1.4 WIND STRESS VECTOR OVER SEA WAVES

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1. INTRODUCTION

Determination of the wind stress over oceans is a fundamental problem of air-sea interaction. The stress vector, $\vec{\tau}$, is the tangential force per unit area exerted by the wind on the surface. In practice the stress is usually measured by a sonic anemometer at level of order 10 m above the sea surface. The stress vector at some level well above the viscous sublayer may be represented directly by the following relation (eddy-correlation method):

$$\vec{\tau} = -\rho(<u'w'>\vec{i} + <v'w'>\vec{j}), \qquad (1)$$

where $\vec{i}$ and $\vec{j}$ represent the longitudinal (x - axis) and lateral (y - axis) unit vectors, $< >$ is a time or/and spatial averaging operator, u, v or w are the longitudinal, lateral, and vertical velocity components, respectively, and $(')$ denotes fluctuations about a mean value. It is a common practice to align the x - axis with wind direction at a reference height, z. Thus $\tau_x = -\rho<u'w'>$ is the downstream stress, and $\tau_y = -\rho<v'w'>$ is the cross-wind stress. The following sign conversion for stress is used, $\tau_x > 0$ if the longitudinal stress component is facing in the wind direction and vice versa, τ_y is positive (negative) if the lateral stress component is directed to the right (left) of the wind vector.

The magnitude of the stress vector, $|\vec{\tau}|$, is numerically equal to the magnitude of the momentum flux, τ. For this reason there is a common practice to do not differentiate between stress and momentum flux.

The angle α between the stress and wind vectors is calculated according to

$$\alpha = \arctan(<v'w'>/<u'w'>), \qquad (2)$$

where positive angles of α correspond to the stress vector oriented to the right of the wind direction.

In most analyses to date, the direction of the stress vector is generally assumed to be aligned with the wind. Thus, the term $<v'w'>$ in (1) - (2) is ignored assuming that it is unimportant or insignificant with respect to $<u'w'>$. Standard Monin - Obukhov similarity theory (MOST) is based on the assumption that stress and wind vectors are aligned in the same direction, and $<v'w'>$ = 0 by definition. With the exception of several papers, there has been a general lack of investigation concerning the stress vector direction relative to the mean wind and surface waves direction.

Based on field measurements Smith (1980), and Geernaert (1988) reported high values of the crosswind component $<v'w'>$ and angle α in (2). Geernaert et al. (1993) observed that when swell propagates at an oblique direction with respect to the local wind direction, the stress vector has a direction which is in general a blend between the wind direction and the swell direction. Rieder et al. (1994) considered further the influence of the surface waves on wind stress direction. They provided statistically significant evidence that the wind stress lies between the mean wind direction and direction of the long waves.

The Geernaert (1988), Geernaert et al. (1993), and Rieder et al. (1994) studies restricted their analysis to moderate to high wind speeds. In the light wind speed regime, the influence of the surface waves on wind stress direction is more dramatic. It is common place that in calm weather conditions the wind and stress vectors are not aligned, and often the wind and stress directions are nearly opposite (Drennan et al. 1999).

The purpose of this study is to extend these prior analyses by including additional experimental evidence of the influence of surface waves direction on the stress vector direction.

2. BASIC APPROACH

Over the sea, the total stress, $\vec{\tau}$, can be expressed as vector sum of the viscous stress, $\vec{\tau}_{visc}$, turbulent shear stress, $\vec{\tau}_{turb}$, and wave-induced stress (normal or form stress), $\vec{\tau}_{wave}$, (e.g. Hare et al., 1997):

$$\vec{\tau}(z) = \vec{\tau}_{visc}(z) + \vec{\tau}_{turb}(z) + \vec{\tau}_{wave}(z). \qquad (3)$$

In a general case all constituents in (3) depends on a reference height, z. However, under certain conditions (the wind and wave fields are stationary in time and space), it is assumed that $\vec{\tau}$ on the left side of (3) is constant with height, i.e. $\partial\vec{\tau}/\partial z \approx 0$. The amplitude of wave-induced pressure perturbations falls off

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approximately exponentionally with z, and therefore, well away from the surface, $\vec{\tau}_{wave}$ tends to zero. Assuming that $\vec{\tau}$ is invariant with height (constant flux layer), changes of $\vec{\tau}_{wave}$ with height must be compensated by variations of $\vec{\tau}_{turb}$ and $\vec{\tau}_{visc}$. The layer where the influence of $\vec{\tau}_{wave}$ cannot be neglected is known as the wave boundary layer (WBL). It is generally believed that above WBL, but within the surface layer, standard MOST is applicable for description of the momentum transfer.

The wave-induced stress is associated with the atmospheric pressure distribution across the front and rear faces of the waves. In the case of a pure unimodal wave field $\vec{\tau}_{wave}$ is aligned with the direction of the wave propagation. The fundamental difference between airflow over land and sea derives from mobility of the water surface. Traditionally this phenomenon is described in terms of wave age. Based on wave age, the sea state is classified into young (or developing) sea and mature (decaying) sea. Wave-induced stress components in the marine surface layer show strong dependence on wave age, and range from positive to negative values. For young seas the longitudinal component of wave-induced stress is positive, i.e. $(\tau_{wave})_x > 0$ (respectively to wind direction, x axis). With increasing wave age, $(\tau_{wave})_x$ decreases, reaches zero, and reverses sign in the case of the old seas, $(\tau_{wave})_x < 0$. The fact that the wave-induced stress can be positive as well as negative is a key point in the understanding of the stress vector orientation over ocean waves.

It is generally assumed that surface gravity waves can be separated into pure wind sea and swell waves. Wind surface waves are short waves and travel much more slowly than the wind, while swell are long and fast traveling ocean waves. Generally wind waves and swell propagate in different directions. Swell has a period and wavelength that is not associated with local winds. In the majority of cases the wave energy of swell is contained in a narrow range around the peak frequency in the wave spectrum, and it is separated from the wave energy of wind dominant waves. Thus, it makes sense to split $\vec{\tau}_{wave}$ into two parts, $\vec{\tau}_{wave} = \vec{\tau}_{wave\,1} + \vec{\tau}_{wave\,2}$, where $\vec{\tau}_{wave\,1}$ and $\vec{\tau}_{wave\,2}$ are due to pure wind waves and swell respectively. Combining this assumption and Eq. (3) yields:

$$\vec{\tau}(z) = \vec{\tau}_{shear}(z) + \vec{\tau}_{wave\,1}(z) + \vec{\tau}_{wave\,2}(z), \qquad (4)$$

where $\vec{\tau}_{shear} = \vec{\tau}_{visc} + \vec{\tau}_{turb}$.

It the case of mixed wind sea and swell it is thought that $\vec{\tau}_{wave\,1}$ and $\vec{\tau}_{wave\,2}$ in (4) are governed by their own wave age (two peaks in the wave spectra are expected). Since the swell usually travels faster and short waves more slowly than the wind, in the majority of cases $(\tau_{wave\,1})_x > 0$ and $(\tau_{wave\,2})_x < 0$. However, reverse signs are also possible in transient conditions. The case $(\tau_{wave\,1})_x < 0$ is associated with decaying wind conditions, e.g. after the passage of a storm or gale, when the total stress may also reverse sign to negative, $\tau_x < 0$. The case $(\tau_{wave\,2})_x > 0$ is associated with strong winds traveling in the same direction as swell or with counter-swell. The last leads to enhancement of the total stress (e.g. Drennan et al. 1999). Unlike the wave-induced stress, the shear stress is always positive, i.e. $\tau_{shear} > 0$.

Note that the direction of wind waves is frequently close to the wind direction, and therefore the vectors $\vec{\tau}_{shear}$ and $\vec{\tau}_{wave\,1}$ are about co-linear. Substituting of $\vec{\tau}_1 \equiv \vec{\tau}_{shear} + \vec{\tau}_{wave\,1}$ and $\vec{\tau}_2 \equiv \vec{\tau}_{wave\,2}$ into (4) gives

$$\vec{\tau}(z) = \vec{\tau}_1(z) + \vec{\tau}_2(z). \qquad (5)$$

Eq. (5) shows that the total stress tends to be governed by two vectors aligned with wind and swell direction respectively. Thus, rather than a decomposition of $\vec{\tau}$ in a fixed rectangular Cartesian reference frame associated with the wind alone and used in (1), consider a decomposition in a fixed non-rectangular reference frame associated with the wind and swell directions (5). Fig. 1 shows decomposition of the stress vector.

According to the above discussion, the vector $\vec{\tau}_1$ may face in to the wind direction ($\tau_1 > 0$), as well as in the opposite direction ($\tau_1 < 0$). Similarly, $\vec{\tau}_2$ may be faced in the swell direction ($\tau_2 > 0$), and in the counter-swell direction ($\tau_2 < 0$). Combinations of these cases gives all possible situations associated with the wind stress directions. Some of these situations are prohibited, e.g. in counter swell τ_2 can be only negative.

Strictly speaking the conceptual scheme discussed above is derived for the values at the wavy surface, although the vector balance in Eqs. (4) - (5) is valid at any

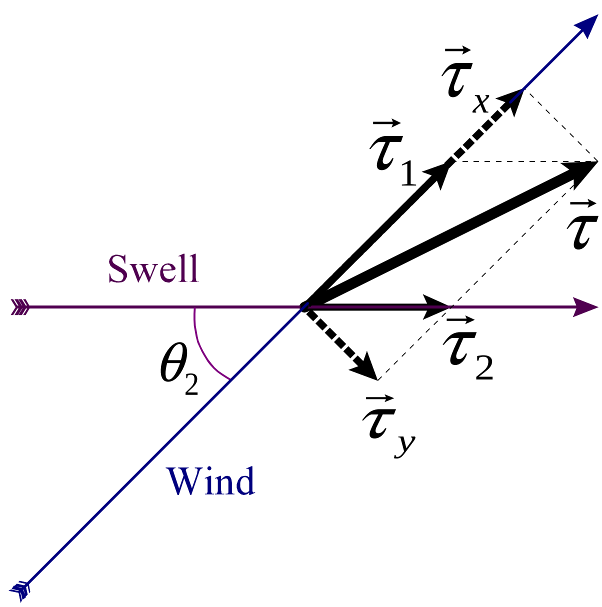

Figure 1. Decomposition of the stress vector, $\vec{\tau}$, into $\vec{\tau}_x$ and $\vec{\tau}_y$ in a wind-associated coordinate system, and into $\vec{\tau}_1$ and $\vec{\tau}_2$ in a wind-swell coordinate system.

height. However, the extrapolation of the surface stress to the elevated measurements is not a trivial problem. This is because both $\tau_{wave\,1}(z)$ and $\tau_{wave\,2}(z)$ generally are not described by a simple exponentially decaying profiles and have a more complicated nonmonotonic structure. Among other things, it was found that the wave-induced stress may reverse sign with height several times (e.g. Hare et al. 1997). Thus, different constituents in the right side of (5) vary with height in different ways and the vector balance shown in Fig. 1 will be changed with height, including cases when the stress vector will lie in different sectors created by wind-swell directions. Comparison of the above approach with field data is given in the next section.

3. FIELD DATA ANALYSIS

We use data collected by the NOAA Environmental Technology Laboratory and Woods Hole Oceanographic Institution during three R/P *FLIP* campaigns. Data were taken in Pacific in September 1993 during SCOPE, in April - May 1995 during MBL II, and in September 1995 during COPE.

In the SCOPE experiment the R/P *FLIP* was moored about 15 km northwest off San Clemente Island (off the southern California coast). A northwest swell was moderate but almost always present, and the direction of the waves was very constant (about 300^o). Fig. 2 presents directional characteristics of the wind and surface stress vector as function of the wind speed during the SCOPE. For winds $U \gtrsim 5$ ms^{-1} the mean stress direction is generally in line with the wind and dominant waves direction (Fig. 2*b*, *c*). This result agrees with previous studies, e.g. Geernaert et al. (1993), Rieder et al. (1994). As wind speed decreases the stress vector deviates significantly from wind and swell direction. In the case $2 \lesssim U \lesssim 4$ ms^{-1} with background swell, the stress vector lies at an obtuse angle between the wind direction and the opposite wave direction, i.e. it is facing in the direction which is opposite to the direction of wave propagation, $\tau_1 > 0$ and $\tau_2 < 0$. For better visualization, we consider two cases, U=6 ms^{-1} and 3 ms^{-1}, and in both cases the wind blows from the west (270^o) and the swell direction is 300^o (Fig. 2*a*). When U = 6 ms^{-1}, supposedly $\tau_2 > 0$ and the stress angle is between 270^o and 300^o. In the case U = 3 ms^{-1} supposedly $\tau_2 < 0$ and the stress angle is between 270^o and 120^o, i.e. stress has approximately a south-southwest direction (Fig. 2*c*). In light winds, $U \lesssim 1.5$ ms^{-1}, the stress vector, on the average, is nearly opposite to wind and swell direction. The regime where the surface stress is aligned opposite to the wind direction corresponds to upward momentum transfer (Grachev and Fairall 2001).

During the MBL II experiment R/P *FLIP* was moored 50 km west of Monterey, California. Wind and swell directions were predominantly from the northwest, as well as in the SCOPE. These conditions are typical of those generally found off the coast of California. For this reason Fig. 3 shows stress behavior similar to Fig. 2. Thus, according to Figs. 2 and 3 deviation of the stress vector direction from the wind vector direction during light winds

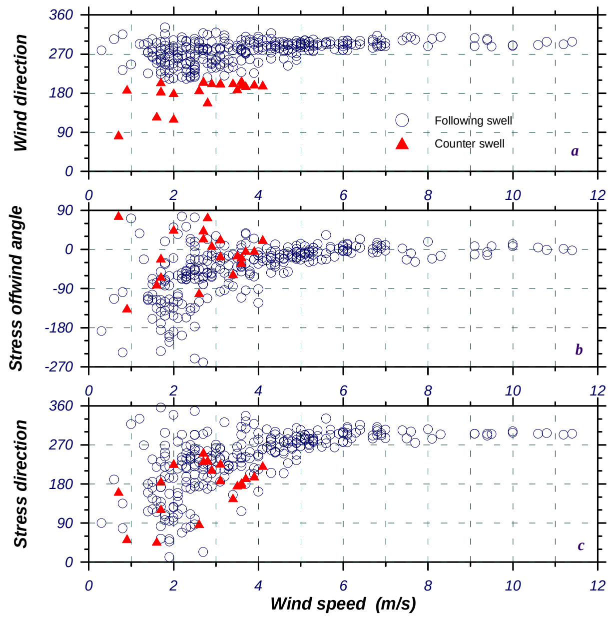

Figure 2. Wind and stress directions during SCOPE as function of wind speed: (*a*) the true wind direction, (*b*) stress offwind angle, α, based on Equation (2), and (*c*) the true stress direction. All angles are calculated using the meteorological convention ("from"), e.g. 270^o means wind (or stress) is from west, negative angles (*b*) corresponds to counter-clockwise rotation. Open circles represent cases when wind follows swell and triangles are counter-swell runs.

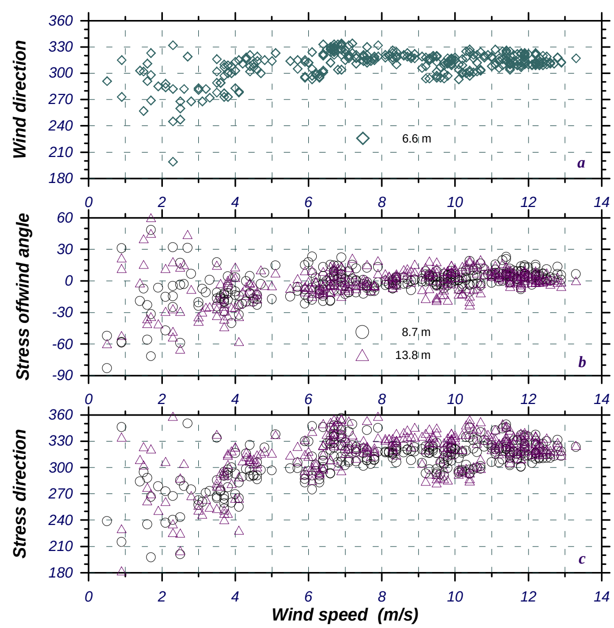

Figure 3. Wind and stress directions (at 2 levels) during MBL II experiment as function of wind speed: (*a*) the true wind direction measured at 6.6 m above sea surface, (*b*) stress offwind angle, α, according to (2), (*c*) the true stress direction. Open circles and open triangles in panels *b* and *c* represent stress measurements at 8.7 m and at 13.8 m above sea surface respectively. Data presented here were taken during May 2 - 8, 1995.

is not just random, and it is governed by both the swell direction and the wind direction.

In the COPE experiment *FLIP* was moored at 150 m depth about 20 km off the coast of northen Oregon just west of Tillamook. Conditions were variable with winds from 0 to 17 ms^{-1}, heavy swells traveling most of time about crosswind (Fig. 4). Fig. 5 shows that the stress vector over September 23-28 generally lies between wind and swell directions (Fig. 4), i.e. $\tau_1 > 0$ and $\tau_2 > 0$ (Fig. 1). High values of α (Fig. 5*a*) are generally associated with light wind events. Upward momentum flux in Fig. 4*c* is caused by decaying wind waves, since the swell is about perpendicular to the wind. A sign reversal occurs at $U \approx 4$ ms^{-1} that is consistent with results of Drennan et al. (1999) obtained in Lake Ontario, and it is higher than $U \approx 2$ ms^{-1} obtained by Grachev and Fairall (2001) for an ocean swell regime. This variation may be associated with higher slopes of wind waves as compared to ocean swells. The stress vector at $t \approx 25.5$ (Fig. 5*a*) turns about 180°, and finally it is nearly opposite to the wind, but perpendicular to the swell. It is particularly remarkable that the stress vector turns in different directions at different levels. Fig.5 at $t \approx 23.6$ shows an example of high values of α for high winds, $U \approx 9$ ms^{-1}. This case is associated with counter swell regime, $\tau_1 > 0$ and $\tau_2 < 0$

4. CONCLUSIONS

In the general case stress is a vector sum of the (i) pure shear stress (turbulent and viscous) aligned with the mean wind, (ii) wind wave-induced stress aligned with the direction of the pure wind sea waves, and (iii) swell-induced stress aligned with the swell direction. The direction of the wind wave-induced stress and the swell-induced stress components may coincide with, or be opposite to, the direction of wave propagation (pure wind waves and swell respectively). As a result the stress vector may deviate widely from the mean wind flow including cases when stress is directed across or even opposite to the wind.

5. REFERENCES

Drennan, W. M., K. K. Kahma, and M. A. Donelan, 1999: On momentum flux and velocity spectra over waves. *Boundary-Layer Meteorol*., **92**(3), 489 – 515.

Geernaert, G. L., 1988: Measurements of the angle between the wind vector and wind stress vector in the surface layer over the North Sea. *J. Geophys. Res.*, **93**(C7), 8215 – 8220.

Geernaert, G. L., F. Hansen, M. Courtney, and T. Herbers, 1993: Directional attributes of the ocean surface wind stress vector. *J. Geophys. Res.,* **98**(C9), 16,571 – 16,582.

Grachev, A. A. and C. W. Fairall, 2001: Upward momentum transfer in the marine boundary layer. *J. Phys. Oceanogr.,* (in press).

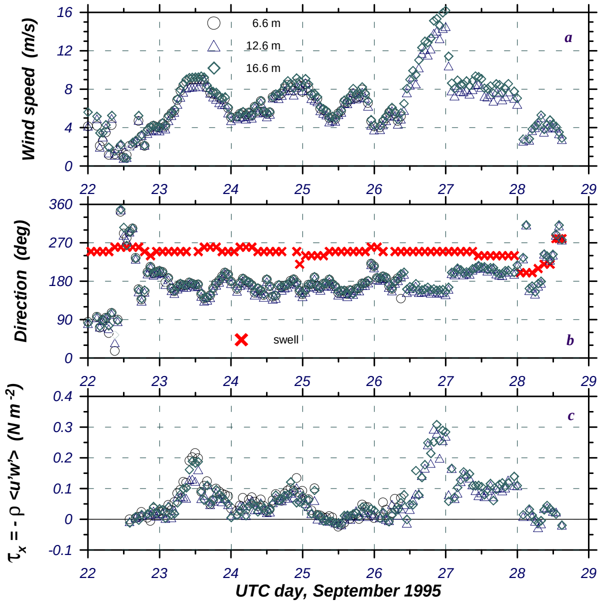

Figure 4. Time series of wind speed (*a*), true wind and swell direction (*b*), and downwind stress component (*c*) during COPE. Circles, triangles and diamonds represent 1 hr averaged sonic anemometers measurements at 6.6 m, 12.6 m, and 16.6 m respectively.

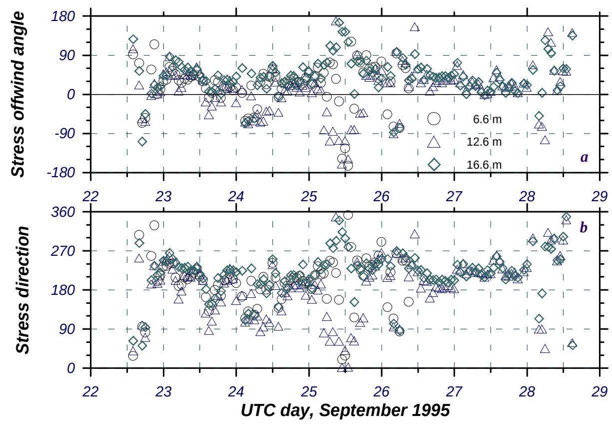

Figure 5. Time series of the stress offwind angle, α, (*a*), and the true stress direction (*b*) during COPE.

Hare, J. E., T. Hara, J. B. Edson, and J. M. Wilczak, 1997: A similarity analysis of the structure of airflow over surface waves. *J. Phys. Oceanogr.,* **27**, 1018–1037.

Rieder, K., J. A. Smith, and R. A. Weller, 1994: Observed directional characteristics of the wind, wind stress, and surface waves on the open ocean. *J. Geophys. Res*., **99**(C11), 22,589 – 22,596.

Smith, S. D., 1980: Wind stress and heat flux over ocean in Gale Force Winds. *J. Phys. Oceanogr.,* **10**, 709–726.