Observations of wind, waves, and the mixed layer: the scaling of surface motion*

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Abstract

Fluxes across the air/sea boundary have proven hard to parameterize, yet there is hope that this puzzle will soon yield to the dual effects of improved understanding and measurement techniques. The fluxes are linked to both wave dynamics and the generation of quasi-coherent motions throughout the mixed layer. These latter are, in turn, linked to shears across the thermocline, wind stress, wave-current interactions, and wave breaking. Extensive measurements of wind, waves, stratification, and mixed layer motions have been made in the open ocean over the past decade, including several large-scale experiments involving Doppler sonars. These data sets are used to investigate scaling of the motion at the surface by wind and waves. For example, comparing the surface velocity scale measured by Doppler sonar to wind friction velocity and the surface Stokes' drift, it is seen that this velocity scale favors the Stokes' drift rather more than current theories suggest. Large variations in the proportionality factor between events suggests that some other yet to be determined parameter is also important. Variations in the final mixed layer depth and in estimated wave breaking strength are suggested starting points for further investigation.

1. Introduction

The oceanic surface mixed layer is the link by which the air and sea are coupled. The form and strength of the mixing motion are important to concerns such as the fluxes of heat, gases, and nutrients, and to the growth and health of marine life. Improved understanding of these processes depends in some measure on our understanding of mechanisms and dynamics of the mixed layer.

One-dimensional "slab-models" of the mixed layer have performed remarkably well[1-5]. In these, the density profile erodes from the surface downward, producing a uniform layer over the remaining deeper profile. The erosion rate is controlled to maintain a threshold value of the bulk Richardson number, depending only on the depth of the layer and the jumps in velocity and density at the base[3]. Surface stirring by wind and waves can cause continued slower erosion[6], and inhibits restratification. Surface stirring has been parameterized in the energy budget as proportional to the third power of wind friction velocity $(u*)^3$; however, the constant of proportionality

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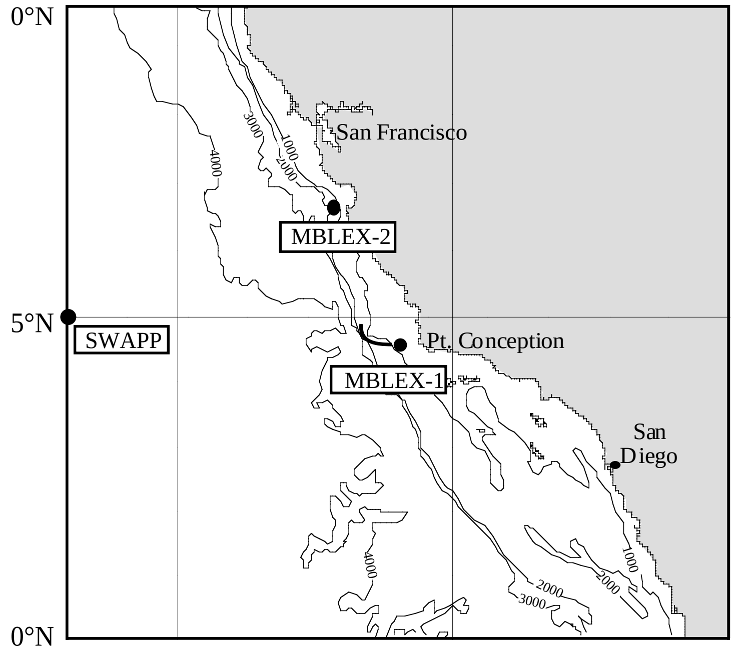

Figure 1. Locations of SWAPP and MBLEX experiments, including *FLIP's* drift-track over the significant storm event in MBLEX-1.

appears to vary with location. *Li et al.*[4,7] suggest that Langmuir circulation is involved, so deepening should depend on a combination of wave Stokes' drift and wind stress, as suggested by current theories and models for the forcing of Langmuir circulation. Thus wave climate variations would cause the "stirring parameter" to vary.

To investigate wind-mixing at the surface of the ocean, observations of wind stress, waves, stratification, velocity profiles, and surface fields of radial velocity and acoustic backscatter intensity have been made over several month-long experiments during the past couple of decades (figure 1). Scaling of the surface motion is sought as a function of wind, waves, etc. Here the rms velocity near the surface is examined, as measured by acoustic Doppler sonars. Theoretical considerations suggest that the near-surface velocity might scale as $V \propto (u^* U^S)^{1/2}$, where u^* is friction velocity and U^S the surface Stokes' drift due to the waves. However, the observations reviewed here indicate that $V \propto U^S$ within each wind event, once Langmuir circulation is established. The constant of proportionality varies significantly from one event to another, so averaging over several events destroys the correlation. These two observations suggest that (1) fully developed Langmuir circulation does not scale the same way as in current theories of initial growth, and (2) some additional variable is needed to parameterize this motion.

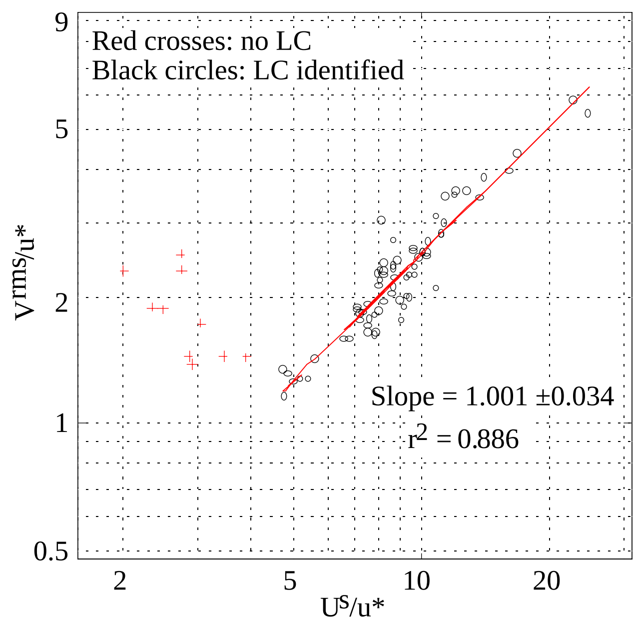

Figure 2. Scaling of the rms radial surface velocity takes the general form $V \sim u^*(U^s/u^*)^n$. The value of n is sought as the slope of (V/u^*) versus (U^s/u^*) on a log-log plot. This figure indicates a well-determined value for n very near 1.0; i.e., $V \sim U^s$, with no dependence on u^* once Langmuir circulation is well formed. Values before year day 67.66, when there were no signs of Langmuir circulation, are shown as red crosses but not included in the fit.

2. The Data.

Data from 2 field experiments are considered: the "Surface Waves Processes Program" (SWAPP), which took place in March of 1990, and leg 1 of the "Marine Boundary Layer Experiment (MBLEX-1), which took place in Feb.-March 1995 (Figure 1). In both, the surface velocities were estimated from surface-grazing acoustic Doppler sonar data. In SWAPP, 4 inverted side-scan style beams were used to trace the time-space evolution of features along 4 directions, distributed at 45° increments. In MBLEX, a newer "Phased Array Doppler Sonar" (PADS) was used to image a continuous area 30° in bearing by 450 m in range. Details concerning the former are found in *Smith*[8] and concerning the latter in *Smith*[9].

Wind and Stokes' drift are primary input parameters. In both experiments, wind stress was estimated from sonic anemometer data via eddy-correlation methods. Stokes' drift was derived using data from resistance-wire wave arrays, yielding surface elevations and tilts as functions of frequencies up to 0.5 Hz[10]. The results are converted to Stokes' drift via

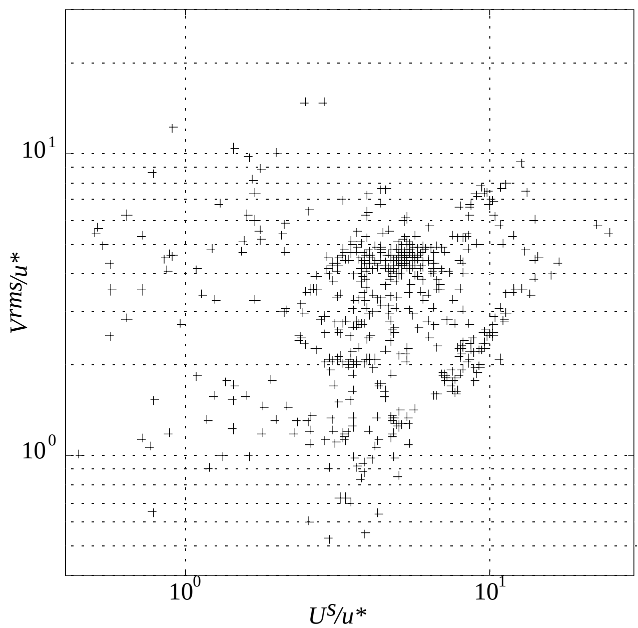

Figure 3. All data points from SWAPP and MBLEX-1, plotted without regard to event or whether LC features were identified. No correlation is seen, and it appears that almost an order of magnitude uncertainty in V^{rms} must be tolerated.

linear theory and integrated over the directional-frequency spectrum to estimate the net drift at the surface. Additional details concerning instrumentation for SWAPP may be found in *Smith*[8], and for MBLEX in *Smith*[9]. MBLEX-1 provided only one clear storm event. In SWAPP, five distinct time segments may be identified. However, only the second and third segments have both steady wind directions and a wide range of wave age (henceforth denoted SWAPP-2 and SWAPP-3).

Surface velocity data averaged over 1 to 3 minutes are employed. The MBLEX-1 (PADS) data were averaged with a moving window that tracks the mean advection across the imaged area as the average is formed (see *Smith*[9] for details). The SWAPP data were processed with a dual spatial-temporal lag technique to isolate coherent signals while also tracking advection along the beam (see *Plueddemann et al.*[11] or *Smith*[12] for details). The data were corrected for the spatial response of the instruments, estimated from simulated data. The data have a characteristic depth-scale of 1 to 2 m.

3. Results: Scaling of Surface Motion.

Do previously observed or suggested scalings for the near-surface rms velocity hold up over the combined data set? In the absence of wave forcing,

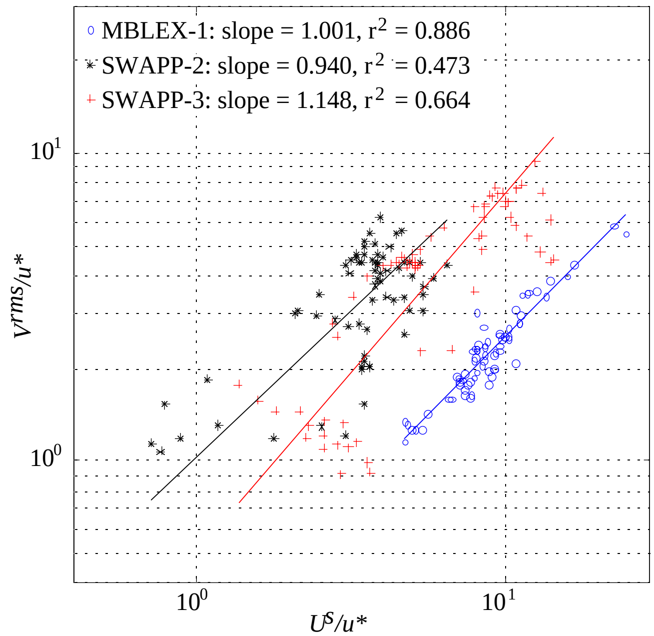

Figure 4. The empirical fits for *n* for each "clean event" treated separately. Within each event, the fit is fairly tight. However, the vertical offset of the lines varies significantly over the three events.

the only velocity scale would be the wind friction velocity $u*$. Based on theories for initial growth of Langmuir circulation, it has been suggested that the cross-wind velocity fluctuations should scale roughly with either the geometric mean of the friction velocity and Stokes' drift[11], $(u*U^S)^{1/2}$, or with[12] $(u*^2U^S)^{1/3}$. The suggested scalings for the surface velocity associated with Langmuir circulation can be cast in the general form $V \sim u* \, (U^S/u*)^n$. The value of n is thus sought as the slope of the best fit line to $log_{10}(V/u*)$ versus $log_{10}(U^S/u*)$. The results for MBLEX-1 are reviewed in Figure 2; points where surface streaks associated with Langmuir circulation are not evident are marked with +'s and excluded from the fit. Provided that "non-streak" points are excluded, the value n=1 is found, with little uncertainty (r^2=0.89; error bounds on the slope are a standard deviation derived by the bootstrap method[13] with 5000 trials). In other words, once the Langmuir circulation is well developed, $V \sim U^S$, and wind stress no longer enters directly in scaling the motion. This implies a strong influence of the waves on the flow (and nonlinearity, since a threshold must be applied for the existence of Langmuir circulation).

A natural question is whether this is just an isolated case. To address this question, SWAPP data were reanalyzed. Figure 3 shows the log-log plot for all SWAPP and MBLEX data points, without regard for the existence of stripes or non-stationary conditions. It would be easy to dismiss any correlation from this plot; however, it should be recognized that (1) the parameter U^S might be a proxy for another wave parameter, and the relation between these might vary between wind events, (2) there could be other parameters influencing the relation, and (3) there are valid reasons to exclude non-stationary and "non-stripy" conditions. It is wise to examine the relation on a case-by-case basis, to see if there is a hidden relation. The two usable SWAPP events ("SWAPP-2" and "SWAPP-3") are plotted together with the "MBLEX-1" event in figure 4. The regressions support the value n=1 for the exponent. Although the SWAPP fits are not as tight as for the MBLEX-1 data, they are still statistically significant at well over 95%. Intriguingly, there is considerable offset between the lines, especially between SWAPP and MBLEX (by a factor of about 5), but also between the two SWAPP events (by a factor of about 2). Some other aspect of the environment must be affecting the relation.

What could be responsible for the observed variation in velocity scale V^{rms}? Possible candidates include variations of scaled depth of the mixed layer kh, effective wave-induced viscosity[9,14] ν_t, a directional effect of the horizontal Coriolis component[15], or suppression by the buoyancy of the near-surface bubble cloud[9]. A summary of some relevant parameters is given in Table 1. The first 6 parameters summarize the observations for the 3 events; the rest are derived from these. An effective wave period T^S is derived from the surface Stokes' drift, assuming the variations in mean-square wave steepness are not very large: then $U^S \propto T^S$. The corresponding wavenumber is computed from T^S via linear dispersion. Given the purported importance of wave Stokes' drift to the generation of Langmuir circulation, this proxy for the wave period and length scales seems appropriate.

Table 1

Parameters that may influence the surface velocity scale.

Event / Parameter		MBLEX-1	SWAPP-2	SWAPP-3
V^{rms}/U^S		0.25	0.95	0.67
W^{dir}		SE	SSE	NNW
W^{max}	(m/s)	15	10	13.6
$u*$	(cm/s)	1.65	1.1	1.5
U^S	(cm/s)	7.0	4.5	7.5
h	(m)	25	25	45
T^S	(s)	10.7	6.9	11.5
k	(m^{-1})	0.035	0.085	0.031
kh		0.87	2.12	1.37
F'		0.53	0.77	0.66
$(u*^2U^S)^{1/3}$	(cm/s)	0.124	0.082	0.119
ν_t	(cm^2/s)	698	190	770

The directions of MBLEX-1 and SWAPP-2 are similar, but the V-scaling differs by the largest ratio. This appears to rule out both the opposing swell and the horizontal Coriolis hypotheses. The estimated wave-induced viscosity is largest for SWAPP-3, but this is intermediate in V-scaling, so it is rejected. The overall density of the near surface bubble-cloud is presumably set by the level of wave breaking. A reasonable indicator of this[9] is $(u^{*2}U^S)^{1/3}$. This parameter has the right trend in magnitude, although the MBLEX-1 and SWAPP-3 values are relatively close. Finally, there is the scale depth *kh* of the mixed layer. It is important to distinguish here between the development of ΔV, V^{rms}, h, U^S, and k over the course of an event versus the differences between events. These develop in parallel over the course of a wind event; however, what is of interest is whether they develop either at different rates or from different initial values between events. Here the "scaled depth" is based on final or quasi-equilibrium values of *h* and *k*.

A point to consider is that the layer-averaged convergent force should be subtracted from the surface value, since this works to depress the thermocline rather than drive circulation. For roughly exponential decay with the depth-scale of the Stokes' drift, this leads to a reduced net force at the surface,

$$F' = (F_0 - \overline{F})/F_0 = 1 - h^{-1}\int_{-h}^{0} e^{-2kz}dz = 1 - (2kh)^{-1}(1 - e^{-2kh}), \qquad (1)$$

that varies smoothly from 0 at kh=0 to 1 as *kh* gets large. The wind-wave forcing mechanism is reduced for very thin layers, and reaches the full predicted strength as the mixed layer becomes deeper than the wave's scale-depth. The effect is in the right direction, but is again too weak to explain the full differences observed between the three events. It appears that further investigation is needed to select between the alternatives and to determine why and when suppression of the motion occurs.

4. Conclusions

The rms velocities associated with the low-frequency features scale tightly with the Stokes' drift alone over the course of individual wind events, rather than with the wind or a combination of wind and waves. The relation is nonlinear in that a threshold must be set for the existence of Langmuir circulation before it holds. Further, the "constant of proportionality" between surface velocity variance and Stokes' drift varies significantly between events. It is suggested that this is related to the ratio of wavelength to mixed layer depth, as parameterized by the "final" or maximal values. Dynamic effects of the near-surface bubble layer could also play a role.

In each event considered here, the mixed layer deepened rapidly, then remained fairly constant, with very slow (if any) continued erosion. This is consistent with current thinking, where the "bulk dynamics" of shear across the thermocline due to inertial motion is the primary agent for deepening in the open ocean. Surface stirring by the combined action of wind and waves may help maintain the mixed layer after this, and may induce additional slow deepening. In any case, the inertial current "bulk Richardson number" mechanism remains the dominant term in wind-induced mixing of the surface layer.

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