CORRESPONDENCE

Reply to “Comments on ‘Langmuir Turbulence and Surface Heating in the Ocean Surface Boundary Layer’”

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ABSTRACT

The differences between the conclusions of Noh and Choi and of Pearson et al., which are largely a result of defining different length scales based on different quantities, are discussed. This study shows that the layer over which Langmuir turbulence mixes (nominally \( h_{TKE} \)) under a stabilizing surface buoyancy flux should be scaled by a combination of the Langmuir stability length \( L_L \) and initial/nocturnal boundary layer depth \( h_0 \) rather than by the Zilitinkevich length.

Noh and Choi (2018, hereinafter NC) recently submitted a comment on the published work of Pearson et al. (2015, hereinafter PGPB). In their comment, Noh and Choi suggest that the depth of the thermocline should be scaled by the Zilitinkevich scale \( L_Z \) (Zilitinkevich 1972), as opposed to PGPB who suggested that the mixed and boundary layer depths scale as a combination of the Langmuir stability length \( L_L \) (Belcher et al. 2012) and initial ocean surface boundary layer (OSBL) depth \( h_0 \). In this reply, we first summarize the different depth scales used in NC and PGPB. We then reexamine the results of NC and PGPB to identify the root of any discrepancies. Finally, we demonstrate that PGPB’s main conclusions are unchanged, discuss how NC’s work has encouraged us to reconsider elements of PGPB, and present a summary and outlook for this work.

Noh and Choi’s comment encourages clarity around different depths within the OSBL. In Fig. 1, we demonstrate these depths along with the LES profiles used to derive them. The first \( h_{wb} \) is the depth at which a linear fit to the near-surface buoyancy flux \( w_0b_0 \) reaches zero. The second \( h_{TKE} \) is the depth at which turbulence kinetic energy (TKE) transport tends to zero. Finally, \( h_N \) is the depth of maximum stratification \( N^2 \). Conceptually, \( h_{wb} \) estimates the depth over which turbulence homogeneously mixes temperature \( u \) because this “\( \theta \)-mixing layer” must have constant \( \partial w_0b_0/\partial z \) with depth [salinity is constant in these large-eddy simulations (LES), so \( \theta \) is proportional to buoyancy], and \( h_{TKE} \) is the depth over which turbulence mixes TKE. Both \( h_{wb} \) and \( h_{TKE} \) relate to the processes (turbulence) driving the evolution of the OSBL and can be diagnosed from LES but are difficult to measure in observations. Meanwhile, \( h_N \) is a function of stratification, an emergent property of the turbulent OSBL, and is easy to diagnose in observations but offers less insight into...
turbulent processes within the OSBL. Each depth has different utility; to parameterize the evolution of the OSBL, the depths relating to the processes driving this evolution, $h_{\text{TKE}}$ and $h_{\text{wb}}$, are most useful, but for comparison between LES and generic observations, $h_N$ is most useful because of the ease of observing $N^2$. It should be noted that PGPB did not use the above notation and instead called $LL$ the surface buoyancy flux, $w_0$ is the OSBL depth before heating is applied, and (2) $fB$ decreases as seen in Fig. 1, where we compare LES with nonrotating (Grant and Belcher 2011) scenarios. Previous work demonstrated several scenarios where $h_{\text{wb}}$ would be a good (PGPB, their Figs. 2, 4b; NC, their Figs. 1a,b) or poor (Grant and Belcher 2011, their Figs. 3, 6c; NC, their Figs. 1c,d) estimate of the $\theta$-mixing layer. The dependence of $h_{\text{wb}}$ on $f$ shown by NC could therefore be attributed to $h_{\text{wb}}$ capturing more of the thermocline as $f$ decreases as seen in Fig. 1, where we compare LES with $f = 0$ and $f = 1.4 \times 10^{-4} \text{s}^{-1}$, and in NC (their Figs. 1a,b vs 1c,d).

In contrast to $h_{\text{wb}}$, the TKE transport depth $h_{\text{TKE}}$ (Fig. 1b) diagnoses the depth over which turbulence mixes TKE in both rotating (Grant and Belcher 2009) and nonrotating (Grant and Belcher 2011) scenarios. PGPB compared LES values of $h_{\text{TKE}}$ against Eq. (1) in Fig. 10b, but they did not demonstrate whether this scaling performs better than the $L_Z$ scaling proposed by NC. To test this, Fig. 2 shows $h_{\text{TKE}}/h_0$ from LES as a function of $L_Z/h_0$ and as a function of the PGPB scaling. The scaling proposed by PGPB with $h_{\text{TKE}} = f(L_z, h_0)$ performs better than $h_{\text{TKE}} = f(L_z)$, even without considering LES with $L_Z = \infty$. This figure is analogous to Fig. 3 of NC, but here we show $h_{\text{TKE}}$ rather than $h_{\text{wb}}$, and we contrast $L_Z$ scaling with the PGPB scaling rather than with the Monin–Obukhov length. There is good

Figure 1. Demonstration of the different depth definitions in NC and PGPB using LES profiles of (a) buoyancy flux $\overline{w'b'}$, (b) TKE transport, and (c) temperature. Profiles are shown for two simulations with $f = 1.4 \times 10^{-4} \text{s}^{-1}$ (solid) and $f = 0$ (dashed). Gray lines show the length scales $h_{\text{wb}}$ in (a), $h_{\text{TKE}}$ in (b), and $h_N$ in (c) for their respective simulation. Simulations have $L_L = 93 \text{m}$ and are from the SS and SN simulation sets of PGPB.
agreement between the PGPB scaling and LES (dashed line signifies perfect agreement). When the LES results are scaled by $L_Z$, they show more spread in $h_{TKE}$ than the PGPB scaling. Data are only shown from simulation sets where $f$ or $h_0$ were varied, TKE transport profiles were available (hence no NC simulations), and the data could be plotted on both figures. The nonrotating simulations of PGPB have $L_Z = \infty$ but plot close to the PGPB scaling (not shown). The dependence of $h_{TKE}$ on a length scale other than $L_L$ or $L_Z$ was anticipated by the nonlinear relationship between $h_{TKE}$ and $L_L$ for $L_Z = \infty$ (PGPB, their Fig. 9b, black crosses).

Following NC, we have been encouraged to reconsider PGPB, and we believe that more care should have been taken to discuss the physical meaning of each layer, as we have done above, and the conditions under which their physical interpretations are no longer appropriate. Because $h_{TKE}$ robustly measures the TKE mixing layer in all simulations, while $h_{wb}$ diverges from the $\theta$-mixing layer for small $f$, PGPB should have emphasized more strongly the collapse of $h_{TKE}$ in their Fig. 9b rather than the (less complete) collapse of $h_{wb}$ in their Fig. 9a.

NC commented that the scaling of the seasonal thermocline by $L_Z$ is supported observationally (Lee et al. 2015; Yoshikawa 2015), however, these studies typically measure $h_N$. Calculating $h_{TKE}$ directly from observational data would require measurement of turbulent velocities and their correlations, which is beyond the scope of present global observations. It should also be noted that the time and depth scales of diurnal variability are smaller than seasonal variability, which could preclude different physical balances.

PGPB and Goh and Noh (2013) argue that scalings that depend on $h_0$ and $L_Z$, respectively, could appear from energetic budget arguments. However, to the extent of our knowledge no extant work has provided a robust physical justification of why $L_Z$ or $h_0$ should be important scalings for the Langmuir turbulence mixing layer under diurnal cycling. In particular, two key assumptions made by Zilitinkevich (1972) in justifying $L_Z$ scaling for shear-driven turbulence have both been shown to be poor approximations in Langmuir turbulence, namely, that turbulence mixes momentum along the Eulerian current shear (Smyth et al. 2002; McWilliams et al. 2014) and that there is a standard Richardson number criterion for stability (Li et al. 2016).

In summary, LES provides information about turbulence, which can be used to define depths that are directly related to the processes driving the OSBL evolution but may be difficult to diagnose in observations. TKE transport provides a robust definition of the TKE mixing depth $h_{TKE}$ across a wide range of parameter space. We showed that $h_{TKE}$ agrees with the scaling proposed by PGPB. Meanwhile, NC showed that $h_{wb}$ is affected by variations in $f$ and scales reasonably with $L_Z$. We suggest that the latter result is because as the thermocline becomes thicker and more heat is mixed down into it, $h_{wb}$ captures more of the ($f$ dependent) thermocline. There are several interesting avenues of research on the stable, wave-driven OSBL suggested by PGPB, NC, and the present work. These include understanding the relationships between depth scales that are easily observed (e.g., $h_N$) and those that are calculated directly from OSBL turbulence (e.g., $h_{TKE}$), investigating what determines the buoyancy flux.
into the thermocline (and hence the deviations of $h_{wb}$ from the $\theta$-mixing layer), and robustly diagnosing the mechanisms by which $L_z$ and $h_0$ affect the vertical structure of the OSBL.

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REFERENCES


