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Comparison of wind-stress algorithms and their influence on wind-stress curl using buoy measurements over the shelf off Bodega Bay, California

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Abstract

The main objectives of this study were to compare three wind-stress algorithms of varying intricacy and estimate the extent to which each method altered computed wind-stress curl. The algorithms included (1) a simple bulk formula for neutral conditions that is dependent only on wind velocity components; (2) a formula that in addition to dependence on wind components includes a simplified effect of thermal stability through differences in air and sea temperatures; and (3) an algorithm that includes full treatment of dynamics and atmospheric stability. Data for the analysis were from a field program that used a special buoy network off Bodega Bay during 28 June–4 August 2001.

A diamond-shaped setup of five closely separated buoys in Bodega Bay allowed for one of the first attempts to compute wind-stress curl over the ocean using buoy measurements. Based on an analysis of the available dataset, the marine layer over Bodega Bay is characterized by positive wind-stress curl with a median value around 0.2 Pa $(100\,\mathrm{km})^{-1}$ and maximum values reaching 2.5 Pa $(100\,\mathrm{km})^{-1}$. Positive wind-stress curl was observed for all wind speed conditions, whereas negative wind-stress curl episodes were associated mostly with low-wind conditions.

Comparison of wind-stress curl computed using the three algorithms showed that differences among them can be significant. The first and third algorithms indicated similar stress curl (difference around 10%), but the differences between these two and the second algorithm were much higher (approximately 40%). The reason for the difference is the stability correction, which in the third algorithm strongly decreases with an increase in wind speeds, but stays at a similar level for all wind speeds in the second algorithm. Consequently, for higher wind speeds the variability of wind stress calculated using the second algorithm is greater than for the other two algorithms, causing significant differences in computed wind-stress curl (root mean-square error equal to 0.19 Pa $(100\,\mathrm{km})^{-1}$).

Despite the apparent biases in computed wind stress and wind-stress curl among the algorithms, all of them show a significant trend of decreasing sea-surface temperature (SST) with increasing wind-stress curl. The bootstrapping analysis has revealed that both the along-shore wind stress and wind-stress curl have noticeable correlation with the changes in the sea-surface temperature as an indirect indication of the upwelling. An additional analysis, based on the low-pass filtered

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data, showed also significant agreement between the measured divergence in the cross-shore surface transport and the wind-stress curl computed for all three algorithms.

Keywords: Upwelling; Northern California; Drag coefficient; Algorithm; Wind stress; Curl

1. Introduction

Wind stress and wind-stress curl are crucial to ocean dynamics in coastal areas and over the open ocean (Jones and Toba, 2001). Routine measurements of wind and wind stress were sparse until recent years when satellite data became available. Satellite detection of surface winds and stress, however, is limited in coastal regions where the strongest gradients of wind and wind stress exist. Consequently, estimation of wind stress and wind-stress curl in these areas still relies on occasional aircraft measurements (Beardsley et al., 1997; Enriquez and Friehe, 1995; Rogers et al., 1998), sparse buoy measurements (Winant and Dorman, 1997), and numerical modeling (Beg-Paklar et al., 2001; Samelson et al., 2002; Koračin et al., 2004; Dorman et al., 2006).

Many algorithms for calculating wind stress using available buoy-measured winds have been developed, as reviewed by Jones and Toba (2001). It appears that the drag coefficient that relates wind velocity to wind stress is a complicated variable that depends on many factors, including wind velocity components, atmospheric stability, surface fluxes, sea-surface temperature (SST), and sea state. Since the relationship between wind and wind stress is not linear, differences in the calculated stress using various algorithms can induce significant differences in computed wind-stress curl.

Wind-stress algorithms are of varying degrees of intricacy. Drag-coefficient algorithms that use only wind velocity components, for instance, can induce similar computed stress and wind-stress curl (Samelson et al., 2002; Koračin et al., 2004). Algorithms for drag coefficient that also include simplified treatment of atmospheric stability through air–sea temperature differences (Hellerman and Rosenstein, 1983) and algorithms that include atmospheric stability (Fairall et al., 1996a, b) can produce significantly different results compared to algorithms including only wind velocity components. As shown by Beardsley et al. (1997) for the West Coast wind regime, however, even simple methods such as Large and Pond (1981) produce wind-stress values that in some cases differ by less than the measurement errors from more advanced algorithms, such as Fairall et al. (1996a).

In order to assess the differences in estimating wind stress by various algorithms and the related impact on wind-stress curl estimation, we examined three commonly used algorithms: (1) the Large and Pond (1981) algorithm based on wind velocity components; (2) the Hellerman and Rosenstein (1983) algorithm based on both wind velocity components and the correction due to the air–sea temperature difference; and (3) the Fairall et al. (1996a, b) algorithm based on wind velocity components, atmospheric stability, and skin SST. Since wind-stress curl is one of the forcing mechanisms of coastal ocean upwelling, it is important to understand the extent to which various wind-stress algorithms alter computed stress curl.

2. Description of wind-stress algorithms

2.1. Large and Pond (1981) scheme

Large and Pond (1981) developed a simple formula consisting of a bulk algorithm for calculating the drag coefficient using only wind velocity

$$C_{D,\mathrm{LP}} = 1.2\times10^{-3},\quad \text{for } 4\leqslant|V|\leqslant 11\,\mathrm{m\,s^{-1}},$$
$$C_{D,\mathrm{LP}} = (0.49+0.065|V|)\times10^{-3},\quad \text{for } 11\leqslant|V|\leqslant 25\,\mathrm{m\,s^{-1}},$$
$$\tau_{X,\mathrm{LP}} = \rho\, C_{D,\mathrm{LP}}\, u|V|,$$
$$\tau_{Y,\mathrm{LP}} = \rho\, C_{D,\mathrm{LP}} v|V|, \tag{1}$$

where $|V|$ is the absolute value of the wind velocity ($\mathrm{m\,s^{-1}}$), $\tau_{X,\mathrm{LP}}$ and $\tau_{Y,\mathrm{LP}}$ are the east–west and north–south wind-stress components (Pa), u and v are the east–west and north–south wind-speed components ($\mathrm{m\,s^{-1}}$), and ρ is the air density ($\mathrm{kg\,m^{-3}}$). This algorithm has been used in many studies such as Dorman et al. (2000), Samelson et al. (2002), and Koračin et al. (2004).

2.2. Hellerman and Rosenstein (1983) scheme

The next level of sophistication in calculating the drag coefficient and subsequently wind stress is to include air–sea temperature differences in addition to the wind velocity. This approach gives a relatively