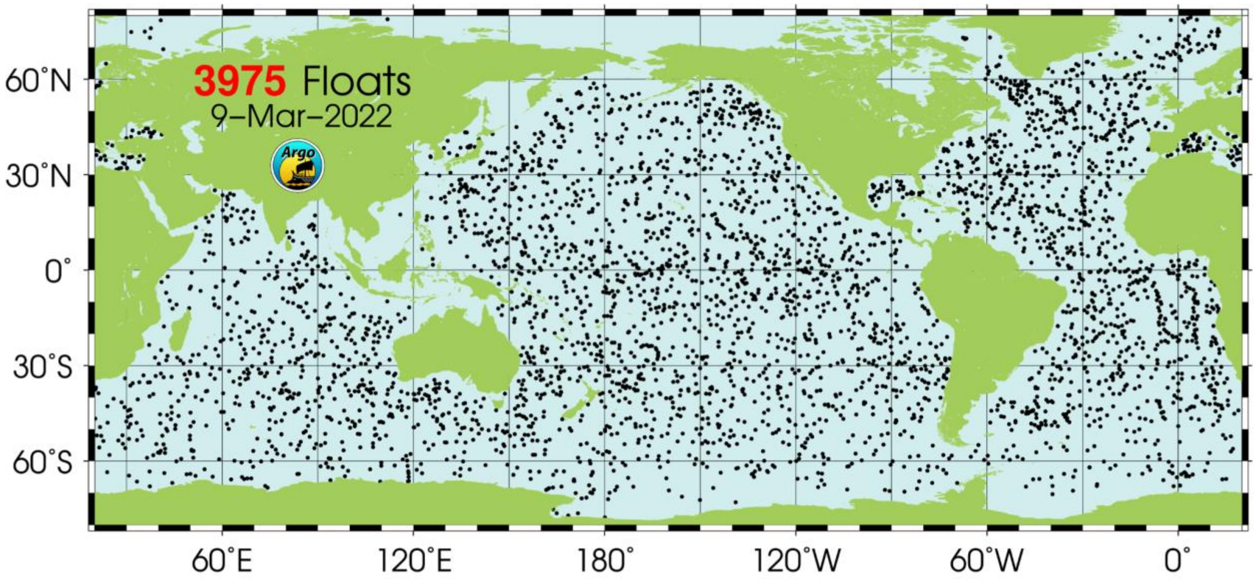


Figure 2: Global array of Argo profiling ocean drifters.

XBT and AXBT expendables

Two additional sets of ocean vertical temperature profile data come from expendable sensors. XBTs (eXpendable BathyThermographs) are launched from repeat ship transects, research ships, and ships of opportunity. The XBT network is maintained by NOAA Atlantic Oceanographic and Meteorological Lab (AOML, https://www.aoml.noaa.gov/phod/goos/xbt_network/). AXBTs (Airborne EXpendable BathyThermographs) are launched from aircraft as part of NOAA hurricane surveillance flights in the eastern Pacific Ocean, as well as some opportunistic US field program research flights in the Pacific. These data are archived at the NOAA National Center of Environmental INformation (NCEI).

TAO/TRITON moorings

The TAO (Tropical Atmosphere/Ocean)/TRITON (Triangle Trans-Ocean Buoy Network) instrumented mooring array is currently operated through the NOAA National Buoy Data Center (NDBC) in partnership with JAMSTEC (Japan Agency for Marine-Earth Science and Technology). Fig 3 shows all moorings that have been deployed since the mid 1990s, though not all are reporting and not all variables are recorded at all stations (https://tao.ndbc.noaa.gov/tao/data_download/search_map.shtml). Planning is ongoing to upgrade the TAO array through the Tropical Pacific Observing System effort (TPOS; https://tropicalpacific.org/). Presently, these buoys provide ocean vertical profiles of temperature, salinity, and currents. Buoys at 0°, 140°W and 110°W (discontinued) have Oregon State University χ-pods for measuring turbulent dissipation rate (https://www.pmel.noaa.gov/tao/drupal/chipod/index.html). Surface meteorology is also measured: rain rate is available at some buoys while most buoys measure surface air temperature and humidity, sea level pressure, and vector wind. Solar and infrared downwelling radiative fluxes are measured at some buoys. A recent Ocean Best Practices Workshop report detailed the challenges and opportunities on obtaining more surface in-situ radiative fluxes across tropical oceans (Cronin et al. 2020). When all these meteorological parameters are measured at the same buoy plus at least near-surface ocean temperature (current and salinity improve estimates but are not technically required), these inputs can be used to estimate the surface net, sensible, latent, and momentum fluxes from bulk algorithms such as COARE (Fairall, et al. 1996a,b, 2003, Edson et al. 2013).

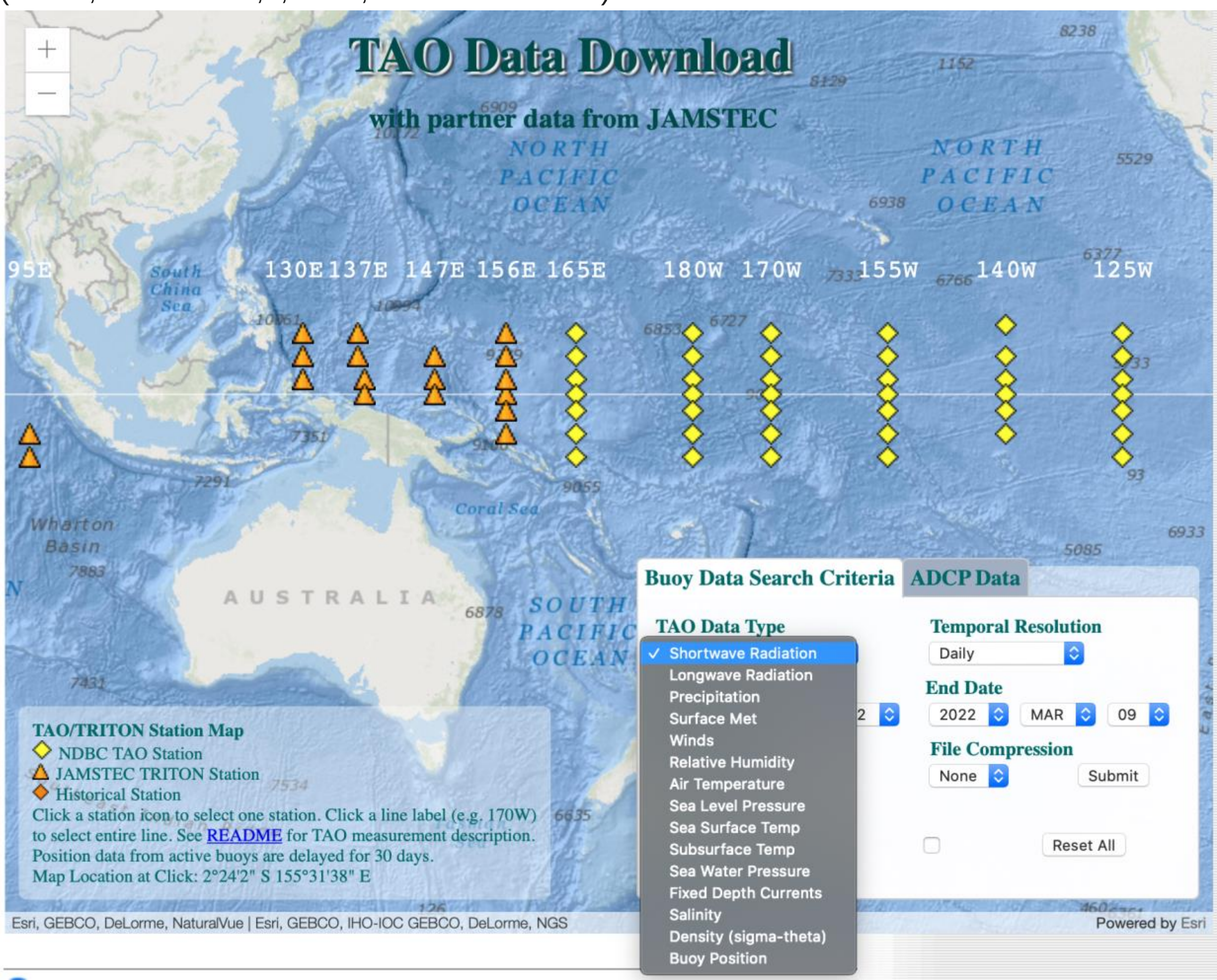


Figure 3. TAO mooring locations and potential data fields available at some buoys for certain time periods.

Ocean Reference Station (OceanSITES) moorings

The NOAA Global Ocean Monitoring and Observations (GOMO) program maintains data from several Ocean Reference Stations (OceanSITES, https://globalocean.noaa.gov/Research/Ocean-Reference-Stations-OceanSITES). These moorings offer deep ocean salinity, temperature, and current profiles as well as surface buoys for near-surface ocean, meteorological, and air-sea flux data. Unlike the operational TAO array, the OceanSITES instrument packages are expanded with several redundant sensors and the buoys are serviced for repairs, full equipment replacements, and calibrations. In the tropical Pacific, the WHOTS (Woods Hole Oceanographic Institution Hawaii Ocean Timeseries (HOT) Site) buoy is located near Hawaii and the KEO is deployed in the Kuroshio Extension Region just east of Japan. KEO is maintained by the NOAA Pacific Marine Environmental Lab (PMEL). The WHOTS buoy is part of the Hawaii Ocean Timeseries (HOT) network of oceanographic moorings and ship records collected around Hawaii since 1987 (http://www.soest.hawaii.edu/HOT_WOCE/index.php). The OceanSITEs data are publicly available but purposefully withheld from the Global Telecommunications System responsible for collecting and assimilating observations into global numerical prediction models (https://public.wmo.int/en/programmes/global-telecommunication-system). OceanSITES datasets are designed to serve as independent benchmarks for model evaluation.

GO-SHIP

The Global Ocean Ship-Based Hydrographic Investigations Program (GO-SHIP) refers to additional ship-based repeat datasets collected on vertical profiles of temperature, salinity, conductivity, pressure, and currents, as well as ocean carbon data: https://www.go-ship.org/DataDirect.html.

Repeat Glider Transects (Solomon Sea)

Ocean gliders have repeated horizontal transects of vertical profiles across the Solomon Sea from 2007 to present, between eastern Papua New Guinea and the Solomon Islands. This forms one of the only public in-situ long-term datasets of physical oceanography in the Maritime Continent (see Fig. 2). As the glider transits horizontally, it pitches up and down to collect vertical profiles of temperature, salinity, and velocity, from which horizontal transport is inferred (Kessler et al. 2019a, 2019b, 2021): https://spraydata.ucsd.edu/SolomonSea/

SAMOS reporting of surface ocean, atmosphere, and radiation data from ships

All ships in the UNOLS (University National Oceanographic Lab System) and NOAA fleets automatically report their near-surface oceanographic, near-surface meteorological, and radiative flux data through the SAMOS (Shipboard Automated Meteorological and Oceanographic System) operated through Florida State University. These data can be used to calculate surface air-sea bulk fluxes using the COARE bulk flux algorithm (Fairall, et al. 1996a,b, 2003, Edson et al. 2013). The SAMOS ocean, meteorology, and air-sea flux database grows each day as research cruises are performed, repeat maintenance cruises are performed to service mooring arrays, and during transects between field experiments.

Global Surface Drifter Array

The NOAA Atlantic Oceanic and Meteorological Lab (AOML) manages the Global Drifter Array or Global Drifter Program (GDP), with contributions from many countries (https://www.aoml.noaa.gov/phod/gdp/index.php). The array consists of ~1,300 satellite-tracked drifters (Figure 4). Buoys sense SST, sea level pressure, and ocean surface wave height/direction in real time. The buoys are drogued at 15 m depth, and their positions are used to estimate ocean mixed-layer currents (Elipot et al., 2016).

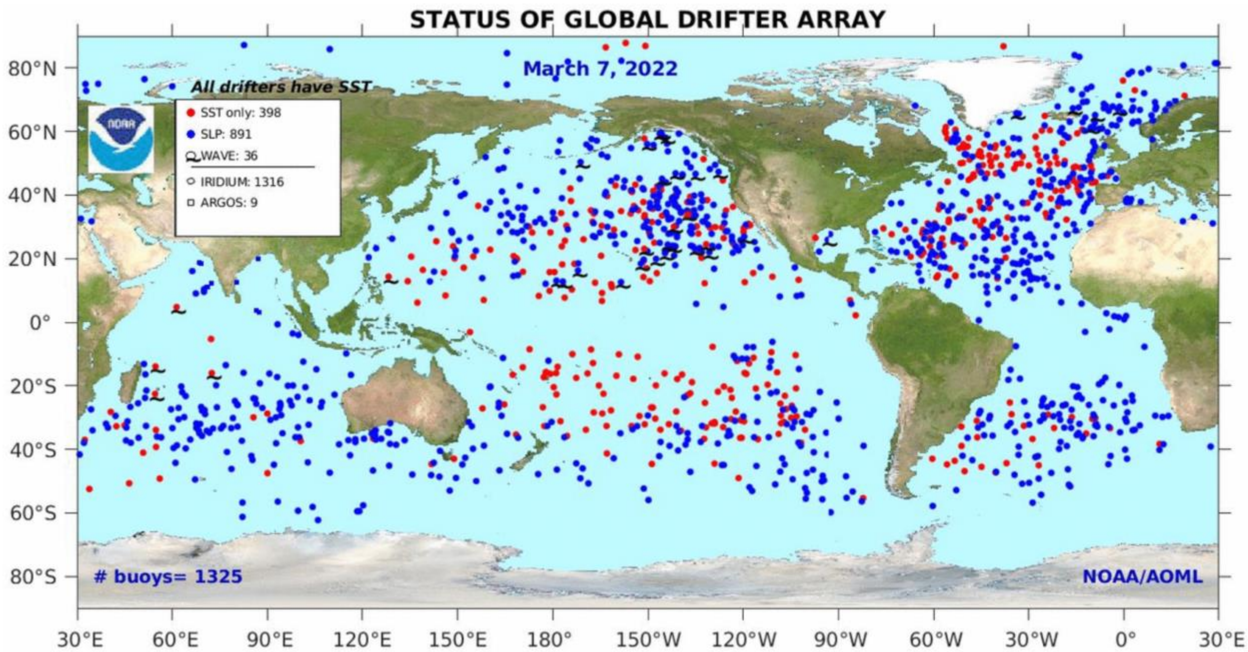


Figure 4. Status of the Global Drifter Array operated through NOAA AOML

CDIP surface buoys

The University of California San Diego's CDIP (Coastal Data Information Program) buoys report significant wave height, peak wave period, peak wave direction, and sea surface temperature (Fig. 5, https://cdip.ucsd.edu/m/stn_table/). Two CDIP buoys exist in the tropical western Pacific on the southern tip of the Mariana Islands, seven CDIP buoys are deployed near Hawaii, and one buoy is deployed near American Samoa (Fig. 5). Commercial wave buoys and drifters such as SOFAR, Nortek, and Datawell may also have data coverage over the Pacific. Though their data may be shared with global numerical weather prediction centers for input and data assimilation, these data are not publicly available.

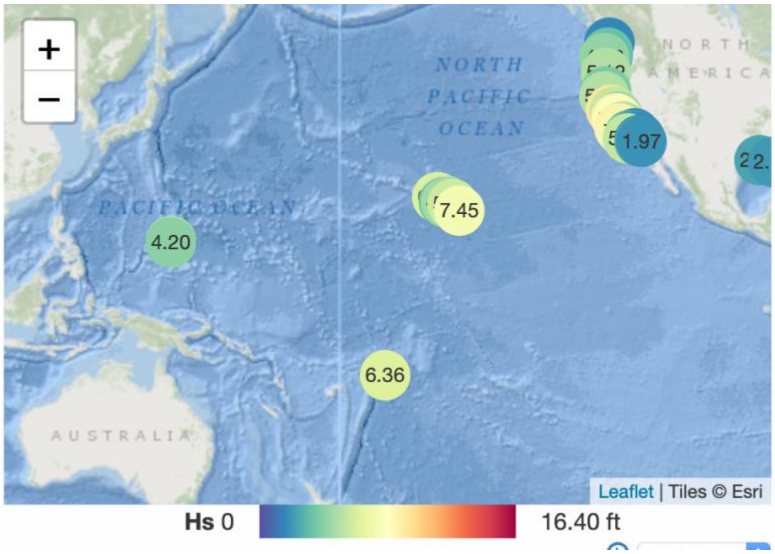
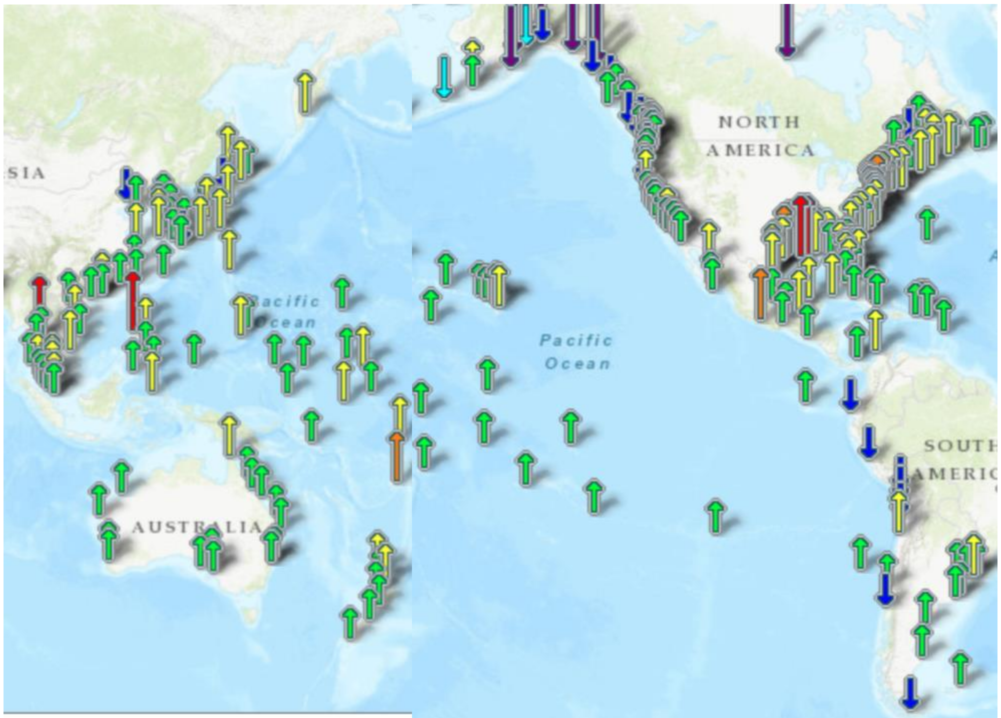


Figure 5. Locations of CDIP buoys with shading indicating significant wave height, Hs.

Tide Gauges

NOAA collects and provides sea level height data at several Pacific stations (Fig. 6) through the Center for Operational Oceanographic Products and Services, which has collected these data for over 150 years (https://tidesandcurrents.noaa.gov/sltrends/). Very few of these stations also collect other oceanographic or meteorological measurements.



The map above illustrates relative sea level trends , with arrows representing the direction and magnitude of change. Click on an arrow to access additional information about that station.

Relative Sea Level Trends

mm/yr (feet/century)

Above 9	6 to 9	3 to 6	>0 to 3	-3 to 0	-6 to -3	-9 to -6	Below -9
(Above 3)	(2 to 3)	(1 to 2)	(0 to 1)	(-1 to 0)	(-2 to -1)	(-3 to -2)	(Below -3)

Figure 6. Tide gauges reporting to NOAA (https://tidesandcurrents.noaa.gov/sltrends/)

NDBC surface stations and moorings

Some additional islands in the western Pacific collect surface and ocean meteorological data that report to the NOAA NDBC (Fig. 7, which also shows buoys from Fig. 2-6). More island data may be available upon request or through specific country websites.

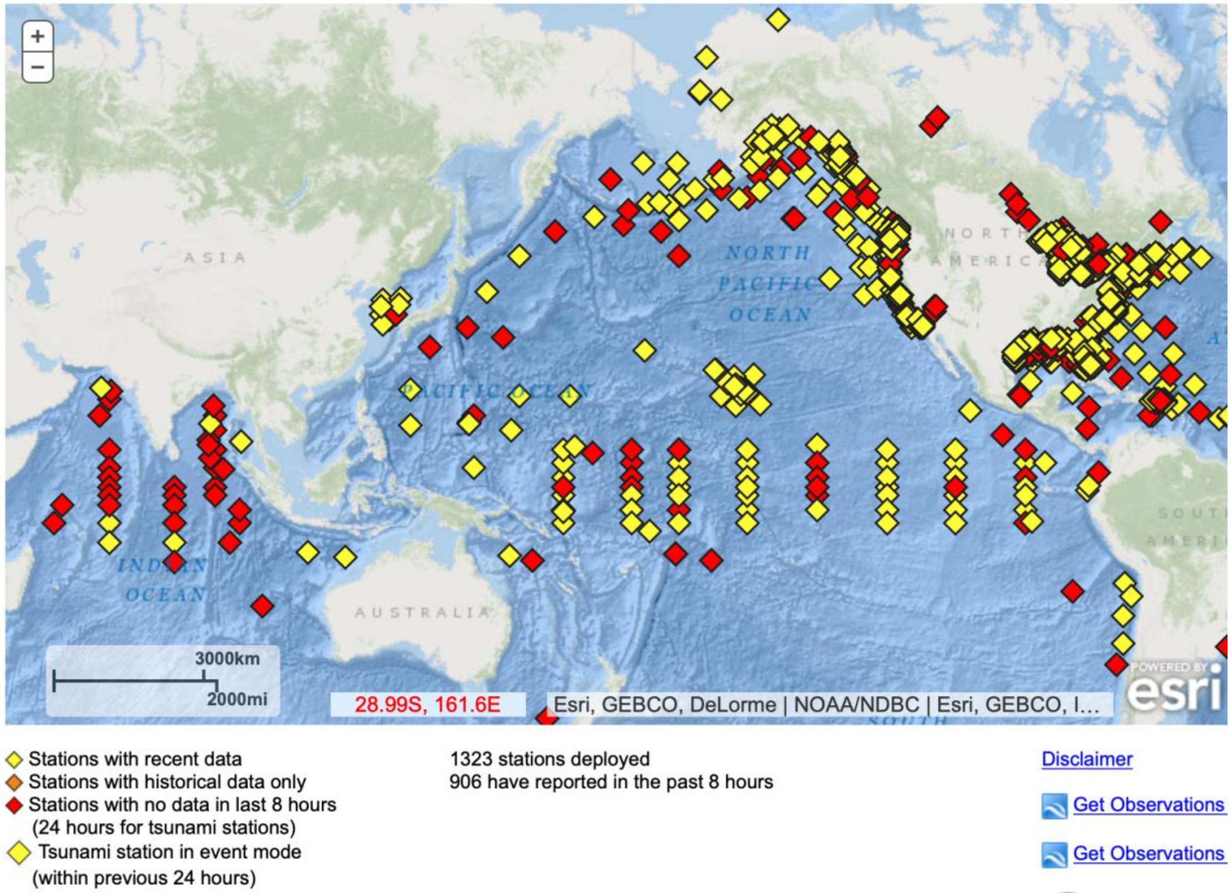


Figure 7. NDBC archive of ocean buoys consisting of TAO/TRITON, CDIP, ORS/OceanSITES buoy arrays (Figures 2-6) and a few additional buoys.

Saildrones

Saildrones missions in the Pacific Ocean have been carried out since 2017 (Meinig et al., 2019). Saildrones collect data of surface meteorology including radiative fluxes, near-surface ocean properties, and sometimes vertical profiles of currents. These data can currently be used to calculate bulk air-sea fluxes. Efforts are ongoing to measure direct eddy covariance fluxes of momentum from Saildrones (Cronin et al., 2019). Not all saildrone vehicles have the same instrument package or capabilities. The Pacific Ocean Saildrone data are maintained at NOAA PMEL (https://www.pmel.noaa.gov/ocs/saildrone).

Atmospheric Vertical Profiles

NOAA maintains and distributes the Integrated Global Radiosonde Archive (IGRA), a collection of historical and near-real-time radiosonde and pilot balloon observations that provide high vertical resolution, quality-controlled records of temperature, relative humidity, dewpoint depression, wind direction, and wind speed (Durre et al. 2006, Durre et al 2018). Additionally, IGRA provides sounding-derived moisture and stability parameters for each sounding with suitable resolution and input fields. While this archive is expansive (Fig. 8), records from small islands within the tropical belt (Fig 8, red markers) are extremely limited, particularly in the central and eastern Pacific ocean. The presence of land can impact the marine character of these records, even over small tropical islands. For example, the remote equatorial western Pacific island of Nauru, which measures only 6 km long by 4 km wide, has been shown to impact atmospheric boundary layer structure and generate cloud streets that can extend hundreds of kilometers downwind (Long and McFarlane 2012). Separate from IGRA, the DOE Atmospheric Radiation Measurement program used to maintain twice daily soundings and surface meteorological observation stations on Manus Island (1996-2014) and Naru Island (1998-2013) in the far western tropical Pacific (Long et al. 2013, 2016, the so-called Tropical Western Pacific sites, TWP). The decommissioning of these rare sounding sites created a large loss in the ocean-atmosphere tropical Pacific observing system. The lack of in-situ soundings representative of marine environments in the tropical Pacific results in a void of records suitable for objective analysis, the calibration/validation of space-based observations, and the validation of models and reanalysis.

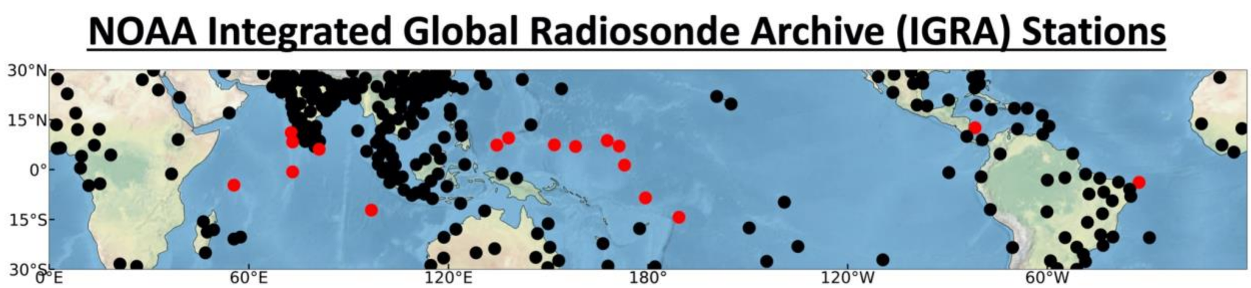


Figure 8. NOAA IGRA stations, where red markers indicate ”small island” stations within the tropical belt +/-15°), defined as stations whose nearest corresponding 0.25° ERA5 reanalysis grid point has a land fraction less than 10%.

NOAA hurricane surveillance flights in the eastern tropical Pacific Ocean in boreal summer also deploy dropsondes when appropriate, and are archived at NOAA NCEI. Additionally large amounts of soundings may be launched from ships during field experiments.

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