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TOWARDS FULLY AUTONOMOUS OCEAN OBSERVING: COUPLING HETEROGENEOUS ROBOTIC ARRAYS WITH DATA-ASSIMILATING MODELS AND AUTONOMOUS PATH PLANNING

KISS: Satellites to Seafloor

In 2013–2014, the Keck Institute for Space Studies (KISS) conducted a six-month study to investigate the premise that

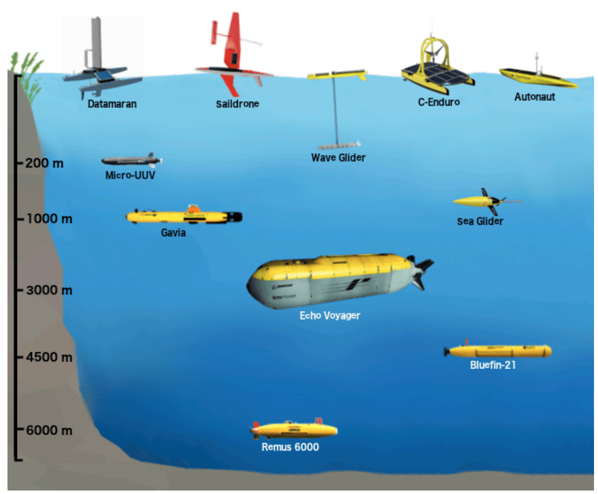
autonomous, coordinated groups of ocean robots *could significantly advance our ability to obtain ocean* ***observations needed to constrain the marine carbon cycle****.*

The key conclusion was a need to:

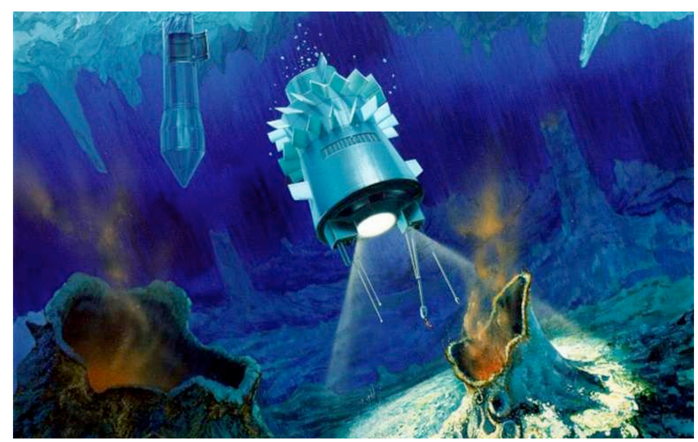
Develop techniques that allow heterogeneous groups of robots to autonomously update ocean sampling strategies with the help of numerical ocean forecasts and remotely sensed observations

Oceanographic programs that involve the deployment of large number of vehicles are becoming more common.

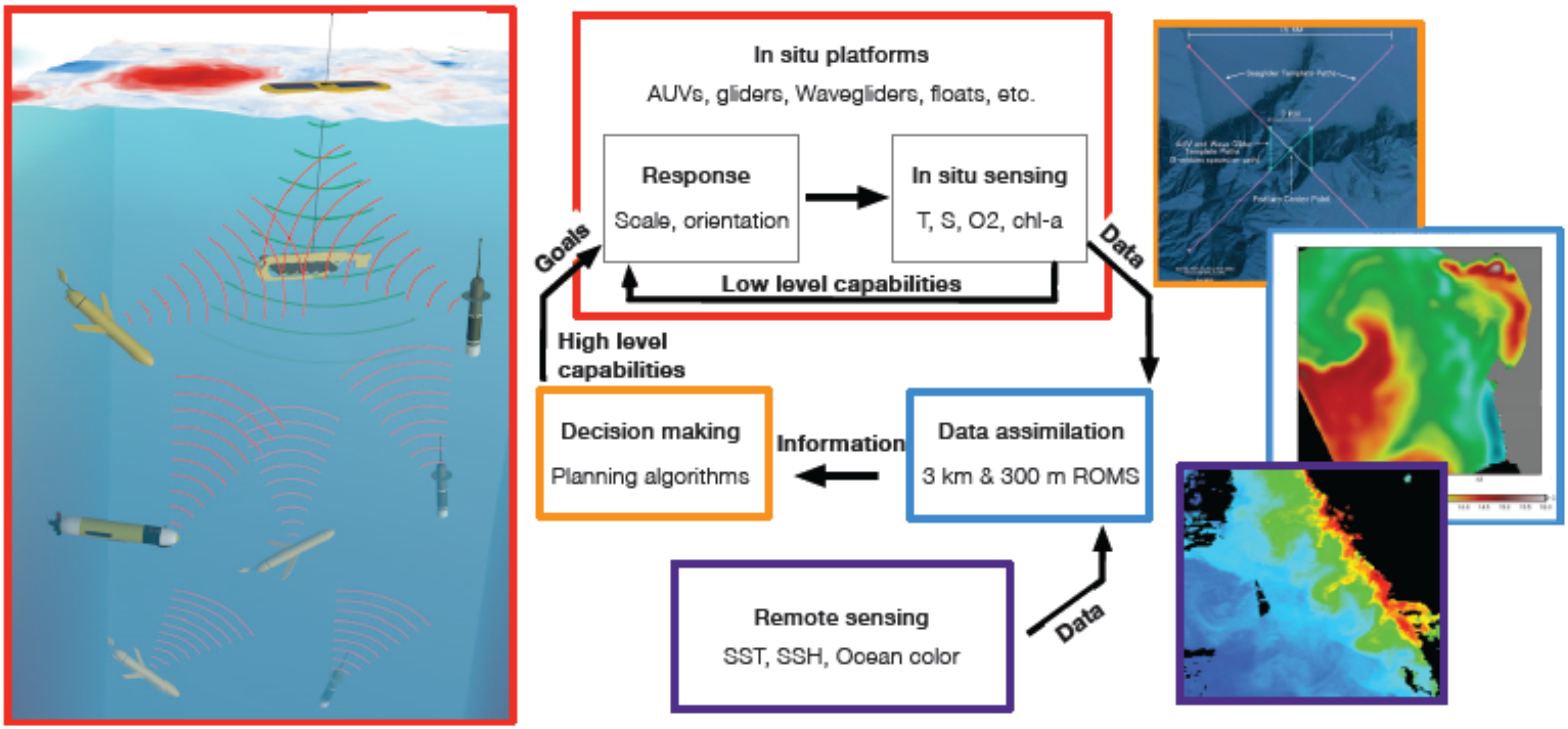
Coincident measurements about physical, chemical, and biological variables requires sensors that not typically on a single platform.



Future exploration of extreme environments (Ocean Worlds) needs to be achieved with minimal communications.



CLOSED-LOOP AUTONOMY CONCEPT



Thompson et al. 2015, 2017

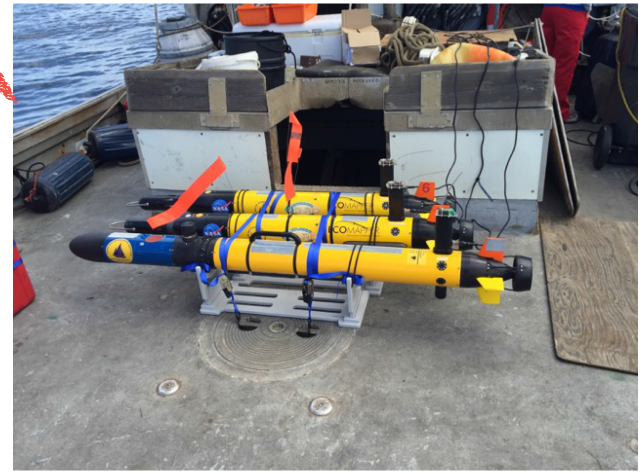
- Previous works on adaptive sampling: Autonomous Ocean Sampling Network (Curtin et al., 1993)
- Main contribution: Inclusion of autonomous analysis of ocean model forecast in the decision making.
- Goal of KISS project: **Closed-loop autonomy tested in the field**.

I-OBSERVING PLATFORMS

FINER RESOLUTION

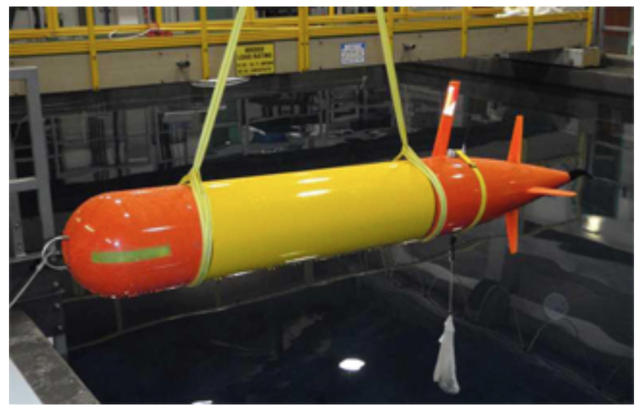
- Multiple vehicles –in number and type
- Different capabilities, complementing each other
- Complementing other data from remote sensing

LONGER AUTONOMY



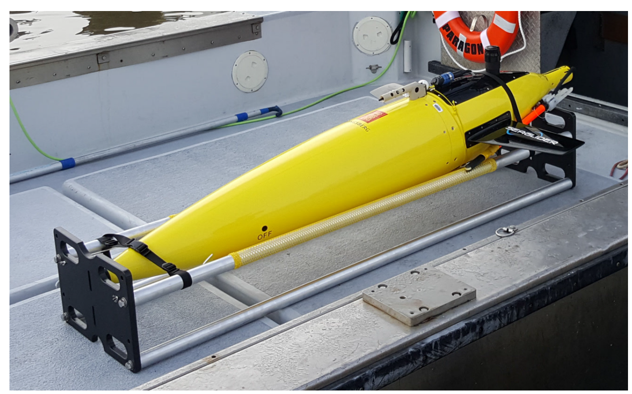
IVER type AUV

- Autonomy ~O(day)
- Max. depth ~ 10s m
- Hztal. resol. ~ O(m)



Tethys-class LRAUV

- Autonomy ~O(weeks)
- Max. depth ~ 100 m
- Hztal. resol. ~ 100s m

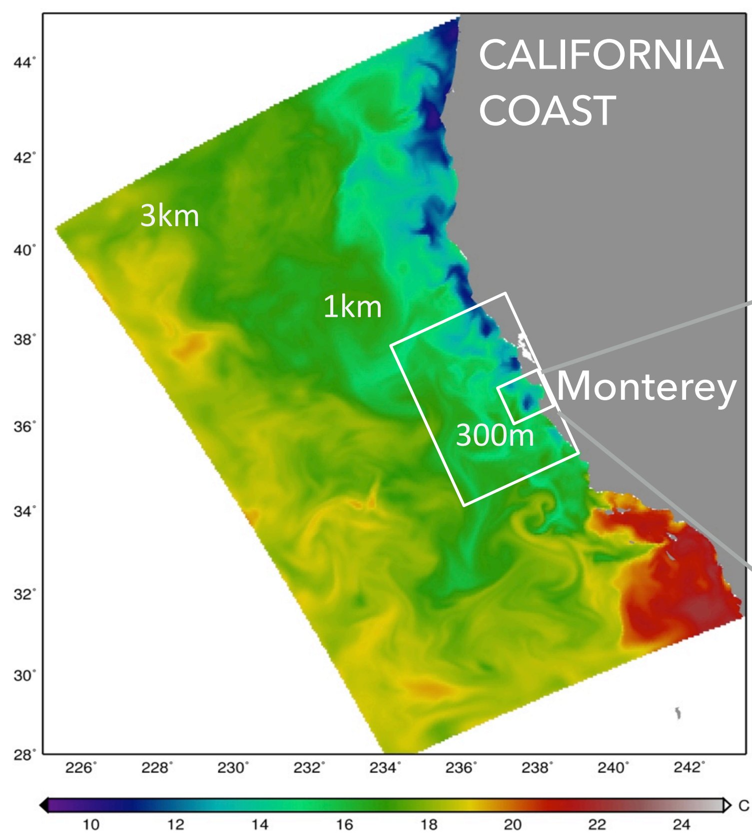


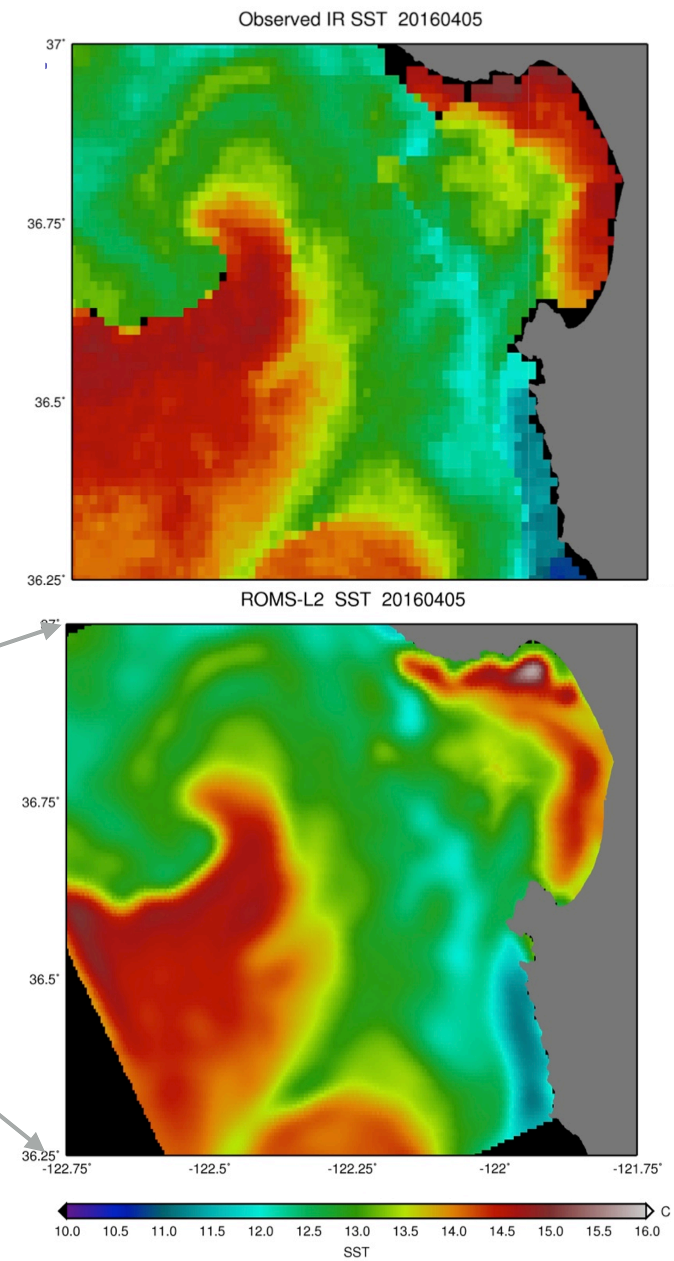
Kongsberg Seaglider

- Autonomy ~months
- Max. depth ~ 1000m
- Hztal. resol. ~ O(km)

II-FORECAST MODEL

- Regional Ocean Modeling System (ROMS), near real-time data-assimilation of satellite and in situ data
- Run every 6-h in nowcast and daily in forecast mode, with hourly output
- ROMS 300m output reproduces fine-scale structures

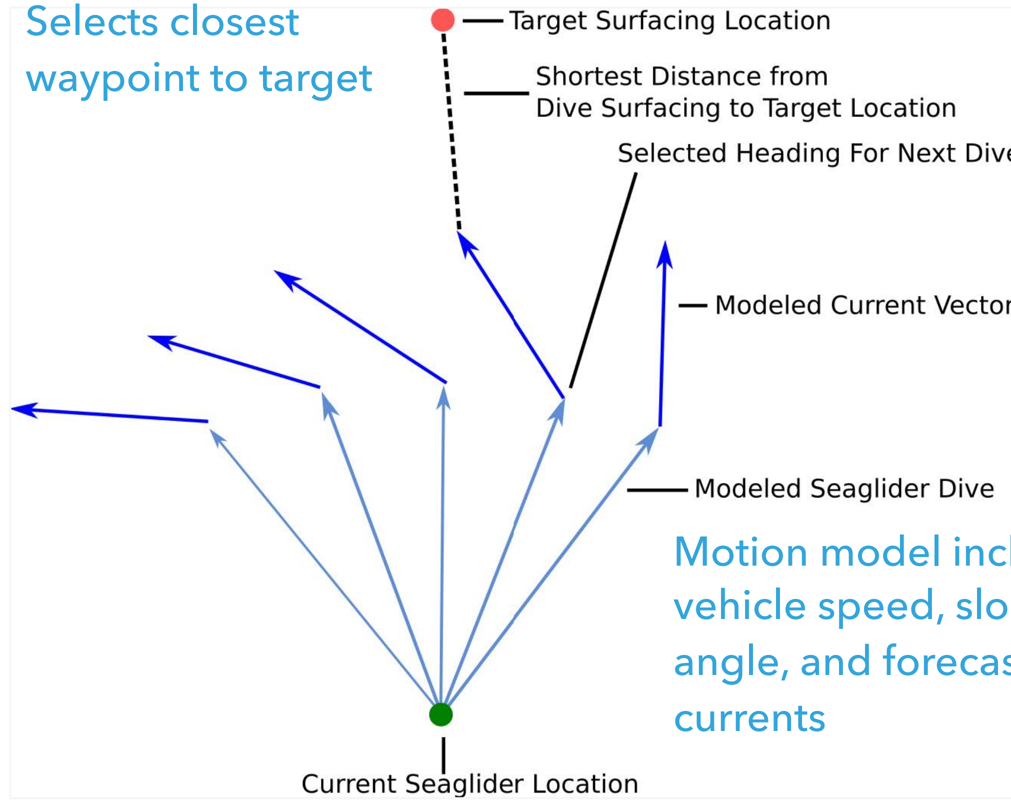




III-NAVIGATION PLANNER

- Allows to command vehicles without human intervention (no pilots required)
- Uses a motion model to optimize waypoints
- Sends waypoints to the glider control software

Selects closest waypoint to target



Motion model includes vehicle speed, slope angle, and forecasted currents

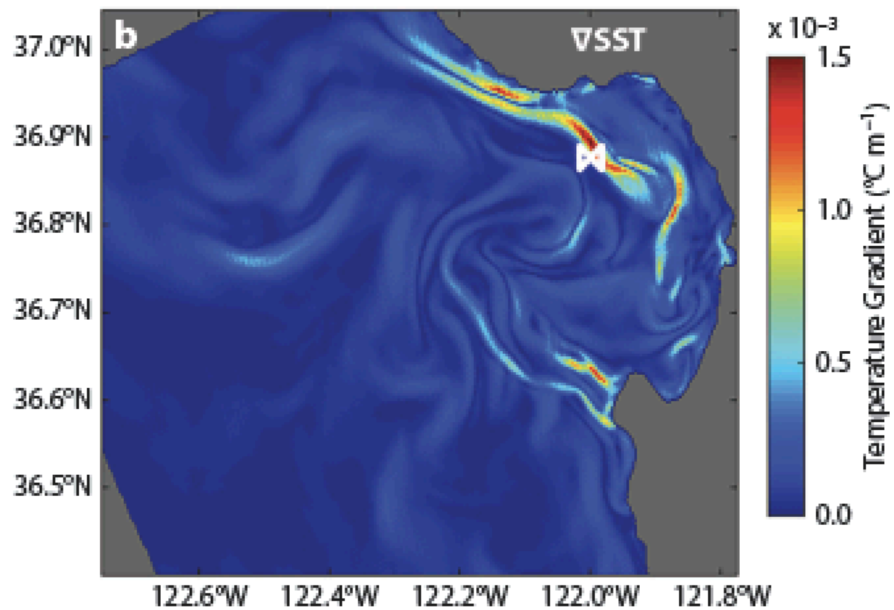
Motion model simulates different options/paths to reach the target

Branch et al., 2016; Clark et al., submitted

IV–FEATURE DETECTION PLANNER

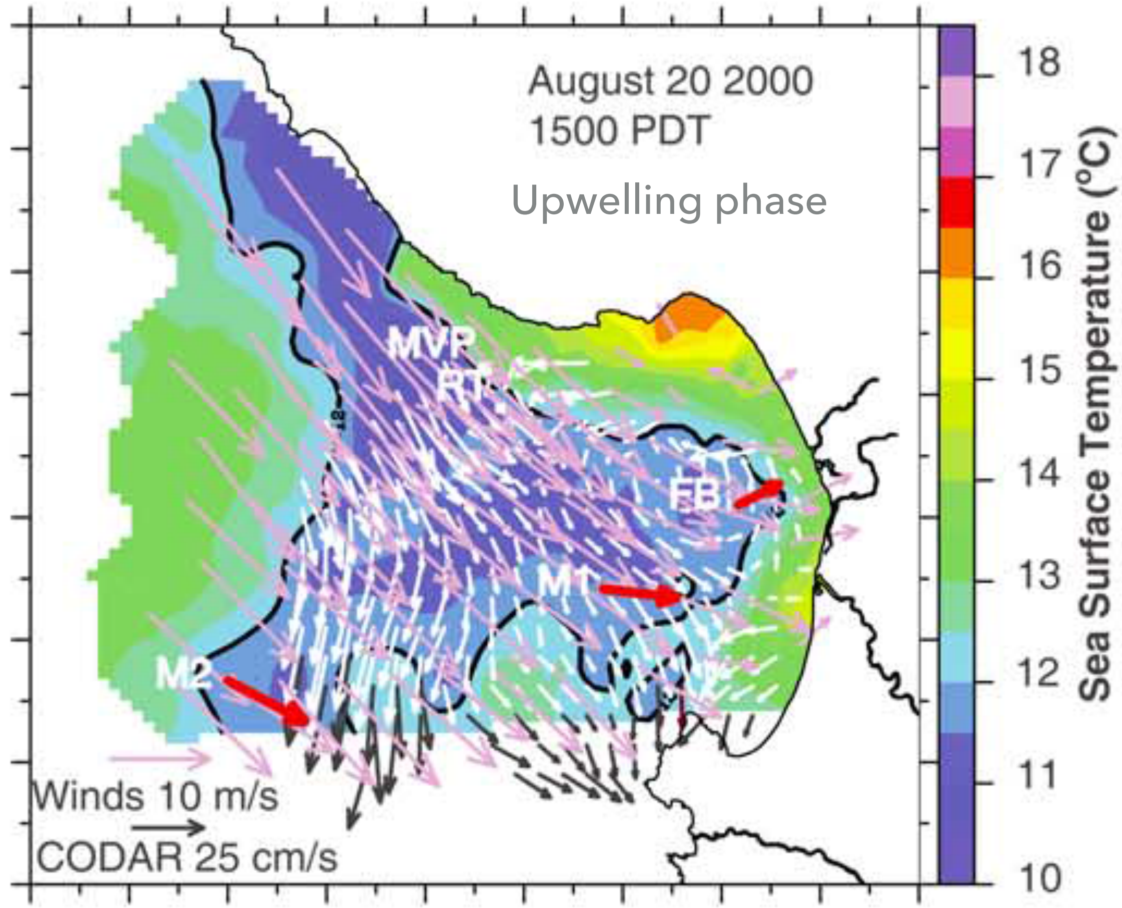
- Takes human ``out of the loop" by autonomously choosing most interesting sampling regions
- Analyzes existing data fields (ROMS and in situ) to select areas of interest
  - User-defined features: E.g., Lateral gradients of density, temperature, spiciness… (we'll see several examples)
- **Collected data sent back into the model, "closing the loop"**

ROMS 300m forecast



TWO FIELD TESTS IN MONTEREY BAY: SCIENCE MOTIVATION

- Rapid ocean response to wind events
- Evolution of fronts
  - Vertical structures
  - Submesoscales
- Active collaboration with MBARI
- Two field experiments: 2016 and 2017

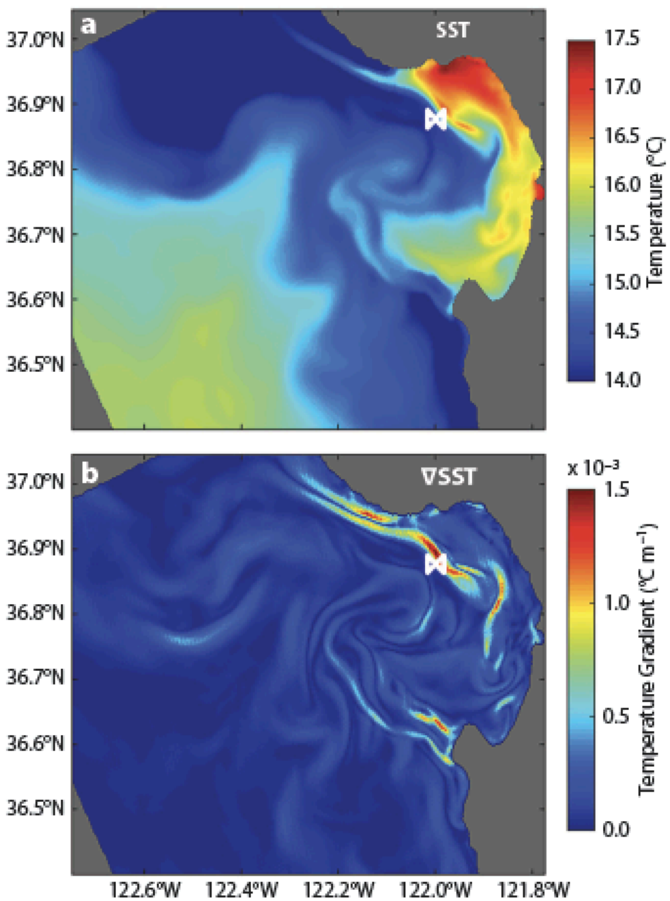


Steven Ramp et al. 2005

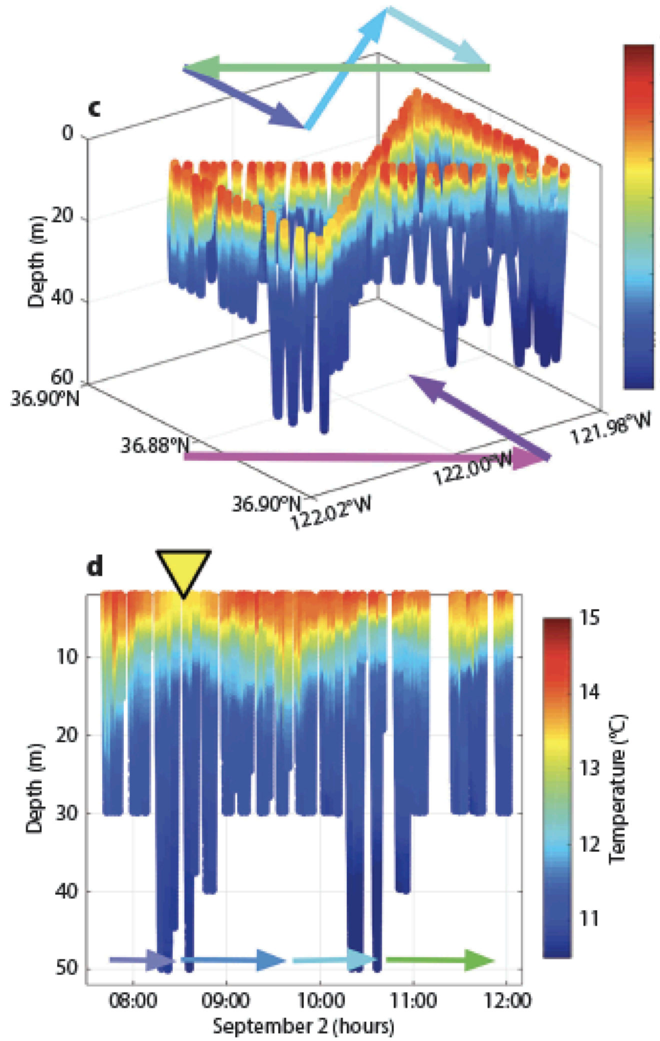
KISS 2016 EXPERIMENT

- 3 IVERS, 1 Seaglider
- 1 week, August 2016

Used SST fields from model forecast to autonomously detect gradients (FD planner)



IVER in situ data to test model



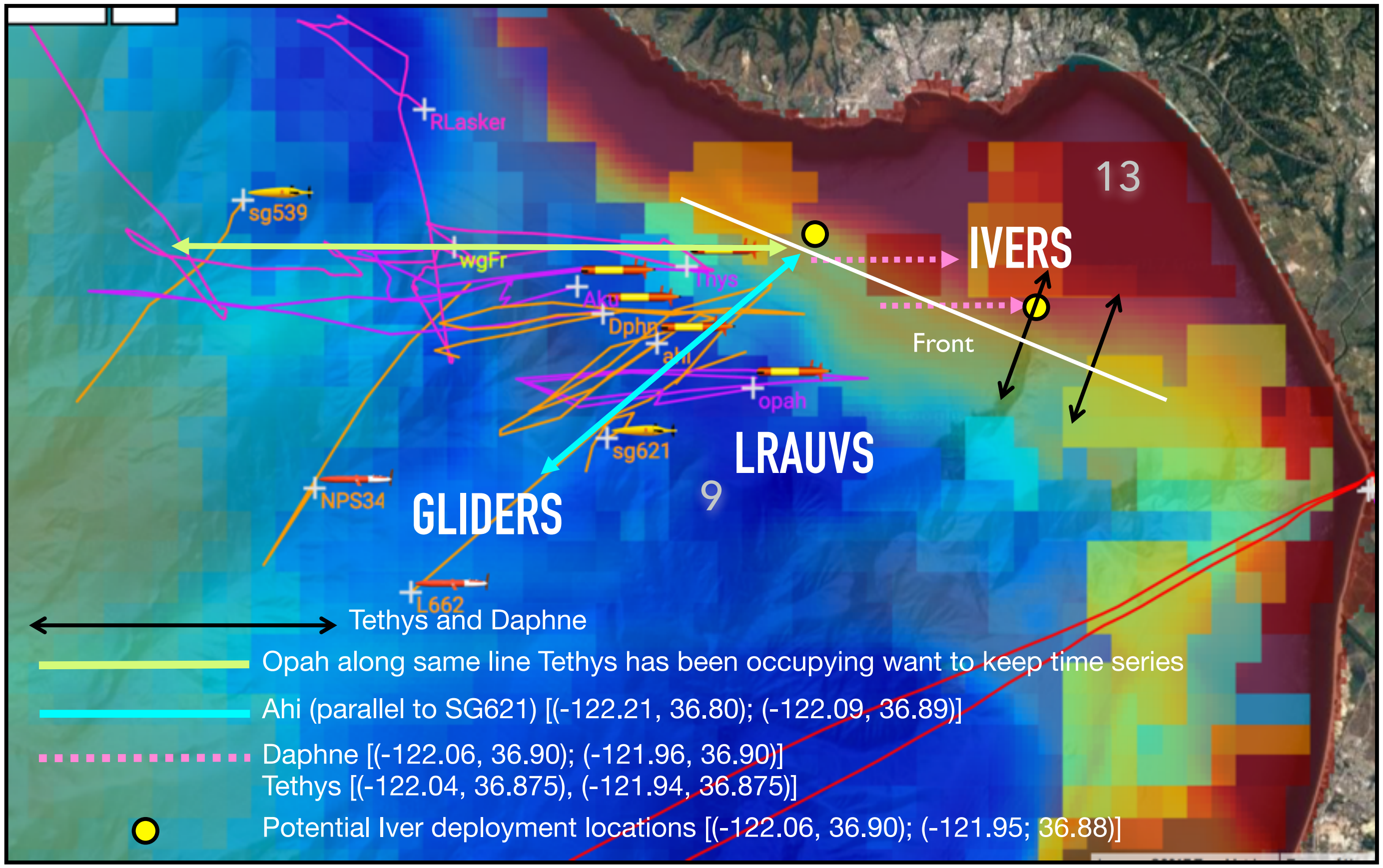
- Timeframe (Daily)
  - 0500 Model forecasts
  - 05:30 Run feature detection analysis
  - 0600 Boat departure
  - 0630 IVERs in water
  - Data analysis to compare model forecast/real data

Achievements:

- Forecast model output was successfully tested
- Sampled the rapid evolution of fine-scale structures (observed changes within hours)

KISS-CANON (MBARI) 2017 EXPERIMENT

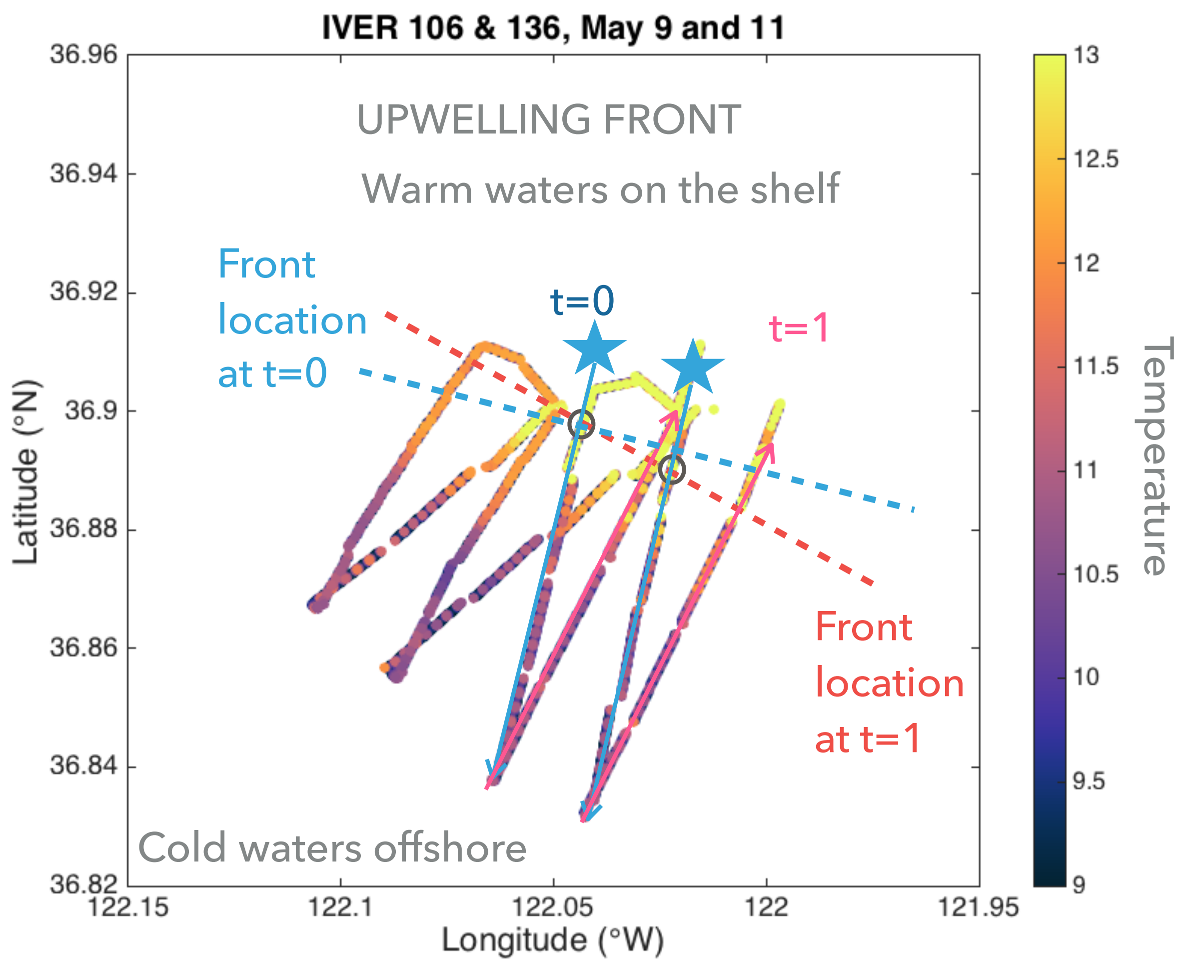
- Vehicles:
  - 2 IVERs on the shelf
  - 5 LRAUVs over the upper slope
  - 2 Seagliders over the lower slope
- Considering vehicle capabilities for an optimal sampling of the upwelling system
- 0300 Daily model forecasts available



FEATURE DETECTION PLANNER (II)

- IVERs: Started every morning with the analysis of SST fields from model forecast to detect surface gradients (as in 2016)
- **Main goal: Reorient the sampling array in real time**
- Real-time feature detection based on lateral gradients (T, density)
- Real-time retasking vehicles after the front was found
- Vehicle reorientation: Fitting line along frontal detection points, and re-direct assets perpendicular to that line
- Achievement: No human intervention required to reorient the vehicles

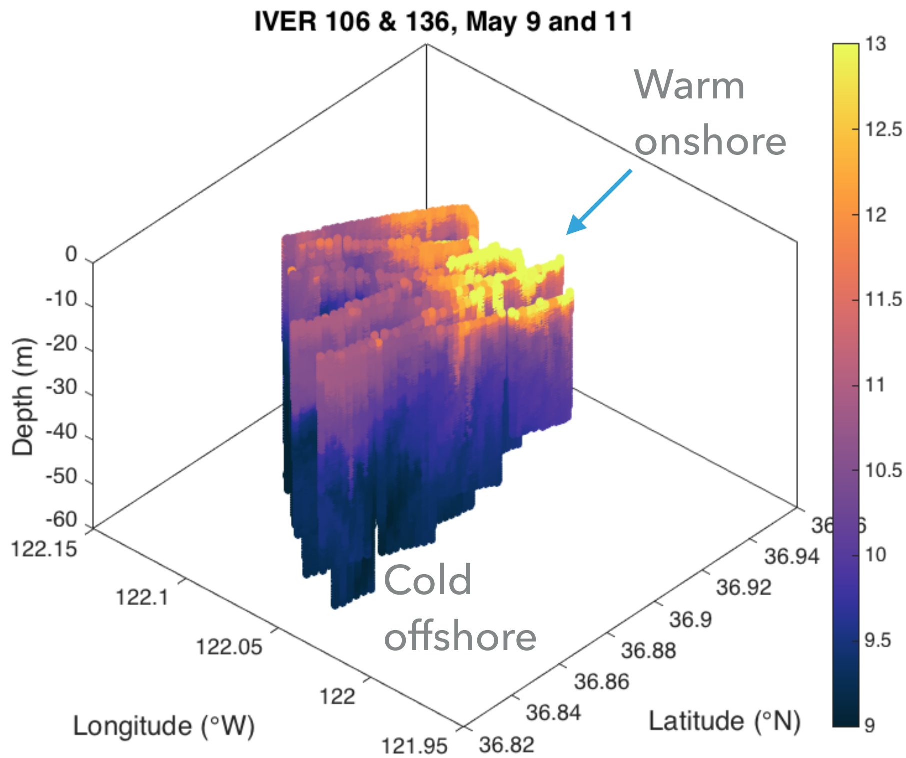
MAP VIEW OF IVER DATA



Branch et al. submitted

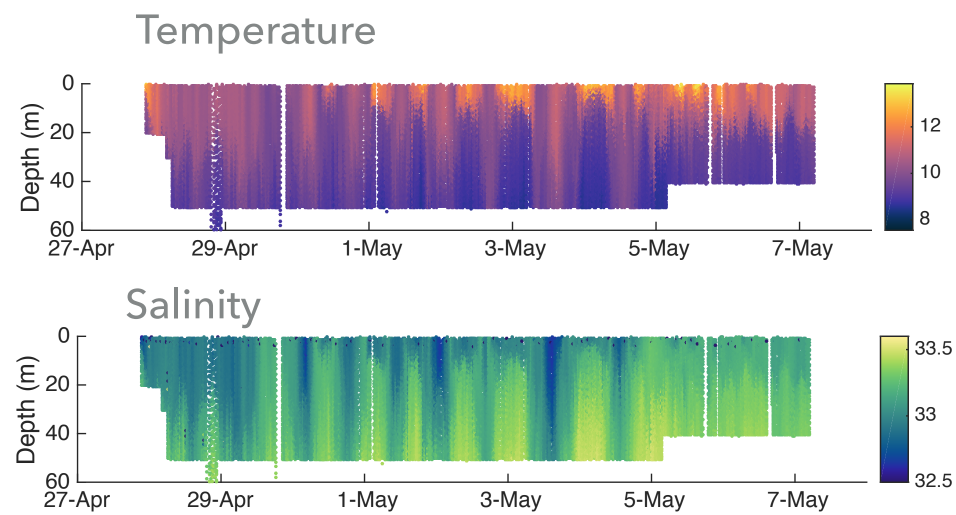
INSHORE DATA: IVERS

- Three days of retasking
- Rapid evolution of shallow frontal structures on the shelf



UPPER FRONT EVOLUTION: LRAUVS

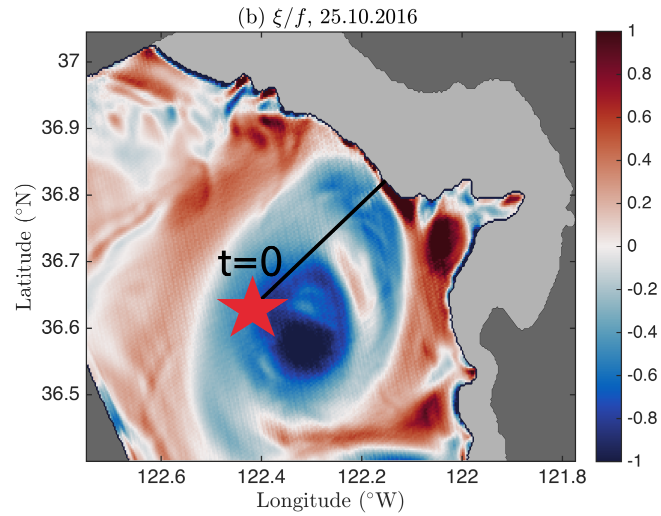
- Similar protocol over the slope shows onshore/offshore migration of the front

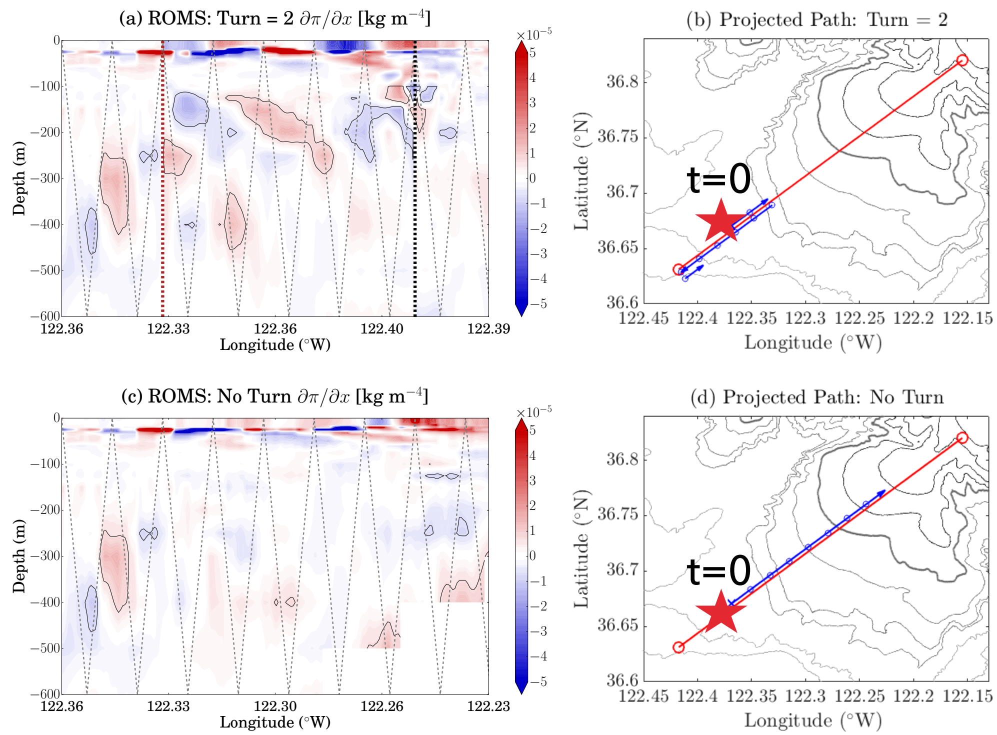


- Achievements of the 2017 field experiment:
  - Autonomous re-tasking, re-orienting the assets' cross-frontal sampling
  - Observed the evolution of the upwelling using three types of platforms

FEATURE DETECTION PLANNER (III)

- Deep-ocean, implementation in 2016
- Goal: Maximize number of sampled ``features" –defined as lateral gradients of spiciness (density) – according to model forecast
- Using a transect ``template" the FD planner would simulate multiple path options (``turn-around options")
- Each option would be analyzed and quantified as bulk transect ``scores" > FD planner would select the best sampling choice for that day
- Repeated daily, for 7 days (model output available at 0500).
- Achievement: Feature detection planner successfully oriented the glider towards regions with largest number of features





Flexas et al. 2018

SUMMARY

- KISS ``closed-loop” concept tested in the field
- Multiplatform approach (IVER, LRAUV, gliders)
- Without anyone directing the vehicles, the planners managed to re-task and re-orient the vehicles, adjusting sampling patterns in real-time based on autonomous decision making
- Assimilation of in situ data improved model forecast and sent the instruments to more interesting places
- There is a number of **potential future applications** for autonomous ocean sampling:
  - Large-scale autonomous field programs, e.g. **SWOT CalVal experiment**
  - **Under-ice exploration**

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