9

Ocean Reference Stations

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1. Introduction

OceanSITES is an international network of deep ocean observatories that provide reference time-series for ocean and climate studies. While moorings form the backbone of the network, some stations comprise frequent shipboard observations. With dozens of advanced sensors on these platforms, the time-series are high quality, high resolution (hourly or better in many cases), and long (decades long in some cases). Most stations are interdisciplinary, measuring various aspects of the physical and biogeochemical environment from the sea floor to the atmosphere. All data are made publicly available, in a common format, many in near-real time. In this chapter we describe the motivation for, and the requirements and challenges of this network. Because the network includes more than 105 stations, for practical reasons, our overview of individual stations will focus on the subset of stations that make data available in near-real time. Our goal here is to provide an introduction to the network and provide information and links that will help the reader explore the network further.

2. Water world

We live on a water world. Over 70% of the Earth surface is covered by oceans. On the remaining 30%, human population is not distributed evenly, but instead is most dense in coastal regions. The oceans can affect climate and weather by absorbing, transporting, and emitting heat and gases such as carbon dioxide (Figure 1). Without the poleward heat transport by the ocean currents, the tropics would tend to steadily warm, while the poles would steadily cool. In the high latitudes, heat loss and ice formation generate very dense water at the surface that sinks to the interior and bottom of the ocean, driving the global thermohaline circulation. The oceans also absorb CO_2, thus reducing the effects of anthropogenic climate change.

Because of the high heat content of water, the ocean temperature has much less variability than the atmosphere, particularly the atmosphere over land. While at a given location over land surface air temperature can have a range of up to 90°C, air temperature at a given location over open ocean generally has a range of less than 20°C, and the overall ocean temperature range is roughly 30°C (Figure 2). As such, the oceans typically have a

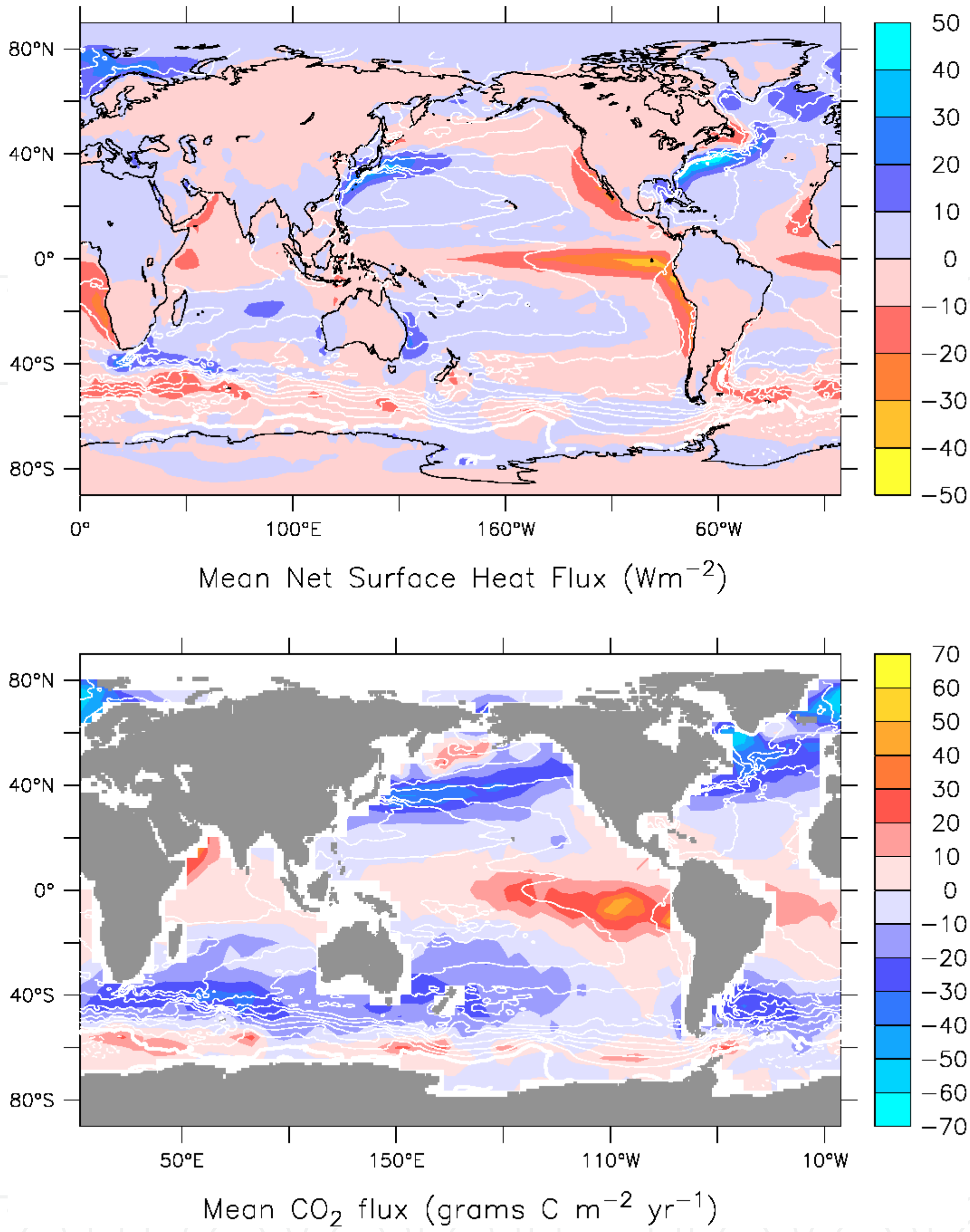

Fig. 1. Mean net surface heat flux in units watts per m^2 based on ECMWF 40-year reanalyses (ERA40) (top) and net surface CO_2 flux in units grams of carbon per m^2 per year, based on the Takahashi et al. (2009) air-sea CO_2 flux climatology (bottom). A positive flux indicates a flux from the ocean to the atmosphere. Note that the color scale is inverted for the CO_2 flux. At the equator, heat enters the ocean through the surface and CO_2 outgasses. White contours indicate mean dynamic sea level height (Rio & Hernandez, 2004).

moderating effect on weather and climate. Indeed, because 2.5 m of water has the same heat capacity per unit area as the whole height of the atmosphere, relatively small changes in the sea surface temperature distribution can have a significant influence on the atmosphere above, particularly in warm water regions such as the tropics, as shown in Figure 3 and discussed below. Approximately 41% of rainfall over land is of maritime origin (Oki & Kanae, 2006). Evaporation, which provides this precipitable water, is strongly dependent upon temperature.

Significantly more moisture is evaporated where the surface water is warm, fueling deep convection and precipitation (Figure 3). Small shifts in the location and temperature of very warm water can thus cause shifts in the atmospheric convection and weather patterns, both locally and global (Ding et al., 2011; Wallace & Gutzler, 1981).

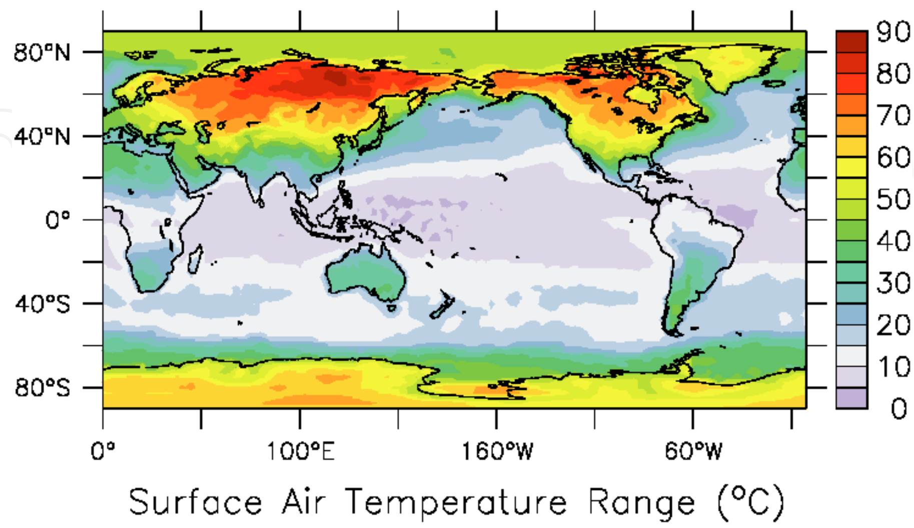

Fig. 2. Air temperature range based upon daily averaged ERA40 values in units degrees Celsius.

Because of the Earth's rotation, the direct ocean response to wind forcing is an upper ocean transport that is to the right of the wind in the Northern Hemisphere (NH) and to the left of the wind in the Southern Hemisphere (SH). The easterly trade wind and westerly jet stream, and the placement of the continents, thus tend to cause convergence and divergence patterns that result in higher sea level in the subtropics and lower sea level in the subpolar regions (Figure 1). To a certain extent, the sea level height anomalies can be considered as streamlines of the surface flow. Water, that would tend to flow downhill, is deviated to the right in the NH and to the left in the SH, so that the adjusted flow is along the anomalous sea level height isobars. Consequently, the trade winds and jet streams result in an anticyclonic subtropical gyre in each of the ocean basins. The NH westerly jet stream also supports a cyclonic subpolar gyre in the North Pacific and North Atlantic, while in the SH, the jet stream drives an eastward flowing Antarctica Circumpolar Current. Directly at the equator, the axis of rotation is perpendicular to the vertical (gravity), making vertical motion near the equator much more dynamic both in the atmosphere and ocean. This, together with the effects of the warm water on precipitable water, causes the ocean and atmosphere to be much more coupled in the tropics than elsewhere. Changes in the ocean surface temperature can result in changes in the atmospheric deep convection and winds, which can in turn affect the ocean temperature structure.

While the ocean drift in most parts of these gyres is slow (~25 cm/s), in some parts, such as the western boundary currents and the circumpolar current, speeds can be up to 2 m/s near the surface and 25 cm/s at depth, corresponding to a transport of order 100 x 10^6 m^3/s. While the analogy has its limits, these ocean currents can be considered as a conveyor belt, carrying heat, salt, and marine ecosystems. Warm currents carry heat poleward, and return currents and the deep thermohaline circulation carry cool water equatorward, resulting in a large-scale meridional overturning circulation.

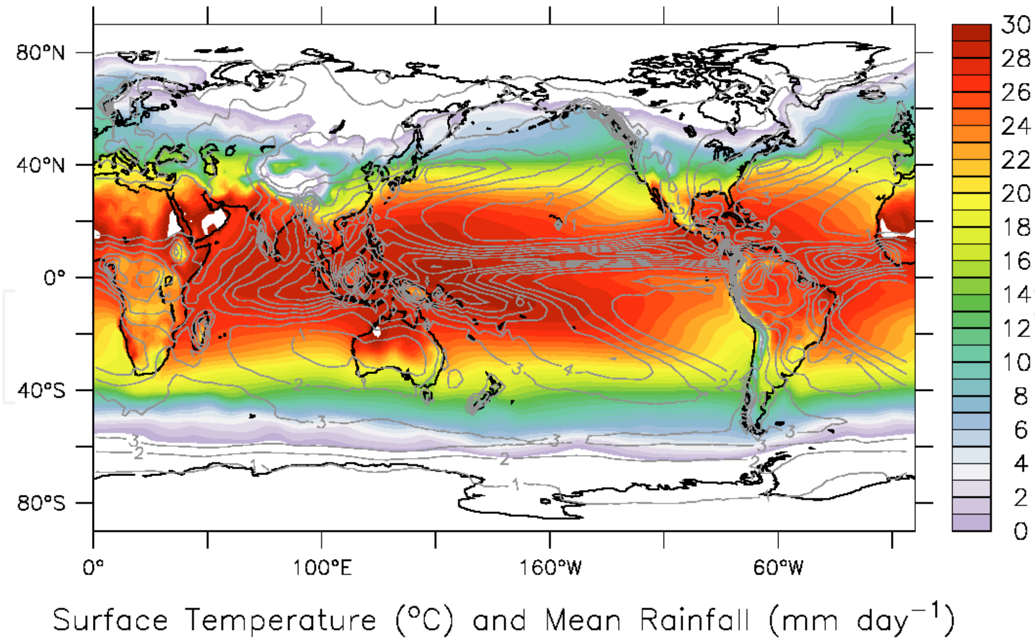

Fig. 3. Mean surface temperature from ERA40 in units °C (only values greater than 0 are shown), and precipitation from the Global Precipitation Climatology Project in units mm per day (contoured).

Marine life, which lives within this dynamic environment, can be quite sensitive to the ocean temperature. Many animals reproduce, feed, or migrate only within a limited temperature range. Temperature also affects the buoyancy of the water, which can trap nutrients and dissolved inorganic carbon within the euphotic zone where photosynthesis and primary production occur. During blooms, CO_2 is used in the production of both organic and inorganic biogenic particles, a portion of which sink into the deeper ocean and are regenerated into CO_2 through respiration and dissolution. This export of CO_2 is referred to as the "biological pump" of the carbon cycle. During respiration, oxygen is depleted. Anoxic water, devoid of dissolved O_2, is generally barren of macroscopic life. Temperature also affects the solubility of dissolved gasses and thus the concentrations of dissolved O_2 and CO_2: As the surface water cools, it can hold and absorb more CO_2. Thus as the surface water cools and sinks, atmospheric CO_2 is absorbed into the water and exported into the deep ocean, a process referred to as the "solubility pump" of the carbon cycle.

The distribution of CO_2 within the ocean is also critical to the pH of the water and the concentration of carbonate ions, which is a basic building block of skeletons and shells for a many marine organisms, including corals, shellfish, and marine plankton (Feely et al., 2004). As the ocean absorbs more anthropogenic CO_2, the CO_2 reacts with the seawater to form carbonic acid (H_2CO_3). This then dissociates to form a bicarbonate ion (HCO_3^-) and a hydrogen ion (H^+), which can react with carbonate ions (CO_3^{2-}) to form bicarbonate (HCO_3^-). The net effect of the increased CO_2 is thus a decrease in pH and a decrease in the carbonate ion concentration, a process referred to as ocean acidification (Feely et al., 2010). The reduction in carbonate ion affects the saturation state of calcium carbonate ($CaCO_3$) and is critically important as it directly affects the ability of some $CaCO_3$ secreting organisms to produce their shells or skeletons. When pteropods were exposed to undersaturated water, their $CaCO_3$ shells showed notable dissolution (Orr et al., 2005).

Like global weather maps of wind, barometric pressure, and atmospheric humidity and temperature properties, global maps of the ocean circulation, sea level, and temperature and salinity properties are needed to visualize, quantify, and understand the ocean physical variability (Cazenave et al., 2010; Schmitt et al., 2010; Talley et al., 2010; Wijffels et al., 2010). For understanding and quantifying the ocean and atmosphere interactions, maps of the air-sea fluxes of heat, moisture, momentum, and gasses are needed (Fairall et al., 2010; Gulev et al., 2010). Likewise, for understanding and quantifying changes to the carbon cycle, maps of the atmospheric and seawater pCO_2, dissolved O_2 concentration, pH, and nutrients are needed (Gruber et al., 2010). Monitoring and predicting O_2 concentration levels is critical for assessing the effects of the biological pump both on the carbon cycle and the ecosystem. Monitoring and mapping changes in the ocean acidification is likewise critical for understanding the biological impacts of increased of anthropogenic CO_2 (Feely et al., 2010).

To make these maps, satellites, ships, floats, drifters, and moored buoys gather data that are routinely ingested into numerical models (Eyre et al., 2010). However, across the broad ocean, as compared to the land, observations are sparse. To validate and assess these modeled fields, as well as to assess satellite remotely sensed fields, in situ observations are needed as reference data (Send et al., 2010). Reference data are also needed for evaluating the processes and mechanisms that affect the ocean environment and ecosystems, and for developing parameterizations of processes that cannot be fully resolved within the numerical models (Lampitt et al., 2010a).

3. Reference ocean data

3.1 Requirements

Reference data, by definition, must be high quality, with quantified uncertainty that is small relative to the signal that is being measured. Uncertainties are determined by the measurement resolution, by investigation of sensor performance in the field, and through calibrations that are traceable to a standard at national metrology institutes such as the U.S. National Institute of Standards and Technology. Measurement resolution is determined by the sensor's precision and sampling frequency. If the sampling frequency is lower than the Nyquist frequency of the signal, errors can arise due to aliasing. In particular, biases can result if the sample frequency is identical to the signal frequency. For example, in regions such as the tropics where the diurnal cycle is large, surface temperature measurements will be biased high if the samples are only during the daytime. Likewise, in regions where the annual cycle is large, measurements may be biased high if they are only sampled during the summer.

Figure 4 shows the spectral bandwidth of various oceanographic signals that have periodicities that range from order of seconds (surface waves), to minutes (internal waves in very high stratification), hours (diurnal cycle, tides, inertial oscillations, internal waves), days (storm forced variability, hydrodynamic instabilities, mesoscale eddies), months (planetary waves, seasonal cycle), years (El Niño, gyre-scale variability), decades (gyre-scale, meridional overturning), and longer (anthropogenic forcing). For some processes that depend upon variables in a nonlinear way, variability in these parameters at one scale may affect variability in the process at another scale. Turbulence generally causes a cascade of energy from low to high frequency. However, high-frequency variability can also, in some cases, rectify into the longer scales. For example, since the efficiency of surface forcing depends upon the stratification, large diurnal co-variations in the forcing and stratification in the tropics can rectify and impact intraseasonal and longer timescales, thus affecting the coupled ocean-atmosphere interactions (Bernie et al., 2007; Guemas et al., 2011; Shinoda, 2005).

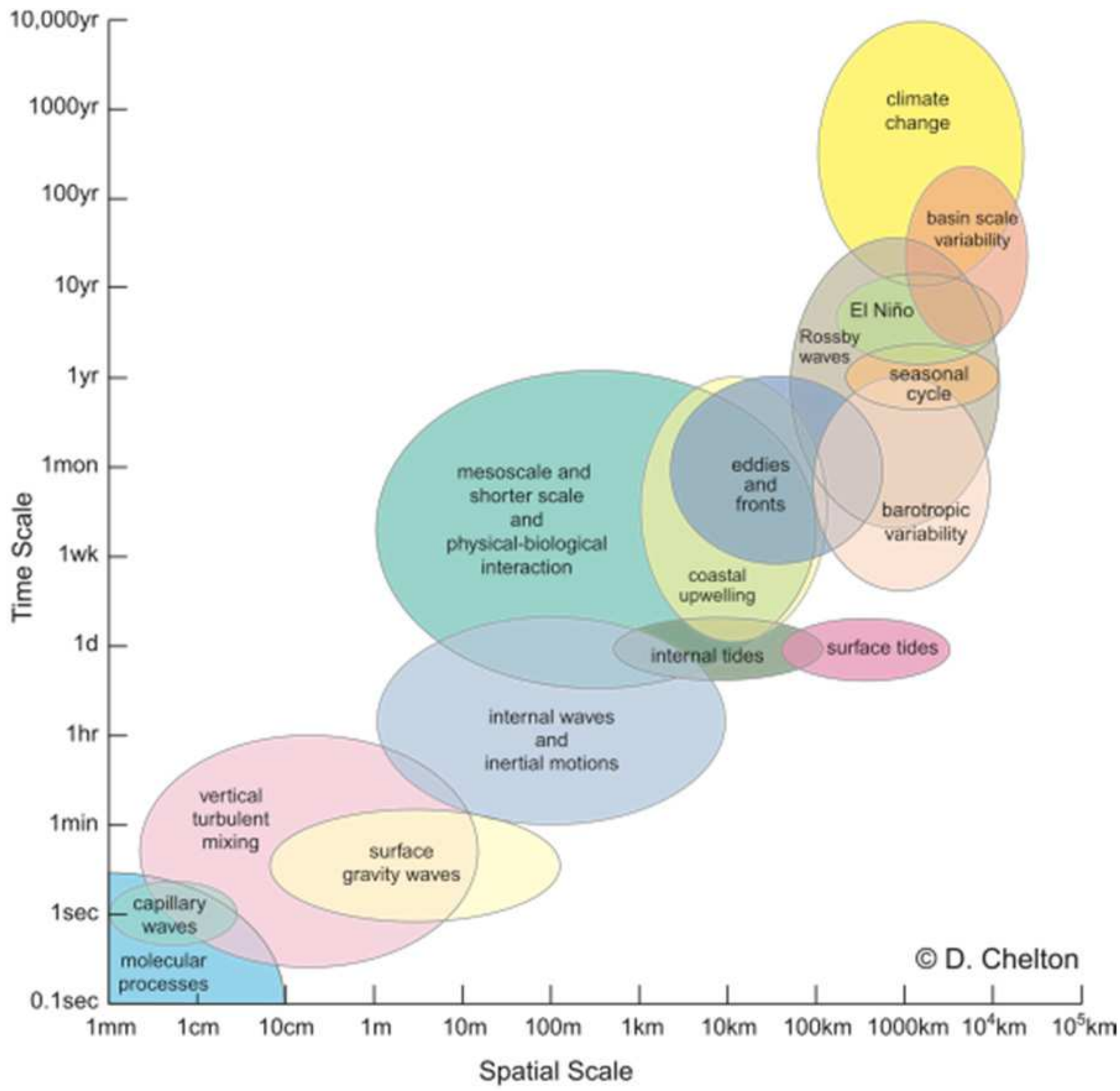

Fig. 4. Time and space scales of ocean variability (courtesy D. Chelton, Oregon State University, after Dickey (2001)).

3.2 A network of open ocean reference stations

For resolving high-frequency variability, moorings are the ideal platform, as the resolution of the moored sensors is generally limited only by constraints on the battery life and duration objectives. With the mooring refreshed at regular intervals (generally 6–12 months), these stations can provide long-term, high-resolution, accurate time-series. Moorings thus form the backbone of the global network of OceanSITES reference stations (Lampitt et al., 2010a; Send et al., 2010). The OceanSITES network, shown in Figure 5, is an element of the Global Ocean Observing System, which is a system within the Global Earth Observing Systems of Systems (GEOSS).

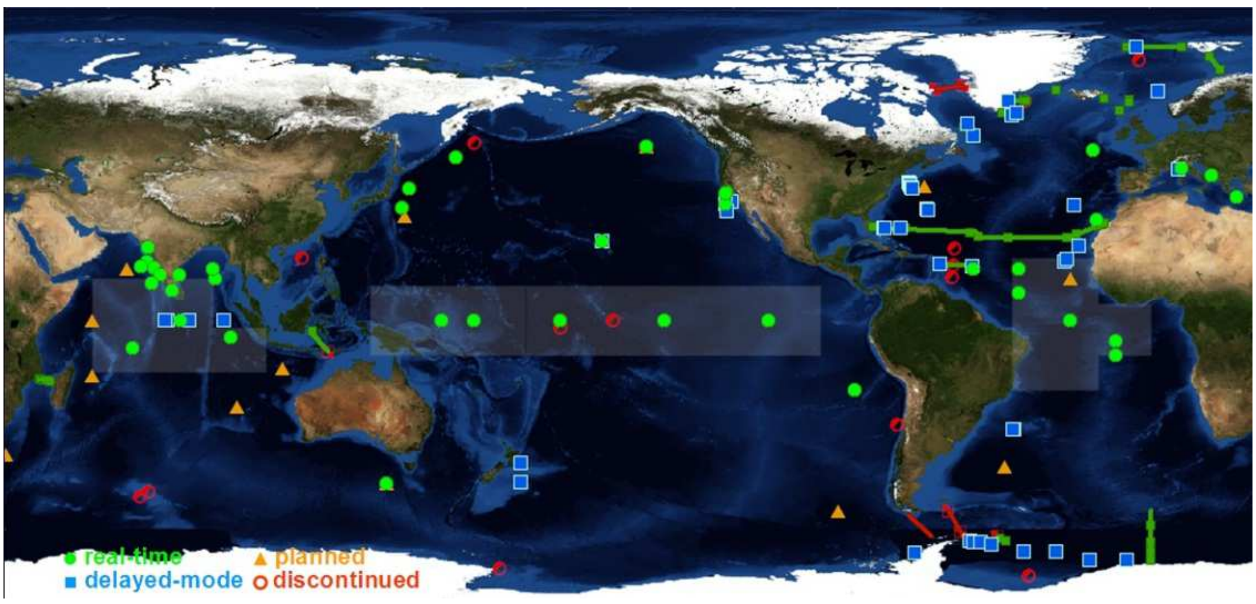

Fig. 5. OceanSITES network of reference stations, as of 2010 (figure courtesy http://www.oceansites.org/network/). Stations with near-real-time data are shown as green circles. Observatories without data telemetry are shown as blue squares. Transport stations are shown as small green squares and regular transport transects are shown as green lines. Planned stations are shown as orange diamonds; discontinued stations and transects are indicated in red.

At present, the OceanSITES network is a collection of stations operated by scientists throughout the world, supported through their national agencies, who agree to the basic requirements of data quality and open data with common formats. The vision is that the OceanSITES network would be interdisciplinary: "a worldwide system of deepwater reference stations: providing high resolution measurements, the full depth of the ocean, multi-year time scales, dozens of variables, real-time access." Indeed the OceanSITES acronym stands for OCEAN Sustained Interdisciplinary Timeseries Environment observation System. In practice, however, not every station monitors the full suite of physical and biogeochemical variables that characterize the local ocean environment. Within the array, moored buoys that carry meteorological sensors to characterize the exchanges or fluxes of heat, momentum, freshwater, and gases (e.g., carbon dioxide) across the air-sea interface are referred to as air-sea "flux" stations. These moorings also generally carry sensors on their anchor line to monitor the physical and sometimes biogeochemical environment in the upper ocean. Other moorings and frequently visited stations, referred to as "observatories," have as their primary objective monitoring the biogeochemical properties within much of the water column. Finally, the purpose of the "transport" stations is to monitor the ocean currents and transport.

3.3 Data latency

While some of the mooring stations have surface buoys that allow telemetry of near-real-time data; other mooring stations are entirely subsurface, and must be recovered to obtain the data. This can introduce a delay in the data availability of more than a year. With telemetered data, analyses can begin almost immediately, thus accelerating the research. Telemetry also acts as important insurance on the data. If the mooring is lost, the telemetered data may be the only source of the data. Having telemetry also allows the operators to identify and address problems in current and future deployments, thus minimizing data gaps. Finally, in some cases, the telemetered near-real-time data are used to assimilate into a short-term weather forecast, for which every hour of latency implies an hour of forecast.

Due to the sparse nature of oceanographic data, there is often a desire to assimilate all data possible, including reference data. Model operators often argue that an individual measurement is weighted in a way that it will not introduce a bullseye pattern in the fields and make the product appear falsely accurate when compared with the reference time-series. Reference data are, by definition, supposed to be independent of the products for which they are used to assess. A World Meteorological Organization (WMO) data identification number containing the digits "84" indicate that they are reference data. Protocols are being developed to identify when reference data are being assimilated.

The delayed mode data, available after internally recording instruments are recovered and processed, also have unique value. Because of limited bandwidth and technical challenges for telemetry of ocean data, the real-time data are only a subset of the data available on the moorings. Internally recorded data may have sampling rates of every 1 minute and faster, whereas hourly data may be what was telemetered. Further, the recovered instruments are post-calibrated; thus, the delayed mode data have less uncertainty associated with their accuracy. In general, the delayed mode data are the highest quality data at a reference stations.

4. The OceanSITES network of reference moorings

In the following section we provide an overview of individual stations within the OceanSITES network, focusing on stations that telemeter data to shore. These include all of the air-sea flux stations, many of which also serve as biogeochemical observatories or are coordinated with nearby observatory and transport stations. A few subsurface observatories also have a small surface buoy used exclusively for telemetry. Because of the complexity of the network it is not possible to describe the network in its entirety. Our purpose here is to provide an introduction and information for further exploration of the network. As a start, the reader is directed to the OceanSITES network website: http://www.oceansites.org.

At roughly $30,000-50,000 per day, shiptime is a significant component of the overall cost of the deep ocean mooring array. These costs and the limited number of global-class research vessels have necessitated efficient use of the fleet. For example, mooring maintenance cruises are often used for long-term coordinated observations. Likewise, while the stations themselves carry a suite of sensors for monitoring multiple variables, the stations also offer opportunities for other coordinated observations. Nearly all stations have been sites of process studies, involving multiple platforms (ships, extra moorings, drifters, floats, aircraft, etc.). In the following overview, we describe some of these activities, although a full list is not feasible.

4.1 Tropics

4.1.1 The Global Tropical Moored Buoy Array (GTMBA)

The network has its densest coverage in the tropics (Figure 6). The tropical moored buoy array began in the eastern equatorial Pacific in the early 1980s and expanded to cover 8°S–8°N across the Pacific with moorings and shiptime at present provided by the US National Oceanic Atmospheric Administration (NOAA) and the Japan Agency for Marine-Earth Science and Technology (JAMSTEC). The NOAA portion of the Pacific array is referred to as the Tropical Atmosphere and Ocean (TAO) array and the JAMSTEC portion is referred to as the Triangle Trans-Ocean Buoy Network (TRITON) array. As discussed below, the primary purpose of the TAO/TRITON array is to observe, better understand, and predict the El Niño-Southern Oscillation (ENSO). In 1997, the array expanded into the Atlantic with moorings from NOAA and shiptime provided by Brazil, France, and the US. The primary purpose of the Atlantic array, referred to as the Prediction and Research Moored Array in the Atlantic (PIRATA), is to observe, better understand, and predict seasonal, interannual, and longer variability, including both ENSO-like and meridional modes of variability. In 2000, the array expanded into the Indian Ocean, with moorings provided by the US, Japan, India, and China, and shiptime provided by India, Indonesia, France, Japan, and the Agulhas Somali Current Large Marine Ecosystems project. The primary purpose of the Research Moored Array for African-Australian Monsoon Analysis and Prediction (RAMA) is to advance monsoon research and forecasting.

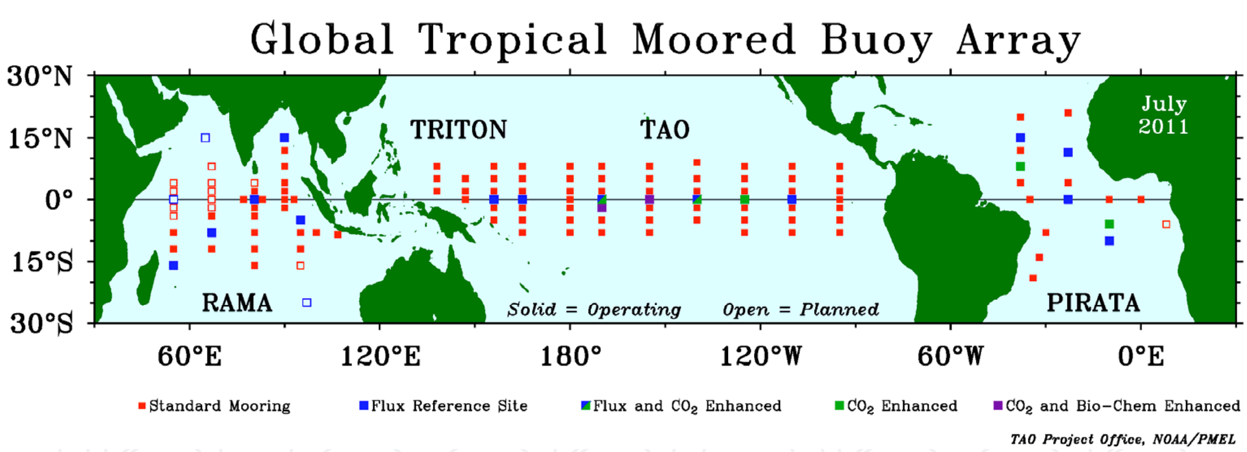

Fig. 6. Global Tropical Moored Buoy Array, as of July 2011. Flux reference stations are indicated by a blue square. Courtesy M. McPhaden, NOAA Pacific Marine Environmental Laboratory (PMEL).

Within the tropical Pacific, surface trade winds tend to blow from the cool waters off of South America to the warm waters off of Indonesia, where the wind converges and rises in deep convective clouds. As can be seen in Figure 7, as the warm water shifts eastward, the region of wind convergence and deep convection shifts eastward, resulting in the ENSO cycle, with teleconnections to global weather and climate patterns (Bouma et al., 1997; Diaz & Markgraf, 2000).

The standard suite of sensors on the tropical buoys includes wind speed and direction, air temperature and humidity, surface salinity, and surface and subsurface temperature. A number of the moorings, however, are enhanced with additional sensors to monitor the air-

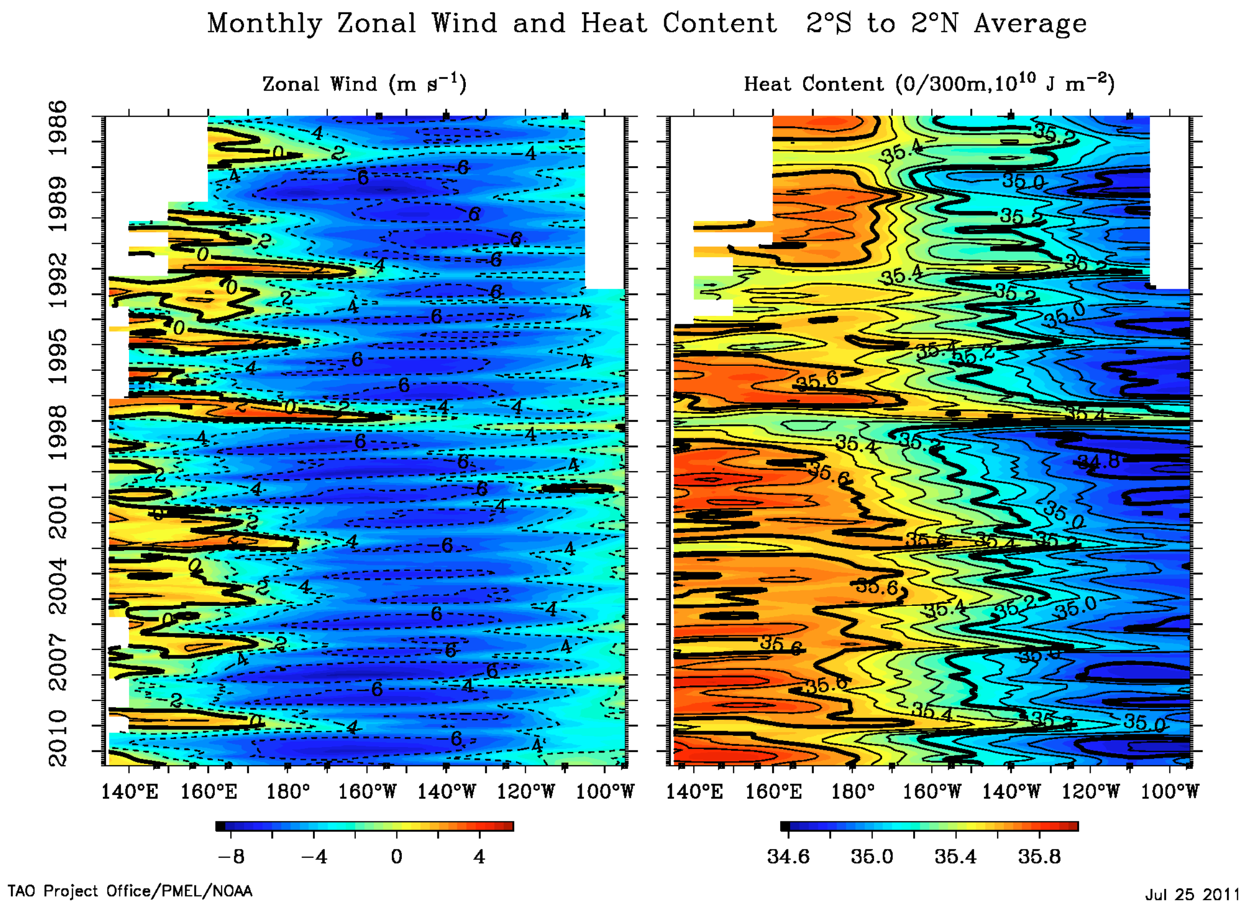

Fig. 7. Zonal wind (left) and upper 300 m heat content (right) time-series along the equatorial Pacific, as measured by the Pacific Tropical Atmosphere Ocean (TAO) /Triangle Trans-Ocean Buoy Network (TRITON) array. This figure was generated using the data display webpage, courtesy of the TAO project office of NOAA PMEL: http://www.pmel.noaa.gov/tao/jsdisplay/.

sea heat, moisture, and carbon dioxide fluxes; upper ocean salinity; and currents. The most heavily instrumented of these sites are designated as flux stations. The entire GTMBA, together with these specialized flux stations, contribute to the OceanSITES network of deep ocean reference stations (Figure 5).

Through the decades there have been several large international process studies built around the array, including the Coupled Ocean Atmosphere Response Experiment in the western tropical Pacific in 1992–1993 (Webster & Lukas, 1992), the Eastern Pacific Investigation of Climate in 2001 (Cronin et al., 2002; Raymond et al., 2004), and the GasEx 2001 study of physical, chemical, and biological factors controlling pCO_2 fluxes in the eastern equatorial Pacific (Sabine et al., 2004). In the Atlantic, African Monsoon Multidisciplinary Analyses (AMMA) occurred 2005–2007 (Lebel et al., 2011). The Cooperative INDian Ocean experiment on intraseasonal variability in the Year 2011 / Dynamics of the Madden-Julian Oscillation (CINDY/DYNAMO) experiment in the Indian Ocean is planned for 2011. Maintenance cruises for the array have also been opportunities for ship-based ancillary projects, including regular hydrographic and Acoustic Doppler Current Profiler (ADCP) sections (Johnson et al., 2002); water sample (Behrenfeld et al., 2006) and atmospheric boundary layer measurements (Fairall et al., 2008); underway surface pCO_2 (Feely et al., 2006) and chlorophyll fluorescence (Behrenfeld et al., 2006); and regular deployments of ARGO floats (Roemmich et al., 2009) and surface drifters (Lumpkin & Pazos, 2007), among other activities. For more information on the Pacific TAO/TRITON array, see McPhaden et al. (1998); for the Atlantic PIRATA array, see Bourlès et al. (2008); and for the Indian Ocean RAMA array, see McPhaden et al. (2009). Data and information can be accessed through the GTMBA project website: http://www.pmel.noaa.gov/tao/global/global.html.

4.1.2 Stratus reference station mooring west of Chile

The Stratus reference station mooring, located west of Chile at 20°S, 85°W in 4450 m depth water, was initiated in 2000. During the 1990s it became clear that nearly all coupled general circulation models had significant biases in the tropical Pacific that impeded their ability to properly reproduce the ENSO variability (Mechoso et al., 1995). In particular, nearly all models had too warm SST and too little stratus cloud in the eastern boundary region just west of Chile. As a result, these models tended to produce convective rainfall north and south of the equator, rather than just north of the equator as shown in Figure 3. The air-sea fluxes as well as the dynamics of the ocean and atmosphere in this data sparse region were poorly known, and any further progress required new data from the region. Thus, in 2000, with support from NOAA, a reference surface mooring, referred to as the "Stratus" mooring, was deployed at 20°S, 85°W. The mooring provides quality surface meteorology and air-sea fluxes of heat, freshwater and momentum, and CO_2. Annual cruises to maintain the buoy have provided opportunities for intensive ship-based measurements, particularly of the atmospheric boundary layer (Bretherton et al., 2004). In 2008, the international process study VAMOS Ocean-Cloud-Atmosphere-Land Study Regional Experiment (VOCALS-REx) (Wood et al., 2011) was anchored by the Stratus mooring. For more information on the Stratus reference mooring see Colbo & Weller (2007). The project website can be found at: http://uop.whoi.edu/projects/Stratus/stratus.html.

4.1.3 Northwest Tropical Atlantic Station (NTAS)

The NTAS surface mooring was established in 4700 m depth water near 15°N, 51°W to investigate surface forcing and oceanographic response in a region of the tropical Atlantic with strong sea surface temperature (SST) anomalies and the likelihood of energetic local air–sea interaction on interannual to decadal timescales. Two modes of coupled air-sea variability are found in the tropical Atlantic, a dynamic mode similar to the Pacific ENSO and a thermodynamic mode characterized by changes in the cross-equatorial SST gradient. Forcing for these modes may be by synoptic atmospheric variability, remote forcing from ENSO, and extratropical forcing from the North Atlantic Oscillation (NAO). Relationships between tropical SST variability, the NAO, and the meridional overturning circulation, as well as between the two tropical modes, are poorly understood.

The NTAS site is co-located with the easternmost subsurface mooring of the Meridional Overturning Variability Experiment (MOVE) "transport" array, which monitors the deep southward branch of the North Atlantic meridional overturning circulation west of the Mid-Atlantic Ridge. Annual cruises to NTAS are shared with MOVE. Funding for NTAS and MOVE is primarily from NOAA. For more information see Kanzow et al. (2008). The NTAS and MOVE project websites can be found at: http://uop.whoi.edu/projects/NTAS/ntas.html, and http://mooring.ucsd.edu/index.html?/projects/move/move_results.html.

4.1.4 Tropical Eastern North Atlantic Time-Series Observatory (TENATSO) and Cape Verde Atmospheric Observatory (CVAO)

CVAO meteorological and atmospheric chemistry measurements and TENATSO-moored physical and biogeochemical measurements in the tropical eastern North Atlantic were initiated in 2006. In 2008, routine ship visits to TENATSO were initiated to collect physical and biogeochemical measurements at TENATSO. CVAO is located on a small Cape Verde island (Sao Vicente) at 16.8°N, 24.9°W, while the TENATSO ocean station is located in 3600 m depth water ~93 km north of the island at 17.6°N, 24.2°W. Like other tropical stations, this is a region of intense air-sea interaction. Being downwind of the Mauritanian upwelling, the ocean and atmospheric data can be used to link biological productivity and atmospheric composition. The location is critical for climate and greenhouse gas studies and for investigating dust impacts on marine ecosystems. CVAO atmospheric reference data contribute to the Global Atmospheric Watch (GAW) program of the WMO, and TENATSO is part of the EuroSITES network (http://www.eurosites.info/), which contributes to the global OceanSITES network. CVAO and TENATSO are funded by Germany, UK, and the EU. For more information, see: Read et al. (2008). CVAO and TENATSO websites can be found at: http://ncasweb.leeds.ac.uk/capeverde/, http://tenatso.ifm-geomar.de/, and http://www.eurosites.info/tenatso.php.

4.2 North Pacific

4.2.1 Kuroshio Extension observatories and JAMSTEC biogeochemical observatories K2 and S1

The NOAA Kuroshio Extension Observatory (KEO) surface mooring is located south of the Kuroshio Extension jet at 32.3°N, 144.5°E in 5700 m depth water, and the JAMSTEC KEO (JKEO) surface mooring is located north of the jet at 38°N, 146.5°E in 5400 m depth water. KEO was initiated in 2004 during the Kuroshio Extension System Study (KESS) (Donohue et al., 2008) and JKEO was initiated in 2007. Both KEO and JKEO monitor the air-sea fluxes of heat, moisture, momentum, and carbon dioxide, as well as the upper ocean temperature, salinity, and near-surface currents in the region of very large ocean heat loss in the western North Pacific (Figure 1). The large heat fluxes occur during winter, when cold, dry continental air blows over the warm ocean current. As can be seen in Figure 1, similar regions of high ocean surface heat loss are seen in all basins (Cronin et al., 2010). This strong oceanic warming of the atmosphere can affect the surface winds, clouds, storm development, and, potentially, the storm track. The large air-sea heat fluxes also can affect the formation of water masses, or mode water. The KEO site is located in the subtropical mode water formation region and the JKEO site is located in the central mode water formation region (Oka et al., 2011a, 2011b). Mode waters are formed and modified at the surface, and, after they subduct beneath the surface layer, they generally preserve these characteristics as they circulate through the ocean (Hanawa & Talley, 2001; Oka & Qiu, 2011).

Beginning in 2011, KEO will be enhanced with additional sensors to monitor ocean acidification and the net biological production of oxygen in the surface waters. The carbon cycle and its biological pump are also being monitored at the JAMSTEC biogeochemical observatories, which include K2 in the western subarctic Pacific at 47°N, 160°E in 5200 m depth water and S1 in the western subtropical gyre at 30°N, 145°E in 5900 m water depth.

K2 was initiated in 2001 and S1 was initiated in 2010. Both the western and eastern regions of the subarctic Pacific are expected to experience significant effects of ocean acidification during the next century from the absorption of anthropogenic CO_2 (Orr et al., 2005).

Routine measurements from the JAMSTEC mooring maintenance cruises have included hydrographic, atmospheric profile sounding sections, and underway meteorological and oceanographic measurements, among other activities (Tokinaga et al., 2009). All four stations are visited regularly during JAMSTEC biogeochemical cruises. For more information on the KEO array, see Cronin et al. (2008) and Konda et al. (2010). For Station K2, see Kawakami et al. (2007). Project websites can be found at: http://www.pmel.noaa.gov/keo/, http://www.jamstec.go.jp/iorgc/ocorp/ktsfg/data/jkeo/ and http://www.jamstec.go.jp/res/ress/hondam/index_e.html.

4.2.2 Hawaii Ocean Time-series (HOT)

One of the most iconic long time-series is the famous "Keeling" curve showing the increase in atmospheric CO_2 observed at Mauna Loa since 1958 (Figure 8). While the atmospheric CO_2 has seasonal peak-to-peak variations of ~7 parts per million (ppm), over the past five decades, the CO_2 concentration has steadily increased by more than 10 times that amount due to anthropogenic sources.

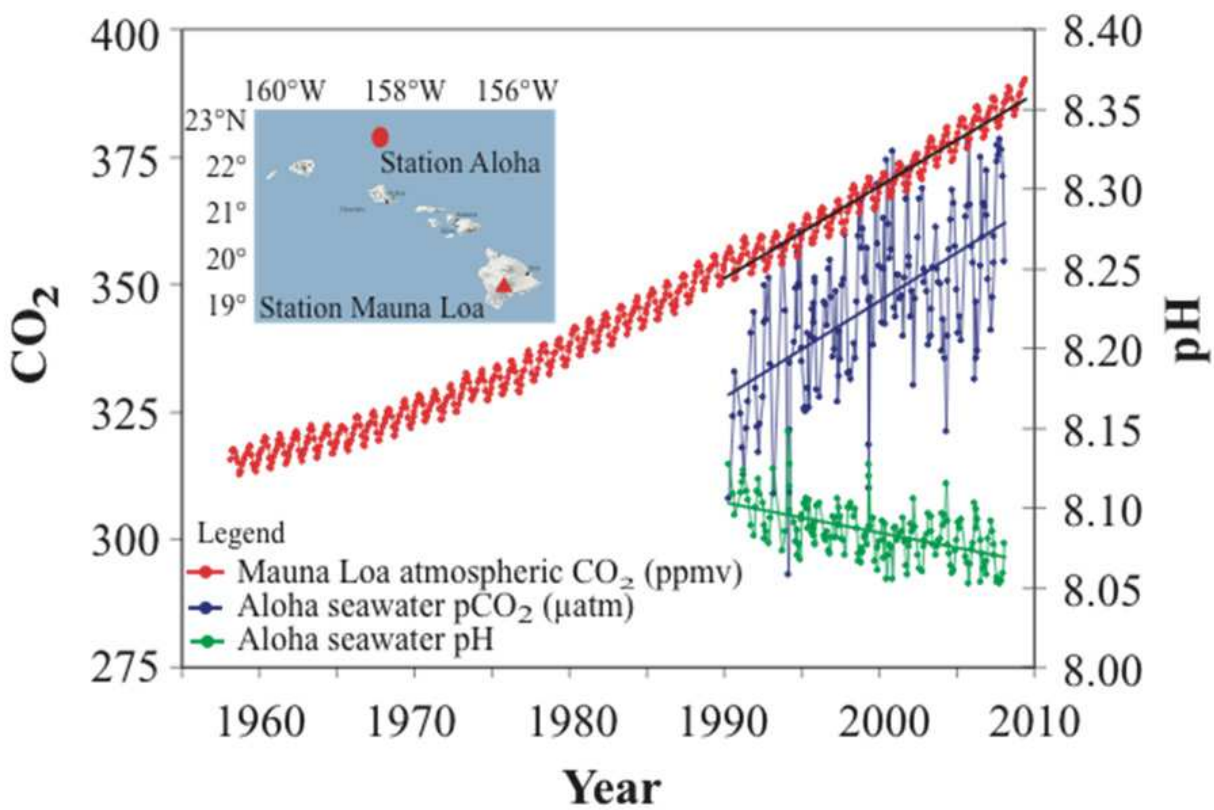

Fig. 8. Time-series of atmospheric CO_2 at Mauna Loa, in parts per million volume (ppmv; red), surface ocean pCO_2 (μatm; blue) and surface ocean pH (green) from the Hawaii Ocean Time-series Station ALOHA. Note that the increase in oceanic CO_2 over the past 17 years is consistent with the atmospheric increase within the statistical limits of the measurements. From Doney et al. (2009), after Feely et al. (2008).

A corresponding oceanic time-series at an observatory station in 4780 m depth water, 100 km north of the island of Oahu, was initiated in 1988 through the Hawaii Ocean Time-series (HOT) program, funded primarily by the US National Science Foundation (NSF). As shown in Figure 8 (Doney et al., 2009; Feely et al., 2008) the rise in pCO_2 is observed in the surface waters, and because it interacts with seawater to form carbonic acid as discussed in Section 2, this rise is also associated with a decrease in the water's pH. Essentially, the absorption of anthropogenic CO_2 is causing the waters to become more corrosive.

As shown in Figure 8, the sea surface CO_2 has rapid natural variability due to variations in the ocean temperature, mixing, upwelling, and biological processes. While much of this variability is captured in the monthly cruises to the HOT ALOHA (A Longterm Oligotrophic Habitat Assessment) observatory, there is significant variability at higher frequencies. Thus, with funding from NOAA and additional funding from NSF, in 2004, a surface reference station flux mooring was deployed at the observatory site. The mooring measures surface oceanic and atmospheric pCO_2 at three hourly intervals, and meteorological and other physical measurements even more frequently. For more information on the HOT program, see Karl et al. (2003). The project websites can be found at: http://hahana.soest.hawaii.edu/hot/hot_jgofs.html and http://uop.whoi.edu/projects/WHOTS/whots.html.

4.2.3 Station Papa in the eastern subarctic Pacific

One of the oldest ocean time-series is Ocean Station Papa, which began in December 1949 as part of the ocean weathership program. Station Papa is located at 50°N, 145°W in the eastern subarctic Pacific in 4260 m depth water. During its first year the site was occupied by a US Coast Guard ship. For the next three decades it was occupied continuously by Canadian ships on 6-week rotations. Taking meteorological and oceanic measurements, information was radioed to shore and contributed to the weather forecasts during this period. With the advent of the satellite era in the early 1980s, the Canadian Weathership Program was terminated. The Line-P program funded by Canadian Fisheries and Oceans, however, continued to make shipboard measurements on transects from Victoria, Canada, to Station Papa 3–6 times per year. Standard Line-P measurements include hydrography (Crawford et al., 2007), O_2 (Whitney et al., 2007), phytoplankton biomass and nutrient samples (Peña & Varela, 2007), zooplankton net tows (Mackas et al., 2007), chlorophyll, transmissivity, as well as dissolved inorganic carbon and total alkalinity (Wong et al., 2002), among other measurements. The present program samples three times per year, in February, May-June, and August-September.

Through the decades, Station Papa has been the location of numerous process studies, including, among others: the Mixed Layer Experiment in 1977 (Davis et al., 1981), Subarctic Pacific Ecosystem Research in 1984 (Miller, 1993), Storm Transfer and Response Experiment in 1980 and 1981 (Large et al., 1986), Ocean Storms in 1987 (Paduan & Niiler, 1993), and the SOLAS/SERIES iron enrichment experiment in 2003 (Boyd et al., 2004; de Baar et al., 2005). From 2007 to 2009, an NSF funded Carbon Cycle process study included support for a flux reference station mooring at Station Papa to monitor the carbon cycle and ocean acidification, in addition to the physical and meteorological environment (Emerson et al., 2011). In order to continue the mooring station on an ongoing basis, in 2009, support for the reference station mooring was transferred to NOAA. Shiptime for annual mooring maintenance has been provided by the Canadian Line-P program. The US NSF Ocean Observatory Initiative (OOI) plans to enhance this station in the coming years with additional moorings and sensors to make station Papa one of its four global nodes. For more information on Station Papa and Line-P, see Freeland (2007) and Peña & Bograd (2007). The project websites can be found at: http://www.pmel.noaa.gov/stnP/ and http://www.pac.dfo-mpo.gc.ca/science/oceans-eng.htm.

4.2.4 Monterey Bay Aquarium Research Institute (MBARI) moorings, California Current Ecosystem (CCE) moorings, and the California Oceanic Cooperative Fisheries Investigation (CalCOFI)

The MBARI moorings were in the California Current system at 36.7°N, 122°W in 1600 m and 36.7°N, 122.4°W in 1800 m water depth were first deployed in 1989. The moorings carry physical, meteorological (air-sea flux), and biogeochemical sensors. Ecosystem productivity and the biogeochemical cycling of elements in the California upwelling regions is regulated by physical processes that vary on daily to multidecadal time scales. As with other observatories described here, through these concurrent measurements of physics, chemistry, and biology, changes in biological and chemical fluxes associated with the physical variability can be estimated and used to develop predictive models. These moorings are funded primarily through support from the David and Lucile Packard Foundation, with support for bio-optical measurements from NASA. For more information, see Chavez et al. (1997). The project website can be found at: http://www.mbari.org/oasis/.

With funding from NOAA, two multi-disciplinary moorings, CCE1 and CCE2, are being sustained off Point Conception at 33.5°N, 122.5°W and 34.3°N, 120.8°W in 4000 m and 800 m of water, respectively. CCE1 was initiated in 2008 and CCE2 was initiated in 2010 and carry physical, meteorological, biogeochemical, and ecosystem sensors. The moorings contrast the productive upwelling regime near the coast and the open-ocean regime in the center of the southward flowing low-salinity Californian Current, and are co-located with repeat stations of the CalCOFI shipboard sampling grid, and a glider repeat transect. CCE1 and CCE2 provide real-time data and connectivity to sensors along the mooring wire down to several hundred meters depth, and have spare capacity for adding and telemetering additional community-provided sensors. Ground-truthing for chemical and optical/acoustic ecosystem observations is provided by CalCOFI cruises. The CalCOFI program began in 1949 for the purpose of studying the ecological aspects of the sardine population collapse off California. Initially monthly cruises, the present sampling is quarterly cruises to 75 stations in a 1.9 x 10^5 km^2 grid located off the coast of Southern California and provides unique long-term time-series at select locations in the southern California Current. For more information on CalCOFI, see: Ohman and Venrick (2003). The CCE and CalCOFI project websites can be found at http://mooring.ucsd.edu/cce/.

4.3 North Atlantic

4.3.1 Bermuda Atlantic Time-series Study (BATS)

Biweekly ship-based observations at "Hydrostation S", in 3300 m depth water 25 km SE of Bermuda, began in 1954, making this one of the few ocean time-series that exceeds 50 years. In October 1988, monthly cruises were extended to the BATS station located in 4500 m depth water approximately 80 km SE of Bermuda. These monthly (and biweekly during spring bloom periods) BATS cruises had a broader focus on the biogeochemistry and hydrography of the Sargasso Sea ecosystem. The site is located within the North Atlantic subtropical gyre, similar to the HOT location in the center of the North Pacific subtropical gyre. From 1994 through 2007, a surface mooring at this site, referred to as the "Bermuda Testbed Mooring" (BTM), carried a suite of meteorological, physical, and biogeochemical sensors. At present the BATS observations are supported primarily through NSF research grants. Funding cuts to the BTM, however, caused this long, high-resolution time-series to be discontinued in 2007. As discussed later, one of the main challenges of the reference station network is securing sustained funding. For more information on hydrostation S, see Phillips & Joyce (2007); for BTM and BATS, see Dickey et al. (2001). Project websites can be found at: http://www.bios.edu/research/bats.html and http://www.opl.ucsb.edu/btm.html.

4.3.2 Central Irmingir Sea (CIS)

The CIS observatory, established in 2002, is located about 200 km east of the southern tip of Greenland, at 59.4 ºN, 39.4 ºW in a water depth of 2800 m. The instrumentation is optimized for resolving physical and biogeochemical processes in the mixed layer, with sensors that monitor temperature, salinity, currents, nitrate, pCO_2, O_2, and fluorescence, among other variables. Wintertime surface cooling can be intense and very deep mixed layer depths have been observed, indicating deep water formation. Because weather conditions have been a perpetual challenge, the mooring has a small surface element for real time data transmission, but does not carry meteorological sensors.

The NSF OOI plans to enhance this station in the coming years with additional moorings and sensors to make the CIS station one of its four global nodes. Currently, CIS is funded by Germany and the EU. For more information, see: http://www.eurosites.info/cis.php.

4.3.3 Porcupine Abyssal Plain (PAP)

The PAP observatory is located in 4850 m depth water south of the North Atlantic Current, at 49°N, 16.5°W, in a region with a relatively flat seafloor. The mooring, equipped with sediment traps at three depths, was first deployed in 1989 to study and monitor the open ocean water column biogeochemistry, physics, and benthic biology. Capability has steadily increased to include upper ocean biogeochemical variables such as CO_2, chlorophyll and nutrients in 2002. In 2009, the station was enhanced to monitor surface meteorology and thus the observatory became an air-sea flux station as well. PAP is located in a region with large ocean absorption of atmospheric CO_2. Surface mixed layers are deep during winter, and during springtime the mixed layer becomes shallow, supporting a widespread phytoplankton bloom. PAP observations thus allow monitoring of the carbon cycle from the atmosphere to the abyss and its physical and biological pumps.

PAP is funded primarily by the UK Natural Environment Research Council (NERC) and the EU, and is part of the EuroSITES network. For more information on PAP see Lampitt et al. (2010b). The project webpage can be found at: http://www.noc.soton.ac.uk/pap.

4.3.4 European Station for Time-series in the Ocean Canary Islands (ESTOC)

The ESTOC observatory, located about 100 km north of the Canary Islands at 29.2ºN, 15.5ºW in 3610 m depth water, was initiated in 1994 with monthly ship visits to the station that included a sediment trap mooring and nearby subsurface current meter mooring. Since 2002, the station has been occupied by a surface mooring that measures upper-ocean physical and biogeochemical variables and surface meteorology. In 2007, the sediment trap mooring was terminated and in 2008, the surface mooring was upgraded to monitor air-sea fluxes. As it is windward of the Canary Islands, the station avoids wake effects of the Canary Current and northeast trade winds. It is also far enough from coasts and islands to serve as a reference for satellite images and altimetry.

Funding for ESTOC has come from the EU, the German Research Foundation (DFG), and national and regional projects from Spain and the Canary Islands. At present, funding from the governments of Spain and the Canary Islands comes primarily through the Canary Oceanic Platform (PLOCAN; http://plocan.eu). For more information on ESTOC, see Neuer et al. (2007) and González-Dávila et al. (2010). ESTOCS is part of the EuroSITES network and its websites can be found at: http://www.eurosites.info/estoc.php and http://www.estoc.es/.

4.4 Mediterranean Sea

4.4.1 Mediterranean Moored Multi-sensor Array (M3A) network

The M3A network includes three reference stations which contribute to the EuroSITES and OceanSITES networks: POSEIDON/E1-M3A in the south Aegean Sea at 35.8ºN, 24.93ºE (initiated in 2000), E2-M3A in the Adriatic Sea at 41.84ºN, 17.76ºE (initiated in 2004), and the W1-M3A in the Ligurian Sea at 43.81ºN, 9.12ºE (also initiated in 2004). All three moorings carry suites of sensors to monitor the surface meteorology and air-sea fluxes, directional wave parameters, upper ocean temperature, salinity, currents, and biochemical parameters in the euphotic zone. Biogeochemistry within the Ligurian Sea is also monitored by the DYFAMED station described below. All three M3A stations are in water depth greater than 1200 m. The M3A network is funded by Italy, Greece, and the EU. For more information, see: http://www.eurosites.info/.

4.4.2 Dynamics of the Atmospheric Fluxes in the MEDiterranean (DYFAMED) station in the Ligurian Sea

The DYFAMED station in the Ligurian Sea at 43.42ºN, 7.87ºE was initiated in 1988 with the deployment of a mooring with sediment traps at 200 m and 1000 m, in water depth of 2350 m. Since 1991, monthly cruises have been performed as well to observe the physical and biogeochemical variability throughout the water column. In 1999, a nearby surface mooring was deployed by Météo-France to monitor the surface meteorology and wave parameters. Ocean physical parameters are also measured at present by sensors mounted on the sediment trap mooring. DYFAMED is currently funded by France and the EU. For more information, see Marty (2002) and the project websites: http://www.obs-vlfr.fr/dyfBase, and http://www.eurosites.info/dyfamed.php.

4.5 Southern Ocean

4.5.1 Southern Ocean Time-Series (SOTS)

SOTS (Trull et al., 2010) commenced in 1998 with a sediment trap mooring program (SAZ; Trull et al., 2001) located in the Sub-Antarctic Zone 650 km south of Tasmania at 46.75°S, 142°E, in 4600 m of water. The site was expanded in 2003 with the addition of the Pulse mooring, to understand biogeochemical processes in the surface ocean, and again in 2010 with the addition of the Southern Ocean Flux Station (SOFS; Schulz et al., 2011) climate mooring, autonomous drifting profilers, and gliders. The Southern Ocean "Roaring Forties" is notorious for its storms, waves, and strong currents. Its Circumpolar Current is a route by which water can be carried from the South Atlantic Ocean to the South Indian Ocean and the South Pacific. As waters, formed at the surface in the Subantarctic Zone, sink and flow under warmer subtropical and tropical waters, they carry CO_2 into the deep ocean, out of contact with the atmosphere. Through this subduction process, oxygen and nutrients are also supplied to deep ocean ecosystems throughout much of the global ocean. It should be noted that this is the only OceanSITES surface mooring south of the Tropic of Cancer. SOTS is funded through the Australian Integrated Marine Observing System (IMOS; Hill, 2010; Meyers, 2008). For more information, see: http://imos.org.au/sofs.html.

5. Challenges facing the network

5.1 Long term commitment

Obtaining long time-series requires commitment: organizational, institutional, and scientific. Funding organizations that can support a long-term project do not always exist. In many cases, these long time-series are funded through 3–5 year research grants and the time-series is vulnerable to the funding cycle. If the research proposal with a 3-year time horizon is rejected, the long time-series is discontinued, as was the case of the 13-year surface mooring time-series at the BATS observatory discussed above. Likewise, for the very long time-series, the scientists who initiated the time-series may no longer be involved. During the transition in leadership, the institution's interest in the station can play a critical role in the ultimate success of the transition. Ultimately, the value of the station is determined by how the data are used, which depends upon the scientific importance of the station, the suite of measurements and their quality, the data latency and availability, and the ease with which the data can be used (Karl, 2010).

5.2 Public data and common data formats

OceanSITES has an active data management group that developed a self-documented netCDF (network common data form) format that all station operators agree to use. (For more information, see http://www.oceansites.org/data/). All station operators also agree to submit their data in this common format to Data Assembly Centers (DACS) that, in turn, forward data to two Global Data Assembly Centers (GDACS) that mirror each other: one at the NOAA National Data Buoy Center (NDBC) in the US and one at the Institut Français de Recherche pour l'exploitation de la MER (IFREMER) in France. Both GDACS can be accessed through the OceanSITES website provided above.

5.3 Governance

OceanSITES began as a volunteer group. Recently it has become an Action Group of the Data Buoy Cooperation Panel (DBCP) of the Joint WMO and International Oceanographic Commission's (IOC) Technical Commission for Oceanography and Marine Meteorology (JCOMM) (http://www.jcomm.info/index.php?option=com_content&task=view&id=76

&Itemid=76). With support of a technical staffer at JCOMM and staff from the NOAA NDBC in the US and IFREMER in France, OceanSITES has made significant progress on developing governance. The executive committee includes representatives for each ocean, for the physical and biogeochemical communities, and from the data management panel. The OceanSITES data management team includes scientists and technical staff from the various DACS and GDACS. An emphasis has been placed on making all data openly and easily available at no cost to the user.

The OceanSITES also has a scientific steering team that includes the principal investigators (station operators) from all OceanSITES reference stations. The scientific steering team is charged with developing and reviewing the network and its data requirements and data management, coordinating the implementation of the network, identifying gaps in the network and synergies with other programs, and ensuring the integration of the network into the overall global ocean observing system. While many of the stations were initiated prior to or independently from the OceanSITES network, by becoming part of the network, the stations can significantly increase their user base and thereby increase the value of the station. Admittance into the network, however, carries responsibility, particularly in terms of providing open and easy access to the data.

5.4 High latitudes

As can be seen in Figures 5 and 6, most open ocean surface moorings are located in the tropics. While this is in part because the tropical environment is much more benign (it is much easier to maintain a mooring in tropical conditions than in the “Roaring Forties”), the primary reason is that, as discussed earlier, the ocean and atmosphere are highly coupled in the tropics. The tropical oceans can thus have a strong influence on the tropical and global atmosphere. However, higher latitudes are important to monitor as these source regions form various different water masses, are living environments for important fisheries, and are where the CO_2 solubility pump occurs and is the driver for the downwelling limb of the thermohaline circulation. Furthermore, model studies indicate that ocean acidification will lead to the high latitude surface waters becoming undersaturated with respect to calcium carbonate biominerals (e.g. aragonite, calcite) within a matter of decades (Orr et al., 2005). This would have a detrimental effect on the high latitude ecosystems and reference stations are needed to quantify these changes.

As we seek to use ocean and coupled ocean-atmosphere models to investigate the ocean’s role in climate variability and change, there is great interest in knowing the fluxes across the ocean’s surface integrated over its entire surface and in assessing whether the models accurately represent those surface integrals. Yet, the high latitudes have few reference stations and our knowledge of the regional surface meteorology, air-sea exchanges, and physical and biogeochemical dynamics, is poor. It is thus a high priority to expand ocean reference stations to the high latitudes.

6. The future

OceanSITES seeks to encourage the sustained support of ocean reference stations. As discussed above, many of the stations are supported through partnerships that involve multiple scientists, institutions, agencies, and nations. Hope for expansion into the high latitudes is at hand, as is shown by the Australian site south of Tasmania, SOTS, mentioned above. The US NSF OOI is also initiating four deep-ocean, full water column, interdisciplinary reference stations. These stations, referred to as “global nodes,” would be located at strategic sites within the three-dimensional circulation of the global oceans, including two currently existing OceanSITES reference stations: Station Papa in the eastern subarctic Pacific, and CIS, in the Irminger Sea southeast of Greenland. The two other global nodes are in the Argentine Basin at 42°S, 42°W, and in the Southern Ocean, southwest of Chile at 55°S, 90°W. Further contributions to the high latitude sites and continued efforts to develop common, multidisciplinary instrumentation to be deployed at each site would complete the global array of ocean reference stations.

7. Conclusion

We live on a water world. Weather and climate over land cannot be isolated from that over and within the ocean. In order to understand the global heat balance, hydrological cycle, and carbon cycle, it is necessary to observe, understand, and map the physical, chemical, and ecosystem environment with sufficient temporal, horizontal, and vertical resolution. This is the purpose of the Global Ocean Observing System (GOOS), which is a system within the GEOSS. The network of OceanSITES reference stations is an integral part of the GOOS. Data from these reference stations detect rapid changes and episodic events as well as long-term changes. These reference data are made available to the public to further our understanding of our changing world. The data are used to validate and assess satellite products and improve our ability to monitor the globe remotely. Scientific researchers are using these data to study mechanisms controlling the climate and ecosystems and to test and improve numerical models used for predicting future changes. Our ability to plan, adapt, and cope with future changes in weather, climate, and ecosystem depends crucially upon our ability to monitor and predict these changes. Through dedication and commitment, the OceanSITES network provides the baseline data for these efforts.

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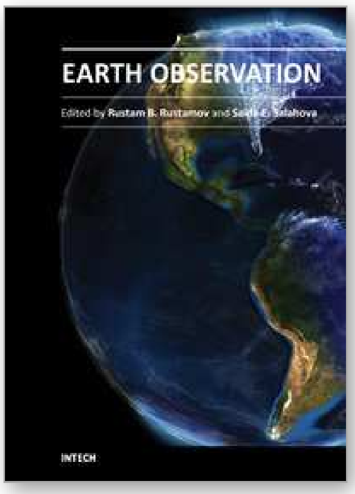

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Today, space technology is used as an excellent instrument for Earth observation applications. Data is collected using satellites and other available platforms for remote sensing. Remote sensing data collection detects a wide range of electromagnetic energy which is emitting, transmitting, or reflecting from the Earth's surface. Appropriate detection systems are needed to implement further data processing. Space technology has been found to be a successful application for studying climate change, as current and past data can be dynamically compared. This book presents different aspects of climate change and discusses space technology applications.