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OCEAN SURFACE CURRENT MEASUREMENTS IN THE SUB-MESOSCALE OCEAN DYNAMICS EXPERIMENT

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ABSTRACT

The Sub-Mesoscale Ocean Dynamics Experiment (S-MODE) is a NASA Earth Ventures Suborbital Investigation designed to test the hypothesis that oceanic frontogenesis and the kilometer-scale ("submesoscale") instabilities that accompany it make important contributions to vertical exchange of climate and biological variables in the upper ocean. These processes have been difficult to resolve in observations and models. A necessary step toward testing the hypothesis was to make accurate measurements of upper-ocean velocity fields over a broad range of scales and to relate them to the observed variability of vertical transport and surface forcing. To achieve that, we used aircraft-based remote sensing, satellite remote sensing, ships, drifter deployments, and a fleet of autonomous vehicles. This paper will provide a brief overview of the S-MODE measurements, with a special focus on surface current measurements.

Index Terms— Ocean eddies, ocean currents, air-sea interaction, remote sensing

1. INTRODUCTION

The overall goal of the Sub-Mesoscale Ocean Dynamics Experiment (S-MODE) EVS-3 investigation is to test the hypothesis that "submesoscale" ocean dynamics make important contributions to vertical exchange of climate and biological variables in the upper ocean (Farrar et al. 2020). This requires coordinated application of newly developed in situ and remote sensing techniques, with the goal of providing an unprecedented view of the physics of submesoscale eddies and fronts and their effects on vertical transport in the upper ocean. S-MODE is using measurements from a novel combination of platforms and instruments, along with data analysis and modeling, to test the hypothesis.

One of the major novelties of S-MODE is that we are attempting to estimate the vertical velocity in the ocean by measuring horizontal velocity gradients. Using the facts that sea water is approximately incompressible and that the mean vertical velocity at the sea surface is approximately zero (i.e., that sea level is not changing rapidly), we can estimate the vertical velocity at a given depth as the vertical integral of the horizontal divergence from the surface to that depth. The major challenge of this approach is that it is sensitive to errors in the horizontal velocity

This, and the fact that horizontal velocity gradients are central in frontal and submesoscale dynamics (e.g., in vorticity dynamics; McWilliams, 2016) has led us to have a special focus horizontal velocity gradients and on understanding the accuracy of velocity measurements made by different techniques (e.g., Hodges et al. 2023). In this abstract and the associated presentation, we will give some

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details about the S-MODE campaigns and the different velocity measurements that we made.

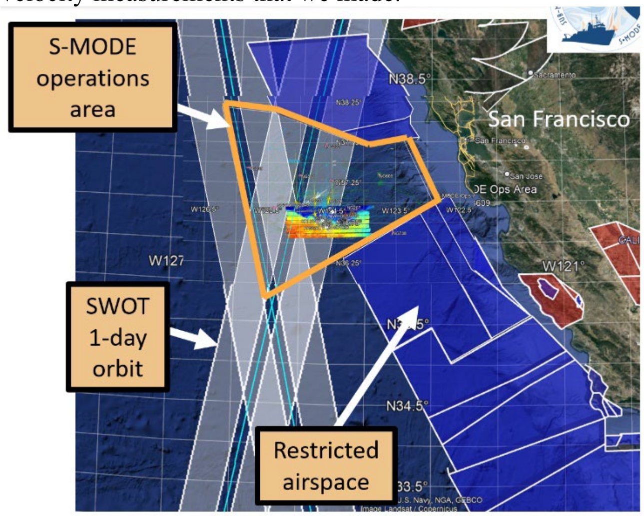

Figure 1: The S-MODE study region offshore of San Francisco (orange polygon). The SWOT 1-day repeat cal-val orbit is indicated with white shading, and the offshore restricted airspace areas that limited our potential operating areas are indicated by blue polygons. The colored area inside the orange polygon illustrates the area that could be covered in one flight by the NASA B-200 aircraft.

2. SCIENCE GOALS, OBJECTIVES, AND APPROACH

Model studies (e.g., Uchida et al. 2022) and limited observations (e.g., D'Asaro et al., 2018) indicate that submesoscale vertical exchange is concentrated near km-scale fronts and eddies. High-resolution simulations have outpaced our observational capabilities, but observational techniques have matured rapidly over the past decade. S-MODE seeks to make a comprehensive set of measurements of the dynamical variables needed to validate and discriminate between the high-resolution simulations. To test the hypothesis that submesoscale ocean dynamics make important contributions to vertical exchange in the upper ocean, the S-MODE Science Team has set these science goals:

1) Quantitatively measure the three-dimensional structure of the submesoscale features responsible for vertical exchange.
2) Quantify the role of air-sea interaction and surface forcing in the dynamics and vertical velocity of submesoscale variability.
3) Understand the relation between the velocity (and other surface properties) measured by remote sensing at the surface and that within and just below the surface boundary layer.
4) Diagnose dynamics of vertical transport processes at submesoscales to mesoscales.

The approach used in S-MODE was motivated by recent experiments that have shown the benefit of combining multiple, diverse platforms to enable measurements across a range of spatial and temporal scales (Shcherbina et al. 2013; D'Asaro et al. 2018). First, satellite remote sensing informed direct aircraft remote sensing which, in turn, informed the targeting of in-situ measurements. Second, multiple in-situ platforms, both ships and a variety of autonomous platforms, were combined to simultaneously measure large values of the km-scale density gradients, vorticity and divergence, that distinguish submesoscale motions from mesoscale and internal wave motions. Third, measurements were made in a Lagrangian coordinate system, tracking the evolving submesoscale features as they move within the larger, more energetic mesoscale currents.

The nominal study site was approximately 200 km west of San Francisco (Figures 1). The site was conveniently located to NASA Ames Research Center in the San Francisco area, and the study region overlaps the SWOT (Surface Water Ocean Topography; Morrow et al., 2019) cal-val region (Wang et al. 2018, 2022). We conducted a 14-day Pilot campaign in October 2021, and we conducted month-long intensive operating periods (IOPs) in October 2022 and April 2023. The experiment collected simultaneous measurements using several airborne instruments, including the NASA DopplerScatt instrument (Rodriguez et al. 2018), the NASA PRISM instrument (Mouroulis et al. 2014), the SIO MASS instrument (Melville et al. 2016) and the UCLA MOSES (Multiscale Observing System of the Ocean Surface) instrument. In conjunction with the airborne measurements, in situ data were obtained using surface drifters, autonomous surface vehicles (Wave Gliders, Saildrones), Lagrangian floats that follow the 3D flow (D'Asaro et al., 2018), vertically profiling autonomous underwater vehicles (gliders), and a research vessel. These measurements are complemented with satellite observations of sea surface height, winds, SST, and ocean color.

The different measurement platforms are depicted schematically in Fig. 2, and information about the various instruments carried by these platforms is given in Table 1.

One novel and exciting aspect of S-MODE is its focus on measurements of horizontal velocities and their gradients, both from remote sensing and from arrays of in situ platforms (Table 1). The DopplerScatt instrument (Rodriguez et al., 2018), flying on a NASA King Air B200 aircraft, can produce a nearly synoptic map of ocean surface currents over a 100-by-100-km area in a single 4-hour flight (Fig. 1). We used arrays of Saildrones (Zhang et al., 2019) and Wavegliders (Lenain and Melville, 2014) carrying ADCPs to estimate horizontal gradients of velocity at kilometer scales, in order to estimate the divergence and vorticity of the horizontal currents. These measurements are complemented by velocity measurements from gliders, drifters, and the ship.

All of the data from the S-MODE program are being made publicly available via the NASA Physical

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Instrument	Variables	Platform
NASA-JPL Doppler Scatterometry (DopplerScatt)	Ocean surface current and wind	NASA KingAir B200
UCLA Multiscale Observing System of the Ocean Surface (MOSES)	Sea Surface Temperature (SST)	NASA KingAir B200
NASA-JPL Portable Remote Imaging Spectrometer (PRISM)	Ocean color (hyperspectral imagery)	NASA G-V
Scripps Institution of Oceanography (SIO) Modular Aerial Sensing System (MASS)	Directional Wave spectra; Sea surface topography; SST; ocean color (hyperspectral imagery)	Twin Otter DHC-6 (Twin Otter International)
Ocean Surface Drifters	Surface flow trajectories	Self-contained, deployed from Research Vessel (R/V)
Lagrangian Floats	Three-dimensional flow trajectories, vertical velocity	Self-contained, deployed from R/V
Meteorological Packages	Wind speed and direction, air temperature, pressure, humidity, and radiative heat fluxes	Wave Gliders, Saildrones, R/V
Fixed-depth Conductivity/Temperature Sensors	Upper ocean temperature and salinity	Wave Gliders, Saildrones, R/V
Profiling Conductivity/Temperature/Depth (CTD) Sensors	Temperature and salinity at various depths	Seagliders, Saildrones (winch), Lagrangian Floats, R/V (ECO CTD)
Bio-optics Sensors	Chlorophyll concentration, optical backscatter	Seagliders, Wave Gliders, Saildrones, R/V (ECO CTD)
Acoustic Doppler Current Profilers (ADCPs)	Ambient water velocity, acoustic backscatter, turbulence intensity	Seagliders, Wave Gliders, Saildrones, Lagrangian Floats, R/V

Table 1: Instruments that were be used in the S-MODE campaigns.

Oceanography Distributed Active Archive Center (PO.DAAC; see https://podaac.jpl.nasa.gov/S-MODE).

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