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THE SENSITIVITY OF UPPER OCEAN STRUCTURE TO TIME VARYING WIND DIRECTION

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Abstract. Observations and models show that sudden changes in the magnitude of the wind stress which occur within a time interval of one-half inertial period are most effective in increasing surface current speeds and mixing the upper layers of the ocean. The purpose of the present study is to quantify the effects of concurrent time dependent wind direction. The Mellor-Yamada level 2 1/2 turbulence closure model is used. A series of model runs was executed in order to determine the relative sensitivity of mixed layer depth and sea surface temperature to wind speed as compared with the rate of change of wind direction. The results indicate that the accuracy and time resolution of wind direction should be given special consideration in the design and interpretation of field experiments which will be used for testing prognostic mixed layer models.

Introduction

Observations and numerical experiments of the upper ocean show that sudden changes in the magnitude of the wind stress (within one-half inertial period) correlate with increased surface current speeds and rapid deepening of the mixed layer (e.g., Pollard, 1970; and Mellor and Durbin, 1975). Klein (1980) found that wind stress pulses applied at the inertial period result in enhanced mixed layer depths because of a resonance mechanism. However, Klein's simulations were restricted to uni-directional wind stress conditions. The onset of major wind events commonly is characterized by changing wind direction (e.g., Hertzman et al., 1974). While several simulations of the mixed layer have been quite successful, the relative importance of wind stress magnitude compared with the rate of change of wind stress direction has not been examined in detail to our knowledge. This question is relevant to the experimental design (e.g., required accuracy and time resolution of wind stress direction) of upper ocean experiments and the interpretation of resulting data. For example, satellite-borne scatterometers (sidelooking radar with large incidence angles) have been used to determine vector wind stress fields over the world's oceans (e.g., Huang, 1979; O'Brien, 1981; and Satellite Surface Stress (S^3) Working Group, 1982). These data are used as input for models of upper ocean dynamics and ocean circulation. The tremendous potential of this technique is compelling. The focus of this study is to quantify the effects of variability in wind direction which accompanies impulsive wind stresses lasting one-half inertial period. Thus, the intent is to isolate one effect rather than to simulate a particular data set which would be difficult to interpret because of competing processes.

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Model

The Mellor and Yamada (1982) level 2 1/2 turbulence closure model was chosen for the present study. This model and its simpler counterpart, level 2, have been quite successful in simulating observations of upper ocean structure (e.g., Mellor and Durbin, 1975). The model includes equations for mean zonal and meridional momentum, heat conservation, turbulent kinetic energy, turbulent length scale, and an equation of state. Model assumptions include: hydrostatic balance, Boussinesq approximation, low Rossby number, boundary layer approximation, and no vertical advection. The expressions for turbulent fluxes may be written in a classical K-theory form. The vertical eddy diffusivity of momentum, K_M, for example, may be written as a product of a turbulent velocity, a turbulent length scale, and a stability function which approaches zero as the flux Richardson number (the ratio of negative buoyancy production to shear production) exceeds a value of approximately 0.2. The details of the model have been described extensively elsewhere (e.g., Blumberg and Mellor, 1981). The model runs utilize 101 vertical grid points for the upper 60 m of the water column and the time step is 1 h. The duration of each run is 48 h. The model is driven by a wind stress obtained from the quadratic drag law. Its magnitude is given by

$$\tau_o = \rho_a \; C_{10} U_{10}^2 \qquad (1)$$

where ρ_a is the density of air, C_{10} is the drag coefficient, and U_{10} is the mean wind speed at 10 m above the ocean surface. The value of C_{10} is set equal to 1.4×10^{-3} for all runs (see Paulson and Simpson, 1981, and Dickey and Simpson, 1982, for further discussion of C_{10} variability). The surface heat flux is set equal to zero for all runs because only high wind speed cases are considered and attention is focused on the short term response. The effects of solar heating under conditions of high wind speed (U_{10}>20 m s^{-1}) are generally negligible (Simpson and Dickey, 1981a,b). Clearly, surface heat fluxes could not be excluded if the long term relaxation were of interest. The same initial linear stratification (Brunt-Väisälä period equals 15.3 min) used by Simpson and Dickey (1981a) and Dickey and Simpson (1982) is employed and the mean currents are initially zero. For simplicity, geostrophic velocities are neglected and uniform salinity is assumed. The lat-

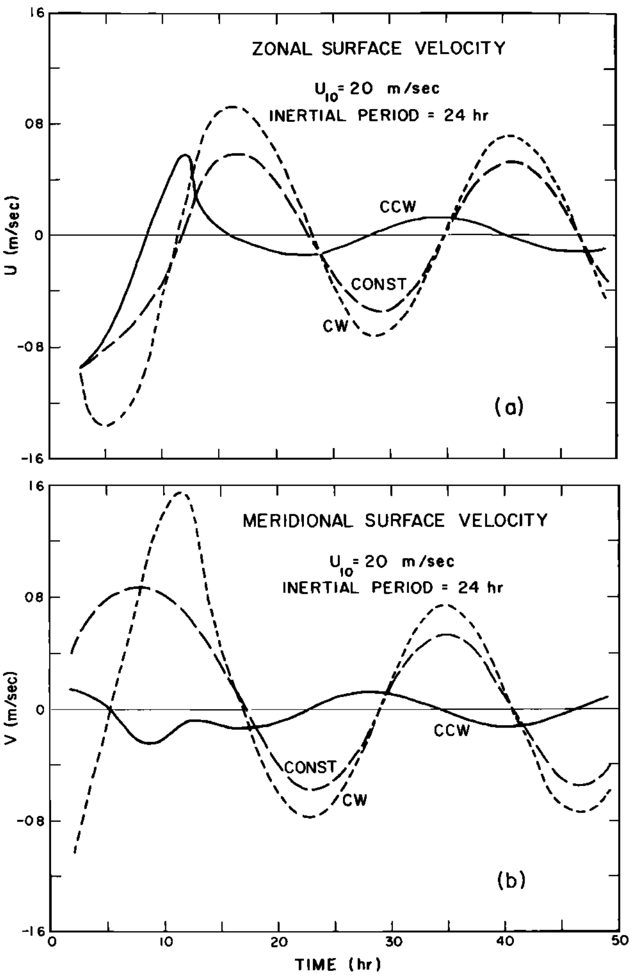

Fig. 1 a) Time series of zonal surface velocity for constant (CONST), clockwise rotating (CW), and counter-clockwise (CCW) rotating wind stress vectors. b) Time series of the corresponding meridional surface velocity. The wind stress is zero after 12 h (see equations 2 and 3).

itude chosen for the study is 30°N and the local inertial period, T_i, equals 24 h.

Results

For a non-rotating wind stress vector, the most intense response of the upper ocean occurs when the duration of the wind stress is equal to one-half inertial period. The model runs to be discussed employ impulsive forcing which lasts for one-half inertial period. The zonal and meridional components of the wind stress vector are chosen to be of the form

$$\left.\begin{aligned} \tau_{ox} &= \tau_o \cos\omega t \\ \tau_{oy} &= -\tau_o \sin\omega t \end{aligned}\right\} \quad 0 \leq t \leq T_i/2 \qquad (2)$$

and

$$\tau_{ox} = \tau_{oy} = 0 \qquad t > T_i/2 \qquad (3)$$

where ω is the frequency of rotation of the wind stress vector and t is time. The following three cases will be considered in detail: (1) unidirectional wind stress (CONST) or $\omega = 0$, (2) wind

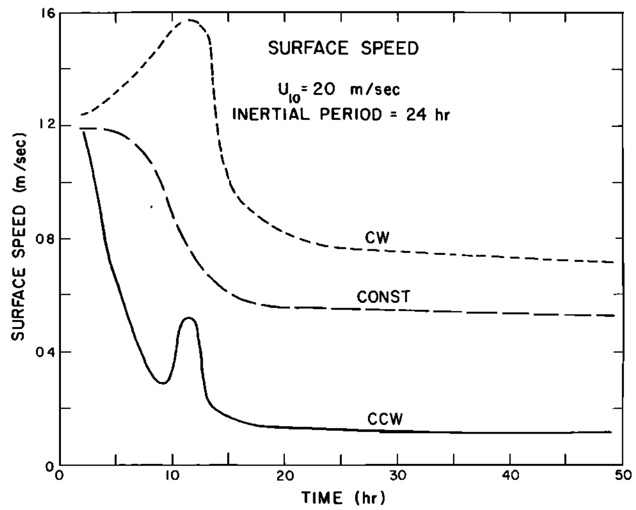

Fig. 2. Surface speed time series for constant (CONST), clockwise rotating (CW), and counter-clockwise (CCW) rotating wind stress vectors.

stress vector rotating clockwise with inertial period (CW) or $\omega = + f$, and (3) wind stress vector rotating counter-clockwise with inertial period (CCW) or $\omega = -f$. In all cases $U_{10} = 20$ m s^{-1} and f is the Coriolis parameter evaluated for 30°N.

The zonal and meridional components of the mean surface velocities are shown in Figs. 1a and 1b. After spin-up, the amplitude of each component is greatest for the clockwise forcing and smallest for the counter-clockwise forcing. This occurs because the clockwise wind stress vector is nearly in phase with the generated surface current velocity vector. Therefore, the clockwise wind stress reinforces the surface current. The resulting surface speeds (Fig. 2) are almost eight times greater for the clockwise case than for the counter-clockwise case. The peaks in surface

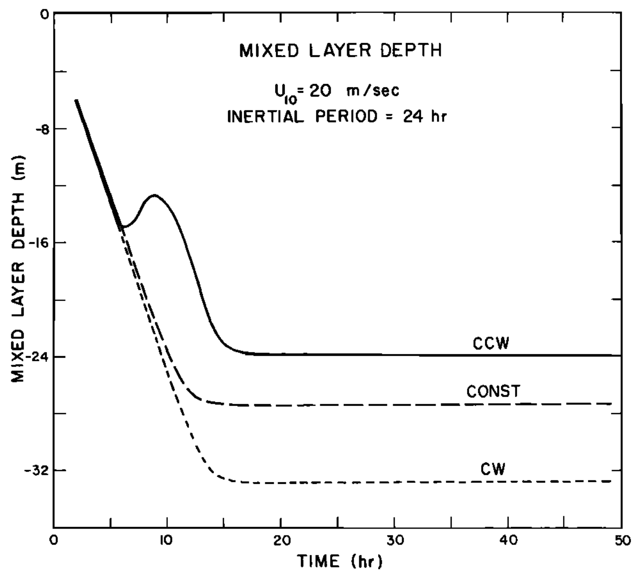

Fig. 3. Mixed layer depths as functions of time for constant (CONST), clockwise rotating (CW), and counter-clockwise (CCW) rotating wind stress vectors.

speed for the CW and CCW cases occur at about $t = T_i/2$. This is the time at which the currents generated at t = 0 by the initiation of the wind stress have rotated through 180° and are nearly aligned with the applied wind stress vector. Significantly greater shear necessarily occurs at the base of the mixed layer with the clockwise forcing. Hence, the associated mixed layer depths are approximately 35% greater than those of the counter-clockwise case (Fig. 3). Under these conditions (e.g., forcing duration equals one-half inertial period) maximum mixed layer depths generally are proportional to wind speed. This implies that a range of constant wind speeds which vary by 35% would produce equivalent changes in the mixed layer depth. The temporary retreat of the mixed layer seen in the CCW case results from reduced shear caused by the opposing effects of the initial setup and those which accompany the wind

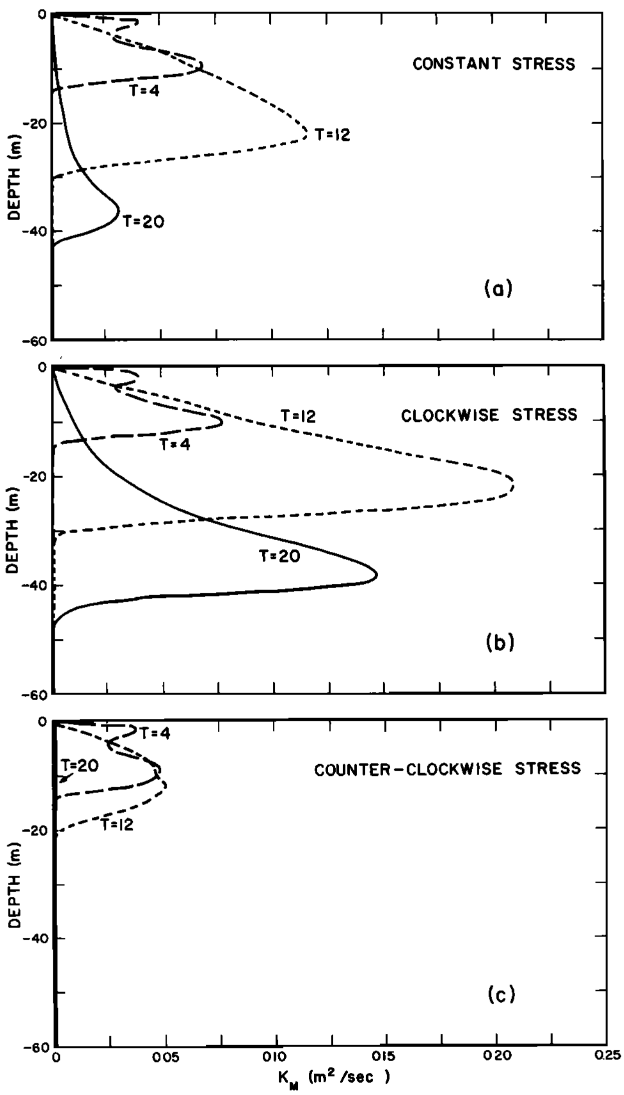

Fig. 4. Vertical profiles of eddy diffusivity of momentum for a) constant (CONST), b) clockwise rotating (CW), and c) counter-clockwise (CCW) rotating wind stress vectors. Profiles are shown for 4, 12, and 20 hours after initiation of wind stress.

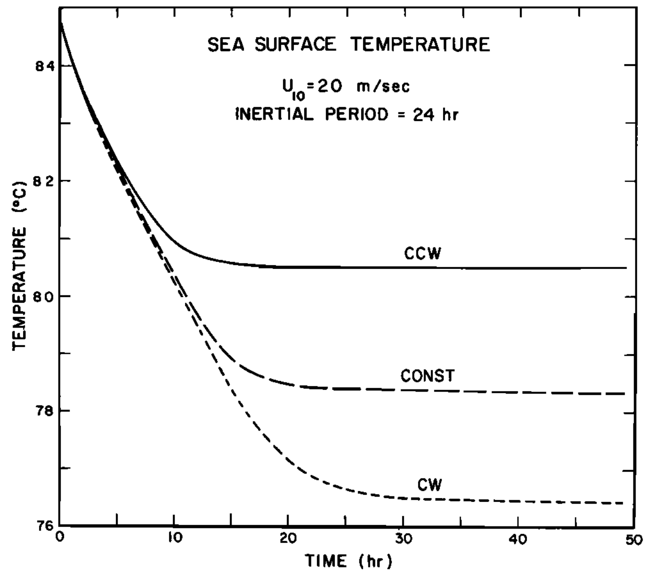

Fig. 5. Sea surface temperature versus time for constant (CONST), clockwise rotating (CW), and counter-clockwise (CCW) rotating wind stress vectors.

stress vector in the time interval centered near $t = T_i/4$. Remnant shear generated turbulence, characterized by flux Richardson numbers less than approximately 0.2, persists near the base of the mixed layer after forcing ceases in all cases. The shortest lifetime of the residual turbulence is associated with the counter-clockwise case (~ 20 h) while the longest lifetime corresponds to the clockwise case (~ 48 h). Vertical eddy diffusivities of momentum are shown in Fig. 4 for the three cases at 4, 12, and 20 h after the onset of the wind stress. In all three cases the relative maximum in vertical eddy diffusivity propagates downward in time and the greatest values occur at 12 h. The largest values of eddy diffusivity occur for the clockwise case (Fig. 4b) and the smallest for the counter-clockwise case (Fig. 4c). This is consistent with the previous velocity shear and mixed layer arguments. Sea surface temperatures are greater (~ 0.4°C) for the counter-clockwise case than for the clockwise case (Fig. 5). The time necessary for sea surface temperature to reach steady-state is longest for the clockwise case. Additional runs used U_{10}= 10 m s^{-1} instead of U_{10}= 20 m s^{-1}. Surface speed, mixed layer depth, and sea surface temperature were evaluated at t = 30 h for the clockwise and counterclockwise cases. The percentage difference between the two cases was determined for each parameter. These percentages were similar to those computed for the U_{10}= 20 m s^{-1} runs. The U_{10}= 10 m s^{-1} results should be interpreted with qualification because 10 m s^{-1} is near the transition between heat and wind dominated regimes (Simpson and Dickey, 1981a).

Approximately forty runs were executed in order to illustrate the importance of wind directional variability compared to wind stress magnitude or alternatively U_{10}. The time dependence of the wind stress is given by equations 2 and 3. Thus, runs with various combinations of values of

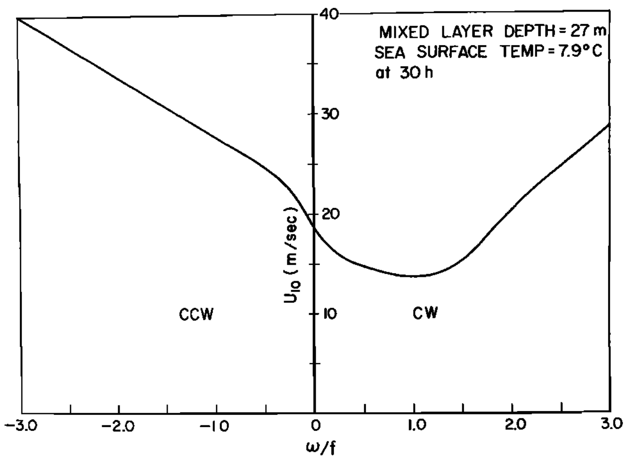

Fig. 6. Values of U_{10} versus wind stress vector rotation rate ω (normalized by the inertial frequency, f) which result in a mixed layer depth of 27 m and a sea surface temperature of 7.9°C after 30 h of the onset of the wind. The wind stress is zero after 12 h (see equations 2 and 3) as in previous figures.

wind stress vector rotation rates and U_{10} were done. Pairs of values of U_{10} and ω/f which result in a mixed layer depth of 27 m and a sea surface temperature of 7.9°C at t= 30 h are shown in Fig. 6. The minimum wind speed required to achieve this condition is accompanied by a wind stress vector which rotates clockwise at the inertial frequency (ω = f). This is a nearly resonant condition. The sensitivity to the sense of direction change can be seen by comparing the wind speed of 15.0 m s^{-1} for ω = 0.5 f (clockwise) to the wind speed of 24.5 m s^{-1} for ω = −0.5 f (counterclockwise). The inertial period is inversely proportional to the sine of the latitude and thus the time resolution requirements for the wind stress vector are most severe at higher latitudes.

The S^3 Working Group has recommended that scatterometer accuracies of 2 m s^{-1} or 10% of the wind speed (whichever is larger) and ± 20° in wind direction be maintained with coverage at 6 h intervals. As discussed by the S^3 Working Group, this set of conditions would be inadequate to resolve wind shifts associated with the passage of frontal features which are effective in generating inertial motions. The S^3 Working Group has recognized the need to supplement scatterometry with standard operational meterological procedures. The results of the present study suggest that wind direction variability at times is as important as wind speed magnitude in predicting upper ocean structure. It appears that methods of supplementing scatterometer data as suggested by the S^3 Working Group are required for proper implementation of upper ocean models on the basis of wind direction variability as well as wind stress magnitude variability.

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References

Blumberg, A.F., and G. L. Mellor, 1981: A coastal ocean numerical model. International Symposium on Mathematical Modelling of Estuarine Physics, Hamburg, J. Sunderman, Ed., Springer-Verlag.

Dickey, T. D., and J. J. Simpson, 1982: The influence of optical water type on the diurnal response of the upper ocean. In press, Tellus.

Hertzman, O., M. Miyake, and S. Pond, 1974: Ten years of meteorological data at Ocean Weather Station PAPA. Manuscript Report #29, Institute of Oceanography, University of British Columbia, Vancouver, B.C., Canada, 46 pp.

Huang, N. E., 1979: New developments in satellite oceanography and current measurements. Rev. of Geophys. and Space Phys., 17, 1558-1569.

Klein, P. 1980: A simulation of the effects of air-sea transfer variability on the structure of marine upper layers. J. Phys. Oceanogr. 10, 1824-1841.

Mellor, G. L., and P. A. Durbin, 1975: The structure and dynamics of the ocean surface mixed layer. J. Phys. Oceanogr., 5, 718-728.

Mellor, G. L., and T. Yamada, 1982: Development of a turbulence closure model for geophysical fluid problems. Rev. of Geophys. and Space Phys., 20, 851-875.

O'Brien, J. J., 1981: The future for satellite-derived surface winds. Oceanus, 24, 27-31.

Paulson, C.A., and J. J. Simpson, 1981: The temperature difference across the cool skin of the ocean. J. Geophys. Res., 86, 11044-11054.

Pollard, R. T., 1970: On the generation by winds of inertial waves in the ocean. Deep-Sea Res., 17, 795-812.

Simpson, J. J., and T. D. Dickey, 1981a: The relationship between downward irradiance and upper ocean structure. J. Phys. Oceanogr., 11, 309-323.

Simpson, J.J., and T. D. Dickey, 1981b: Alternative parameterizations of downward irradiance and their dynamical significance. J. Phys. Oceanogr., 11, 876-882.

Satellite Surface Stress (S^3) Working Group, 1982: Scientific opportunities using satellite wind stress measurements over the ocean. Report of the Satellite Surface Stress Working Group, J.J. O'Brien, Chairman, Nova University/N.Y.I.T. Press, Fort Lauderdale, FL, 153 pp.

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