Untangling a Web of Interactions Where Surf Meets Coastal Ocean

In 2017, an ocean research team launched an unprecedented effort to understand what drives ocean currents in the overlap regions between surf zones and continental shelves.

Point Sal protrudes from the California coastline in this aerial view of the study site for the 2017 Inner Shelf Dynamics Experiment. A wide variety of instruments, situated aboard ships, boats, and satellites and deployed in the ocean and on land, collected massive amounts of data on the characteristics and movements of ocean water in this region where sea and shore interact. Credit: Gordon Farquharson

By James Lerczak, John A. Barth, Sean Celona, Chris Chickadel, John Colosi, Falk Feddersen, Merrick Haller, Sean Haney, Luc Lenain, Jennifer MacKinnon, James MacMahan, Ken Melville, Annika O'Dea, Pieter Smit, Amy Waterhouse, and TongTong Xu 2 May 2019

Winds and waves drive the coastal ocean's waters to flow and mix. So do differences in temperature, salinity, the topography of the seafloor, and a host of other factors. All these factors overlap and interact in complex patterns that influence where ocean creatures make their homes and where waterborne materials, both natural and human made, are dispersed along our coasts. The coastal physical oceanography community has made great strides in understanding the dynamics that drive water motions and density distributions in the coastal ocean. They have also worked to demonstrate the importance of these dynamics to coastal communities and ecosystems.

In the inner shelf region, where the continental shelf and shore regions overlap and their processes interact, challenges to our understanding persist.

Over the past several decades, oceanographers have undertaken large field experiments to quantify coastal dynamics and their impacts. Often, these studies have been partitioned into specific regions of the coastal ocean and focused on specific processes: wind effects over the continental shelf or wave effects close to shore, for example. However, in the inner shelf region, where the continental shelf and shore regions overlap and their processes interact, challenges to our understanding persist [*Lentz and Fewings (https://doi.org/10.1146/annurev-marine-120709-142745)*, 2012].

In the summer and fall of 2017, a group of researchers sponsored by the U.S. Office of Naval Research (ONR) undertook an unprecedented seagoing and numerical ocean modeling experiment. The Inner Shelf Dynamics Experiment investigated the nonlinear, interacting processes that drive currents and transport in this important coastal region.

Studying Sea and Shore and Where They Overlap

The Coastal Ocean Dynamics Experiment (CODE (https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1029/JC092iC02p01455)) of the early 1980s was a major collaborative effort to explore wind-driven circulation on the continental shelf in northern California [*Beardsley and Lentz (https://doi.org/10.1029/JC092iC02p01455)*, 1987]. These experiments produced a data set unprecedented for its time, and they inspired and motivated many field and numerical experiments on stratified wind-driven flows over midcontinental shelves (water depths around

50–100 meters).

Closer to shore, wave dynamics and wave-driven transport have been studied in great detail by the nearshore science community. In particular, a suite of experiments (http://www.frf.usace.army.mil/duck94/DUCK94.stm), including Duck94 and SandyDuck, at the U.S. Army Corps of Engineers Field Research Facility in Duck, N.C., was seminal in expanding knowledge of surf zone dynamics [e.g., *Long and Sallenger (https://doi.org/10.1029/95EO00315)*, 1995].

The less explored inner shelf, with typical water depths ranging from 5 to 50 meters, is the region where the surf zone (https://eos.org/research-spotlights/wave-energy-affects-surf-zone-heat-budget) meets and interacts with the coastal ocean. Within the surf zone, breaking waves dominate the dynamics and can drive large wave-averaged flows, such as rip currents. On the density-stratified continental shelf, several mechanisms compete to drive currents, including wind forcing, bathymetric influences, tides, submesoscale eddies, and shoaling and breaking nonlinear internal bores (https://eos.org/research-spotlights/nearshore-internal-bores-increase-hypoxia-risk) and waves.

At the inner shelf, the dynamics that typify both the nearshore and continental shelf are in play. These overlapping dynamics lead to highly nonlinear, interacting processes that regulate the alongshore and across-shore transport of water, water properties (e.g., temperature), and waterborne materials (e.g., sediment, dissolved gases, plankton, and contaminants). These inner shelf processes vary over a wide range of spatial and temporal scales, and their interactions are poorly understood. In addition, interactions between currents and variable coastal bathymetric features (e.g., headlands) enhance the complexity of transport.

The Inner Shelf Dynamics Experiment aims to understand the interacting nonlinear dynamics of the inner shelf and identify and quantify the processes that drive the exchange of water properties and waterborne materials across this region over a range of temporal and spatial scales.

This ONR Departmental Research Initiative is centered around an extensive, multi-institutional field experiment coordinated with numerical modeling efforts to study a 50-kilometer stretch of the central California coast that straddles Point Sal and includes the region offshore of Vandenberg Air Force Base (Figure 1).

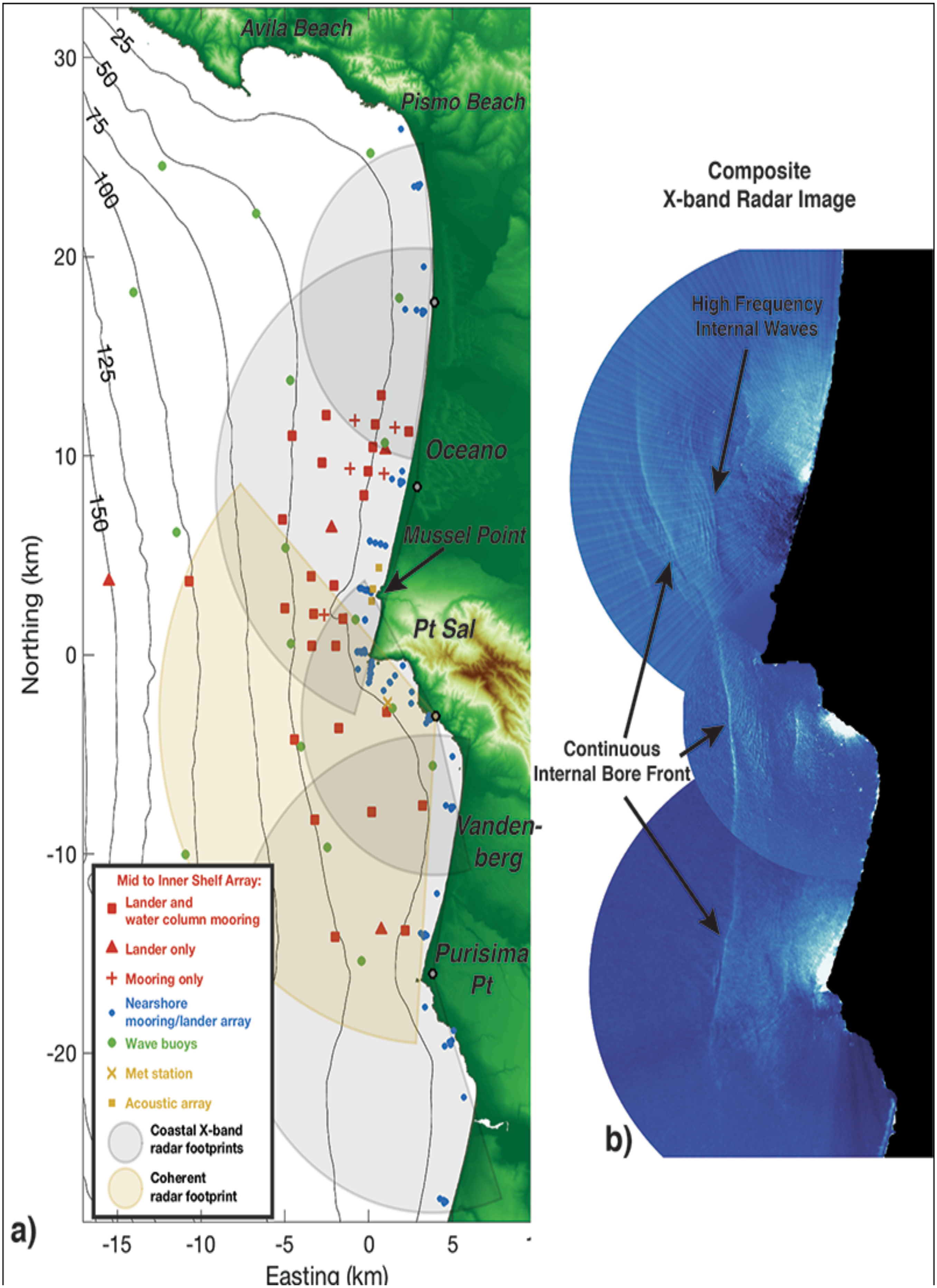
Avila Beach
Pismo Beach
Oceano
Mussel Point
Pt Sal
Vanden-berg
Purisima Pt
25
50
75
100
125
150
30
20
10
0
-10
-20
Northing (km)
-15
-10
-5
0
5
Easting (km)
a)
Mid to Inner Shelf Array:
Lander and water column mooring
Lander only
Mooring only
Nearshore mooring/lander array
Wave buoys
Met station
Acoustic array
Coastal X-band radar footprints
Coherent radar footprint
Composite X-band Radar Image
High Frequency Internal Waves
Continuous Internal Bore Front
b)

Fig. 1. (a) Map of the Inner Shelf Dynamics Experiment study site, showing locations of moorings and bottom landers and measurement footprints of coastal X band and coherent radar systems. Contour lines represent water depth in meters. (b) Composite image of X band radar ocean surface measurements (time averaged to remove surface gravity waves) showing surface signatures of inner shelf processes, including coherent internal bore fronts and high-frequency internal waves. Credit: (a) Jim Lerczak; (b) Sean Celona

Our overarching goals are the following:

improving our understanding of inner shelf hydrodynamics
developing and improving the predictive capability of a range of numerical models to simulate the three-dimensional circulation, density, and surface wave field across the inner shelf
coupling a suite of remote sensing platforms with in situ measurement arrays to produce a synoptic description of inner shelf processes across the study region

Sensors at Sea and in the Sky

During the field component of the experiment, which took place from late August to November 2017, we obtained a diverse and unprecedented suite of in situ and remote sensing measurements.

Moorings and Landers. We installed a broad array of 176 mooring and bottom lander (https://www.usgs.gov/media/images/oceanographic-equipment-deployment) platforms to make in situ time series measurements that spanned the continental shelf to the nearshore in water depths ranging from 150 to 6 meters (Figures 1a and 2). These measurements included temperature, salinity, velocity, surface wave, turbulence, and meteorological measurements. The array focused on three regions with different bathymetric features: a region with a fairly straight, planar beach (Oceano); a coastal headland (Point Sal); and a region between two coastal capes (Vandenberg).

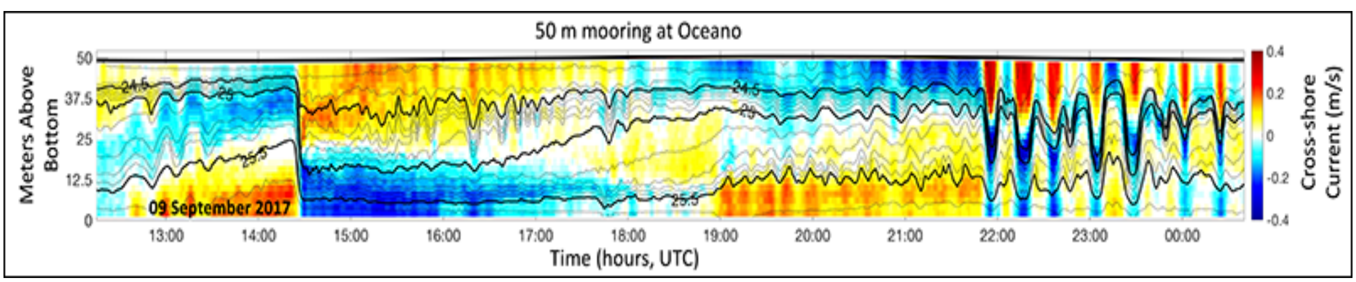

Fig. 2. Twelve-hour time series of density anomaly (observed density minus 1,000 kilograms per cubic meter; contoured) and cross-shore current (color shaded) as a function of depth from

the mooring-lander pair at a water depth of 50 meters at the Oceano array. A sharp internal bore front arrives at this location at 14:30 Coordinated Universal Time (UTC). A packet of high-frequency internal waves arrives at 22:00 UTC. Credit: Jim Lerczak

Shipboard Surveys. We conducted coordinated shipboard surveys during three intensive operation periods. We used three ships: R/Vs *Sally Ride*, *Oceanus*, and *R. G. Sproul* (the *Sproul* was funded with University of California Ship Funds). We also used four boats: R/Vs *Kalipi*, *Sally Ann*, *Sounder*, and *Sand Crab*.

Rapid profiling with a conductivity, temperature, depth (CTD) package across an internal bore front (long foam line) near the Oceano array on the small boat R/V *Kalipi* (Oregon State University). Credit: Jim Lerczak

Instruments deployed from the vessels included acoustic Doppler current profilers (https://www.whoi.edu/page.do?pid=8415&tid=282&cid=819) (ADCPs (https://eos.org/research-spotlights/how-do-deep-sea-gravity-currents-transport-sediment-so-far)); profiling conductivity, temperature, depth (CTD (https://oceanexplorer.noaa.gov/facts/ctd.html)) packages; towed undulating vehicles; echo sounders; and a profiling turbulence sensor package. We deployed a bow chain to obtain highly spatially resolved temperature, salinity, and turbulence measurements in the upper 20 meters of the water column (Figures 3 and 4). In addition, we installed marine X band radars on two of the ships to measure surface gravity waves and wave-averaged surface currents.

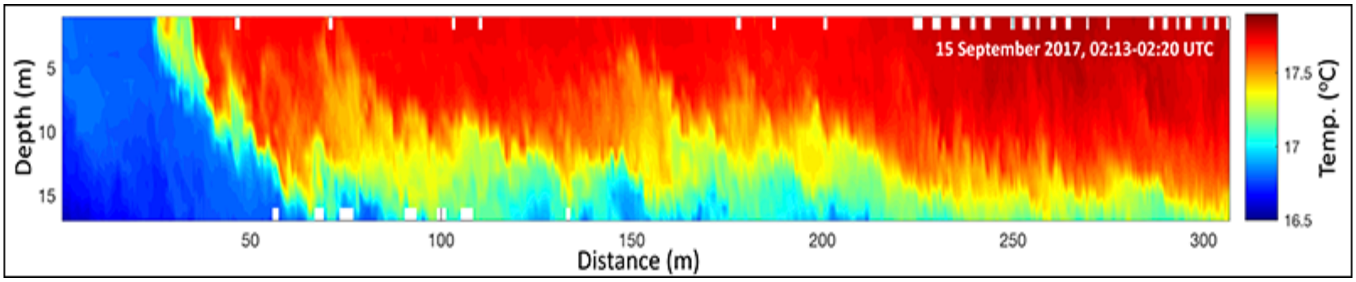

Fig. 3. High-resolution temperature cross-shore section of a sharp front in the upper water column at the Oceano array of the Inner Shelf Dynamics Experiment study site at a water depth of 40 meters, obtained from the bow chain attached to the R/V *Sally Ride*. Credit: Sean Haney and Jennifer MacKinnon

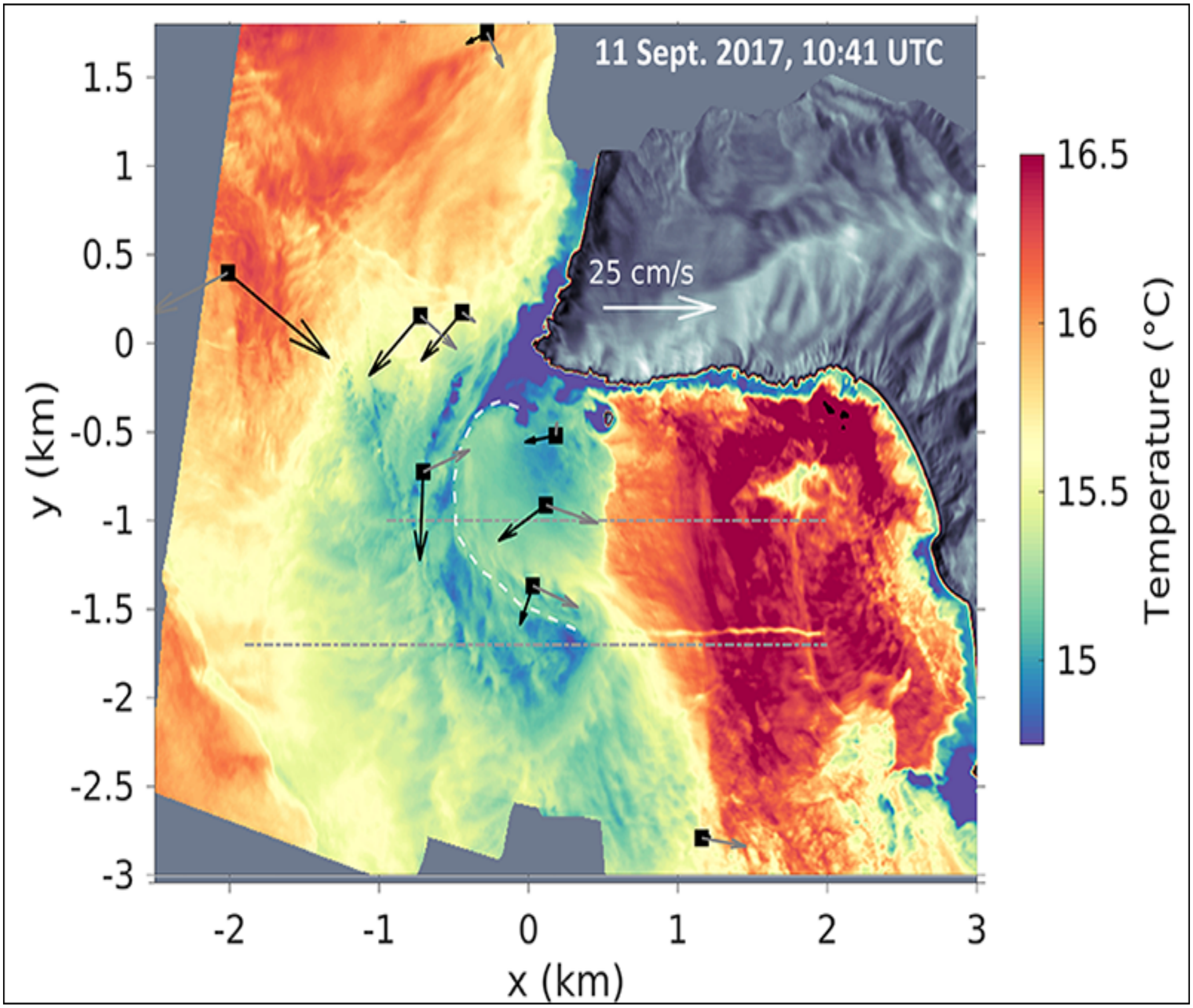

Fig. 4. This longwave infrared image of sea surface temperature near Point Sal on 11 September 2017 at 10:41 UTC shows a curving wake (indicated by the white dashed line) caused by flow separation in the lee of Point Sal. Black squares are locations of ADCP landers, and black and gray vectors show near-surface and near-bottom currents, respectively (10-minute averages). Gray dash-dotted lines indicate repeated transect lines of the small boats R/V *Sally Ann* (Scripps Institution of Oceanography) and R/V *Sounder* (Applied Physics Laboratory, University of Washington). Credit: Mike Kovatch, Ken Melville, and Luc Lenain

The coordinated surveys were designed to resolve shoaling nonlinear internal waves (https://eos.org/project-updates/breaking-internal-tides-keep-the-ocean-in-balance), wind-driven circulation, flow separation at headlands, and interactions between internal waves, headland flows, and rip currents ejected from the surf zone (Figure 5).

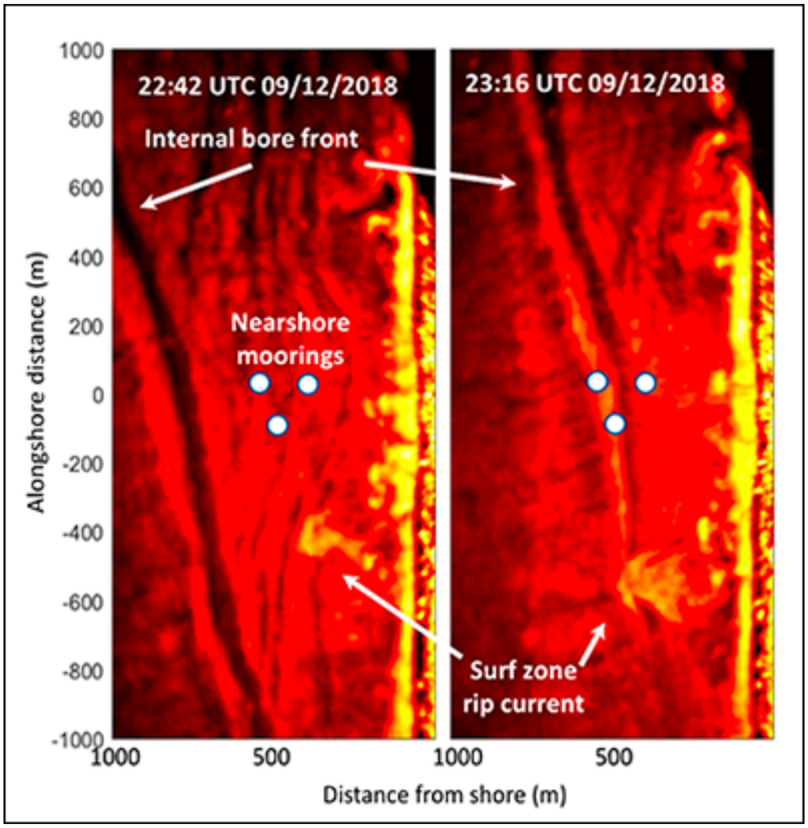

Fig. 5. Time-averaged X band radar images showing an internal bore front approaching the surf zone east of the Oceano array and interacting with an ejecting rip current. Credit: Annika O'Dea

Drifters. We deployed more than 50 real-time tracking, GPS-equipped drifters from small boats on daily missions throughout the intensive operation periods. Drifters were released in coordinated patterns to measure surface transport pathways, dispersion, and vorticity across various spatial scales. Several of the drifters were integrated with additional instrumentation, including Doppler profilers for turbulence measurements, conductivity and temperature probes, and meteorological sensors.

Remote Sensing. Several remote sensing platforms incorporated a range of sensors to measure surface signatures of inner shelf processes. Two aircraft were equipped with optical and thermal infrared cameras (Figure 6), lidar, and interferometric synthetic aperture radar (SAR) sensors.

Four coastal X band radar systems had sampling footprints that spanned the entire study site (Figures 1 and 5). They measured surface gravity waves; tracked internal waves; and identified buoyant fronts, eddies, and small-scale instabilities. We also acquired more than 50 satellite

SAR and optical images. In addition, we used small aerial drones with both optical and infrared cameras to characterize smaller-scale features of interest.

Fig. 6. Aerial photographs of an internal bore front propagating toward Mussel Point. The photo on the right shows instabilities developing on the internal bore front. Credit: Nick Statom

State-of-the-Art Instrumentation. The cutting-edge technology used in this experiment, which included off-the-shelf sensors as well as highly integrated, in-house instrumentation, allowed us to take novel measurements and approaches. Moored instrumentation (e.g., fast-response thermistors and five-beam ADCPs) collected time series data for the 2.5-month duration of the experiment with sampling frequencies as high as 100 data points per second.

We used satellite telemetry to transmit many of the observations, allowing us to incorporate real-time data acquisition directly into multiscale forecast models. For example, observations from Spoondrift Spotter directional wave buoys were transmitted to a computational back end to reconstruct a data-driven, real-time regional surface wave nowcast.

GusT (http://mixing.coas.oregonstate.edu/papers/GusT2016.pdf), a new turbulence probe, was developed and constructed under this project by Jim Moum of Oregon State University. This probe has sensors to measure turbulent temperature and current fluctuations as well as absolute speed. Approximately 80 GusTs were deployed on bottom landers, mooring lines, profiling sensor packages, and the bow chain. They provided turbulence measurements over a range of locations, within the upper and bottom boundary layers as well as within the interior of the water column.

Coupled, Multiscale Forecast and Hindcast Simulations. We also developed a multiscale ocean modeling system for the experiment region. We used regional ocean, atmosphere, and wave models to prescribe open boundary conditions and atmospheric forcing. We are using nested multigrid simulations with horizontal resolutions ranging from 3 kilometers to 22 meters to simulate observed ocean variability at the experiment study site and provide an integrated model-observation platform to address the key science questions.

Putting the Data to Use

The Inner Shelf Dynamics Experiment is unprecedented in the scope of processes sampled in the coastal ocean, the number of instruments used, and the diversity of measurement and modeling platforms used.

The Inner Shelf Dynamics Experiment is unprecedented in the scope of processes sampled in the coastal ocean, the number of instruments used, and the diversity of measurement and modeling platforms used. We have used this experiment to collect an unparalleled data set, which we are analyzing to quantify the dominant and interacting physical processes at work in the inner shelf and to determine the spatial scales and temporal variability of transport pathways in the region.

The observations from this new field experiment will test and improve model predictions and quantify remotely sensed measurements, encompassing a broad range of mechanisms, including surface gravity and internal waves, Stokes drift (https://www.youtube.com/watch?v=oPplzgEcyGc) and rip currents, submesoscale eddies, and wind-driven flows. The experiment and the data set it produced will keep coastal physical oceanographers busy in the decades to come.

More information about the experiment is available at www.apl.washington.edu/innershelf (http://www.apl.washington.edu/project/project.php?id=inner_shelf) and scripps.ucsd.edu/projects/innershelf (https://scripps.ucsd.edu/projects/innershelf/).

Acknowledgments

We gratefully acknowledge the funding support for this experiment from the Office of Naval Research, Littoral Geosciences and Optics program. We also acknowledge two anonymous reviewers who provided helpful comments on this article. The participating institutions were

Oregon State University; Scripps Institution of Oceanography; University of Washington Applied Physics Laboratory; Naval Postgraduate School; Naval Research Laboratory; Georgia Institute of Technology; Sofar Ocean Technologies; University of Miami; Florida State University; University of California, Los Angeles; University of California, Santa Cruz; University of Michigan; University of Southern Mississippi; and Delft University of Technology.

References

Beardsley, R. C., and S. J. Lentz (1987), The Coastal Ocean Dynamics Experiment collection: An introduction, ***J. Geophys. Res.***, ***92***(C2), 1,455–1,463, https://doi.org/10.1029/JC092iC02p01455 (https://doi.org/10.1029/JC092iC02p01455).

Lentz, S. J., and M. R. Fewings (2012), The wind- and wave-driven inner-shelf circulation, ***Annu. Rev. Mar. Sci.***, ***4***, 317–343, https://doi.org/10.1146/annurev-marine-120709-142745 (https://doi.org/10.1146/annurev-marine-120709-142745).

Long, C. E., and A. H. Sallenger Jr. (1995), Experiment at Duck, N.C., beach explores nearshore processes, ***Eos Trans. AGU***, ***76***(49), 501–507, https://doi.org/10.1029/95EO00315 (https://doi.org/10.1029/95EO00315).

Author Information

James Lerczak (jlerczak@coas.oregonstate.edu (mailto:jlerczak@coas.oregonstate.edu)) and John A. Barth, Oregon State University, Corvallis; Sean Celona, Scripps Institution of Oceanography, La Jolla, Calif.; Chris Chickadel, Applied Physics Laboratory, University of Washington, Seattle; John Colosi, Naval Postgraduate School, Monterey, Calif.; Falk Feddersen, Scripps Institution of Oceanography, La Jolla, Calif.; Merrick Haller, Oregon State University, Corvallis; Sean Haney, Luc Lenain, and Jennifer MacKinnon, Scripps Institution of Oceanography, La Jolla, Calif.; James MacMahan, Naval Postgraduate School, Monterey, Calif.; Ken Melville, Scripps Institution of Oceanography, La Jolla, Calif.; Annika O'Dea, Oregon State University, Corvallis; Pieter Smit, Sofar Ocean Technologies, San Francisco, Calif.; Amy Waterhouse, Scripps Institution of Oceanography, La Jolla, Calif.; and TongTong Xu, School of Civil and

Environmental Engineering, Georgia Institute of Technology, Atlanta

Citation: Lerczak, J., et al. (2019), Untangling a web of interactions where surf meets coastal ocean, *Eos, 100,* https://doi.org/10.1029/2019EO122141. Published on 02 May 2019.