

MIXED-LAYER SHEAR RELATED TO WIND STRESS IN THE CENTRAL EQUATORIAL PACIFIC

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ABSTRACT

Sixteen months of wind and current profile observations in the central equatorial Pacific show the response of the upper ocean shear to local wind forcing. The shear at the ocean surface is significantly correlated with the wind stress in direction, but not in magnitude. This implies that the vertical eddy viscosity coefficient (A_v) is proportional to the square of the wind speed or to the stress.

Using this variable eddy viscosity coefficient in Stommel's (1960) model of the Equatorial Undercurrent, we calculate shears in the mixed layer that compare well with the observations. The flow is downwind on the equator and tends toward an Ekman spiral off the equator. The depth to which the model applies increases with the wind speed and is close to the Ekman depth ($2A_v/|f|$)^{1/2} at 2° from the equator. The application of the model to the observations is insensitive to the method of estimating the layer depth.

1. INTRODUCTION

The central equatorial Pacific surface layer is characterized by small vertical density gradients and a strong pycnocline that separates it from the deeper ocean. These conditions lead to the rapid development of ageostrophic shear flows directly driven by the wind and decoupled from the deeper circulation (Hisard et al., 1970, Wyrski et al., 1981, Donguy et al., 1984, Leetmaa and Wilson, 1985). Previous studies have been based on occasional current profile sections, or, in the NORPAX Tahiti Shuttle, on a period of time in which the winds were quite steady. Here we investigate the relationship between local winds and upper ocean shear in a 16-month time series including 41 sections, and spanning a period of major wind changes: the 1982-83 El Niño.

2. DATA

During March 1982 through June 1983, as part of the PEQUOD project (Pacific Equatorial Ocean Dynamics), 21 cruises were made in the central equatorial Pacific (Firing et al., 1983). Profiles of absolute current velocity and temperature together with shipboard wind observations were obtained every half degree from 3°N to 3°S along 159°W (Fig. 1).

Current velocities and temperatures were sampled at about 10-m vertical intervals using the Pegasus acoustic dropsonde (Spain et al., 1981). The surface velocity was averaged from the drift of the Pegasus before recovery, an interval ranging from a few minutes to an hour. Descending and ascending Pegasus profiles were averaged and linearly interpolated at 2-m intervals, then smoothed and interpolated to 20-m intervals starting at 40 m. The 20-m velocity was calculated using a parabolic fit to the surface velocity, the smoothed 40-m velocity, and the unsmoothed intermediate data. The endpoints were given extra weight.

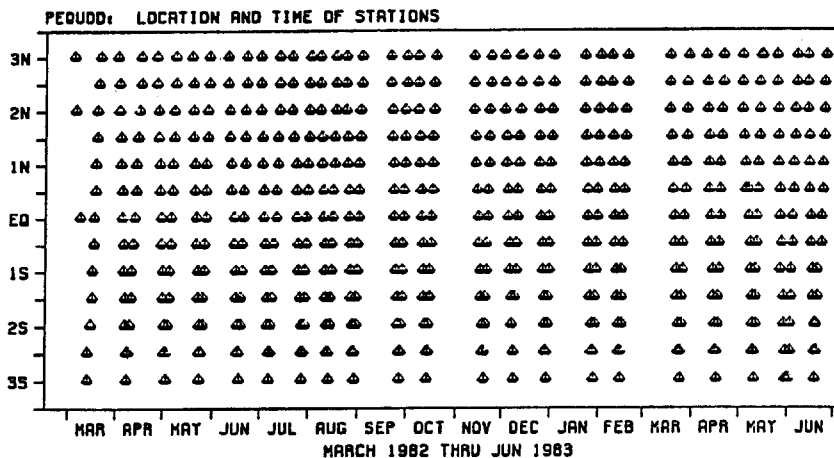


Fig. 1. Location of the stations along 159°W during the PEQUOD program.

Vertical shear of the horizontal currents was computed at each station at various levels. For the surface, the shear was calculated from a parabolic fit to the processed velocities at 0, 20, and 40 m. First order finite differences were used to calculate the shear at 10, 30, 50 and 70 m. The coarseness of these shear estimates was primarily due to limits imposed by the current profiling method. The relationship of these estimates to the actual shear structure of the ocean will require more investigation, including new measurements with better resolution and accuracy.

The wind stress was assumed proportional to the wind velocity squared: $\tau = \rho_a C_D |\underline{U}| \underline{U}$ with ρ_a the air density, \underline{U} the wind velocity at 10 m above the sea surface and C_D the drag coefficient. C_D was considered constant ($C_D = 1.14 \times 10^{-3}$, Large and Pond, 1982) since only wind speeds smaller than 10 m/s were included in the study.

Confidence limits for correlation analyses were estimated using an integral time scale of 25 days (Davis, 1976, 1977), calculated from the time series at 3°N (Fig. 1) where the sampling interval was the most regular. The corresponding number of equivalent degrees of freedom, 17, was considered as representative for the time series at each latitude, and as a very conservative estimate for the data set as a whole, disregarding latitude.

3. SHEAR - WIND STRESS CORRELATIONS.

Using all 492 profiles, the correlation between the magnitudes of the wind stress and shear vectors at the sea surface was not significantly different from zero; but the directions of the vectors were significantly correlated (over the 99% confidence level, Fig. 2). This has important consequences for the eddy viscosity coefficient (A_v), given as: $A_v = \tau / \rho u_z = \rho_a C_D U^2 / \rho u_z$, with ρ the density of water and u_z the surface shear magnitude. If the surface shear magnitude does not depend on the wind speed, then A_v must be proportional to the square of the wind speed. This was confirmed by the following alternative analysis, involving the Cartesian rather than the polar components of the vectors.

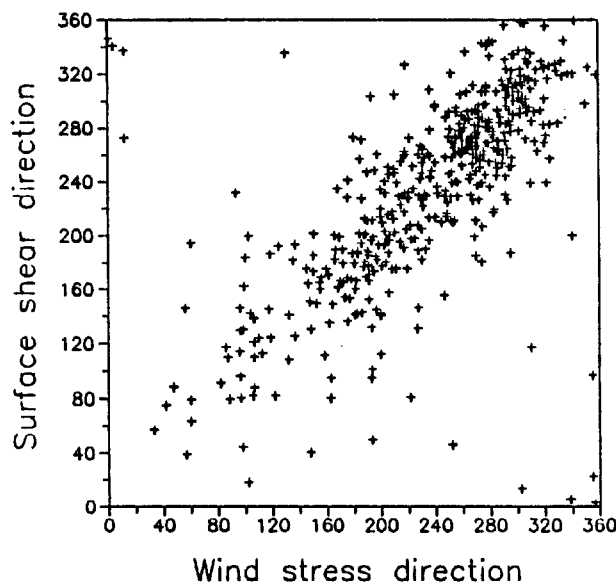


Fig. 2. Surface shear vs. wind stress directions from 492 data pairs. The directions increase clockwise from true North. The correlation coefficient is 0.7.

Values for A_v at different wind speeds were obtained from the correlations between wind stress and surface shear, separating zonal and meridional components. The correlations in the range of 1 - 10 m/s at 1 m/s intervals were all significant at the 95% confidence level, and for wind speeds higher than 4 m/s they were over the 99% level. A linear regression of A_v vs. wind speed (Fig. 3) gave:

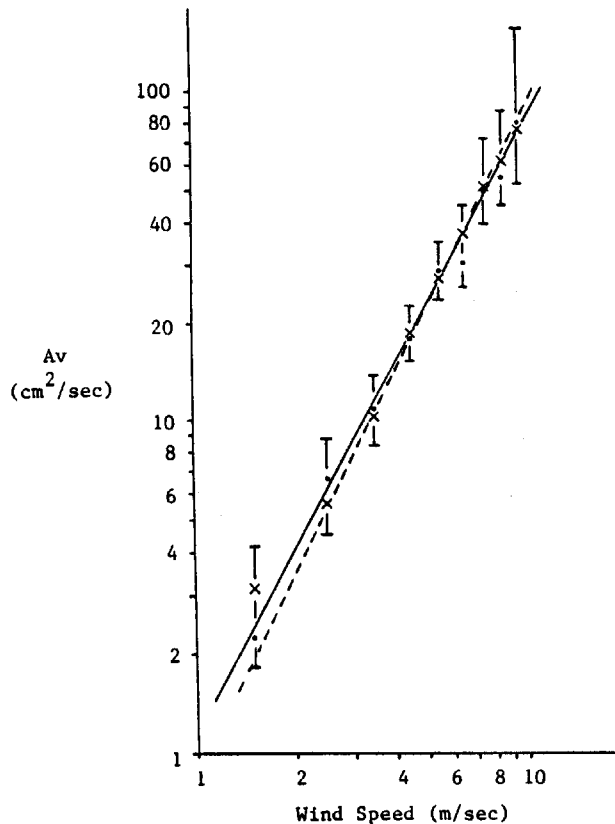


Fig. 3. Logarithmic plot of the vertical eddy viscosity coefficient (A_v) for different wind speeds (U). The crosses (X) correspond to the zonal and the dots (.) to the meridional components. The solid line is the linear regression fit, and the dashed line corresponds to $A_v \sim U^2$. The bars are the 95% confidence limits.

$$A_v = a (U/U_0)^b ; \quad 1 \text{ m/s} < U < 10 \text{ m/s} \quad (1)$$

with U = wind speed in m/s, $U_0 = 1$ m/s, $a = 1.16 \text{ cm}^2/\text{s}$ and $b = 1.85$.

This shows A_v varying nearly as the square of the wind speed. The quadratic relation, also shown for comparison in Fig. 3, is:

$$A_v = c U^2 ; \quad c = 1 \times 10^{-4} \text{ sec} \quad (2)$$

This result implies that any approximation of A_v as constant in the mixed layer can be valid only over a narrow range of wind speeds. It is expected that eddy diffusivity responds to the wind speed in a similar manner.

Only the correlations between colinear components of the wind stress vs. surface shear were significant. The correlations of the cross components (e.g., meridional shear vs. zonal stress), which could have indicated a turning of the shear due to the Coriolis force, were not statistically significant. At deeper levels the turning appeared to be a consistent feature. To study this turning and to estimate the depth of direct

influence of the wind on the surface layer, the inner covariance (Mooers, 1973) and inner correlation were calculated.

The inner covariance between the shear vector (u_z, v_z) and the wind stress vector (τ^x, τ^y) for a sample of N observations is defined as:

$$\begin{aligned} \text{Cov}(T^*, U_z) &= \sum_{j=1}^N |T'_j| |U_z'_j| \exp\{i(\phi_j - \theta_j)\} \\ &= |\text{Cov}(T^*, U_z)| \exp(i\phi_{1nn}) \end{aligned}$$

where T and U_z are the complex representations of the wind stress and shear in terms of their zonal and meridional components (i.e., $T = \tau^x + i\tau^y = |T| \exp(i\theta)$ and $U_z = u_z + iv_z = |U_z| \exp(i\phi)$), and the primes denote demeaned quantities. ϕ_{1nn} gives the turning of U_z with respect to T . The normalized covariance is the inner correlation:

$$\begin{aligned} K_{1nn} &= \text{Cov}(T^*, U_z) / [\text{Var}(T) \text{Var}(U_z)]^{1/2} \\ &= |K_{1nn}| \exp(i\phi_{1nn}) \end{aligned}$$

where $\text{Var}(X) = \text{Cov}(X^*, X)$.

The inner correlations between wind stress and shear at 10 and 30 m for each latitude are shown in Fig. 4. The magnitude of the vectors in the complex plane gives the correlation between the variables, and the phase is a measure of the mean angle from the stress vector to the shear vector. At 10 m the correlations were significant at almost all latitudes, but the angles were near zero. The 30-m shears were not significantly correlated (at the 95% level) with the stress but were consistently rotated clockwise north of the equator, and, to a lesser degree, counterclockwise south of the equator.

The inner correlations between the shear at 10 and 30 m, 30 and 50 m, and 10 and 50 m depth were obtained in order to observe the shear turning (Fig. 5). The phase of the complex vectors showed clearly a rotation of the shear with respect to depth, with clockwise turning in the northern hemisphere and counter-clockwise in the southern. This was observed regularly in the three cases. The correlations between 10 and 30 m depth were all significant at the 95% confidence level, and between 30 and 50 m they were over the 99% confidence level. Between 10 and 50 m the correlations were not significant (at the 95% confidence level), but were consistent with the 10 to 30 m and 30 to 50 m rotations.

The observed correlation between wind and shear, and the anticyclonic rotation of the shear with depth, suggest Ekman layer dynamics. The simplest model of Ekman dynamics near the equator is that of Stommel (1960). In the next section this model is used to predict the shear generated from the observed winds, which is then compared with the observed shear.

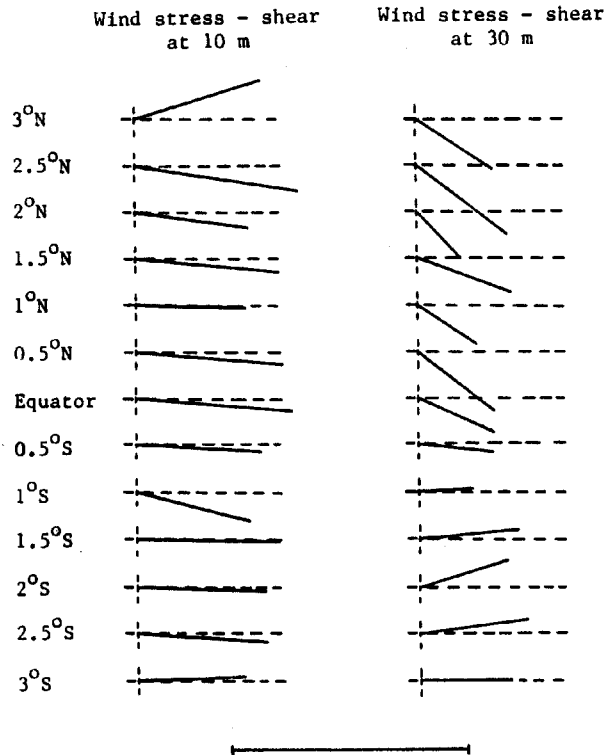


Fig. 4. Inner correlations in the complex plane between wind stress and shear at 10 and 30 m depth respectively, at each latitude. The phase indicates the turning of the shear with respect to the wind stress. The bar at the bottom of the figure represents a correlation of magnitude one.

4. APPLICATION OF STOMMEL'S MODEL

Stommel's 1960 model was originally applied to the Equatorial Undercurrent but is actually better suited to the study of shear in the mixed layer. It assumes steady linear flow in a homogeneous surface layer driven by the wind stress. The surface layer is decoupled from the deeper circulation by imposing a condition of zero momentum flux at the bottom of the layer. Only vertical friction is considered. The model gives a parabolic downwind velocity profile on the equator, blending smoothly into a surface Ekman layer far from the equator. There are two free parameters: A_v and the mixed layer depth h . A third parameter, the Ekman depth $(2A_v/|f|)^{1/2}$, is a function of latitude. In the following we will explore the behavior of the model in several ranges of wind speed with various methods for choosing the free parameters.

First, the shear at 10 and 30 m was modeled using a constant $A_v = 35 \text{ cm}^2/\text{s}$ and with the base of the layer defined as the shallowest point where the vertical temperature gradient exceeded $0.05^\circ\text{C}/\text{m}$. Comparing modeled versus observed shears for 440 stations (Fig. 6), the correlation coefficients were 0.59 (significant at 95%) for the zonal and meridional comparisons at

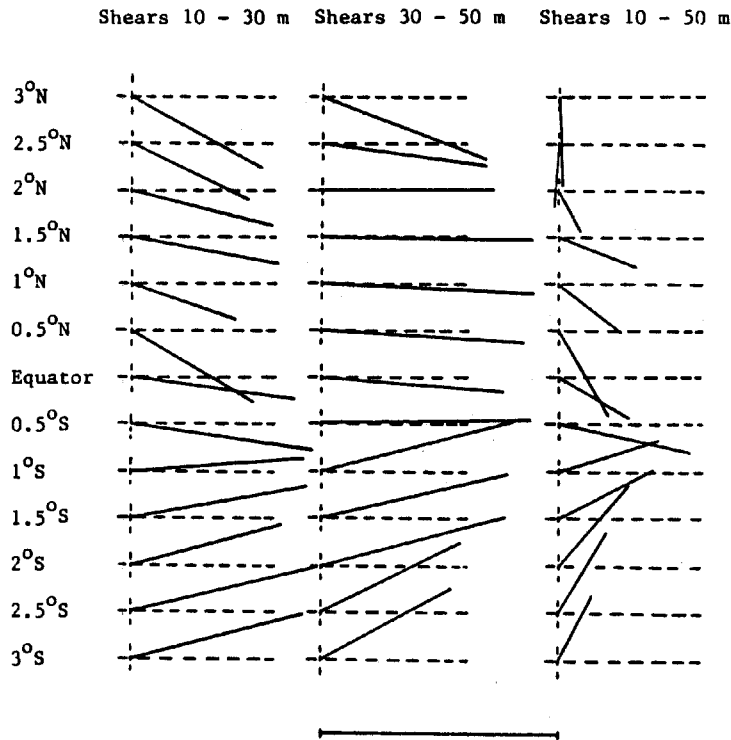


Fig. 5. Inner correlations in the complex plane between shear at 10 and 30 m, 30 and 50 m, and 10 and 50 m depth at each latitude. The phase indicates the turning of the deeper shear with respect to the shallower shear. The bar at the bottom of the figure represents a correlation of magnitude one.

10 m. At 30 m the correlations were 0.51 and 0.43 for the zonal and meridional components, and were significant at the 95% and 90% confidence levels respectively. The data in Fig. 6 seem to occupy mainly the first and third quadrants, although their distribution in those quadrants is rather diffuse; this indicates that with a constant value for A_v , the model can give a proper description of the direction of the shear, but its magnitude is poorly determined.

A notable improvement in the shear modeling was obtained when the value for A_v was calculated using eq.(1). The correlation coefficients from the comparisons in the zonal and meridional components increased to 0.74 and 0.72 respectively at 10 m, and to 0.59 and 0.46 at 30 m (Fig. 7).

To evaluate the effect of the wind speed on the model performance, the shear was calculated for different wind ranges and compared with the observations (Table 1). Only the shear above the depth of the mixed layer was used, so the number of samples decreased with depth. The correlations increased at higher wind speed, although the differences were not statistically significant. However, the regularity of this behaviour at all depths indicates that the model performs better at high wind speeds. An important pattern was that the higher the wind speed, the greater the depth where the correlations were still significant. This depth was

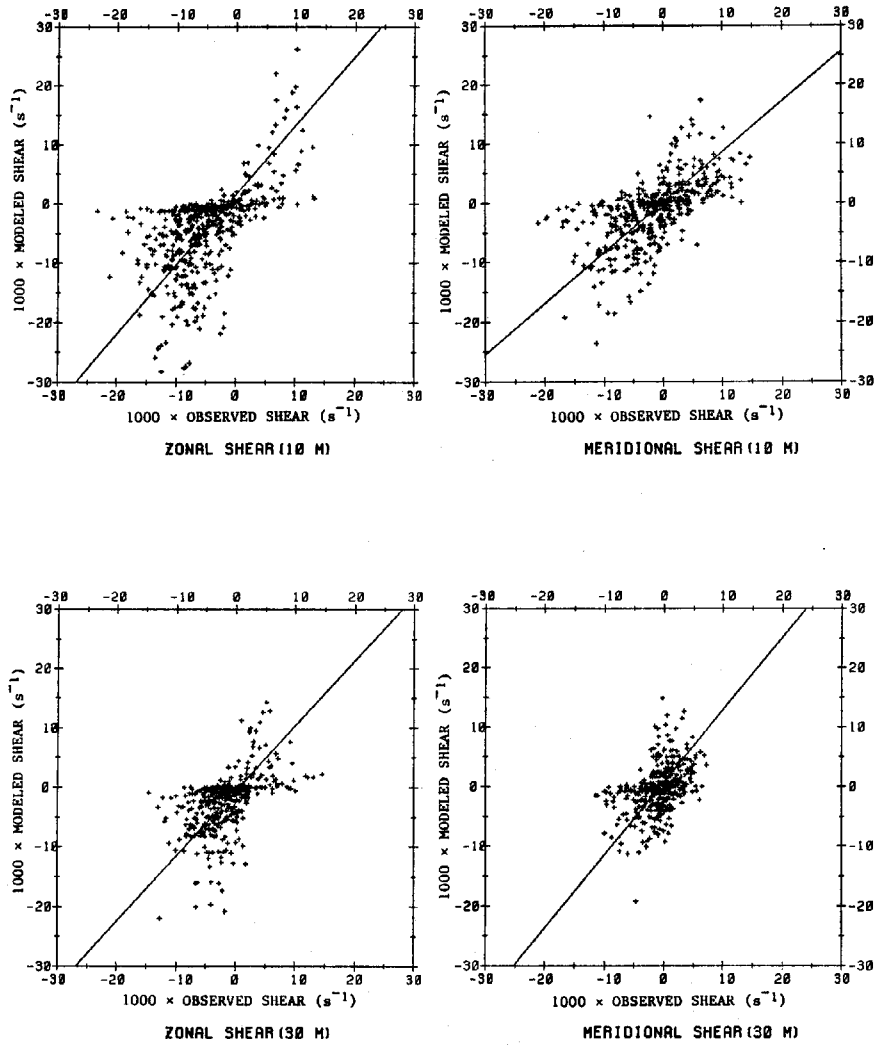


Fig. 6. Comparisons between modeled and observed shear for the zonal and meridional components at 10 and 30 m depth. A constant value of $A_v = 35$ cm^2/s was used in the modeling.

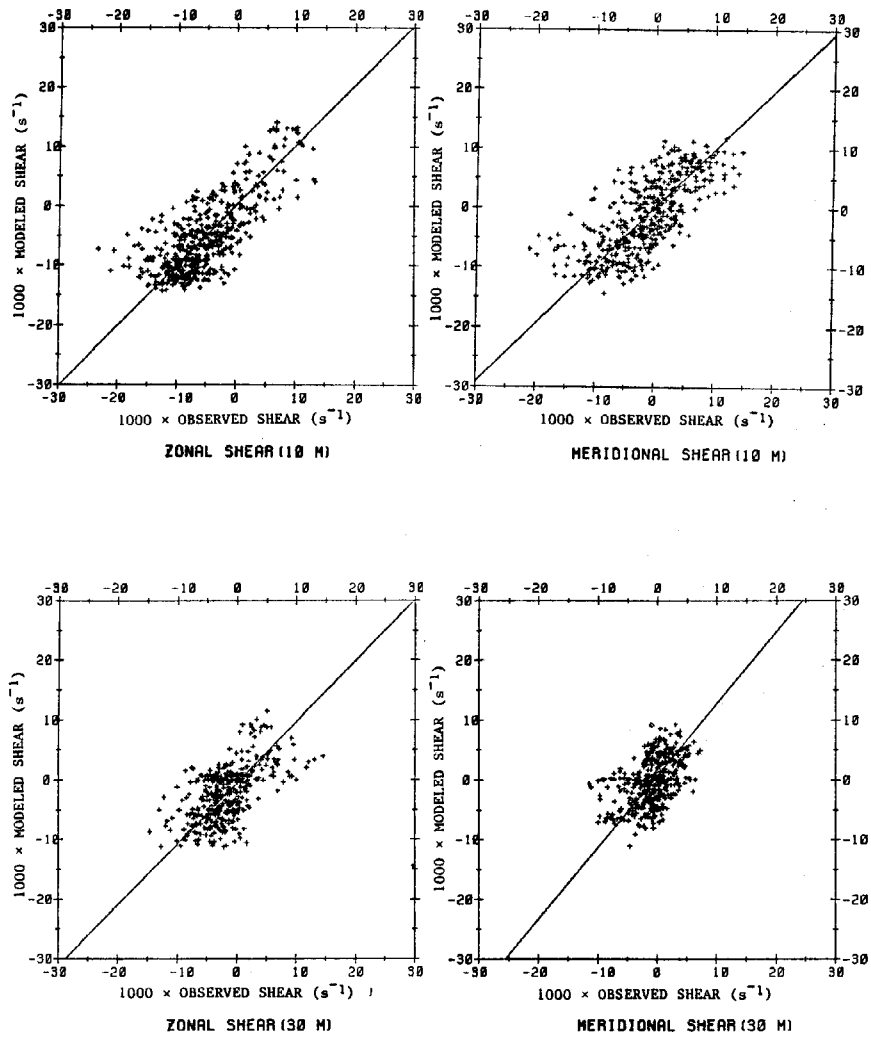


Fig. 7. Comparisons between modeled and observed shear for the zonal and meridional components at 10 and 30 m depth. A_v values depending on the wind speed were used in the modeling (eq.(1) in the text).

Table 1. Correlation coefficients between modeled and observed shears at different depths and wind ranges. The coefficients in parenthesis are not significant at the 95% confidence level. N is the number of data pairs.

Depth (m)	Component	Wind speed (m/s)		
		0.4 - 3	3 - 6	6 - 9
10	Zonal	0.55	0.76	0.83
	Meridional	0.61	0.74	0.78
	N	107	202	131
30	Zonal	(0.22)	0.62	0.71
	Meridional	(0.09)	0.48	0.62
	N	88	175	109
50	Zonal	(0.11)	(0.47)	0.63
	Meridional	(-0.06)	(0.30)	0.57
	N	75	150	90
70	Zonal	(-0.03)	(0.37)	0.59
	Meridional	(-0.03)	(0.21)	(0.43)
	N	66	111	66
	Ekman depth at 2° lat. (m)	~ 10	~ 30	~ 45

comparable to the depth of the Ekman layer at 2°, using a value for A_v given by eq.(2). This suggests that the applicability of the model is limited to an Ekman depth proportional to the wind speed.

The model was tested for sensitivity to the mixed layer depth criterion. Four criteria were used: a constant depth of 50 m, the depth where the temperature difference from the surface was greater than 1°C, the depth where the vertical temperature gradient was greater than 0.05°C/m, and the 28°C isotherm depth (Table 2). No significant difference was obtained among the various criteria for h , although the temperature gradient criterion gave slightly better correlations than the constant depth.

5. DISCUSSION AND CONCLUSIONS

The present study has several serious limitations:

- (1) The vertical resolution of the Pegasus allows us to look at the upper ocean shear only on scales of 20 m or more.

Table 2. Correlation coefficients between modeled and observed shears at 10 and 30 m depth, using different mixed layer depth criteria in the modeling. All the coefficients are significant at the 95% confidence level. N is the number of data pairs.

Depth (m)	Component	Mixed layer depth criteria			
		Constant 50 m	$T_0 - T_1$ > 1°C	$T_{1-1} - T_1$ > .05°C/m	28°C depth
10	Zonal	0.71	0.79	0.79	0.75
	Meridional	0.76	0.75	0.75	0.76
	N	369	330	333	315
30	Zonal	0.52	0.64	0.64	0.52
	Meridional	0.55	0.53	0.53	0.51
	N	369	276	284	285

(2) The study was done with the standard version of the Pegasus data set which was not optimized for looking at small-scale shear, and in which adjacent points are not statistically independent.

(3) The surface drift velocity is heavily weighted in the analysis but, as was pointed out by Pierre Flament during this workshop, it may have been contaminated by wave rectification.

(4) The role of density stratification in the upper ocean has not been addressed.

(5) Finally, although the temporal sampling was better than in any previous series of current profiles, it was still inadequate to permit a fully time dependent rather than a quasi-steady model, and it yields statistical results that are far less robust than one would like.

In spite of these limitations, we have reached important conclusions. The surface shear in the central equatorial Pacific is correlated with the local wind in direction, but not in magnitude. This implies that the vertical eddy viscosity coefficient is proportional to the square of the wind speed, or to the wind stress. With this variable eddy viscosity coefficient, Stommel's (1960) Equatorial Undercurrent model predicts mixed layer shears that compare well with observations. The downwind flow on the equator and the rotation by the Coriolis force off the equator as predicted by the model are seen in the observations. The model is insensitive to the mixed layer depth parameter. The depth to which the model applies increases with the wind speed and is comparable to the Ekman depth at 2° off the equator.

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