Working group prospectus
Small-scale processes in the upper ocean and their interaction with the Earth's climate system

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Motivation

The upper ocean is crucial to our climate, with its intricate processes having wide-ranging effects on the Earth's climate system. These processes occur at many time and space scales, spanning from turbulence to the large-scale circulation, however it is the small-end of this spectrum that cannot be directly modeled in global climate simulations and hence represent an ongoing source of uncertainty in the understanding and forecasting of climate variability. Small-scale processes break dynamical barriers, moving tracers between different components of the climate system and impacting boundaries like those between the deep and surface oceans (Smith et al. 2016; Wenegrat et al. 2018; Su et al. 2018), the ocean and atmosphere (e.g., Seo et al. 2023), coastal and open waters (Zhang et al. 2023), and the ocean and ice regions (Manucharyan and Thompson 2017). The interconnected role of these upper ocean dynamics on marine ecosystems underscores their significance to the overall climate system (Mahadevan 2017; Taylor and Thompson 2023). Understanding when, where, and how these processes take place, and their future fate in a changing climate is critical. Their influence not only shapes our climate, but their accurate representation is also essential for improving climate model projections and devising science-backed climate solutions. However, to date, only one parameterization of submesoscale processes has been implemented in global climate models (Fox-Kemper et al 2008; 2011), leaving the effect of small-scale ocean dynamics severely underrepresented in climate forecasts. Given its significance, a comprehensive and interdisciplinary review of the role of upper ocean small-scale processes in the interconnected climate system is timely. A US CLIVAR working group is the ideal – and perhaps the only – platform for the task. This is also one of the recommendations from the 2023 US CLIVAR summit meeting.

The urgent need for this working group is underscored by the recent advances in modeling and observations, including the launch of the SWOT (Surface Water and Ocean Topography) mission. With an investment of over 1 billion dollars, SWOT's sophisticated remote sensing technology will enable groundbreaking research of the upper ocean physics through an abundance of new data (Morrow et al. 2019, Fu et al., 2024). Evaluations of SWOT's primary instrument emphasize its potential to drive interdisciplinary research, given its clear imagery and extensive coverage of coasts, estuaries, sea-ice zones, and ice shelves. Notably, SWOT can detail regional small-scale ocean circulations in these areas. The upcoming NASA PACE mission will further enhance remote sensing capabilities for studying ocean biogeochemistry. Similar upcoming European missions, such as ESA Harmony likewise promise an unprecedented integrated view into small-scale ocean processes and the myriad of ways in which they affect the climate system.

Furthermore, advances in high-resolution ocean modeling, such as efforts by NASA ECCO-GEOS to run coupled km scale global simulations, provide both a toolset for understanding processes and multi-scale interactions, and a preview of the future of global climate modeling. Coastal resilience, climate solutions, and related priorities are at the heart of multi-agency agendas, including those of US CLIVAR. As these satellite initiatives and high-resolution simulations promise insights into previously uncharted small-scale processes, we're on the cusp of a transformative period in small-scale oceanic research. However, we see it as imperative that the resulting process-level understanding be translated into an understanding of the climate-scale impacts. This working group will play a pivotal role in fast-tracking the community's embrace of these novel technologies and data sources, and ensuring that results of this work are connected to US CLIVAR's goal of advancing the understanding and prediction of climate variability.

The POS and PSMI panels have collaboratively established this working group proposal. Its primary role is to foster an interdisciplinary community that will assess current scientific knowledge, pinpoint areas of need, and offer direction for the future in terms of theory, simulations, and observations. Both panels see the objectives as aligning closely with their core priorities. We also would like to build on the momentum of the air-sea interactions working group (Seo et al. 2023) and a recent international workshop on submesoscale air-sea interaction (described in more detail in the section below). Here, our focus will expand to encompass a wide range of areas (including the coasts and high-latitudes) of the ocean and other climate systems with a special focus on the 1 - 100km scales which were less scrutinized in the past but now resolved by SWOT. This will further highlight the ocean's integral role in the climate context.

Objectives

The dynamic nature of upper ocean processes and their fundamental role in the climate system demands an interdisciplinary approach. Our attention is on the new satellite missions SWOT and PACE, regional field campaigns, and high-resolution coupled simulations, and their potential utility in studying small-scale ocean processes and their interactions with other climate system components. Recognizing this, the primary objectives of the working group are as follows:

Foster an Interdisciplinary Community

Our aim is to cultivate a cohesive community that bridges disciplines with overlapping interests in upper ocean physics, marine biogeochemistry and climate. The specific targeted communities include small-scale process physical oceanography community that encompasses those involved in NASA S-MODE and SWOT field campaigns, US CLIVAR mesoscale air-sea interactions working group, high-resolution global and regional ocean simulations, coastal and cross-shelf exchange research community, ocean-cryosphere interaction community, PACE science teams and community, bio-physical interaction research community, etc. International participants will represent similar efforts taking place in Europe (e.g., Harmony, Seastar, and Digital Twin earth modeling). The working group will be composed of representatives from each community for focused review studies.

Review current gaps in theory, observations, and models

A comprehensive review will be undertaken to identify and elucidate the existing gaps in our understanding of small-scale processes in the upper ocean's role in the climate system. Systematic reviews in each topical area do exist, but they either generally do not draw interdisciplinary connections or lack a focus on the climate impacts. We will therefore focus on bringing different topics and research communities together, emphasizing their connections to climate variability. For example, what is the status of coastal circulation prediction? To what extent is the coastal altimetry community ready to add SWOT measurements to the existing products, and how will this impact our understanding of climate at the coasts? Do we fully understand the oceanic processes between 1 and 100 km scales in the open ocean? Recent work suggests small-scale processes may play a globally important role in the upscale energy cascade as well as energizing turbulent mixing of the boundary layer. How might the cumulative effects of small-scale processes modify climate through both physical and biogeochemical pathways? What additional measurements do we need for marginal sea ice zone studies beyond ICESat-2 and SWOT? What new interdisciplinary research is to be enabled by SWOT and/or PACE? Where is parameterization development most likely to be impactful in improving ocean and climate modeling accuracy? What strategies can be developed to assess the global impact of processes on scales which are not generally accessible via direct global modeling?

Provide guidance on best practices

Leveraging the expertise within the community, the working group will develop guidelines on best practices for interdisciplinary research, including best practices on data management (which for example can be particularly demanding at the high-resolutions considered here), code sharing, OSSE studies, using theory to guide campaign development, verification of theories from observations, model-observation comparison, and so on. This will not only ensure the robustness and reliability of our studies but also pave the way for future researchers in this domain.

Inform future observing system design

In tandem with our guidelines on best practices, we will provide insights and recommendations on the design of future observing systems. By marrying our understanding of upper ocean processes with recent technological advancements, we aim to provide guidance for future small-scale ocean observations from in-situ as well as space.

Workplan

1. 1-12 months: Conduct reviews
   a. Formulate sub-groups for literature reviews on each topic with a focus on identifying critical gaps in understanding, observation, and model development again with a particular focus on climate impacts. The topics include (1) Small-scale Ocean dynamics and theory; (2) Coastal circulation dynamics and observations (including engagement with coastal process working group); (3) Marginal ice zone; (4) Marine ecosystem and physical-biogeochemical interactions; (5) Air-sea interactions (With representation of the air-sea interactions working group from Villas Boas).
   b. Conduct monthly tag up to discuss progress, interconnections among groups and Q&A. Each sub-group will conduct their own review on their topic and discuss with other sub-groups during the monthly tag ups.
   c. Implement a public webinar series with guest speakers to inform the working group review and broader community on small-scale ocean processes and climate.
2. The end of year 1: Organize an open community workshop with the dual objectives of reviewing and summarizing the findings from Task 1 and fostering community engagement. This

workshop will serve as a critical platform for identifying knowledge gaps and establishing best practices, thereby guiding the design of future observing systems. Additionally, it will offer an opportunity for the broader community to contribute insights and feedback that will enrich the review manuscript.

3. Finalize manuscript and submit for publication (12-23 months)
   a. Curate repositories of data sets and open-source tools
   b. Monthly tag ups and manuscript writing
   c. Continue monthly webinars of new studies
4. Organize a session and a townhall for OSM26 (near the end of the second year)
   a. During the townhall, we will summarize the working group findings and the manuscript
   b. Invite the community to share new research in the OSM26 session.
5. Create open-source repositories for the technical code and documents as the working group archive (24-30 months)

Collaborations

Within US CLIVAR

Coastal Process Working Group: Recognizing the intricate dynamics at the interface of land and sea, our collaboration with the Coastal Working Group will be pivotal. The interplay of small-scale processes in the upper ocean with coastal phenomena can significantly influence coastal weather patterns, sea-level variations, and marine ecosystems. Joint endeavors with this group will ensure a complementary effort in this topic.

Air-Sea Interactions Working Group: The recently concluded efforts of the Air-Sea Interaction Working Group have laid a solid foundation upon which we can build. Their experience will guide us on organizing our working group. By dovetailing their outcomes with our focus on small-scale ocean processes not covered in their review, we can achieve a deeper understanding of how these interactions manifest at the interface with other elements of a broader climate system.

International Partnerships

SWOT Adopt-a-Crossover Teams: Under the endorsement of International CLIVAR, the SWOT Adopt-a-Crossover initiative has gathered more than 15 international teams, many of whom are keen on continuous engagement with CLIVAR. Our collaboration with these international teams will offer a unique opportunity to leverage the data from the SWOT mission, enhancing our understanding of small-scale processes in various oceanic regimes across the globe.

Atmosphere-Ocean coupling at the (sub)mesoscale: A recently concluded international workshop at the Lorentz Center (Netherlands) brought together an interdisciplinary community with both atmospheric and oceanic perspectives to discuss the gaps in our understanding of small-scale air-sea interaction. This workshop was co-chaired by Wenegrat (PSMIP) and Larry O'Neill (Air-Sea Interaction Working Group) among others, and highlighted the significant gaps in our understanding of upscale (in time and space) impacts of small-scale air-sea interaction processes. This group is currently developing a whitepaper, which will set a series of objectives that will be helpful guide this US CLIVAR working group, and we further propose the addition of several international members to represent these research communities.

Team composition

The team will be led by the POS and PSMI panels. The team composition is as follows.

	Name	**Institution**	**Expertise**
1	Jacob Wenegrat*	U. Maryland (chair)	theory, simulation
2	Jinbo Wang	JPL (co-chair)	SWOT, high-res simulations
3	Monique Messié	MBARI (co-chair)	ecosystems
4	Bia Villas Boas*	Colorado School of Mines (co-chair)	air-sea, surface waves, theory, observations, remote sensing
5	Andy Thompson	Caltech	theory, observation, physics-bio-sea ice
6	Sahra Kacimi*	JPL	polar, sea ice
7	Momme Hell*	NCAR	winds, waves, sea ice
8	Channing Prend*	Caltech/UW	biogeochemistry
9	Amala Mahadevan	WHOI	submesoscale bio-physical interaction
10	Louise Nuijens	TU Delft	wind and clouds
11	Dhruv Balwada*	Columbia U	theory, machine learning
12	Lia Siegelman*	UCSD/SIO	turbulence theory, remote sensing
13	Leah Johnson	UW/APL	observations, theory
14	Dan Whitt*	NASA/AMES	high-res simulation of physical and biogeochemical processes, low-latitude processes
15	Ke Chen	WHOI	POS panel, coastal processes
16	Bob Hallberg	NOAA/GFDL	global high-res simulations
17	Luke Van Roekel	LANL	turbulence, coupled ocean atmosphere interactions

* Early career

Resources requirement

We will need budget for the following activities:

- One dedicated 3-day long workshop, travel support for ~ 20 working group members and/or early careers
- Administrative support for webinar organizing, document sharing, travel logistics
- Publication fees for one open-access manuscript (e.g., to BAMS)

- $1000 AWS credit for sharing code and online analysis

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