Ocean Reference Stations

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1. Project Summary – Ocean Reference Stations

Rationale: The Woods Hole Oceanographic Institution (WHOI) Ocean Reference Station project is carried out to provide critical, sustained observations of a key region of the ocean – the trade wind region. As the earth sits in space, sunlight heats the earth in a broad, equatorial region. The ocean and atmosphere both are driven by the thermal gradients between the equator and the poles; the oceans, with their ability to store, transport, and release heat and moisture to the atmosphere, play an important role in weather and climate. Air that is heated rises at the equator and descends in the subtropics, resulting in broad regions of winds flowing from the east to the equator. Around the globe these easterly trade wind regions cover roughly 50% of the ocean surface, in a wide belt spanning the equator. These regions are where the equatorial concentration of solar heating leads to net ocean heating and where in turn large evaporation and accompanying latent heat flux provides energy and moisture to drive the atmosphere over a range of scales, from the general Hadley circulation that is the source of the trade winds down to hurricanes intensified by that heat and moisture. They are also where the ocean provides CO_2 to the atmosphere in contrast to the higher latitudes where the ocean gains CO_2 from the atmosphere. Integrated across the expanse of the trade wind regions, errors and uncertainties in the exchange of heat, freshwater, momentum, and compounds such as CO_2, can challenge our ability to understand the way in which the atmosphere and ocean interact and how that interaction should be represented in models used to predict weather and climate variability.

To provide sustained, climate-quality observing of the trade wind region, we have developed surface moorings with the capability of making sustained, accurate observations at the sea surface and in the water column and have chosen and occupied three key trade wind sites. These surface moorings are known as Ocean Reference Stations (ORS). The three sites, shown in Figure 1, are the Stratus ORS, the NTAS (Northwest Tropical Atlantic Station) ORS, and the WHOTS (WHOI Hawaii Ocean Timeseries Site) ORS. Together, the three sites form a comprehensive array in two ways. First, they sample distinct branches of the trade wind regime. The black squares in Figure 1 are the positions of NTAS and Stratus relative to WHOTS based on their position within the trade wind system; note that Stratus, at the furthest distance from the region of convergence between the Northeast and Southeast Trades, samples the region of descending atmospheric flow in the Hadley circulation and the origin of the trade winds, while

NTAS, samples they trade winds close to the convergence zone which is the ascending branch of the Hadley circulation, and WHOTS samples the fully developed trade winds in between. Second, the three sites have regional attributes. Stratus is under the persistent marine stratus clouds that characterize the region offshore of northern Chile, in a cool eastern boundary current regime and, due to the proximity of the Andes, away from the tracks of energetic synoptic weather systems; atmospheric, oceanic, and coupled models continue to fail to correctly represent the physics at work there and typically yield sea surface temperatures that are too warm. NTAS lies in the North Atlantic trade wind regions through which the hurricanes that reach eastern North America track, and accurate representation of how the ocean's heat and moisture in this region fuel the growth of those hurricanes is needed. WHOTS, close to the Hawaiian Islands where the Keeling time series documents the increase of atmospheric CO_2, provides not only a critical benchmark time series of oceanic CO_2 but also an emerging record of links between changes in the regional hydrological cycle (rainfall, evaporation) and the variability and dynamics of the upper ocean there due to changes in ocean salinity.

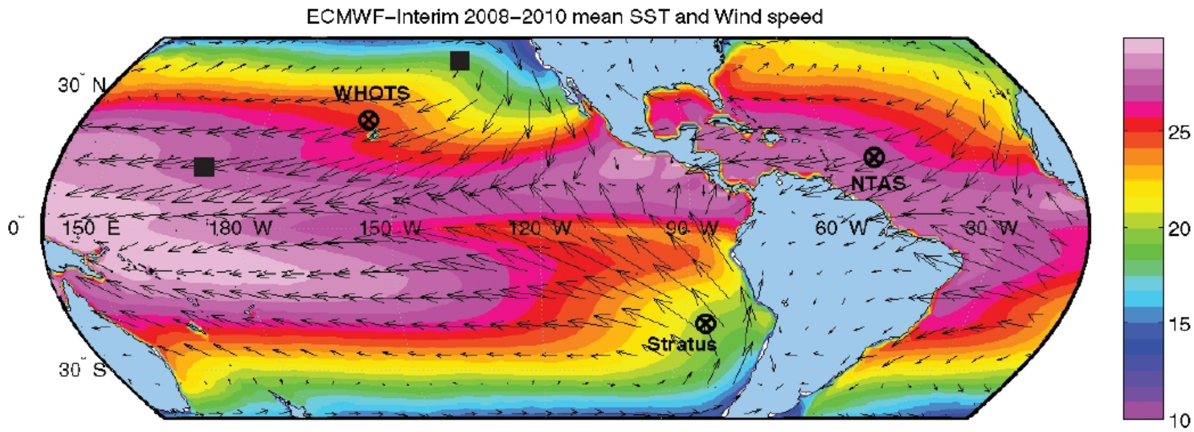

Figure 1. SST (colors) and surface wind vectors from the ECMWF-Interim reanalysis for the period 2008-2010. The positions of the Stratus, NTAS and WHOTS ocean reference station buoys are indicated. The corresponding virtual positions of the Stratus and NTAS buoys, relative to the North Pacific Hadley circulation and SST, are indicated by black squares. From Dr. Roger Lukas, Univ. of Hawaii, partner at WHOTS.

The reasons for our approach, the use of surface moorings for sustained observations, are: 1) the need to obtain high temporal resolution, sampling down to minutes to record high amplitude, short-lived events in the surface meteorology, air-sea fluxes, and upper ocean structure, 2) the need to sample with high vertical resolution in the stratified upper ocean that is in close contact to the atmosphere and links the upper ocean to the interior of the ocean, 3) the need to sample a changing environment in a sustained way, and 4) the need to provide continuous time series at a point for validation, verification, and calibration of models and remote sensing methods. Designing and building a surface mooring, developing and using accurate instruments with low-power consumption that can run unattended, instrumenting the surface buoy with these meteorological and pCO2 sensors and the mooring line with temperature, salinity, velocity, and other ocean sensors, and carrying out on-site verification of the moored instrumentation when the ship services the mooring each year are the best technical approach and the one we use at the three ORS. The resulting meteorological and oceanographic observations provide a set of high quality air-sea fluxes of heat, freshwater and momentum as well as upper ocean heat and salt content. The scientific rationale for the collection of these flux products is manifold: 1) to describe the upper ocean variability and the local response to atmospheric forcing; 2) to motivate and guide improvement to atmospheric, oceanic, and coupled models; 3) to calibrate and guide improvement to remote sensing products and capabilities; and 4) to provide anchor points for the development of new, basin scale fields of the air-sea fluxes. Model, satellite, and climatological fields of surface meteorology and air-sea fluxes have large errors; high quality, in-situ time series are the essential data needed to improve our understanding of atmosphere-ocean coupling and to create more accurate global fields.

Scope: The work done under this project accomplishes seeks to do the following: 1) maintain long-term surface moorings, known as Ocean Reference Stations, in three key trade wind locations, one in the North Atlantic, one in the North Pacific, and one in the South Pacific, 2) use the data from these moorings to accurately quantify the local climatologies and variability of the air-sea fluxes, sea surface temperature, surface currents, upper ocean heat content and transport, and, with NOAA partners, the air-sea flux of carbon dioxide, and 3) use the data collaboratively to improve understanding of the processes and dynamics at these sites and thus the numerical models of the atmosphere, the ocean, and the coupled atmosphere-ocean applicable to these regions.

Three Ocean Reference Stations are being maintained: A site at 20°S, 85°W under the stratus cloud deck off northern Chile (Stratus), the Northwest Tropical Atlantic Station (NTAS) at 15°N, 51°W, and a site north of Hawaii near the Hawaii Ocean Time-series (HOT) site at 22.75°N, 158°W known as the WHOI Hawaii Ocean Time-series Station or WHOTS. Moorings at the Stratus and NTAS sites were first deployed in 2000 and 2001, respectively, and became long-term Ocean Reference Stations. WHOTS was established in 2004, in collaboration with investigators at the University of Hawaii who have made shipboard and moored observations in that region in recent years. Each of these sites is visited once per year. Before the cruise the new instruments are calibrated and prepared and the surface buoy and mooring are built. During the year, real time data flow and quality is monitored. After the cruise, instruments are calibrated and refurbished, data are recovered and processed, and the cruise is documented.

Anticipated data, products, outcomes: In FY2014, the WHOI Ocean Reference Station project carried out cruises to the three sites to recover moorings that had been in service for a year or more and deploy new moorings. NTAS was serviced by the NOAA Ship RH Brown in October 2013. Stratus was serviced by the NOAA Ship RH Brown during a February and March 2014 cruise. WHOTS was recovered and redeployed in July, 2014 on the NOAA Ship Hi'ialakai. Each cruise resulted in the collection of the internally recorded data on the instrumentation on the buoy and the mooring line and supporting data sets from the ships, such as meteorological data for comparison with the buoy meteorological data. From the deployment of a new buoy onward, the surface meteorological data are available in near-real time, with hourly averages typically telemetered via Service Argos. The WHOI Ocean Reference Station data are not placed on GTS; instead they are used as independent data for validation of models by users such as ECMWF (European Centre for Medium Range Weather Forecasts) and NCEP (National Centers for Environmental Prediction) and for quantification of error in fields such as the surface fluxes by investigators working in coordination with the CLIVAR Global Synthesis and Observations Panel (GSOP).

NOAA had been unable to provide ship time (e.g., the NOAA Ship R. H. Brown) to service Stratus in 2013, so by the time of the scheduled FY2014 cruise, the mooring had been deployed for 21 months, far beyond the planned 12 months. Signifiant loss of surface meteorological, air-sea flux, and ocean time series data resulted from the length of the deployment and the resultant expiration of battery packs and exhaustion of data storage capacity. Further, a shackle on the mooring failed in January 2014 at month 20; and most of the Stratus 12 mooring fell to the sea floor, with a number of instruments being crushed with loss of the instruments and their data.

The NTAS buoy broke free of its mooring on 23 September 2014 and was tracked as it drifted west towards the Lesser Antilles. Initial reports from a recently completed buoy recovery offshore of Martinique indicate that the wire rope parted at a 6 m depth termination. This indicates that the rest of the mooring and the subsurface instruments fell to the sea floor. Recovery will be attempted during the mooring service cruise in December 2014, but the expectation is that most of the instruments will be crushed and we will suffer loss of the instruments as well as all non-telemetered subsurface data.

The web sites associated with the three WHOI Ocean Reference Stations are the primary means for documenting work each year, sharing real time data, and providing archived data. The key Web Sites are: NTAS – http://uop.whoi.edu/projects/NTAS/ntas.html; Stratus – http://uop.whoi.edu/projects/Stratus/stratus.html; and WHOTS - http://www.soest.hawaii.edu/whots/ and http://uop.whoi.edu/WHOTS/projects/whots.html. For each site the WHOI web page provides an overview, detailed description (with links to mooring diagrams and technical reports), access to real time data, and access to archived data. Real time data are quality controlled on an ongoing basis, and sensors that degrade are flagged, with data removed from real time access. After the moorings are recovered, quality control and processing is directed first to develop high quality time series of surface meteorology and air-sea fluxes; these time series are typically available within twelve months of recovery, allowing post-deployment sensor calibrations to be completed first. The present new year of surface meteorology and air-sea fluxes is then merged with previous time series to make continuous time series; this is the products that are most requested by various users. Processing and preparation of data files for the ocean sensors then follows, with temperature and salinity done first. Work on the velocity data provides the most challenge due to the impacts of biofouling and fishing gear on current meters and the greater complexities of quality controlling current meter data.

Intended Users: The users of Ocean Reference Station data are: 1) Numerical Weather Prediction (NWP) centers, including the National Centers for Environmental Prediction (NCEP) in the United States, the European Centre for Medium-Range Weather Forecasts (ECMWF) in Europe, the Centre for Australian Weather and Climate Research (CAWCR); 2) researchers and research programs seeking to quantify error in surface meteorologicalm air-sea flux, and ocean state fields such as the CLIVAR Global Synthesis and Observations Panel (GSOP) and the GODAE Ocean View (follow on to GODAE, the Global Ocean Data Assimilation Experiment); 3) climate modeling groups and groups analyzing the realism of climate models, including NCAR (National Center for Atmospheric Research) in the U.S. and the international SURFA (Surface Flux Analysis) project where ORS data are used as validation truth for examining the performance of many different climate models from different countries; 4) those analyzing and assessing the realism of satellite retrievals at the sea surface (sea surface temperature) and of surface meteorology (e.g., winds) and surface waves, including investigators at NASA (National Aeronautics and Space Administration) and ESA (European Space Agency); 5) those working to developed gridded fields of air-sea fluxes of heat, moisture, and momentum to accurately determine and monitor these fields on a global basis, including Dr. Lisan Yu at WHOI, whose OAFlux project uses the ORS data to validate the OAFlux fields; 6) investigators and researchers studying air-sea interaction, cloud physics, and upper ocean dynamics at key locations, such as under the marine stratus clouds off Chile (Stratus) and in trade wind locations such as NTAS and WHOTS; 7) investigators working under VOCALS (VAMOS Ocean Cloud Land Atmosphere Study, where VAMOS is the Variability of the American Monsoon Systems of the international CLIVAR (Climate Variability research program)), which has focused on improved understanding and prediction of the marine stratus and its impacts on climate over the Americas; 8) investigators working to improve undertsanding of and model representations of eastern boundary regions of oceans and their complicated physics and biology, including the oxygen minimum zone; and 9) ocean model developers and users at US research and operational model centers, who use the time series of ocean variability at the ORS to examine the realism of ocean models and the time series of surface fluxes to evaluate the forcing fields they use to drive their ocean models.

Users of the ORS platforms in addition to our effort include: 1) the National Data Buoy Center (NDBC), an NDBC surface wave package is installed on the Stratus and NTAS ORS to provide surface wave data in the extremely data sparse eastern South Pacific and the northwest tropical Atlantic, 2) NOAA PMEL (Pacific Marine Environmental Laboratory), which has installed instrumentation to measure carbon dioxide in the surface waters at the Stratus and WHOTS ORS, and 3) investigators from WHOI, LDEO (Lamont-Doherty Earth Observatory of Columbia University), the Institut fur Meereskunde an der Universitat Kiel (IFMK), and Dr. Sam Laney (WHOI, funded by NASA to study ocean color) who have installed or will be installing instrumentation to study ocean mixing, oceanic oxygen minimum layers, and ocean color. The three ORS have also been equipped with Temperature/Salinity (T/S) instruments near the sea floor and now contribute deep T/S data to the OceanSITES effort to contribute to the Deep Ocean Observing System (DOOS).

2. Scientific and Observing System Accomplishments

Overview: In FY2014 we carried out a cruise to each of the three ORS as described above. NTAS was serviced by the NOAA Ship RH Brown in October 2013. Stratus was serviced by the NOAA Ship RH Brown during a February and March 2014 cruise; this cruise was done in collaboration with NDBC and one tsunami warning (DART) installation was also serviced on the cruise. WHOTS was recovered and redeployed in July 2014 on the NOAA Ship Hi'ialakai. We have in parallel worked on the analyses and publication, with 6 papers out or submitted in reviewed journals. Among the highlights are the finding, in the first nine years of data from the Stratus ORS, of significant trends in wind speed, wind stress, latent heat flux, and het heat flux (Weller, 2014). Increases in wind speed, wind stress, and latent heat flux over nine years were 0.8 m s^{-1}, 0.022 N m^{-2}, and 20 W m^{-2} or 13, 29, and 20% of the respective nine-year means. The decrease in the annual mean net heat flux was 39 W m^{-2} or 104% of the mean.

Deliverables: In our recent Work Plan we identified as the basic deliverable the data from the ORS. The deliverables from the ORS are indeed the data, supported by the documentation of the cruises and methods used to collect the data. The directly observed data fall into three main categories: 1) Surface meteorology and air-sea fluxes. The surface wind speed and direction, air temperature, relative humidity, barometric pressure, incoming shortwave radiation, incoming longwave radiation, and rain rate are measured at a once per minute rate. Logged at the same time are buoy bridle temperature and salinity; 2) Surface oceanographic data. The ORS buoys are typically equipped with multiple floating or fixed point temperature sensors to obtain ocean temperature at or close to the sea surface. In addition, an effort is made to place a shallow fixed point current meter or to use an upward looking high-resolution Doppler profiler to obtain a value to be used as surface current; 3) Ocean observations of temperature, salinity, and velocity along the mooring line in the upper thermocline and surface layer; Stratus has recently added dissolved oxygen measurements. The surface meteorology, surface temperature, and surface current are used with the bulk formulae to compute a fourth product: 4) Air-sea fluxes of heat, freshwater, and momentum; 5) Deep T and S - All of the ORS moorings include additional sensors to obtain deep ocean temperature and salinity (within 40 m of the seafloor). Ancillary observations by cooperating investigators add: 6) surface wave data by NDBC at Stratus and NTAS; 7) pCO_2 by NOAA PMEL at Stratus and WHOTS; 8) dissolved oxygen observations at Stratus by Lothar Stramma from Kiel, Germany; and 9) in the water radiance observations at WHOTS by Sam Laney of WHOI. Surface meteorology is available in real time and the remaining data follow as described above.

We should now have 37.8 buoy-years of data from the three ORS. The data return from WHOI-deployed meteorological and upper ocean instrumentation on ORS had been sustained at high level over much of the initial 31 buoy-years of deployments. For our FY2012 annual report we had compiled statistics for “usable data” – data of sufficient quality to be carried to post processing and used in analysis, although in some cases requiring post calibration or adjustment. For meteorological variables we find usable data return of 93.5% at Stratus (over 10 years), 96.5% at NTAS (over 10 years) and 97.7% at WHOTS (over 7 years). It is important to note that because we deploy redundant meteorological sensors on each buoy, a single instrument failure does not compromise the deliverables. Considering the deliverable for surface meteorology a single record of surface meteorological variables created from the best performing sensor of each pair, the usable data return increases further from the values quoted above. For subsurface variables we find usable data return of 90.1% at Stratus (over 10 years) and 92.5% at NTAS (over 9 years). The high usable data return allows continuous multi-year time series of air-sea fluxes and upper ocean response to be constructed which serve a variety of purposes.

However, as we have carried out the work in recent years, the challenges of maintaining sustained time series sites have been evident. There is the 7-month gap in NTAS during 2012 and another 3-month gap anticipated in 2014. Stratus was not serviced in 2013, stayed out for 20 months, and had a resulting loss of data and instrumentation. However, the surface moorings remain a very effective methodology, as shown in Table 1. The WHOTS mooring has been on station100% of the desired time. The Stratus and NTAS moorings have provided 94% and 95% of the planned station time.

This is a very important statistic, as we find that record length is a key determinant of statistical significance in examining trends and in now being able to develop in-situ records to examine interannual to decadal variability. Our methodology of deploying meteorological

Ocean Reference Station	Mooring Days Sought	Mooring Days Achieved	% Achieved
Stratus	4560	4286	94
NTAS	4793	4553	95
WHOTS	3651	3651	100
Sum (days)	13004	12941	96
Sum (years)	35.6	34.2	96

Table 1. ORS mooring performance, updated to the last recovered deployments. The mooring days sought are the days desired between planned servicing. The mooring days achieved are the days the mooring stayed on station as planned.

instrumentation with sufficient redundancy to ensure close to 100% return of high quality surface meteorological and air-sea flux time series has been particularly effective as seen in Table 2.

Ocean Reference Station	Meteorological/Flux Days Sought	Meteorological/Flux Days Achieved	% Achieved
Stratus	4560	4555	99.9
NTAS	4420	4420	100
WHOTS	3651	3651	100
Sum (days)	12631	12626	100
Sum (years)	34.6	34.6	100

Table 2. Performance statistics for the three ORS, showing close to 100% success at returning high quality, basic one-minute sampled surface meteorological time series and associated air-sea flux time series. This is based on meeting the goal of one complete, one-minute time series set, including wind speed and direction, incoming shortwave and longwave radiation, air temperature and humidity, barometric pressure, rain rate, and sea surface temperature. This is also based on the days that the ORS buoys were on station, so does not reflect data missed when the moorings broke.

Collection of oceanographic data from moored instruments faces some unique challenges including biofouling and entanglement by fishing line. Additionally, it is difficult to deploy more than one instrument at the same depth, so the strategy of redundant sensors used in mounting meteorological sensors on the buoy tower cannot be followed. Instead, we deploy ocean sensors with sufficiently close vertical spacing along the mooring line to achieve the coverage needed, for example, to compute mixed layer depth with desired accuracy. Taking each ocean sensor as a stand-alone observation with no redundant, alternate data source, Table 3 reports on raw ocean data capture performance. In spite of the challenges, data return has been good.

Ocean Reference Station	Ocean Data Days Sought	Ocean Data Days Achieved	% Achieved
Stratus	4559	3990	86
NTAS	4420	3955	90
WHOTS	3277	2929	89
Sum (days)	12256	10874	89
Sum (years)	33.6	29.8	89

Table 3. Performance statistics for the three ORS, showing success rates at returning basic time series from each ocean sensor. This is based on ever ocean sensor deployed, and does not benefit from any redundancy stemming from closely spaced sensors recording the same variable. This is also based on the days that the ORS buoys were on station, so does not reflect data missed when the moorings broke.

The ORS in particular address the following ocean observing system program deliverables:

• **Sea surface temperature and surface currents**. The ORS surface buoys have been instrumented to give improved sea surface temperature observations. Floating sea surface temperature sensors and temperature sensors embedded at shallow depth directly into the foam buoy hulls have added unique capability. Because they sample surface and near-surface ocean temperature and because they have collocated, high quality air-sea fluxes, ORS data sets are sought by investigators working on diurnal warm layer dynamics and remote sensing of SST. ORS Stratus data were used by Prytherch et al. (2013) and by Weller et al. (2014) in studies of the dynamics and predictability if the diurnal warm layer. ORS data have been supplied to other investigators studying diurnal warming and remote sensing of SST (e.g. Bill Emery, Dudley Chelton). All three ORS have shallow current observations, which are used in computing of the air-sea fluxes, where the surface wind relative to the surface current is needed (Stratus and WHOTS –10 m depth; NTAS – 6 m depth).

• **Ocean heat content and transport.** The ORS buoys are equipped with temperature, salinity, and velocity sensors from the upper thermocline to the surface (at Stratus, these go deeper, to 1,800 m). As a result, the temporal evolution of the mixed layer and its heat storage can be tracked as well as the heat content of the upper ocean. At the same time, the velocity observations and surface forcing data allow net upper ocean transports to be computed and for that transport to be decomposed into wind-driven and geostrophic transport components.

• **Air-Sea Exchanges of Heat Momentum and Freshwater.** The ORS are equipped to make state of the art, sustained air-sea flux observations, providing the air-sea exchanges of heat, freshwater and momentum. At the three ORS we can define a local climatology and quantify anomalous departures in wind forcing, local heat balance, and local hydrologic cycles. We had at the end of last year revisited and uniformly reprocessed the first 11 years of Stratus surface meteorological and air-sea flux data for Stratus and NTAS, and the first 9 years of the same data for WHOTS; were are now adding the more recent data. These now provide unique, high quality benchmark time series on the air-sea exchanges of heat, momentum, and freshwater. The ORS surface meteorological and air-sea flux data, uniquely, are both high quality and withheld from real-time assimilation into weather and climate models. As such these data are in demand (e.g. from the CLIVAR GSOP), so we are setting up a new menu item on http://uop.whoi.edu called 'Reference Data Sets' to serve these data and supporting metadata.

• **Ocean Carbon Uptake and Content**. Collaboration with Chris Sabine at NOAA PMEL has added pCO_2 observations to Stratus and WHOTS.

FY2013 Achievements: In FY2014 we carried out a cruise to service each of the three ORS, quality controlled and processed data, and served data to users.

Scientific Advancements: The major scientific advancement is the continued development of sustained, withheld, high-quality time series of surface meteorology, air-sea fluxes, and oceanic variability. These are supporting a number of our findings as well as are in demand by other investigators. At the same time we have begun an effort to synthesize ORS analyses with regional data.

The longer Stratus record now available allowed Holte et al. (2014) to re-examine the heat and salt budgets of the upper ocean in the Stratus region and improve upon the earlier work by Colbo and Weller (2007). In this work the data from Argo floats in the region is used (Figure 2). The

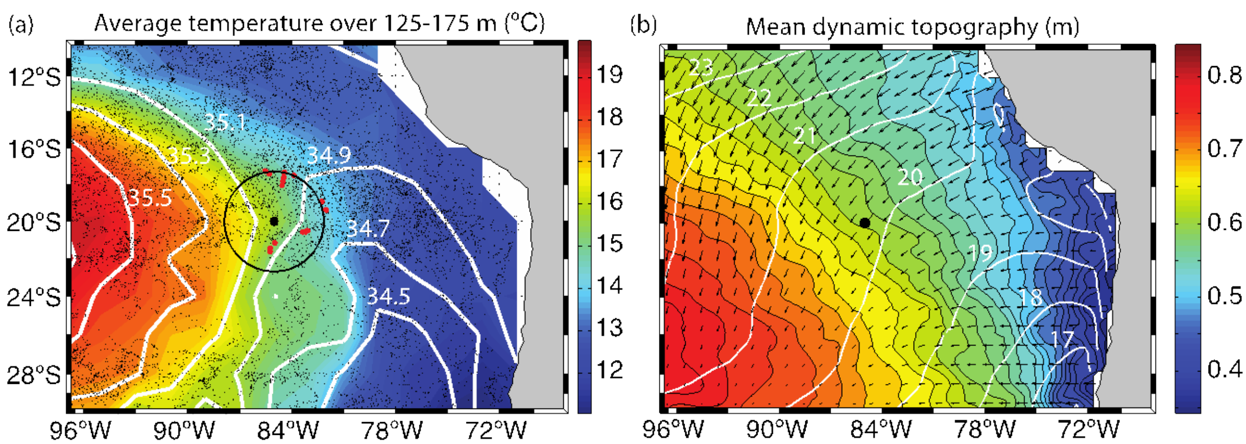

Figure 2. From Holte et al. (2014), panel a shows the Stratus ORS site at 20°S, 85°W and the small black dots are 12,628 Argo float profiles used to map the temperature (color) and salinity (white contours) fields in the region. Panel b shows the Ekman transport (arrows), mean SST contours (white), and dynamic topography (color).

major new finding is that horizontal advection plays the major role in cooling and freshening the upper ocean; the implication of this is that eddy heat and salt flux divergences are less important than suggested by Colbo and Weller (2007). This greatly improves the basis for using the Stratus ORS record for validation/verification of ocean models.

At the same time, we have found that heat and salt balances are not necessarily stationary, as Weller (2014) reports finding long-term trends in surface meteorology and air-sea fluxes at the Stratus ORS (Figure 3). Using the first ten years of Stratus data, which provide nine full calendar years, statistically significant trends were found in wind speed, wind stress, latent heat flux, and het heat flux. Increases in wind speed, wind stress, and latent heat flux over nine years were 0.8 m s^{-1}, 0.022 N m^{-2}, and 20 W m^{-2} or 13, 29, and 20% of the respective nine-year means. The decrease in the annual mean net heat flux was 39 W m^{-2} or 104% of the mean.

The vertical structure of the ocean at the Stratus ORS and the presence of a low oxygen layer has been the focus of continued attention through our partnership with German investigators (Lothar Stramma, Kiel). Stratus mooring points to the role of ocean processes in freshening and cooling the ocean mixed layer. There is a shallow mode water below the surface layer that is a potential source of the required cooling and freshening, but the presence of the low oxygen or oxygen minimum layer just below that mode water poses questions about the realism of invoking strong vertical mixing. To address this, we have added oxygen sensors and added instruments from Stramma. In addition, we have pooled our profiling float data (10 profiling floats with oxygen sensors were deployed in VOCALS REx) and worked with our German colleagues in a regional analysis of the low oxygen layer (Czeschel et al., 2014). Figure 4 shows the dissolved oxygen at

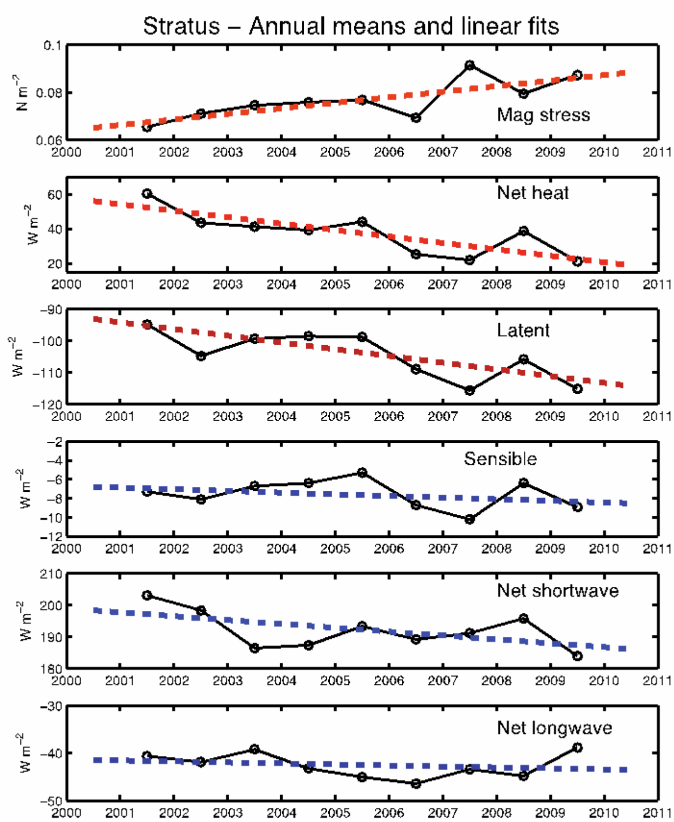

Figure 3. Annual means of the magnitude of the wind stress, the net air-sea heat flux (positive indicates heating of the ocean), and the four components of net heat flux: latent, sensible, net shortwave, and net longwave heat fluxes. The slopes of the linear fits are significantly non-zero for wind stress, net heat flux, and latent heat flux.

different depths in the eastern tropical Pacific. The presence of a low oxygen layer below the seasonal thermocline at the Stratus ORS presents additional challenges to our understanding of the balance between mixing and advection processes while at the same time providing a field for model validation that involves biogeochemical as well as physical dynamics.

WHOTS, like the other ORS, records local air-sea forcing (exchanges of heat, freshwater and momentum) as well as local ocean variability. The WHOTS site is dominated by easterly trade winds, but experiences occasional lulls when winds drop to just a few m s^{-1}. Thus, this data set, like that from the Stratus ORS and the NTAS ORS will be used in a new research effort between Weller and Plueddemann and Lukas and Potemra at Hawaii to use ORS data to examine the causes of model bias and error in the tropics. We are at present processing the WHOTS data we collected this summer to extend the surface meteorological and air-sea flux time series to July 2014.

Our partnership with the University of Hawaii (R. Lukas with NSF funding) and the integration of WHOTS with other Station Aloha observing efforts (e.g. HOT, ACO, see http://aco-ssds.soest.hawaii.edu/ALOHA) provide significant added value. Recent work by R. Lukas points to several processes acting to control the local ocean state, including changes in the balance between surface rainfall and evaporation and transports by eddies of masses of water from distant locations. It is found that salinity in the mixed layer is increasing in association with a negative freshwater flux (loss of freshwater from the ocean) while temperature is decreasing,

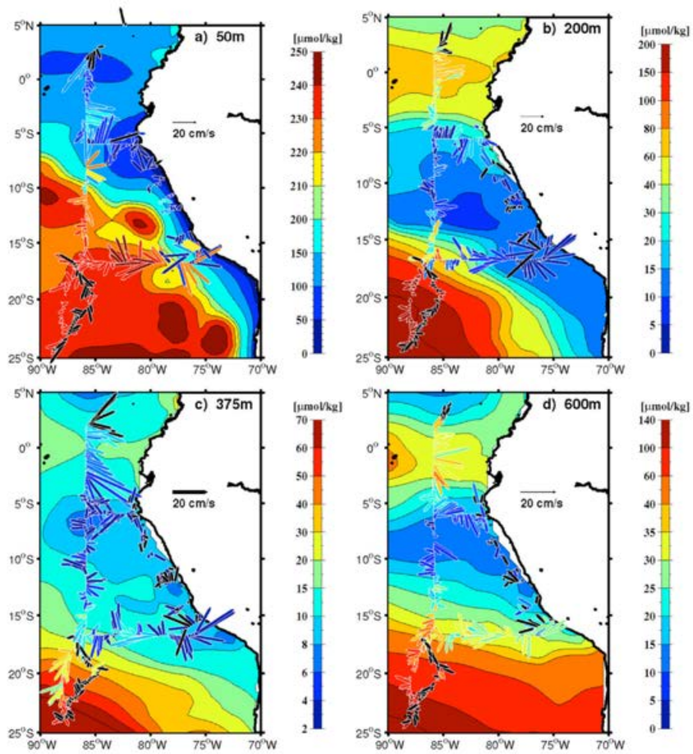

Figure 4. Dissolved oxygen contoured at different depths in the eastern tropical Pacific, from Czeschel et al. (2014).

resulting in a density increase that is statistically significant over the first 8 years of the WHOTS record. Comparisons between WHOTS and global models (e.g. ECMWF ERA-Interim) show that the ORS observations are regionally representative, yet the models do not necessarily show seasonal to decadal variability in surface fluxes consistent with those of the observations.

Evaluation of upper ocean trends relative to the regional hydrological cycle and observed and modeled surface fluxes is an area of ongoing effort.

The NTAS ORS is in a region where the mechanisms controlling SST and upper ocean heat content are of interest. A decade of data (2001-2011) allows a typical year to be characterized from observations. The seasonal cycle dominates the net heat flux, with the migration of the ITCZ modulating cloud cover and rainfall (Fig. 5). Interannual variability is evident in the minimum and maximum seasonal values as well as the timing of seasonal transitions. The extent to which NWP forecasts and reanalyses reproduce the amplitude and timing of the annual cycle and seasonal transitions is being evaluated. NTAS is a region where interaction between wind, evaporation and SST are important, and there is interest in the role of advective cooling during periods of wind relaxation when evaporative cooling is reduced and thus there is a tendency for local SST increase (without advection).

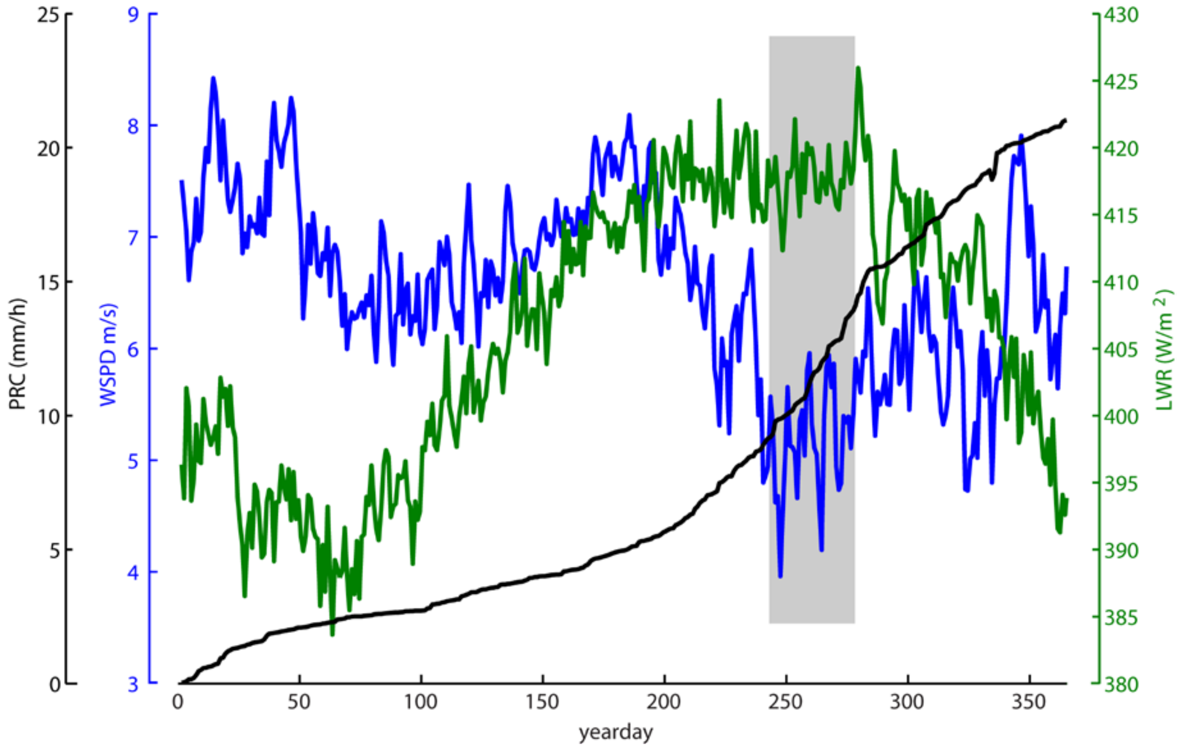

Figure 5. Ten-year mean (2001-2010) annual cycle of cumulative precipitation, wind speed and incoming longwave radiation for NTAS. September to early October (shaded region) is when the ITCZ influences the site, and is characterized by low wind, steady cloud cover and increased precipitation.

Significance of these scientific advancements: The ORS results are particularly significant in two areas: 1) Benchmarking three trade wind sites – the three ORS now provide accurate local climatologies of surface forcing and upper ocean variability. As such they form the basis for us to go forward and examine model errors and biases and identify those that are characteristic of how these models represent the trade wind region. They also form the basis for tracking anomalies in surface forcing and upper ocean heat content and identifying the spatial representativeness of such anomalies by looking at decorrelation scales in the atmosphere (in model and OA Flux fields) and in the ocean (in Argo float data). 2) Quantifying the processes at work to maintain the state of the upper ocean – the combination of accurate local forcing and good time/space resolution in the upper ocean allows us to identify the major contributors to local heat, freshwater, and momentum balances. Stratus, for example, at first obtained accurate fluxes that showed, in contrast to models, that the upper ocean there was heated by the atmosphere and needed ocean processes for cooling and freshening. Subsequently, Stratus data has motivated modelers and other researchers to examine the roles of ocean eddies and vertical mixing. In the immediate future, the Stratus ORS will serve as a focal point for collaborative study of the low oxygen layer found below the upper thermocline.

Impacts of lack of funding: Two funding pressures are evident.

First, the reduced funds available for use of NOAA and charter vessels has greatly increased the uncertainty of the timing the cruises to recover and redeploy the ORS. For example, there was no ship time available in 2013 to visit the Stratus ORS, so the mooring was not visited for 20 months and suffered a mechanical failure in January 2014. Data were lost, and instrumentation was lost. NTAS has also encountered challenges such as working from the Fisheries Survey Vessel Pisces in 2012, which is not designed to support mooring operations, and the planned cruise on the UNOLS vessel Endeavor in 2014, which has operational limits at a sea state close to the mean sea state at the NTAS site. Setting a surface mooring requires either a ship with a multibeam depth sounder or a ship with a single point depth sounder and ~5 days of additional time to steam a pattern to do the mapping. The ship should also have an Acoustic Doppler Current Profiler (ADCP) to observe the currents during mooring deployments and a well calibrated, climate quality set of meteorological sensors to validate the moored meteorological sensors. Lack of bottom mapping capability greatly increases the risk of mooring failure. Lack of an ADCP increases the risk during mooring deployment of an unsuccessful deployment. Lack of shipboard meteorological sensors requires us to deploy at additional cost such a set of sensors.

Second, flat budgets have resulted in steady erosion of resources. We no longer purchase over-the-side insurance, and we would need to request funds from the program to replace any significant loss of moored equipment and instrumentation. Funds for shipping are constrained, and the loss of the NOAA Ship Ron Brown in the Pacific has required additional shipping expenditures to ship to meet charter vessels in port as opposed to loading/unloading from the Brown in Charleston. Further, new policies by NOAA OMAO limit the option of using the Brown to carry gear loaded ahead of time or left on board, and thus increase project costs for shipping. A modest increase in the 2014 budget is being used to restore some lost engineering support salary time to one engineer, who plays a key role in supporting our meteorological systems.

Websites:
The key Web Sites are: NTAS – http://uop.whoi.edu/projects/NTAS/ntas.html;
Stratus – http://uop.whoi.edu/projects/Stratus/stratus.html;
and WHOTS - http://www.soest.hawaii.edu/whots/ and
http://uop.whoi.edu/WHOTS/projects/whots.html.

Data Collection Specifics:

a. Ocean Reference Station data are used as withheld data to validate models. To ensure they are not assimilated, data are not placed on GTS.

b. Telemetered, real time data are available at:

1. WHOI http://uop.whoi.edu
2. OceanSITES ftp://data.ndbc.noaa.gov/data/oceansites/DATA/ (in project subdirectories) and ftp://ftp.ifremer.fr/ifremer/oceansites/DATA/ (e.g. /NTAS /STRATUS /WHOTS
3. OceanSITES via THREDDS: http://dods.ndbc.noaa.gov/thredds/dodsC/data/oceansites/DATA/catalog.html
4. As NDBC "partner platforms":
   http://www.ndbc.noaa.gov/station_page.php?station=41nt0 (NTAS)
   http://www.ndbc.noaa.gov/station_page.php?station=32st0 (Stratus)
   http://www.ndbc.noaa.gov/station_page.php?station=station=51wh0 (WHOTS)

c. Delayed mode data are found at WHOI (http://uop.whoi.edu) and at the OceanSITES ftp servers and THREDDS server listed above

d. Data are archived at uop.whoi.edu and at the OceanSITES servers at NDBC and IFREMER. Data are submitted at the original sampling rate. Additional products, such as hourly averaged data sets are also provided.

e. The web site where data can be accessed is http://uop.whoi.edu, also from OceanSITES.org, via the "data" page (via NDBC/IFREMER GDACs)

f. Yes, we have picked up the data from the NDBC OceanSITES GDAC.

g. We follow this plan: Near real time, telemetered data are available from uop.whoi.edu. Delayed mode, processed data are available from the OceanSITES GDACs at Ifremer and NDBC. We will insert this statement on our website, http://uop.whoi.edu. We will also support the OceanSITES data management plan, which is under development.

3. Outreach and Education

Teacher at Sea: The ORS effort each year makes space available on its cruises to the NOAA Teacher at Sea program. Stratus has hosted seven Teachers at Sea, one cruise being subject of one of the children's books on Teacher at Sea published by NOAA. In Arica, Chile past participation by a Chilean Teacher at Sea has been kept alive by hosting visits from her present classes in the port of Arica. WHOTS has hosted four Teachers at Sea; WHOTS also hosted a NOAA Hollings Scholar on a cruise.

Video: ORS Stratus hosted volunteer Diane Suhm on the Stratus cruise on the NOAA Ship Ron Brown in 2010 and funded her to produce a video documenting that cruise. This video was recently provided to the Climate Observation Division. A shorter version has run on cable TV in

Massachusetts and will be used at public lectures in Woods Hole. A variety of (non-professional) video footage is also available from NTAS and Stratus cruises.

Student Participation and Training: The Stratus cruises, whenever possible, offer space to undergraduate and graduate students to provide hands on experience at sea. This year, two undergraduates from the University of Concepcion were on board the NOAA Ship RH Brown. A graduate student from the University of Chile, Santiago made radiosonde observations in the wind jet off the coast of Chile on one cruise. Students from the University of Concepcion, Concepcion, Chile have participated on several Stratus cruises. Graduate students and postdocs from Bigelow Marine Laboratory, George Mason University, Colorado State University, WHOI, the University of Washington, the University of California, Santa Barbara, the University of Hawaii, CICESES (Centro de Investigación Científica y de Educación Superior de Ensenada, Baja California), Southampton Oceanography Centre, UK (now National Oceanography Centre), University of Miami, the University of Buenos Aires, and Texas A&M University have also participated. An excellent example of impact is Dr. Carlos Moffat. He sailed on a Stratus cruise as an undergraduate at Univ. of Concepcion, liked the work, came to WHOI for graduate school, and returned to Univ. of Concepcion as faculty in oceanography. WHOTS and NTAS provide space and research opportunities as available for undergraduate and graduate students from the University of Hawaii (WHOTS) and the Scripps Institution of Oceanography (NTAS). On the NTAS-7 cruise, Joint Oceanographic Institutions (JOI) Program Assistants Jessica Sharoff and Karinna Sjo-Gaber documented science and life at sea, through an interactive website: Mission 15-51. They contacted over 1, 000 teachers, museums and media outlets, and communicated live during the 16 days of the cruise via the website and a blog targeting school children, teachers, museums and the general public.

Regional Outreach: Stratus has used opportunities derived from sailing from different Central and South American ports for regional outreach. Staff from INOCAR (Institute of Naval Oceanography) in Ecuador, the Hydrographic Division of the Peruvian Navy (DHN), the Institute of Marine Sciences of Peru (IMARPE), and the Hydrographic and Oceanographic Service of the Chilean Navy (SHOA) have joined Stratus cruises.

4. Publications and Reports

4.1. Publications by Principal Investigators

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4.2. *Other Relevant Publications* (this year)

Using data or results from Stratus, NTAS or WHOTS:

VAMOS Ocean-Cloud-Atmosphere-Land Study (VOCALS)
Editor(s): C. R. Mechoso, B. Albrecht, H. Coe, C. Fairall, G. Feingold, R. Garreaud, A. Hall, R.

Weller, R. Wood, C. Twohy, and M. Alonso Balmaseda. Special Issue jointly organized between Atmospheric Chemistry and Physics Discussions and Ocean Science Discussions (this is an on-line journal with ongoing submissions)

5. Slides