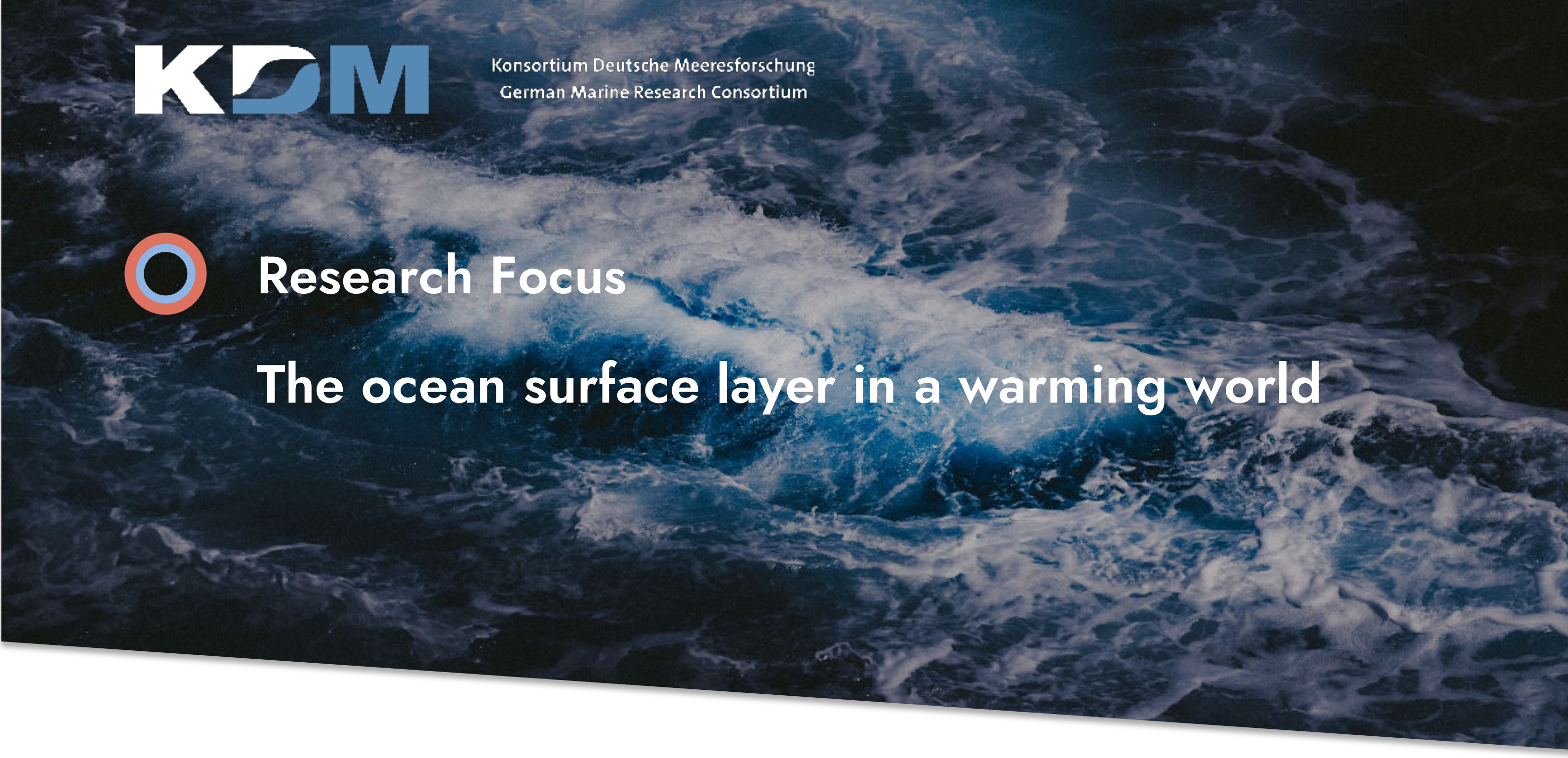

Research Focus

The ocean surface layer in a warming world

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A research focus theme of the German oceanographic community

KDM Strategy Group on Ocean Circulation and Climate

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The following is a proposal for a strategic initiative launched by the Ocean Circulation & Climate Strategy Group of the German Marine Research Consortium (KDM). The group addresses research priorities to better understand the interaction of ocean circulation and climate change. In the past years, this group has developed strategies to better understand the Gulf Stream and Atlantic Ocean circulation. With this new proposal, the Strategy Group is charting its work beyond 2026.

Motivation

The ocean mixed layer (ML) is the well-mixed ocean surface layer where temperature and salinity are nearly uniform, overlying the stratified waters below where temperature and salinity change with depth. While oceanic properties vary widely from the tropics to polar regions, and from the deep ocean to marginal seas, the presence of a ML is nearly universal (see Fig.1). This ocean surface layer modulates interactions between the ocean and atmosphere, between the ocean and sea ice, and represents the region of the ocean most strongly illuminated by sunlight that drives biological production and the biological carbon pump. For example, the ML determines how atmospheric forcing is experienced by the deep ocean and modulates oceanic fluxes to and from the atmosphere thereby affecting winds and cloud formation. While present nearly everywhere, the ML experiences dramatic regional and temporal changes due to heating and

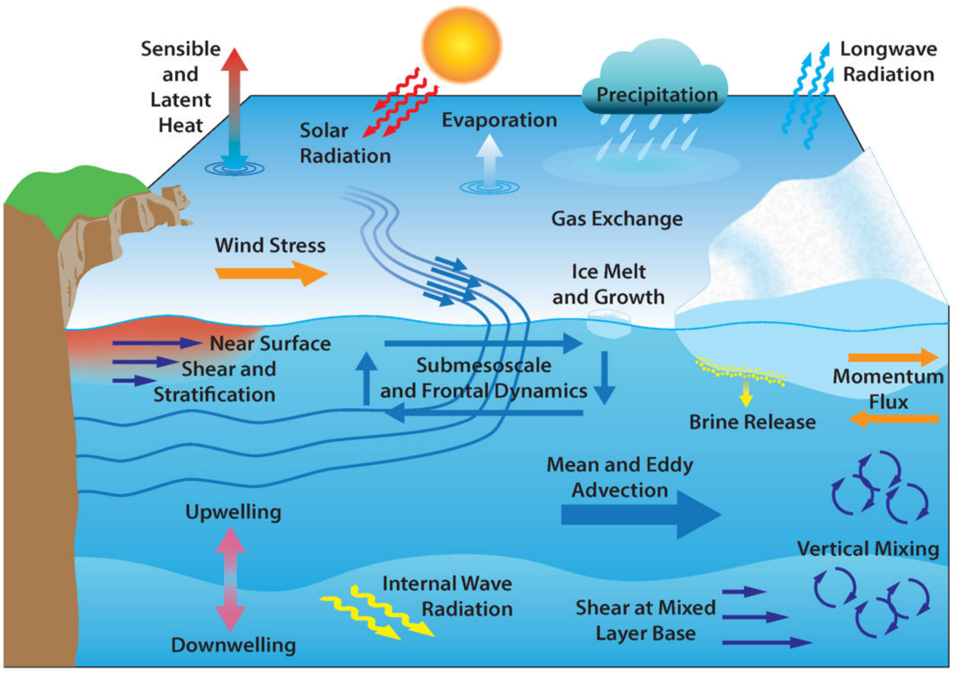

Figure 1: Ocean surface layer processes regulating the exchanges between the stratified ocean below and the atmosphere / sea ice above. Submesoscale frontal dynamics play a pivotal role.

cooling, precipitation and evaporation, sea-ice formation and melt, and atmospheric and ocean circulation. Consequently, the ML can sometimes be as shallow as a few meters and, at other times, it may extend a few thousand meters vertically. The strongest marine heat waves, fastest ocean currents and sharpest oceanic fronts are all found in the ML. Ocean heat waves have caused devastating effects on marine ecosystems, including fish stock decline and coral bleaching events. Under global warming, the strongest changes in temperature and salinity in the ocean have been in the ML, being in direct contact with the warming atmosphere. Global average sea surface temperature (SST) is projected to rise by 0.9°C by the end of this century (IPCC), with an increase in heat waves and storminess. Oceanic fronts represent zones of strong vertical exchanges of heat, carbon and nutrients associated with upwelling, downwelling and turbulent mixing, thereby mediating the ocean's role in taking up excess heat and carbon in a warming world.

Science Case

While the SST has risen globally over the past decades, the warming signal is spatially inhomogeneous, with e.g. the Southern Ocean SST showing hardly any warming signal – even though most of the anthropogenic warming the oceans have experienced was absorbed by the Southern Ocean. In addition, state-of-the-art coupled climate models – used for future projections – show strong regional SST biases compared to observations, for instance in the major upwelling regimes in the tropical and subtropical eastern basins of the world oceans. As a consequence of the warming, the upper ocean stratification has increased in recent decades and is projected to continue. While a stratification increase might be expected to coincide with a shallowing of the ML, indeed the opposite has been observed. MLs in both summertime and wintertime have deepened significantly over the past few decades (see also Fig. 2). Areas, in which climate models project strong future reductions of the ML thickness include the subpolar North Atlantic, the Nordic Seas and parts of the Atlantic sector of the Southern Ocean, whereas the Arctic Ocean is thought to experience a future increase in ML thickness because of retreating sea ice. The future development of the ML is also crucial for the projected efficacy of the "physical pump" for the fluxes of anthropogenic CO_2 into the interior of the ocean. This includes associated factors such as the very thin surface film on top of the ML and the stratification between the ML and the ocean interior. In particular, the climate models fail to resolve the processes associated with oceanic fronts in the ML, which are ubiquitous features of the ocean. So-called submesoscale processes play a fundamental role in the redistribution of heat, salt, and marine biomass, as they act to extract properties and energy from the larger-scale flow field and transfer them to scales where mixing occurs. Thin low-density layers created at the sea surface by radiative forcing, precipitation or sea ice melt may

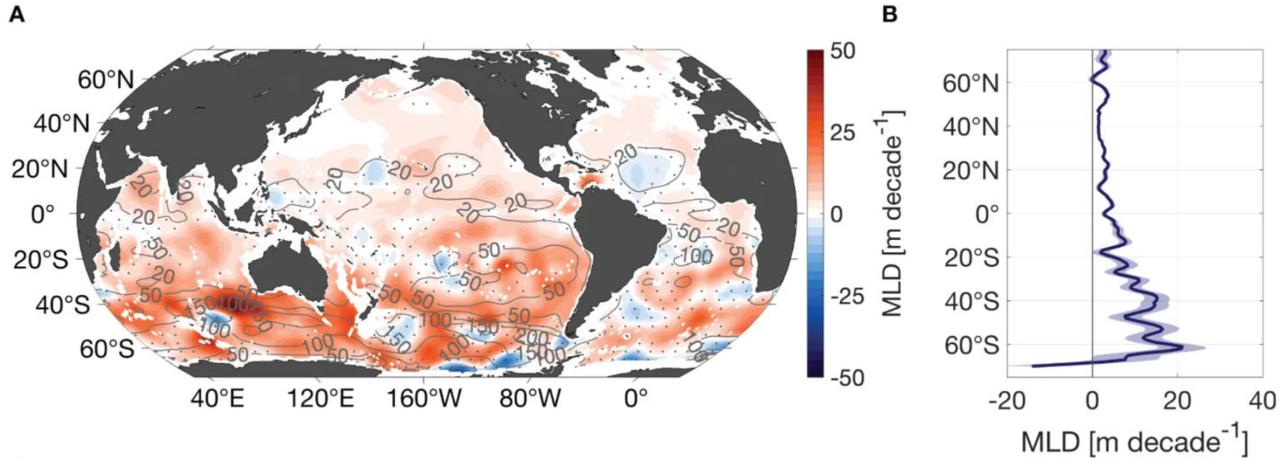

Figure 2: Decadal trend of the mixed layer depth in July-September and (B) trend of the corresponding zonal mean for the period 2006-2021 (from Roch et al., 2023).

strongly modulate turbulent air-sea heat fluxes, wind power input and gas exchange depending on wind, surface waves and subsurface turbulence. Here we suggest a concerted approach to quantify the role of these critical processes in a warming world.

Timeliness

This research theme is timely for several reasons. Firstly, strong biases of ML properties in global climate models and strong projected sensitivities of the ML in a changing climate make high-frequency and frontal dynamics an important subject of study. This is even more relevant as climate models are getting closer to resolving mesoscale and submesoscale circulation features (eddies, filaments, ML instabilities). With the increasing model resolution, adequate observations must be provided for validating identified processes in the model simulations and to develop parameterizations for processes still not resolved by the models. While this method is certainly suitable for more stable historical conditions it is not clear how the model's sensitivity to climate change is affected, which asserts a systematic uncertainty on global and regional climate projections (such as in the framework of the CMIP). Consequently, the next big frontier in ocean and climate models is the representation of submesoscale processes and associated air-sea interaction.

Also, there are exciting novel observational capabilities. Data from a new generation of satellite missions is becoming available - such as SWOT - which are able for the first time to resolve submesoscale circulations features. New observational capabilities (e.g., gliders and towed platforms), when combined with traditional platforms (moorings, buoys and wave radar) have enabled the German oceanography community to develop expertise for the experimental study of submesoscale/frontal phenomena - from the polar regions to the tropics. Other promising marine autonomous platforms such as wavegliders and saildrones - ideally suited for the study of the surface ocean - have reached a mature level of development, so that the German oceanographic community could take them on board.

Societal Need

There is a strong societal need for the development of improved marine data products related to the circulation, stratification and fluxes at the sea surface. The science we suggest carrying out is designed to develop surface layer processes from a mechanistic understanding towards regional and global impacts. As highlighted above, understanding the surface layer is crucial for the projected efficacy of the "physical pump" for the fluxes of anthropogenic CO_2 into the interior of the ocean. The understanding we envision to provide supports a better quantification of physical parameters influencing surface focused carbon sequestration efforts. Other important applications are marine rescue operations, marine pollution (e.g., oil spills and plastic litter), harmful algae blooms, and environmental impact assessment of human activities. Finally, even at the envisioned spatial resolution of next generation ocean and earth system models, small-scale processes will need to be parameterized. A more in-depth understanding of these processes will lead to better constrained parametrizations and to a decrease in model biases and weaknesses and ultimately to improved (physics-informed) projections.

Approach

Our overarching goal is to quantify the roles of submesoscale frontal processes / fluxes on a global scale. We take a three-pronged approach, relying on a combination of focused in situ observations, process modelling, remote sensing on a regional scale, and global climate modelling.

A starting point for the German science community would be to concentrate observational research in focus areas covering tropical, subpolar and polar oceans. The rationale for the individual areas is

– Tropical Upwelling areas (SST bias in climate models, strong heat uptake and CO2 outgassing, upward nutrient flux and biological productivity, marine heat waves);
– Arctic Ocean (Strong projected deepening ML and increased vertical heat flux under retreating sea ice - halocline already eroding especially in marginal ice regions);
– Subpolar North Atlantic (strong projected reduction of ML depth; window to the deep ocean; carbon uptake);
– Atlantic Sector of Southern Ocean (strong projected reduction of ML depth; window to the deep ocean; ocean heat and carbon uptake); and
– Marginal Seas (such as OSPAR and HELCOM regions).

Use of submesoscale-resolving process modelling in the focus areas combined with new remote sensing products would help to assess the representativeness of the submesoscale fluxes revealed by in situ observations in space and time. Use of mesoscale resolving climate models with different parameterizations of submesoscale processes finally allow for an integration of the results obtained in the focus regions on a global scale.

Goal and Outcomes

Despite its fundamental role in the oceans' role in climate, submesoscale impacts are currently not systematically considered in the CMIP framework that guides the IPCC assessment of ocean and climate changes. In fact, the latest IPCC report mentions the term submesoscale ocean processes only on two occasions - showing that it is clearly underrepresented in its importance. One of the strategic outcomes of our initiative would be to create actionable knowledge relevant for upcoming IPCC assessments of ongoing and future climate change. Specific fields would include:

– Better understanding of the role of submesoscale and high-frequency processes including surface waves for air-sea exchange of heat, momentum and anthropogenic carbon as well as the corresponding fluxes between the ML and the ocean interior,
– Rigorous assessments of model deficiencies in focus regions, development of parameterizations and improvements of model predictions and projections, and
– Impact of the processes on regional and global scale (such as subduction, upwelling, momentum transfer, etc).

Additional impact would be created by the

– generation of new data products of societal relevance,
– strengthening of research competence of the German scientific community in ocean observations and modelling, and
– education of new generation of scientists.

References

Roch, M., P. Brandt and S. Schmidtko (2023) Recent large-scale mixed layer and vertical stratification maxima changes, Front. Mar. Sci., 10, 1277316, doi:10.3389/fmars.2023.1277316, 2023.