New perspectives on Natal Pulses from satellite observations

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[1]   More than 6 years of high-frequency sea surface temperature (SST) imagery are used to follow perturbations at the inshore front of the Agulhas Current, between the northern Natal Bight and Port Elizabeth. Selected case studies as well as a front detection algorithm applied to the SST data provide some new insights into the dynamics of Natal Pulses and the variability of the northern Agulhas Current. Over the measurement period, the path of the Agulhas Current's inshore front does not exhibit any seasonality. Instead, large excursions in the Agulhas Current's inshore front are dominated by the intermittent passage of offshore cyclonic meanders from the Natal Bight and Port Edward regions to Port Elizabeth. SST imagery reveals that as they progress downstream, Natal Pulses interact with the topography to form secondary offshore meanders which propagate in the lee of the original perturbation. Over time, these secondary meanders dissipate, remerge with the original Natal Pulse, or detach from the Agulhas Current. Fluctuations in the Agulhas Current inshore path do not display the same frequency characteristics at all transects. From the northern Natal Bight to Port Edward both the size and frequency of Natal Pulses increases, while south of Port Edward the number of Natal Pulses decreases. At Port Elizabeth, the number of Natal Pulses observed is lower in comparison to previous estimates, with an average of 1.6 Natal Pulses per year.

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1.   Introduction

[2]   The Agulhas Current forms the western boundary of the Indian Ocean subtropical gyre. It flows along the continental shelf of southeast Africa, from about 27°S to 40°S, where it reverses in a tight retroflection loop to become the Agulhas Return Current. With a mean transport estimated to about 70 Sv ($1 \, \text{Sv} = 10^6 \, \text{m}^3 \, \text{s}^{-1}$) and current speeds often in excess of $2 \, \text{m s}^{-1}$, the Agulhas Current constitutes the strongest western boundary current of the Southern Hemisphere [*Lutjeharms*, 2006; *Bryden et al.*, 2005]. The oceanography of the southern Agulhas, from Port Elizabeth (34°S) to the southern tip of the Agulhas Bank is reminiscent of other western boundary current systems, with the frequent occurrence of meanders, eddies and plumes. By contrast, the current in the northern Agulhas displays remarkably little variability. From the northern Natal Bight (28°S) to Port Elizabeth, the Agulhas Current is an intense and narrow flow which closely follows the continental shelf. Observations have shown that in the northern Agulhas, the current is encountered in close prox-imity to the shore for about 80% of the time [*Grundlingh*, 1983; *Bryden et al.*, 2005]. The stability of the northern Agulhas has been attributed to the topographic steering of the current by the steep continental slope [*Lutjeharms and van Ballegooyen*, 1984; *de Ruijter et al.*, 1999].

[3]   In their study on the stability of the Agulhas Current, *de Ruijter et al.* [1999] argue that instabilities in the northern Agulhas can only develop at the Natal Bight, an embayment of the northern Agulhas where the steepness of the continental slope relaxes. These instabilities, first observed by *Harris et al.* [1978] have been termed Natal Pulses after their region of origin [*Lutjeharms and Roberts*, 1988]. Natal Pulses have been described as large solitary meanders in the Agulhas Current associated with a cold water core and a cyclonic circulation inshore of the current [*Lutjeharms and Roberts*, 1988; *Bryden et al.*, 2005]. The formation, growth and propagating speed of Natal Pulses have been inferred from in situ measurements [*Beal and Bryden*, 1999; *Bryden et al.*, 2005], satellite remote sensing imagery such as sea surface temperature (SST) [*Lutjeharms and Roberts*, 1988] or altimetry [*de Ruijter et al.*, 1999; *van Leeuwen and de Ruijter*, 2000], as well as from numerical modeling experiments [*Biastoch et al.*, 2008; *Tsugawa and Hasumi*, 2010]. Previous studies on Natal Pulses have shown that these offshore meanders originate in the Natal Bight as a result of a barotropic instability and grow steadily in size as they propagate downstream with phase velocities of 10 to 20 km d^{-1} [*van der Vaart and de Ruijter*, 2001; *Lutjeharms*, 2006]. Natal Pulses occur at irregular time intervals of 50 to 240 days [*de Ruijter et al.*, 1999], with a mean frequency of 4 to 6 per year [*Bryden*

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et al., 2005; *Lutjeharms*, 2006]. Lagrangian float observations have revealed that Natal Pulses can extend to the full depth of the Agulhas Current [*Lutjeharms et al.*, 2001]. Natal Pulses strongly influence coastal and shelf regions where they drive localized upwelling [*Bryden et al.*, 2005] and participate in the export of pollutants or fish larvae from the northern to the southern Agulhas regions. Natal Pulses are also thought to play an important part in the downstream variability of the Agulhas Current and the subsequent leakage of warm and salty Agulhas Current water into the Atlantic ocean. In particular, they have been linked to the formation of Agulhas Rings [*van Leeuwen and de Ruijter*, 2000] and on some occasion to early retroflections [*Lutjeharms and van Ballegooyen*, 1988; *Rouault et al.*, 2010].

[4] Most satellite-based SST observations of Natal Pulses have been undertaken using the NOAA/NASA Advanced Very High Resolution Radiometer (AVHRR) [*Lutjeharms*, 2006]. Merged maps as well as along-track altimetry have been used to detect and track Natal Pulses [*de Ruijter et al.*, 1999; *van Leeuwen and de Ruijter*, 2000]. Both altimetry and SST imagery are remote sensing methods which are severely challenged in the northern Agulhas. The proximity of the current to the shore (from about 20 km to 50 km) and its relatively invariant path make it difficult for altimeters to accurately capture the flow dynamics [*Rouault et al.*, 2010]. Steric height in the Agulhas Current dominates the sea surface height signal and features of the circulation with periods less than 70 days are poorly resolved in today's along-track altimetry data sets [*Byrne and McClean*, 2008]. In addition, altimetry-based observations suffer from significant data loss up to 50 km from the coast due to factors such as land contamination or atmospheric errors [*Vignudelli et al.*, 2008; *Madsen et al.*, 2007]. Accurately capturing the dynamics of the northern Agulhas Current at the event scale using data sets such as the AVHRR SST which have a relatively low temporal resolution (daily) can also prove difficult due to the extensive and persistent cloud coverage above the Agulhas Current [*Rouault et al.*, 2000].

[5] High-frequency data acquisitions from the geostationary Meteosat Second Generation satellite (MSG-2) allow a better imaging of the rapidly evolving mesoscale and submesoscale features of the northern Agulhas Current. The Spinning Enhanced Visible and InfraRed Imager (SEVIRI) is MSG-2's main payload. SEVIRI images the Earth at a 15 minutes sampling interval using 12 spectral channels with spatial resolutions of 1 km and 3 km. SEVIRI provides 20 times more information than previous Meteosat satellites with unique capabilities for imaging the ocean's surface. In this paper, over 6 years of SEVIRI SST data are used to track perturbations in the northern Agulhas Current and follow their evolution as they progress downstream from the northern Natal Bight to Port Elizabeth. Hence the focus of this paper is not so much on the origin of perturbations in the northern Agulhas or the generation of Natal Pulses, but rather on the evolution of these perturbations downstream and on the variability of the northern Agulhas Current. Synoptic observations of the northern Agulhas Current at a high-frequency show that a number of nonlinear processes can occur at the Agulhas Current inshore front. The SEVIRI SST imagery provides some new insights on the variability of the northern Agulhas Current and on the nature of Natal Pulses. The data and methodology used in this study are presented in

section 2. In section 3, we use both case studies as well as time series of the position of the Agulhas Current's inshore front derived at six transects to characterize Natal Pulses and further our understanding of the northern Agulhas Current variability. The results of the study are discussed in section 4, followed by a summary in section 5.

2. Data and Method

[6] SST data collected from the SEVIRI instrument onboard the MSG-2 geostationary satellite are used to identify examples of instabilities in the northern Agulhas Current as well as derive time series of the position of the Agulhas Current's inshore front across six transects. The region of study and the positions of the selected transects appears in Figure 1a. The transects, located between 29°S and 34°S, are referred to as the Natal Bight North, Natal Bight, Natal Bight South, Port Edward, East London and Port Elizabeth transects. The SST data set used for our analysis consists in the Ocean and Sea Ice Satellite Application Facility (OSI-SAF) experimental hourly SST product (http://www.osi-saf.org), available on a 0.05°grid ($\simeq$ 5 km) and processed by the French ERS Processing and Archiving Facility (CERSAT). All analyses are undertaken using the declouded SST with no additional flag applied. More than 6 years of hourly SST data collected between 1 June 2004 and 19 October 2010 are used to derive time series of the position of the Agulhas Current's inshore front. All case studies presented in the paper are based on daily composite maps derived from the hourly SST imagery. The time series analysis is conducted using 3 day moving averages of SST, centered on the day of acquisition and with weights values of [1,3,1].

[7] Like other western boundary currents, the Agulhas Current is an intense and narrow flow characterized by strong velocity gradients and a central warm core, with isopycnal lines sloping steeply toward the coast [*Goschen and Schumann*, 1990; *Casal et al.*, 2009; *Bryden et al.*, 2005]. In the northern Agulhas, large SST gradients are encountered between the Agulhas Current and coastal and shelf waters [*Lutjeharms*, 2006]. This is particularly true off the Natal Bight and Port Elizabeth regions, where the Agulhas Current drives a semipermanent upwelling circulation [*Rouault et al.*, 1995; *Lutjeharms*, 2006]. The distinct thermal signature of the Agulhas Current as well as the large SST gradients at its inshore boundary should make SST a suitable tracer for tracking the path of the Agulhas Current's inshore front. The method for the inshore front detection algorithm involves deriving an approximate position for the Agulhas Current core and then searching for the current's inshore boundary between the estimated core position and the coastline. SST values are extracted from the 3 day average maps in a band of 15 km around the transect lines. The median over the width of the SST band is then computed prior to searching for the positions of the Agulhas Current core and inshore front. Before searching for the Agulhas Current core, SST transects are smoothed with a Gaussian filter of sigma value 2 to remove large spikes. All local SST maxima encountered over a 50 km moving window are identified and the local maximum associated with the largest SST is then selected as the point where the Agulhas Current core lies. For the position of the Agulhas Current inshore front, all local maxima in the SST gradient and over a 75 km moving window are identi-
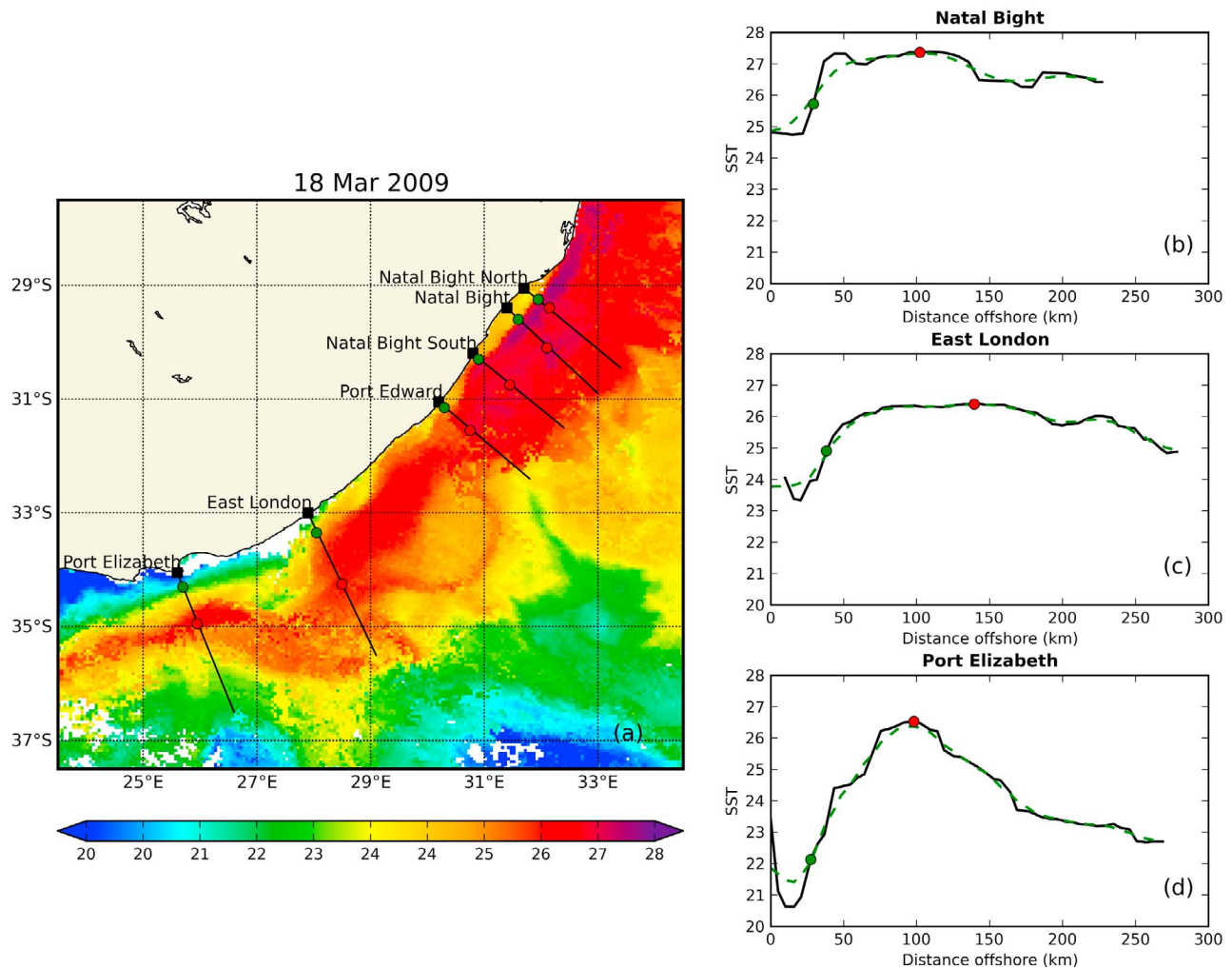
Figure 1. Example of output from the Agulhas front detection algorithm applied on a 3 day average map of SST (in °C) centered around 18 March 2009. (a) A color contour map of SST over the region of study. The position of the Agulhas Current was tracked along six transects plotted as thin black lines and referenced to as Natal Bight North, Natal Bight, Natal Bight South, Port Edward, East London and Port Elizabeth. The position of the Agulhas Current core detected using the algorithm is plotted with a red dot while a green dot shows the position of the detected Agulhas Current inshore front. SST as well as the identified Agulhas Current core and inshore front positions are plotted for three selected transects at the (b) Natal Bight, (c) East London and (d) Port Elizabeth. The solid black lines in Figures 1b, 1c and 1d correspond to the SST along the transect, while the dotted green line shows the smoothed SST profiles used for the estimation of the Agulhas Current core's position.

fied. The local peak associated with the largest SST gradient and located closest to the Agulhas Current core is then selected as the position of the inshore front. When no local maxima are found within the transect, absolute maxima are selected. In the search for the Agulhas Current's inshore front position, minimal smoothing with a Gaussian filter of sigma value 1 is undertaken to avoid removing the gradients all together. Window lengths for the algorithm are selected to capture SST features associated with the Agulhas Current, such as the doming of the SST at the center of the Agulhas Current or the sharp increase in SST at the Agulhas Current front followed by its slow decrease to beyond the current core. Both the window size and smoothing criterion are set with the aim to minimize the selection of spikes, small patches of warm or cold water or large homogeneous water bodies. The

size of the moving window does not impact on the scale of the Natal Pulses which can be identified by the algorithm. An example of algorithm output for the 3 day composite map of 18 March 2009 is provided in Figure 1.

[8] In our analysis of the Agulhas Current's front movements, Natal Pulses are defined as excursions in the path of the Agulhas's inshore front exceeding 30 km from the mean in the 10 day low-passed time series. The Natal Pulses detected in the time series are therefore selected using only the following two simple criteria: (1) that the Agulhas Current inshore front meander more than 30 km from its mean position and (2) that the Natal Pulse lasts for a period of 10 days or more. The region of origin, the direction of propagation of the perturbations or the existence of an inshore cyclonic circulation, are not taken into account when identifying Natal

Pulses. Any offshore meander observed at the inshore front and which does not qualify as a Natal Pulse according to our criterion is simply referred to as an offshore meander. The threshold of 30 km selected for the detection of Natal Pulses is chosen based on a previous study which reported that Natal Pulses grow from about 30 km in the Natal Bight to 200 km or more [*van Leeuwen and de Ruijter*, 2000]. In their analysis of in situ measurements off Port Edward, *Bryden et al.* [2005] found that the average timescale associated with alongshore fluctuations in the Agulhas Current equalled 10.2 days, with Natal Pulses lasting between 50 and 70 days. Currently, observations combining several altimeters are able to observe mesoscale features of the ocean circulation at a sampling frequency of about 10 days [*Le Traon and Dibarboure*, 2002]. The selection of a 10 day low-pass filter therefore seems appropriate for the detection of Natal Pulses and allows us to better compare our results with previous observations of Natal Pulses from altimetry.

[9] The effects of varying the 30 km size threshold or the 10 day cutoff period of the low-pass filter on the number of Natal Pulses detected along each transect were addressed in a sensitivity study. The number of Natal Pulses detected at each of the transects using size thresholds of 20, 30 and 40 km was determined. The effect of varying the low-pass cutoff period from 7 to 14 days was also addressed. The sensitivity study shows that changing the properties of the low-pass filter or the size threshold for the detection of Natal Pulses impacts on the number of Natal Pulses detected at most transects. The detection of Natal Pulses along each transect is most sensitive to a lowering of the size threshold from 30 km to 20 km. The northern Natal Bight, Natal Bight and Southern Natal Bight transects, all located in the region of origin of the Natal Pulses, show marked increases in the number of Natal Pulses detected when lowering the size threshold from 30 km to 20 km. The tendency of Natal Pulses to grow downstream from their region of origin implies that the Natal Pulse detection algorithm becomes less and less sensitive to a lowering of the size threshold south of the Natal Bight South transect, with little or no change in the number of Natal Pulses estimated at the East London and Port Elizabeth transects.

[10] Absolute geostrophic current velocities are used to support the analysis conducted on the SST data. The absolute geostrophic currents are derived by combining Maps of Sea Level Anomaly (MSLA) produced by AVISO to the CNES-CLS09 Mean Dynamic Topography (MDT) of *Rio et al.* [2005]. The MSLA consist in a merged data set of the latest sea surface height measurements available from the OSTM/Jason-2, Jason-1 and Envisat altimeters. It is provided on a rectilinear grid with a 1/3° spatial resolution. The derivation of the CNES-CLS09 MDT involves similar methods to those described by *Rio et al.* [2005], but benefits from the assimilation of extended data sets of drifting buoy velocities (1993–2008) and dynamic heights (1993–2007). The CNES-CLS09 MDT enables a better definition of the velocity gradient across the Agulhas Current and improves the portrayal of the Agulhas Current dynamics from altimetry [*Rouault et al.*, 2010]. The AVISO product suffers from the same limitations as other altimetry data set and is not expected to provide accurate measurements near the coast (within 50 km) or to resolve the mesoscale circulation over periods of less than 10 days. In the case studies presented in sections 3.1.1, 3.1.2

and 3.1.3, the AVISO near real-time product (NRT) is used as an indication of the general oceanic circulation and offshore mesoscale activity. At the Port Elizabeth section, where the current lies furthest to the shore, the delayed time (DT) AVISO product (completed with weekly values extracted from the NRT product from 31 March 2010 onward) is used to support our analysis.

3. Results

3.1. Instabilities at the Agulhas Current Front

[11] The SEVIRI SST imagery reveals a number of mesoscale and submesoscale processes at the inshore front of the Agulhas Current. Some of the instabilities observed include oscillations along the inshore boundary of the current, plumes and frontal eddies. Most of the instabilities observed at the inshore front of the Agulhas Current seem to develop during the downstream propagation of Natal Pulses along the Agulhas Current's edge. While the origin and offshore extent of the Natal Pulses may vary, the triggering of instabilities associated with the downstream progression of Natal Pulses seem to follow one common pattern. Section 3.1.1 provides an example of the initial stages of development of an Agulhas inshore front instability during the passage of a Natal Pulse. In sections 3.1.1, 3.1.2 and 3.1.3, different scenarios for the evolutions of instabilities at the Agulhas Current's inshore boundary are showcased. The three case studies selected for this paper are aimed to provide an overview of the different modes of evolution for the instabilities observed at the Agulhas Current inshore front.

3.1.1. Meander Dissipation

[12] Figure 2 shows an example of instabilities observed at the Agulhas Current's inshore front between Port Edward and East London. In mid-May 2007, an anticyclonic eddy originating from the East Madagascar Current reaches the waters offshore the Natal Bight and triggers the development of a Natal Pulse around 15 May 2007 (not shown) in a manner similar to that previously described by *Schouten et al.* [2002]. By 4 June 2007, the small Natal Pulse has moved southward and can be seen at 29.5°E and 32.5°S in Figure 2a. Part of the anticyclonic eddy responsible for triggering the Natal Pulse appears in shades of grey in Figure 2a, between 31°S and 32°S.

[13] The oscillation associated with this Natal Pulse is clearly visible when looking at the 23°C isotherm, plotted as a red contour line in Figure 2. The trailing edge of the Natal Pulse (located at about 29.6°E, 31.8°S), starts interacting with the shelf, generating a small offshore meander upstream. By 7 June 2007, the upstream instability resulting from the interaction of the Natal Pulse with the topography has evolved into a secondary offshore meander of similar amplitude to that of the original Natal Pulse (Figure 2b). The SST composite map of 10 June 2007 (Figure 2c) shows that after 3 days, the initial Natal Pulse has significantly shrunk in size and has progressed just south of East London. In the mean time, the secondary offshore meander upstream of the initial Natal Pulse has remained fairly stationary and has grown in amplitude. The SST imagery collected on 13 June 2007 (Figure 2d) shows that the initial Natal Pulse perturbation has dissipated. Its progress downstream to 27.2°E, 33.7°S can only be evaluated thanks to the presence of relatively cooler water on the shelf. By contrast, the secondary
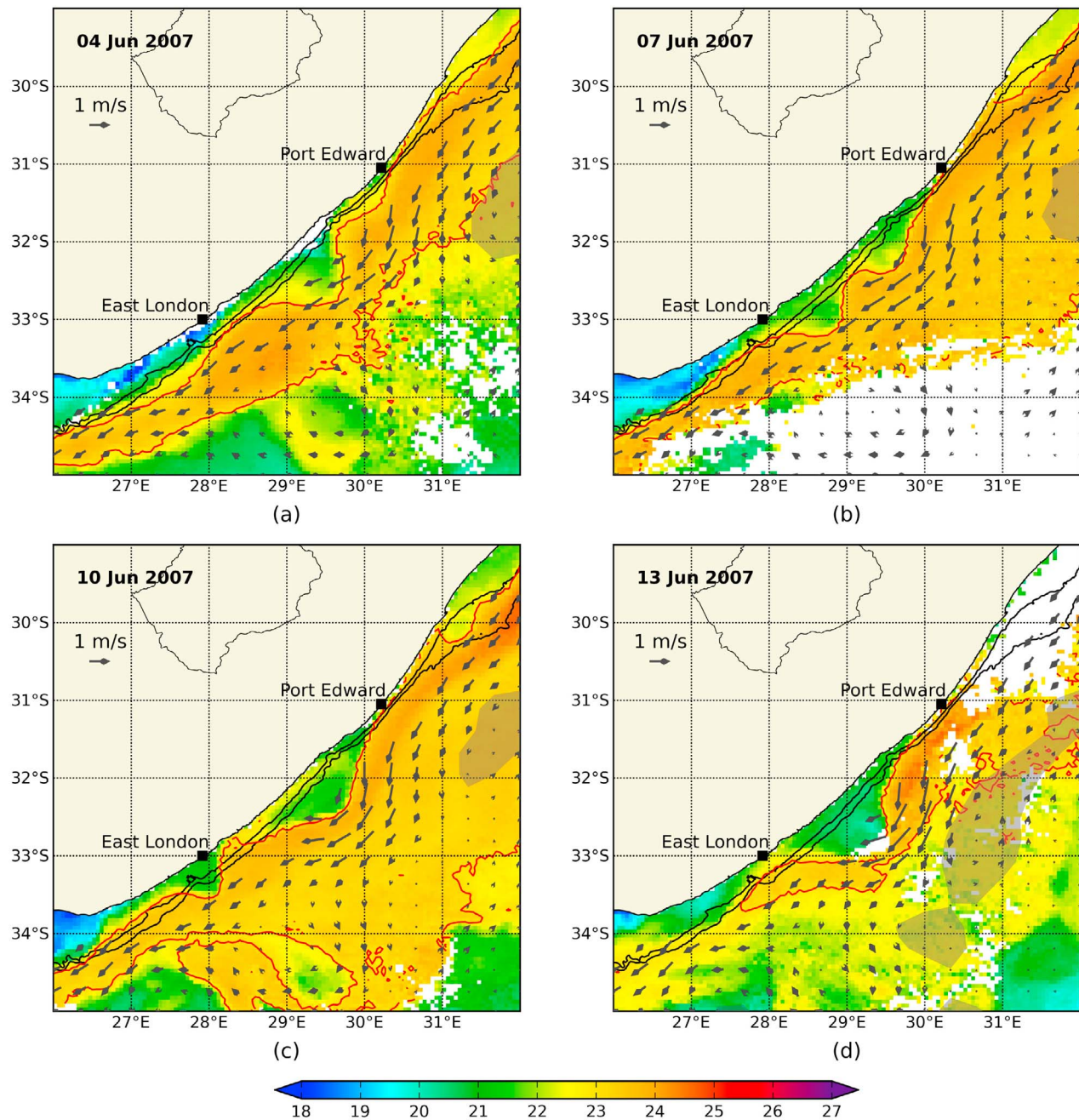
Figure 2. SST daily composite maps (in °C) showing the development of an upstream perturbation during the passage of a Natal Pulse between Port Edward and East London. The red contour line marks the position of the 23°C isotherm. Overlaid are absolute geostrophic current vectors derived by combining the AVISO MSLA (NRT) product to the CNES-CLS09 MDT. The shaded areas provide an indication of the presence of an anticyclonic eddy at the offshore edge of the Agulhas Current. The positions of the 200 m and 1000 m isobaths are plotted as black contour lines.

upstream offshore meander has expanded further, now approximating 90 km in diameter. It is this secondary offshore meander, which on 5 July 2007, is detected as a Natal Pulse near Port Elizabeth. To be noted is the presence of an anticyclonic flow at the offshore boundary of the Agulhas Current from 4 to 13 June 2007. The growth of the secondary offshore meander from 10 to 13 June 2007 occurs during a

period of intensification in the offshore anticyclonic circulation (Figures 2c and 2d).

[14] Observations of SEVIRI SST maps show that on their journey from the Natal Bight to Port Elizabeth, Natal Pulses systematically interact with the coastal topography to generate upstream perturbations. These upstream offshore meanders occur when the trailing edge of the original Natal
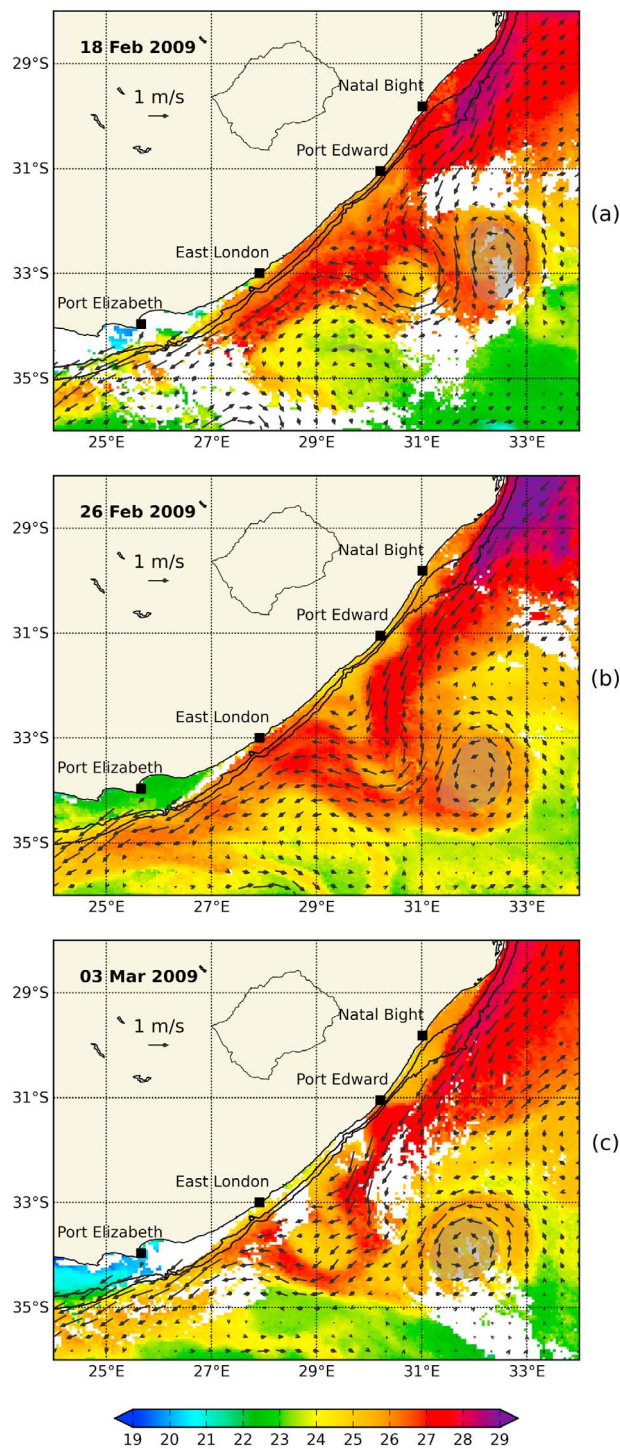
Figure 3. Example of merging meanders revealed from daily SST composite maps (in °C) in February and March 2009. (a) A large Natal Pulse centered at 31°E, 33°S (b) merges with an upstream instability located at 29.5°E, 32.5°S and (c) evolves into a single cyclonic meander. Overlaid are absolute geostrophic current vectors derived by combining the AVISO MSLA (NRT) product to the CNES-CLS09 MDT. The shaded areas in Figures 3a, 3b and 3c are an indication of the presence of an anticyclonic eddy at the offshore edge of the Agulhas Current. The positions of the 200 m and 1000 m isobaths are plotted as black contour lines.

Pulse comes in close proximity to the shore (as seen in Figure 2c). During the initial phase of development of the upstream meander, there is often a warm water plume of Agulhas Current water flowing northward along the coastal region. Interactions between Natal Pulses and the topography were observed at multiple locations between the Natal Bight and Port Elizabeth, with each Natal Pulse often generating upstream instabilities more than once on their downstream course to Port Elizabeth. Characterizing and quantifying the upstream meanders formed during the passage of Natal Pulses is difficult as they vary in size, occur over short timescales and develop sporadically over the northern Agulhas Current region. The fate of these secondary upstream meanders also varies. The meanders might flatten in shape and dissipate while others such as that presented in Figure 2, might grow in size and propagate southward as separate perturbations in the Agulhas Current. On other occasions, the secondary upstream offshore meanders progress downstream to later remerge with the Natal Pulse initially responsible for their inception. Section 3.1.2 provides such an example of merging instabilities at the Agulhas Current's inshore front.

3.1.2. Meander Merging

[15] Interactions between successive offshore meanders can lead to intricate structures at the Agulhas Current's inshore front such as that observed in the SST imagery of Figure 3. On 18 February 2009, a large Natal Pulse centered at 31°E, 33°S between Port Edward and East London is observed (Figure 3a). Warm surface waters originating from the Agulhas Current have entrapped cooler coastal waters in a cyclonic circulation. Absolute geostrophic currents associated with the Natal Pulse are around 1 m s^{-1}. On 26 February 2009 (Figure 3b), the Natal Pulse has become elliptical in shape and is now situated at 30°E, 34°S. The Agulhas front shows oscillatory motions upstream of the Natal Pulse. In particular, one cyclonic offshore meander has progressed downstream to 29.5°E, 32.5°S, directly north of the original Natal Pulse. By 3 March 2009 (Figure 3c), both the Natal Pulse and the offshore meander directly upstream of it have merged near East London to form one large Natal Pulse centered at 29°E, 33.5°S. This large Natal Pulse will continue further downstream to reach Port Elizabeth in early April 2009. Between 18 February and 3 March 2009, an anticyclonic eddy interacts with the offshore boundary of the Natal Pulse. Figure 3 shows that secondary offshore meanders formed during the passage of a Natal Pulse can in turn grow and generate their own upstream instability. What follows is a train of meanders in the path of the initial Natal Pulse perturbation, as shown in Figure 3b, where the first of the upstream generated offshore meander centered at 29.5°E, 32.5°S is followed by two small upstream perturbations, with the first one located directly offshore Port Edward and a second perturbation visible in the Natal Bight.

3.1.3. Meander Occlusion

[16] Occasionally, Natal Pulses become so unstable that they develop an enclosed cyclonic eddy which detaches from the Agulhas Current to move further offshore. Over more than 6 years of observations, the detachment of an offshore meander from the Agulhas Current was observed on only two occasions. The first observation of an eddy occlusion event occurred off the Natal Bight in January 2005 (not shown). The other case of an offshore meander detaching from the
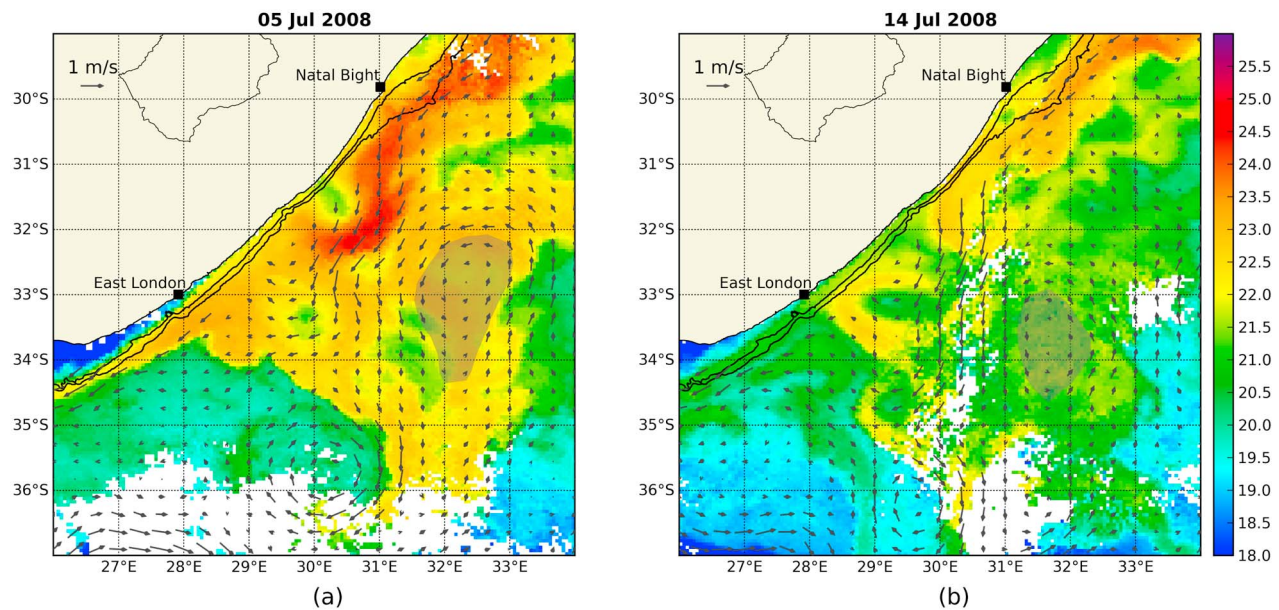
Figure 4. Evidence of Natal Pulse detachment revealed from daily SST composite maps (in °C) in July 2008. Color contours of SST are overlaid with absolute geostrophic current vectors derived by combining by combining the AVISO MSLA (NRT) product to the CNES-CLS09 MDT. A Natal Pulse initially observed at 30°E, 33.5°S on 5 July 2008 becomes an occluded cyclonic eddy and separates from the Agulhas Current. On 14 July 2008, the occluded eddy has progressed to 29.3°E, 34.7°S. The positions of the 200 m and 1000 m isobaths are plotted as black contour lines.

Agulhas Current occurred in July 2008, during the development of the largest Natal Pulse identified near Port Elizabeth over the June 2004 to December 2010 period. The evolution and eventual detachment of the July 2008 offshore meander is shown in Figure 4. On 5 July 2008 (Figure 4a), a Natal Pulse is observed at 30°E, 33.5°S. An offshore meander centered at 30.2°E, 31.5°S can also be seen upstream of the Natal Pulse. Both the Natal Pulse and the upstream meander are associated with a belt of warm Agulhas water (>22°C) surrounding a core of cooler water (≃20°C) of coastal origin. The SST map derived on 14 July 2008 shows that the upstream meander has progressed downstream to 29.7°E, 33°S. This upstream meander has grown threefold within 1 week and is now associated with a well-defined cyclonic circulation. Shades of yellow associated with the 22°C SST contour show warm Agulhas water looping back in a cyclonic motion just offshore East London. Over the same period, the original Natal Pulse has moved to 29.3°E, 34.7°S and has become an enclosed cyclonic eddy, separated from the Agulhas Current. At the offshore boundary of the Natal Pulse, there is an anticyclonic eddy which moves downstream and which can be seen in vector plots of the geostrophic currents in Figure 4.

[17] High-frequency SST data acquisitions from the MSG-2 geostationary satellite reveal that a range of dynamical processes occur at the inshore front of the Agulhas Current. Case studies presented in sections 3.1.1, 3.1.2 and 3.1.3 show that during their downstream progression, Natal Pulses observed at the Agulhas Current's inshore front do not always grow steadily in size. Instead, the southward progression of Natal Pulses is often associated with the triggering of new upstream instabilities which propagate downstream together with the initial pulse. The observed mesoscale and submesoscale instabilities at the Agulhas' inshore edge develop over short periods of time (typically less than 1 week). As they progress downstream, instabilities triggered at the inshore front of the Agulhas Current during the passage of Natal Pulses either dissipate, remerge with the original pulse or detach from the current. Over extended period of time, Natal Pulses therefore result from the downstream propagation of either 1 or a group of successive offshore meanders at the inshore boundary of the Agulhas Current. In section 3.2, we attempt to evaluate how the instabilities which develop at the Agulhas Current's inshore front impact on the variability of the whole northern Agulhas Current by monitoring the position of the Agulhas Current's inshore front throughout more than 6 years of SST observations.

3.2. Variability at the Inshore Front of the Northern Agulhas Current

[18] The position of the Agulhas Current inshore front derived along 6 transects of the northern Agulhas using the method described in section 2 is plotted in Figure 5. The Natal Pulses identified in Figure 5 represent extended periods of offshore meandering in the Agulhas Current associated with the passage of either 1 or a group of offshore meanders. About 80% of the detected Natal Pulses could be confirmed using SST and merged altimetry maps. The front detection algorithm performs best at the Natal Bight and Port Elizabeth transects, where stronger temperature gradients between the Agulhas Current and coastal waters are encountered [*Lutjeharms*, 2006]. Failures in the algorithm to correctly identify the position of the Agulhas Current's inshore front result from various factors, ranging from missing data or poor data quality (due principally to cloud contamination) to very weak SST gradients or a complex SST structure around the
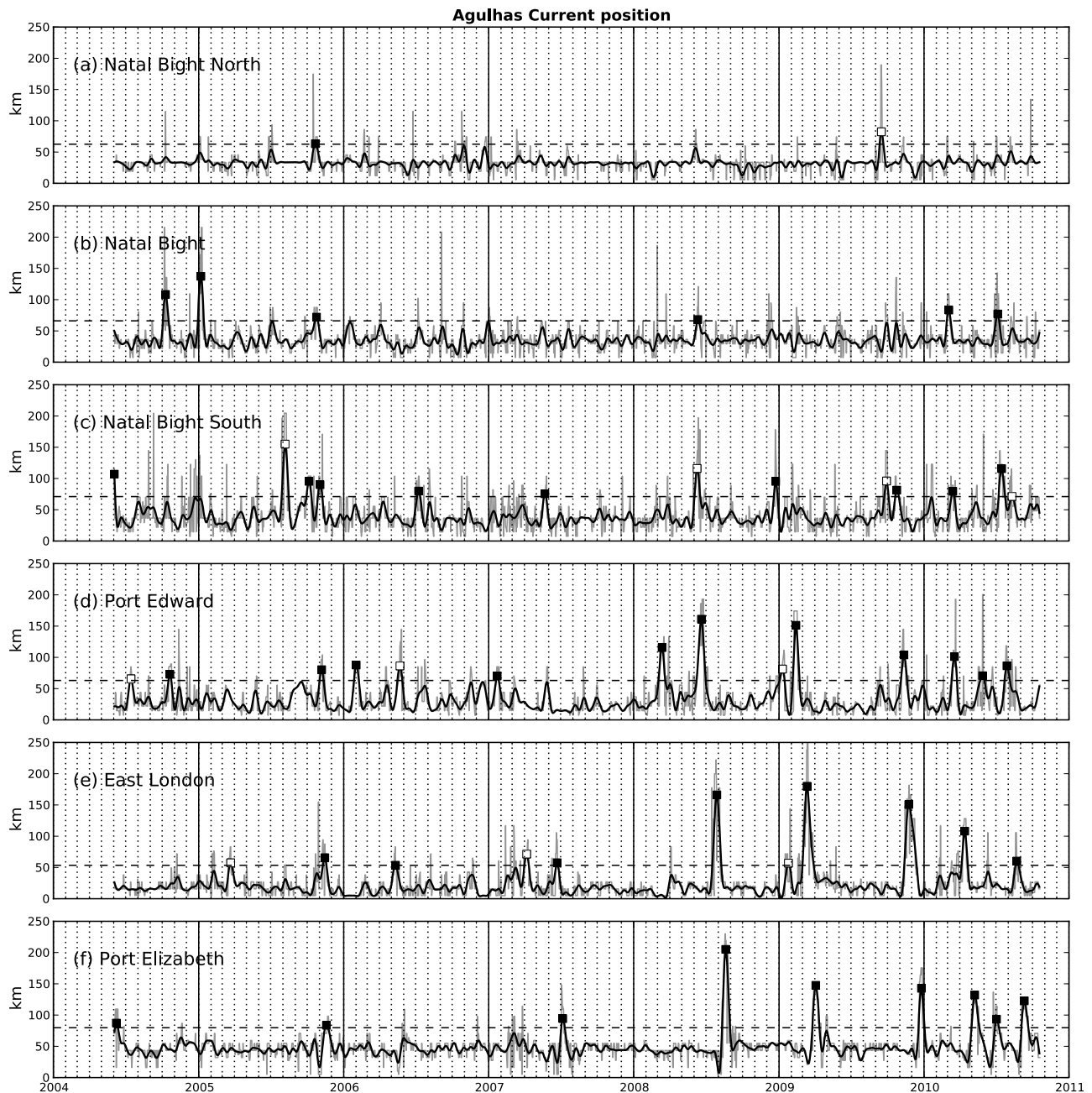
Figure 5. Position of the Agulhas Current inshore front relative to the shore estimated at the (a) Natal Bight North, (b) Natal Bight, (c) Natal Bight South, (d) Port Edward, (e) East London and (f) Port Elizabeth transects estimated from 3 day moving averages of SEVIRI SST. The horizontal black line represents variations from the mean position of the Agulhas Current inshore front after applying a 10 day, fourth-order Butterworth low-pass filter. The dashed line shows the 30 km threshold used for the identification of Natal Pulses. Natal Pulses in the Agulhas Current are identified by black squares. Natal Pulses which could not be confirmed after visual examination of SST maps have been plotted as white squares. Solid vertical lines mark 1 January for each year, while the dashed vertical black lines indicate the beginning of each month.

Agulhas Current. In the northern part of our study region, weak SST gradients between the Agulhas Current core and offshore regions at times lead to the Agulhas Current core position being estimated too far offshore. Wrong estimates of the Agulhas Current core position can in turn induce errors when deriving the position of the Agulhas Current's inshore

front. In the region between the southern Natal Bight and East London, the proximity of the Agulhas Current to the coast represents an additional challenge for the detection of the inshore front of the Agulhas Current. When the current hugs the coastline, the few number of data points which remain available to perform a search for the inshore gradient can lead

to errors when estimating the position of the current's inshore edge. Overall, the front detection algorithm is able to detect most Natal Pulses successfully. Off the Natal Bight, the landward edge of the Agulhas Current lies on average 36 km from the coast, at a position which roughly corresponds to the location of the 200 m isobath (Figure 5a). Standard deviations in the Agulhas Current's inshore front position average to about 19 km. These results are in good agreement with the mean and standard deviation (15 km) estimated by *Grundlingh* [1983] for the position of the Agulhas Current using hydrographic data collected off the Natal Bight. Along the Port Elizabeth transect, the inshore boundary of the Agulhas Current is found to lie on average 49 km from the coast, with standard deviation in its path of about 22 km. The mean position and standard deviation of the inshore front of the Agulhas Current near Port Elizabeth derived here, agree with those estimated by *Goschen and Schumann* [1990] (mean of 51 km and standard deviation of 24 km) at the same location (Cape Recife) and over a 3 year period.

[19] One of the interesting results coming out of the analysis is the lack of seasonal variability in the position of the Agulhas Current's inshore edge across all selected transects. From the northern Natal Bight to Port Elizabeth, variations in the position of the Agulhas Current's inshore front are instead dominated by the irregular passage of offshore meanders. The frequency and size of these meanders vary from one transect to the next. At the Natal Bight North transect, the position of the Agulhas Current's inshore front exhibits little variability, with only 1 Natal Pulse identified around 21 October 2005. From the northern Natal Bight to Port Edward, the number of Natal Pulses increases from 6 at the Natal Bight transect, to 9 at the Natal Bight South transect and reaches a maximum of 11 at the Port Edward transect. From Port Edward to Port Elizabeth, fewer Natal Pulses are observed at the Agulhas Current's inshore front with only 8 Natal Pulses detected off East London and 9 near Port Elizabeth. The largest Natal Pulse is detected near Port Elizabeth in August 2008, when the current meanders about 160 km offshore from its mean position. This particular event was previously identified by *Rouault et al.* [2010] as a precursor to the anomalous early retroflection of the Agulhas Current in September/October 2008.

[20] The front detection analysis shows that not all Natal Pulses observed in the Agulhas Current's path grow steadily in size as they progress downstream. The two largest Natal Pulses observed at the Natal Bight transect around October 2004 and January 2005 for example do not propagate downstream to Port Elizabeth. The Natal Pulse of October 2004 decreases in size downstream while that observed in January 2005, which corresponds to the case of eddy occlusion mentioned in section 3.1.3, detaches from the Agulhas Current before it reaches Port Edwards. Similarly two of the Natal Pulses identified at the Port Elizabeth transect around 18 November 2005 and 6 July 2007 do not exhibit significant growth from their region of origin to Port Elizabeth. In the case of the Natal Pulse observed off Port Elizabeth in July 2007, the reason for the Natal Pulse not expanding was highlighted in section 3.1.1. On the low-passed time series both the initial pulse detected at the Natal Bight South transect on 22 May 2007 and the one detected near Port Elizabeth on 7 July 2007 appear to be due to one single meander propagating downstream when in reality, it was observed in

section 3.1.1, that this Natal Pulse constituted of to two separate instabilities at the Agulhas Current's inshore front. The properties of all Natal Pulses that progressed southward to Port Elizabeth and which are identified by black markers in Figure 5f are summarized in Figure 6. The origin of these Natal Pulses, their propagation speeds and the extent of the offshore meandering associated with their passage are plotted in Figures 6a, 6b and 6c, respectively. From the 9 Natal Pulses detected at the Agulhas Current's inshore front off Port Elizabeth, 6 find their origin in the region of the Natal Bight and 2 are detected first at the Port Edward transect. The first Natal Pulse detected at the Port Elizabeth transect occurs at the beginning of the measurement period and for this reason, its region of origin cannot be determined. In Figure 6a, the Natal Pulses which reached Port Elizabeth are classified as merging, dissipating or occluding based on the type of instability that developed during their downstream progress. This classification, undertaken using visual observations of SST maps, appears to indicate that most of the secondary meanders that develop during the passage of Natal Pulses later remerge with the initial perturbation. However, this result is purely indicative of what could be observed from the SEVIRI data set. A proper quantification of the number of dissipating, merging or occluding instabilities associated with Natal Pulses could only be undertaken using high-frequency in situ measurements at multiple transects locations. Figure 6b shows that Natal Pulses generally have propagation speeds between 10 and 20 km d^{-1}, in agreement with previous findings [*van der Vaart and de Ruijter*, 2001]. One exception is found in the Natal Pulse of November 2005, which displays much larger propagation speeds. Figure 6c confirms that the growth of Natal Pulses downstream is not always monotonic. From June 2004 to the end of 2007, the position of the Agulhas Current's inshore front near Port Elizabeth shows remarkably little variability as only three small Natal Pulses are observed (Figure 5f). Deviations from the mean inshore path of the Agulhas Current associated with these 3 Natal Pulses are less than 50 km. From 2008 to 2010, both the size and the number of Natal Pulses observed near Port Elizabeth increase, with 6 Natal Pulses causing fluctuations in the inshore path of the Agulhas Current of 91 km from the mean, on average.

3.3. A Retrospective on Natal Pulses From Altimetry

[21] Cyclonic motions over the continental shelf associated with the passage of Natal Pulses induce flow reversals at the mean position of the Agulhas Current core (located at 25.8°E, 34.7°S according to *Rouault et al.* [2010]), with the current direction changing from southwesterly to northeasterly. A time series of the eastward current velocity extracted at 25.8°E, 34.7°S shows that all Natal Pulse events identified using the SEVIRI SST front detection algorithm are associated with large fluctuations in the eastward geostrophic flow. In the AVISO time series, anomalous events are defined as variations in the eastward flow exceeding 1 standard deviation from the mean. From the 10 anomalous events detected using the AVISO eastward current velocity at 25.8°E, 34.7°S, 9 correspond to Natal Pulses identified with the SST front detection algorithm (Figure 7). While the AVISO eastward current anomaly does not necessarily relate well to the scale of the Natal Pulses, the AVISO data set appears to provide an
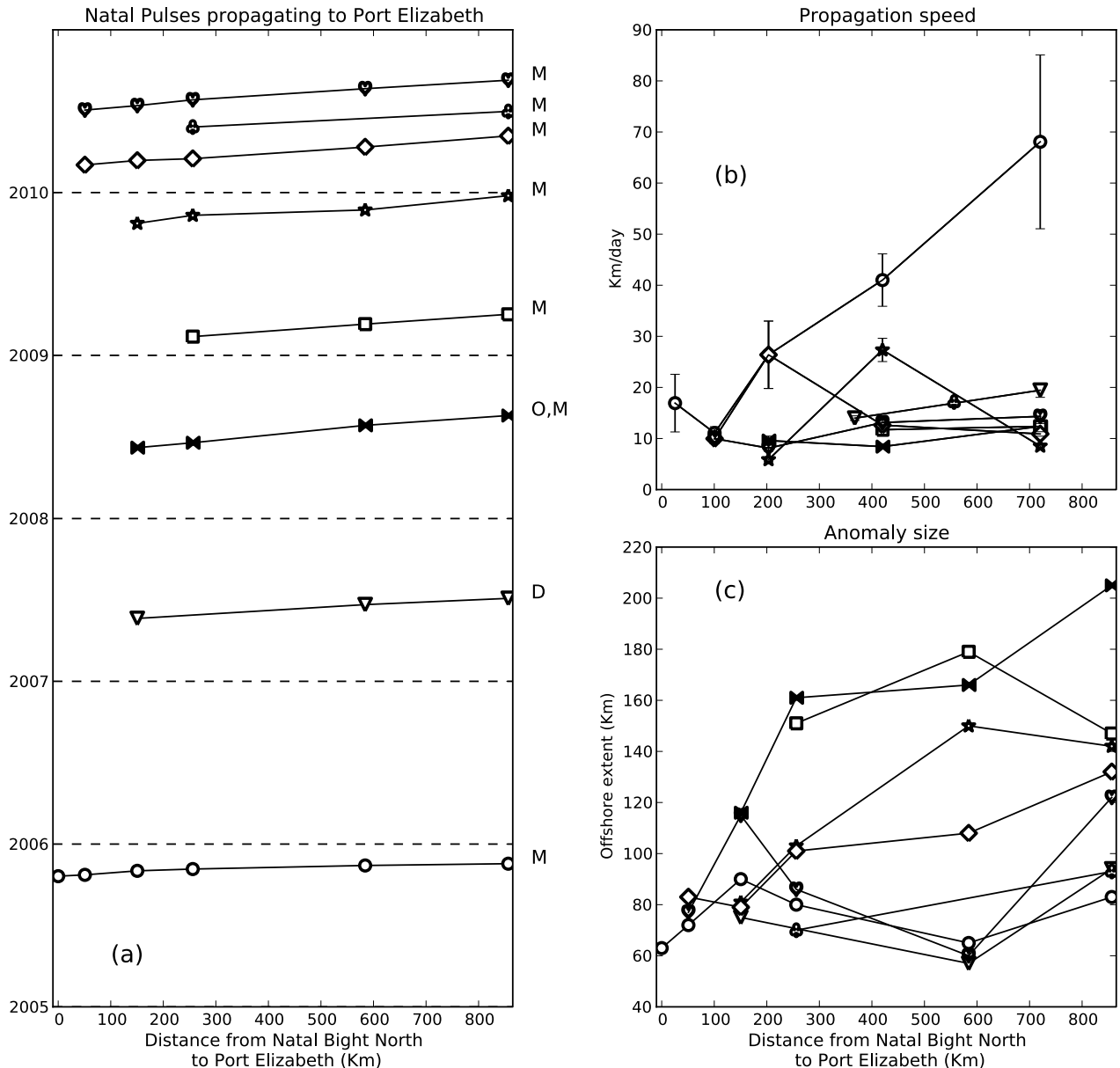
Figure 6. Origin and properties of the Natal Pulses which reached the Port Elizabeth transect. (a) The propagation of each Natal Pulse detected near Port Elizabeth from their region of origin. Each Natal Pulse propagating at the inshore boundary of the Agulhas Current can be identified by its marker. The label on the x axis represents the distance in km from the Northern Natal Bight to the Port Elizabeth transect with markers showing the position of each transect on the line plots. The letters M, O and D on the right-hand side of Figure 6a indicate instances of merging (M), occluding (O) and dissipating (D) instabilities associated with the Natal Pulses. (b) Propagation speeds derived for all Natal Pulses are plotted with error bars showing the uncertainty associated with using 3 day SST composites. (c) The offshore deviation from the mean position of the Agulhas Current's inshore front associated with the passage of the Natal Pulses.

excellent indicator for the occurrence of Natal Pulses offshore Port Elizabeth.

[22] One surprising result of the SEVIRI SST front detection analysis is that from June 2004 to the end of 2010, few Natal Pulses were observed at Port Elizabeth. On average the number of Natal Pulses reaching the waters off East London and Port Elizabeth only amounted to about 1.6 per year. Building on the good correlation between the AVISO and the

Agulhas Current's inshore front time series (Figure 7), a time series of the eastward geostrophic current at 25.8°E, 34.7°S is used to estimate the frequency of occurrence of Natal Pulses over a 17 year period. Variations in the eastward current derived from the AVISO data set between 14 October 1992 and 8 December 2010 are plotted in Figure 8. As in Figure 7, fluctuations in the eastward current velocity exceeding 1 standard deviation from the mean are used as indication of
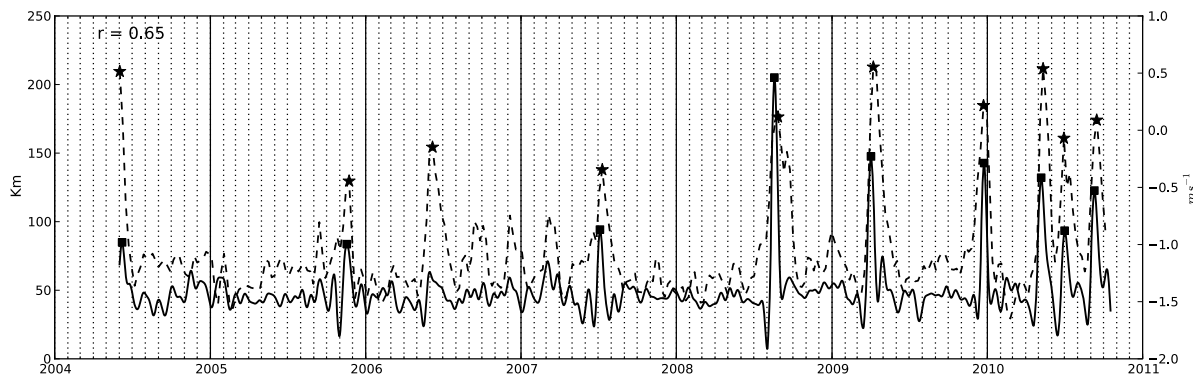
Figure 7. Variations in absolute geostrophic current velocities at the Agulhas Current core associated with the passage of Natal Pulses offshore Port Elizabeth. The low-passed position of the Agulhas Current's inshore front is plotted as a black line with Natal Pulses identified by black squares. The eastward current velocity extracted at 25.8°E, 34.7°S from the AVISO maps of absolute geostrophic velocities is plotted as a dashed black line with stars showing fluctuations in the eastward current velocity greater than 1 standard deviation. A Pearson's correlation coefficient r of 0.65 is found between the 7 day low-pass time series of the Agulhas Current inshore front and the absolute eastward geostrophic velocity at the Agulhas Current core. The correlation coefficient r is highly significant at the 99% confidence interval. Solid vertical lines mark 1 January for each year, while the vertical dashed black lines indicate the beginning of each month.

Natal Pulse events. The average number of Natal Pulses detected using the AVISO data set over the 17 year AVISO time series averages to 1.65 per year, an estimates which compares well with that derived from our SST front detection analysis.

[23] Using AVISO maps of absolute dynamic topography and associated geostrophic currents (not shown), it is possible to relate some of the events detected in Figure 8 to previous observations of Natal Pulses. For example, the Natal Pulse observed on 6 October 1993 by *van Leeuwen and de Ruijter* [2000] can be seen in Figure 8. The Natal Pulses identified by *Lutjeharms et al.* [2001, p. 116] and in July 1998 and in May/June 2004, are also apparent in Figure 8. Using the AVISO merged maps of absolute dynamic topography, it was possible to identify all 5 Natal Pulses observed by *Bryden et al.* [2005] off Port Edward in April 1995, September 1995, November 1995, December 1995 and March 1996. From these 5 Natal Pulses, 3 observed in April 1995, September 1995

and March 1996 seem to disappear from the merged altimetry maps before reaching Port Elizabeth.

4. Discussion

[24] Previous studies [*Bryden et al.*, 2005; *Lutjeharms*, 2006] have consistently pointed to the Natal Pulse as the dominant mode of variability upstream of the Agulhas Retroflection. While our analysis of the Agulhas Current's inshore front supports the hypothesis that downstream propagating offshore meanders are the dominant drivers of variability in the northern Agulhas, it also shows that large excursions in the Agulhas Current's path are not necessarily associated with the passage of one large solitary offshore meander. Instead, Natal Pulses are often the result of 1, 2 or more cyclonic offshore meanders, which together, progress southward at the inshore border of the Agulhas Current. Undulations at the inshore front of the Agulhas Current upstream of Port Elizabeth have been previously noted by
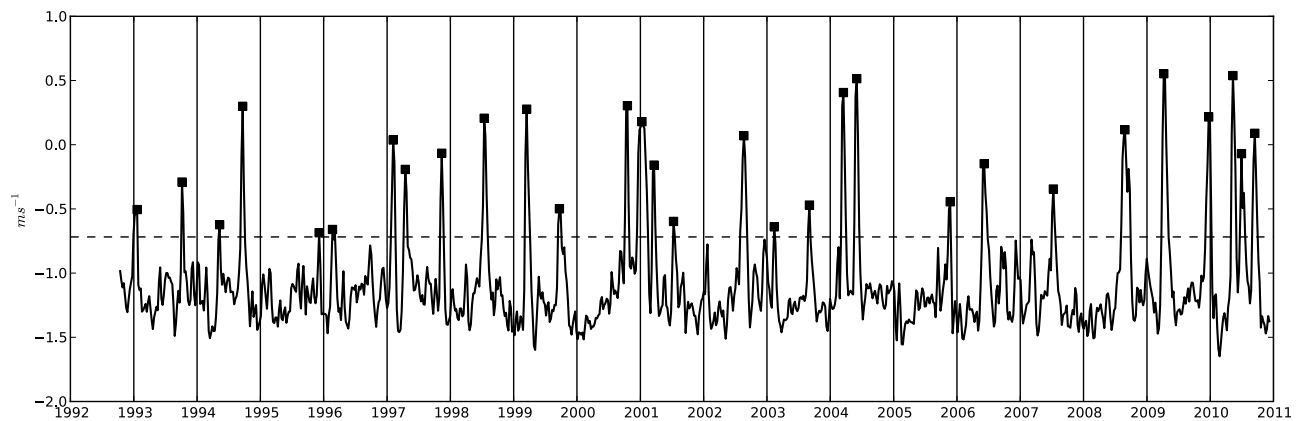
Figure 8. Eastward current at 25.8°E, 34.7°S extracted from the AVISO maps of absolute geostrophic velocities. Eastward current velocity fluctuations exceeding 1 standard deviation from the mean are identified with black squares. Solid vertical lines mark 1 January for each year.

Goschen and Schumann [1990], who suggested that such oscillations might occur prior to the formation of shear edge eddies. Current measurements undertaken in the northern Agulhas in 1976 and 1977 [*Schumann*, 1983] have shown the sporadic occurrence of wave-like oscillations between Port Edwards and Richards Bay (north of the Natal Bight). These meandering motions propagated northward along the coast with a speed of 3.9 m s^{-1} (14 km d^{-1}) and were associated with marked current and temperature variations, with upwelling and associated offshore flow in the upper layers. In his analysis, *Schumann* [1983] could not relate the wave-like motions to atmospheric perturbations and expressed uncertainty as to the generation mechanism for these northward propagating coastal waves. In a study on Natal Pulses, *van Leeuwen and de Ruijter* [2000] used SST imagery collected on 27 February 1987 (plate1-a) to identify 2 consecutive offshore meanders at the landward edge of the Agulhas Current. From these two large offshore meanders, only one could be detected off the southeast African coastline less than a month later (plate1-b). *Van Leeuwen and de Ruijter* [2000] suggested that the two pulses observed on 27 February 1987 might form part of a unique Natal Pulse event but provided no explanation as to why a Natal Pulse should consists of two meanders and why the same Natal Pulse would later become a single meander. *Takeda* [1983] showed that changes in the vorticity structure of the water column over a varying topography can induce the formation of topographically trapped waves, with the properties of the generated waves being dependent on the rate of stretching and shrinking of the vortex tubes. In his studies of the "interactions of an eddy with a continental slope," *Wang* [1992] found that cyclonic eddies impinging on a coastal shelf and slope induce wave-like perturbations whose dispersion relation obey that of shelf-trapped mode. Laboratory and numerical experiments conducted by *Sanson and van Heijst* [2000] showed that interactions between barotropic cyclonic vortices and a steep continental slope can generate an intense meandering current along the slope from which new cyclonic vortices are formed. Observations of SST imagery and the case studies presented in section 3 show that in a similar fashion, when the trailing edge of a Natal Pulse comes in close proximity to the coast, a secondary offshore meander can be generated upstream of the initial perturbation. Interactions between offshore meanders and the topography can lead to the formation of 1 or more upstream meanders each traveling southward with the initial Natal Pulse. Near the coast, the downstream propagation of Natal Pulses and their associated frontal instabilities induce wave-like oscillations which might resemble those associated with northward propagating coastal trapped waves.

[25] High-frequency SST observations collected from the SEVIRI instrument onboard MSG-2 have shown that Natal Pulses are complex and rapidly evolving features of the Agulhas Current associated with a range of nonlinear processes. The interaction of Natal Pulses with the continental shelf and the concomitant development of upstream instabilities (as seen in Figures 2, 3 and 4) is a possible indication of a direct cascade of energy toward the smaller scales. A recent paper on the oceanography of the South African east coast [*Roberts et al.*, 2010] also suggests that erosion of cyclonic eddies at the inshore boundary of the northern Agulhas Current occurs.

[26] Figure 5 shows that the frequency characteristics of the northern Agulhas Current's inshore front vary regionally. From the northern Natal Bight to Port Edward, both the size and frequency of Natal Pulses increase while south of Port Edward, there is a reduction in the number of Natal Pulses observed. The Natal Bight appears to be a key region for the development and growth of instabilities in the northern Agulhas. Vortex stretching due to the sudden steepening of the continental slope from the northern Natal Bight to the southern Natal Bight could provide a mechanism by which negative (cyclonic) vorticity is input into the main flow and which feeds the growth of Natal Pulses southward [*Huppert and Bryan*, 1976]. Oceanic eddies at the boundary of the Agulhas Current might also constitute a source or sink of vorticity for Natal Pulses. Theoretical investigations have shown that both cyclonic and anticyclonic eddies reaching a stable jet will generate meanders [*Stern and Flierl*, 1987; *Bell and Pratt*, 1992]. Previous studies have pointed to Mozambique anticyclonic eddies as being the main trigger for the development of Natal Pulses [*de Ruijter et al.*, 1999; *Schouten et al.*, 2002]. This was recently confirmed by *Tsugawa and Hasumi* [2010] who found that upon reaching the coastline, anticyclonic eddies extracted water from the shelf and slope and generated cyclonic vorticity through vortex stretching, resulting in the formation of a Natal Pulse. In case studies 3.1.1 and 3.1.2, the growth of cyclonic meanders was concurrent with the presence of an anticyclonic eddy on the seaward border of the current. In both case studies 3.1.1 and 3.1.3, the cyclonic meander closest to the anticyclonic eddy was seen to expand while the original cyclonic perturbation located further downstream decreased in size. The data sets used in this study are limited and further investigations would be required to undertake a vorticity budget and precisely assess the influence of both cyclonic and anticyclonic eddies on the expansion of Natal Pulses.

[27] One surprising result of the SST analysis is that very few Natal Pulses are observed between June 2004 and the end of 2010. On average the number of Natal Pulses reaching the waters off Port Elizabeth only amounts to about 1.6 per year. A retrospective analysis of altimetry data seems to confirm that on average only 1.6 Natal Pulse per year reach the latitude of Port Elizabeth. With the exception of *Goschen and Schumann* [1990] who found that approximately 2 Natal Pulses occur per year, most previous studies on Natal Pulses have estimated their frequency at 4 to 6 per year. Our current knowledge of Natal Pulses relies on scarce in situ observations, some analyses of altimeter data [*de Ruijter et al.*, 1999; *van Leeuwen and de Ruijter*, 2000] and a few numerical studies [*Biastoch et al.*, 2008; *Tsugawa and Hasumi*, 2010]. Upstream of Port Elizabeth, where the current lies close to the shore, altimetry data sets suffer considerable data loss due to land contamination [*Madsen et al.*, 2007; *Vignudelli et al.*, 2008]. The scarcity of altimeter observations between the Natal Bight and East London combined to a previously poorly resolved Mean Dynamic Topography (MDT) in the Agulhas Current region represent serious challenges when attempting to follow rapidly evolving features such as Natal Pulses [*Byrne and McClean*, 2008; *Rouault et al.*, 2010]. To date the most extensive dataset of the northern Agulhas Current consists in a 9 month record of moored array data collected off Port Edward in 1995 [*Bryden et al.*, 2005]. Other in situ observations of the northern Agulhas Current include

237 hydrographic sections of mainly vertical temperature profiles collected across eight transects between the northern Natal Bight and Port Elizabeth [*Grundlingh*, 1983].

[28] Our analysis suggests that the number of Natal Pulses decreases from Port Edward to Port Elizabeth. One could argue that the threshold selected for the identification of Natal Pulses in their region of origin is too restrictive and limits the number of Natal Pulses detected through our analysis. For example, the Natal Pulse observed by *Schouten et al.* [2002] in May/June 2000 would probably have been too small in size to qualify as a Natal Pulse under our selection criteria. However, changing the size threshold for the identification of Natal Pulses would not modify the result that very few Natal Pulses reach the Port Elizabeth transect. Natal Pulses have been defined as large intermittent and solitary meanders [*Lutjeharms and Roberts*, 1988] that "invariably" originates in the Natal Bight and which "always grows in seaward extent on translating downstream" [*Lutjeharms*, 2006, p. 114]. Due to limitations in previous satellite remote sensing data sets, it was not possible in the past to accurately follow perturbations from the Natal Bight all the way south to Port Elizabeth. Based on the assumption that Natal Pulses would always grow downstream and could only originate from the Natal Bight region, most southward propagating offshore meanders observed in the northern Agulhas Current and with spatial scales ranging from 30 to 250 km have been labeled Natal Pulses. As our knowledge on the variability of the northern Agulhas progresses, it becomes necessary to reexamine what constitutes a Natal Pulse.

5. Conclusion

[29] A front detection algorithm applied to more than 6 years of SST imagery was used to track fluctuations in the path of the northern Agulhas Current. Time series of the Agulhas inshore front derived between the Natal Bight and Port Elizabeth showed no seasonality in the position of the Agulhas Current and confirmed that variability at the northern Agulhas Current's inshore front is dominated by the intermittent passage of Natal Pulses. Different patterns of variability were observed within the northern Agulhas Current, with an increasing number of Natal Pulses detected between the northern Natal Bight and Port Edward, followed by a drop in the number of Natal Pulses south of Port Edward (Figure 5). High-frequency observations from the SEVIRI sensor showed that as they propagate southward, Natal Pulses grow and start to interact with the topography to generate a secondary meander which either splits, remerges or detaches from the original perturbation. The generation of smaller eddies during the passage of Natal Pulses (as seen in Figures 2, 3, and 4) provides a possible indication of a cascade of energy toward the smaller scales and could explain the downstream decrease in the number of Natal Pulses south of Port Edward. Over more than 6 years of SST observations, only 1.6 Natal Pulses per year was found to reach the latitude of Port Elizabeth. A retrospective analysis using altimetry data offshore Port Elizabeth appears to confirm that on average, approximately 1.6 Natal Pulses per year reach the southern Agulhas Current. The high spatial and temporal resolution of the SST data set used in this study allow for a better imaging of the northern Agulhas Current dynamics compared to previously used remote sensing techniques.

Some of the features revealed in the SST imagery expose crucial knowledge gaps in our current understanding of the northern Agulhas Current and the need for new theoretical and observational studies.

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