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14. ABSTRACT
The objective of this Multi-University Research Initiative (MURI) grant, subtitled, "The Adaptive Sampling and Prediction System (ASAP)" was to learn how to deploy, direct, and utilize autonomous vehicles [and other mobile sensing platforms] most efficiently to sample the ocean, assimilate the data into numerical models in real or near-real time, and predict future conditions with minimal error. The scientific goal was to close the heat budget for a control volume surrounding a three-dimensional coastal upwelling center, and identify via the magnitude of the terms the relative importance of the surface fluxes, boundary layer processes, alongshore advection, and mesoscale interactions in determining the temperature changes within the box. The work resulted in seven publications in refereed journals authored or co-authored by the PIs, and the eighth is in advanced preparation.

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Optimal Asset Distribution for Environmental Assessment and Forecasting Based on Observations, Adaptive Sampling, and Numerical Prediction

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This grant was initially awarded to Steve Ramp at the Naval Postgraduate School. It was then moved to the Monterey Bay Aquarium Research Institute (MBARI) when Steve took the position of the Central and Northern California Ocean Observing System. After Steve left MBARI, Fred Bahr was appointed to take the position of PI at MBARI where the grant was administered from. A subaward was Soliton Ocean Services Inc. to Steve Ramp to complete the work on the grant. Computations in support of Steve Ramp's work were carried out by Fred Bahr at MBARI. Additionally, since Fred Bahr was at MBARI, he took over the administrative duties for the grant.

Below is the final report submitted by Steve Ramp summarizing the grant and his work supported by Fred Bahr's computations.

LONG-TERM GOAL

The long-term goal is to enhance our understanding of coastal oceanography by means of applying simple dynamical theories to high-quality observations obtained in the field. My primary area of expertise is physical oceanography, but I also enjoy collaborating with biological, chemical, acoustical, and optical oceanographers to work on interdisciplinary problems. I collaborate frequently with numerical modelers to improve our predictive capabilities of Navy-relevant parameters in the littoral zone.

OBJECTIVES

The objective of this Multi-University Research Initiative (MURI) grant, subtitled, "The Adaptive Sampling and Prediction System (ASAP)" is to learn how to deploy, direct, and utilize autonomous vehicles [and other mobile sensing platforms] most efficiently to sample the ocean, assimilate the data into numerical models in real or near-real time, and predict future conditions with minimal error. The scientific goal is to close the heat budget for a control volume surrounding a three-dimensional coastal upwelling center, and identify via the magnitude of the terms the relative importance of the surface fluxes, boundary layer processes, alongshore advection, and mesoscale interactions in determining the temperature changes within the box.

APPROACH

The mobile assets for this project included 10 gliders (6 Slocum vehicles from WHOI and 4 Spray vehicles from SIO), 3 propeller-driven vehicles (DORADO from MBARI and 2 Odysseys from MIT), a research aircraft (NPS TWIN OTTER) and several support ships (SHANA RAE, POINT SUR, ZEPHYR, SPROUL, NEW HORIZON). Given these resources and the objectives above, a control volume (Figure 1) was selected for the 2006 experiment. The box, approximately 40 x 20 km, enclosed the upwelling center that is of central scientific interest. Six gliders were deployed along "racetracks" within the box and 4 were deployed as "rockers" oscillating back-and-forth along the boundaries, one on each end and two covering the offshore side. Using a combination of autonomous and human-activated control, the gliders were coordinated as a group to optimize the sampling coverage of the control volume in response to the ever-changing current conditions. A pair of bottom-mounted acoustic Doppler current profilers (ADCPs) was also deployed along the southern boundary of the box to sample and report the internal wave environment in real time via a Seaweb underwater network.

The real-time observations were ingested into the NCOM, HOPS, and ROMS numerical ocean models each evening for predictive runs for the following day. Assets were then re-allocated to optimize sampling coverage and minimize model predictive error. See also annual report of the same name by Prof. Naomi Leonard of Princeton, for more detail on the coordinated control, adaptive sampling, and numerical prediction aspects of this program.

WORK COMPLETED

This project is nearing completion, but a small subset of the original PIs is still pursuing the Holy Grail, namely closing the heat budget for a three-dimensional upwelling center in an eastern boundary current. The targeted region is the ASAP box off Point Año Nuevo, California [Leonard et al., 2010; Ramp et al., 2011] (Figure 1). The idea is to use all available assets to determine the surface flux and the fluxes through the sides of the box, as well as the local change inside the box, thereby enlightening the governing dynamics. The assets include the NPS CIRPAS aircraft, which conducted daily overflights for 15 straight days, a fleet of gliders patrolling the sides and interior of the box, and shipboard and AUV-based surveys. In an earlier publication, Davis [2010] found that the Spray gliders alone were inadquate to compute terms in the heat budget, except for a heavily averaged result showing the upwelling overturning cell on the offshore side of the box. In lieu of this, we have decided to combine the glider data with the NRL NCOM model [Shulman et al., 2007; 2010] to compute the mean and eddy fluxes through the sides of the control volume. The assimilation of the glider data into the NCOM model has been shown to produce a significant increase in the model's predictive skill [Shulman, 2009]. We also used the Navy COAMPS atmospheric model [Hodur, 1997; Doyle et al., 2009] to refine the atmospheric flux estimates. The models produce dynamically consistent output on a regular grid, which greatly facilitates the computation of the mean and eddy fluxes. The basic methodology being used is similar to that used during the CODE experiment [Lentz, 1987; Lentz et al., 2010]. The surface flux computations are complete (see below). The NCOM model output as computed by I. Shulman (NRLSSC) is now in the hands of Ramp and Bahr and they are using it to compute the lateral fluxes and $\partial T / \partial t$. The manuscript is about three-fourths written.

RESULTS

The heat conservation equation governing a control volume is given by:

$$\rho_0 c_p \left(\frac{\partial T}{\partial t} + \nabla \bullet (\vec{u}T) + \frac{\partial}{\partial z}(wT) \right) = \frac{\partial Q}{\partial z} \qquad (1)$$

where ρ_o is the mean density of sea water, c_p is the specific heat, and T is temperature. To produce stable estimates and quantify the error, daily averages of each term in (1) were chosen as the shortest reasonable time step to use. The total heat flux through the sea surface is given by:

$$Q = Q_{SW} + Q_{LW} + Q_{sen} + Q_{lat} \qquad (2)$$

where the terms on the right-hand side represent the incoming short wave, net long wave, sensible, and latent heat fluxes respectively.

Time series of the aircraft and buoy observations vs. the COAMPS® model output (Figure 2) were used to determine how best to estimate each of the surface flux terms (2). The airborne sensors performed well but sampled only roughly 2.5 hours per day. To produce daily averages for the latent and sensible flux terms, all the COAMPS® points within the ASAP control volume footprint (189 points) were first averaged together to form a spatially-averaged value. These values (Figure 2a, b blue line) were then calibrated against the aircraft values sampled during the flight window and the corrected model output (Figure 2a, b black line) was used to compute the daily averages. The model output for the latent heat flux was uniformly higher than the values observed by the aircraft (Figure 2a) while the sensible heat flux agreement was quite good (Figure 2b).

The model short- and long-wave fluxes were compared against MBARI buoy M1 (Figure 2c, d). The agreement for the sensible fluxes was quite good except on cloudy days (August 3, 4, 13, and 14) when the model drastically overestimated the short wave fluxes (Figure 2d). This is due to a well-known problem in the way COAMPS models low-level clouds [Shulman et al., 2007]. Fortunately, the spatial scales of the shortwave fluxes are large for this region, and the buoy can safely be regarded as representative of the ASAP region. The buoy data were therefore used to compute daily averages of the shortwave fluxes for the ASAP box. The model/data comparison for the long-wave fluxes once again showed the model to be systematically higher than the buoy, especially on cloudy days (Figure 2c). The buoy time series was again used to compute the long-wave daily averages, since it appeared to make more physical sense, especially when compared to the buoy shortwave.

The results show that the incoming shortwave radiation was the dominant term, even when averaged over the dark hours, which accounts for the large standard deviation. The net long-wave radiation was small and negative, which reduced Q slightly, and the sensible and latent fluxes were both small and positive. The next step is to combine the surface flux results with fluxes through the side boundaries as computed using the NCOM data-assimilating model.

IMPACT/APPLICATION

All recent Navy METOC publications indicate that autonomous vehicles are the way of the future in battlespace environmental assessment. The Naval Oceanographic Office has already initiated procurement of large numbers of gliders and significant numbers of propeller-driven vehicles. Experiments such as ASAP will help the Navy to learn how to utilize these vehicles most effectively, to maximize the information returned, and to assimilate the data into numerical models for environmental prediction. It has been demonstrated that assimilation of glider data into Navy models improves nowcasts, hindcasts, and 1.0-1.5 day forecasts [Shulman et al., 2009].

TRANSITIONS

The virtual control room (COOP) or its derivatives, developed during ASAP, has been used to support several subsequent Navy field experiments including the MB08 "Oktoberfest" experiment and the Impact of Typhoons on the Ocean in the Pacific (ITOP) experiment. Model improvements (i.e. nested model boundary forcing from HYCOM vs. NCOM) are continually being incorporated into Navy real-time systems.

RELATED PROJECTS

NRL BIOSPACE Experiment summer 2008
MB08 "Oktoberfest" ocean color and harmful algal bloom experiment
San Francisco Bayweb I and II, spring and summer 2009, San Francisco Bay - Acoustic networking of ocean sensors in a high-current, high-noise environment.
MBARI CANON Experiment (ongoing)
Project MISSION in Singapore (proposed)

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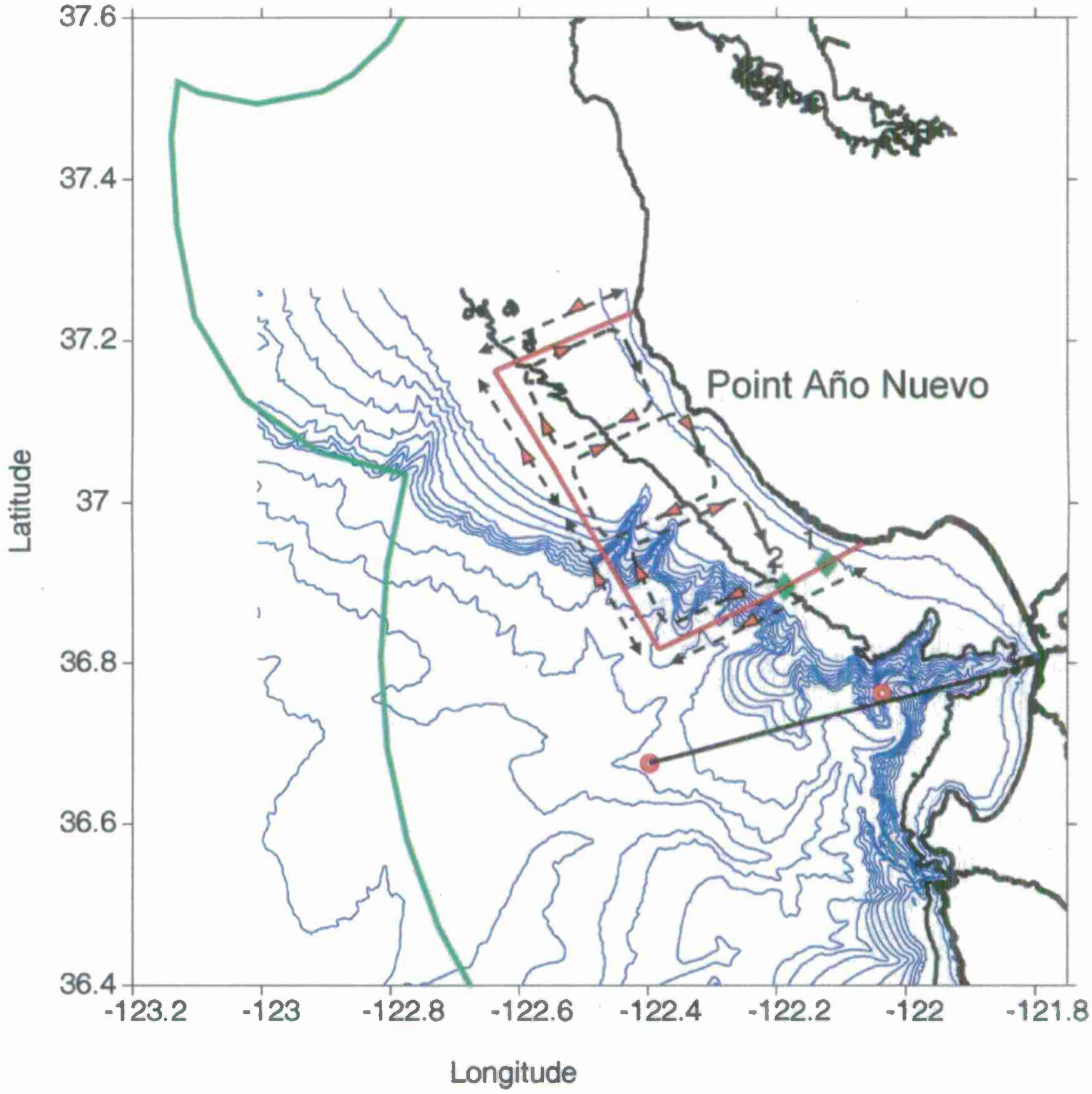

Figure 1. Schematic of the ASAP sampling plan during August 2006. The Slocum gliders covered the interior and the Spray gliders oscillated along the boundaries. The open red circles indicate the MBARI buoys.

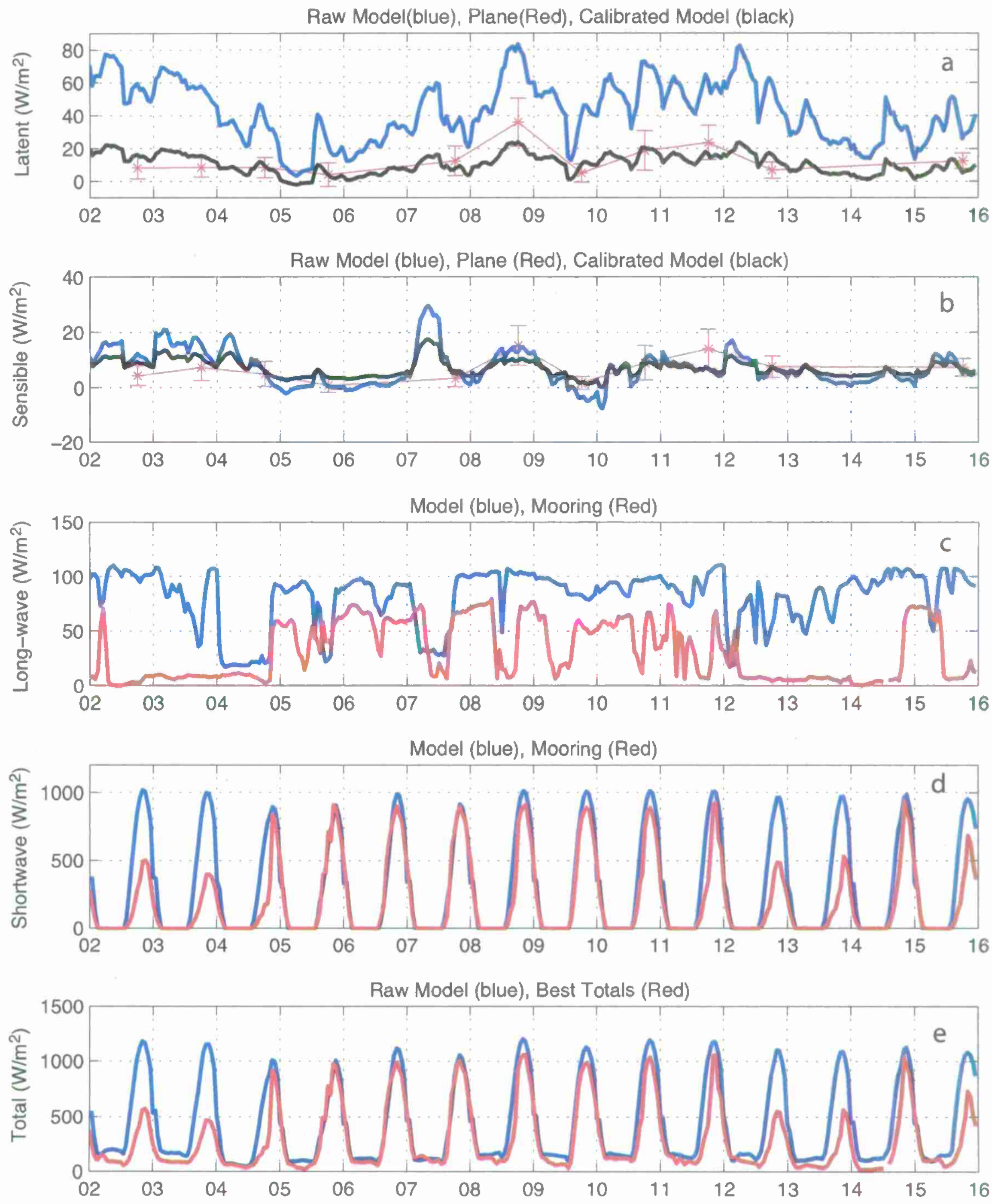

Figure 2. Comparisons of the heat flux terms from the Navy COAMPS® model with observed fluxes from the NPS CIRPAS aircraft (a, b) and MBARI buoy M1 (c, d). The sum of the four terms representing the total heat flux is at the bottom (e).