S-MODE: 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 kilometer-scale ("submesoscale") ocean eddies make important contributions to vertical exchange of climate and biological variables in the upper ocean. To test this hypothesis, S-MODE will employ a combination of aircraft-based remote sensing measurements of the ocean surface, measurements from ships, measurements from a variety of autonomous oceanographic platforms, and numerical modeling. The field campaign will consist of two month-long intensive operating periods (IOPs) that will be preceded by a smaller-scale pilot experiment to test and improve operational readiness and to compare measurements made from different platforms. The pilot experiment was delayed because of the 2020 coronavirus pandemic, and it is currently planned for October-November 2020.

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

1. INTRODUCTION

The ocean surface boundary layer that lies at the interface of the ocean and the atmosphere makes up only about 2% of the global oceans, but it plays a critical role in the climate system because it mediates the atmosphere-ocean exchange of important properties like heat, nutrients, oxygen, and carbon. Submesoscale ocean dynamics (horizontal wavelengths of 0.2-25 km, time scales of hours to days) are hypothesized to play an important role in vertical exchange, both between the atmosphere and the surface layer and between the surface layer and the deeper ocean. Our ability to simulate submesoscale ocean dynamics has outpaced our ability to observe them, and recent studies using high-resolution global ocean models suggest that vertical transport of heat by submesoscale variability is indeed a significant factor in the climate system; for example, [1] showed that improved resolution of submesoscale variability leads to changes in mean air-sea heat fluxes in the midlatitudes that are an order of magnitude larger than the global radiation imbalance associated with the greenhouse effect.

The vertical transport of matter and energy in the ocean cannot be accomplished efficiently by the mesoscale and larger-scale flow fields, which have very small vertical velocities (of order 1-10 m/day or less). The transition from

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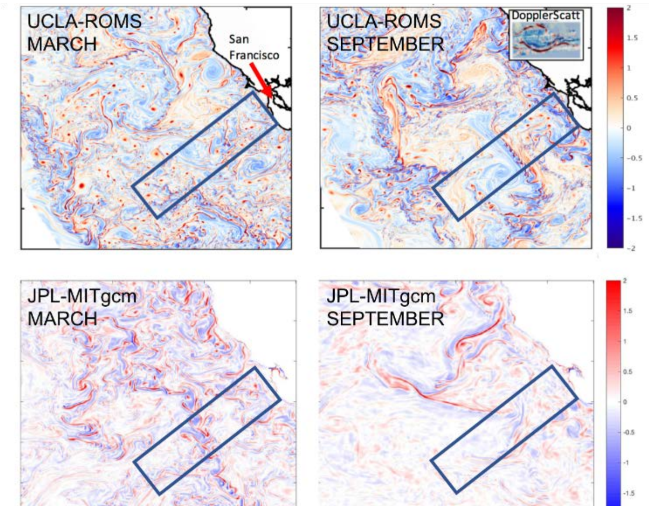

Figure 1: Surface vorticity off Central California in two submesoscale-resolving models in March (left column) and September (right column). Regional ROMS (top row 500 m resolution) and JPL-MITgcm (bottom row, ~ 2km resolution) show different seasonal cycles. The rectangle in the upper left shows our experiment domain. The vorticity has been normalized by the local value of the Coriolis parameter. The inset in the upper-right panel is the normalized vorticity measured by DopplerScatt in the Gulf of Mexico [13], shown with the same distance scaling and color scale as in the model fields.

the mesoscale dynamical regime to the submesoscale regime is characterized by increasingly strong vertical velocities [2]. The distinctively large vertical velocities occur primarily in ageostrophic secondary circulations across the horizontal surface density gradients, and induce large vertical buoyancy flux (known as restratification) [3] and large biogeochemical fluxes between the euphotic surface layer and underlying gradient layers (e.g., the nutricline; [4, 5]). The associated vertical transport is hypothesized to have important consequences for oceanic biology, chemistry, and physics.

Our understanding of submesoscale motions and their vertical exchange comes primarily from numerical simulations. While all models with sufficient resolution predict the existence of submesoscale motions, there are large variations in their quantitative predictions. For example, Fig. 1 compares fields of surface relative vorticity (a variable that highlights submesoscales) for two models currently used to simulate the performance of the upcoming SWOT satellite [4], [5]. Although they both show submesoscale fronts and eddies, the higher-resolution ROMS simulation shows a stronger dominance of cyclonic eddies over fronts, while the MITgcm shows a larger seasonal difference between March and September.

These differences highlight the uncertainties in such simulations. The key distinctive features of the submesoscale-- the sharp fronts, high vorticity at these fronts and associated large vertical velocities-- occur at the smallest scales resolved by the models. Their amplitudes are thus sensitive to resolution (e.g. Fig. 1) and to the details of the numerics and damping at the grid scale. Increasing the resolution toward 100m increases the strength of the submesoscale features, but also brings the grid to the same scales as the parameterized boundary layer turbulence. Proper subgrid schemes to deal with this overlap are still experimental. Furthermore, models and theory indicate both that submesoscale motions are sensitive to the boundary layer turbulence (e.g. turbulent thermal wind; [6]) and that the boundary layer turbulence itself is affected by the submesoscale gradients [7]). These effects are only partially included in models.

The physics of air-sea interaction at submesoscales is another poorly constrained factor in simulation of submesoscale dynamics and their associated vertical transport. Submesoscale vorticity can be much larger than the vertical component of Earth's rotation rate, which can fundamentally alter the wind-driven vertical transports (known as Ekman pumping; [8], [9]). In addition, the boundary layer turbulence is primarily forced by air-sea fluxes that are computed from bulk-exchange coefficients that have not been validated at submesoscales. The fluxes can be modulated by the SST gradients at fronts, by the frontal currents themselves and by variations in the surface wave field propagating across the velocity gradients of these fronts [10]. Given these uncertainties, a major goal of S-MODE is to make detailed measurements of the submesoscale variability and compare these with model predictions.

2. SCIENCE GOALS AND OBJECTIVES

Model studies (Fig. 1) and limited observations (e.g., [11]) 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.

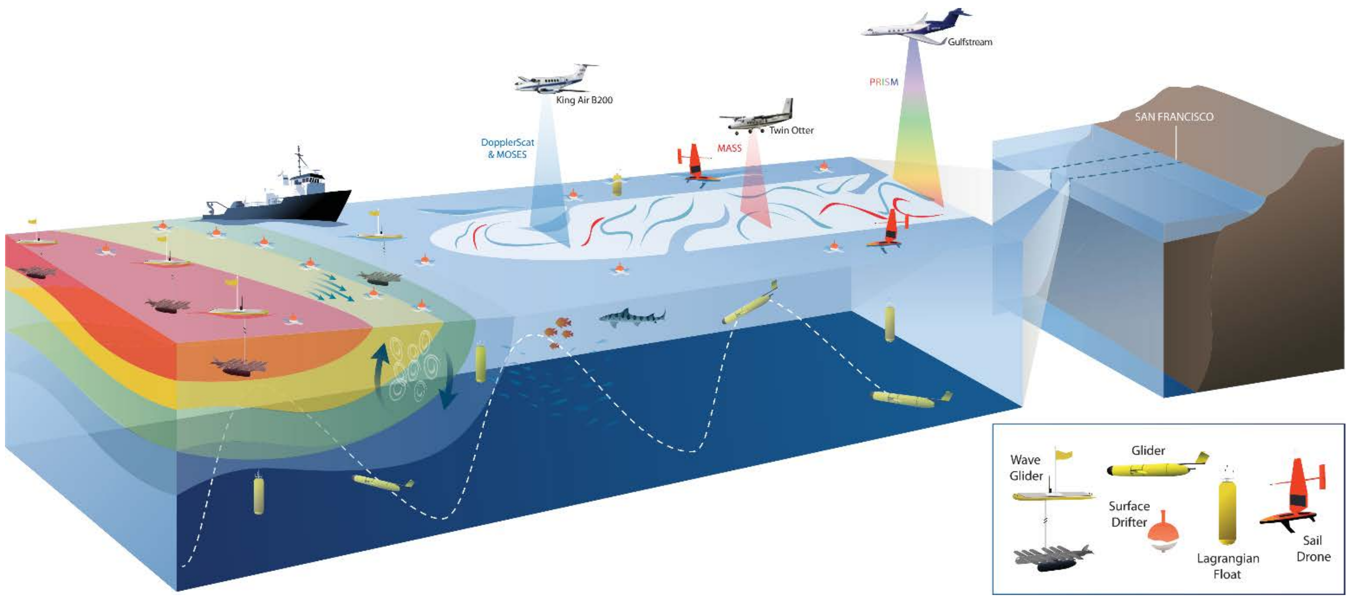

Figure 2: Schematic depiction of the S-MODE investigation. (Illustration by Jennifer Matthews, SIO.)

3. IMPLEMENTATION, INSTRUMENTS AND PLATFORMS

The complexity, size and rapid evolution (hours to days) of submesoscale motions has made them difficult to measure. They are much larger than ships, but small and rapidly evolving compared to typical ship surveys, small for many satellite remote sensing footprints, and difficult to distinguish from inertia-gravity waves because they occur on similar spatial and temporal scales. Over the last decade, new instrumentation and techniques have been developed to overcome these difficulties.

The approach planned for S-MODE is motivated by recent experiments that have shown the benefit of combining multiple, diverse platforms to enable measurements across a range of spatial and temporal [11], [12]. First, satellite remote sensing will inform direct aircraft remote sensing which, in turn, will inform the targeting of in-situ measurements. Second, multiple in-situ platforms, both ships and a variety of autonomous platforms, will be 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 will be 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 is centered approximately 150 km offshore of San Francisco (Figures 1-2). There will be a 10-day Pilot campaign late in October 2020, and there will be month-long intensive operating periods (IOPs) in October 2021 and April 2022. The experiment will collect simultaneous measurements using several airborne instruments, including the NASA DopplerScatt instrument [13], the NASA PRISM instrument [14], the SIO MASS instrument [15] and the UCLA MOSES (Multiscale Observing System of the Ocean Surface) instrument. In conjunction with the airborne measurements, in situ data will be obtained using surface drifters, autonomous surface vehicles (Wave Gliders, Saildrones), Lagrangian floats that follow the 3D flow [11], vertically profiling autonomous underwater vehicles (gliders), and a research vessel. These measurements will be 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 [13], 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. We plan to use arrays of Saildrones [16] and Wavegliders [17] 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 would be complemented by velocity measurements from gliders, drifters, and the ship.

All of the data from the S-MODE program will be made publicly available via the NASA Physical Oceanography Distributed Active Archive Center (PO.DAAC).

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 will be used in the S-MODE campaigns.

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