Final Report

Airborne Remote Sensing of Inner Shelf Internal Waves and Sub-mesoscale Features

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MAJOR GOALS

The inner shelf region is characterized by subsurface processes at a wide range of scales that express observable signatures at the surface of the ocean. For example, internal waves generated at the shelf edge are associated with strong surface roughness and velocity signatures that can be measured with remote sensing instruments such as radars and infrared imagers (e.g., *Marmorino et al*., 2004; *Zappa and Jessup*, 2005). Fronts and eddies also generate increased surface roughness, and typically cause changes in surface temperature that are detectable by remote sensing techniques. Remote sensing instruments also measure surface processes, such as surface gravity waves and slicks. While this sensitivity to both surface and subsurface processes provides a comprehensive view of the inner shelf, it complicates analysis of individual phenomenon. Our long-term goals are to develop methods to extract geophysical parameters, such as wave amplitude, current magnitude and direction, and mixing, from remote sensing data and to contribute to the understanding of inner shelf processes with our observations. Our specific objectives are to: (1) Measure geophysical parameters of internal waves and inner shelf currents over spatial scales of kilometers and temporal scales of hours using remote sensing techniques, (2) Improve estimation of internal wave parameters from SAR by using ATI-derived surface velocity, (3) Observe and measure surface signatures, velocities, and mixing lengths associated with internal bore dissipation and eddies using surface temperature maps, and (4) use remote sensing and in situ data to explore and quantify the surfzone-inner shelf exchange.

APPROACH

Our methodology was focused on large scale remote sensing using thermal infrared (IR), visible band (EO), and C-Band synthetic aperture radar (SAR). All of these instruments are combined in the Compact Airborne System for Imaging the Environment (CASIE) and flown onboard a Cessna 182 light aircraft. We surveyed the Inner Shelf region north and south of Pt Sal CA during the main experiment in September and October 2017. Simultaneous in situ data from a small boat and from collaborators (drifters, moorings, other small and large vessels) were used in the analysis.

RESULTS

Analysis included remotely tracking internal wave (IW) fronts in the inner shelf for a multi-investigator analysis of IW speeds. We finished final analysis and revisions for the paper (M.

Moulton lead author) on temper effects of rip plume dynamics injected into the inner shelf. We have finalized submissions of our processed data for public archive in the UCSD library system.

We extracted inner shelf fronts as part of a multi-investigator study (and resulting manuscript, all lead by M. Spydell, SIO) for analyzing IW speeds in the inner shelf. We analyzed both visible image and μASAR surface backscatter maps (both part of the APL airborne data set) to determine front locations on 10 October 2017. The day was chosen to coincide with satellite, drifter, and mooring data that captured an internal wave front that propagated from 4 km off shore to the immediate vicinity of Pt. Sal. An example of the visible band and SAR remote sensing imagery of the IW front is shown in Figure 1. Here, the water mass difference is differentiable in the ocean color with the nearshore water more turbid (brighter) than the offshore water. The SAR data show the front is visible as decreased backscatter due to surfactant suppression of short waves at front convergence. This is somewhat different than most instances of SAR front identification, which often shows enhanced front backscatter due to current-induced steepening of short waves there. The remote sensing data has been assimilated with in situ measurements by M. Spydell into a front arrival time map (Figure 2), and all the measurements show good agreement and detail the motion and deformation of the IW front in the complicated bathymetry near Pt. Sal. The data has been incorporated into a manuscript (M. Spydell is first author) in revision to JPO which compares the front transit times with idealized gravity current propagation speeds and IW speed predictions.

We have finalized analysis of a remotely sensed and model runs for a publication on the thermal variation effects on rip current plume injection into the inner shelf and published it in *Moulton et al*. (2021). In this recent effort, we added additional observations of cool and warm plumes to double the total previous observations in an effort to fortify the statistics, and we have also added observations of the alongshore variation of the surfzone width. We found that the newly added statistics were consistent with the previous data, where cool plumes extended an average of 1.8 (1.7 in earlier data) surfzone widths (SZWs) offshore, and warm plumes extending an average of 2.7 (2.6 in earlier data) surfzone widths offshore (Figure 3). Modeled rip current plume behaviors are still consistent with field observations in this updated analysis. We find that average SZW-normalized modeled plume extents are 2.4 for cool plumes and 3.6 for warm plumes, thus similar to the observed field data where warm plumes extend about one SZW further offshore than cool plumes. We also note that the distribution of warm plumes, for modeled and observed, is more widely spread. Temporal evolution of the modeled plume surface extents indicates that modeled cool plumes stabilized to an approximately constant value, whereas the warm plume extents increased in time (Figure 4). This analysis of the plume speed evolution is consistent with the observed plume length distribution differences. Future research should address the controls on plume structure including sources of horizontal and vertical temperature stratification and lateral and vertical mixing of the plume.

Finally, we have completed data archiving for all of our data including in situ boat survey data (CTD, ADCP) and remote sensing data (SAR, IR and RGB image data) to the UCSD library data archive organized by SIO.

IMPACT/IMPLICATIONS

This data and analysis has is part of a large, well organized and well sampled field effort that spans the complicated inner shelf region. Our research has added examples of the complexity of the sea surface temeprature in the inner shelf and shown that exchange of fluid between the surf zone and inner shelf is complex and may be controlled by sublte density difference that interact at a range of scales from meters to kilometers and larger. This data set will continued to be analyzed and used for model development and validation.

TECHNOLOGY TRANSFER AND RELATED PROJECTS

This data will serve as an example case for the NUWC UPSIDE program. Airborne microSAR data from the is project was used to motivate future ONR-funded work to study wave parameter retrieval at rocky coasts.

PUBLICATIONS AND PRESENTATIONS

Peer-reviewed papers:

Moulton, M., Chickadel, C. C., and Thomson, J. (2021) Warm and cool nearshore plumes connecting the surf zone to the inner shelf, *Geophysical Research Letters, 48,* 10. doi:/10.1029/2020GL091675.

Spydell, M.S., Suanda, S.H., Grimes, D.J., Becherer, J., Mcsweeney, J.M., Chickadel, C., Moulton, M., Thomson, J., Lerczak, J., Barth, J. and Macmahan, J., (2021) Internal Bore Evolution across the Shelf near Pt. Sal, California, Interpreted as a Gravity Current. *Journal of Physical Oceanography*, *51*(12), pp.3629-3650.

Kumar, N., Lerczak, J. A., Xu, T., Waterhouse, A. F., Thomson, J., Terrill, E. J., ... Moulton. M. … Chickadel C. … & Ahn, S. (2021). The inner-shelf dynamics experiment. *Bulletin of the American Meteorological Society*, *102*(5), E1033-E1063.

Conference papers:

Aslebagh, S., G. Farquharson, J. Sahr, and R. Romeiser (2018) Wave-dependent directional biases in airborne ocean surface current estimation, *International Geoscience and Remote Sensing Symposium, 2018 IGARSS*.

Presentations:

Chickadel, C., M. Moulton, J. Thomson, A. Waterhouse, J. MacKinnon, J. Moum, and J. Becherer, Horizontal temperature length scales on the inner shelf due to breaking internal waves, *Ocean Sciences Meeting,* San Diego CA, Feb 2020.

Moulton, M., C Chris Chickadel, and Jim Thomson, Remote Sensing and Modeling of Warm and Cool Plumes Connecting the Surf Zone and Inner Shelf*, Ocean Sciences Meeting,* San Diego CA, Feb 2020.

Chickadel, C. C., M. Moulton, and G. Farquharson (2018), *Spatial and temporal scales of internal waves, fronts, and eddies on the inner shelf*, Abstract CD11A-04 presented at 2018 Ocean Sciences Meeting, Portland, OR, 12-16 Feb.

M. Moulton, C. C. Chickadel, and J. M. Thomson (2018), *Observations of rip-current and internal-wave driven exchange between the surf zone and inner shelf*, Abstract CD14C-0071 presented at 2018 Ocean Sciences Meeting, Portland, OR, 12-16 Feb.

M. Moulton, C. Chickadel, G. Farquharson (2017) *Airborne remote sensing of inner shelf processes*, 2017 Coastal Ocean Dynamics Gordon Research Conference.

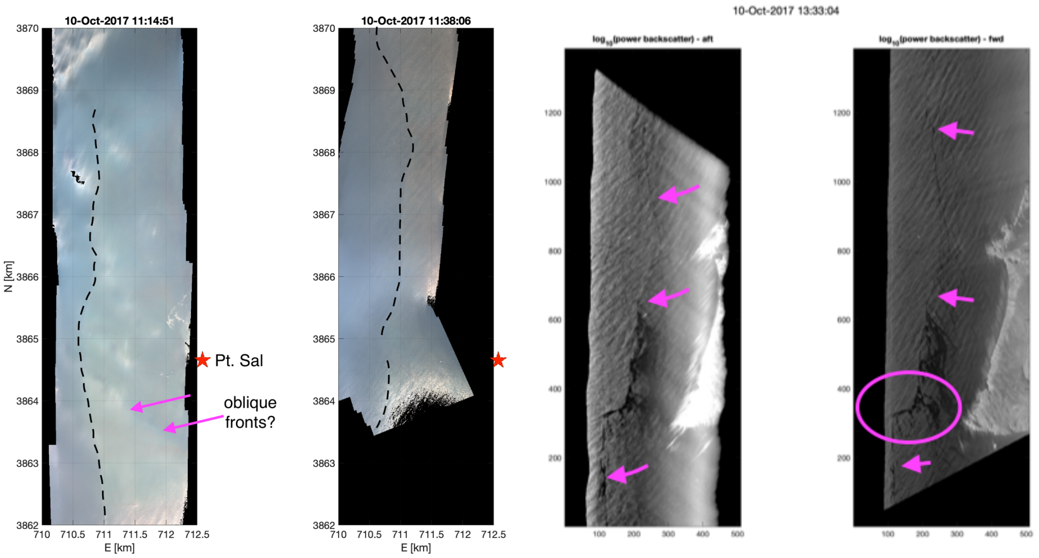
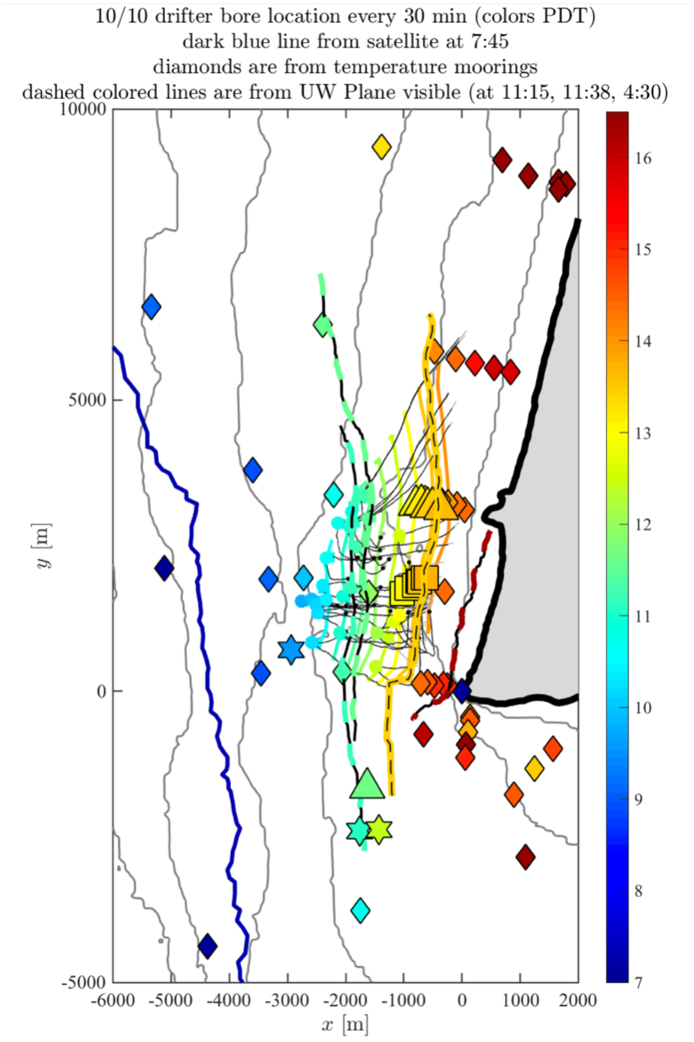


Figure 1. *(left and center-left) Pair of RGB mosaics from the APL plane showing the position of an internal wave front advancing shoreward in the vicinity of Pt. Sal. The front is visible due to the water mass color difference on either side. (center-right and right) Backscatter power images from the APL μASAR showing the same IW front at a later time. The front is visible in these maps as low backscatter due to accumulation of surfactants in the front.*



w/ ships...
triangles: Sounder times
squares: Sally Ann times
stars: Oceanus

&
UW plane radar based time
(orange w dashed black)

&
UW plane visible at 16:30

Figure 2. *IW front arrival time map courtesy M. Spydell. APL-airborne remotely sensed front positions are marked by dashed lines (four total front locations are noted). Moorings and drifter locations are marked by the filled symbols.*

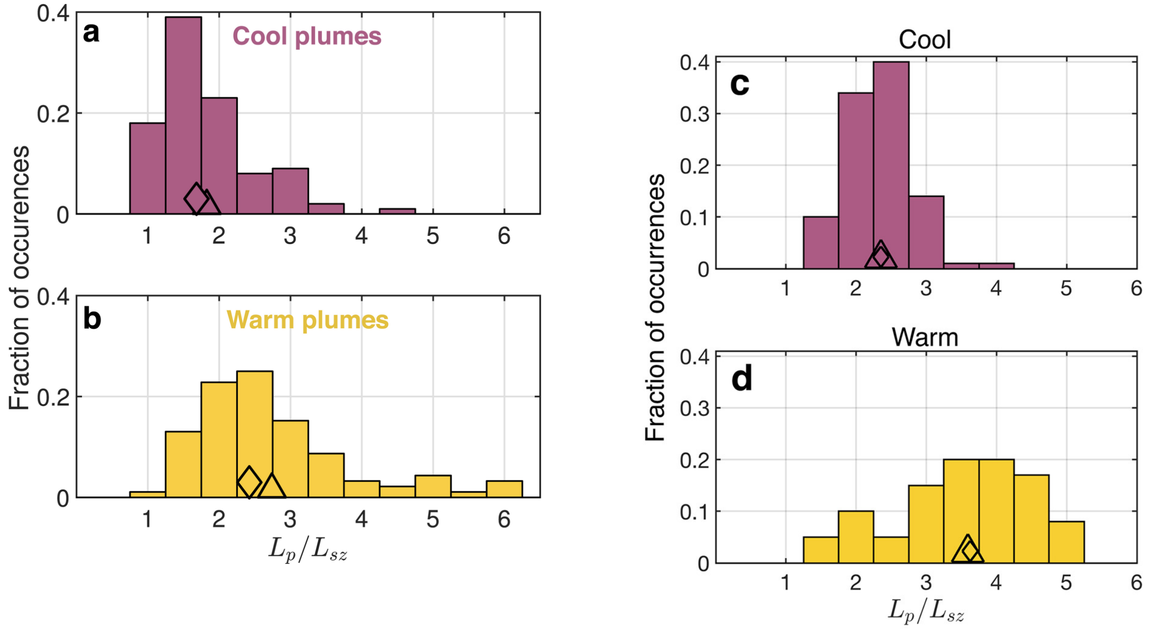


Figure 3. *Histograms of the number of occurrences of (a) cool and (b) warm plumes in infrared imagery versus the ratio of the plume cross-shore surface extent. The average cross-shore surface extent (triangle on x axis) is 1.8 for cool plumes and 2.7 for warm plumes, and the median cross-shore surface extent (diamond on x axis) is 1.7 for cool plumes and 2.4 for warm plumes. Histograms of the fractional number of occurrences of (c) cool and (d) warm plumes in a suite of model simulations sampled at a range of times versus the normalized plume surface cross-shore extent (triangle: average, diamond: median). [from Moulton et al., 2021]*

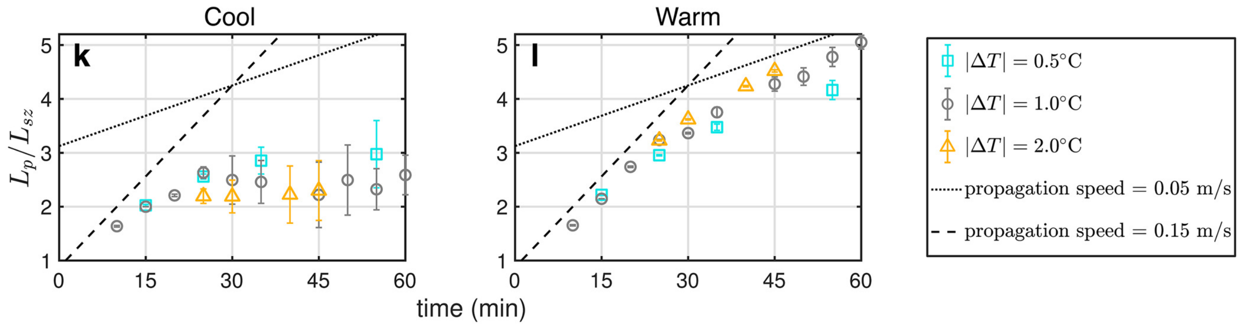


Figure 4. *Average plume extent time series for modeled cool (k) and warm (l) plumes. constant propagation speeds and initial plume-ocean temperature differences are noted by color and symbol.*

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The inner shelf region is characterized by subsurface processes at a wide range of scales that express observable signatures at the surface of the ocean. Our long-term goals are to develop methods to extract geophysical parameters, such as wave amplitude, current magnitude and direction, and mixing, from remote sensing data and to contribute to the understanding of inner shelf processes with our observations. We surveyed the Inner Shelf region north and south of Pt Sal CA during the main experiment in September and October 2017 using a manned aircraft with infrared, visible, and radar imaging instruments. Simultaneous in situ data from a small boat and from collaborators (drifters, moorings, other small and large vessels) were used in the analysis. Our analysis of imagery and radar data resulted in documenting and mapping the spatial deformation and speed of internal waves and bores. We also demonstrated the temperature effect on inner shelf surfzone exchange through modulation of rip current plumes. Modeling corroborated remote sensing data to show that cold plumes subduct beneath surface waters, while warm plumes spead as a gravity flow.

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