Program: Science-driven Autonomous and Heterogeneous Robotic Networks: A vision for Future Ocean Observations

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Project website:
http://www.kiss.caltech.edu/new_website/techdev/seafloor/seafloor.html

Brief summary of progress to date

Objectives

This project will sample the three-dimensional time-varying upper ocean using multiple ocean robots adaptively controlled by on-shore autonomous planning algorithms that exploit information from prediction models, remote sensing data, and in situ data obtained by these robots. The scientific focus is to optimize the robotic sampling capabilities in order to resolve evolving small-scale (submesoscale) ocean instabilities.

Our specific objectives include:
1. Design a framework in which a fleet of heterogeneous surface and underwater ocean robots receive directives from shore-based models that consider the health, sensing, navigation, and communication characteristics of the robots.
2. Develop algorithms to autonomously determine sampling strategies designed to maximize information gain and based on a combination of in situ observations and shore-based data-assimilating forecast ocean models.
3. Implement and assess the technologies in a week-long 2016 experiment involving multiple AUVs and both surface Wave Glider and subsurface gliders to observe the physical and biogeochemical dynamics of the upper ocean over a 7 day period. Shore-based adaptive surveying and autonomous planning algorithms will combine data from these robots and remote sensing data with a Regional Ocean Modeling System (ROMS) to plan future robot trajectories. This will work be carried out in collaboration with colleagues at MBARI and will inform the design of a larger field program in 2017.

Technical Approach

To accomplish the proposed objectives, we will demonstrate the ability of heterogeneous groups of robots to autonomously determine sampling strategies with the help (two-way feedback) of numerical ocean forecasts and remotely-sensed observations (Figure 1).

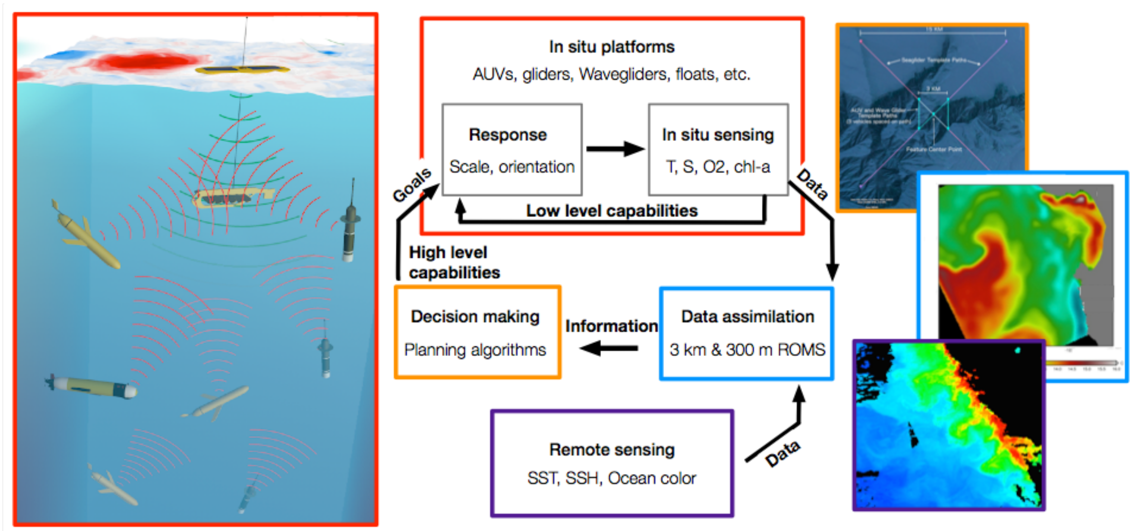

Figure 1. *Schematic and work flow of the Satellites to the Seafloor Keck Institute for Space Studies (KISS) concept. The design calls for a combination of in situ (red) and satellite-based (purple) measurements to be assimilated into a high resolution numerical model (blue). Both model output and observations are passed to a suite of planning algorithms (orange) that direct the in situ observing array accounting for the varying capabilities and health of each instrument. Right hand panels show an example of a path-planner template (orange), sea surface temperature in Monterey Bay from the 300-m resolution numerical output (blue, see Figure 2), and coastal California ocean color from the NASA Visible Infrared Imaging Radiometer Suite (VIIRS) scanning radiometer (purple).*

2016 Field program, Monterey Bay, CA

Our first field program was carried out in Monterey Bay between July and October 2016. The observing system consists of three elements: (i) a 300-meter resolution ROMS (Regional Ocean Modeling System) free-surface, terrain-following, primitive equations ocean model developed especially for this project; (ii) a suite of planning software that both identifies the location of specific scientific targets based on the ROMS output and autonomously determines the optimal sampling strategy for a heterogeneous array of autonomous vehicles; and (iii) a fleet of three AUVs, two ocean gliders and one Tethys-class Long-Range AUV, the latter through a collaboration with MBARI (Monterey Bay Aquarium Research Institute). The goal of the project was to generate daily forecasts from the ROMS model, based on data assimilated from both our autonomous vehicles and other external products, to target strong frontal and upwelling regions. We then worked closely with Jim Christman, caption of the R/V Shana Rae, to deploy our autonomous vehicles at these sites to both validate the ROMS output and to sample the evolving submesoscale circulation at these locations.

Regional Ocean Modeling System (ROMS)

During the KISS field experiment, a nested ROMS-based coastal ocean modeling and data assimilation system provided both nowcast and forecast on a daily basis. ROMS is an open-source model developed by the oceanographic community. In the configuration used here, the innermost ROMS domain covers the greater Monterey Bay region to about 75~km offshore with a horizontal resolution of approximately 300~m. It is nested within an intermediate ROMS domain with a horizontal resolution of 1.1~km covering the coast from Pt. Reyes to Morro Bay out to about 250~km offshore. The outermost ROMS domain covers the entire California coastal ocean from north of Crescent City, California to Ensenada, Mexico with a resolution of 3.3~km (Figure 2). In the vertical there are 40 unevenly-spaced sigma levels used in all three ROMS domains with the majority of these clustered near the surface to better resolve near-surface processes.

As an example of the significant impact that increased horizontal resolution can have on the fidelity of the representation of small-scale features in the model fields, Figure 2 shows the daily mean sea surface temperature (SST) on 5 Apr 2016 as observed by AVHRR/MODIS (Advanced Very High Resolution Radiometer/Moderate-resolution Imaging Spectroradiometer), as well as the daily output of the model nowcasts with increasing resolutions from 3 km to 1 km and 300 m. On this particular day, a large standing mesoscale eddy is observed off the continental shelf. This feature is associated with warmer SSTs and separated from warmer coastal water by a band of lower SST related to a wind-driven upwelling front. Submesoscale features associated with small-scale eddies and filaments that are not well simulated by the relatively coarser models at 3 km and 1 km resolutions are reproduced by the model at 300~m resolution, e.g. a filament of warmer SST located at 36.9°N and 122.5°W. Furthermore, the lateral scales and intensity of the cooler upwelled waters are more accurately captured in the 300 m ROMS model.

Feature Detection and Path Planning

The KISS observing system relies on a suite of feature detection algorithms, applied to the ROMS model output, to identify “target” locations for the in situ assets. Targets are defined by persistent submesoscale physical oceanographic structures. With an appropriate sensor payload, the sampling strategies described herein are equally applicable to features defined by biological and/or chemical signatures. During the field program, a range of different upper ocean diagnostics were considered, including surface vorticity, lateral buoyancy gradients and surface speed. Ultimately, we used horizontal SST gradients to detect surface fronts. The planning algorithm not only identified regions of enhanced SST gradients, but also tracked the evolution of these features over a period multiple days using gridded, three-dimensional, time-dependent ROMS ocean model with a time step of one hour.

The path planner produces control directives, that instruct the assets to follow a template path relative to the identified feature. Two different template paths were developed: straight transects for the slower instrumentation, such as gliders, and bowtie shapes for faster assets, AUVs. The path planner simulates the movement of an asset through the ocean using a movement model that dictates the undulation of the vehicle at a glide slope to the designated depth applying the control directive and the interpolated ROMS current velocity at the relevant latitude, longitude, depth, and time.

Critically, the same planning algorithm accommodates assets with different characteristics. For our Monterey study, we used ocean gliders and AUVs. Despite the difference in vehicle characteristics (AUVs much faster, gliders much deeper diving), the same planning algorithm was used for both types of vehicles. Glider plans are regenerated each surfacing. For the AUS's plans were generated daily for both moving and stationary features and provided to the AUV operational team for deployment.

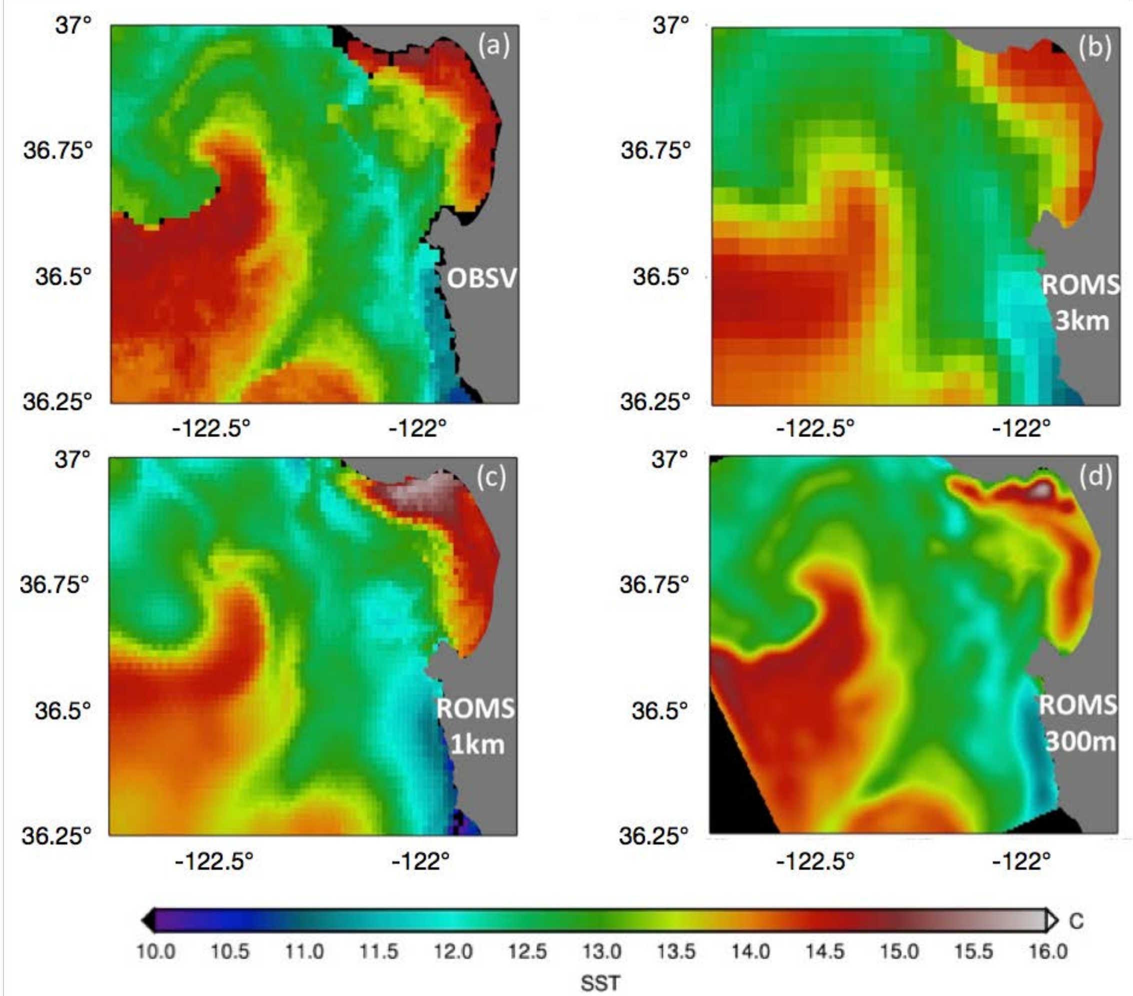

Figure 2. *Sea surface temperature (°C) for 5 April 2016 (a) as observed by AVHRR/MODIS satellites, and as simulated in the three nested ROMS domains: (b) California 3 km, (c) central California 1 km and (d) Monterey Bay 300 m.*

Glider and AUV operations

Two different classes of autonomous vehicles were deployed during this field program: underwater gliders and propelled autonomous underwater vehicles (AUVs). The long-term gliders, one Seaglider (SG621) and one Spray glider (NPS34), were deployed in July 2016 to provide an overview of the hydrographic and biogeochemical properties of the study area. The gliders were piloted to sample perpendicular to the continental slope, which hosts a series of frontal currents, in particular at the shelf break Figure 3a.

The gliders were flown in parallel sections with a lateral separation of ~20 km, which permits calculation of lateral gradients at the submesoscale.

The paths generated using the ROMS model were applied during an intensive AUV field program. This program was supported by the *R/V Shana Rae* operating out of Santa Cruz, CA. A typical operational cycle was to leave dockside at 0500 with the AUVs fully charged and missions loaded, steam to targeted feature locations, deploy vehicles, monitor their progress, and recover early afternoon. *Shana Rae*'s 10 knots with a steaming time of around 2 to 3 hours resulted in the selection of features within this range from Santa Cruz. Deployment and recovery operations were accomplished off the fantail through use of the A-frame.

The observing platforms used for this field experiment consisted of three Iver2 (Ocean Server Technology Inc.) autonomous underwater vehicles (AUVs). All three of the vehicles were equipped with a 25 kHz Woods Hole Oceanographic Institution acoustic micro-modem and a hull-mounted Neil Brown conductivity/temperature sensor (Ocean Sensors Inc.). Additionally, two vehicles were configured with the YSI 6-Series Multiparameter Water Quality Sonde for sensing various biochemical parameters. All three vehicles operated at the most energy efficient speed of 2.5 knots and endured mission lengths of approximately 3.5 hours while expending less than 60% of total battery capacity. All three vehicles conducted undulating dives to depths of 20 meters, 40 meters, 60 meters, and 80 meters in a bow-tie type trajectory in a 3 km^2 area. Figure 3 displays an example of trajectory and temperature data gathered by the AUVs on September 2, 2016.

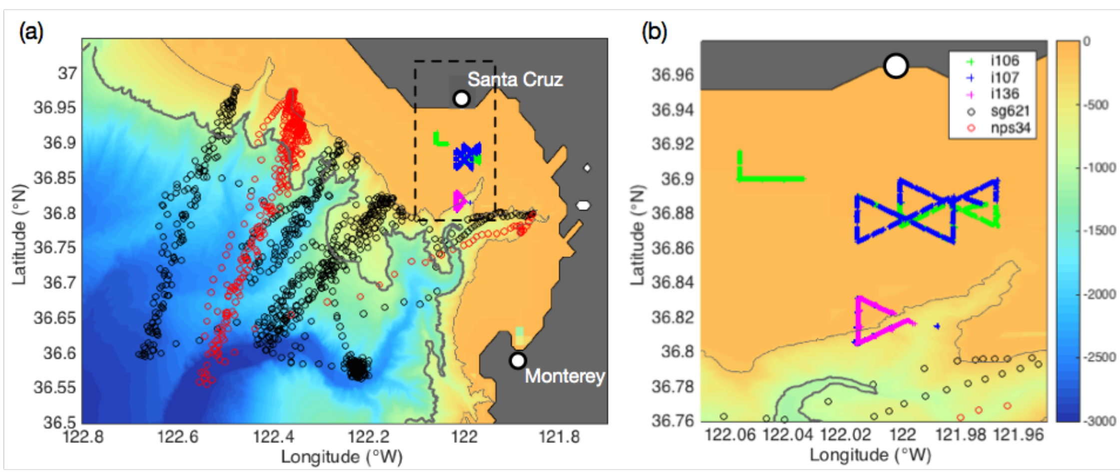

Figure 3. *(a) Locations of all profiles carried out during the KISS field program in Monterey Bay between July and October, 2016. Each symbol indicates a different asset, summarized in the legend in panel (b): gliders (SG621, NPS34) and Iver-class AUVs (i106, i107, i136). The region of intensive AUV deployments over the continental shelf is expanded in panel (b). In both panels, the bathymetry (m) is given by the color; the 200 m and 1000 m isobaths are contoured.*

Results

An example of the implementation from 2 September, 2016 is summarized in Figure 4. Panels (a) and (b) show snapshots of SST and the gradient of SST from the ROMS model corresponding to the expected deployment time of the assets (1500 UTC). The autonomous feature detection accurately captured the strong temperature front (approximately 1°C km^{-1} and mapped out a butterfly pattern shown in white in these panels. As shown in panels (c) and (d), two AUVs (i106 and i107) were deployed just before 1500 UTC and carried out the sampling pattern for a period of approximately four hours. The vertical structure of the temperature shown in panel (c) indicates that mixed layers were very shallow, ~20 m. However, even over this small domain, the AUVs were able to capture significant lateral temperature gradients. The yellow triangle in panel (d) highlights a period of reduced near-surface temperature, with temperature changing just over 1°C. This temperature difference is nearly half of the temperature drop across the front shown in panels (a) and (b). This feature is persistent over a period of 30 minutes, suggesting that it is not the signature of internal waves or longer tidal variability. The reduced surface temperature is also apparent as the glider returns to the western side of the butterfly at the end of its sampling pattern.

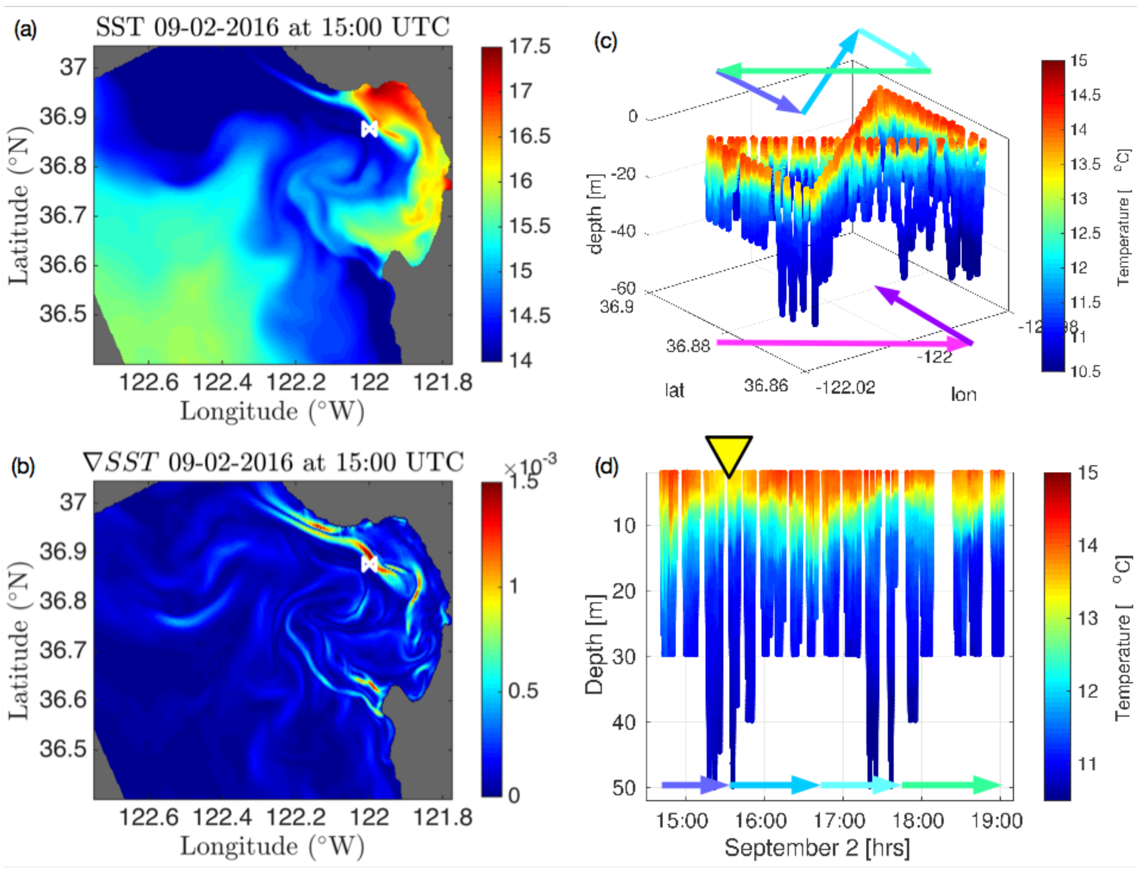

Figure 4. *(a) Sea surface temperature (°C) and (b) sea surface temperature gradient (°C m^{-1}) from the 300 m ROMS model output on 2 September 2016 at 1500 UTC. In each panel, the white butterfly pattern indicates the sampling position determined by the planner. (c) Temperature and position of two Iver vehicles (i107, upper arrows; i106, lower arrows) on 2 September 2016. (d) Temperature time series from Iver vehicle i107. The colored arrows correspond to the legs of the butterfly, as shown in panel (c). The position of the upwelling front is indicated by the yellow triangle.*

The frontal structure captured by the AUV resulted in a 1°C temperature anomaly over a distance of ~1 km. This is equivalent to a lateral buoyancy gradient of 10^{-5} s^{-2}, which is indicative of a strong submesoscale front. Although the front was not located at the center of the sampling array, the fidelity between the model output and the observations is remarkable. A limitation of this concept demonstration is the relatively short duration of the AUVs. This curtailed our ability to track the evolution of the front in time in order to determine both the fidelity of the numerical model over longer periods of time and the ability of the path planner to follow the movement of the front. In future iterations, a combination of model output and in situ observations will be used to update the sampling patterns (Figure 1).

In addition to the near real-time experiments carried out over the continental shelf, we also explored autonomous methods for detecting submesoscale fronts and optimizing sampling of these features without human intervention. Our targeted ``features'' for this activity are thermohaline structures, subducting from below the mixed layer into the deep ocean. A detailed description of the feature tracking activities is presented in (Flexas et al. 2017). Using the ROMS forecast, a series of simulated transects are determined along a track, nominally perpendicular to the continental slope (Figure \ref{fig:glider}a). For a given period, the simulated glider track can either continue straight or can be directed to “turn back” if a front is detected. Turning back on the front allows for multiple realizations of the high-gradient region over a short period of time. The track selected is the one that optimally crosses the strongest lateral gradients. This track is then autonomously delivered to the glider as a series of way points.

Based on model estimations, the sampling “gain”, defined as the amount of high-gradient region sampled, is 50% larger for gliders that are autonomous piloted by the feature-tracking planner, as compared to a sampling pattern that simply samples across the entire width of the continental slope.

2017 Field program, Monterey Bay, CA

Our year 2 field experiment has been scheduled for April 25-Mary 10, 2017 in Monterey Bay. This field work will be coordinated with the 2017 CANON (Controlled, Agile, and Novel Ocean Network) experiment with colleagues at the Monterey Bay Aquarium Research Institute (MBARI; http://www.mbari.org/science/upper-ocean-systems/canon/). CANON is an interdisciplinary effort that utilizes smart, autonomous devices designed to cooperate with each other to collect time-varying spatial observations of upwelling plumes, associated fronts, and chemical features.

Our collaboration this year with MBARI provides the additional benefit that they will be testing a suite of up to six Long-Range AUVs (LRAUVs). The target area, along the continental shelf break, strongly overlaps with the physical processes we seek to capture with our KISS field work. The field program has been divided into three stages that are described below.

Stage 1: Glider Mesoscale Survey

Purpose: Mesoscale survey; ROMS validation; Prioritize LRAUV deployment sites
Available assets: 3-5 ocean gliders
Sampling period: 1 April to 25 April

Three gliders will carry out parallel sections across the boundary between the offshore eddy and the upwelling front (marked by a strong SST gradient). Each leg will be ~50 km in length, separated by a distance of ~20 km. Up to 10 realizations of this region will be carried out during a four-week period. Comparisons will be made to the ROMS output. This data will be used to identify regions of enhanced submesoscale structure that will guide the deployment location of the LRAUV/hybrid glider array. Direction calculations of mesoscale potential vorticity, strain and divergence will be compared to summer-time values from 2016 field program.

Autonomy implementation: If an extra glider is available, we will use a combination of assimilated ROMS output and acquired glider data to estimate eddy edge; this requires a focused edge-detection glider.

Stage 2: Glider Submesoscale Survey

Purpose: Submesoscale survey of target region; ROMS validation; Baseline sampling of LRAUV deployment region.
Available assets: 4 ocean gliders + [Waveglider]
Sampling period: 25 to 30 April

Two nested crosses centered on a region of the mesoscale eddy with strong lateral gradients, based on the earlier mesoscale survey. A single longer track will be retained for mesoscale context. The inner sections will be 10-20 km. A Waveglider could be used to determine larger-scale surface gradients. This submesoscale survey will confirm planned deployment locations for the LRAUVs. The LRAUVs may participate in this survey. A similar submesoscale survey could be carried out further offshore later in the campaign (after the CANON experiment).

Autonomy implementation: Use additional assets (LRAUVs, gliders) to carry out a dynamic submesoscale sampling pattern; orientation and translation evolves with time to follow front.

Stage 3: Joint AUV-glider dynamic survey

Purpose: Nested sampling of submesoscale variability; High temporal resolution from LRAUVs; Attribution of subduction events; impact on export
Available assets: 4 gliders + 4 LRAUVs + [sediment trap float]
Sampling period: 1 May - 10 May

Gliders will resume static “mesoscale” array across the front. Three LRAUVs will fly in parallel within the mesoscale domain with an adaptive orientation. Deployment location will be based on *in situ* and ROMS output. An additional option is to have the LRAUV array track the movement of the sediment trap float, based on the ROMS circulation. During the ten day period, at least two different types of autonomous planning could be tested: (i) planning based on ROMS model alone; (ii) planning based on real-time, *in situ* observations.

Autonomy implementation: Access to near real-time re-planning based on asset data will permit re-planning within the ROMS cycle, e.g. every several hours as dictated by vehicle surfacing and data availability; process all data older than 15 minutes - 1h surfacing.

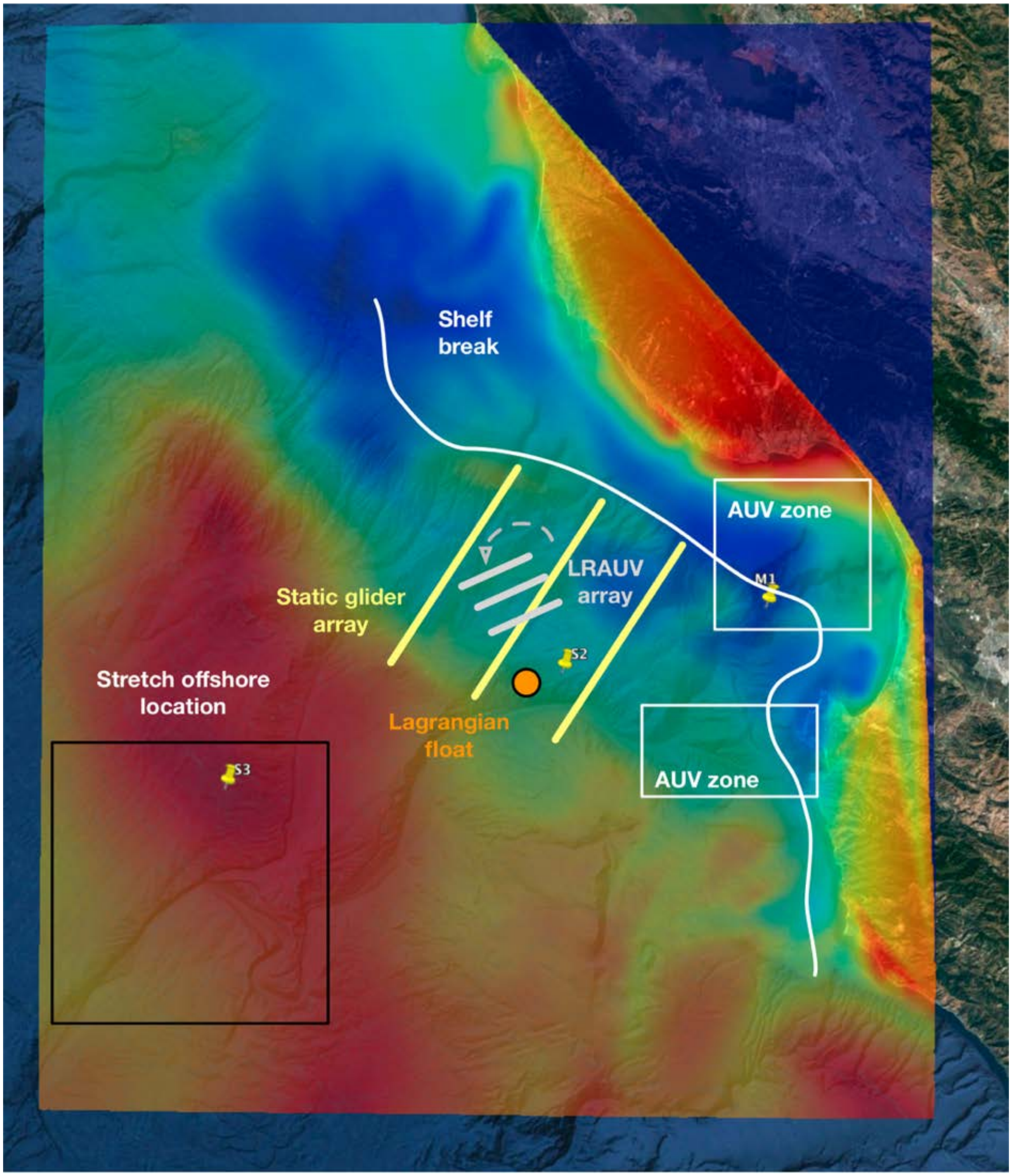

Figure 5. *Schematic of the 2017 KISS field program showing the combination of a fixed mesoscale glider array with a dynamic submesoscale-resolving array carried out with three LRAUVs flying in parallel. This work will complement activities focused on the continental shelf involving the Iver-class AUVs.*

Status of Collaborations (Campus/JPL/External)

The team is distributed across four institutions: Caltech, JPL, WHOI and RSS. Throughout the summer of 2016, in preparation for the 2016 field experiment, and since Decmeber of 2016, in preparation for the 2017 field experiment, our group has met every week. We meet at the Tolman/Bacher House on the Caltech campus with RSS, JPL and Caltech members of the team attending in person; team members from WHOI participate through WebEx. We held a face-to-face meeting at the 2016 AGU meeting in San Francisco. Project co-I's Thompson, Chao and Chien have also made multiple visits to MBARI to meet with project collaborators Francisco Chavez, Brett Hobson and Yanwu Zhang. Caltech senior researcher, Mar Flexas, spends time both on campus and on lab, allowing her to work closely with project members in both locations.

To respond to the unique challenges of project management of such a distributed team, we have appointed Dr. Yi Chao (an external Co-I) as the Project Manager (PM) who will serve as a single point of contact for all project management related activities.

We have implemented the following measures to ensure efficient communication and information sharing amongst team members:

- *Project mailing list.* A project wide mailing list kiss_ocean@googlegroups.com) has been setup, so that everyone involved in the project can be properly informed. All the emails to this project mailing list are archived at a web site with sorting capabilities.
- *Project meeting.* A regular project meeting has been held on a weekly basis. The local investigators from the campus, JPL and RSS will meet at KISS while other investigators will join by a dedicated telephone (United States +1 (626) 521-0013; Access Code: 808-247-733) and web (https://global.gotomeeting.com/join/808247733) access using the reliable Gotomeeting tool.
- *Project task list.* A master project task list with associated schedule, deliverable and receivable has been established on Google Doc (https://docs.google.com/spreadsheets/d/1t3MS2SF_l6TrvKNBEutyvSLiTE__M0VkEtHvO2jhZn4/edit#gid=294007075) where everyone involved in the project can add new tasks and make regular update of the task progress.
- *Large file sharing.* For large data file (including model output) sharing within the project, we have established a secured (with user name and password protection) FTP server (sftp -oPort=19 kiss@west.rssoffice.com).
- *Small file sharing.* For small data sharing (e.g., images, movies, WORD document, PPT presentations), we have established a Dropbox directory (https://www.dropbox.com/home/KissTechnicalDevelopment) with multiple sub-directories.

Papers / Technical Reports to date

Published

- Troesch, M., S. Chien, Y. Chao and J. Farrara. Planning and control of marine floats in the presence of dynamic, uncertain currents, Proc Intl Conference on Automated Planning and Scheduling, London, UK, June 2016.
- M. Troesch, S. Chien, Y. Chao and J. Farrara. Evaluating the Impact of Model Accuracy in Batch and Continuous Planning for control of marine floats, Planning and Robotics Workshop, Intl Conference on Automated Planning and Scheduling, London, UK, June 2016.
- A. Branch, M. Troesch, S. Chien, Y. Chao, J. Farrara, A. Thompson. Evaluating Scientific Coverage Strategies for a Heterogeneous Fleet of Marine Assets Using a Predictive Model of Ocean Currents, Workshop on Scheduling and Planning Applications, Intl Conference on Automated Planning and Scheduling, London, UK, June 2016.
- A. Branch, M. Troesch, S. Chu, S. Chien, Y. Chao, J. Farrara, A. Thompson, J. Kinsey, D. Fratantoni, Closed Loop Detection, tracking, and observation of Oceanographic Phenomena in Dynamic, Uncertain Currents, Software Demonstration Track, International Conference on Automated Planning and Scheduling, London, UK, June 2016.

Under review / In preparation

- Thompson, A.F., Y. Chao, S. Chien, J. Kinsey, M.M. Flexas, J. Farrara, D. Fratantoni, A. Branch, S. Chu, M. Troesch, B. Claus, J. Kepper, 2017. Satellites to Seafloor: Towards fully autonomous ocean sampling. *Oceanography*, **submitted** and under consideration for special issue on Autonomous and Lagrangian Platforms and Sensors (ALPS).
- Chao, Y., and coauthors, 2017. Development, implementation and validation of a California coastal ocean modeling, data assimilating and forecasting system. *Deep Sea Res.* II*,* **submitted.**
- Flexas, M.M., M.I. Troesch, S. Chu, A. Branch, S. Chien, A.F. Thompson, J.D. Farrara, Y. Chao, 2017. Autonomous sampling of ocean submesoscale fronts with ocean gliders and numerical forecasting. *Journal of Atmospheric and Oceanic Technology*, **submitted**.
- B. Claus, J. Kepper, S. Suman, and J. Kinsey. Closed Loop One-Way-Travel-Time Navigation using Low-Grade Odometry for Autonomous Underwater Vehicles. *Journal of Field Robotics,* **submitted**, under review.
- M. Troesch, S. Chien, Y. Chao, J. Ferrara, J. Girton, J. Dunlap, Autonomous Control of Marine Floats in the Presence of Dynamic, Uncertain Ocean Currents, *Journal of Atmospheric and Ocean Technology*, **submitted,** under review.
- J. Kepper, B. Claus, and J. Kinsey. MEMS IMU and One-Way-Travel-Time Navigation for Autonomous Underwater Vehicles. *In Proceedings of the 2017 IEEE Oceans Meeting.* **Accepted**, to appear.
- A. Branch, M. Troesch, M. Flexas, A. Thompson, J. Ferrara, Y. Chao, S. Chien, "Predictive control for glider station keeping," AI in the Oceans and Space Workshop, International Joint Conference on Artificial Intelligence, Melbourne, Australia, August 2017. **In preparation.**

Presentations / Conferences to date

- Troesch, M., S. Chien, Y. Chao and J. Farrara. Planning and control of marine floats in the presence of dynamic, uncertain currents, Proc Intl Conference on Automated Planning and Scheduling, London, UK, June 2016.
- M. Troesch, S. Chien, Y. Chao and J. Farrara. Evaluating the Impact of Model Accuracy in Batch and Continuous Planning for control of marine floats, Planning and Robotics Workshop, Intl Conference on Automated Planning and Scheduling, London, UK, June 2016.
- A. Branch, M. Troesch, S. Chien, Y. Chao, J. Farrara, A. Thompson. Evaluating Scientific Coverage Strategies for a Heterogeneous Fleet of Marine Assets Using a Predictive Model of Ocean Currents, Workshop on Scheduling and Planning Applications, Intl Conference on Automated Planning and Scheduling, London, UK, June 2016.
- A. Branch, M. Troesch, S. Chu, S. Chien, Y. Chao, J. Farrara, A. Thompson, J. Kinsey, D. Fratantoni, Closed Loop Detection, tracking, and observation of Oceanographic Phenomena in Dynamic, Uncertain Currents, Software Demonstration Track, International Conference on Automated Planning and Scheduling, London, UK, June 2016.
- J. Kepper, B. Claus, and J. Kinsey. Satellites to the Seafloor: Ocean Observation using Multiple Heterogeneous UUVs. *2017 Naval Oceanographic Office Operators Meeting*
- J. Kinsey. Tapping the Unexplored at Home: Space Parallels. *2017 MIT New Space Age Conference*
- Steve Chien, Harvey Mudd College. “From Monterey Bay to Autonomous Marine Vehicles to explore the Earth’s Oceans and search for life on other planets and moons.” Jan. 25, 2017.

Undergraduate students, graduate students and postdocs who have worked on the project

- Zachary Erickson (Caltech Graduate Student)
- Brian Claus (WHOI Postdoc)
- James Kepper (WHOI Masters Student)