PMEL Contributions to the OceanSITES Program

H. Paul Freitag*, Michael J. McPhaden*, Meghan F. Cronin*, Christopher L. Sabine *,
Dai C. McClurg†, and Patrick D. McLain*
*NOAA/Pacific Marine Environmental Laboratory
7600 Sand Point Way NE, Seattle, WA 98115-6340 USA
†Joint Institute for the Study of the Atmosphere and Ocean (JISAO)
Box 354235, University of Washington, Seattle, WA 98195-4235 USA

***Abstract*— The OCEAN Sustained Interdisciplinary Timeseries Environment observation System (OceanSITES) is built around a worldwide network of long-term, deepwater reference stations measuring many oceanographic and meteorological variables of relevance to climate and biogeochemical cycles. OceanSITES is a contribution to the Global Ocean Observing System and international research programs. PMEL is a major contributor to OceanSITES in the context of the Tropical Ocean Atmosphere/Triangle Trans-Ocean Buoy Network (TAO/TRITON) mooring array in the tropical Pacific, the Pilot Research Moored Array in the Tropical Atlantic (PIRATA), preliminary moorings of a planned array in the Indian Ocean, the new Kuroshio Extension Observatory (KEO) in the Kuroshio Extension's recirculation gyre, and proposed high latitude moorings in the sub-Arctic Pacific at Ocean Weather Station PAPA and in the sub-Antarctic Zone south of Australia. The KEO mooring and a small subsample of moorings within the larger tropical arrays have been enhanced to measure heat, fresh water, and momentum fluxes. Sample time series of bulk variables and computed fluxes are presented and are compared to NCEP and ECMWF reanalysis products.**

Many OceanSITES locations have been selected to address multi-disciplinary problems in biogeochemical cycles as well. At present a total of eight OceanSITES moorings carry a stand-alone system to monitor air-sea carbon flux, including five TAO sites and the KEO site. An expansion of the carbon systems to other OceanSITES locations including the proposed PMEL high-latitude sites and additional TAO flux sites is planned.

I. INTRODUCTION

Fluxes of heat (turbulent and radiative), fresh water (evaporation and precipitation), and momentum (wind stress) couple the atmosphere and ocean at the air-sea interface. In the past decade, significant progress was made in improving surface wind stress analyses for seasonal-to-interannual forecasting and diagnostics through atmospheric model and satellite-based analyses. Nonetheless, there continue to be large differences in currently available wind stress products, and a great sensitivity in tropical ocean model simulations forced with these different products. There has likewise been progress in the past decade in determining fields of heat and fresh water fluxes from satellite measurements and from atmospheric models that assimilate satellite and in situ observations. However, the uncertainty in these fields is even greater than for surface wind stress. Heat fluxes represent a large negative feedback on dynamically generated interannual timescale sea surface temperature (SST) anomalies in the equatorial cold tongue regions of the Atlantic and Pacific and are important for generating SST anomalies elsewhere in the tropics and at higher latitudes. Evaporation and precipitation affect surface layer water mass variability, upper ocean stratification, and therefore the surface layer heat balance, SST, and upper ocean currents. From a meteorological perspective, precipitation is an integral measure of tropospheric heating, which drives the general circulation of the atmosphere.

TABLE I
LOCATION AND DATE OF FIRST DEPLOYMENT OF PMEL ATLAS MOORINGS ENHANCED FOR HEAT, FRESH WATER AND MOMENTUM FLUX MEASUREMENTS. SITES WITH ONLY MONTH AND YEAR NOTED ARE NOT YET DEPLOYED, BUT THE DEPLOYMENT IS SCHEDULED WITHIN THE NEXT YEAR. SITES INDICATED WITH TBD (TO BE DETERMINED) ARE INCLUDED IN THE OCEANSITES CATALOG FOR DESIRED FLUX MEASUREMENTS AND MAY BE DEPLOYED WITH ATLAS MOORINGS IN THE FUTURE

Ocean Basin and Array or Site Name	**Flux Site Location**	**Date First Deployed**
Atlantic PIRATA	10°S 10°W	9 June 2006
	0° 23°W	13 June 2006
	15°N 38°W	November 2006
Pacific TAO	0° 110°W	14 April 2006
	0° 140°W	September 2006
	0° 170°W	24 June 2006
	0° 165°E	13 July 2006
Pacific PAPA	50°N 145°W	TBD
Pacific SPG	47°N 160°E	TBD
Pacific KEO	32°N 144°E	16 June 2004
Pacific SAZ	47°S 140°E	TBD
Indian Ocean	25°S 97°E	TBD
	15°N 90°E	TBD
	0° 80°E	22 October 2004
	8°S 67°E	January 2007
	15°N 65°E	TBD
	0° 55°E	TBD
	16°S 55°E	TBD

Four equatorial Pacific moorings within the TAO Array, three PIRATA moorings, eight moorings in the Indian Ocean and the KEO mooring have, or are scheduled to have, full air-sea heat, moisture and momentum flux measurement capability as a contribution to the OceanSITES program (www.oceansites.org). Additional PMEL contributions in the subpolar Pacific and Southern Ocean have been proposed. Table 1 and Fig. 1 summarize these current and planned

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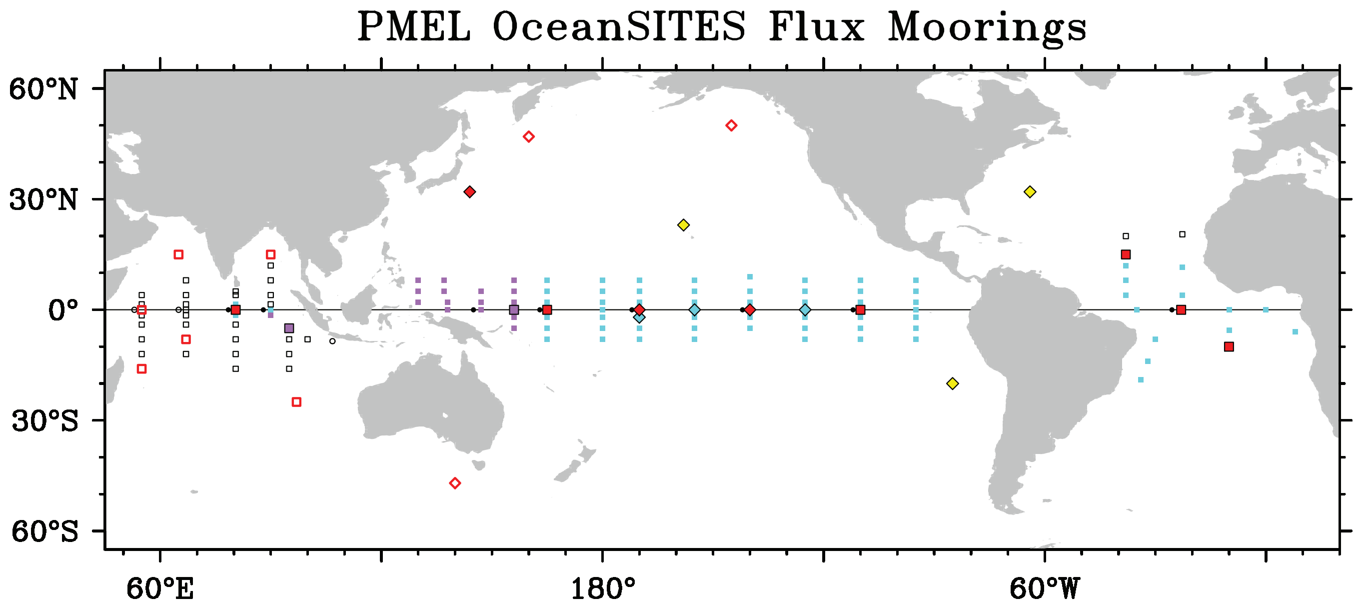

Fig. 1. Location of PMEL OceanSITES moorings. Large red symbols indicate sites measuring heat, fresh water and momentum fluxes. Diamond symbols indicate CO_2 flux measurements. Smaller symbols indicate other moorings within the TAO/TRITON, PIRATA and Indian Ocean moored arrays. ATLAS moorings are blue and TRITON moorings are magenta. Yellow diamonds indicate PMEL CO_2 instrumentation on non-PMEL moorings. Unfilled symbols indicate possible future sites. Filled or open black circles indicate subsurface ADCP moorings. Two TRITON flux sites are indicated by large magenta squares.

enhanced measurement sites. Note, however, that the tropical moored buoy arrays in their entirety are considered contributions to OceanSITES, since each mooring provides data useful for estimation of wind stress, latent and sensible heat fluxes, and in some cases shortwave radiation.

Flux site locations were selected due to their proximity to regions of large air-sea exchange or regions in which our knowledge of flux rates is limited. For example, the KEO site region is characterized by some of the largest heat transfer rates from the ocean to the atmosphere found in the North Pacific. The proposed flux sites in the western equatorial Indian Ocean and Arabian Sea are located in regions where several heat flux products indicate large heat transfer from the atmosphere into the ocean and a site in the eastern subtropical Indian Ocean is located in a region where the flux products indicate large heat transfer from ocean to atmosphere (Fig. 2, courtesy Lisan Yu, WHOI). The mooring in the Bay of Bengal is located in a region where the flux products vary substantially such that even the sign of the long-term mean flux cannot be determined with confidence at present.

II. Instrumentation

PMEL's flux measurement program is based on Next Generation Autonomous Temperature Line Acquisition System (NX ATLAS) moorings [1] with enhancements for the required additional measurements. In addition to primary measurements of wind, air temperature, relative humidity, and surface and subsurface temperature in the upper 500 m, the flux moorings also measure shortwave and longwave radiation, precipitation, sea level pressure, ocean surface and subsurface conductivity, and velocity. The sensors used in the NX ATLAS and their locations on the mooring are listed in Table 2. Instrument specifications, calibration procedures, and accuracy of the primary measurement sensors are specified in [2], [3], and [4]. Rain gauge calibration method and accuracy is given in [5]. Surface meteorological instrumentation from NX ATLAS buoys of PMEL, TRITON buoys of the Japan Agency for Marine-Earth Science and Technology (JAMSTEC), and Improved METeorological (IMET) buoys of the Woods Hole Oceanographic Institution (WHOI) performed comparably during a shore based intercomparison [6].

III. Sample Data

One of the first ATLAS moorings enhanced specifically for OceanSITES flux measurements was deployed in the Indian Ocean near 0° 80°E. Daily mean time series of surface measurements over the first 6 months of the deployment exhibit a period of transition between Southwest and Northeast Monsoon regimes, followed by the establishment of the Northeast Monsoon (Fig. 3). Superimposed on the seasonal cycle of winds is significant variability on daily to intraseasonal timescales. The ocean's response to the seasonal change in wind is evidenced by the establishment of a strong eastward near-surface current, the Wyrtki Jet [7] which is opposite in direction to the typical westward flowing South Equatorial Current in the Pacific and Atlantic. After the period of monsoon transition the near-surface currents are more typical of the Northeast Monsoon Current. The sea surface temperature (SST) and mixed layer depth also exhibit significant intraseasonal variability of order 1°C and 50 m, respectively. These measurements, combined with estimates of surface turbulent fluxes from the same buoy, can be used to compute net surface heat flux (Fig. 4) and examine the mixed layer heat balance.

TABLE II

INSTRUMENTATION USED ON NX ATLAS MOORINGS ENHANCED FOR FLUX MEASUREMENTS

Measurement	**Sensor Type**	**Measurement Height(–)/ Depth(+) Above/Below Sea Surface**
Wind Speed and Direction	Low-latitude moorings: R.M. Young model 05103 propeller and vane Mid- and high-latitude moorings: Gill WindSonic	–4.0 m
Buoy Orientation	E.G. and G. model 63764 or KVH models LP101-5 or C100	–3.0 m
Air Temperature and Relative Humidity	Rotronic Instrument Corp. model MP-100	–3.0 m
Short Wave Radiation	Eppley Laboratory model PSP (modified for TAO with Delrin case)	–3.5 m
Long Wave Radiation	Eppley Laboratory model PIR (modified for TAO with Delrin case)	–3.5 m
Precipitation	R.M. Young model 50203-34 (modified by PMEL)	–3.5 m
Barometric Pressure	Paroscientific: MET1-2	–3.0 m
Water Temperature	NX ATLAS Module using Yellow Springs Instruments thermistor model 46006	13 or more depths between 1 m and 500 m
Salinity	NX ATLAS Module using Sea Bird Electronics conductivity cell	8 or more depths between 1 m and 150 m (500 m for KEO)
Ocean Current	Sontek Argonaut MD	1 to 5 depths between 5 m and 200 m

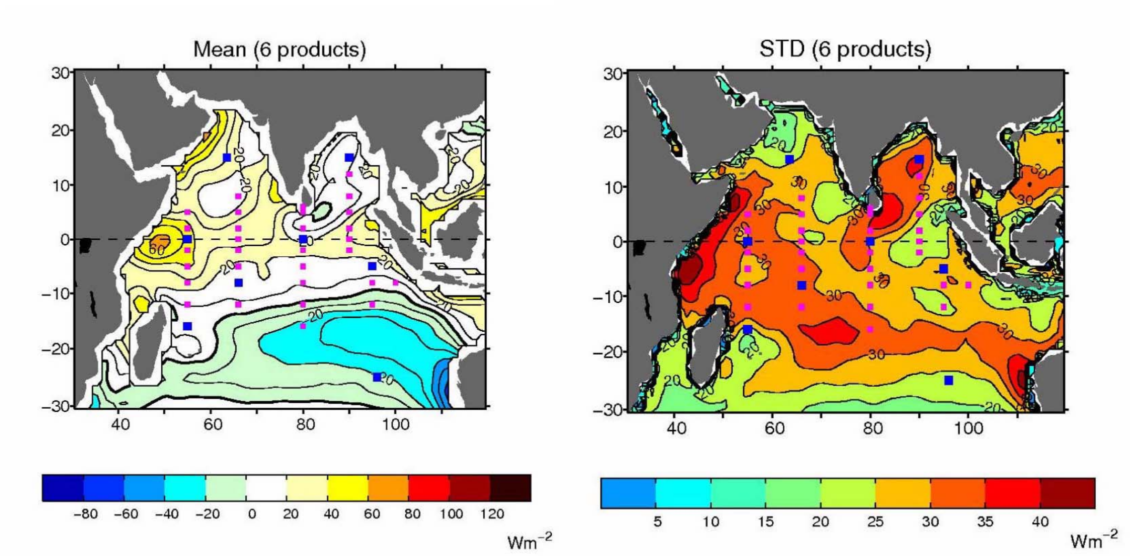

Fig. 2. Mean (left) and standard deviation (right) from six heat flux products. Courtesy of Lisan Yu, WHOI.

IV. HEAT FLUX ACCURACY

Prior to OceanSITES, ten ATLAS moorings within the TAO Array along 95°W were enhanced for surface net heat flux measurements from 2000 through 2003 as part of the Eastern Pacific Investigation of Climate Processes (EPIC) program. At approximately 6-month intervals during mooring maintenance cruises, shipboard measurements of the same parameters were also made. After careful consideration of space-time variability in measurement systems, comparison of the buoy and ship net heat flux (Fig. 5) indicates that the measurement uncertainty is about 10 W m^{-2} [8]. Ship-based meteorological data were analyzed to estimate the effect of time/space separation on measurement variability. Time averages of 2 weeks or more are necessary for comparison of buoy data to Numerical Weather Prediction (NWP) reanalyses. Fluxes from the moorings along 95°W were compared to several NWP reanalyses: the NCEP/NCAR Reanalysis, the NCEP/DOE Reanalysis and the ECMWF 40-year Reanalysis. These comparisons indicate that all reanalyses had too much latent heat loss and too little radiative warming in the convective region of the intertropical convergence zone (ITCZ) north of the equatorial cold tongue. In the stratocumulus region at and south of the equator, the NCEP/NCAR reanalysis had too little latent heat loss and all reanalyses had too much radiative warming.

V. MOORED CO_2 MEASUREMENTS

The ocean plays an important role in regulating the amount of CO_2 in the atmosphere via fluxes across the air-sea interface and in regulating climate variability and the impact that humans have on the global environment. Time series measurements of ocean carbon and air sea exchange help

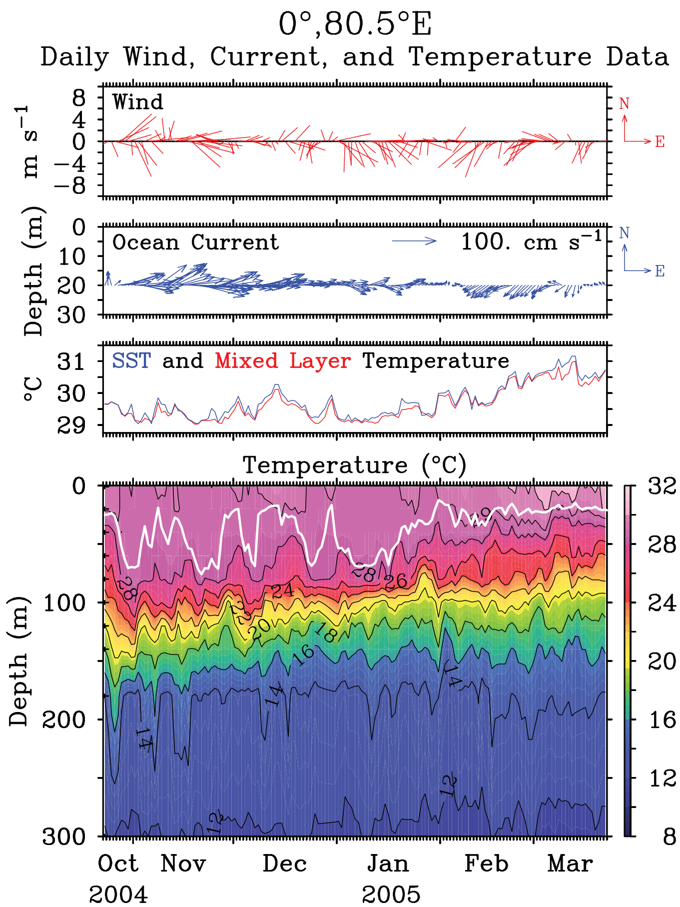

Fig. 3. Daily wind and 20 m current vectors, sea surface and mixed layer temperature, temperature from the sea surface to 300 m depth, and mixed layer depth from an ATLAS mooring near 0° 80°E in the Indian Ocean.

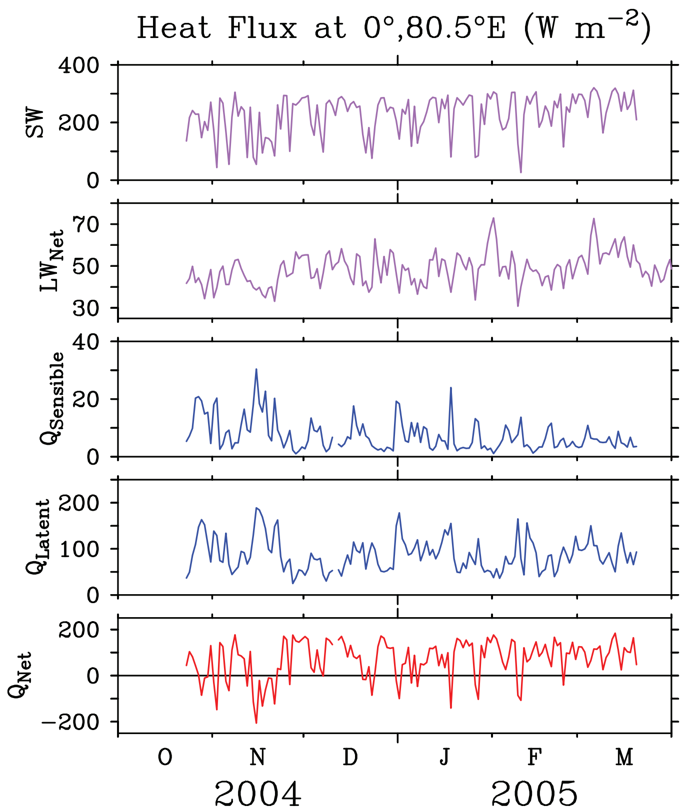

Fig. 4. Short wave, net long wave, sensible, latent and net surface heat flux measured and computed from an ATLAS mooring near 0° 80°E in the Indian Ocean.

provide information on carbon cycle variability on timescales ranging from hours to years. The PMEL CO_2 Program is building a network of CO_2 systems to be deployed on as many of the OceanSITES moorings as possible as an enhancement to the reference site suite of flux measurements. Moored CO_2 measurements are presently made at seven locations in the Pacific Ocean and one site in the Atlantic Ocean. The present sites include five TAO moorings, the KEO mooring, and non-PMEL moorings off of Hawaii and Bermuda (Fig. 1, Table 3).

The prototype for the moored CO_2 system was developed by F. Chavez and G. Friederich at the Monterey Bay Aquarium Research Institute (MBARI). Working with PMEL scientists, the MBARI group has been measuring air-sea CO_2 differences (ΔpCO_2) using a non-dispersive infrared (NDIR) analyzer (LiCor 6252) on two TAO moorings since December 1996. Since the NDIR analyzer only measures the CO_2 concentration in air, the MBARI researchers developed a novel design for a low power equilibrator that equalizes the CO_2 concentrations in a small fixed volume of air with the CO_2 concentrations in the surface seawater. By measuring the difference in CO_2 concentrations in marine air and in the air equilibrated with surface seawater, the direction and magnitude of air-sea CO_2

TABLE III

LOCATION AND DATE OF FIRST DEPLOYMENT OF MOORINGS FROM WHICH pCO_2 IS MEASURED. SITES INDICATED WITH TBD (TO BE DETERMINED) HAVE BEEN PROPOSED AS FUTURE pCO_2 SITES.

Array or Site Name	CO_2 Site Location	Date First Deployed
	0° 110°W	TBD
	0° 125°W	7 September 2003
	0° 140°W	20 September 2003
TAO	0° 155°W*	11 December 1996
	2°S 170°W*	2 December 1996
	0° 170°W	4 July 2005
	0° 165°E	TBD
BTM**	32°N 64°W	22 October 2005
PAPA	50°N 145°W	TBD
HALE-ALOHA**	23°N 158°W	20 December 2004
STRATUS**	20°S 85°W	September 2006
SPG	47°N 160°E	TBD
KEO	32°N 144°E	28 May 2005
SAZ	47°S 140°E	TBD

* indicates MBARI system on TAO mooring

** indicates non-PMEL mooring

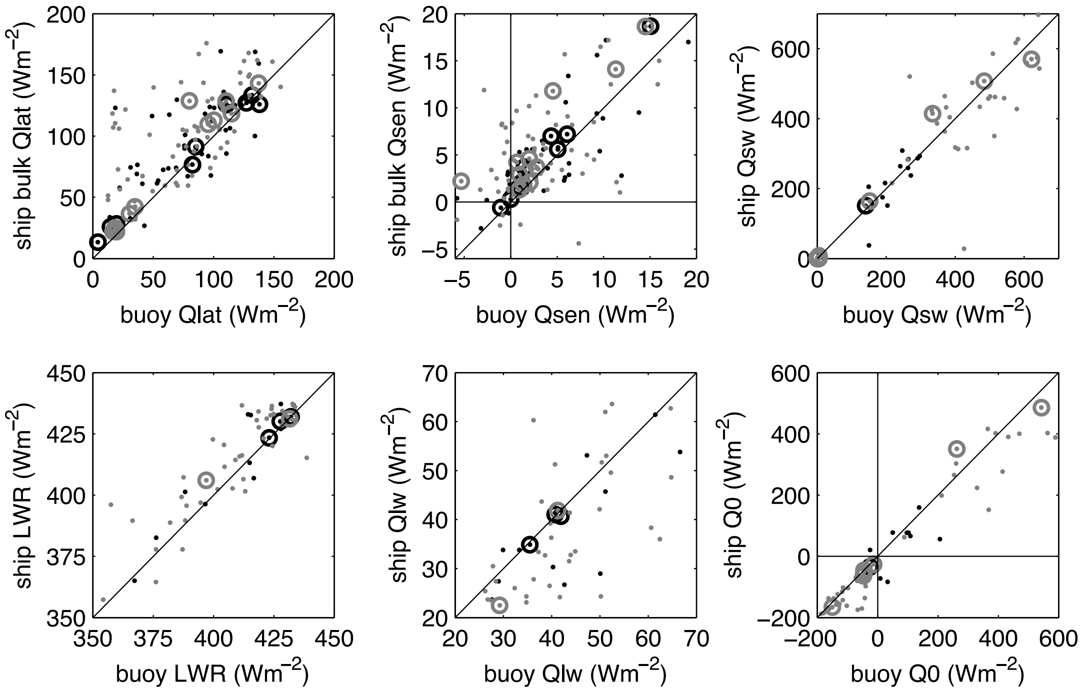

Fig. 5. Scatterplots of 24-hour-averaged (black) and 6-hour-averaged (grey) buoy and ship measurements of latent ($Q_{\rm lat}$), sensible ($Q_{\rm sen}$), net shortwave ($Q_{\rm sw}$), net long wave ($Q_{\rm lw}$) and net (Q_0) surface heat flux and downwelling longwave radiation (LWR) measurements. Dots indicate measurements from the ship and the nearest buoy. Circles indicate that the ship and buoy were less than $\sim$10 km apart at the center of the averaging interval. From Cronin et al., (2006) Fig. 10.

exchange can be determined [9,10]. Based on the technology developed at MBARI, the PMEL CO_2 group developed a modular moored pCO_2 system and began deploying these systems on the OceanSITES flux reference stations in 2003 with a goal of outfitting 60 mooring sites by 2012. The PMEL systems are similar to the original MBARI design but they use a single path NDIR (LiCor 820) instead of the dual path model. Rather than making a direct differential measurement of the air-seawater difference, the PMEL system makes independent measurements of the marine air and equilibrated seawater. These measurements allow us to better interpret the mechanisms underlying variability in the CO_2 fluxes, but comes at the cost of having to include standard gases to calibrate the system. The CO_2 data collected by the PMEL systems are transmitted to the lab and posted to the web daily (http://www.pmel.noaa.gov/co2/moorings/).

Time series of the difference between the oceanic and atmospheric mole fraction of CO_2 ($xCO_{2\rm ocn}$ – $xCO_{2\rm air}$) at four locations in the equatorial the Pacific Ocean show very large positive values, indicating that the region is a significant source of CO_2 from the ocean to the atmosphere (Fig. 6). In addition, these moored CO_2 data exhibit significant variability over a wide range of timescales that cannot be fully characterized from shipboard measurements. Large variations range on timescales from diurnal changes caused by warming of the surface layers during daylight hours, to variations on the order of days to weeks caused by tropical instability waves and Kelvin waves, to seasonal variations related to cycles in temperature and biology, to interannual changes related to atmospheric CO_2 growth rate and changes in upwelling strength associated with ENSO cycling. Some of these trends appear to be coherent across the different longitudes while other events appear to be isolated to a particular mooring location. The development of the moored CO_2 network will help to better understand the time and length scales of CO_2 variability in the ocean and the changing role of the ocean as a sink for CO_2 released from human activity.

VI. Summary

PMEL is a major contributor to the OceanSITES ensemble of long-term, moored time series measurements. Moorings at seven tropical and subtropical sites in all three major ocean basins are presently equipped to measure surface fluxes of heat, fresh water, and momentum. Additional sites both in the tropics and higher latitudes are either scheduled or proposed for implementation. Aside from these specially instrumented sites, the tropical moored arrays in their entirety also contribute to the goals of the OceanSITES program. Moored flux measurements have been cross validated with shipboard measurements and have been used to assess the accuracy of several NWP reanalyses. CO_2 instrumentation is deployed at seven mooring sites in the Pacific, one site in the Atlantic, and additional sites have been proposed. These carbon measurements add a biogeochemical component to the OceanSITES network for multidisciplinary studies of the global carbon cycle and climate system variability.

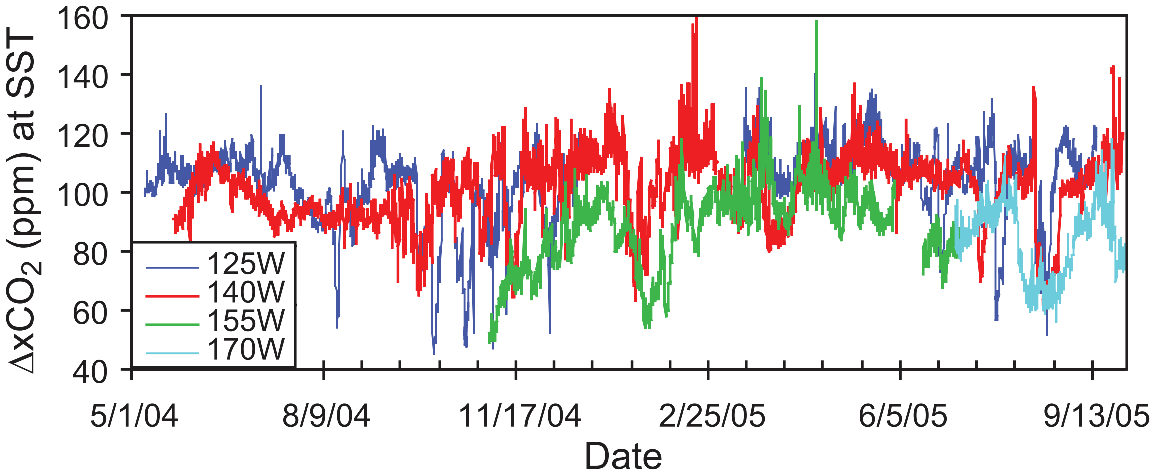

Fig. 6. Time series plot of ΔxCO_2 (ocean CO_2 mole fraction determined at sea surface temperature–atmosphere CO_2 mole fraction) at four locations (0°, 125°W; 0°, 140°W; –2°S, 155°W; 0°, 170°W) in the equatorial Pacific Ocean.

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