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**Project Title:** "Southern Ocean Uptake in the MPAS-Ocean Model"
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**Award To:** NATIONAL CENTER FOR ATMOSPHERIC RESEARCH (NCAR)

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## EXECUTIVE SUMMARY:

The research added to the understanding of Southern Ocean Uptake in the following ways.

1) No single process in the model could be "tuned" to improve Southern Ocean uptake of heat, $CO_2$ and CFCs.

2) More comprehensive studies revealed that multiple aspects of the model are important; in particular the general circulation control of deep (>200m) stratification (Small et al., 2019) and salinity contributions to the shallow (< 200 m) stratification (DuVivier et al, 2018). These two aspects are not strongly connected. The first can be very much improved by increasing horizontal resolution, primarily because of more transport of high salinity water from the Indian Ocean into the Southern Ocean south of Africa, so we now know that "parameterizing" this salinity source will be one necessary step to improving the Southern Ocean uptake at low resolution.

3) However, the second was found to be more than just a resolution issue, which may explain why many studies have found that higher resolution improves only some aspects of model solutions, but degrades others. Even in cases where the surface wind is too strong, the shallow stratification is sufficient to inhibit vertical mixing even though the salinity stabilization is weak compared to observations. The conclusion is that the process responsible for mixing through the stable salinity barrier above 200m is missing from the model. Therefore, a second necessary step is to find the process then incorporate it into the model. The project focused on ocean surface wave driven Langmuir turbulence as the source of additional mixing by studying Large Eddy Simulations (LES) of Southern Ocean boundary layers as they eroded a realistic salinity barrier. The wind, buoyancy and wave driven boundary layer turbulence was found to be well described by Monin-Obukhov similarity by developing similarity functions of the wave driving, and combining these with the established wind and buoyancy functions (Large et al., 2018a). These functions and a novel analysis of the momentum flux and vertical shear fields from the LES revealed two distinct aspects where the boundary layer turbulence was much more organized than expected, and hence much more amenable to implementation in the model (Large et al., 2018b). First, there is a robust non-local across-shear transport of momentum throughout the ocean boundary layer; a hitherto missing process.

> Furthermore, this transport is related to the across-shear component of the wind stress in the same way that non-local buoyancy transport is related to the surface buoyancy flux, both in the ocean and atmosphere. Even the coefficients are similar in the convective limit. Second, the turbulent fluxes of momentum and buoyancy are distributed through the ocean boundary layer of the LES in a very orderly fashion given by a single shape function that appears to be applicable to both momentum and buoyancy, with or without surface wave driving.

Thus, a very technically effective and economic path to incorporating surface wave driving in the vertical mixing scheme of the model is now clear. The high degree of order found for ocean boundary layer turbulence, including Langmuir turbulence, is more amenable to empirical models than to statistical turbulence models, and the computational cost is very much less. Fortuitously, the empirical K-Profile Parameterization is already implemented in the model and the wave-driving similarity function, the non-local momentum transport and the vertical shape function are straightforward enhancements.

## MODEL COMPUTATIONS

The Large Eddy Simulation (LES) model is well tested and documented (e.g., Sullivan et al. 2012; J. Phys. Oceanogr.), and has been adapted to simulate ocean boundary layers. The model dynamics integrate the wave-averaged, incompressible, and Boussinesq, Craik-Leibowich equation set (McWilliams et al. 1997; J. Fluid. Mech.). The model dynamics integrate the wave-averaged, incompressible, and Boussinesq Craik-Leibowich equation set (McWilliams et al. 1997). The additional terms arising from phase-averaging over the surface waves include: Stokes-Coriolis, vortex force and a Bernoulli pressure head in the momentum equations, and horizontal advection by Stokes-drift in the scalar equations, as well as additional production of sub-grid-scale energy by vertical gradients of Stokes drift (Sullivan et al. 2007; J. Fluid Mech.). Thus, the LES represent a solution to the Navier-Stokes equations including processes responsible for non-local buoyancy and momentum transport.

The LES experiments utilized resources of the National Energy Research Scientific Computing Center, a DOE Office of Science User Facility supported by the Office of Science of the U.S. Department of Energy under Contract No. DE-AC02-05CH11231.

## PROJECT PUBLICATIONS REFERENCED

DuVivier, A.K., W.G. Large and R.J. Small, 2018: Argo observations of the Deep Mixing Band in the Southern Ocean: A salinity modeling challenge. J. Geophys. Res., **123**, doi: 10.1029/2018JC014275.

Large, W.G., E.G. Patton, A.K. DuVivier, P.P. Sullivan and L. Romero, 2019a: Similarity theory in the surface layer of large-eddy simulations of the wind, wave and buoyancy forced Southern Ocean. J. Phys. Oceanogr., Submitted.

Large, W.G., E.G. Patton, A.K. DuVivier and P.P. Sullivan, 2019b: Non-local transport and implied viscosity and diffusivity throughout the boundary layer in LES of the Southern Ocean with surface waves.. J. Phys. Oceanogr., Submitted.

Small, R.J., A.K. DuVivier, D. Whitt, M. Long, I. Grooms, W.G. Large, 2019: On the control of Subantarctic deep stratification by the ocean general circulation. J. Geophys. Res., In Prep.