Air-Sea Interaction Processes at Light Winds Observed from a Coastal Tower

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ABSTRACT


Airflows, sea-surface waves, near-surface currents and X-band radar sea-returns were measured from a nearshore tower in 4-m deep water located in the Delaware Bay, during the passage of typical weather patterns. Intermittent violent momentum transfers, burstings, from air to water were clearly observed from measurements of the airflow turbulence. The scaling of mean periods between bursts and between sweeps with dominant wave period and the outer and inner variables of the turbulent airflow confirms that both, dominant wind waves and energy containing airflow eddies, share a role in the triggering of burstings. The three-dimensionality of the airflow in the field facilitates the reattachment manifested by the sweep events, and makes the latter similar to the bursts in terms of number and contribution to the mean Reynolds stress. The contribution of bursting events to the mean Reynolds stress is stronger than in laboratory flows and exceeds 100%. Wavelet analysis was applied to the surface wave data, and revealed uniformly distributed instants of bursts and sweeps over dominant wind wave profile. Using surface elevations and radar return data, no modifications of the surface roughness were found during bursting events.

ADDITIONAL INDEX WORDS: Turbulence, intermittence, wind waves, radar return.

INTRODUCTION

The study of energy input from the wind to the water surface is important for the proper understanding of fluxes between the atmosphere and oceans (Phillips, 1980). Forecasting of destructive forces of waves, in which the remotely sensed data is an important ingredient, can be benefited from the correct picture of energy exchange between airflow turbulence and water surface.

The problem of intermittent Reynolds stress, surface roughness production, and radar returns is of interest to oceanographers and remote sensing scientists. The spikes in the shear stress (vertical flux of horizontal momentum), named 'burstings', has long been identified first in boundary layer flows over solid surfaces (Kim et al., 1970; Rao et al., 1971; Corino and Broadkey, 1969), and then over wind waves in laboratory (Kawamura and Toba, 1988) and in the field (Chambers and Antonia, 1981; Boppe and Neu, 1995). It was shown that burstings were the major contributors to the mean downward momentum flux.

Significant efforts were directed to study the frequency of appearance of burstings, their contribution to the momentum flux, and applicability of different detection schemes. The periods between bursts in the field were claimed to have no dependence on the surface wave field, and sweeps were not

97108 received 30 August 1997; accepted in revision 9 February 1998.
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The influence of wind shear stress modulation on the radar backscatter modulation (MTF, modulation transfer function) started to attract attention in the recent years, HARA and PLANT (1994), SCHMIDT et al. (1995). The essence of these works is that the local equilibrium of Bragg scatterers is modulated not only by orbital currents but by the wind stress modulation as well. Although rigorous as models, these studies do not present direct evidences for wind stress modulation in ensemble with underlying waves. They arrive at a hypothetical wind stress modulation indirectly, as a residual from the total measured hydrodynamic MTF and calculated on the basis of the orbital straining (PHILLIPS, 1984). Wind stress in these models is presented as a linear superposition of Fourier components and is convolved with the surface height frequency spectrum. While it is shown that the wave-coherent momentum flux can be the major contributor to the total momentum flux at particular artificial conditions (BANNER, 1990), in more realistic conditions the intermittent burstings seem to be much better contributors. However, the correlation between airflow burstings, sea-surface roughness, and radar return is still not well understood. The radar return during these highly transient phenomena and its significance in the net backscatter is not clear either. Airflow reveals intermittent behavior starting from low winds where the scatterometric wind errors are the largest. The role the intermittency may play in these errors is not known and needs to be evaluated.

Thus, a comprehensive suite of field records is studied here in an attempt to give answer to the above. These records, performed in the Delaware Bay, consist of simultaneous observations of air flows and surface roughness, in terms of surface elevations and radar returns. Considered are three quite different cases of environmental conditions which show the involvement of different environmental parameters in the bursting generation.

EXPERIMENTAL SET-UP

Tower Description

The field station is located in the Delaware Bay, about 600 m offshore in 4-m deep water, as shown in Figure 1. It is

Figure 1. Tower location. The inset shows the selected 5-min averages of winds for this study.

Figure 2. Tower view and instrument setup.
A three-axis sonic anemometer (Applied Technologies, SWS-211/3K) was mounted at the end of the boom, as shown in Figure 2. It consists of an array of sonic transducers separated by 15 cm, and has accuracies of 1 cm s\(^{-1}\) for the wind speed and 0.1° for the wind direction. The anemometer has a fast response to wind fluctuations and a selective sensitivity to wind components along clearly defined axes. It yields three wind-velocity components, U, V and W, and temperatures at a rate of 10 Hz; each of these is later averaged for 5 min. The relevance of this averaging time for studying of microscale phenomena is justified in Geernaert (1990) and in Mahrt et al. (1995). The horizontal streamwise and spanwise components of the airflow, denoted as u and w correspondingly, are retrieved from the sonic U and W channels using:

\[
u = W\sin\theta + U\cos\theta, \quad w = W\cos\theta - U\sin\theta.
\]

Here, \(\theta = \tan^{-1} (W/U)\) where brackets indicate the five-minute average. The estimates of \(\theta\) are transformed into the True North values, \(\theta_0\), on account of sonic orientation relative to the True North. The magnitude of the wind speed is calculated as \(U_m^2 = (U)^2 + (W)^2\). The test showed that there is little difference between vector and scalar averaging for our data. The vertical component of the airflow, denoted as v, is retrieved from the sonic without any transformation of the coordinate system, \(v = V\).

The wind fluctuations \(u', v'\) and \(w'\) were derived by subtracting the corresponding averaged values, \(\langle u \rangle, \langle v \rangle, \text{ and } \langle w \rangle\) from the instantaneous wind components \(u, v,\text{ and } w\). Similarly, the temperature fluctuations, \(T'_v\), were retrieved from \(T'_v = T_v - \langle T_v \rangle\). Thus the five-minute averages of the wind-friction velocity, \(u_\tau\), were derived using:

\[
u_\tau = \left((u'v')^2 + (w'v')^2\right)^{1/4}
\]

The Monin-Okukhov length, \(L\), is thus derived via:

\[
L = -\frac{\langle T_v \rangle u_\tau^3}{\kappa g (v'T'_v)}
\]

### Table 1. Radar look direction.

<table>
<thead>
<tr>
<th>Run</th>
<th>Radar Look Direction, Deg</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>59</td>
</tr>
<tr>
<td>2</td>
<td>300</td>
</tr>
<tr>
<td>3</td>
<td>390</td>
</tr>
</tbody>
</table>

Figure 3. The time variation of wind for Run 1. The data were collected on August 11, 1994. The sonic (open circles) and onshore tower (filled circles) data are respectively 5- and 10-min average.
Figure 4. The time variation of wind for Run 2. The data were collected on August 29, 1994. The sonic (open circles) and onshore tower (filled circles) data are respectively 5- and 10-min average.

Figure 5. The time variation of wind for Run 3. The data were collected on August 30, 1994. The sonic (open circles) and onshore tower (filled circles) data are respectively 5- and 10-min average.
Savchenko et al. has a flat frequency response from d.c. to about 15 Hz. Fourier spectra of the wavegauge signal were calculated to retrieve \( \lambda_r, T_r \) and \( c_p = \lambda_r / T_r \), the apparent wavelength, period and the phase speed of the dominant waves, correspondingly. An antialiasing filter of 15 Hz is applied to all elevation series.

Subsurface Current

Subsurface currents were measured with an X-Y electromagnetic current meter (Marsh-McBirney Model 523), as shown in Figure 2. The meter has a resolution of 0.9 cm s\(^{-1}\).

Radar Backscattering

An X-band (10.28 GHz) continuous-wave (CW) Doppler radar was mounted underneath the boom, as shown in Figure 2. The radar is a simple Gunnplexer transceiver with a transmitted power of 20 mW and a horn antenna to form a conical beam. The antenna beam has a 25° width at -3 dB from the maximum transmit/receive power. The illumination spot on the mean water surface is elliptical with approximate dimensions of 40 cm \( \times \) 25 cm. The radar includes a Gunn oscillator, a Shottky diode mixer/detector, and a ferrite circulator, all mounted in a small wave guide cavity. The acquired signal was a time series of voltages corresponding to the phase and magnitude modulations of the returned power from the target surface. Whenever possible, the radar was pointed upwind, and the incidence angle \( \theta_i \) was fixed at 45° (Figure 2). The radar look directions, in degrees clock-wise from the True North are given in Table 1.

The polarization of the transmitted and received radiation was vertical. The radar signal was sampled at 300 Hz. For our experimental setup, the power received by the main lobe of radar antenna is

\[
P_r = \frac{P_t G^2 \lambda_n^4 \sigma}{(4\pi)^2 r_s^4}
\]

where

- \( P_t \) is the transmitted power,
- \( G \) is the antenna gain,
- \( \lambda_n \) is the radar wavelength,
- \( \sigma \) is the radar backscatter cross section,
- \( r_s \) is the distance to the surface.

From laboratory calibrations we evaluated that surface-normal reflections would be suppressed by 34 dB in the antenna side lobes. To describe radar return from the ocean surface first and second order, Bragg theories were developed. The second order Bragg theory considers the tilting of Bragg resonance ripples by the underlying long waves. Then the normalized radar backscatter cross section, that is \( \sigma \) divided by the illumination area, is given in a simplified form by (Plant, 1990)
\[ \sigma_o = 16 \pi k_0 \int |g_p(\theta, \alpha, \phi)|^2 F(2k_0 \sin \theta', 0) \times P(\alpha, \phi) \, d\alpha \, d\phi \]

where \( k_0 \) is the radar wavenumber,
\( g_p \) are the Bragg scattering geometric coefficients,
(\( \alpha, \phi \)) are the along-wind and cross-wind slopes, respectively,
\( P(\alpha, \phi) \) is the probability density function of surface slopes,
and \( \theta' \) is the local angle of incidence,
\( F(2k_0 \sin \theta', 0) \) is the power density of Bragg resonance ripples in the along-wind direction.

The Doppler frequencies in the radar signal can be described according to TRIZNA (1985) as
\[ f_d = \frac{2}{\lambda_0} [V_p + c(k_0) + V_s + V_w + V_t \sin \theta, \]

where \( V_p \) is the orbital velocity of the dominant waves, \( c(k_0) \) is the phase velocity of Bragg scatterers with wavenumber \( k_0 \), \( V_s \) is the Stokes drift current, \( V_w \) is the wind-induced drift current, and \( V_t \) is the tidal current. Note that \( c(k_0) \) can be as the intrinsic velocity of the Bragg ripples, as the phase velocity of longer, steep waves which produce parasitic waves (STOKES, 1847) with a wavelength \( k_0 \). It has been shown by BANNER and FOOKS (1985) that an X-band radar is responsive to such waves. Thus the radar signal contains information on a wide variety of surface features.

### Table 2. Selected environmental parameters.

<table>
<thead>
<tr>
<th>Run</th>
<th>( \lambda ) (m)</th>
<th>( T ) (sec)</th>
<th>c/u</th>
<th>( u ) (cm s(^{-1}))</th>
<th>( y' )</th>
</tr>
</thead>
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<td>30</td>
<td>11</td>
<td>6233</td>
</tr>
<tr>
<td>2</td>
<td>4.5</td>
<td>1.7</td>
<td>70-15</td>
<td>4-22</td>
<td>1706-9387</td>
</tr>
<tr>
<td>3</td>
<td>6.9</td>
<td>2.1</td>
<td>22</td>
<td>20</td>
<td>13066</td>
</tr>
</tbody>
</table>

Figure 7. Surface elevations frequency spectra, for (a) Run 1, (b) Run 2, and (c) Run 3.
EXPERIMENTAL CONDITIONS

The data acquired from our field measurements are presented as three cases in this paper: Runs 1, 2 and 3 are made on August 11, 29, and 30, 1994, respectively. To compare with the preexisting conditions, the time series of the wind field from these data runs are shown in Figures 3, 4, and 5. Solid circles in the figures represent the 10-min averages of on-shore tower data, while the open circles indicate the 5-min averages of the sonic data. The sonic wind is slightly lower than the land-station wind; this is partially caused by the difference of measurement heights. The wind directions from both measurements follow the same trend.

We choose to work with the winds having the longest possible fetches. Thus Run 1 is compiled from the first half on August 11, Run 2 incorporates all of the August 29, and Run 3 is the last half of August 30. To have an easy glimpse on the selected winds and Delaware Bay fetch, the resulting set of winds is shown in the inset of Figure 1, where the vectors represent the five-minute averages of calculated $u_{10}$. Time-vector diagrams of $u_{10}$ winds and surface currents as measured simultaneously with the EM current meter are shown in Figure 6. During Run 1, digital records of currents were not provided. In addition, the tide was very low and the current-meter sensor was not in the water all the time. The single current velocity value shown in Figure 6 is compiled from the instants of normal operation.

Examples of frequency spectra of surface heights during selected conditions are given in Figure 7. Each of them is a 20 min. average. The influence of currents is most significant for Runs 1 and 2, when the current is in upwind direction. Its impact begins to be obvious for frequencies in the wave height spectra above 4–5 Hz. In contrast, the current during Run 3 is in direction generally perpendicular to the wind and does not have as big influence, Figure 7c. The overall averages of $\lambda_p$ and $T_p$, the wave age, wind-friction velocity, $u_*$, and the wall distance, $y^+$, over duration of data run are given in Table 2. The wall distance is defined as $y^+ = y_0 u_*/v$, where $v = 15 \times 10^{-6} \text{ m}^2 \text{ s}^{-1}$ is the kinematic viscosity of air and $y_0$ is the elevation of the sonic anemometer above the mean water level. Note, the given wave age estimate is an average of 5-min estimates of wave ages, it is not the ratio of averaged $c_p$ and $u_*$.

The observed winds are converted to $u_{10}$ and corrected for stratification, $u_{10N}$, using procedures described in Geernaert (1990). These are shown in Figure 8a versus the wind-friction velocity. Neutral conditions prevailed over Run 1 and 3. Run 2 initially was under stable conditions which were destructed into neutral conditions under the influence of picking up winds at the end. The corresponding wave ages are shown in Figure 8b.

The angle between the stress and the wind as a function of stability for three days of observation is presented in Figure 9. The latter is comprised from the 5-min averaged data points. The solid line does not present some strong correlation, rather it confirms earlier findings for open ocean conditions (Geernaert, 1988) that the angle between the wind stress and wind velocity, $\theta_s$, has the tendency to shift from positive to negative values as the atmospheric conditions change from unstable to stable. The large rms values (error bars) in Figure 9 are contributed mainly by the variations of the wind stress direction.

WIND BURSTING ALGORITHM

The detection of bursting was accomplished using Variable Interval Time Averaging technique (VITA) as used before by Kawamura and Toba, (1988) and Boppe and Neu, (1995). Whenever $(u' v')/(\sigma_u \sigma_v) < -1$ a bursting is detected, after which the event is further localized and classified as a burst ($v' > 0$) or a sweep ($v' < 0$). Here $\sigma_u$ and $\sigma_v$ are the root mean square fluctuations of $u$ and $v$, respectively. We assume that the time scale $\tau_e$ of every event is defined by the mean streamwise component ($u$) and the dominant wavelength $\lambda_p$.
of the sea surface waves: $\tau_n = \lambda/(u)$ (Kawamura and Toba, 1988). In terms of number of samples it is $N_s = \tau_s f_s$, where $f_s$ is the sampling frequency. We define a five-minute estimate of contribution in moments of bursts and sweeps as

$$C_{b,s} = \frac{\sum_{i=1}^{N_s} P_i \delta_{b,s}(i)}{\sum_{i=1}^{N_s} P_i}$$

where $N_s$ is the number of samples in a 5-minutes interval, $P_i$ is the property of interest, and $\delta_{b,s}(I)$ is the mask function yielded by the bursting algorithm, Figure 10. We study properties $(u'v')$, mean-square (MS) surface elevations and radar return. The occurrence of bursts and sweeps is defined as $O_{b,s} = N_{b,s}/N_s$, where $N_{b,s}$ is the number of bursts or sweeps in the 5-minutes interval. $O_{b,s}$ must be treated as the portion of the five minute interval occupied by bursts or sweeps. The algorithm of bursting detection is applied to the $(u'v')$ series and is shown in Figure 10.

The wavelet decomposition of the dominant surface waves is invoked to study the relation between the phase of the dominant waves and moments of the first appearance of burst and sweep events. The wavelet transform is written as (Chui, 1992)

$$\tilde{\eta}(t', T) = \frac{1}{\sqrt{T}} \int_{-\infty}^{\infty} \psi^*(\frac{t - t'}{T}) \eta(t) \, dt$$

where

$$\psi(t) = \exp\left(-\frac{t^2}{2} + j2\pi t\right)$$

and $\psi^*$ is its complex conjugate, which is known as “standard Morlet wavelet”. It has been successfully applied for studying of air-sea interaction processes, Liu et al. (1995). Shen and Mei (1993), employing wavelet analysis, showed the inherent intermittency in the time series of surface elevations, and hypothesized that this is a reflection of the intermittent momentum flux.
RESULTS AND DISCUSSION

A sample of time series of $v', u'v'/\sigma_s$, surface elevations, $\eta$, and the envelope of the radar return, $\sigma$, after the 66-th second of Run 1 is shown in Figure 11. The high of the pulsed dotted lines in the $u'v'/\sigma_s$ series indicate instants of bursts and sweeps. For the 5-min segment, a portion of which is shown in Figure 11, $\sigma_s = 0.047$ m$^2$ s$^{-2}$. Thus, an individual ejection for this segment is detected whenever $u'v' < -0.047$ m$^2$ s$^{-2}$.

The numbers and the periods of bursts and sweeps versus $u_*$ are clustered during Run 1 when the environmental conditions are fairly steady, Figure 12. For Run 3, the numbers and periods are steady although $u_*$ increases from about 16 to 27 cm s$^{-1}$. A tendency of increasing number of bursting (and shorter periods) with decreasing wind stress can be drawn from Run 1 and 3. During Run 1 the current is exactly opposing the wind, which may facilitate burstings by increasing the wave steepness. During Run 3 the current and wind are almost perpendicular, Figure 6. A factor which is very likely to increase the period between burstings in this case is the period of dominant wind waves which is noticeably larger for Run 3, (Figure 7 and Table 2). This picture is not supported by Run 2. During this run the mean period between burstings decreases as $u_*$ increases, and the period between sweeps in particular decreases almost 6 times. Boppe and Neu (1995) consider only bursts and report similar dependency which contrasts with what is observed here for Run 1 and 3. The decreasing periods with increasing $u_*$ are first reported in laboratory flows over flat plate, Kim et al. (1971). It is worth noting that Run 2 is a quite dynamic case, with atmospheric stratification and wind quickly shifting from very stable and light to neutral and strong, respectively. At the end of the run, the wind-friction velocity is the highest for this run but the waves are the youngest and under strong forcing, Figure 8b. Unfortunately, wave ages, fetches and stratifications are not reported for all winds in Boppe in Neu (1985) and the only given value for the wave age is 24. Our Run 2, apparently short fetch at the end, clearly shows decreasing wave age (Figure 8b) during which the period between sweeps decreases, the same being valid for bursts, though not so dramatically. Thus the data from Run 2 is an interesting implication on the influences of stratification and wind forcing on bursting phenomena.

In the earliest laboratory studies of bursting phenomena over solid surfaces, attempts have been made to scale the periods between burstings with inner and outer variables, $u_*^{2/3}$ and $U_*/\delta^*$ respectively, (Corino and Brodkey, 1969; Kim et al., 1971; Rao et al., 1971). Here, $U_*$ and $\delta^*$ are the free-stream velocity and displacement thickness, respectively. There is no report in the literature on similar studies in real or laboratory modeled air-sea boundary layers. In an effort to unify the upper boundary for the observed turbulent flows in the field and in laboratory, it is chosen than $U_* = U_{10w}$. It is important to have stratification-corrected winds to properly model vertical wind profile and to better relate the field and the neutral conditions in laboratory. It is shown
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Figure 12. Number of (a) bursts and (b) sweeps, and mean period between (c) bursts and (d) between sweeps observed during 5 min intervals. The symbols are the same as in Figure 8.

here that stratification can be very stable in the coastal area and then swiftly change, Figure 8a. Thus, the estimates of \( u \) and \( U_{10} \) are used to model logarithmic vertical wind profile with stratification corrections (Geernaert, 1990) and to calculate \( \delta^* \), \( \theta \) and \( R_e \), the last two being the momentum displacement thickness and the corresponding Reynolds number.

The 5-min estimates of the periods between bursts and between sweeps scaled with the dominant wind wave period, inner, and outer variables, versus \( u \) and \( R_w \) are shown in Figures 13 and 14. In all cases special care is taken to pick up the peak frequency of the wind waves, since in some cases swell dominates the surface elevations spectrum, Figure 7a. Figures 13 and 14 show that the scaled mean burst and sweep periods are better aligned about \( T_u/T_p = 3 \) for Run 1 and 3. This would not be the case if the swell period, which is almost constant for all runs, had been used. Obviously, this scaling is not appropriate for Run 3, speaking that dominant wave period only is not sufficient to scale burstings periods. An interesting feature is that burst and sweep periods are of similar magnitude.

The scaling with the inner and outer variables of the turbulent flow does not align bursting periods as well as it is shown for flows over solid surfaces, Rao et al. (1971). This is not surprising for it has already been shown the involvement of the underlying wave field. The remarkable feature is that the scaling with the outer variable groups the nondimensional burstings periods around 30 (Figures 13 and 14), and the value reported by Rao et al. (1971) is 32 for their orders of magnitude smaller momentum thickness Reynolds number, \( R_w \approx 10^3 \div 10^4 \). In agreement with Rao et al. (1971) and all summarized there studies, the scaling with the inner variables produces worse results, Figures 13 and 14.

Next are presented estimates of that portion of observed parameters, contributed during bursting events. Bursts and sweeps contribution to the along-wind component of the stress vector, \( \langle u'v' \rangle \), are presented in Figure 15a. On average for Run 1 and 3, bursts contribute only slightly more than sweeps, correspondingly 59% versus 51%. The numbers reported in the previous works (Chambers and Antonia,
to it from burstings is significantly reduced during stable stratification.

The contribution to the MS surface elevations from the periods of bursts and sweeps is shown in Figure 15b. This picture almost repeats occurrences (Figure 16), showing that there is no significant augmentation of the surface elevations over this frequency range during detected events. The contribution to the MS surface elevations is merely proportional to the time occupied by the events. The MS radar return further confirms this picture, Figure 15c. On average, bursts and sweeps occupy only about 20% of the observation time; Figure 16, giving the dominant surface wavelength is taken as the length scale in the calculation of the time (grouping) scale of the ordered motions. However, the individual spikes in the Reynolds stress, $u'v'$, are actually much shorter, Figure 11.

The first immediate explanation is that the duration of the shear stress spikes (the individual ejections and inrushes), even when grouped into a burst and sweep, is shorter than...
Air-Sea Observation from a Coastal Tower during various atmospheric conditions in the coastal marine atmospheric boundary layer. The temporal and spatial scales of the ordered motions studied here are much finer than in the previous field works due to the use of a sonic anemometer and smaller wall distances. For the neutral conditions and wide range of $U^*$, the burst and sweep periods increase with increasing $u_*$ and decreasing wave age. However, during strong wind forcing and small wave ages, conditions similar to the short fetches in laboratory, this dependence can be completely inverted with more frequent events at higher winds. During very stable conditions, there are clear indications that the stratified atmosphere tends to increase the period between burstings.

Smaller periods between burstings, or more frequent events, are observed when the surface currents oppose the wind. This may be facilitated through increased wave steepness and following enhancement of airflow separation. The periods between burstings scale well with the periods of dominant wind waves, though the resulting scatter confirms that not only wave parameters are involved. The scaling with the outer variables of the airflow gives better results than the scaling with the inner ones. This is an evidence that during various atmospheric conditions in the coastal marine atmospheric boundary layer. The temporal and spatial scales of the ordered motions studied here are much finer than in the previous field works due to the use of a sonic anemometer and smaller wall distances. For the neutral conditions and wide range of $U^*$, the burst and sweep periods increase with increasing $u_*$ and decreasing wave age. However, during strong wind forcing and small wave ages, conditions similar to the short fetches in laboratory, this dependence can be completely inverted with more frequent events at higher winds. During very stable conditions, there are clear indications that the stratified atmosphere tends to increase the period between burstings.

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the energetic, large scale eddies are strongly involved in the generation of bursts and sweeps. This finding is consistent with the works over solid surfaces and is extended here for air-sea interface, with $R$, and at $y^+$ being orders of magnitude larger.

On average, bursts and sweeps contributions to the total Reynolds stress, $(\langle u'v' \rangle)$, are similar. The instants of appearance of the events are not correlated with the phase of dominant waves, which is another evidence that it is not only the wave field that plays a role in the generation of the ordered motions.

ACKNOWLEDGMENT

The authors are grateful for the sponsorship of their research provided by the Remote Sensing Program, Office of Naval Research under Grant N00014-93-0345.

LITERATURE CITED


