Windrows in Global Models: Does Langmuir Mixing Matter for Climate?

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I. Abstract

Global wave and wind field data from AVISO and TOPEX altimetry, the ERA40 reanalysis, and the NOAA WaveWatch III model were used to formulate a climatology of the relationship between wave and wind variables. This climatology, along with ideas from Li and Garrett (1997), were used to parameterize Langmuir mixing (LMx) in CCSM. 20^{th} century simulations show significant, yet sensitive, effects from including LMx, with deeper mixed layers and improved CFC concentrations in the Southern Ocean.

II. Langmuir Cells and Mixing

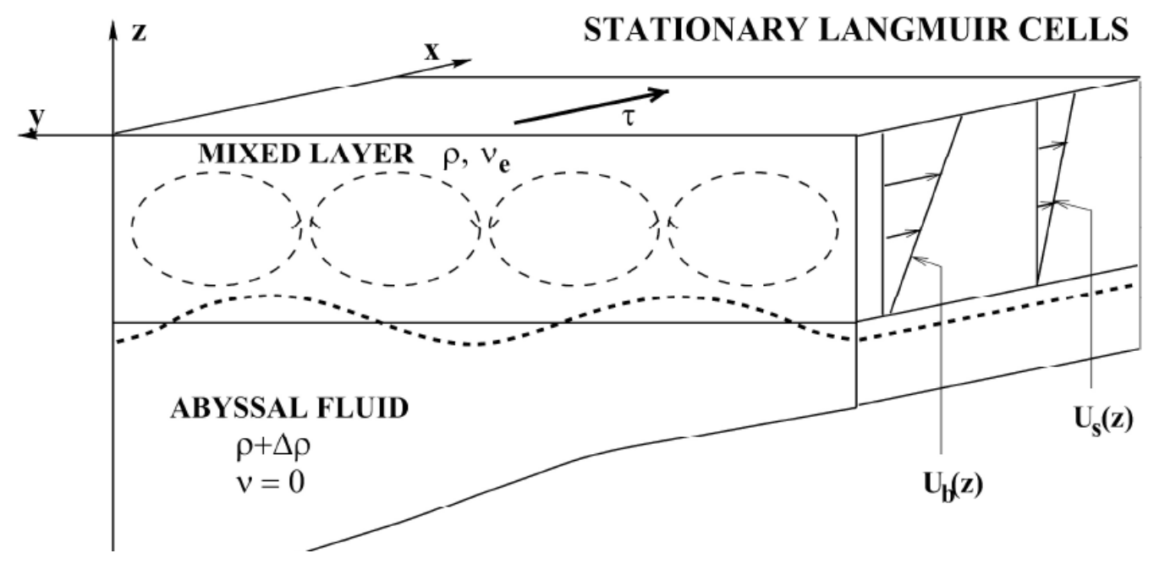

Figure 1: Cartoon of Langmuir Cells

Langmuir cells (LC) are small overturning cells (10-100m wide and 1-10km long) that form in the near-surface ocean when wind and waves are moving approximately in the same direction. Depending on the speed of the wind and waves, these cells can increase greatly increase the amount of mixing in the mixed layer. Observations indicate that even when these cells are not obvious, Langmuir turbulence (LT)–a disordered jumble of LC–can lead to near-surface turbulent kinetic energy double what is expected without LMx (D'Asaro, 2001). The turbulent Langmuir number, $La = (u^*/u_s)^{1/2}$ (McWilliams et al., 1997), is a non-dimensional parameter useful in inferring the additional Langmuir mixing, where u^* is the skin friction velocity from wind and u_s is the Stokes drift veloctiy of the waves.

III. Potential Importance of Langmuir Turbulence

The ocean surface acts as a filter on ocean-atmosphere communication of momentum, energy, and chemical tracers (e.g., $C0_2$) and contains the euphotic region where phytoplankton grow. Submesoscale and smaller (¡10 km) physics create and preserve this environment, so it is important to accurately model and parameterize these unresolved scales in this turbulent region. Before this work, it was unclear how important a role LMx may play in deepening the mixed layer since this region that is already well-mixed. Observations differ as to the importance on LMx: some show rapid deepening of the mixed layer in the presence of LC (Smith, 1998; Li et al., 1995; D'Asaro, 2001), others do not (Weller and Price, 1988). Large Eddy Simulations (LES) indicate potent effects of LT (McWilliams et al., 1997; McWilliams et al., 1999; McWilliams and Sullivan, 2001; McWilliams et al., 2007; Harcourt and D'Asaro, 2008).

This work set out to determine whether on a global scale conditions are sufficiently favorable for LT that they may play a frequent enough role to affect the climatology of the ocean surface layer. It was suspected that some observations might fall where these circulations were expected to be weak ($La_t \gg 1$), while others where they were strong ($La_t \ll 1$).

Currently, the NCAR CCSM model uses the KPP mixing scheme (Large et al., 1994) to account for near-surface mixing. LMx is included only indirectly through tuning–the parameterization is trained against data but does not include explicit wave information. It was generally supposed the ocean wave field is usually fully-developed, so wave information could be inferred (Pierson, Jr. and Moskowitz, 1964). Fully-developed waves have $La_t \approx 1/\sqrt{10}$. In additon to measuring surface height, altimeters are able to measure wave height, wind speed, and wave period. TOPEX altimetry and ERA40 reanalysis (assimiliating ERS altimetry and wave buoy data) both indicate that the variability of Langmuir number is likely to be much larger (see figure below).

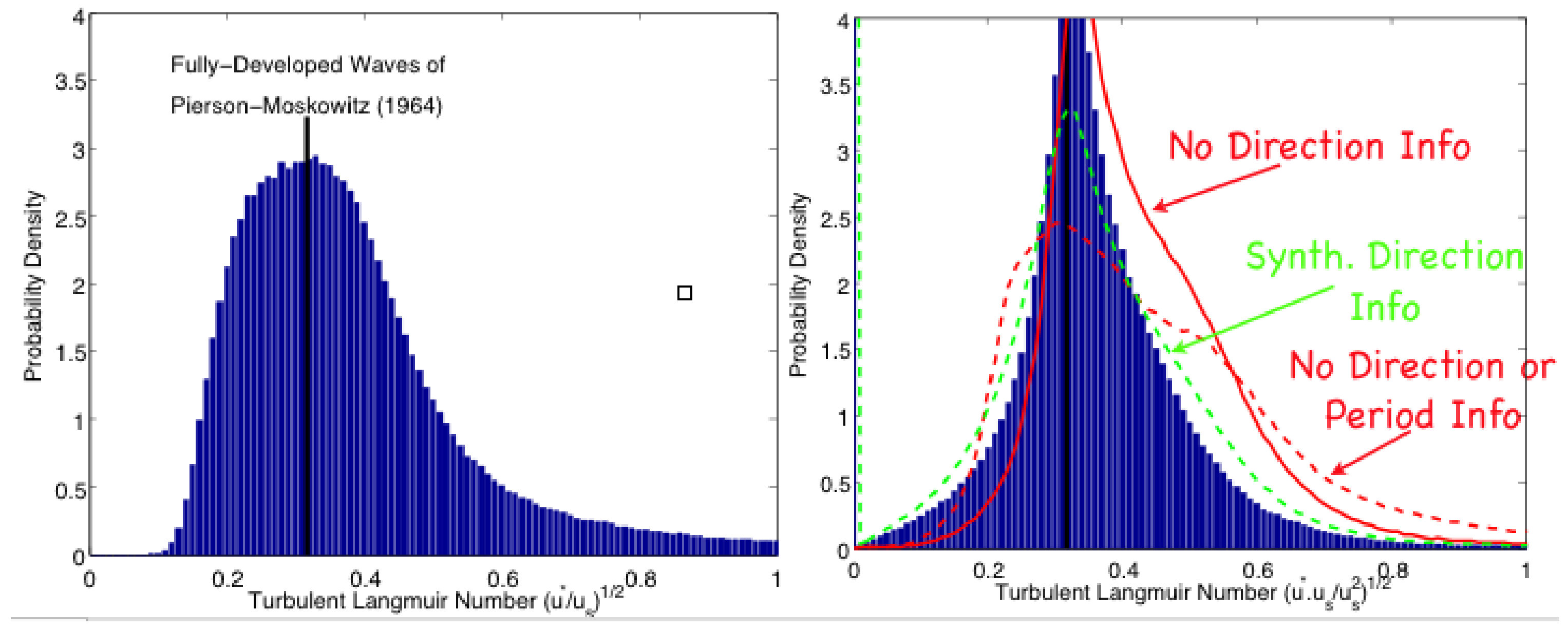

Figure 2: Langmuir number from satellite altimetry (left), and WaveWatch III data (right).

IV. Estimating a Climatology of Langmuir Number

One potential reason for the mismatch of Langmuir circulation in observations is the diverse character of forcing. Sullivan (pers. comm.) finds in LES that Langmuir mixing is present when wind and waves are misaligned. Circulation may even persist after wind has abated (Sullivan et al., 2008). Thus, we define a directional inverse turbulent Langmuir number:

$$La^{-1} = \begin{cases} \left(\dfrac{u_s \cdot u^*}{|u^*|^2}\right)^{1/2}, & |\theta| < \pi/2; \\ 0, & |\theta| \geq \pi/2. \end{cases}$$

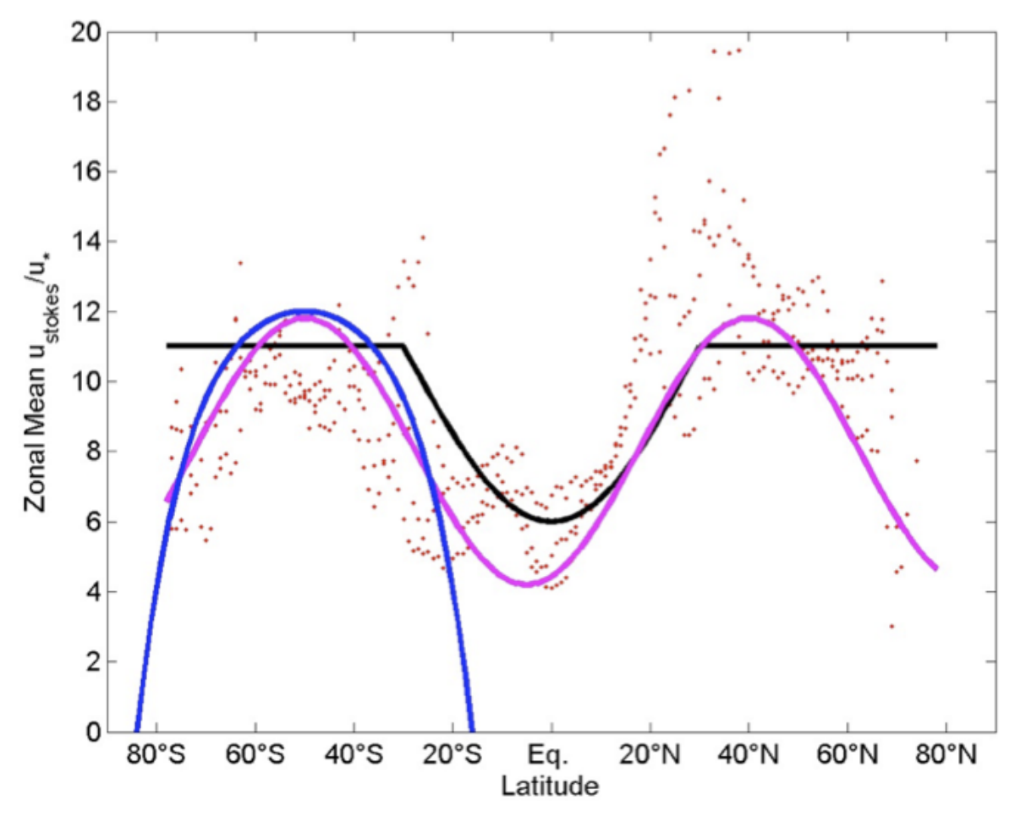

Figure 3: Climatology of $(La^{-1})^2$ (*black*) with scattered data (*red*) and test alternatives

to take into account when θ, the difference in wind and wave directions, was not zero. As an example of the spatial variability of Langmuir number, see the following figure.

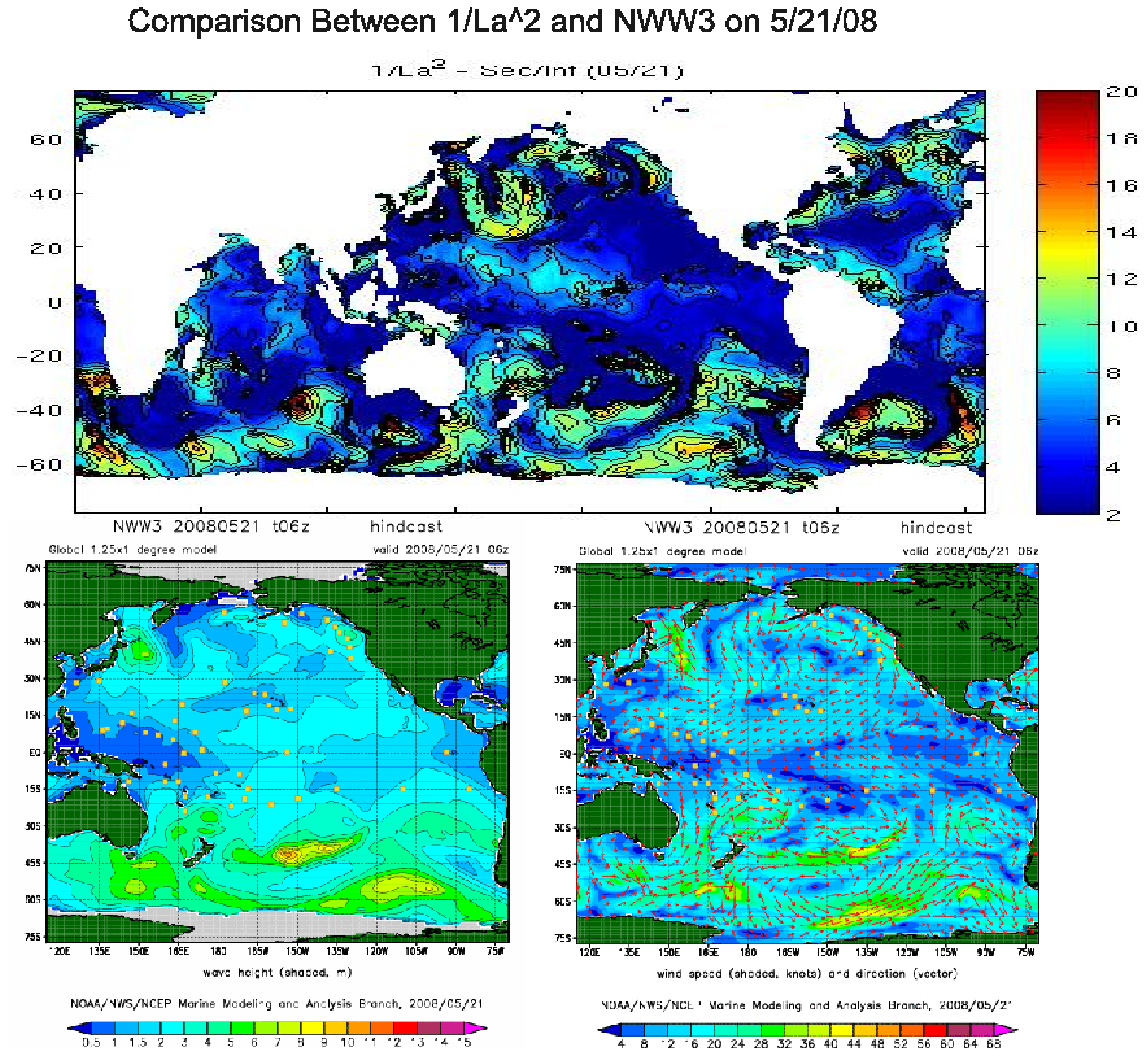

Figure 4: Inverse turbulent Langmuir number squared, (La^{-2}), (top) from NOAA WaveWatch III model global output data (bottom)

V. Crude Parameterization Demonstrates Importance

With the Li and Garrett (1997) energetic scaling for the depth of LMx and an observational result for LC aspect ratio, we find a way to estimate the depth of LMx, H, from u^* and u_s:

$$Fr = \frac{\omega}{NH} \approx 0.6 \qquad \omega \approx \frac{V}{1.5} \approx \frac{\sqrt{u^* u_s}}{1.5}$$

This H is then used to deepen KPP mixing if $H_{kpp} < H$. The Climate model supplies u^*, and we use the La_t climatology to infer u_s, and thereby close the parameterization.

Initial testing of this parameterization in CCSM3.5 deepened the global mean mixed layer substantially ($\approx 10\%$), and *dramatically improved the Southern Ocean shallow mixed layer bias*. However, subsequent tests in CCSM4 revealed that this simple parameterization was extremely sensitive to the details of the climatology (Fig. 3), far beyond the accuracy of what may be inferred from data (Fig. 2). Thus, the importance of LMx on climate is now clear, but accurate modeling of these effects requires more work. Greater sophistication in parameterization is certainly available (McWilliams and Sullivan, 2001; Smyth et al., 2002; Harcourt and D'Asaro, 2008). These improvements will be readily implemented, but a prognostic wave model is required to model the spatio-temporally-evolving wave field. Ongoing work will refine our understanding and uncertainty estimates of Langmuir climatology and couple the WaveWatch III model as a new component of CCSM.

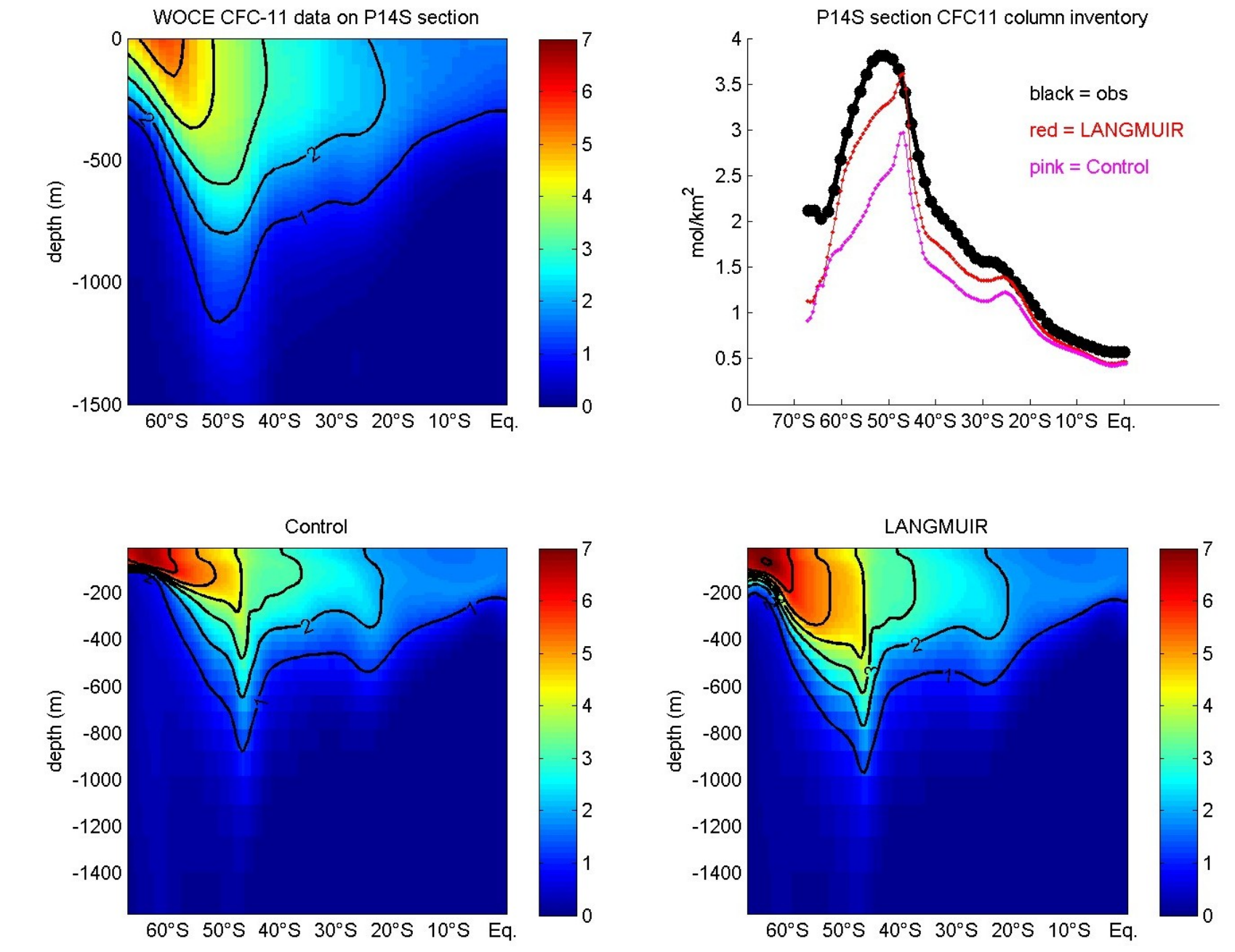

Fig. 5: Southern Ocean CFC bias reduced.

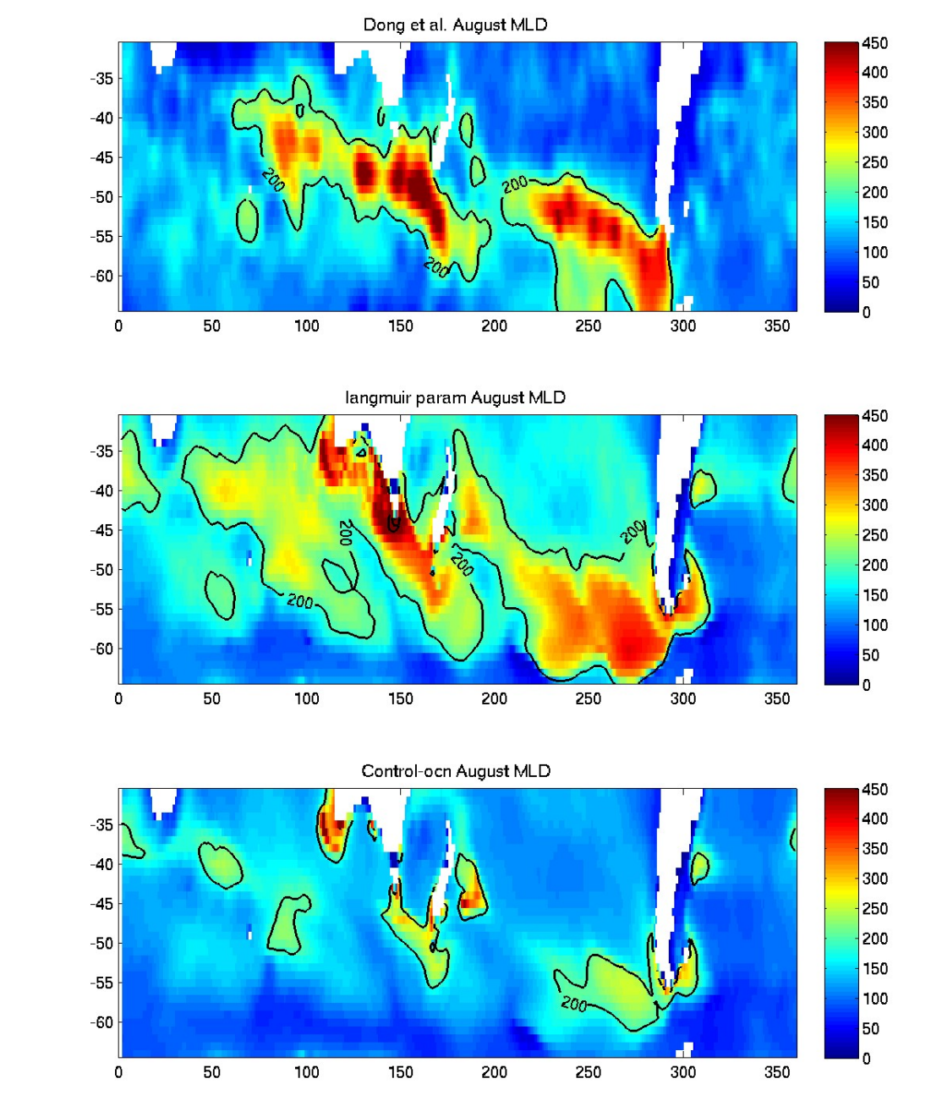

Fig. 6: Mixed layer bias reduced.

VII. Conclusion

We have demonstrated that Langmuir mixing is important in global climate models, but the results are sensitive to implementation details and variations in wave-wind conditions. Thus, ongoing work will develop a reliable parameterization, improve data analysis, and incorporate WaveWatch III as a CCSM model component.

Students Supported

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Erik Baldwin-Stevens, CU Aerospace Engineering Master's Candidate

Papers in Preparation

Webb, Baldwin-Stevens, Danabasoglu, Fox-Kemper, Hamlington, Large, Peacock: Global Model Sensitivity to Estimated Langmuir Mixing in preparation for JGR-Oceans

Webb, Baldwin-Stevens, Fox-Kemper: Estimating Stokes Drift from Mean Wave Variables, in preparation for Ocean Modelling

Funded to Continue Related Work

NASA 08-PO08-0011: Langmuir Circulations: Observing and Modeling on a Global Scale ($774k, $482k to CU), PIs: Fox-Kemper, Julien, Chini, Knobloch

NSF OCE-0934737: CMG Collaborative Research: Multiscale Modeling of the Coupling between Langmuir Turbulence and Submesoscale Variability in the Oceanic Mixed Layer ($1.4M, $502k to CU), PIs: Fox-Kemper, Julien, Chini, D'Asaro & Harcourt (UW)

CU ISG: Small Waves, Big Climate: Effects of Surface Gravity Waves on Climate ($21k)

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