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14. ABSTRACT

This project is a study of vertical mixing processes in surface boundary layers and subsurface barrier layers of the Northern Arabian Sea (NAS) using Large Eddy Simulation (LES) techniques and turbulence-parameterizing Second Moment Closure (SMC) models, both as column models and implemented in a regional circulation models. The major goals of this study are to contribute to our long-term efforts to understand: 1) The dynamics of barrier layers and surface mixed layers in the N. Arabian Sea; 2) The penetration of radiative and atmospheric fluxes into the ocean interior; 3) Interaction of finescale and submesoscale processes in barrier layer formation; and 4) Characteristics and impact of internal gravity waves trapped above barrier layers. COAWST coupled modeling framework from the SWAN surface wave model.

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Northern Arabian Sea Circulation – autonomous research (NASCar) DRI: A Study of Vertical Mixing Processes in the Northern Arabian Sea

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Objectives

This project is a study of vertical mixing processes in surface boundary layers and subsurface barrier layers of the Northern Arabian Sea (NAS) using Large Eddy Simulation (LES) techniques and turbulence-parameterizing Second Moment Closure (SMC) models, both as column models and implemented in a regional circulation models. The major goals of this study are to contribute to our long-term efforts to understand:

- The dynamics of barrier layers and surface mixed layers in the N. Arabian Sea
- The penetration of radiative and atmospheric fluxes into the ocean interior
- Interaction of finescale and submesoscale processes in barrier layer formation
- Characteristics and impact of internal gravity waves trapped above barrier layers

Objectives in working towards these goals within the NASCar DRI include using turbulence-resolving LES and regional ocean models (ROMS) using a range of SMC mixing parameterizations to simulate upper ocean processes associated with barrier layer formation and evolution, and with both diurnal vertical restratification and mixing processes. These modeling goals emphasize the role of surface waves in upper ocean mixing processes, driving LES and upper ocean turbulence closures with surface wave forcing from observations or, for ROMS, through the COAWST coupled modeling framework from the SWAN surface wave model. A major objective is to extend existing LES and ROMS process modeling to evaluate theories of the impact of surface wave-driven mixing through comparisons with NASCar field experiment data.

Accomplishments

LES and SMC techniques were used to predict mixing both within and vertically adjacent to the halocline separating the surface mixing layer and the subsurface barrier layers in the NAS. Simulations included both processes of formation through vertical forcing and horizontal advection across a salinity gradient. An important focus was the testing, implementation and validation of improved turbulent mixing parameterizations in conjunction with LES modeling, autonomous field observations, and regional-scale operational and process modeling, focused on predicting the response to surface forcing.

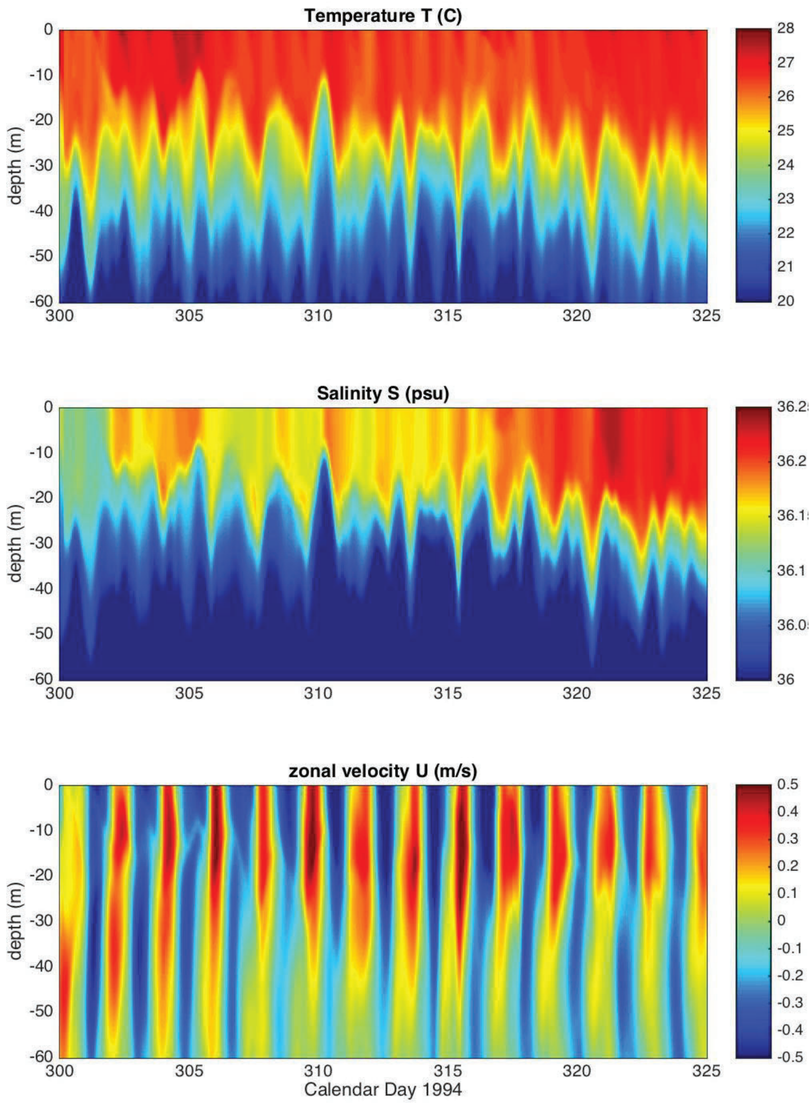

Figure 1: Virtual station time series of upper ocean temperature, salinity and zonal velocity from regional ocean model (ROMS) coupled to a surface wave model (SWAN) through a SMC model of vertical mixing in the upper ocean by Langmuir turbulence, and driven by surface fluxes from the 1994-1995 ONR Arabian Sea Experiment. Steady mixed layer salinification driven by evaporation under strong diurnal forcing, accompanied in these results by near-inertial internal waves and pycnocline heaving permitted in this small-domain 3D column model, a feature not typically included in 1D column models.

Subsequent efforts focused on the role of wave-driven upper ocean turbulence, and on modeling to study those vertical mixing processes whose critical evaluation in ocean models is enabled by currently available NAS data sets. Given a paucity of full directional wave spectra coincident with NAS boundary layer observations, parameterizations of wave-enhanced turbulence were implemented in the COAWST version of the ROMS regional ocean model, which includes coupling to the SWAN surface wave model and the WRF atmospheric model. Implementations in 1-dimensional versions of the coupled model (Fig. 1) have demonstrated significant impacts on the accurate prediction of the formation of barrier layers through vertical mixing processes with steady forcing.

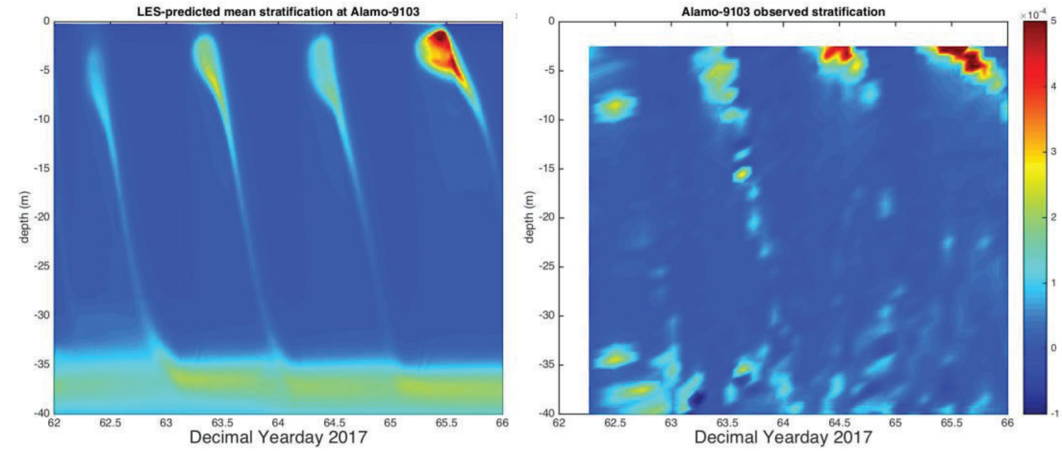

Figure 2: Subset of model-data comparison between LES and NASCar profile data from Alamo float 9103 (Steve Jayne; communicated data), between 3-7 March 2017 (decimal yeardays 62-67). Profiles of stratification N^2 show the diurnal cycle shoaling the mixed layer to less than 5m under strong shortwave insolation and light winds, separated by night-time convection to 35m driven by surface cooling.

Interest in diurnal restratification and vertical mixing processes under strong NAS shortwave radiative daytime forcing has motivated a more detailed analysis of vertical heat and scalar fluxes in Langmuir turbulence. This has led to the identification of nonlocal scalar fluxes driven by Langmuir turbulence as an important vertical flux process not yet included in either nonlocal first moment closures (i.e. KPP) or in second moment closures (eg Mellor-Yamada, Kantha-Clayson, Canuto, k-epsilon, etc...), including the Harcourt (2013; 2015) closure for Langmuir turbulences. The absence from the mid-to lower mixed layer of these nonlocal vertical fluxes, driven by their formation in near-surface Langmuir jets, can potentially impact the accuracy of predicting diurnal restratification. Significant impacts are more likely to be found at mid-depth in the restratifying layer and under intermediate shortwave radiation strength, as near-surface stratification is more strongly impacted by additional mixing from wave-breaking, and restratification under very strong solar insolation rapidly extinguishes Langmuir turbulence. Comparisons with NASCar autonomous measurements (Fig 2) generally supported predictive skill of LES and closure models, but typically lacked well-characterized surface forcing necessary to distinguish between competing theories of near-surface physical processes.

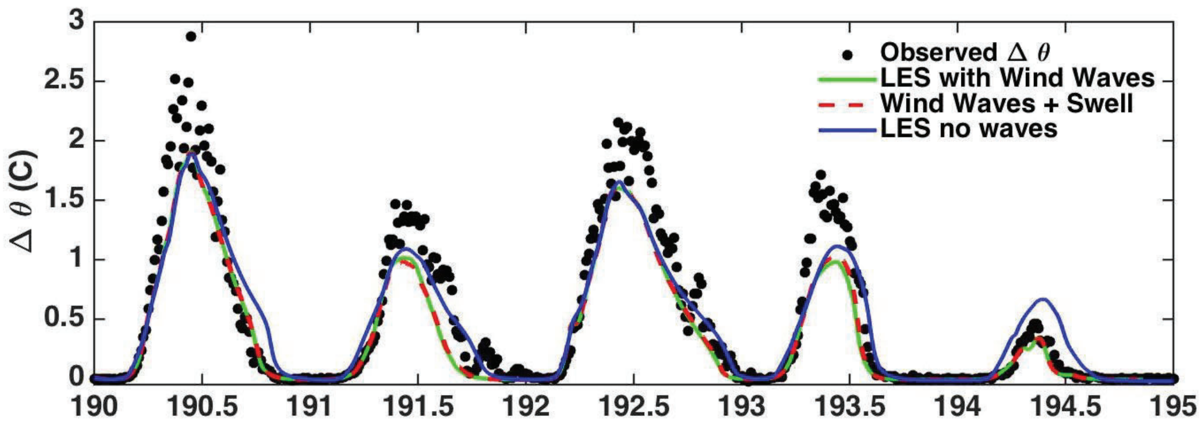

Figure 3: Detail of model-data comparison between LES and Arabian Sea Experiment data, for a series of days (190-193) with weak winds, followed by a day of strong winds (194). Models under weak winds tend to underpredict surface heating, while models with wave-turbulence effects do a better job of predicting surface temperature under significant wind forcing.

Further examination of near-surface vertical mixing processes in the NAS therefor used both Large Eddy Simulation (LES) and turbulence closure modeling for direct model-data comparison. LES techniques were applied to long-term mooring and meteorology records from a prior ONR NAS field campaign (Ostrom et al., 1996), to evaluate predictions of upper ocean turbulent mixing processes that govern SST on timescales between a few hours to several weeks (Fig. 3). Some results from LES modeling of NAS diurnal cycling over periods of several weeks, and model-data comparisons based on 1994-5 measurements during the ONR Arabian Sea Experiment. These comparisons found that, contrary to earlier modeling results of Janssen (1993) based on first moment local closure modeling, wave breaking does not significantly impact near-surface stratification in the NAS during the in the early spring season observed in that experiment and again in the NASCar DRI field experiment. While general results for diurnal cycle daytime temperatures tended to be ambiguous, comparisons under strong wind conditions pointed clearly to the importance of wave-turbulence interaction through the Craik-Leibovich vortex force in moderating these daytime temperatures under conditions of strong wind and wave forcing.

The experience of model-data comparisons in NASCar and to other NAS and also similar low-latitude Atlantic locations led to development of some parameterizations of surface layer turbulence dynamics and empirical scaling predictions for near-surface thermodynamic and passive scalar gradients. Initial development of these in a theoretically-focused paper by Kukulka and Harcourt (2017). Subsequent application of these ideas in a UW graduate student paper by Zheng et al. (2021) also appropriately credits NASCAR DRI for the role in early formulation of the scaling approach used, the development of theoretical ideas from the model-data comparisons in the NAS, and the identification in particular of night-time near-surface gradients as an area where uncertainties of light absorption characteristics are reduced, but where the signal is still well-measured by highly accurate temperature measurements at moorings.

Additional work on model implementations of improved closures accounting for relevant wave-turbulence interactions included assisting NRL Stennis with the implementation in Navy models by Martin and Savelyev (2016) and subsequent work with colleagues to implement them in the COAWST wave-coupled version of ROMS (Liu et al., 2021). These advances in model capabilities are what are needed to make more physically accurate predictions of surface and mixed layer evolution in the North Arabian Sea, as well as in other regions of relatively shallow mixed layers.

Impact/Applications

NASCar DRI results bear on the predictive skills of regional scale models, particularly in areas with barrier layer formation. While accuracy in predicting these layers bears on the skill of coupled atmospheric models that depend on SST, progress in understanding the finescale and submesoscale processes of their formation will have broader impacts on ocean modeling skill.

Products

This study has directly contributed to two peer-reviewed publications (Kululka and Harcourt, 2017; Zheng et al., 2021) and a conference presentation (Harcourt wet al., 2016). It has also contributed in formative or supporting roles to an additional technical report (Martin and Savelyev, 2016) and another peer-reviewed publication (Liu et al., 2021).

Training and Development

The PI Harcourt was relatively new to using the ROMS regional ocean model at the beginning of this project, and also to using it coupled to SWAN (or WRF) for that matter. Self-education was being supplemented by attendance at a workshop on using the COAWST modeling system, hosted by J. Warner (USGS) at WHOI. Harcourt has worked on implementing and disseminating new models of upper-ocean mixing by Langmuir turbulence in both 1-D column models and 3D ocean circulation models.

Dissemination

Results have been disseminated through an article (Kukulka and Harcourt, 2017), and through participation in NASCar DRI meetings and a program review, and through results through a presentation at the ocean Sciences meeting of the AGU in February, 2016 in New Orleans. Harcourt has consulted as well with P. Martin, I. Savelyev G. Jacobs (NRL) on implementing the SMC of Langmuir turbulence in the NCOM ocean model, coupled to the WaveWatch 3 surface wave model.

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