Wind and Current Forcing Combine to Drive Strong Upwelling in the Agulhas Current

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ABSTRACT

Strong upwelling events inshore of the Agulhas Current close to 33.5°S are investigated. These events are important to the exchange of shelf and slope waters, potentially enhancing primary productivity and advecting larvae offshore. Using hydrographic observations, this study shows that a wind-driven upwelling event and a current-driven upwelling event can each advect central waters more than 130 m upward, resulting in a maximum 9°C cooling at 50-m depth over the continental shelf and surface cooling greater than 4°C. The authors use satellite data to assess the frequency and forcing mechanisms of similar cold events from January 2003 through December 2011, defining cold events as days when the sea surface temperature (SST) anomaly is significantly correlated with a local current or wind forcing. The authors identify 47 events with an average length of 2.2 days and SST anomaly of −1.6°C, corresponding to an average 13 days of surface cold events along the Agulhas Current front per year. This study uses combined EOF analysis to characterize these cold events based on four highly correlated forcing mechanisms: alongshore wind speed, wind stress curl, current meandering, and current speed over the slope. The authors find that meanders act in combination with upwelling-favorable winds to force the strongest cold events, while upwelling-favorable winds alone, possibly primed by Ekman veering, force weaker cold events. Most significantly, it is found that the frontal curvature of warm Agulhas Current meanders couples with the atmosphere to drive local wind stress curl anomalies that reinforce upwelling.

1. Introduction

The Agulhas Current is the largest western boundary current in the Southern Hemisphere (Bryden et al. 2005), flowing southwestward along the African continent. Upwelling events in the southern Agulhas Current are of particular interest, since this region is home to several reproductive habitats, including nursery and spawning areas (Hutchings et al. 2002). Upwelling can promote biological productivity, as nutrient-rich water is advected from the adjacent deep ocean onto the shelf (Atkinson et al. 1983; Miller and Lee 1995). Furthermore, when slope waters rise onto the shelf, they displace shelf waters offshore, facilitating the flux of pollutants, coastal runoff, and larvae into the open ocean (Churchill et al. 1986; Porri et al. 2014). Upwelling events may be especially important in western boundary current systems where the mean current acts as a strong barrier to lateral mixing (Bower et al. 1985).

Upwelling events inshore of western boundary currents can be either current driven or wind driven. Observations show current-driven coastal upwelling is episodic, primarily fueled by eddies that develop when the current becomes unstable and meanders (Brandini 1990; Castro and Miranda 1998; Campos et al. 2000; Stabeno and Van Meurs 1999; Gawarkiewicz et al. 2001; Okkonen et al. 2003). Meanders induce upwelling along their leading edge and downwelling along their trailing edge, related to the dual passage of cyclonic and anticyclonic anomalies (Olson 2002; Campos et al. 2000). Current-driven upwelling can also be caused by an increase in current speed, which intensifies onshore Ekman transport in the frictional bottom boundary layer, causing an upslope flux (Roughan and Middleton 2002). Waters upwelled by this process, called Ekman veering, usually do not reach the surface, but rather “prime” the system for a surface cold event when another upwelling-favorable forcing mechanism is present (Roughan and Middleton 2002; Goschen et al. 2015).

Wind-driven upwelling events are due to either Ekman suction or offshore Ekman transport (Gill 1982). In the Southern Hemisphere and the Agulhas Current, negative wind stress curl forces surface divergence and upward motion in the ocean, commonly referred to as
Western boundary upwelling events have been studied extensively within the Brazil Current system. Brandini (1990) discovered that nutrient concentrations along the shelf inshore of the Brazil Current peak when meanders are present. Solitary meanders bring nutrient-rich South Atlantic Central Water (SACW) up to the depth of the shelf break, while the addition of upwelling-favorable alongshore winds are necessary to bring SACW onto the shelf (Campos et al. 2000; Castelao et al. 2004). Castelao and Barth (2006) showed that wind stress curl can be just as important a contributor to upwelling as alongshore winds. Meanders have also been shown to upwell central waters within the Gulf Stream (Flierl and Davis 1993; Lee et al. 1981).

In the southern Agulhas Current, where instabilities are large, meanders (or Natal pulses) drive the strongest mode of temperature variability over the midshelf region and offshore edge of the Agulhas Bank, influencing the circulation 110 days out of the year (Krug et al. 2014). Farther north where the shelf and slope are narrow, the core of the Agulhas Current is found as close as 20 km offshore and acts as a barrier to mixing (Beal and Bryden 1999) so that instabilities are smaller and upwelling events are thought to be rarer.

Goschen et al. (2012) investigated upwelling events on the northeastern tip of the Agulhas Bank (Algoa Bay) using several moorings along the 30-m isobath, each with temperature recorders at depths of 10, 15, 20, and 30 m. Over a period of 400 days, they identified 55 upwelling events at the most active site of Woody Cape and connected most of these events to coastally trapped waves and upwelling-favorable alongshore winds. Upwelling events were defined as a 1°C or more drop in temperature at 30 m in a 24-h period. In a follow-up study using the same coastal moorings, Goschen et al. (2015) investigated the role of six separate meander events on upwelling, neglecting the role of winds. They found upwelling lasted 1–3 weeks during meander events, with an average rate of 1.8 m day⁻¹. For two of the events cold water did not reach the surface at these inshore sites.

Studies conducted to the north of the Agulhas Bank highlight the role of multiple mechanisms in forcing upwelling events (Walker 1986; Lutjeharms et al. 2000). Here, we use hydrographic data in the Agulhas Current to the northeast of the Agulhas Bank to investigate the full extent of isopycnal lift during two very different upwelling events. We then combine these observations with satellite data to characterize and quantify cold events over a 9-yr period at the site of the Agulhas Current Time-Series Experiment (ACT) array (Beal et al. 2015). We assess the frequency of cold events with a surface signature and examine the role of meanders, current strength, and upwelling-favorable winds as forcing mechanisms.

2. Data and methodology

For our study of upwelling inshore of the Agulhas Current, we use hydrographic and satellite data from the location of the ACT mooring array (Beal et al. 2015; Figs. 1, 2). In this region the shelf is about 25 km wide out to the 150 m isobath, and the Agulhas Current core is located 40 km offshore on average over the steeply descending continental slope. For our analysis, we focus on the continental slope and shelf region down to a depth of 500 m and out to the 2500 m isobath, located 75 km from the coast.

a. Hydrographic data

We use inshore data from four separate hydrographic transects across the Agulhas Current close to 33.5°S, 27.5°E, collected during ACT cruises. Temperature, salinity, and pressure measurements were taken using a CTD and full-depth velocity measurements using lowered acoustic Doppler current profilers (LADCP). The CTD package included a 12-bottle rosette and a Sea-Bird SBE911 with dual temperature, conductivity, and oxygen sensors plus an altimeter. For the LADCP, a dual 300-kHz configuration was used during the April 2010 cruise, and a hybrid configuration (300 kHz upward looking, 150 kHz downward looking) was used during the February 2013 cruise.

During the April 2010 cruise, a hydrographic transect line, hereinafter called meander line 1, was collected during 7–11 April 2010, just prior to the passage of a large solitary meander (Figs. 1a,c, stations 1–8). Meander line 1 captures the encroachment of the Agulhas Current onto the continental shelf associated with the leading edge of the solitary meander (Krug et al. 2014). A second hydrographic transect, hereinafter called meander line 2, was collected within the inshore cyclone of the fully developed solitary meander’s crest on 17 April 2010 (Figs. 1b,d, stations 21–28). For a more thorough treatment of the characteristics of the April 2010 meander, see Leber and Beal (2014) and Leber and Beal (2015).

During the February 2013 cruise, wind line 1 was collected over 2 days of strong northeasterly winds from 17 to 18 February 2013 (Fig. 2c, stations 20–13) and...
captured significant cooling over the shelf associated with Ekman transport (coastal upwelling) and possibly Ekman veering. A second hydrographic transect, which we call wind line 2, was collected over 25–26 February 2013 (Fig. 2d, stations 34–41). Though winds were still northeasterly, during wind line 2 they had reduced in magnitude by about half, and there is no longer a surface upwelling signature over the continental shelf.

b. Satellite data

To identify cold events, we employ daily, 1.5-km-resolution, gridded sea surface temperature (SST) data from the
Specifically, we use the global, level-4 Multiscale Ultrahigh Resolution (MUR) GHRSST dataset, which combines SST observations from several instruments using optimal interpolation on a 0.011° global grid. This product has an advantage over MODIS, which has been more typically used for studies in this region (e.g., Goschen et al. 2012), during cloudy days. However, Xie et al. (2008) show that this product can have large coastal biases in water shallower than 40 m. Hence, we detect cold events using area-averaged SST over a region that extends from the coast out to the 2500-m isobath (Fig. 1a). Excluding data over waters shallower than 40 m does not significantly alter the results presented here.

To separate cold events from seasonal and longer timescale variability, we apply a 30-day, high-pass filter to SST to get SST anomalies (SSTAs). We define cold events as days when SSTA is less than 1.96 standard deviations below zero (the mean for our filtered time series) or below $-2.12^\circ C$. This threshold was chosen for two reasons: First, it incorporates the SSTA values for both of the cold events we observed with in situ measurements. Second, and most important, it represents a threshold at which cold events significantly correlate with wind and current forcing mechanisms. This gives us confidence that we are capturing local upwelling, rather than alongshore advection of cold waters, which could potentially intrude along the shelf from the Agulhas Bank to the south. Our

![Image](https://example.com/image.png)
method identifies far less cold events than Goschen et al. (2012), whose coastal mooring data were able to detect subsurface cold events of smaller magnitude and spatial scale.

We assess local forcing mechanisms using satellite altimetry and wind data. We use the filtered along-track sea level anomaly (SLA) product from Archiving, Validation, and Interpretation of Satellite Oceanographic Data (AVISO) along track number 96. The along-track data are provided every 10 days with a horizontal resolution of 12.4 km. We use the SLA to define two separate current-driven forcing mechanisms: meandering and Ekman veering caused by increased current strength. Meanders drive upwelling along their leading edge and within their inshore cyclone (Lutjeharms et al. 2000). At times of increased current strength, Ekman veering forces upwelling within the bottom boundary layer (Roughan and Middleton 2002). Meanders are identified as times when inshore SLA is anomalously low, and Ekman veering is identified as times when the Agulhas Current is anomalously strong. Both anomalies are calculated at $233.525^\circ$S and $27.625^\circ$E, approximately 40 km offshore and at the mean position of the Agulhas Current. In this way we identify meanders in agreement with Elipot and Beal (2015), which are validated against the ACT mooring data.

Current strength anomaly $\nu'_g$ is given by

$$\nu'_g = \frac{f}{g} \left( \frac{\partial \text{SLA}}{\partial x} \right),$$

where $\nu'_g$ is the anomalous, southwestward, cross-track, geostrophic velocity along the slope, $f$ is the Coriolis force, $g$ is gravity, SLA is the sea level anomaly, and $x$ is the along-track direction, positive to the southeast. We apply a 30-day, high-pass filter to all forcing mechanism time series to isolate the high-frequency variability. This removes the annual cycle of Agulhas Current speed, which is a maximum in austral summer (Fig. 3), in agreement with Krug and Tournadre (2012). Both current-driven forcing mechanisms, $\nu'_g$ and SLA, are interpolated linearly to daily values. For illustration purposes, we also use the mapped absolute dynamic topography (MADT) product from AVISO to show the shape of the meander in Fig. 1 and the position of the Agulhas Current in our EOF composites (Fig. 7).

Wind-driven forcing mechanisms are calculated using cross-calibrated multiphase (CCMP) 10-m winds (Atlas et al. 2011). CCMP winds are a global, $1/4^\circ$, 6-hourly, wind vector product. Winds are produced using a variational analysis method that combines data from several remote sensing systems and in situ measurements with a first guess of the wind field (Hoffman et al. 2003). CCMP winds are validated against moored ocean buoys to which they agree within 0.8 m s$^{-1}$. To isolate the high-frequency variability, we apply a 30-day, high-pass filter to both the zonal and meridional components. This removes the seasonal cycle of alongshore winds and wind stress curl (Fig. 3). The filtered wind data are averaged within the same box used for SSTAs. Wind stress curl is determined using the Large and Pond (1981) wind stress formulation. CCMP data are available only through the end of 2011, so we limit our analysis to the time period from January 2003 through December 2011.

SSTAs and all four forcing mechanisms are 30-day, high-pass filtered to remove seasonality, and their means are zero. For other basic statistics on SSTAs and the four

![Fig. 3. Seasonal cycles of SST (blue), geostrophic velocity (green), wind stress curl (red), and alongshore winds (black). Seasonal cycles were determined by first calculating daily averages and then smoothing with a 15-day sliding window.](image-url)
defined forcing mechanism anomalies, see Table 1. Note that negative values of the forcing mechanisms are upwelling favorable, and positive values are downwelling favorable.

3. Results

a. Hydrographic observations of upwelling events

1) MEANDER-INDUCED UPWELLING

Meander line 1 (Figs. 1a,c) captured the Agulhas Current just prior to separation, while meander line 2 (Figs. 1b,d) captured the current core 120 km offshore. LADCP velocities show the core of the current shifted onshore over the shelf during meander line 1 and far offshore during meander line 2, indicative of a propagating meander event. Comparison between these two lines shows that there was a 4.5°C drop in temperature close to the surface, associated with an outcropping of the γ = 24.9 neutral density surface (γ; Jackett and McDougall 1997), which is upwelled from its position at 25 m depth 8 days earlier. Maximum cooling of 9°C is found at middepth (50 m) over the shelf (Fig. 1), coinciding with an uplift of the neutral density surface γ = 26.7 and signifying upwelling of South Indian Central Water (SICW; Beal et al. 2006). Central waters are lifted from within the Agulhas Current at about 200 m depth, up the continental slope, and onto the shelf during this meander event. For a more thorough description of this propagating meander event and a quantification of its associated isopycnal and dia-

pynclal fluxes, see Leber and Beal (2014) and Leber and Beal (2015).

Satellite data corroborate that this cold event occurred during the passage of a large solitary meander, accompanied by a negative (upwelling favorable) wind stress curl anomaly (Fig. 1c). The area-averaged inshore SSTA prior to the passage of the meander on 9 April 2010 is 1.2°C. This value falls to −2.5°C on 16 April 2010 and stays below our cold event threshold through 22 April 2010 for an event length of 7 days. The average SLA over our upwelling box (Fig. 1b) during this time is −0.11 cm, or −1.7 standard deviations below its mean, indicative of a meander-driven event. Wind stress curl falls to one standard deviation below its mean on 22–23 April 2010. The relationship between meanders and wind stress curl will be explored further in section 3b(2).

2) WIND-INDUCED UPWELLING

In February 2013, we observed an upwelling event driven by strong northeasterly winds. Comparison between our in situ hydrographic data from wind lines 1 and 2 show a 4°C drop in temperature at the sea surface associated with this event (Fig. 2a). Unlike the meander-driven upwelling of April 2010, LADCP velocities (Figs. 2c,d) show that the Agulhas Current maintains its position along the shelf break during this time. For this particular event we use shipboard wind data since CCMP wind data are unavailable. Shipboard wind data reveal a strengthening of the upwelling-favorable northeasterly winds on 17 February 2013 (Fig. 2a). Despite the different forcing, the structure of cooling is very similar to that seen in the meander-driven upwelling event, with a maximum 9°C cooling at a depth of 50 m over the shelf and a 190-m uplift of the γ = 26.7 neutral density surface, representing upwelling of SICW (Fig. 2b).

During this wind event, satellite data show that inshore SSTA within our boxed region is below the cold event threshold for only 1 day (17 February 2013; −2.42°C), during which upwelling-favorable alongshore winds averaged −11 m s⁻¹ (Fig. 2c). Our next in situ occupation of this region was 8 days later, and these data show that the upwelling event is over. Alongshore winds have weakened to −5 m s⁻¹ and isopycnals have relaxed to more typical depths (Fig. 2b).

Although we have identified this as a wind event, we cannot rule out that Ekman veering may have played a role. As compared to the relaxed isopycnals before the meander event (Fig. 1c), the relaxed isopycnals after the wind event are more uplifted over the slope (Fig. 2d) and the 24.9 isopycnal still outcrops, albeit very close to the coast. Moreover, LADCP velocities show the current core inshore of its mean position after the wind event,
with anomalously strong velocities at the shelf break. These factors point to the possibility that Ekman veering at depth may have primed the isopycnals for an upwelling event once winds became favorable, as has been found in the East Australia Current (Roughan and Middleton 2002). Thus, it could be that the combination of Ekman veering along the slope and northeasterly winds at the surface resulted in this large surface-intensified cold event.

It is interesting that both the meander and wind events cause the same magnitude temperature change and neutral density uplift over the shelf and slope despite the different time scales and forcing mechanisms of the events. Next, we use satellite data to expand our analysis to the 9-yr period spanning 2003 through 2011.

b. Satellite observations of cold events

1) CENSUS OF COLD EVENTS

For the time period between 2003 and 2011, we find 102 days of cold events, representing 47 individual events with an average length and standard deviation of 2.2 ± 1.4 days (Fig. 4). Our directly observed cold events of 2010 and 2013 are well represented by our SSTA threshold, which is based on correlation with local forcing. There are between 1 and 12 cold events per 1-yr period with an average of 5.9 (Fig. 5). Given the average length and frequency of cold events, we find 13 days of surface cold events in the Agulhas Current per year. The distribution of SSTA is skewed slightly toward cold events, with a range from −2.8° to 2.3°C. Cold events range in length from 1 to 7 days. The correlation between length and maximum strength (minimum SSTA) is −0.44, which is significant at the 99% level. Hence, longer events are also colder events.

We identify far fewer upwelling events than Goschen et al. (2012), whose moorings were in the shallow waters of the inner shelf about 150 km to the southwest of the ACT line. Their moorings were positioned in the more variable waters of the Agulhas Bank and able to detect smaller, subsurface signals related to local winds and coastally trapped waves. Our analysis targets mesoscale cold events with a surface signature that occur within the Agulhas Current proper, where the continental slope and front place stronger dynamical constraints on variability.

2) FORCING MECHANISMS OF COLD EVENTS

Characterizing cold events in terms of forcing mechanisms is complicated by the fact that the four potential forcing mechanisms are not independent (Table 2). For example, we find SLA and $\nu'$ are strongly anticorrelated. During a meander, inshore SLA is anomalously low due to the meander’s associated inshore cyclone. At the same time, this cyclone induces an inshore countercurrent; hence, $\nu'$ is anomalously positive. On the other hand, during times of increased current strength, and hence anomalously negative $\nu'$, SLA typically increases due to encroachment of the current onto the shelf. Alongshore winds and wind stress curl are also strongly anticorrelated. Since wind strength tends to decrease offshore, a negative wind stress curl is associated with a positive alongshore wind and vice versa. Finally, alongshore wind and $\nu'$ are positively correlated: a strong negative alongshore wind drives offshore transport that tends to strengthen the pressure gradient across the current, leading to increased geostrophic velocity (Lee and Williams 1988). To elucidate the covariabilities of the four forcing mechanisms and their joint impact on SSTA, we use combined EOF analysis of...
these five quantities. Combined EOF is a method used to study the coupling between several variables by decomposing their correlation matrix into eigenvectors (Kutzbach 1967). We interpret these eigenvectors (EOFs) as coupled modes of variability where two or more forcing variables act together to force SSTA. To determine the patterns of variability associated with cold events, we base the combined EOF analysis on observations during cold events only.

We find that the first two combined EOFs of these four forcing mechanisms explain together 74% of the variability during cold events (Fig. 6). The patterns associated with these two EOFs are shown in Fig. 7. Since we have isolated only cold event observations, the anomalies of SSTA for each mode are anomalies around a negative mean. Hence, negative phases of each mode represent stronger cold events, while positive phases represent weaker cold events. The positive phase does not represent positive SSTA.

The first EOF (Fig. 6, left) shows that 43% of the variance of cold events can be explained by meanders acting during times of upwelling-favorable wind stress curl (negative phase of EOF1) or by upwelling-favorable alongshore wind acting alone (positive phase of EOF1). The second EOF (Fig. 6, right) shows that 31% of cold event variance is explained by meanders during times of upwelling-favorable alongshore wind (negative phase of EOF2) or by upwelling-favorable wind stress curl (positive phase of EOF2) acting alone. We find no clear role for Ekman veering in our analysis. Although the EOF analysis (Fig. 6) exhibits negative $\nu'_x$ during weaker events (positive phases of EOF1 and EOF2), the mean $\nu'_x$ during cold events is strongly positive due to the influence of meanders, and therefore negative $\nu'_x$ anomalies do not relate to upwelling-favorable conditions (Table 3). However, Ekman veering has been found to play a significant role in upwelling in the East Australia Current (Roughan and Middleton 2002; Schaeffer et al. 2014), and it is likely that subsurface data are needed to properly identify the role of Ekman veering in the Agulhas Current.

The patterns associated with the two leading modes of cold event variance are illustrated in Fig. 7, which shows composite maps. The weaker cold event of EOF1 (Fig. 7b) is strikingly similar to the February 2013 wind event (Fig. 2). In this case, the Agulhas Current remains against the continental slope, as illustrated by MADT (Fig. 7) and cross-sectional velocity (Fig. 2), while northeasterly winds drive surface cooling. For the weaker cold event of EOF2 (Fig. 7d) the Agulhas Current is once again unperturbed, while the cold event is now driven by upwelling-favorable wind stress curl. It is possible that Ekman veering is playing a role to prime the system for upwelling during these wind-driven events, yet this is not evident from our analysis. Stronger cold events are clearly associated with meanders, with the core of the Agulhas Current pushed far offshore and cool SST found within an inshore cyclone (Figs. 7a,c). These strong events are also associated with upwelling-favorable winds: upwelling-favorable wind stress curl in the case of EOF1 and upwelling-favorable alongshore winds for EOF2. Our April 2010 upwelling event resembles EOF1 in its negative phase (Fig. 7a). Overall, upwelling-favorable winds are important for every type of cold event, and meanders are important only for the strongest cold events. A mean composite for all cold events (Fig. 7e) gives a muddied picture, since it averages over both meander and non-meander events; the combined EOF analysis is more successful at characterizing cold events and their

### Table 2. Correlation matrix for the four forcing mechanisms (as defined in the text): SLA, $\nu'_x$, wind stress curl, and alongshore wind. Correlations marked with a single asterisk are significant at the 94% level, and those marked with a double asterisk are significant at the 99% level.

<table>
<thead>
<tr>
<th></th>
<th>Wind stress curl</th>
<th>Alongshore wind</th>
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<tbody>
<tr>
<td>SLA</td>
<td>$-0.77^{**}$</td>
<td>$0.13$</td>
</tr>
<tr>
<td>$\nu'_x$</td>
<td>$-0.14$</td>
<td>$0.19^*$</td>
</tr>
<tr>
<td>Wind stress curl</td>
<td></td>
<td>$-0.83^{**}$</td>
</tr>
</tbody>
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mechanisms than a simple composite. Finally, we show, for context, the time series mean composite (Fig. 7f), where inshore SSTA and all four forcing mechanisms are near zero and the Agulhas Current is found in its mean position along the continental slope.

Our analysis shows that the strongest cold events, accounting for the largest amount of variability, result from upwelling-favorable wind stress curl in combination with a meander (negative phase of EOF1). For our observed April 2010 meander-driven cold event, we saw the development of a negative wind stress curl anomaly toward the end of the event. This relationship between wind stress curl and meandering may be evidence of oceanic frontal systems influencing local wind stress patterns, as has been observed, for example, in the western Arabian Sea (Vecchi et al. 2004). To investigate this coupling in the Agulhas Current, we follow Chelton et al. (2007) and consider the correlation between the crosswind SST gradient and the wind stress curl. We find a correlation of 0.57 for the entire time series, which is significant at the 99% level. This correlation strengthens slightly to 0.61 when we consider upwelling events only. Hence, the migration of the warm Agulhas Current front during a meander event can drive local wind stress curl, such that upwelling is enhanced further. This is a significant result that shows that mesoscale coupling between the ocean and the atmosphere is a positive feedback on meander-driven upwelling within the Agulhas Current.

4. Discussion and conclusions

Using hydrographic data that spans the continental shelf and Agulhas Current close to 33.5°S, we show, for the first time, that central waters from below 200 m are pulled up onto the shelf during upwelling events, leading to maximum cooling of 9°C at middepth over the shelf. Maximum surface cooling during these events was 4°–4.5°C, related to outcropping of the γ = 24.9 neutral surface close to the shelf break. Although similar in structure, these two observed upwelling events were associated with very different forcing mechanisms. The first week-long event was due to upwelling inshore of a propagating meander of the current, while the second event, lasting only a day or two, was associated with an upwelling-favorable alongshore wind event, possibly primed by Ekman veering.

We expand on our hydrographic observations to quantify and characterize cold events in the Agulhas Current between January 2003 and December 2011 using satellite data. We identify 47 upwelling events, defined as cold SST anomalies, which are correlated with local wind or current forcing. Upwelling events are between 1 and 12 days long with an average of only 13 days of surface cold events in the Agulhas Current each year. Forcing mechanisms for upwelling are highly correlated and difficult to disentangle; hence, we developed a new technique to characterize cold events using combined EOF analysis. We find stronger cold events are forced by meanders acting during times of upwelling-favorable winds, while weaker cold events are forced by upwelling-favorable winds, possibly primed by Ekman veering. Our findings are similar to those in the Brazil Current, where the strongest upwelling events are also associated with offshore meandering, upwelling-favorable winds, and uplift of central waters onto the shelf (Campos et al. 2000; Castelao and Barth 2006). Most significantly, we find that the strongest cold events in the
Agulhas Current result when a mesoscale meander couples with the atmosphere to enhance upwelling-favorable wind stress curl, which acts as a positive feedback on upwelling.

A significant weakness of our extended analysis is our reliance on satellite data to characterize upwelling events, such that subsurface upwelling events remain undetected. These are likely to be much more frequent than surface events, as found on the inner shelf (Goschen et al. 2012), and Ekman veering can be expected to play a clear role (Roughan and Middleton 2002). Yet, because of the

Fig. 7. Six panels showing weighted composites for each phase of the first two EOF modes as well as means for cold events and the time series. Colors are GHRSST SST using the color bar on the right. The vectors show alongshore wind and are plotted at every third point. The black contours show wind stress curl in intervals of $10^{-3}$ from $-4 \times 10^{-3}$ to $4 \times 10^{-3}$, with negative values dashed and positive values solid. The blue vector outlined in white shows the direction and magnitude of $\nu_x$. The red contours are mapped absolute dynamic topography from AVISO in 0.25-m intervals.
strong dynamical constraints of the sloping bottom and Agulhas front at our study site, we might predict upwelling events to be, if not less frequent, then shorter in duration, than those documented at Goschen’s sites. Farther downstream, where Agulhas Current meanders are larger and the shelf far broader, upwelling events have been shown to support episodic biological productivity over the Agulhas Bank (Lutjeharms et al. 2000; Jackson et al. 2012). At our site, 150 km north and east of the Agulhas Bank, strong upwelling events with a surface signature appear to be rare and of short duration, and there is so far no evidence for a local influence on biological productivity (McClain and Atkinson 1985). Hence, the major importance of these isolated upwelling events may be related to their ability to advect surface waters offshore, which can create larval population sinks (Porri et al. 2014; Weidberg et al. 2015) and disperse inshore pollutants (Churchill et al. 1986).

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REFERENCES


**Table 3.** Table showing the mean of high-pass filtered SSTA and forcing mechanisms for cold events only as well as the net result (mean plus or minus one standard deviation) for each phase of each EOF mode. Forcing mechanisms are upwelling-favorable when they are negative.

<table>
<thead>
<tr>
<th></th>
<th>Cold event mean</th>
<th>Stronger events EOF 1</th>
<th>Weaker events EOF 1</th>
<th>Stronger events EOF 2</th>
<th>Weaker events EOF 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>SSTA (°C)</td>
<td>−1.62</td>
<td>−1.81</td>
<td>−1.53</td>
<td>−1.78</td>
<td>−1.50</td>
</tr>
<tr>
<td>SLA (m)</td>
<td>−0.02</td>
<td>−0.12</td>
<td>0.06</td>
<td>−0.09</td>
<td>0.04</td>
</tr>
<tr>
<td>$\nu'$ (m s$^{-2}$)</td>
<td>0.12</td>
<td>0.35</td>
<td>0.00</td>
<td>0.27</td>
<td>0.02</td>
</tr>
<tr>
<td>Wind stress curl (N m$^{-2}$)</td>
<td>0.0046</td>
<td>−0.0103</td>
<td>0.0202</td>
<td>0.0170</td>
<td>−0.0107</td>
</tr>
<tr>
<td>Alongshore wind (m s$^{-1}$)</td>
<td>−0.7</td>
<td>3.8</td>
<td>−5.2</td>
<td>−4.4</td>
<td>3.3</td>
</tr>
</tbody>
</table>


