CORRESPONDENCE

Reply to "Comments on 'Langmuir Turbulence and Surface Heating in the Ocean Surface Boundary Layer'"

BRODIE C. PEARSON

Department of Earth, Environmental and Planetary Sciences, Brown University, Providence, Rhode Island

ALAN L. M. GRANT

Department of Meteorology, University of Reading, Reading, United Kingdom

JEFF A. POLTON

National Oceanography Centre, Liverpool, United Kingdom

STEPHEN E. BELCHER

Met Office, Exeter, United Kingdom

(Manuscript received 6 September 2017, in final form 15 January 2018)

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 $\overline{w'b'}$ 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 θ because this "θ-mixing layer" must have constant $\partial\overline{w'b'}/\partial z$ with depth [salinity is constant in these large-eddy simulations (LES), so θ 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

Corresponding author: Brodie C. Pearson, brodie_pearson@brown.edu

DOI: 10.1175/JPO-D-17-0176.1

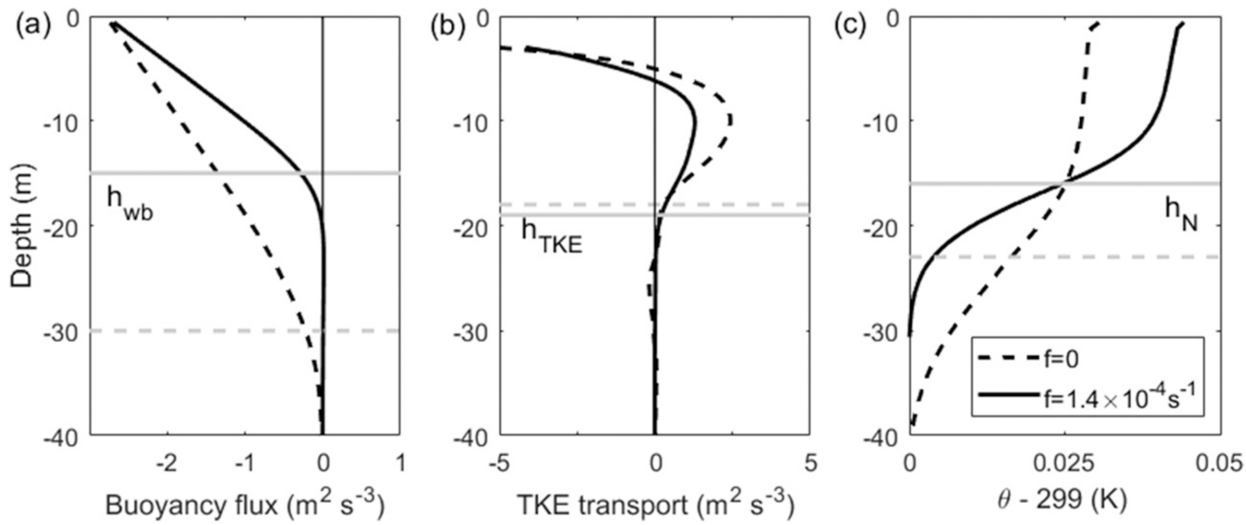

FIG. 1. Demonstration of the different depth definitions in NC and PGPB using LES profiles of (a) buoyancy flux $\overline{w'b'}$, (b) TKE transport, and (c) temperature. Profiles are shown for two simulations with $f = 1.4 \times 10^{-4}\,\mathrm{s}^{-1}$ (solid) and $f = 0$ (dashed). Gray lines show the length scales h_{wb} in (a), h_{TKE} in (b), and h_N in (c) for their respective simulation. Simulations have $L_L = 93$ m and are from the SS and SN simulation sets of PGPB.

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_{TKE} and h_{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 h_{TKE} and h_{wb} the boundary layer and mixed layer depths, respectively. This seemed reasonable terminology for large f, where $h_{\mathrm{TKE}} > h_{wb}$, but is not suitable as $f \to 0$ and $h_{wb} > h_{\mathrm{TKE}}$ (Figs. 1a,b).

PGPB proposed that h_{TKE} does not vary significantly with f (Fig. 1b) and can be estimated as

$$h_{\mathrm{TKE}} = h_0/[1 + (2\beta)^{-1} h_0/L_L], \qquad (1)$$

where $L_L = -w_{*L}^3/B_0$, w_{*L} is the velocity scale of Langmuir turbulence (Grant and Belcher 2009), B_0 is the surface buoyancy flux, h_0 is the OSBL depth before heating is applied, and $(2\beta)^{-1} = 3$. In contrast, NC highlight the important point that h_N (which PGPB did not consider) and h_{wb} vary with f; specifically, they scale well with $L_Z \propto u_*^2/(fB_0)^{1/2}$, where u_* is the velocity scale of shear turbulence and $u_* \propto w_{*L}$ in the present simulations. PGPB did propose Eq. (1), with $(2\beta)^{-1} = 3.5$, to estimate h_{wb} but also stated the caveat that as f decreases, h_{wb} is no longer a good estimate of the θ-mixing layer. This is because h_{wb} is based on the assumption that $\overline{w'b'}$ varies from its surface value to zero at the base of the θ-mixing layer. As a result, h_{wb} is a good estimate of the θ-mixing layer when the buoyancy flux into the thermocline is small, such as for an infinitely thin thermocline. However, as $f \to 0$ the thermocline becomes thicker, the buoyancy flux into the thermocline increases (Fig. 1, dashed lines), and h_{wb} overestimates the depth of the θ-mixing layer ($h_{wb} > h_N$ and h_{TKE}). The mixing of heat within the thermocline is driven by shear turbulence (Grant and Belcher 2011). Previous work demonstrated several scenarios where h_{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 θ-mixing layer. The dependence of h_{wb} on f shown by NC could therefore be attributed to h_{wb} capturing more of the thermocline as f decreases as seen in Fig. 1, where we compare LES with $f = 0$ and $f = 1.4 \times 10^{-4}\,\mathrm{s}^{-1}$, and in NC (their Figs. 1a,b vs 1c,d).

In contrast to h_{wb}, the TKE transport depth h_{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_{TKE} against Eq. (1) in their 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_{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 $h_{\mathrm{TKE}} = f(L_L, h_0)$ performs better than $h_{\mathrm{TKE}} = f(L_Z)$, even without considering LES with $L_Z = \infty$. This figure is analogous to Fig. 3 of NC, but here we show h_{TKE} rather than h_{wb}, and we contrast L_Z scaling with the PGPB scaling rather than with the Monin–Obukhov length. There is good

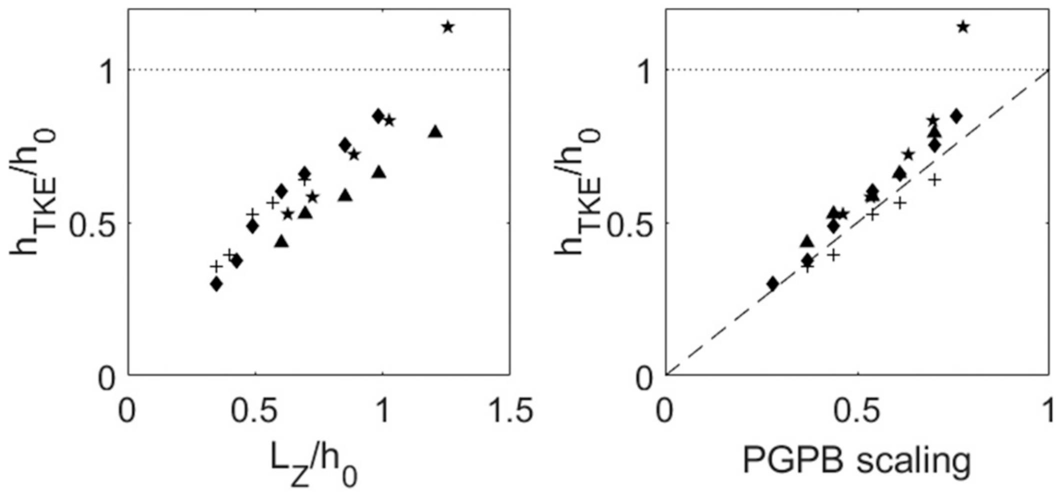

FIG. 2. Comparison of (left) NC and (right) PGPB scalings for h_{TKE}/h_0. The PGPB scaling is $[1 + (2\beta)^{-1}(h_0/L_L)]^{-1}$ with $(2\beta)^{-1} = 3$. Results are shown from the simulation sets of PGPB with varying planetary rotation (SW, SM, SS) and initial layer depth h_0 (SH) and are denoted by the same symbols as PGPB. The dashed line represents perfect agreement with the PGPB scaling.

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 θ-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 θ-mixing layer), and robustly diagnosing the mechanisms by which L_Z and h_0 affect the vertical structure of the OSBL.

Acknowledgments. Feedback from two anonymous reviewers improved this work. This work was supported by a grant from the Office of Naval Research N00014-17-1-2963 and from the National Environment Research Council under the OSMOSIS project NE/I020083/1.

REFERENCES

Belcher, S. E., and Coauthors, 2012: A global perspective on Langmuir turbulence in the ocean surface boundary layer. *Geophys. Res. Lett.*, **39**, L18605, https://doi.org/10.1029/2012GL052932.

Goh, G., and Y. Noh, 2013: Influence of the Coriolis force on the formation of a seasonal thermocline. *Ocean Dyn.*, **63**, 1083–1092, https://doi.org/10.1007/s10236-013-0645-x.

Grant, A. L. M., and S. E. Belcher, 2009: Characteristics of Langmuir turbulence in the ocean mixed layer. *J. Phys. Oceanogr.*, **39**, 1871–1887, https://doi.org/10.1175/2009JPO4119.1.

——, and ——, 2011: Wind-driven mixing beneath the oceanic mixed layer. *J. Phys. Oceanogr.*, **41**, 1556–1575, https://doi.org/10.1175/JPO-D-10-05020.1.

Lee, E., Y. Noh, B. Qiu, and S. Yeh, 2015: Seasonal variation of the upper ocean responding to surface heating in the North Pacific. *J. Geophys. Res. Oceans*, **120**, 5631–5647, https://doi.org/10.1002/2015JC010800.

Li, Q., A. Webb, B. Fox-Kemper, A. Craig, G. Danabasoglu, W. G. Large, and M. Vertenstein, 2016: Langmuir mixing effects on global climate: WAVEWATCH III in CESM. *Ocean Modell.*, **103**, 145–160, https://doi.org/10.1016/j.ocemod.2015.07.020.

McWilliams, J. C., E. Huckle, J. Liang, and P. P. Sullivan, 2014: Langmuir turbulence in swell. *J. Phys. Oceanogr.*, **44**, 870–890, https://doi.org/10.1175/JPO-D-13-0122.1.

Noh, Y., and Y. Choi, 2018: Comments on ''Langmuir Turbulence and Surface Heating in the Ocean Surface Boundary Layer.'' *J. Phys. Oceanogr.*, https://doi.org/10.1175/JPO-D-17-0135.1, 455–458.

Pearson, B. C., A. L. M. Grant, J. A. Polton, and S. E. Belcher, 2015: Langmuir turbulence and surface heating in the ocean surface boundary layer. *J. Phys. Oceanogr.*, **45**, 2897–2911, https://doi.org/10.1175/JPO-D-15-0018.1.

Smyth, W. D., E. D. Skyllingstad, G. B. Crawford, and H. Wijesekera, 2002: Nonlocal fluxes and Stokes drift effects in the K-profile parameterization. *Ocean Dyn.*, **52**, 104–115, https://doi.org/10.1007/s10236-002-0012-9.

Yoshikawa, Y., 2015: Scaling surface mixing/mixed layer depth under stabilizing buoyancy flux. *J. Phys. Oceanogr.*, **45**, 247–258, https://doi.org/10.1175/JPO-D-13-0190.1.

Zilitinkevich, S., 1972: On the determination of the height of the Ekman boundary layer. *Bound.-Layer Meteor.*, **3**, 141–145, https://doi.org/10.1007/BF02033914.