# Role of Langmuir Circulation in the Deepening of the Ocean Surface Mixed Layer

Ming Li,* Konstantin Zahariev, Chris Garrett

Helical motions, known as Langmuir circulation, are a key physical process in the upper ocean but have not yet been incorporated into ocean models. Here, surface mixed layer deepening by Langmuir circulation was added to that due to convection or velocity shear; Langmuir circulation is more important than shear if the velocity difference across the mixed-layer base is less than about 1 percent of the wind speed. In an upper ocean data set, evidence was found for the deepening of the mixed layer by both mechanisms. Thus, Langmuir circulation influences upper ocean diurnal and seasonal changes in stratification.

It has been over 50 years since Langmuir described wind-induced vortices in the surface waters of oceans and lakes, known as Langmuir circulation (*1*). In this, the counterrotating vortices are aligned with the wind and have surface convergence zones that are often marked by narrow bands of foam and flotsam. After a series of ingenious experiments, Langmuir concluded that this phenomenon constitutes the essential mechanism generating the surface mixed layer. This layer is the link between the atmosphere and the deep ocean and directly affects the air-sea fluxes of momentum, heat, and gases (*2*). It is also of great importance for biological productivity and marine pollution (*3*).

Despite Langmuir's pioneering work, the role of Langmuir circulation in forming the mixed layer and in distributing heat and momentum within it has not yet been determined (*4*). Most models of the mixed layer are one-dimensional. In so-called "bulk" models (*5, 6*), changes in the depth and average velocity and density of the mixed layer are specified in terms of the surface buoyancy flux and some combination of the wind stress and the difference of the velocity and density between the layer and the water below it. These bulk models, as well as models that treat turbulence in more detail (*7*), suffer from not explicitly incorporating the key physical processes, such as Langmuir circulation, that are responsible for mixed layer deepening, and it is not at all clear that their parameterization implicitly models these processes correctly. Even after careful calibration of empirical coefficients, the mixed layer models often overpredict the sea-surface temperature in the summer and underpredict it in the fall (*8*), although these discrepancies may also arise from errors in surface fluxes or from advection of water with a different temperature. Here, we attempt to establish the role of Langmuir circulation in the deepening of the mixed layer, using observations to examine a new buoyancy jump criterion derived from a numerical model (*9*).

Wind-driven shear current and surface waves are currently accepted as necessary mechanisms for the generation of Langmuir circulation (*10*). The mean particle (Stokes) drift of surface waves tilts the vertical vortex lines of a near-surface downwind jet to produce streamwise vorticity with surface convergence at the jet maximum; the jet is then reinforced by continued acceleration, by the wind stress, of the converging surface flow.

Using the Craik-Leibovich model, Li and Garrett examined the interaction between Langmuir circulation and preexisting stratification (*9*). The wind stress is estimated from the wind speed $U_w$ through a drag coefficient with the water friction velocity $u_* \approx 1.3 \times 10^{-3}\, U_w$. The Stokes drift current $u_s = 2S_0 \exp(2\beta z)$ is assumed to decrease exponentially with depth $z$, as for a monochromatic wave of wave number $\beta$; for fully developed seas, the surface drift velocity $2S_0 \approx 0.015U_w$ and the Stokes drift current $e$-folding depth $1/(2\beta) \approx 0.12U_w^2/g$, where $g$ is the gravitational acceleration (*11*). Effects of turbulence are parameterized by constant eddy viscosity $\nu$ and eddy diffusivity $\kappa$.

Numerical modeling shows that counterrotating Langmuir cells are generated and may erode the stratified fluid through engulfment and mixing. Langmuir circulation generates vertical velocities in the fluid, but vertical penetration is inhibited by stratification. The cells stop penetrating into the stratified water if the Froude number

$$Fr = \frac{w_{dn}}{(h\Delta b)^{1/2}} \qquad (1)$$

reaches a critical value of 0.9 (*9*). Here, $w_{dn}$ is the maximum downwelling velocity generated by Langmuir cells in homogeneous water, $h$ is the depth of the mixed layer, and $\Delta b$ is the buoyancy jump at the base of the layer. Using model results for $w_{dn}/u_*$, this means that Langmuir circulation will deepen the mixed layer until

$$\Delta b = cu_*^2/h \qquad (2)$$

where $c = 0.72S_0/(\nu\beta)$; values for $\nu$ were adjusted to match vertical velocities between the model results and observations (*9–12*). We estimate that $c \approx 50$ for fully developed seas, although it may be significantly smaller in developing seas (*11*). Equation 2 is similar to that of an entrainment model based on $u_*$ (*13*), but our formula is based on process modeling of Langmuir circulation (which was not present in the laboratory experiments), and the coefficient $c$ gives an explicit dependence on the sea state and turbulence parameterization.

Enhanced shear instability may occur in a horizontally confined region beneath downwelling jets to cause further deepening (*9*), but further work is required to learn how this should be parameterized. For the moment, we assume that it is implicitly included in the bulk Richardson number (Rb) criterion used in the Price, Weller, and Pinkel (PWP) model (*6*). This criterion states that further deepening will not occur if

$$\Delta b \geq 0.65|\Delta \mathbf{u}|^2/h \qquad (3)$$

where $\Delta \mathbf{u}$ is the velocity difference across the base of the mixed layer. Comparison of Eqs. 2 and 3 suggests that engulfment by Langmuir circulation dominates the deepening if

$$|\Delta \mathbf{u}| \leq 9u_* = 0.01U_w \qquad (4)$$

that is, if the velocity difference across the base of the mixed layer is no greater than about 1% of the wind speed, and less in developing seas.

The PWP model can be modified to allow for the mixed layer to deepen if

$$\Delta b \leq \max(50u_*^2/h,\, 0.65|\Delta \mathbf{u}|^2/h) \qquad (5)$$

Instead, we directly examined this buoyancy jump criterion using measurements of the ocean mixed layer. We used the data from the Long-Term Upper Ocean Study (LOTUS) (*14*). The 2-year-long experiment—from May 1982 to May 1984—had four periods within which simultaneous temperature and current profile data were available for periods of 68, 50, 8, and 11 days. The first period was chosen for our analysis as it had the best vertical resolution. The data, obtained from a buoy located at 34°N and 70°W, 300 km from the mean path of the Gulf Stream in the Sargasso Sea, consisted of readings of temperature and ocean currents (eastward and northward) at depths of 5, 10, 15, 20, 25, 35, 50, 65, 75, and 100 m, available at

Centre for Earth and Ocean Research, University of Victoria, Victoria, British Columbia, V8W 2Y2, Canada.

*To whom correspondence should be addressed.

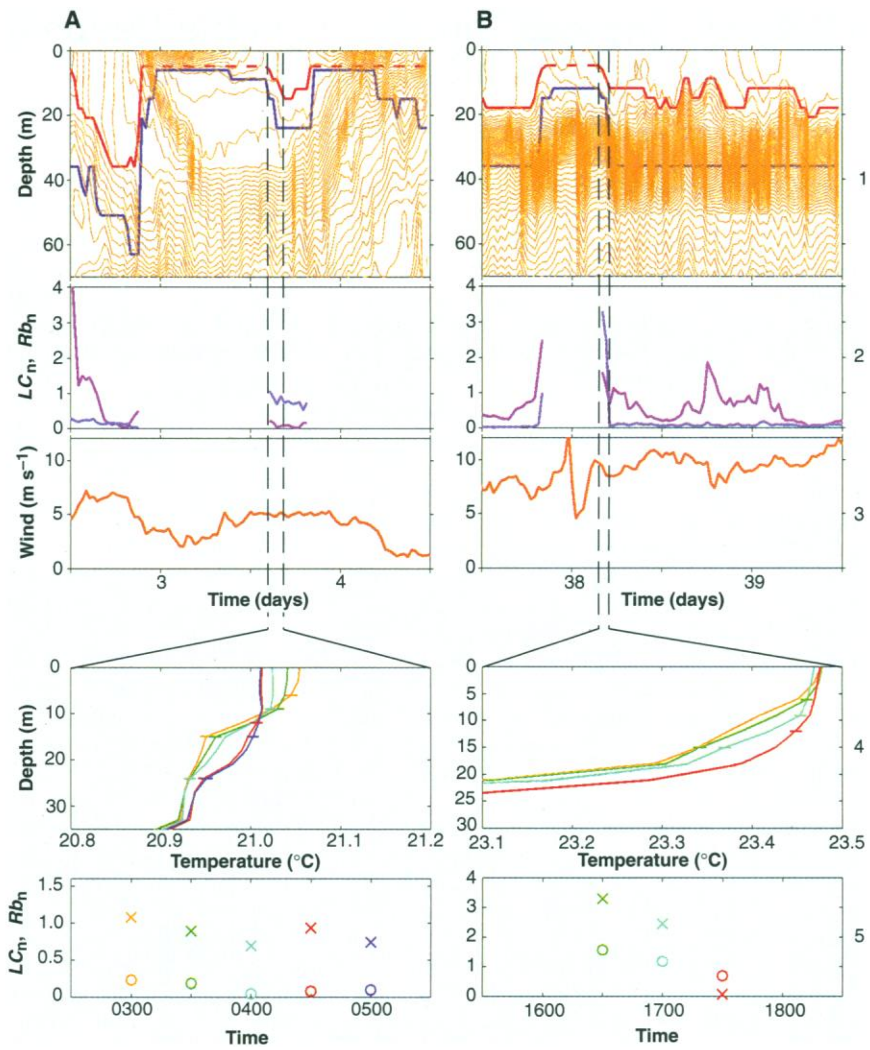



**Fig. 1.** Four separate mixed layer deepening events. (**A**) and (**B**) show deepening events dominated by Langmuir circulation, whereas (**C**) and (**D**) show deepening events mainly driven by shear instability. There are five panels vertically. (1) Isotherms constructed from conductivity-temperature-depth (CTD) measurements are shown as yellow contour lines for a 2-day period. The red line shows the depth of the surface mixed layer, whereas the blue line shows the depth of the base of the transition layer. Mixed layer depths shallower than 5 m cannot be resolved by the data and are drawn as red dashed lines at 5 m. They are excluded from the calculations of the flow indices. (2) Time series of the normalized stability indicators $LC_n$ (blue) and $Rb_n$ (purple). When values of $LC_n$ are greater than 1, mixed layer deepening as a result of Langmuir circulation should occur, whereas when values of $Rb_n$ are greater than 1, deepening due to shear instability should occur. (3) Time series of the wind speed. (4) Successive vertical profiles of temperature during a deepening event. Short horizontal lines mark the depth of the mixed layer (upper line) and the base of the transition layer (lower line). Mixed layers shallower than 5 m and transition layers with bases lying outside the figure are not marked. (5) Corresponding indices $LC_n$ (×) and $Rb_n$ (○). The color sequence used in the last two panels is yellow, green, light blue, red, and blue, representing profiles and indices at half-hour intervals.

15-min intervals starting in mid-May 1982. Simultaneous data were obtained for wind velocities, atmospheric pressure, air temperature, and sea-surface temperature at 0.6 m (*15*). These data were interpolated onto an equally spaced grid with 3-m spacing and filtered and resampled in time to have a new cutoff frequency of 1 cycle per hour. Salinity was a small contributor (<1%) to the buoyancy difference $\Delta b$ and was neglected.

We compared the changes in heat content of the upper 50 m of ocean with those implied by the local surface heat flux. Despite uncertainty in estimating the latter as a result of unreliable humidity measurements (used in the latent heat flux formula), we were able to identify periods when changes in the heat content were incompatible with estimates made from the local heat flux, presumably because of horizontal advection or large internal waves. We avoided these periods in our subsequent analysis as they cannot be used to test one-dimensional models without auxiliary data.

From each temperature profile, we estimated the depth $h$ of the mixed layer as well as the depth $h_{tr}$ of the base of the transition layer. The depth $h$ is defined to be the depth above which the temperature variation is within two-hundredths of a degree but at which the temperature shows a sharp jump. The temperature gradient is large within the transition layer but is less below $h_{tr}$ (*16*). Once values for $h$ and $h_{tr}$ were determined, we calculated the temperature jump ($\Delta T$) between these two depths. The velocity jump $\Delta\mathbf{u}$ is defined as the vector difference between the averaged velocity vector in the mixed layer and the velocity at $h_{tr}$. We obtained the wind stress vector, and hence $u_*$, from the wind measurements using Smith's tables (*17*).

We examined the normalized quantities of the bulk Richardson number ($Rb_n$) and the Langmuir circulation index ($LC_n$)

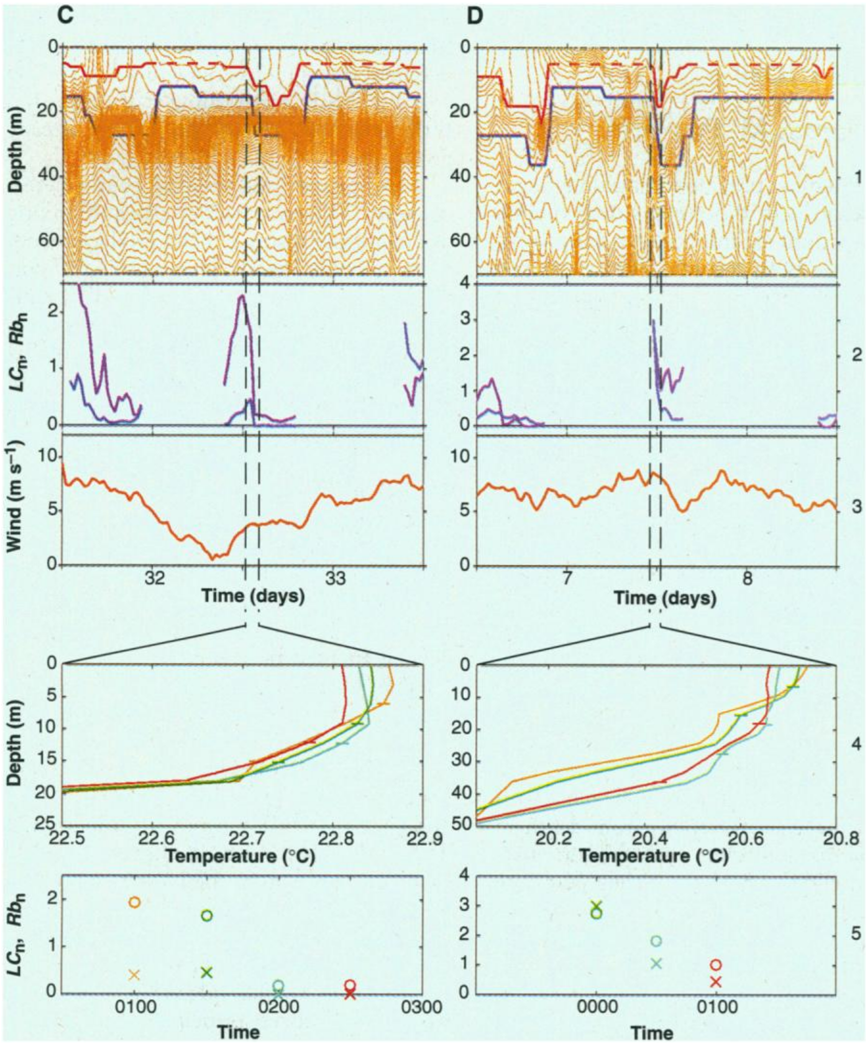
$$Rb_n = 0.65|\Delta\mathbf{u}|^2/(h\Delta b) \qquad (6)$$

and

$$LC_n = 50u_*^2/(h\Delta b) \qquad (7)$$

where $\Delta b = g\alpha\Delta T$ and $\alpha$ is the coefficient of thermal expansion. The PWP criterion and the proposed one representing Langmuir circulation suggest that deepening should occur if either $Rb_n$ or $LC_n$ exceeds 1. We examined the possibility that deepening is dominated by convection by checking changes in the heat content of the mixed layer.

The events illustrated in Fig. 1, A and B, are indicative of mixed layer deepening caused by Langmuir circulation. During the event shown in Fig. 1A, the wind was approximately constant at 5 m s$^{-1}$ and the mixed layer remained shallow before 0300 hours (local time). Surface cooling caused the mixed layer to deepen from 6 to 9 m between 0300 and 0400 hours. It also greatly reduced the buoyancy jump at the mixed layer base (compare the yellow and blue lines in Fig. 1A, panel 4). This precipitated a rapid penetrative deepening (compare the blue and red lines in Fig. 1A, panel 4), although the heat content within the mixed layer was approximately conserved during this period. The Langmuir circulation index $LC_n$ stayed close to 1, though decreasing slightly as the layer deepened. The second event, shown in Fig. 1B, occurred in the afternoon when




solar heating warmed the water. The index $LC_n$ was initially larger than $Rb_n$ and above the critical value of 1, suggesting that the mixed layer was unstable to Langmuir circulation deepening, possibly because of a time lag in the response of the wave field to increasing wind. (Before this, the mixed layer depth was less than 5 m and thus not resolvable.) Mixed layer deepening, and a reduction in $LC_n$, then occurred.

Deepening events shown in Fig. 1, C and D, involved $Rb_n$. In Fig. 1C, in the early morning, $Rb_n$ relaxed from a supercritical value as the mixed layer deepened. In the event shown in Fig. 1D, surface cooling initially reduced the temperature in a shallow surface layer (compare the yellow and green lines in Fig. 1D, panel 4). The buoyancy jump $\Delta b$ was thus reduced, causing both indices $Rb_n$ and $LC_n$ to be greater than 1. Subsequently, the mixed layer rapidly deepened. Langmuir circulation and shear instability may both have contributed to the deepening.

Our proposed criterion for the deepening of the mixed layer by Langmuir circulation will clearly dominate only occasionally but may nonetheless be important to include in models of the surface mixed layer and will generally produce a deeper layer than models without the criterion. In particular, running a model over a diurnal cycle shows how Langmuir circulation may delay daytime restratification of a mixed layer that is deep because of nighttime convection. Increasing insolation will heat the water near the surface and could lead to a thin new surface mixed layer if only the shear criterion is used: if $Rb_n > 1$, an increase in $h$ conserves $h\Delta b$, but momentum conservation would decrease $|\Delta \mathbf{u}|$, thus decreasing $Rb_n$ and allowing the new mixed layer to stabilize. However, an increase in $h$ while $h\Delta b$ is conserved does not change the parameter $LC_n$, so that a shallower mixed layer cannot form unless the wind drops, and Langmuir circulation stops, for a time sufficient for insolation to provide a near-surface buoyancy content $h\Delta b$ of more than $50u_*^2$, where $u_*$ is the friction velocity when the wind resumes. The shallow mixed layer should form in 15 hours for typical values of wind speed ($u_* = 0.01$ m s$^{-1}$) and surface buoyancy flux ($B = 10^{-7}$ m$^2$ s$^{-3}$). Langmuir circulation may thus inhibit the diurnal restratification, although the required time can be much shorter if the wind speed is less, the buoyancy flux greater, and the sea state not fully developed. Over a seasonal cycle, the same argument suggests that in early spring Langmuir circulation may delay the formation of the seasonal thermocline in a deep winter mixed layer, unless the wind stress decreases significantly for a sufficient time.

## REFERENCES AND NOTES


1. I. Langmuir, *Science* **87**, 119 (1938).
2. S. A. Thorpe, *Prog. Oceanogr* **35**, 315 (1995).
3. K. L. Denman and A. E. Gargett, *Annu. Rev. Fluid Mech.* **27**, 225 (1995).
4. S. A. Thorpe, *Q. J. R. Meteorol. Soc.* **118**, 1 (1992).
5. P. P. Niiler and E. B. Kraus, in *Modeling and Prediction of the Upper Layers of the Ocean*, E. B. Kraus, Ed. (Pergamon, New York, 1977), pp. 143–172.
6. J. F. Price, R. A. Weller, R. Pinkel, *J. Geophys. Res.* **91**, 8411 (1986).
7. L. H. Kantha and C. A. Clayson, *ibid.* **99**, 25235 (1995); W. G. Large, J. C. McWilliams, S. C. Doney, *Rev. Geophys.* **32**, 363 (1994).
8. P. Gaspar, *J. Phys. Oceanogr.* **18**, 161 (1988).
9. M. Li and C. Garrett, unpublished results.
10. A. D. D. Craik, *J. Fluid Mech.* **81**, 209 (1977); S. Leibovich, *ibid.* **82**, 561 (1977). G. T. Csanady [*J. Mar. Res.* **52**, 559 (1994)] has recently proposed a slightly different mechanism based on the effects of wind gusts or breaking long waves.
11. M. Li and C. Garrett, *J. Mar. Res.* **51**, 737 (1993).
12. Modeling studies using large eddy simulation (LES) techniques may reduce the sensitivity to turbulence parameterization. See E. D. Skyllingstad and D. W. Denbo [*J. Geophys. Res.* **100**, 8501 (1995)] for an oceanic LES model.
13. E. B. Kraus and J. S. Turner [*Tellus* **19**, 98 (1967)] proposed an entrainment model that assumed that $u_*$ scaled turbulent velocities in the mixed layer, but the dependence on $u_*$ was later disputed by J. F. Price [*J. Fluid Mech.* **90**, 509 (1979)]. He proposed that the rate of entrainment be scaled instead with the velocity difference $\Delta \mathbf{u}$ across the interface, as this resolved the disagreement between two laboratory experiments by L. H. Kantha, O. M. Phillips, and R. S. Azad [*J. Fluid Mech.* **79**, 753 (1977)] and H. Kato and O. M. Phillips [*J. Fluid Mech.* **37**, 643 (1969)]. Later, R. E. Davis, R. deSzoeke, and P. Niiler [*Deep-Sea Res.* **28A**, 1453 (1981)] suggested deepening formulae involving both $u_*$ and $\Delta \mathbf{u}$.
14. M. G. Briscoe and R. A. Weller, *Dyn. Atmos. Oceans* **8**, 243 (1984).
15. We increased the sea-surface temperature readings by 0.063°C as a correction for an apparent instrument offset. Even when the top few meters of the water appeared to be well mixed at night, the readings of the 0.6-m temperature sensor were systematically lower by this amount than those at the 5-m temperature sensor.
16. The estimated depths $h$ and $h_{tr}$ are somewhat subjective, but we checked for consistency in time in isotherms as well as examining individual profiles.
17. S. D. Smith, *J. Geophys. Res.* **93**, 15467 (1988).


18. We thank J. Price for providing us with the LOTUS data. We also thank J. Price, M. McPhee, A. Gnanadesikan, and other colleagues for valuable discussions and the two referees for insightful comments. R. Rutka helped prepare the diagrams. Financial support from Canada's Natural Sciences and Engineering Research Council and the U.S. Office of Naval Research is gratefully acknowledged. K.Z. acknowledges support by a University of Victoria Fellowship.

11 May 1995; accepted 30 October 1995