Generation and Growth Mechanism of the Natal Pulse

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ABSTRACT

The Natal pulses, solitary cyclonic meanders in the Agulhas Current, are reproduced in an ocean general circulation model. The model covers the region around the Agulhas Current with a grid fine enough to reproduce major eddies. The features of the reproduced Natal pulses are consistent with observational evidences in the following respects: they are generated at the Natal Bight when anticyclonic eddies come, move downstream along the Agulhas Current at speeds about 20 km day\(^{-1}\), and grow in its horizontal size as they move. The present simulation shows that the generation and growth of the Natal pulse occurs because of the interaction between the mean flow of the Agulhas Current and an anticyclonic eddy. A supplemental simulation, where the topography of the Natal Bight is modified, indicates that the topography of the Natal Bight does not cause the generation of the Natal pulses, contrary to a previous suggestion.

1. Introduction

The Agulhas Current is a western boundary current that flows southward along the east coast of South Africa. The current changes its direction around the southern tip of Africa and flows back to the Indian Ocean as the Agulhas Return Current. Where the Agulhas Current turns, large eminent anticyclonic eddies, called Agulhas rings, are formed. The Agulhas rings move into the South Atlantic, containing the Indian Ocean water, which is transported by the Agulhas Current and taken into the rings in the ring formation process. Hence, the Agulhas Current connects the Indian Ocean and the Atlantic Ocean, a crucial link of the return path of the global thermohaline circulation.

The Agulhas Current can be divided into two parts, the northern and the southern Agulhas Current, at Port Elizabeth. Although the Agulhas Current and the region around it, called the greater Agulhas Current system (Lutjeharms 2006), are the area showing vigorous eddy activity, the flow path of the northern Agulhas Current is quite stable compared to other western boundary currents such as the Gulf Stream and the Kuroshio. The stability of the northern Agulhas Current is explained by the steep continental slope of this region (de Ruijter et al. 1999). However, the flow path occasionally shows prominent meanders. The meanders were detected in 1970s in a vertical hydrographic section across the current as offshore displacements of the current axis (Grundlingh 1979). Subsequently, infrared satellite imagery captured solitary meanders in the Northern Agulhas Current (Harris et al. 1978). The meanders were named Natal pulses (Lutjeharms and Roberts 1988) because the meanders are generated around the Natal Bight.

The Natal pulses are related to various phenomena in and around the Agulhas Current. For example, the Natal pulses affect the rainfall in the coastal region of South Africa (Lutjeharms and de Ruijter 1996). Moreover, the Natal pulses are considered to control the shedding of the Agulhas rings. Satellite altimetry data show that the Natal pulses are spawned about a half year before the shedding of the Agulhas rings (de Ruijter et al. 1999; van Leeuwen et al. 2000). This correlation indicates that the Natal pulses affect the water exchange between the Indian Ocean and the South Atlantic through the shedding of the Agulhas ring and therefore...
implies that the pulses play an important role in the global thermohaline circulation.

Intensive observations of the Agulhas Current system have been conducted so far, and many features of the Natal pulses are revealed. The Natal pulses are spawned near the Natal Bight and move downstream along the Agulhas Current with phase speeds of about 20 km day$^{-1}$. Sizes of the Natal pulses are about 30 km near the Natal Bight, grow as they move downstream, and sometimes exceed 200 km when they come near Port Elizabeth. From satellite altimetry data, the Natal pulses are spawned sporadically with the periods of 50–150 days (de Ruijter et al. 1999). Observations by current meters and Lagrangian floats show that the meander of the Natal pulses extends over the full depth of the Agulhas Current (Lutjeharsms et al. 2001). Despite the intensive observational studies, a model of generation and growth of the Natal pulses has not been established completely. The generation and growth model has to explain several characteristic features of the Natal pulses. One of the features is that the Natal pulses are generated off the Natal Bight only and not in other regions. The model also has to account for the mechanism of their irregular occurrence and growth described earlier.

There are several theoretical investigations about the generation and growth mechanisms of the Natal pulse so far. de Ruijter et al. (1999) list several possible generation mechanisms; among them, they conclude that barotropic (BT) instability is the most likely. They attribute the uniqueness of the Natal Bight to its relaxed slope. The stability of the flow in the Natal Bight is the weakest in the northern Agulhas Current, which flows on the steep continental slope except in the Natal Bight. Although the flow is turned out to be barotropically stable even in the Natal Bight from their study, they suggest that some perturbation could trigger the instability. Following this, van der Vaart and de Ruijter (2001) inspect the stability of the Agulhas Current in their analytical study and find that an unstable mode shows pulse-like behavior and a propagation speed similar to the Natal pulses. Their result supports the barotropic instability model, whereas the triggering mechanism is left unspecified.

As for the triggering mechanism, de Ruijter et al. (1999) suggest that anticyclonic anomalies can initiate the instability by increasing the flow speed by analyzing gridded sea surface height (SSH) anomaly data. However, the origin of the anomaly is not specified therein because of the coarse resolution of the data. Subsequently, Schouten et al. (2002) clearly show that an anticyclonic eddy from the Mozambique Channel triggers a Natal pulse from ship and satellite observations. Because it can explain the uniqueness of the Natal Bight and also its triggering mechanism is detected by the observations, the generation and growth mechanism based on the barotropic instability is now considered as the most promising.

Many simulations for the Agulhas Current system have been carried out by using ocean general circulation models (OGCMs), but no model simulation has been dedicated to the study of Natal pulses so far. For example, Speich et al. (2006) use a 12-km grid model to investigate the effect of the Agulhas Bank topography on the behavior of the Agulhas Current. These high-resolution simulations, however, cover the region far downstream, and the Natal Bight does not exist in the calculation domain or, even if it exists, it is located too close to the boundary of the model domains. Biastoch and Krauss (1999) carry out a simulation that covers source regions of the Agulhas Current system, but no Natal pulse is reproduced, despite the existence of the Mozambique eddies, which should have triggered generation of the pulses. The absence of the Natal pulse in their model might be due to its resolution of $\frac{1}{10}$°. Reproduction of the Natal pulse by an OGCM is first reported by Biastoch et al. (2008), in a nested-grid simulation of the Agulhas Current system with $\frac{1}{10}$° grid size around South Africa. Because their model focuses on the interbasin exchange, they just report the behavior of the Natal pulses and do not discuss the generation and growth of them.

The authors construct a regional model, which is dedicated to simulate the Natal pulses. The model covers the whole Agulhas Current system and the source regions of the current with high resolution, which is enough to reproduce the major eddies, including the Mozambique eddies. In the model, the cyclonic meanders in the Northern Agulhas Current are reproduced and they show features consistent with the observed Natal pulses. With the model results, the triggering and growth mechanism of the Natal pulses is investigated. One of the advantages of model studies is that the topography can be modified to evaluate its effect. In this study, a supplemental simulation is carried out in which the bottom topography is manipulated to make the slope steep in the Natal Bight to test the topographic constraint for the generation mechanism proposed by de Ruijter et al. (1999).

Section 2 describes the model we use in this study. The reproduced Agulhas Current and Natal pulses are shown in section 3. In section 4, the generation and growth mechanism is discussed.

2. Model

The model used in this study is based on the cubic grid ocean model developed by the Japan Agency for Marine-Earth Science and Technology (Tsugawa et al. 2008) to
carry out global ocean model simulation. Although the model is designed for global model simulation, it can be used like a local model by using a grid-stretching technique called bicylindrical transformation (Murray 1996), which has originally been proposed for transformation of the latitude–longitude grid. A schematic view of the transformed grid is shown in Fig. 1a. In the present model, 256 × 256 grid cells exist on each face of the cube. The average resolution is about 40 km before the transformation. After the transformation, the grid covers the vicinity of the Natal Bight with grid sizes less than 10 km and covers the whole Agulhas Current system with less than 20 km (Fig. 1b). As shown later, the resolution is fine enough to reproduce major eddies of the Agulhas Current system and its source regions. The number of the levels is 43, with thickness of 8 m at the surface that gradually increases to 250 m near the bottom.

In this study, a region around the Agulhas Current system is set as a target region. Although the model covers the whole globe, the role of the area outside the target region is just to provide boundary conditions. In Fig. 1b, the target region is shown as an area enclosed by the circle of 4000 km radius centered at the Natal Bight. Outside the target region, the temperature and salinity on all levels are restored to the annual mean of the World Ocean Atlas 1998 (WOA98; Antonov et al. 1998). The damping constant for restoration is zero on the edge of the restoration region, linearly increases with the distance from the Natal Bight, and then is set constant to 1/30 day$^{-1}$ in the region where the distance exceeds 7000 km from the Natal Bight. The surface forcing, which will be described later, is applied both inside and outside the target region. The surface wind stress generates realistic wind-driven circulation all over the globe and supplies a reasonable flow boundary condition to the target region.

Except for the horizontal grid system, the model is similar to traditional Bryan–Cox–Semtner type of OGCMs (Bryan 1969; Cox 1984; Semtner 1974). The model employs the Boussinesq and hydrostatic approximations, the Arakawa B grid (Arakawa and Lamb 1977), and level coordinate. It employs an explicit free surface method for barotropic mode solver and partial bottom cell (Pacanowski and Gnanadesikan 1998; Adcroft et al. 1997) for bottom topography.

The horizontal friction and diffusion used in present model are biharmonic. Large viscous and diffusion coefficients are employed outside of the target region to suppress numerical instability caused by the coarser resolution there. Both of the viscous and diffusion coefficients near the antipodes of the Natal Bight are set to 5 × 10$^{13}$ m$^4$ s$^{-1}$. The values decrease as the distance from the Natal Bight decreases. Inside the target region, those coefficients are set as constant. The viscous coefficient in the target region is 1 × 10$^{11}$ m$^4$ s$^{-1}$. The diffusion coefficient there is 5 × 10$^{10}$ m$^4$ s$^{-1}$ at the beginning of integration to suppress instability in the initial phase and then decreased to 3 × 10$^{10}$ m$^4$ s$^{-1}$ after the second year of the integration.

Other model settings and parameters are as follows: The bottom topography is generated from 2-minute gridded elevations/bathymetry for the world (ETOPO2; Research Data Archive 2001). The Haney-type (Haney 1971) temperature surface boundary condition is used.

*Fig. 1. (a) Schematic view and (b) grid size (km) of the transformed cubic grid. The egg-shaped line in (b) shows the boundary of the target region.*
In this boundary condition, the thermal flux \( Q \) is given as
\[
Q = Q_{\text{obs}} + (dQ/dT)(T_1 - T_{\text{obs}}) = (dQ/dT)(T_1 - T_\text{obs}),
\]
where \( Q_{\text{obs}} \) and \( T_{\text{obs}} \) are the observed heat flux and sea surface temperature, respectively; \( T_1 \) is the topmost layer temperature; and \( T_\text{obs} = T_{\text{obs}} - Q_{\text{obs}}/(dQ/dT) \) is the apparent atmospheric equilibrium temperature. Surface freshwater flux is converted to virtual salinity flux. All of the surface fluxes and the wind stresses are monthly climatology derived from the dataset of Röске (2001). For the mixed layer, the Pacanowski–Philander scheme (Pacanowski and Philander 1981) is employed.

The initial condition is generated by integrating the model with restoring temperature and salinity of all levels to the WOA98 climatology both outside and inside the target region. The damping constant of restoration is \( 1/30 \) day\(^{-1} \) for the whole globe and all levels. The integration period for initial condition generation is 90 days, during which the surface forcing is also applied. The resulting initial condition has temperature and salinity fields close to the climatology and has velocity field adjusted to the tracer distributions. Five years of integration are carried out from the generated initial condition. The integration is long enough to reproduce the Agulhas Current and the Natal pulse in the target region, as shown later. The results of the fourth and fifth model years are analyzed.

3. Results

a. The Agulhas Current

Before discussing the Natal pulse, the Agulhas Current system in this model is described here. Snapshots of the SSH and surface velocity of the Agulhas Current system are shown in Fig. 2. The pictures show eddies, which are quite similar to the observation of this region as follows.

In the Mozambique Channel, a train of anticyclonic eddies corresponding to the Mozambique eddies appears, and no organized current can be found, as the observation shows (de Ruijter et al. 2002). Around the southern tip of Madagascar, several anticyclonic eddies exist. The anticyclonic eddies are formed at the southeast coast of the island of Madagascar, where the East Madagascar Current turns to the Indian Ocean in the model. The East Madagascar Current in the model turns to a more northern latitude than the observation. The observed East Madagascar Current extends to the southern tip of Madagascar as the southern branch of the East Madagascar Current (SEMC; Siedler et al. 2009). The SEMC separates into two branches: one flows toward the Agulhas Current and the other retroflects to the Subtropical Indian Ocean Countercurrent. In addition to the difference, pairs of cyclonic and anticyclonic eddies are often observed to form dipole structures on the branch of SEMC flowing to the Agulhas Current, whereas only the anticyclones are found in the model. A similar discrepancy between the observation and the model result can be found in the \( 1/10^\circ \) model of Biastoch and Krauss (1999). On the other hand, Siedler et al. (2009) reproduces realistic SEMC with a \( 1/10^\circ \) resolution model. Hence, the discrepancy might be caused by the resolution. Although our model failed to reproduce realistic SEMC, this defect does not suppress the generation of Natal pulse in our model, as shown later.

The Agulhas Current, which flows along the eastern coast of South Africa, starts increasing its velocity near the Natal Bight (Fig. 2b). The stable nature of the Agulhas Current path is well captured, and the Agulhas Return Currents and the Agulhas rings are also reasonably simulated. Figure 2 shows several Agulhas rings that are moving into the Atlantic Ocean.

A Natal pulse is pointed by an arrow in Fig. 2. It is accompanied by an anticyclonic eddy. The anticyclonic eddy is originally a Mozambique eddy, and it triggers the cyclonic meander off the Natal Bight, as shown in the next subsection.

The 2-yr means of the velocity and the barotropic transport are shown in Figs. 3a,b, respectively. In the Mozambique Channel, a southward flow exists along the African continent, though no organized flow appears in the Mozambique Channel in an instantaneous velocity field, as well as in observations. The nearshore side of the anticyclonic Mozambique eddies is averaged to form the southward mean flow. Likewise, a northward flow is formed in the offshore of the southward flow. The net transport in the Mozambique Channel is southward as in Fig. 3b. The East Madagascar Current turns around the southern tip of Madagascar and flows toward the South African coast, whereas it is not clear in the instantaneous flow field because of strong eddy activity (Fig. 2).

The mean velocity of the Agulhas Current starts increasing at just upstream of the Natal Bight. The transport of the Agulhas Current increases downstream because of the inflow from the southwest Indian Ocean subgyre. The current flows off South Africa and eventually changes its direction. The main part of the Agulhas Current turns back there and flows back to the Indian Ocean as the Agulhas Return Current. The volume transport calculated from the mean velocity of the model across the line used in Beal and Bryden (1999) is 80 Sv (1 Sv = \( 10^6 \) m\(^3\) s\(^{-1}\)), which is larger than the observed values, such as 75 Sv in Beal and Bryden (1999) and 69.7 Sv in Bryden et al. (2005).

The vertical section of the mean velocity off Durban is shown in Fig. 3c. The section corresponds to that in Beal
and Bryden (1999). Although some structures disappear in the averaging process, the mean flow structure broadly agrees with the observation. The current axis at the surface is located about 30 km from the coast and shifts offshore baroclinically as the depth increases. The maximum velocity is about 1.3 m s\(^{-1}\), slightly less than those of over 1.5 m s\(^{-1}\) in Beal and Bryden (1999). The difference is possibly due to the resolution, though the 10-km resolution around the Natal Bight is enough to resolve the mesoscale features such as the Natal pulses. It should be also noted that the Agulhas Undercurrent (Beal and Bryden 1999) is absent in the present model, which should flow northward along the shore at 1000 m or deeper. The absence of the undercurrent will be discussed in section 3b.

**b. Natal pulses**

Figure 4 shows evolution of a Natal pulse in the SSH field. The black arrow in each panel indicates the anticyclonic eddy that triggers the generation of the Natal pulses discussed later. On the 1200th and 1346th model days, the anticyclonic eddy is located in the Mozambique
Channel. The northern Agulhas Current flows along the coastline of South Africa without meandering at this time. On the 1406th day, the anticyclonic eddy reaches the Natal Bight and triggers generation of the Natal pulse, as has been reported in an observation (Schouten et al. 2002). On the 1426th day, the Natal pulse is located near East London. The Natal pulse has grown during its trip from the Natal Bight.

Figure 5a shows the vertical section near the Natal Bight on the 1346th day, when the anticyclonic eddy is located far upstream and the Agulhas Current flows near the shore. Note that the section is in the upstream of the section for time mean (Fig. 3a). Hence, the maximum of the flow speed is about 0.8 m s$^{-1}$, slightly less than the maximum speed shown in Fig. 3c. Other features are essentially the same as in the mean velocity section. On the 1406th model day, the Mozambique eddy exists near the Natal Bight (Fig. 4c), whose core is recognized as the depression of isopycnal contours (Fig. 5b). The maximum of the current speed shifts several tens of kilometers offshore compared to that on the 1346th day. The velocity takes negative value at shallow depths near the shore, showing the existence of a cyclonic circulation.
The bottom velocity decreases with depth and takes negative values below 1600 m, showing that the cyclonic anomaly of the pulse reaches deep levels. Although it is consistent with the observation (Lutjeharms et al. 2001), the northward flow in the deep part is possibly weaker than the reality. The northward flow is considered to be related to the Agulhas Undercurrent (Biastoch et al. 2009). They show that the substantial part of the transport of the Agulhas Undercurrent is attributed to the intermittent northward flow associated with the Natal pulse. The present model shows no Agulhas Undercurrent in the mean field, as shown in section 3a. Compared with a flow field of Natal pulse in Fig. 6e of Biastoch et al. (2009), the northward transport of our model is weaker, which might cause the absence of the Agulhas Undercurrent.

Figure 5c shows another section located near East London on the 1426th day, when the Natal pulse exists on the section. The velocity section shows that the core of the maximum velocity is about 150 km from the shore. Some of Natal pulses in reality are reported to reach 200 km in horizontal size (e.g., Pearce 1977; Bryden et al. 2005), and the pulses in the model have grown to a comparable size.

To describe the movement of the Natal pulses, a section is set along the east coast of South Africa, as shown in Fig. 6. Four points, P0–P3, on the section are also shown: P0 is the origin of the section, which is located at the exit of the Delagoa Bight; P1 and P2 are located just upstream and downstream of the Natal Bight, respectively; and P3 is more in the downstream, where the Natal pulses mature after their growth during the movement along the Agulhas Current.

FIG. 5. Snapshot of velocity (m s$^{-1}$) and potential density $\sigma_\text{u}$ for (a) the 1346th day on the section at the Natal Bight, (b) the 1406th day on the same section, and (c) the 1426th day on the section near East London. Shades and black contours are for the velocity component crossing the section, and the white contours are for the potential density.

FIG. 6. The section used for the space–time diagrams. Numbers in parentheses are the distances (km) on the points from the origin P0. The shade shows the depth of the sea floor (m).
In Fig. 7, the Natal pulses are detected as the negative anomalies. Figure 7a shows a space–time diagram of the SSH anomaly along the section in the fourth and fifth model years. As can be seen, many negative anomalies appear and move downstream at almost constant speeds. During these two years, 10 Natal pulses are detected, where the Natal pulses are defined as the cyclonic meanders with anomaly larger than −0.2 m at P3 and with anomaly that can be traced back to the upstream of P2. The frequency of five meanders per year is consistent with the observed frequency, four to five meanders per year (Schouten et al. 2002). The Natal pulse generated at the Natal Bight around 1400th model day in Fig. 7b corresponds to the pulse discussed at the beginning of this subsection. The speed of the Natal pulse is about 20 km day$^{-1}$ downstream of the Bight, corresponding to the observed speeds.

Note that the negative anomaly in Fig. 7b discussed earlier can be traced back to the upstream of the Natal Bight, though the amplitude is small and the moving speed is low compared to those in the downstream of the Natal Bight. In the horizontal SSH field, the negative anomaly accompanies the Mozambique eddy, which triggers the Natal pulse at the Natal Bight. Because of its small amplitude compared to the Mozambique eddy and because of its slow moving speed, the anomaly is less distinct than the Natal pulse in the downstream of the Natal Bight.

Note also that cyclonic meanders, which are different from the Natal pulses, appear in the model. In Fig. 7b, such a cyclonic meander is detected as the negative anomaly that exists at the 1400th day and 600 km from the origin. Although the amplitude and phase speed are similar to the Natal pulse discussed earlier, it is generated in the middle of the northern Agulhas Current (downstream of the Natal Bight). The cyclonic meanders are similar to the Natal pulses, except for the origin of the accompanying anticyclone. From the model SSH field, the anomaly is generated when an anticyclonic eddy that originated south of Madagascar reaches the South African coast (Fig. 4). Such a kind of cyclonic meander has not been observed, because eddies from south of Madagascar always merge with the Mozambique eddies (Schouten et al. 2002). However, the fact that eddies from south of Madagascar trigger the cyclonic meanders provides a hint of the generation mechanism of the Natal pulses, as will be discussed in section 4.

c. Energy conversion rate

To investigate the growth mechanism of the Natal pulse, the energy conversion mechanism from the mean to the perturbed field is investigated. Two energy conversion rates, the baroclinic (BC) energy conversion and the BT energy conversion, are evaluated and compared. The method of calculation for the energy conversion rates is similar to that in Tsujino et al. (2006). They calculated the conversion rates of isolated eddies moving along the Kuroshio. The phenomenon is quite similar to the Natal pulses. The derivation method of the energy conversion terms are described in the appendix.
The baroclinic conversion rate $T_{BC}$ is

$$T_{BC} = \frac{g}{\rho_0} \left( \frac{\partial \sigma_\theta}{\partial z} \right)^{-1} \left( \delta \rho' u' \frac{\partial \sigma}{\partial x} + \delta \rho' v' \frac{\partial \sigma}{\partial y} \right),$$

(1)

and the barotropic conversion rate $T_{BT}$ is

$$T_{BT} = -\left[ u'^2 \frac{\partial \sigma}{\partial x} + u'v' \left( \frac{\partial \sigma}{\partial y} + \frac{\partial \sigma}{\partial x} \right) + v'^2 \frac{\partial \sigma}{\partial y} \right],$$

(2)

where overbars denote time means, the primes denote perturbation from the mean values, $u$ and $v$ are the zonal and meridional velocities, $\rho$ is the in situ density, $\sigma_\theta$ is a horizontally averaged potential density as a reference, and $\rho_0$ is the constant reference density.

The time-mean field used in this analysis is calculated from the fourth and fifth model years (Fig. 8c). Though the Natal pulse events are included in the mean, the contribution of them to the mean is not large, so the mean field and hence the obtained energy conversion rates are acceptable for our purpose. The spatial distribution of BC and BT conversion rates, at the timing when the Natal pulse and the Mozambique eddy described in section 3b are located in the downstream of the Natal Bight, are shown in Figs. 8a,b, respectively.

The BC conversion rate exhibits quadruple structure around the anticyclonic eddy, whereas the most outstanding feature of the BT conversion rate is a large positive value between the Natal pulse and the anticyclonic eddy, where the flow directed to offshore. It indicates that the BT energy conversion occurs through the interaction of the mean flow field and the anticyclonic eddy.

To evaluate the contributions of those conversions, area-averaged conversion rates are calculated. Note that the aim is not to discuss the detailed energy budget but to qualify the relative importance of BC and BT conversion rates. Hence, the average is taken only in the area to the vicinity of the Natal pulse and the Mozambique eddy. A circular area with 200 km radius and centered 50 km east of the maximum of SSH of the Mozambique eddy is defined. The area covers the part containing large conversion rates, as can be seen in Fig. 8.

The vertical distributions of the area-averaged conversion rates are shown in Fig. 9a. The BC energy conversion rate takes both positive and negative values. The BT conversion rate has a large value near the surface, and it decreases as the depth increases. The BT conversion rate is positive everywhere and large compared to BC conversion rate; hence, the BT conversion makes the Natal pulse grow.

Then, the time series of BC and BT conversion rates are calculated (Fig. 9b). To obtain the time series, the rates are averaged within the area defined earlier and the depths between 4 and 1022 m, in which most of the conversion occurs. Both conversion rates are not large when the Mozambique eddy is located in upstream of the Natal Bight. The barotropic conversion rate begins to increase when the Mozambique eddy arrives at the Natal Bight on about the 1400th model day, and it keeps a high value as the Natal pulse goes downstream. On the other hand, the BC conversion rate takes a negative value while the Mozambique eddy flows along the coast of South Africa, suppressing the growth of the Natal pulse. The sum of the conversion rates is positive so that the Natal pulse grows as it flows along the South African Coast. Eventually, the total conversion rate turns into a negative value around the 1430th day. The Mozambique eddy is located near East London on that day and starts leaving the coastline. Thus, the negative conversion rate does not mean the decay of the Natal pulse.

d. Potential vorticity

To have another look of the generation and growth mechanism, the potential vorticity (PV) field is investigated. The PV of an isopycnal layer is defined as

$$q = \frac{f + \xi}{h},$$

(3)

where $q$ is the PV, $f$ the Coriolis parameter, $\xi$ is the relative vorticity, and $h$ is the thickness of the layer. The layer discussed here is between two potential density surfaces, $\sigma_\rho = 26.4$ and $\sigma_\rho = 26.6$. The layer is located in the depths of 200–400 m near the shore so that it is affected by the topography of the Natal Bight.

Before showing the result, the terminology on the PV used in the following is described. Because the sign of the Coriolis parameter $f$ is negative in the Agulhas Current system, PV at a place with small layer thickness $h$ takes a negative but large absolute value. Potential vorticity of large absolute value will be referred to as high hereafter to make the terms high and low correspond to cyclonic and anticyclonic, respectively, in the same way as those in the Northern Hemisphere.

Figure 10a shows that the anticyclonic eddy, which is described in section 3b, touches the coastline north of the Natal Bight. High PV exists along the shore where the anticyclonic eddy touches the coastline. The high PV is advected offshore along the isobaths of the layer. Because the layer thickness is large offshore, the vortex is stretched vertically and the high PV manifests itself there as a cyclonic meander: that is, the Natal pulse.

Figure 10b shows PV when the meander is advected to the downstream. The distribution of low potential vorticity can be described in a similar way to Fig. 10a.
found between Figs. 10a,b, despite of the difference of the bottom topography.

e. Effect of the topography in the Natal Bight

To explain the generation of the Natal pulse by the barotropic instability, de Ruijter et al. (1999) argue that the condition for the barotropic instability is readily satisfied in the place with a strong mean current speed (which implies strong shear) and a less steep bottom slope. The condition is not satisfied in the whole northern Agulhas Current but in the Natal Bight, which has a gentle slope compared to the other part of the northern Agulhas Current, if some perturbation enhances the flow speed there.

According to de Ruijter’s argument, the instability would be suppressed if the Natal Bight had as steep of a slope as the other part. Hence, a supplemental simulation is carried out to evaluate the effect of bottom topography of the Natal Bight. The topography of the model in the supplemental simulation is manipulated to make the slope steep in the Natal Bight as shown in Fig. 11b, whereas the other settings are left unchanged from what is described in section 2. Hereafter, the simulation whose results have been shown in sections 3a
and 3b is referred to as CTL, whereas the simulation with steep topography in the Natal Bight is referred to as TOPO. The Natal pulse should disappear, or at least the uniqueness of the Natal Bight should disappear in TOPO, according to de Ruijter’s argument.

Despite the steep slope in the Natal Bight, a Natal pulse is found in the sea surface velocity field (Fig. 12a) and is accompanied by a Mozambique eddy. During the fourth and fifth years of TOPO, nine Natal pulses, which are counted in the same way as in CTL, are detected (Fig. 12b). The speeds of the Natal pulses are about 20 km day\(^{-1}\) in the downstream of the Natal Bight (Fig. 12c). These features are quite similar to those in CTL. Moreover, the uniqueness of the Natal Bight does not disappear in TOPO.

The energy conversion rates for TOPO are also calculated. Figure 13a shows the time evolution of the baroclinic and barotropic energy conversion rates, which are

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**FIG. 9.** (a) Vertical distribution of the area-averaged energy conversion rates and (b) time series of the volume-averaged energy conversion rates.

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**FIG. 10.** PV \((10^{-6} \text{ m}^2 \text{ s}^{-1})\) of the layer between \(\sigma_\theta = 26.4\) and 26.6, when (a) the anticyclonic eddy locates off the Natal Bight and (b) the eddy locates in the downstream of the Natal Bight. The PV \(q\) is calculated as \(q = (f + \zeta)h\), where \(f\) is the Coriolis parameter, \(\zeta\) is the relative vorticity, and \(h\) is the thickness of the layer. Contours show the depth of the layer \(\sigma_\theta = 26.4\).

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**FIG. 11.** PV \((10^{-6} \text{ m}^2 \text{ s}^{-1})\) of the layer between \(\sigma_\theta = 26.4\) and 26.6, when (a) the anticyclonic eddy locates off the Natal Bight and (b) the eddy locates in the downstream of the Natal Bight. The PV \(q\) is calculated as \(q = (f + \zeta)h\), where \(f\) is the Coriolis parameter, \(\zeta\) is the relative vorticity, and \(h\) is the thickness of the layer. Contours show the depth of the layer \(\sigma_\theta = 26.4\).
calculated by integrating in the same circular area and the same depth range described in section 3c. The circumstance of the energy conversion in TOPO is the same as in CTL. The barotropic energy conversion is positive and large, whereas the baroclinic one is negative. Hence, generation and growth of the Natal pulse is caused by the barotropic instability, whereas the baroclinic energy conversion tends to suppress it. The potential vorticity field is also quite similar to that in CTL (Fig. 13b). High PV is located near the coastline, transported by the offshore flowing current of the Mozambique eddy, and then appears as a cyclonic eddy.

The analysis of the energy conversion rates and PV in TOPO shows that the generation and growth mechanism of the Natal pulse in TOPO is the same as that in CTL, regardless of the topography at the Natal Bight. What is important in the growth mechanism is the interaction between the western boundary current and the anticyclonic vorticity. The topography of the Natal Bight plays no role in this mechanism.

4. Summary and discussion

Eddy-resolving simulations of the Agulhas Current system are performed to simulate the Natal pulses. The resolution of the model is fine enough to reproduce the eddies observed around the Agulhas Current. Particularly, the Mozambique eddies are reproduced, and they trigger the generations of the Natal pulses. The Natal pulses in our model correspond to observed ones in terms of the generation frequency, advection speed, inception place, and size.

The energy conversion rate from the mean to eddy fields is calculated. The main conversion occurs through the barotropic conversion, which is consistent with de Ruijter et al. (1999). The analysis of the energy conversion rate and the potential vorticity shows that the generation and growth mechanism is controlled by the interaction of the mean field of the Agulhas Current and the offshoredward flow of the anticyclonic eddy (the Mozambique eddy). From the energy conversion analysis, the barotropic instability occurs. From the PV analysis, the high PV located near the shore is transported and fed to the Natal pulse.

The slope in the Natal Bight plays no role in the generation and growth mechanism, contrary to de Ruijter et al. (1999). This is supported by the supplemental calculation with steep topography in the Natal Bight, in which the Natal pulses are also reproduced as in the reference simulation.

The uniqueness of the Natal Bight is due not to its gentle bottom slope but to the fact that the Natal Bight is the place where the Mozambique eddy first meets the Agulhas Current. In the downstream of the Natal Bight, no anticyclonic eddy collides with the Agulhas Current so that no Natal pulse is generated. In the upstream of

FIG. 11. Bottom topography (m) around the Natal Bight of the runs (a) CTL and (b) TOPO. The contour levels are 200, 400, 600, 800, 1000, 2000, and 3000 m.
the Natal Bight, the Mozambique eddy does not interact with the Agulhas Current. As described in section 3b, a Mozambique eddy accompanies a weak negative SSH anomaly there, but the negative anomaly is not distinct and is not recognized as the Natal pulse because of the absence of the growth mechanism.

Another model feature also supports the fact that the slope in the Natal Bight plays no role in generation of the Natal pulse: eddies coming from the south of the Madagascar generate cycloic meanders. As described in section 3, such eddies merge with the Mozambique eddies before arriving at the coast of South Africa in the observations, but they reach the coastline in our model.

Although such eddies reach the Agulhas Current at the place with steep bottom slope, they trigger the generation of cycloic meanders.

Many simulations of the Agulhas Current have been carried out so far, but few simulations have successfully reproduced the Natal pulse. Needless to say, the grid size must be fine enough to resolve the Natal pulse. In addition to this, the absence of Mozambique eddies, because of either the lack of the Mozambique Channel in a simulation domain or insufficient horizontal resolution in the channel, also leads to the failure.

Recently, Biastoch et al. (2008) reported reproduction of the Natal pulses by using a nested-grid model. The
resolution around the Agulhas Current is about the same as the simulations presented in this paper. Another simulation in which the nested fine grid region does not cover the Mozambique Channel is performed to eliminate the Mozambique eddy. They find that no Natal pulse is reproduced in this case. Because their research is focused on how the mesoscale features affect the interocean exchange, they do not discuss behavior of the Natal pulse itself in detail. However, the Natal pulses reported in their paper seem to be consistent with our generation mechanism, as described earlier.

There seems to be no reason that a phenomenon such as the Natal pulse takes place only in the Agulhas Current. As discussed earlier, the generation and growth of the Natal pulse is due to the interaction of an anticyclonic eddy and a western boundary current. This situation seems not to be special in the Agulhas Current, but such a pulse is considered as a special phenomenon in the Agulhas Current.

The reason why such a phenomenon is not observed elsewhere could be stated as follows: Because the steep bottom topography strongly stabilizes the current, the Agulhas Current has a very stable path. The stable path makes a mesoscale meander distinguishable. Moreover, the Agulhas Current system has an eddy-active region, the Mozambique Channel, in its upstream. In other current systems, such regions exist but are usually located in the downstream. Hence, an anticyclonic eddy hardly reaches the western boundary current itself.

A phenomenon that is possibly similar to the Natal pulse is observed in the Kuroshio system. Tsujino et al. (2006) discussed the large meander of the Kuroshio. They describe the growth of a small meander, which is similar to the Natal pulse, to the large meander observed south of Japan. An anticyclonic eddy comes to the Kuroshio southeast of the Kyushu Island, which forms a pair consisting of a cyclone in the upper layer and an anticyclone in the lower layer. The pair is advected along the Kuroshio and grows as it moves; sometimes, the cyclone of the pair results in a large cyclonic meander south of Japan. They point out that the growth of the cyclone occurs through the process that the nearshore side high-PV water is transported to the offshore side. Though the baroclinicity is important in the case of Kuroshio, the growth mechanism of the cyclone is similar to that of the Natal pulse.

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APPENDIX

The Barotropic and Baroclinic Energy Conversion Rates

The barotropic and baroclinic energy conversion rates are derived on a quasigeostrophic (QG) assumption. Although it is marginally applicable to the western boundary current, the QG assumption is useful for diagnostic purposes.

By the QG assumption, the horizontal flow field can be decomposed into a leading-order geostrophic flow component \( \mathbf{u} \) and a small ageostrophic component \( \mathbf{u}_a \).
The leading-order balance of the horizontal component of the momentum equation is that of the geostrophic flow,

$$f_0 \dot{z} \times \mathbf{u} = \frac{1}{\rho_0} \nabla_h P,$$  \hspace{1cm} (A1)

where $f_0$ is the Coriolis parameter at a central latitude, $\dot{z}$ is the vertical unit vector, $\rho_0$ is the constant reference density, and $\nabla_h$ is the gradient operator applied in the horizontal plane. The density is decomposed into a depth-dependent background field $\rho$ and a varying field $\delta \rho$ as

$$\rho(x, y, z, t) = \rho_0(z) + \delta \rho(x, y, z, t).$$  \hspace{1cm} (A2)

Thus, the hydrostatic balance is written as

$$\frac{1}{\rho_0} \frac{\partial P}{\partial z} = -\frac{g \delta \rho}{\rho_0}.$$  \hspace{1cm} (A3)

On the QG assumption, the time evolution of the leading-order geostrophic flow $\mathbf{u}$ is described by the momentum, buoyancy, and continuity equations:

$$\frac{\partial \mathbf{u}}{\partial t} + \mathbf{u} \cdot \nabla \mathbf{u} + \beta y \dot{z} \times \mathbf{u} + f_0 \dot{z} \times \mathbf{u}_a = 0,$$  \hspace{1cm} (A4)

$$\frac{\partial \delta \rho}{\partial t} + \mathbf{u} \cdot \nabla \delta \rho + \mathbf{w} \cdot \frac{\partial \rho}{\partial z} = 0, \hspace{1cm} \text{and}$$  \hspace{1cm} (A5)

$$\nabla_h \cdot \mathbf{u}_a + \mathbf{w} \cdot \frac{\partial \rho}{\partial z} = 0.$$  \hspace{1cm} (A6)

Then, the fields are decomposed into two parts. One part is the time-independent basic state, which is denoted by overbars. The basic state corresponds to the unperturbed western boundary current. The other part is the perturbation (or eddy) field, which is denoted by primes. From (A4) and (A5), the time-independent basic state is assumed to satisfy the following equations:

$$\mathbf{u} \cdot \nabla_h \mathbf{u} + \beta y \dot{z} \times \mathbf{u} + f_0 \dot{z} \times \mathbf{u}_a = 0 \hspace{1cm} \text{and}$$  \hspace{1cm} (A7)

$$\mathbf{u} \cdot \nabla_h \delta \rho + \mathbf{w} \cdot \frac{\partial \rho}{\partial z} = 0.$$  \hspace{1cm} (A8)

From (A4) and (A7), the eddy momentum equation is given as

$$\frac{\partial \mathbf{u}'}{\partial t} + \mathbf{u} \cdot \dot{V}_h \mathbf{u}' + \mathbf{u} \cdot \dot{V}_h \mathbf{u} + \mathbf{u} \cdot \dot{V}_h \mathbf{u}' + \beta \dot{z} \times \mathbf{u}' + f_0 \dot{z} \times \mathbf{u}' = 0,$$  \hspace{1cm} (A9)

and from (A5) and (A8),

$$\frac{\partial \delta \rho'}{\partial t} + \mathbf{u} \cdot \dot{V}_h \delta \rho' + \mathbf{u} \cdot \delta \rho' + \mathbf{w} \cdot \frac{\partial \rho}{\partial z} = 0.$$  \hspace{1cm} (A10)

The hydrostatic Eq. (A3) is also rewritten as

$$\frac{1}{\rho_0} \frac{\partial P'}{\partial z} = -\frac{g \delta \rho'}{\rho_0}.$$  \hspace{1cm} (A11)

The eddy kinetic energy (EKE) and the eddy potential energy (EPE) are defined as

$$\text{EKE} = \frac{1}{2} |\mathbf{u}'|^2 \hspace{1cm} \text{and}$$  \hspace{1cm} (A12)

$$\text{EPE} = -\frac{g}{\rho_0} \left( \frac{\partial \delta \rho'}{\partial z} \right)^2.$$  \hspace{1cm} (A13)

Calculating $\mathbf{u} \times (A9)$ and $\mathbf{w} \times (A11)$ gives the equation of EKE,

$$\frac{\partial \text{EKE}}{\partial t} = -\left[ u' u' \frac{\partial \rho'}{\partial x} + u' v' \left( \frac{\partial \rho'}{\partial y} + \frac{\partial \rho}{\partial x} \right) + v' v' \frac{\partial \rho'}{\partial y} \right]$$

$$- u' \cdot \dot{V}_h \text{EKE} - v' \cdot \dot{V}_h \text{EKE} - \frac{1}{\rho_0} \dot{V}_h \cdot (P' \mathbf{u}')$$

$$- \frac{1}{\rho_0} \frac{\partial \mathbf{w}'}{\partial z} - gw' \delta \rho'.$$  \hspace{1cm} (A14)

The equation for EPE is given by multiplying $-g(\partial \sigma_0/\partial z)^{-1} \rho_0 \delta \rho'$ by Eq. (A10) as

$$\frac{\partial \text{EPE}}{\partial t} = g \left( \frac{\partial \sigma_0}{\partial z} \right)^{-1} u' \cdot \dot{V}_h \delta \rho' - u' \cdot \dot{V}_h \text{EPE} - v' \cdot \dot{V}_h \text{EPE}$$

$$+ gw' \delta \rho'.$$  \hspace{1cm} (A15)

Only two terms in the eddy energy Eqs. (A14) and (A15) are relevant to the energy conversion between the eddy and the mean; the other terms are understood as the transport of the eddy energies by the flow or by the pressure work or the conversion of the energy between EKE and EPE. One of the two eddy-mean energy conversion terms is the barotropic energy conversion $T_{BT}$,

$$T_{BT} = - \left[ u' u' \frac{\partial \rho'}{\partial x} + u' v' \left( \frac{\partial \rho'}{\partial y} + \frac{\partial \rho}{\partial x} \right) + v' v' \frac{\partial \rho'}{\partial y} \right],$$  \hspace{1cm} (A16)

and the other is the baroclinic energy conversion $T_{BC}$,

$$T_{BC} = g \left( \frac{\partial \sigma_0}{\partial z} \right)^{-1} \left( \delta \rho' u' \frac{\partial \rho'}{\partial x} + \delta \rho' v' \frac{\partial \rho'}{\partial y} \right).$$  \hspace{1cm} (A17)
REFERENCES


