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Short Communication

Short-term variability in alongshore winds and temperature off Swakopmund, Namibia, during a non-upwelling event in 1998–1999

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Swakopmund is a popular coastal resort in Namibia, especially during the summer holiday season when daily sea temperatures can fluctuate several degrees in a short period. Hourly measurements of the near-bottom water temperature were collected off the Swakopmund Jetty to investigate the thermal variability in relation to local winds. The thermal regime of this coastal region appears to be controlled by the locally forced Ekman offshore transport. Related changes in offshore transport led those of the surf-zone temperature by about one day. A transfer of kinetic energy from the alongshore wind into the temperature field of the nearshore zone dominated relative short time scales (hourly). The longer periods (7–9 days) are associated with the forcing of poleward-directed continental shelf waves. The origin of the 24–25 day frequencies is not clearly understood. However, it characterises the nearshore wind field as well as the water temperature of the surf zone. These relatively long quasi-cycles could originate from rhythmic changes in the regional wind field as a result of changes in the thermal contrast between sea and land areas.

Keywords: coastal upwelling, Ekman offshore transport, nearshore zone, subinertial waves, Swakopmund, temperature fluctuations

Introduction

Understanding of spatio-temporal dynamics of upwelling along the Namibian coast has been the focus of a number of studies (e.g. Shannon and Nelson 1996, Boyd *et al.* 2001, Hardman-Mountford *et al*. 2003). However, there has been little effort to study the processes in the inshore surf-zone area since the early work of Copenhagen (1953) in the Walvis Bay region. The nearshore zone has received little attention mainly on account of its inaccessibility for traditional hydrographic survey methods. Close inshore, vertical mixing is predominantly forced through shoaling and breaking gravity waves (Longuet-Higgins and Steward 1964). Therefore, the direct wind forcing is commonly considered as a second-order effect. However, the overall mixing in the surf zone depends not only on the strength of locally generated waves breaking but also on the vertical stability of the underlying water column (Donelan *et al*. 1997). Related stratification is reflected in the vertical profiles of the water temperature. Independently of solar radiation and wave-generated mixing, the latter also reflects the advection of cold near-bottom water as a result of coastal upwelling. Therefore, a close correlation can be expected between the local thermal regime of the surf zone and the regional Ekman offshore (volume) transport. Surf-zone dynamics might be of lesser importance in the ecology of the major commercially important fish species farther offshore, but should be relevant to the linefishery and the developing aquaculture industry.

Large temperature fluctuations in the nearshore zone off Swakopmund occur during the non-upwelling season (December–April) (Boss 1941). Such historical accounts have been based on short time-series, consisting of only a few daily surface temperature measurements. Recent advances in instrument technology have made it possible to acquire continuous measurements for a wide range of standard meteorological and hydrographic parameters from surf-zone areas. In this paper, the time-series of the local wind, the nearshore bottom current, and the surf-zone temperature, are used to study the impact of regional upwelling dynamics on the thermal regime of the surf zone off Swakopmund during an austral summer season.

Material and Methods

A continuous temperature recorder was deployed at the Swakopmund Jetty (Figure 1) at 8m deep to measure hourly bottom temperatures (T) during the summer of 1998–1999. Measurements started at 12:00 on 27 November 1998 and ended at 14:00 on 12 May 1999.

Concomitant measurements of hourly water temperatures at 3m and 10m deep, the bottom currents at 28m deep, and wind speed and direction were recorded at an oceanographic buoy moored 5km off Swakopmund (Figure 1). It was assumed that these wind records were not appreciably modified by the geography of the hinterland. Wind direction and wind velocity (V_w) were decomposed into zonal (positive to the east) and meridional components (positive to the north). Thereafter, the coordinate system was adjusted for the coastline orientation (32° anticlockwise) to obtain the U (positive onshore) and V (positive equatorward) components respectively. The same procedure was applied to the current measurements for obtaining onshore (positive u) and equatorward (positive v) components. The hourly wind series were used to estimate the power spectra whereas all other statistics were based on daily averages (<u>, <v>, <U>, <V>, <T>) and their related standard deviations (SD = σ). The daily time-series extended over 165 days. The daily kinetic energy MKE = $(\langle U\rangle^2 + \langle V\rangle^2)/2$ describes the available kinetic energy from the wind field into dynamics of the surf zone, whereas the related eddy kinetic energy results from corresponding standard deviations (σ_u, σ_v) to be EKE = $(\sigma_u^2 + \sigma_v^2)/2$. Independently of given phase situations in hourly wind fluctuations, the EKE series describes the overall energetic level for periods shorter than the daily cycle.

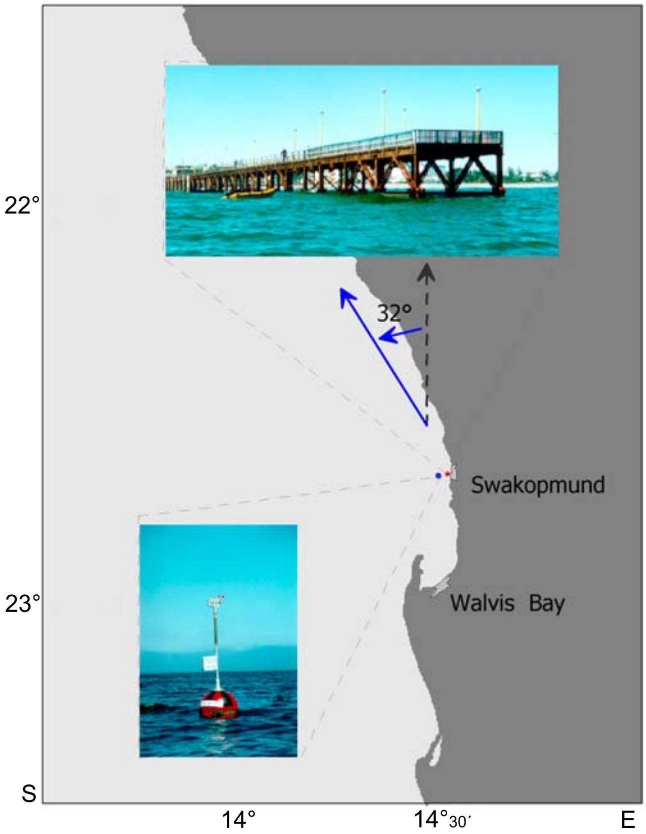

Figure 1: Study area showing the Swakopmund Jetty and the moored oceanographic buoy 5km offshore at a water depth of 28m. Wind and current records from the buoy were adjusted by 32° (anticlockwise rotation of the coordinate system) to obtain the onshore-offshore component (positive shoreward) and the alongshore component (positive equatorward)

At the sea surface, the wind-stress (τ) acts like a body force down to the (unknown) Ekman depth. Following Wu (1969) and Large and Pond (1981), its hourly stress components were estimated by the empirical formula $\tau^{x,y} = 1.625 \times 10^{-3} \times |V_w| \times (U, V)$ (N m^{-2}), whereas the corresponding Ekman offshore volume (E^x) transport per unit length is $E^x = -\tau^y/(\rho_o f) \sim -\tau^y/0.057$ (m^2 s^{-1}). This vertically integrates transports of the entire near-surface Ekman layer with a thickness of few decametres. Here, the standard density of seawater is $\rho_o = 10^3$kg m^3 and the Coriolis frequency is $f = 2\omega\sin\phi$ at the latitude ϕ = 23°S. The angular velocity of earth rotation is $\omega = 7.29 \times 10^{-5}$ (rad s^{-1}). Based on hourly records, daily averages and corresponding standard deviations were computed for each stress component. For comparison, resulting time-series were standardised (mean = 0, SD = 1) to obtain comparable numerical levels. All applied statistical concepts and formulae are standard, as detailed in Wilks (1995).

Results and Discussion

According to Hagen *et al*. (2001), the northern Benguela experienced below average upwelling activity during the winter of 1998–1999, resulting in large shelf areas being covered by relatively warm coastal surface water. Between

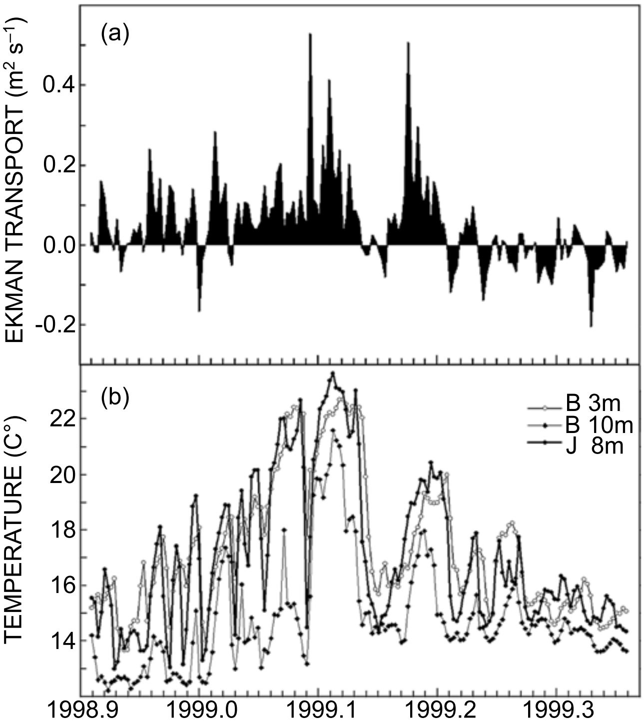

Figure 2: Time-series for the sampling period (between 28 November 1998 and 11 May 1999) for (a) the Ekman onshore transport per unit length as derived from the alongshore wind component (V) measured at the buoy, and (b) the temperature recorded at 3m and 10m deep at the buoy (B) and 8m deep at the jetty (J)

the end of November 1998 and mid-March 1999, relatively weak poleward winds with slightly alternating onshore-offshore components dominated the coastal wind regime off Swakopmund. This period was followed by a change in wind direction to a more equatorward orientation with a small onshore component. The thermal regime of the coastal zone, between the jetty and the monitoring buoy, is controlled by the Ekman offshore transport on time scales of several days. The interaction between gravity waves and the stratified surface layer through vertical mixing is responsible for the observed temperature fluctuations (Figure 2a, b).

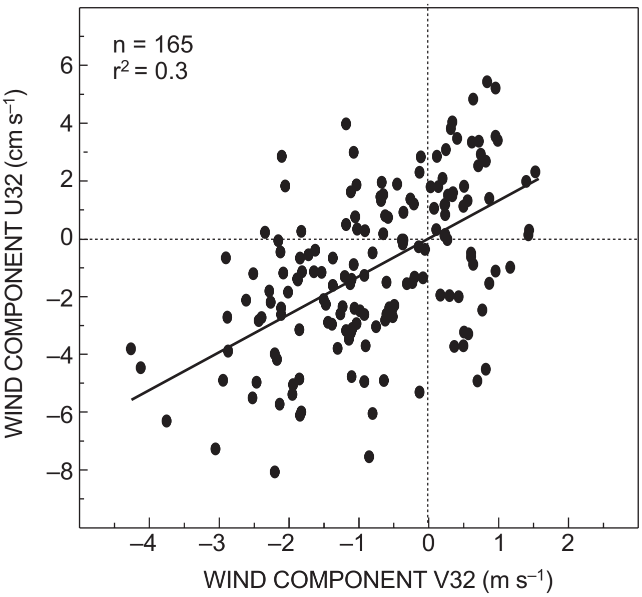

Figure 3: Linear regression between the daily alongshore wind (V32, positive equatorward) and the corresponding onshore (u32, positive) and offshore (u32, negative) current recorded 3m above the seabed at the buoy. Number of samples is denoted by n

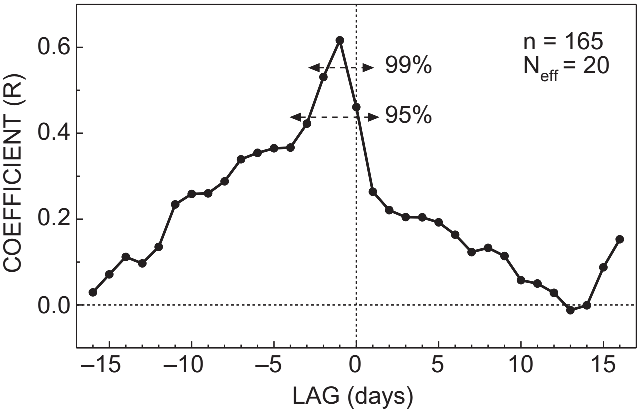

Figure 4: Coefficients (R) of the lag correlation between the daily Ekman offshore transport ($-E^x$) and the jetty temperature (T) plotted in Figure 2 for n = 165 days. Negative lags indicate that ($-E^x$) is leading T; the effective degree of freedom (N_{eff}) results from the integrated cross-correlation function and determines given confidence ranges (dotted lines) by applying the t-distribution

Given the strong similarity between the three temperature series, focus was mainly on the jetty series. Generally, equatorward winds produce offshore transport within the near-surface Ekman layer along the Namibian coast. The generated mass-deficit in the nearshore zones is partly compensated by onshore currents, which transport cooler bottom water towards the surf zone. The positive correlation between the daily alongshore wind component and the corresponding onshore-offshore current above the seabed confirms this, at least in the vicinity of the buoy (Figure 3). The coefficient of determination ($r^2 = 0.3$) indicates that about 30% of fluctuations in the deep onshore-offshore current originates from corresponding variations in the alongshore wind component. The velocity of deep onshore-offshore currents was about 1% of the alongshore wind speed. The cross-correlation between E^x and T reveals that changes in E^x were leading those of T by about one day (Figure 4). This suggests that changes in V of about ±1m s^{-1} would result in a temperature fluctuation of about ±2°C during the following day (Figure 5). Therefore, half of the observed 'next day' temperature variance can be explained by fluctuations of the daily Ekman onshore-offshore transport. The temporal component of the locally generated E^x thus essentially controls that of T as depicted in Figure 6. This relationship could be useful in forecasting daily temperatures along the Swakopmund surf zone. Furthermore, the described one-day lag suggests the existence of an oscillating re-circulation cell off the beach in that region.

The energetic level of hourly temperature fluctuations is represented by daily SDs of the T series. Associated fluctuations in the surf zone were exceptionally strong when the daily wind speed relaxed and resulted in low MKE levels, and when intense hourly wind fluctuations produced a high level in the EKE (Figure 7). On an hourly scale, changes in the V series exhibited a higher energy level than those of

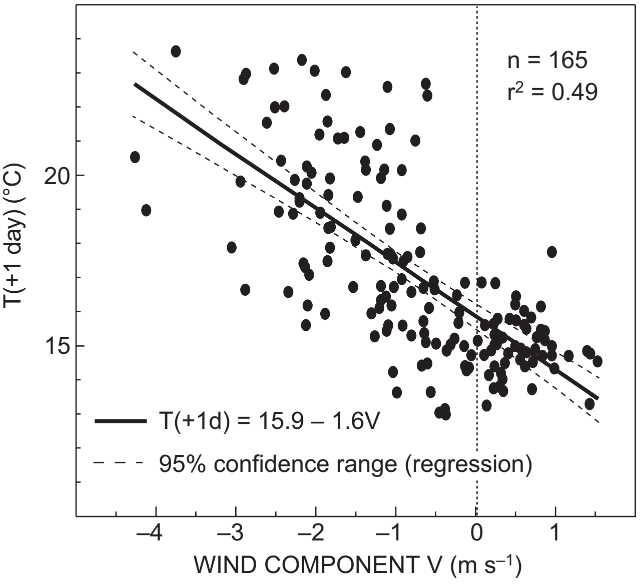

Figure 5: Linear regression between the daily alongshore wind component (V) and the following day jetty temperature T(+1 day) (°C). The 95% confidence range follows the t-distribution

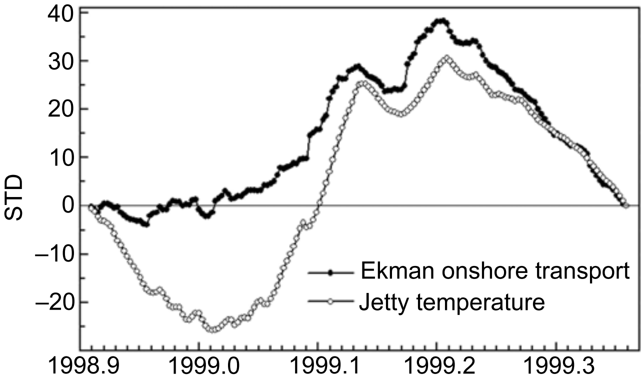

Figure 6: Cumulative series of standardised values (mean = 0, SD = 1) of the daily Ekman onshore transport and corresponding values of the jetty temperature. Different cooling/warming episodes are characterised by decreasing/increasing curve segments

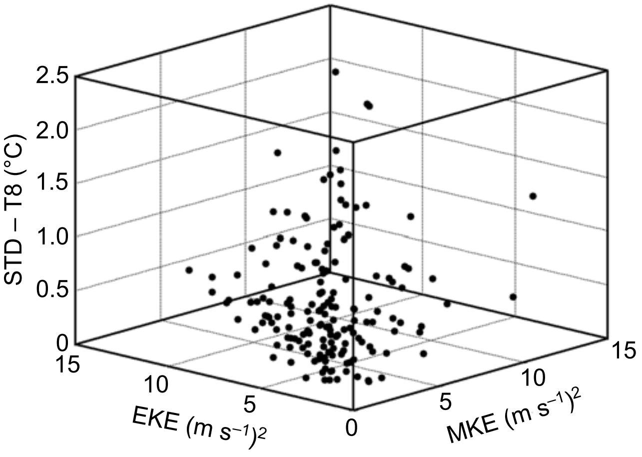

Figure 7: Standard deviations of the jetty temperature $\sigma(T)$ = SD – T8 (°C) at 8m depth vs daily levels of the mean kinetic energy MKE = $(<U>^2 + <V>^2)/2$ and those of the eddy kinetic energy EKE = $(\sigma_u^2 + \sigma_v^2)/2$ resulting from wind records at the buoy

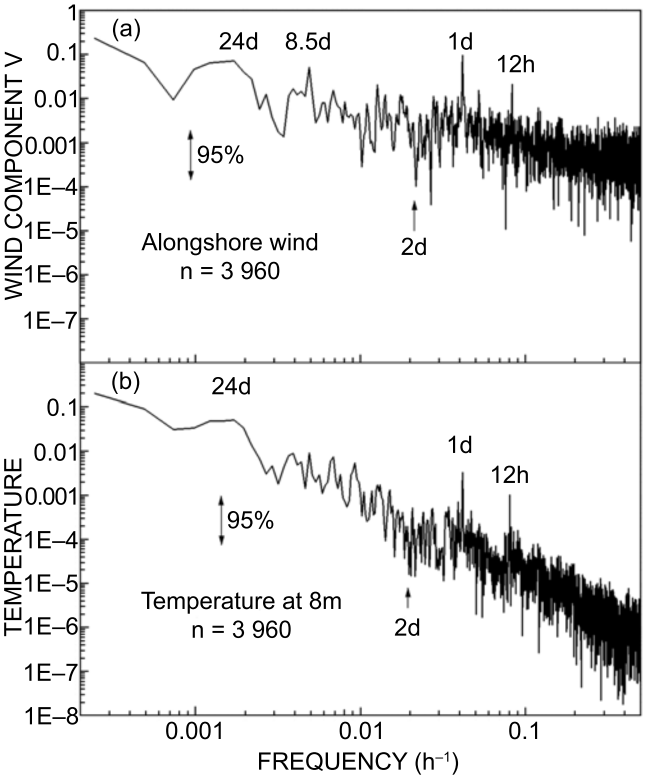

Figure 8: Power spectra obtained from standardised series of (a) the alongshore wind (V) and (b) the corresponding near-bottom temperature at the jetty (T). Only cycles of the half daily tide (12h) and the land-sea breeze (24h) significantly exceed the 95% confidence range (shown by arrow). Note the energetic gap at about 2 days (2d) separating high from low frequency fluctuations; multiday periods are able to force continental shelf waves, but their level only exceeds 80% confidence in the V spectrum; broad peaks indicate a quasi-cycle of about three weeks for the jetty temperature as well as for the alongshore wind; squared amplitudes are scaled on the overall variance and, because the confidence interval widths are proportional to the estimated amplitudes, the resulting confidence range is constant for all spectral estimates plotted vs logarithmic values of the power

the T series. This suggests a persistent energy transfer from hourly wind fluctuations into the thermal regime of the surf zone. The power spectra of the V and T series exhibited comparable characteristics for several period ranges (Figure 8). However, only those representing the semi-diurnal tide (12h), the daily cycle of the land-sea breeze or the diurnal tide exceeded the 95% confidence level (t-distribution). The statistical significance of longer periods decreased as a result of the relatively short time-series used (165 x 24h). Nevertheless, the total energy level increased with increasing period length in both time-series, which can be attributed to the underlying trends (Figure 2). The slight peak in the V power spectrum (80%) at about 8.5 days (0.005cph = cycles h^{-1}) is not visible in the T series. This equates to wind fluctuations with periods of several days up to one week, which may be responsible for the generation of forced continental shelf waves in the Benguela Current (Huthnance 1978, Hagen 1981, Lass and Mohrholz 2005). These waves propagate poleward and have wavelengths of several hundred kilometres. They have major influences on the hydrographical regime of the mid-shelf regions, but their impact on temperature fluctuations disappears in the surf zone. Another peak in the V-component (0.0017cph) indicates a quasi-period of about 24–25 days. It also appears in the spectrum of the U-component (not shown) as well as in that of T. The occurrence of this quasi-cycle in both wind components suggests that changes in the wind direction played a minor role in maintaining this periodicity in the temperature field of the nearshore zone. Therefore, it may be that associated temperature changes originated mainly from corresponding oscillations in the local wind speed, and that the net advection of water masses from far away only played a minor role on the time scale of several weeks. The physical mechanism of the observed 24–25 day cycle is still unclear and requires further investigation. Such wind fluctuations may be associated with an onshore-offshore meandering equatorward 'atmospheric coastal jet' triggered through variations in temperature contrasts between land-sea surfaces. However, such changes could also be considered to be of higher harmonics than the 40–50 days oscillation observed in equatorial wind fields on the global scale (Madden and Julian 1972). Here, related fluctuations in the wind velocity significantly affect oceanic circulation patterns in mid-shelf areas. This could be expected given that the spatial scale of an onshore-offshore meandering of the hypothetical 'atmospheric coastal jet' must markedly exceed the width of the Namibian continental shelf.

Conclusion

Daily sea temperature fluctuations of several degrees are common along the central Namibian coast during the summer. It is shown that these nearshore temperature fluctuations are controlled by the locally forced Ekman offshore transport. It is also evident that the Ekman offshore transport leads the associated temperature fluctuations by one day. This time-lag suggests the existence of a persistent re-circulation cell in nearshore waters off Swakopmund. This significant relationship could be useful as input to an empirically-based forecasting concept to predict nearshore temperatures from wind records. Due to the relatively short time-lag between both series, alongshore advection of temperature anomalies from farther offshore thus plays a minor role in explaining short-term day temperature fluctuations within the surf zone. The local wind field exhibits frequencies of several days, characteristic to the forcing behind barotropic continental shelf waves. These would mainly influence the hydrography of the Namibian mid-shelf zones, with no appreciable influences on the thermal regime of the surf zone. Quasi-periods with a length of about three weeks were identified both in the wind field and the thermal regime of the vertically well-mixed surf zone. Their origin is unclear, but it is speculated that they are produced by an onshore-offshore meandering equatorward-moving 'atmospheric coastal jet', triggered through variations in temperature contrasts between land-sea surfaces.

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