

EKMAN ESTIMATES OF UPWELLING AT CAPE COLUMBINE BASED ON MEASUREMENTS OF LONGSHORE WIND FROM A 35-YEAR TIME-SERIES

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Cape Columbine is a prominent headland on the south-west coast of Africa at approximately 32°50'S, where there is a substantial upwelling tongue, enhancing the ambient upwelling on the shelf, produced by wind-stress curl. From hourly records of wind measured there, the longshore component of wind stress was calculated and the consequent Ekman transport arising through the coastal divergence was estimated.

From a nearly continuous time-series of wind measured at Cape Columbine (32°50'S) lighthouse between late 1956 and early 1992, the longshore component of wind stress was extracted and a model applied to calculate upwelling through the coastal divergence. Although the instruments used to measure the hourly wind vector consisted of a simple damped plate for speed and a wind vane for direction, comparisons with an automatic weather station running intermittently from 1984 onwards gave good agreement. Anemometry was part of the lighthouse keepers' training. Records were kept in case of marine accidents, and the dedication to the task by the lighthouse keepers deemed the dataset to be of scientific value.

During this period, there were nine senior lighthouse keepers and 27 assistant keepers, whose term of duty varied generally between one and four years, with one term of eight years. Each shift was 8 h long. There was a sufficient mix and overlap of officers to ensure that no subjective bias entered into the measurements. The routine hourly measurement was discontinued in 1993. The lighthouse is about 1 km inland, at an elevation of 125 m, and the anemometer is 4 m above ground level and 30 m from the main building. There was no obstruction to the flow of air, except from the lighthouse itself when rare easterly winds blew.

Unfortunately, the records for one complete year (1975) and parts of four other years were misplaced or lost, leaving 96% of the record intact. Hutchings and Taunton-Clark (1990) calculated simple wind-runs of raw data for individual summer seasons from progressive vectors. The envelope of these vectors shows a marked fall-off in the 1980s. The present work differs from that of Hutchings and Taunton-Clark (1990) in that the Ekman divergence is calculated for all seasons. Although the same trends are apparent in their work as presented here, this study points to recent work showing a weakening of winds in the South-East Atlantic caused by events in the polar region.

METHOD OF ANALYSIS

The Godin 51G113 four-day filter (Thompson 1983) was applied successively to three-month segments of the north-south component of wind stress, advancing one month at a time. This resulted in 12 smoothed points per year. The three-month period is sufficiently short to allow for change within a season and the four-day period was sufficiently long to eliminate the thermal effects of the land sea-breeze and propagating coastal lows. The coastline lies at an angle of 3° to true north, so taking the north-south line did not introduce a large error in wind stress.

Within each three-month segment, the resulting filtered series is characterized by long, positive-going segments and shorter, negative-going ones, both modulated at an approximate six-day period. Typically, in the three-month summer segment, there are seven zero crossings, with the average positive-going mean length of 260 h and negative length of 50 h, both with large variance. In winter, these figures change to 10 zero crossings, and means of 130 and 80 h. The area under the positive-going segments was integrated trapezoidally on hourly time-steps. The negative-going segments were ignored. Therefore, the series was effectively rectified, only the upwelling phase being considered.

The integrals are dependent on the type of filter used, so that the estimates of Ekman divergence should reflect this information. Various cosine-Lanczos filters were used, having half power points of 2, 3, 4, 6 and 10 days. It was found that the 4-day filter gave the smoothest profile.

The classic Ekman model is based on a balance between the Coriolis force produced by the rotation of the earth and the frictional force caused by the wind. The wind creates a turbulent upper-friction layer in which the water moves away from the coast to form a tongue at the surface. Integrating the velocity component normal to the coast through this friction

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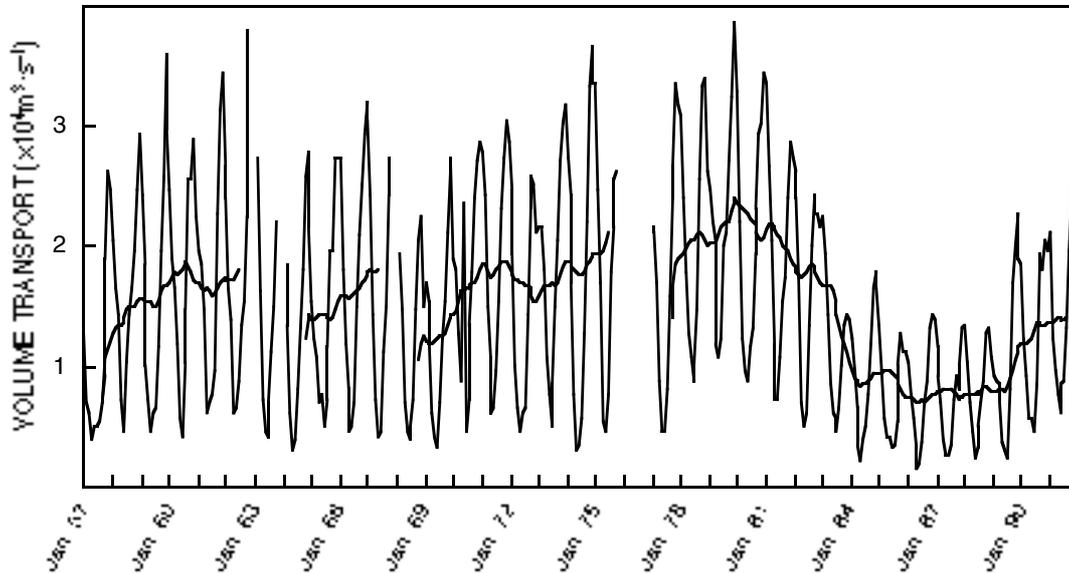


Fig. 1: Three-monthly Thompson-51G113-filtered Ekman total transport at Cape Columbine and the seasonally filtered plot

layer yields the Ekman transport, which is the water displaced from the coast and is a direct measure of the water upwelled. The detail of the turbulent structure and the thickness of the layer are irrelevant to the divergence calculation.

The development of an active turbulent Ekman layer may be constrained by a thermocline. In autumn, a strong thermocline develops at 40–50 m in the vicinity of Cape Columbine, with often shallower, secondary thermocline steps caused by the prevailing wind event (Marine and Coastal Management, unpublished data). Pollard *et al.* (1973) discussed the characteristics of the turbulent layer. In this case, details of the stratification are not available, and the deep thermocline assumption had to be made here.

The steady state model

The following additional assumptions are made in the model:

- (i) slope currents established by accelerating wind are absent;
- (ii) shelf waves, which could suppress upwelling if their cross-shelf phase is adverse, are absent;
- (iii) the curl of wind offshore is negligible as a contributing mechanism to upwelling in comparison

to coastal divergence, and baroclinic waves resulting from variable curl do not affect the Ekman layer;

- (iv) a zero wind speed threshold is used in initiating upwelling;
- (v) the stresses in the friction layer exactly balance the Coriolis forces.

Taking axes y pointing north and x pointing east, with corresponding velocity components v and u , and z pointing upwards, the net Ekman divergence per metre of coastline is obtained by integrating the u component through the water column, and is given by:

$$S_x = \rho \int_0^{\infty} u dz = \frac{\tau_y}{|f|} \text{ kg} \cdot \text{s}^{-1} \cdot \text{m}^{-1}$$

where f , the Coriolis parameter, is $-2\omega \sin\phi$, twice the Earth's angular speed of rotation multiplied by the sine of latitude, and ρ is the density of seawater. The wind stress in the longshore direction, which lies nearly north-south, is

$$\tau_y = C_D \rho_{air} |V| V_y$$

where V_y is the vector component of wind speed in the y (northward) direction, ρ_{air} is the density of air,

taken as $1.22 \text{ kg}\cdot\text{m}^{-3}$, and C_D is the drag coefficient, assumed to be constant throughout the study period at 0.0013 (Kamstra 1985).

This simple form of S_x , as the longshore wind stress divided by the Coriolis parameter, gives a value in kilogrammes per second per metre of coastline. Dividing further by the density of seawater and multiplying by the length of coastline over which upwelling occurs, a total volume transport is obtained. The estimated length of coastline over which the upwelling tongue originates, based on some 50 NOAA thermal satellite images, is 30 km.

By far the largest error occurs in the wind speed, which may be squared when the wind is exactly longshore. Also, the wind measurement was at 130 m above sea level and not at 10 m, which is the standard. There is little to be gained by refining the drag coefficient or the density of air for different atmospheric conditions.

RESULTS

The results of the filtered data are plotted in Figure 1. A further 13-point summation filter was applied to remove seasonal trends and to display the secular variation in the volume transport. This shows a peak and a trough approximately once every seven years up to 1983. Thereafter, there is a sharp fall off in volume, recovering in the early 1990s. During the years 1978–1981, there is an almost twofold increase in winter transport.

Upwelling is perennial on the three-month filtered time-scale. Prior to 1983, the minima, which are around June–July, seldom fall below 0.004 Sv (1 Sverdrup = $10^6 \text{ m}^3 \cdot \text{s}^{-1}$). In contrast, the maxima show a high degree of variance, ranging from 0.025 to 0.04 Sv up to 1983.

An interesting feature is the presence of one or more harmonics near the seasonal period. The effect appears to be especially strong in 1970, but is seen in almost every year.

DISCUSSION

Shannon *et al.* (1992) identified both physical and biological changes within the Benguela system in the early 1980s. Anomalies were detected in sea temperature, currents and particularly winds (using the same Cape Columbine dataset as presented here). Changes in both biomass and biomass distribution were reported in crustaceans, molluscs and both pelagic and demersal

fish species during that period. Shannon *et al.* (1992, p. 271) state that “The 1982/3 anomaly was associated with a major *El Niño* event in the Pacific. Further impetus was given by the 1984 “Benguela *Niño*.”” This was discussed by Shannon *et al.* (1986).

Prominent documented *El Niño* periods during the Cape Columbine time-series were 1957–58, 1965–66, 1972, 1982 and 1991–92 (Allan *et al.* 1996). However, these do not correspond to changes in wind in the series. Furthermore, an *El Niño* event lasts typically one year, whereas the Cape Columbine time-series shows a prolonged period of weakened wind after 1979. It is suggested that an explanation for this is found in polar events rather than in the tropical Pacific.

Wind strength on the west coast of southern Africa is related to the pressure gradient near the coastal boundary, which in turn depends on the strength of the South Atlantic High pressure cell over the South Atlantic. Hurrell and Van Loon (1994) showed that, in the late 1970s, the annual cycle of pressure and winds in the troposphere changed appreciably in the southern hemisphere. Prior to that period, the major component controlling pressure and wind over the mid-latitudes of the South Atlantic had been the semi-annual oscillation. This weakened after 1979 and the first harmonic became dominant. As a result, the weakening of the tropospheric polar vortex was delayed at the end of the winter seasons, during the period under discussion. This had the effect of reducing the amplitude of sea-level pressure variation and weakening winds in the South Atlantic High.

Since 1995, an improved automatic weather station has been in operation at Cape Columbine, which is nearer the coast and at a lower altitude. Because of its different location, it is inadvisable to consider data from that weather station as an extension to the present time-series; but the initial finding is that the wind strength has returned to its pre-1979 magnitude.

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