Global Model Sensitivity to Parameterizing Langmuir Circulation [1]

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I. Abstract

Using data from the NOAA WaveWatch III model, a more realistic climatology of Langmuir circulation was developed to include these global effects. This climatology with an energetic schema adapted from Li and Garrett (1997) was incorporated into CCSM 3.5 to estimate the sensitivity due to Langmuir circulation. Currently, the NCAR CCSM 3.5 model uses a nonlocal K-profile parmerterization to account for unresolved scales, which includes Langmuir mixing in that it is trained against observations. However, the parameterization is locally dependent on wind only and does not include wave information which can be global in nature. 20^{th} century year model runs show potentially significant effects from more realistic treatment of Langmuir circulation, with deeper August mixed layers and altered CO_2 rates in the Southern Ocean.

II. What are Langmuir Cells and Circulation?

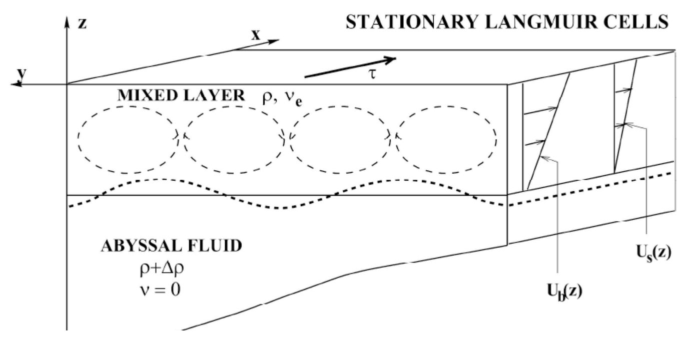

Figure 1: Cartoon of Langmuir Cells

Langmuir cells 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 the amount of mixing in the mixed layer. The turbulent Langmuir number is a non-dimensional constant to measure the additional mixing that occurs when Langmuir cells form and is defined as $La = (u^*/u_s)^{1/2}$ (McWilliams et al., 1997) where u^* is the skin friction velocity due to the wind and u_s is the horizontal stokes drift veloctiy of the waves.

III. Potential Importance of Langmuir Circulation

The ocean surface acts as a filter on ocean-atmosphere communication of momentum, energy, and chemical tracers (e.g., $C0_2$) and is the region where phytoplankton can grow. As a result, it is important to accurately model and parameterize unresolved scales in this turbulent region. It is unclear how important a role Langmuir circulation plays in deepening the mixed layer since it occurs in a region that is already well-mixed. Observations differ as to their importance. However, some see a very strong deepening of the mixed layer in the presence of strong Langmuir circulations (Smith, 1998; Li et al., 1995). Large Eddy Simulation results also indicate that Langmuir circulations have a potent effect over most of the parameter space and can increase mixing and entrainment (McWilliams et al., 1997; McWilliams et al., 1999; McWilliams et al., 2007).

Currently, the NCAR CCSM 3.5 model uses a nonlocal K-profile parmerterization that accounts for Langmuir mixing indirectly. However, the parameterization is trained against data and does not include explicit wave information. It has been commonly thought that this information was not needed since Langmuir cells generally form when waves are fully developed, for which it is well known observationally that $10|u_*| \approx |u_s|$ (Pierson, Jr. and Moskowitz, 1964). This corresponds to a Langmuir number of $1/\sqrt{10}$. In additon to measuring surface height, altimeter satellites are able to indirectly measure wave height and winds through radar backscatter. Recent altimeter satellite data confirms that Langmuir cells generally form for the aforementioned number but it also reveals that there are large regions where wind data only is not enough to determine regions of Langmir circulation.

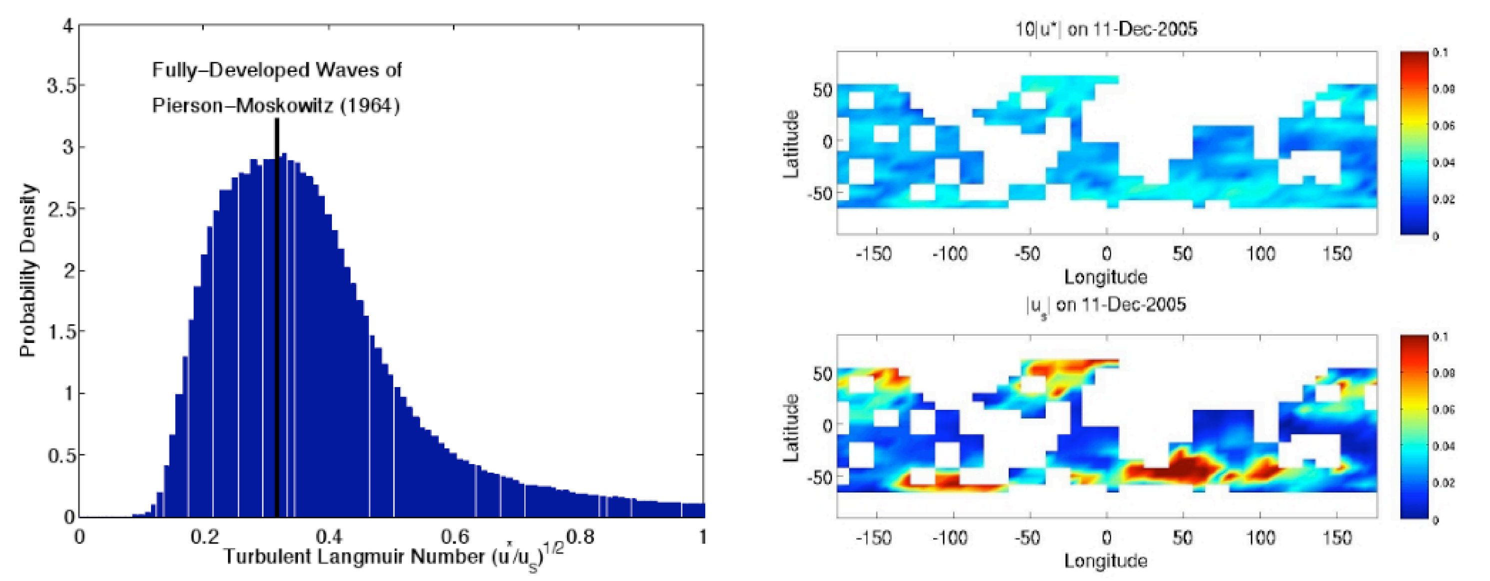

Figure 2: Aviso merged satellite dataset from 11/12/05 to 5/27/08 was used to calculate the (a) average Langmuir number and (b) compare $10|u^*|$ to $|u_s|$

IV. Estimating the Climatology of Langmuir Cells

One potential reason for the mismatch of Langmuir circulation in observations is the diverse character of forcing. While the majority of Langmuir cells form when waves are fully-developed, it is unclear on a global scale how often wavefields formed prior to local wind condtions contribute to Langmuir circulation. Recent work by Sullivan shows that Langmuir circulation is still present when wind and waves are no longer in the same direction and dies off smoothly as the differences increase. Circulation may even persist after wind has abated (Sullivan et al., 2008). This reason alone may contribute to the discrepancy in Figure 2 and for this, a new inverse turbulent Languir number was defined as

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

to take into account when θ, the difference in wind and wave directions, was not zero.

Output from varying days of the NOAA WaveWatch III model was used to calculate La^{-1}. Results indicate that often the ocean is in a regime where LES results indicate that Langmuir circulations should be an important effect ($(La^{-1})^2 \sim 10$).

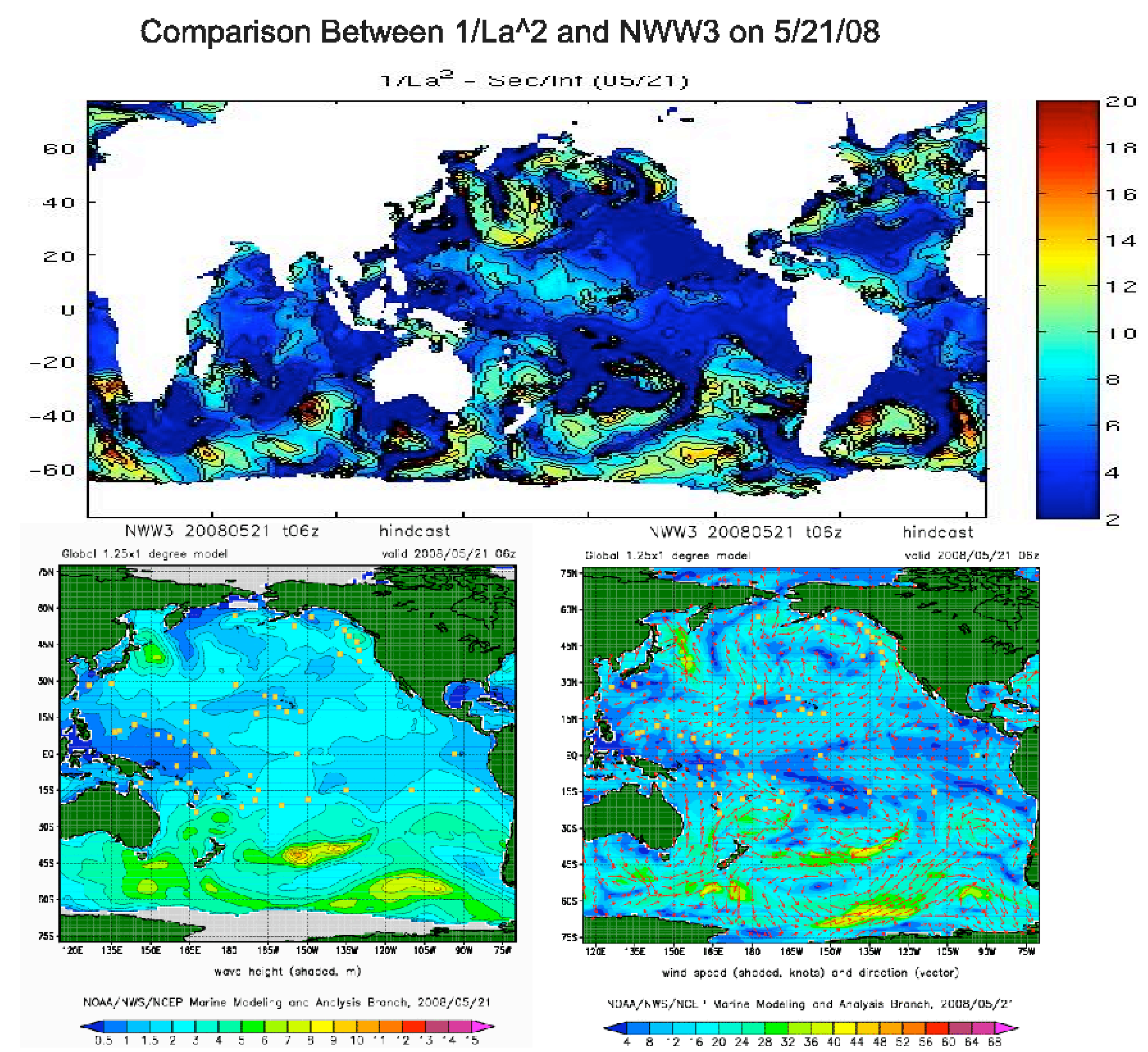

Figure 3: Calculation of inverse turbulent Langmuir number squared, $(La^{-1})^2$, (top) using NOAA WaveWatch III model global output data (bottom)

V. The Parameterization

Following the Li and Garrett (1997) energetic schema and observational rules of thumb, the following schema was used to create a scaling for the depth of LC mixing by balancing the production of potential energy versus Langmuir vertical KE and an observational result for vertical KE based on forcing:

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

Greater sophistication in parameterization is certainly available based on LES results from McWilliams and Sullivan (2001), Smyth et al. (2002). In particular, we anticipate that the development of a prognostic wave model will yield interesting results in light of Section 4. However, at this early stage, we were only interested in assessing the potential magnitude and important effects of such a parameterization. Thus, a rough parameterization was used because of its simplicity in implementation. For further simplicity, we used a 'climatology' of $La^{-1} = 11.0 - \max(5\cos(3 * latitude), 0)$ (Fig. 4).

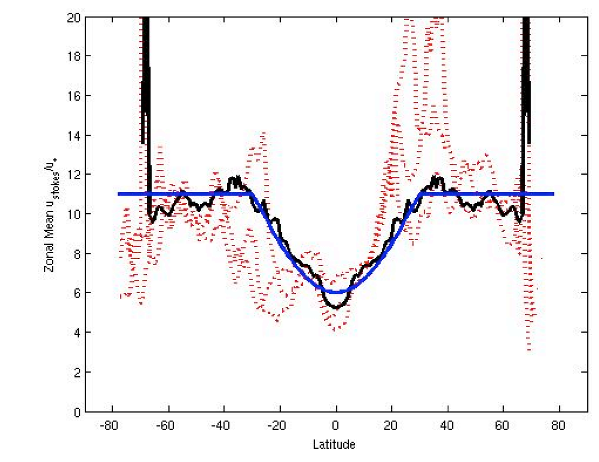

Figure 4: Climatology of $(La^{-1})^2$ (*blue*) based on zonal and seasonal averages (*black*) with summer seasonal data (*red*)

VI. Results

The scaling above demonstrates conclusively that the effects of Langmuir paramterization would indeed be important were they treated more carefully. Substantial changes to mixed layer depth were observed in a number of regions versus a control run. The most noticeable effects were in the August mixed layer depth of the Southern ocean–a well-known shallow bias of CCSM was virtually eliminated when the Langmuir mixing was included, improving tracer (e.g., CFC) uptake at these latitudes (see following figures).

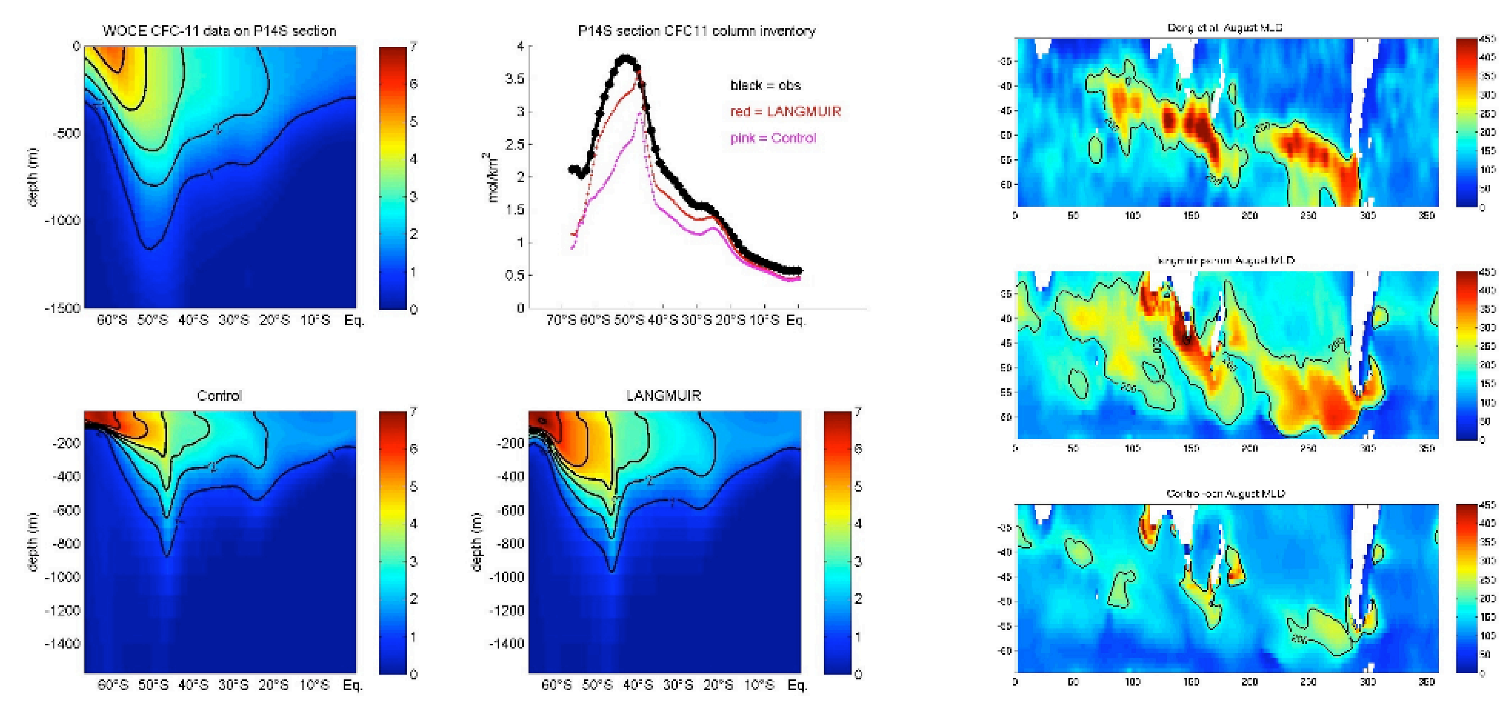

Figure 5: Comparison vs. (a) ship-based observations and (b) profiling float mixed layer depth climatology

VII. Conclusion

While the work here is only a preliminary step toward including Langmuir effects in global climate models, the magnitude of the climate model sensitivity and the tendency toward a reduction of bias in scalar tracer subduction in particular, encourage us to proceed further.

Acknowledgments

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