Surface Mooring Network in the Kuroshio Extension

Meghan F. Cronin, Christian Meinig, Christopher L. Sabine, Hiroshi Ichikawa, and Hiroyuki Tomita

***Abstract*—As a contribution to the Global Earth Observation System of Systems, the National Oceanic and Atmospheric Administration (NOAA) is developing surface moorings that carry a suite of field-proven and cost-effective sensors to monitor air–sea heat, moisture, and momentum fluxes, carbon dioxide uptake, and upper ocean temperature, salinity, and currents. In June 2004, an NOAA surface mooring, referred to as the Kuroshio Extension Observatory (KEO), was deployed in the Kuroshio Extension's (KE) southern recirculation gyre, approximately 300 nautical miles east of Japan. In 2006, a partnership between NOAA and the Japan Agency for Marine-Earth Science and Technology was formed that deployed a second mooring (referred to as JKEO) north of the KE jet in February 2007. KE is a region of strong currents, typhoons, and winter storms. Designing and maintaining moorings in the KE is a challenging engineering task. All data are publicly available. A subset of the data are telemetered and made available in near real time through the Global Telecommunications System and web-based data distribution systems. Data from these time-series reference sites serve a wide research and operational community and are being used for assessing numerical weather prediction analyses and reanalyses and for quantifying the air–sea interaction in this dynamic region.**

***Index Terms*—Air–sea interaction, atmospheric measurements, climate, Global Earth Observation System of Systems (GEOSS), ocean measurements.**

I. INTRODUCTION

OCEANS PLAY an important role in climate by storing, transporting, and releasing heat to the atmosphere. Excess heat received in the tropics is carried poleward by strong western boundary currents—the Gulf Stream in the North Atlantic and the Kuroshio in the North Pacific. In particular, the Kuroshio Extension (KE) carries warm water at a rate of nearly 140 million m^3/s (140 Sv) into the North Pacific [1]. As cold dry air of continental origin comes in contact with this warm water, heat and moisture are extracted from the surface (Fig. 1), resulting in deep convection and rainfall. This excess heat from the tropics is then carried further poleward in the atmosphere through the action of storms, thereby maintaining a global balance of heat [2].

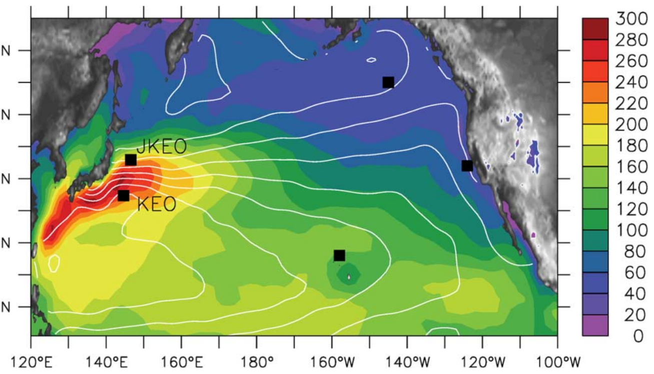

Fig. 1. Climatological latent heat flux for January through March from NCEP/NCAR reanalysis, in units W/m^2. Climatological sea surface heights are shown as white contours and can be interpreted as geostrophic streamlines of flow. Air–sea flux reference sites are indicated by squares. A positive latent heat flux indicates heat loss by the ocean.

Oceans also play an important role in climate by absorbing and sequestering carbon dioxide. The regions of intense air–sea heat fluxes in the Gulf Stream and KE are also characterized by intense uptake of CO_2, while regions of strong upwelling, such as in the eastern equatorial Pacific, are characterized by CO_2 outgassing [3]. Without the oceans to absorb significant amounts of the CO_2 released from human activity, the climate change would be much more pronounced. Thus, air–sea heat and carbon dioxide flux measurements, particularly within western boundary current regions, are a critical element of the Global Earth Observation System of Systems (GEOSS).

Net heat flux across the air–sea interface comprises the net (upward minus downward) radiative fluxes and net turbulent (latent and sensible) heat fluxes. Net radiation estimates are usually based upon direct measurements of the shortwave and longwave radiation, with some assumptions about albedo and emissivity. Turbulent fluxes, however, typically are estimated using a bulk algorithm based upon similarity theory (e.g., [4]) applied to the measured air–sea property differences. In particular, computation of the latent heat flux due to evaporation and the sensible heat flux due to air–sea temperature differences typically require estimates of the wind speed, air and sea surface temperature (SST), and humidity. Similarly, the air–sea carbon dioxide flux requires estimates of the air–sea pCO_2 difference, wind speed, and CO_2 solubility (which is a function of SST and salinity) [5].

In isolation of other processes, the effect of the air-sea flux is a secular change in the ocean surface properties. The fluxes, however, generally do not occur in isolation of other processes. Winds, which directly affect the turbulent fluxes, also can force circulation patterns in the ocean and thus can affect the ocean surface properties through mixing, upwelling, and lateral advection. Through air–sea heat fluxes, shifts in the warm KE can affect the North Pacific storm track and thus affect weather locally and in remote regions [6]. Recent work by [7] and [8] indicate

Manuscript received September 21, 2007; revised April 21, 2008. First published July 25, 2008; current version published September 17, 2008. This work was supported in part by the NOAA Office of Climate Observations and by JAMSTEC.

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Digital Object Identifier 10.1109/JSYST.2008.925982

that feedbacks associated with air–sea heat fluxes in the KE region may also contribute to decadal oscillations in the North Pacific climate.

These processes affecting the SST and salinity also affect the CO_2 solubility and are referred to as the "physical pump." In addition, ocean carbon, and thus the air–sea flux of CO_2, also depends upon bulk biological production and ecological shifts (i.e., the "biological pump"), which can depend upon wind, sunlight, turbulent mixing, upwelling, and lateral advection. Consequently, turbulent heat and carbon fluxes exhibit a rich spectrum of variability from subdiurnal to decadal time scales and are intimately connected with the regional and global environmental conditions.

Strategies for obtaining global air–sea heat and carbon flux fields were reviewed and recommendations were presented at the OceanObs99 conference held in Saint Raphael, France, in October 1999 [9]–[11]. At this meeting, there was uniform recognition that high-resolution time series are required to properly quantify the fluxes and, furthermore, that the global *in situ* observing system could not rely exclusively upon ship-based time series. Ship-based time series are impractical for routine measurements that vary over intervals from a week to a month, they cannot be made during storms or high-sea conditions, and they are too expensive for remote locations.

Although satellites have better spatial and temporal coverage, certain variables cannot be sensed remotely. For example, at present, there is no robust method for monitoring carbon flux remotely. Although the NASA Orbiting Carbon Observatory will monitor the total air column averaged CO_2 concentration, the Kuroshio Extension Observatory (KEO) and JKEO *in situ* measurements will be necessary to interpret these satellite measurements in terms of CO_2 uptake by the oceans (e.g., [12]). Likewise, while satellite remote sensing is able to monitor SST, winds, and short- and long-wave radiation with high accuracy, as noted by [9], remotely sensed near-surface air-temperature and humidity are much more challenging. High-quality *in situ* time series provide an important ground truth testbed for efforts to develop heat flux products based solely upon satellite measurements.

An alternative strategy for determining global heat flux fields is to assimilate the satellite fields, along with *in situ* observations from buoys, ship, drifters, and floats, into a numerical weather prediction (NWP) model. The resulting NWP analyses and reanalyses are physically consistent and can be fairly realistic. Consequently, NWP analyses and reanalyses are used extensively by a broad range of users, both within the scientific community and the general public. Air–sea fluxes from these NWP products, however, can carry substantial systematic biases that compromise our ability to understand and predict changes in the climate patterns. Consequently, [9] recommended that a network of buoy reference stations be deployed to assess biases in the satellite and NWP-derived fluxes, to develop regional tunings and formulations, and to quantify the influence of better temporal resolution.

Reference [11], at this same conference, recommended deploying a network of moored reference stations that carry a full suite of sensors to monitor, study, and predict multiple processes. Instrumental advances over the past 15 years have led to autonomous moorings that are capable of sampling properties of chemical, biological, and physical interest with resolution as good as a minute and a duty cycle of a year or more (e.g., [13], [14]). Consequently, the mooring network was endorsed by [10] for monitoring air-sea carbon flux and biogeochemical processes. It was envisioned that the moored time series could be used to investigate and monitor air–sea fluxes and air–sea interaction, water mass formation and transformation, carbon cycling, and biogeochemical and ecosystem changes. This network of moored "observatories" has since come to be called the Ocean Sustained Interdisciplinary Timeseries Environment observation System (OceanSITES) network.[1] At present, the OceanSITES network of flux reference sites includes approximately a dozen sites in the tropics and a handful of sites at higher latitudes, including five sites within the North Pacific (Fig. 1). In this paper, we describe efforts by the National Oceanic and Atmospheric Administration (NOAA) and the Japan Agency for Marine-Earth Science and Technology (JAMSTEC) to develop an array of surface moorings to monitor air–sea heat and carbon fluxes in the Kuroshio Extension.

II. SURFACE MOORING NETWORK IN THE KE

A. Mooring Operations and Partnerships

As shown in Fig. 1 and previously described, the Kuroshio Extension (KE) is a region of intense air-sea interaction. While there has long been a great desire to have a flux reference site within the KE region, the impetus for launching a site was provided by the Kuroshio Extension System Study (KESS), a two-year, multi-institutional process study, funded primarily through the National Science Foundation [15]. The KEO surface mooring (Fig. 2), funded by NOAA, was launched during KESS and its mooring deployment and recovery operations were performed as piggy-back operations during the three annual KESS mooring cruises beginning June 2004. The KEO mooring site (nominally at 32.4°N, 144.6°E) was chosen to be next to the southernmost KESS subsurface mooring, in the KE recirculation gyre, a region within the lobe of high fluxes that experiences wintertime (17.5 °C) subtropical mode-water formation. By combining the KEO surface and upper ocean data with the KESS subsurface observations, a set of scientific questions were addressed regarding the relationship between air–sea interaction, mode-water formation, and ocean dynamics in the KE system [15].

As a result of scientific collaborations initiated through KESS, a formal partnership between NOAA and the Japan Agency for Marine-Earth Science and Technology (JAMSTEC) was created to extend the surface observations beyond the time period and limited spatial coverage of the KESS process study. The primary objective of this partnership is to improve the long-term observing capacity of the ocean surface fluxes in the North Pacific region. The partnership will facilitate cooperation on a variety of technical and scientific activities. Most immediately, through this partnership, JAMSTEC has spearheaded a second flux reference site, referred to as JKEO, north of the KE jet at 37.9°N, 146.6°E. An NOAA-designed

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[1] [Online]. Available: http://www.oceansites.org/

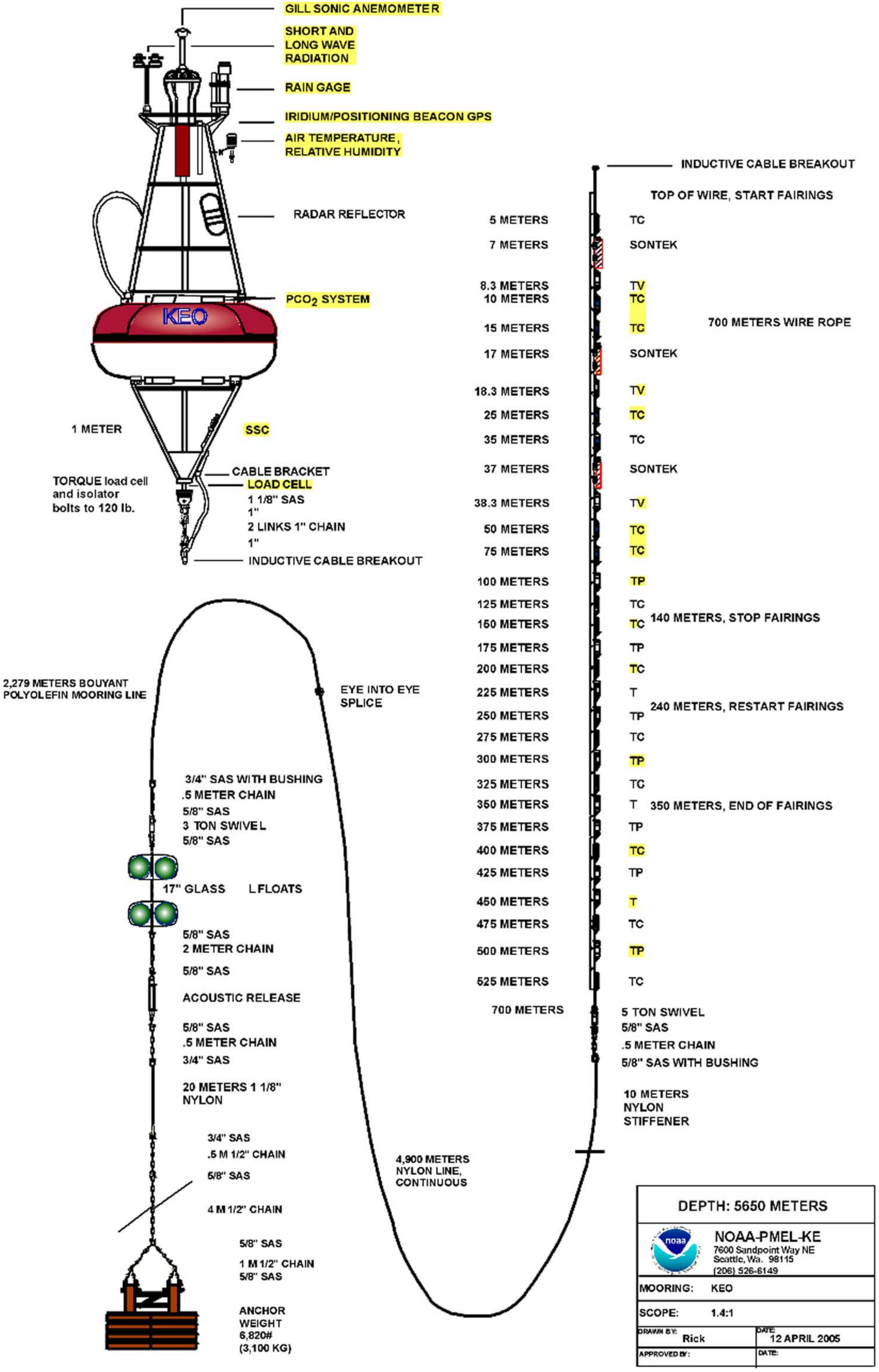

Fig. 2. KEO mooring diagram for buoy deployed in June 2005. Yellow highlights indicate sensors that had telemetered data.

mooring was used for the first JKEO deployment beginning February 2007 and was replaced in February 2008 with a JAMSTEC-designed mooring.

B. Technical Challenges

The challenges of mooring a surface buoy in a western boundary current regime are considerable. Water depth in the KE region is nearly 6000 m. In the core of the KE jet, current speeds can exceed 3 kn at the surface and 0.5 kn in the bottom 3000 m, placing significant strain on the mooring. Typhoons and winter storms can generate damaging winds and waves. Additionally, surface buoys can be vulnerable to shipping traffic and fishing vandalism.

Although the KEO site is south of the mean core of the jet, it is still within the KE jet's meander envelope. To survive the strong currents associated with large-amplitude meanders in the KE jet, PMEL leveraged the design experience gained from equatorial Tropical Atmosphere and Ocean (TAO) moorings and Deep ocean Assessment and Reporting of Tsunami (DART) moorings, making changes specific to the KE conditions. In particular, mooring performance analyses showed that a "slack line" design, with a scope of the mooring line relative to the water depth of 1.4, would significantly reduce the load on the mooring and improve the chance of survival. Slack line moorings had been used successfully with equatorial TAO moorings, but had never been tested in western boundary-type currents. To further reduce the load, fairing was included in the top 500 m and the number of shackles in the line was minimized to lessen the risk of entanglement (Fig. 2). Because of the extensive undersea cable network, the buoy is firmly moored with a minimum 3100-kg anchor. If currents exceed the critical level, the buoy is sacrificed and sinks.

Funding for this "high-risk/high-reward" buoy has been very limited. Thus, to be economical, for initial deployments, TAO moorings were retrofit to survive the harsh environment of the KE region by, for example, filling in and resurfacing the TAO toroid to increase its buoyancy. For the 2007 deployment, the KEO buoy was upgraded to a larger (2.5 m), more robust, discus hull. A newly designed JAMSTEC K-TRITON buoy system was used for the 2008 JKEO deployment.

C. Sensor Suite

Both KEO and JKEO carry a suite of sensors to measure wind speed and direction, air-temperature and relative humidity, rain rate, solar and longwave radiation, atmospheric and sea surface pCO_2, SST and near-surface currents, and subsurface temperature and salinity to 500 m. The NOAA $MapCO_2$ carbon flux package on the JKEO mooring was made possible through collaborations between NOAA Pacific Marine Environmental Laboratory (PMEL) and the Mutsu Institute for Oceanography (MIO) of JAMSTEC. The KEO and JKEO sensors are nearly identical to the suite of sensors that have been on enhanced TAO buoys [16], [17]. However, because the KE region is subject to typhoons, as well as intense winter storms, sonic anemometers are used rather than the more conventional vane and propeller type wind sensor. A subset of data from KEO are shown in Fig. 3 and the air–sea heat fluxes computed from these data are shown in Fig. 4. As discussed in [18], the KEO sensor suite has sufficient accuracy to monitor latent heat flux with sample uncertainty of 16 W/m^2. With averaging, this uncertainty is expected to reduce to under 10 W/m^2. The CO_2 measurements have an estimated accuracy of ~ 1 μatm.

In addition to the sensors for monitoring fluxes and oceanographic structure, the moorings include engineering sensors to monitor the load at the buoy bridle and provide GPS fixes. Data from the load cell, in combination with estimates of the flow, wind, and wave field, are used to model the mooring performance. In particular, these engineering data have been used to fine-tune the fairing placement and component selection [19].

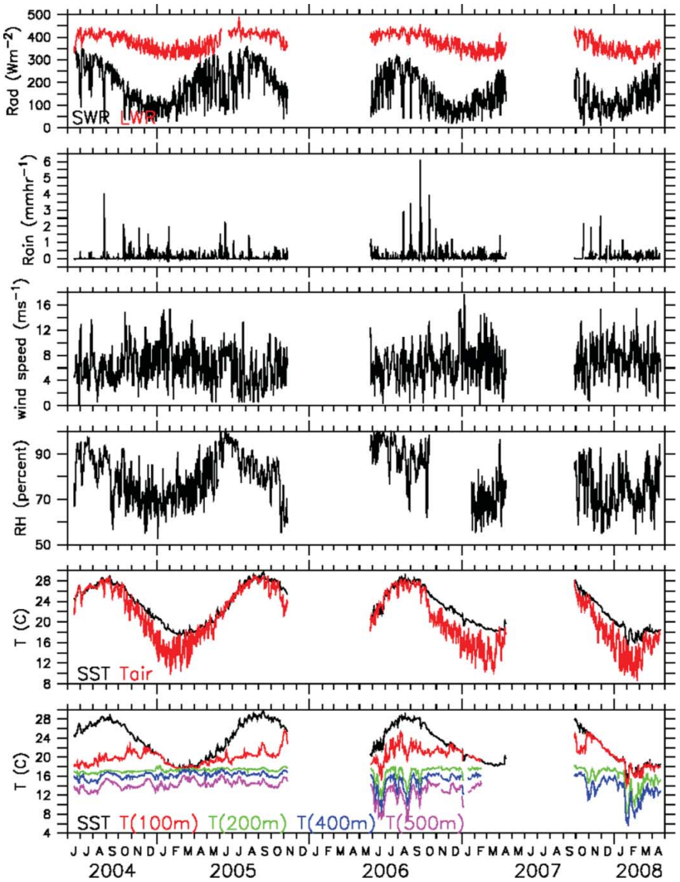

Fig. 3. Daily averaged KEO data. Top five panels show solar (black) and longwave (red) radiations, rain rate, wind speed, relative humidity, and sea surface temperature (SST) (black) and air temperature (red). Telemetered data are used after September 2007. The bottom panel shows SST and subsurface temperatures at several depths. The data gaps are due to mooring line breaks. The first break was caused by a manufacture defect in the nylon mooring line and the second was caused by fishing vandalism. Subsurface time series after May 2006 are based on telemetered data.

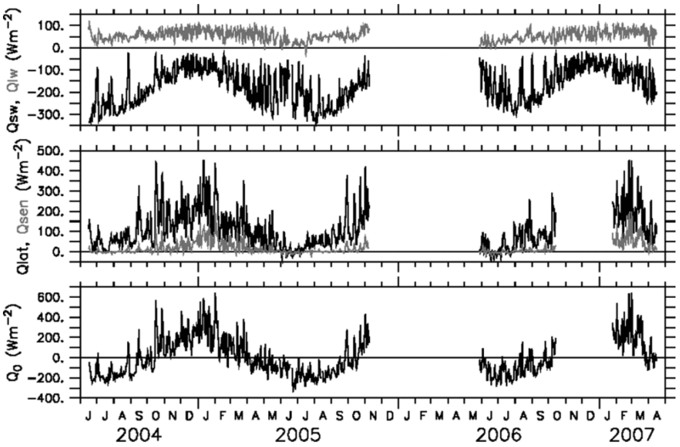

Fig. 4. Daily averaged air-sea heat fluxes computed from delay mode high resolution KEO data. Top panel shows net shortwave radiation (black) and net longwave radiation (grey). Middle panel shows latent heat flux (black) and sensible heat flux (grey). The bottom panel shows net surface heat flux (black). A positive heat flux indicates heat loss by the ocean.

During the 2006 typhoon season, three class-5 typhoons passed over the KEO site. The third typhoon damaged the relative humidity sensor, causing a data gap in the latent heat flux calculation. This sensor was graciously repaired during a Japan Fisheries Agency (JFA) research cruise aboard the R/V *Shoyomaru* in January 2007. The data gap, however, highlighted the need for redundant sensors. With the upgrade for the 2007 KEO deployment, the buoy now carries a barometer and redundant meteorological sensors on an independent data logger and telemetry system. Additional sensors for KEO and

JKEO can be considered for future deployments, assuming these additional sensors do not adversely impact the mooring performance and present sensor suite.

D. *Telemetry and Data Access*

All data collected onboard the KEO and JKEO moorings are publicly available through the project websites for KEO[2] and for JKEO,[3] both of which can be accessed through the OceanSITES data links. Telemetered data are made available in near real time. Recovered, high-resolution data are made available in delay mode, within 6 months (although typically two to three months) of the recovery.

Spot samples of a subset of the data are telemetered in near real time and made available via the Global Telecommunication System (GTS) so they can be assimilated into NWP models by operational meteorological and oceanographic centers. Each site has a unique World Meteorological Organization (WMO) identifying number containing the digits "84," indicating that these systems are time series reference sites. Operational meteorological centers can thus use the reference site data in operational weather forecasts, but then withhold these data from reanalysis products so that the products will remain independent of the time series reference site data used to assess them.

Telemetry takes on added importance, however, in challenging regions like the KE. If the mooring is lost, then scientific analyses must rely upon the telemetered data set. The real-time data are also closely watched for indications that the mooring may need to be rescued or repaired. For example, the KEO mooring broke away from its anchor on April 17, 2007 and got caught in the fast-moving KE jet. Fortunately, the U.S. R/V *Melville* was in the region and was able to recover the buoy and its surface sensors within weeks of the break. It was determined later that the break was caused by fishing vandalism.

III. RESULTS AND RECOMMENDATIONS BASED UPON KEO ANALYSES

As time-series reference sites, the KEO and JKEO time series are being used to assess NWP forecast analyses and reanalyses and other numerical and satellite products. For example, [18] assessed the radiative and turbulent heat flux fields of the National Centers for Environmental Prediction (NCEP)/National Center for Atmospheric Research (NCAR) and NCEP/Department of Energy (DOE) reanalyses (referred to as NRA1 and NRA2) using the first two deployments of KEO and found the following.

- Overall, the NRA latent heat fluxes were too large relative to KEO, indicating that the NWP had too much heat released by the ocean. For NRA1, the latent heat bias was 48 W/m^2; for NRA2, the bias was 62 W/m^2 (there was a 14-W/m^2 bias between the two products).
- Although the magnitude of the fluxes had significant errors, the NRA were able to capture many of the synoptic disturbances. The cross correlation between the KEO latent heat flux and the co-incident NRA latent heat fluxes were greater than 0.9 for both NRA1 and NRA2.
- The bias in the NRA latent heat flux could be reduced significantly by using a more sophisticated bulk algorithm for its heat flux calculations.
- Of all the state variables (SST, humidity, air temperature, and wind speed), humidity contributed the largest source of error to the NRA flux. During summer when prevailing winds are from the south (of maritime origin), the NRA humidity is too low, while during the winter when prevailing winds are from the north (of continental origin), the humidity is too high. Although the prevailing wind systems are well reproduced, the air humidity does not seem to be properly modified by boundary layer effects.
- The NRA SST had significant errors in comparison to KEO measurements. The RMS error in latent heat flux was significantly reduced when the NRA SST was replaced with the Microwave Optimum Interpolation (MWOI) SST, indicating that both reanalyses could be improved by assimilating better SST data.

By using both the KEO and JKEO time series in this type of analysis, the influence of the KE front on the climate system will be much better constrained. Longer time series measurements at these sites, as well as additional sites in the North Pacific, will continue to improve our understanding of air–sea fluxes, leading to better predictions of weather and climate variations.

IV. GLOBAL EARTH OBSERVING SYSTEM OF SYSTEMS

In 2003, the intergovernmental Group on Earth Observations (GEO) recognized that timely, high-quality, long-term global information is required for sound decision-making and began developing a ten-year plan for a "Global Earth Observation System of Systems" (GEOSS). In 2005, 61 countries agreed to the resulting plan for the global network that would encompass *in situ*, airborne, and space-based observations. GEOSS would promote capacity building in Earth observation, building on existing local, national, regional, and international initiatives. As stated in the ten-year plan, contributing systems would share observations and products with the system as a whole, and would take the necessary steps to ensure that the shared observations and products were accessible, comparable, and understandable, by supporting common standards and adaptation to user needs.

Despite funding limitations and the logistical and engineering challenges of maintaining open-ocean moored buoys, there are presently five *in situ* air–sea flux time-series reference sites in the North Pacific: The KEO site south of the KE at 32°N, 145°E; the JKEO site north of KE at 38°N, 147°E; Ocean Station Papa in the Gulf of Alaska at 50°N, 145°W; the Hawaii Ocean time-series station at 23°N, 158°W; and the Monterey observatory at 37°N, 122°W. Data from these buoys are being used in a variety of analyses, including studies of the energy cycle, hydrological cycle, and carbon cycle, and in studies of the upper ocean physics and thermodynamics. These *in situ* time-series reference data are also used to assess numerical weather prediction products and satellite products under a full range of environmental conditions, and will be used as ground truth in upcoming satellite missions, such as the European Space Agency's Soil Moisture and Ocean Salinity mission and the NASA Aquarius mission to measure global sea surface salinity.

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[2] [Online]. Available: http://www.pmel.noaa.gov/keo/

[3] [Online]. Available: http://www.jamstec.go.jp/iorgc/ocorp/ktsfg/data/jkeo/

Although western boundary current regions are extremely challenging, time-series reference sites in these areas are particularly important because intense air–sea interactions there can cause feedbacks in the climate system that can have remote and long-term impacts. The NOAA and JAMSTEC Kuroshio Extension Observatories (KEO and JKEO) show that robust, cost-effective, autonomous flux systems can be maintained even in the harsh environment of western boundary current regions. KEO and JKEO are part of the OceanSITES network of time series reference sites, which is a component of the Global Ocean Observing System (GOOS). Their data are publicly available and serve a wide research and operational community. Additional moorings are needed, however, to monitor the full range of variability that characterizes the North Pacific as envisioned within GOOS and GEOSS. The ocean flux community is addressing the technological challenges and is moving forward with plans to expand this network, which is critical for monitoring the pulse of the Earth's climate system.

ACKNOWLEDGMENT

The authors gratefully acknowledge the captains, crew, and scientific parties that have performed mooring operations and repairs. For KEO, this includes the R/V *Thompson*, R/V *Revelle*, R/V *Melville* from the UNOLS fleet, JAMSTEC's R/V *Kaiyo*, and JFA's R/V *Shoyomaru*. For JKEO, this includes JAMSTEC's R/V *Mirai* and R/V *Kaiyo, and FRA's* R/V *Hokkomaru*. The authors would also like to thank the engineering and science support staff at PMEL for developing and operating the KEO buoys and the JKEO buoy deployed in 2007 by JAMSTEC.[4]

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Mr. Meinig was the recipient of two U.S. Department of Commerce Gold Medals for tsunami research and development and a U.S. patent on a system for reporting high-resolution ocean pressures for tsunami monitoring purposes.

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[4] For further information and to access the KEO and JKEO data, please see http://www.pmel.noaa.gov/keo/ and http://www.jamstec.go.jp/iorgc/ocorp/ktsfg/data/jkeo/

Christopher L. Sabine received the Ph.D. degree in chemical oceanography from the University of Hawaii, Manoa, in 1992.

After spending seven years on the research staff at Princeton University, he moved to Seattle, WA, first as a Research Scientist with the University of Washington's Joint Institute for the Study of the Atmosphere and the Ocean (JISAO) and then as an Oceanographer at NOAA's Pacific Marine Environmental Laboratory. In addition to his position at NOAA, he is an affiliate faculty member with the University of Washington School of Oceanography and a JISAO Senior Fellow. His research focuses on understanding the global carbon cycle. In particular, his work focuses on interpreting inorganic carbon measurements in both the open and coastal oceans. He is active in a number of national and international research program scientific steering committees.

Dr. Sabine was the recipient of several awards, including the Department of Commerce Gold Medal Award for pioneering research leading to the discovery of increased acidification in the world's oceans due to the absorption of carbon dioxide.

Hiroshi Ichikawa was born in Hokkaido, Japan, in May 1949. He received the B.S. and M.S. degrees and the Ph.D. degree in physical oceanography from Kyoto University, Kyoto, Japan, in 1972, 1974, and 1978, respectively.

He was with the Department of Fisheries Science, Kagoshima University, first as a Research Assistant from 1979, and then as a Professor of Oceanography starting in 1998. He was a Visiting Investigator of the Woods Hole Oceanographic Institution in 1988 and 1989. In 2005 he joined the Institute of Observational Research for Global Change (IORGC), Japan Agency for Marine-Earth Science and Technology (JAMSTEC), Kanagawa, Japan, as a Group Leader of the Kuroshio Transport and Surface Flux Group, the Ocean General Circulation Observational Research Program. His major research interest has been the Kuroshio in the East China Sea, and more recently air–sea interaction in the North Pacific, especially in the Kuroshio and Kuroshio Extension region.

Dr. Ichikawa is a member of the Oceanographic Society of Japan, the Japanese Society of Fisheries Oceanography, the American Geophysical Union, the American Association for the Advancement of Science, and other organizations.

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Dr. Tomita is a member of the Oceanographic Society of Japan, the Meteorological Society of Japan, and the American Geophysical Union.