GEOPHYSICAL RESEARCH LETTERS, VOL. 37, L04604, doi:10.1029/2009GL041950, 2010

A connection between the South Equatorial Current north of Madagascar and Mozambique Channel Eddies

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Received 27 November 2009; revised 7 January 2010; accepted 20 January 2010; published 26 February 2010.

[1] Combining high resolution model output and geostrophic currents derived from satellite altimeter data, it is shown that the formation of mesoscale eddies in the Mozambique Channel (MZC) is connected to variability in the transport of the South Equatorial Current (SEC). Lagged cross-correlations of the currents north of Madagascar and vorticities in the MZC, combined with a composite analysis of the model output, show that eddies form in the narrows of the channel approximately 20 weeks following a westward transport pulse in the SEC. A relationship between MZC eddies and the large-scale variability of the South Indian Ocean may have downstream impacts on the Agulhas leakage, the Atlantic Meridional overturning circulation, and thus climate. **Citation:** Backeberg, B. C., and C. J. C. Reason (2010), A connection between the South Equatorial Current north of Madagascar and Mozambique Channel Eddies, *Geophys. Res. Lett.*, *37*, L04604, doi:10.1029/2009GL041950.

1. Introduction

[2] Eddies with spatial scales of approximately 300–350 km dominate the flow regime in the MZC. Altimetry observations indicate that these eddies propagate southward at approximately 3–6 km.d^{-1}, and most modern eddy-resolving models are able to simulate their dimensions and drift reasonably well.

[3] It has been suggested that westward propagating Rossby waves, related to wind anomalies associated with the Indian Ocean Dipole cycle, affect the intensity of the mesoscale activity and the frequency of eddy occurrences in the channel [*Palastanga et al.*, 2006].

[4] Furthermore, mesoscale eddies originating in the MZC have been implicated in generating disturbances in the Agulhas Current that ultimately affect the Indo-Atlantic inter-ocean exchange south of Africa by triggering the shedding of Agulhas rings from the retroflection [e.g., *Schouten et al.*, 2002]. The Agulhas leakage is considered to play an important role in maintaining the Atlantic Ocean meridional overturning circulation and climate [*Peeters et al.*, 2004]. Therefore the thermohaline circulation, and hence climate variations, may be connected to large-scale modes of variability in the Indian Ocean, such as the Indian Ocean Dipole and El Niño Southern Oscillation.

[5] To date, the eddy formation mechanism in the MZC is not well explored. Observations from a current meter mooring array indicate MZC eddies form near the narrows of the channel at 16°S, subsequent to strong poleward currents [*Ridderinkhof and de Ruijter*, 2003]. Furthermore, it has been suggested that their formation is associated with barotropic instabilities of the SEC north of the MZC [e.g., *Biastoch and Krauss*, 1999], and the subsequent shedding of an eddy is due to the geometry of the narrows.

[6] The focus of this study is to analyse vorticity entering the MZC from the north, relating this to the variability observed in the SEC north of Madagascar and to show how it may contribute toward eddy formation in the channel.

2. Data and Methods

[7] An eddy resolving $\frac{1}{10}$th of a degree (10 × 10 km) Hybrid Coordinate Ocean Model (HYCOM) [*Bleck*, 2002] of the greater Agulhas Current system, with 30 vertical layers, and using a 4th order momentum advection scheme [*Backeberg et al.*, 2009] is used in this study. HYCOM combines the optimal features of isopycnic-coordinate and fixed-grid ocean circulation models in one framework. The adaptive (hybrid) vertical grid conveniently resolves regions of vertical density gradients, such as the thermocline and surface fronts.

[8] A detailed analysis and validation of the model has been documented by *Backeberg et al.* [2009]. In particular, the MZC eddies have been shown to be realistically represented in terms of their dimensions, the associated current velocities as well as their formation frequency.

[9] To complement the model results, gridded $\frac{1}{3}$rd of a degree surface geostrophic velocities derived from satellite altimetry sea surface height measurements combined with the mean dynamic topography from Rio05 [*Rio et al.*, 2005] are used. The data are available at weekly intervals from Aviso (www.aviso.oceanobs.com).

[10] To investigate the eddy formation process in the MZC, model vorticity was calculated from the gridded HYCOM current velocities at 10 m and compared with the vorticities derived from the Aviso surface geostrophic currents for the years 2001–2006. Vorticity was used because it describes mesoscale variability in the ocean, and positive values indicate anticyclonic rotation.

[11] A section was defined across the entrance of the channel at 11.5°S, extending from the northern tip of Madagascar westward toward the Mozambican coast at 41°E, then continuing southward along the coast to 14°S. Data along the section was extracted and interpolated to 10 km. The resulting Hovmöller plots of vorticity from HYCOM and Aviso for 2001–2006 along the defined section (Figure 1) show the westward propagation of predominantly positive vorticity features from the northern tip of Madagascar into the MZC.

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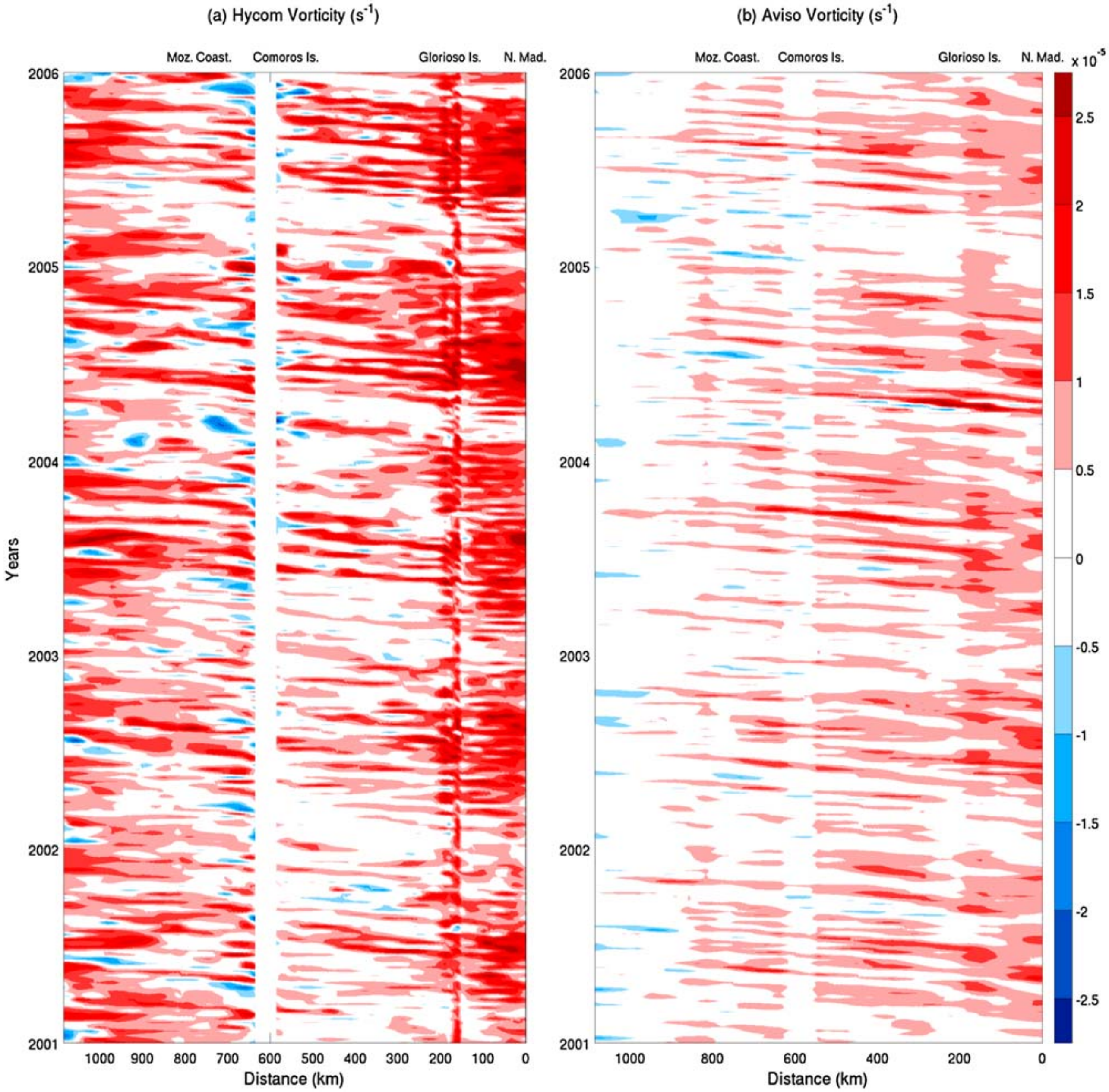

Figure 1. Hovmöller plot of vorticity (s^{-1}) for the section from the northern tip of Madagascar along 11.5°S to the Mozambican coast and southward along the coast to 14°S. The positions of the northern tip of Madagascar (0 km), the Glorioso Islands (~180 km), the Comoros Island (~600 km) and Mozambican coast (~800 km) are indicated at the top of each plot. The missing data in HYCOM and weak vorticities in Aviso at 600 km are due to the presence of the Comoros Islands in the extracted section.

[12] In order to relate the westward propagating vorticity signals evident in the Hovmöller plots to variability in the SEC north of Madagascar, an additional section was defined to extend from the northern tip of Madagascar to 11°S across which weekly transports were extracted from HYCOM (Figure 2a, solid line). The mean transport from this section in HYCOM for the years 2001–2006 is 33 ± 7 Sv (positive westward), which is in good agreement with the previous observational estimate of 27 ± 9 Sv derived from current meters [*Schott et al.*, 1988]. Also plotted in Figure 2a (dashed line) are the weekly vorticities from the first data point in the Hovmöller plot, located at 49°E, 11.5°S. Figure 2b shows the corresponding 5 month running mean of the transports and vorticities in HYCOM. The ECMWF inter-annual forcing used in the model has an anticyclonic wind stress curl anomaly between 2003 and 2006, which may account for the apparent trend in the HYCOM transports and vorticities (Figure 2b). For the Aviso geostrophic currents, weekly U velocities (positive westward) were extracted from the section north of Madagascar. These were averaged spatially along the section and plotted together with the weekly geostrophic vorticities at 49°E, 11.5°S (Figure 2c), and the corresponding 5 month running mean (Figure 2d).

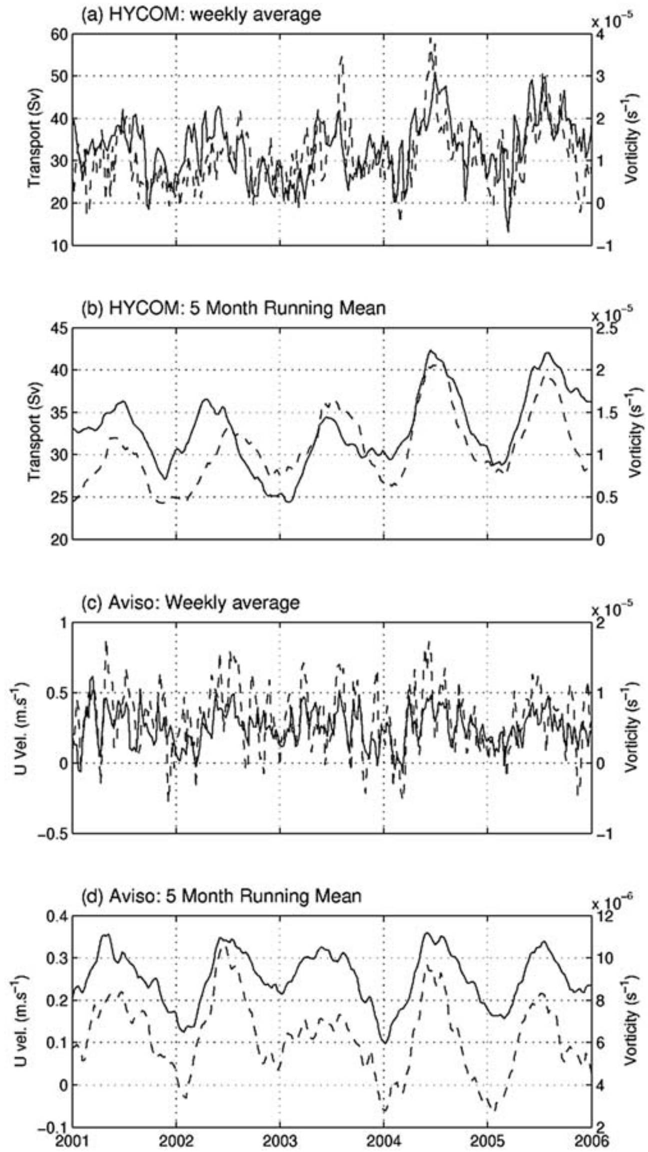

Figure 2. (a) Time series of weekly transports (Sv, solid line) from HYCOM for a section extending to 11°S from the northern tip of Madagascar, with weekly vorticity (s^{-1}; dashed line) for the first data point of the Hovmöller series (Figure 1a). (b) Corresponding 5 month running mean from HYCOM. (c) Weekly Aviso U velocities ($m.s^{-1}$; solid line) for the section north of Madagascar with weekly vorticity (s^{-1}; dashed line) for the first data point of the Hovmöller series (Figure 1b). (d) Corresponding 5 month running mean from the Aviso data.

[13] A lagged cross-correlation of the currents north of Madagascar and vorticity near the Mozambican coast provides an indication of the time-scale at which signals propagate across the entrance of the channel and into the narrows (Figure 3). Two locations along the Hovmöller plot near the Mozambican coast were selected: (1) where the Hovmöller section meets the Mozambican coast at 41.6°E, 11.5°S and (2) further south along the Hovmöller section near the narrows at 41.5°E, 13.9°S. The solid and dashed lines in Figure 3 indicate the cross-correlation sequences between the vorticities at the two locations in the channel and the HYCOM transports (Figure 3a) and Aviso U velocities (Figure 3b) north of Madagascar. A positive lag-correlation indicates that a positive vorticity signal occurs near the Mozambican coast following a westward transport pulse in the SEC north of Madagascar.

[14] To confirm that the formation of MZC eddies is related to such transport pulses, a composite analysis is performed. Weekly vorticity fields were calculated from the model, and the seasonal cycle removed. A region in the MZC between 41°–42.5°E and 15°–17°S was selected and the area average vorticity time series computed. From this time series, positive vorticity events exceeding the 95th percentile were selected to calculate the mean composite vorticity anomaly and corresponding currents (T_{-0}; Figure 4f). This represents the mean of the periods during which particularly strong eddies were simulated in the narrows of the MZC. Following this, composite maps of the weeks preceding these eddy events were calculated for T_{-20}, T_{-15}, T_{-9}, T_{-7} and T_{-5} weeks before T_{-0} (Figures 4a–4e, respectively).

3. Discussion and Conclusion

[15] Both the HYCOM and Aviso vorticity Hovmöller plots (Figure 1) clearly show positive vorticity signals propagating westward from the northern tip of Madagascar to the Mozambican coast. The predominantly positive vorticity is probably due to friction at the inshore edge of the SEC, which drives anticyclonic motion as it flows westward past the northern tip of Madagascar. This behaviour is similar, but in the opposite direction, to cyclonic motion occurring in the southern extension of the East Madagascar Current as it flows westward past the southern tip of Madagascar [*Siedler et al.*, 2009]. The vorticity signal in HYCOM is significantly stronger than observed in Aviso, due to the higher horizontal resolution of the model data.

[16] From the Hovmöller plots, the positive vorticity signals are estimated to propagate across the northern entrance of the MZC at approximately 5–9 $km.d^{-1}$ (HYCOM) and 6–10 $km.d^{-1}$ (Aviso), which is slower than estimated propagation velocities of Rossby waves at 12°S (16 $km.d^{-1}$) [*Heffner et al.*, 2008], but agrees well with the eddy propagation velocities calculated from satellite altimetry at these latitudes [*Chelton et al.*, 2007].

[17] In addition to the mesoscale pulsing, both the model and altimetry data show a strong seasonal cycle east of the Comoros Islands (Figure 1), with maximum (minimum) vorticities occurring in the austral winter to spring (summer to autumn) (Figures 2b and 2d). The model suggests there to be some evidence of seasonality on the Mozambican side of the channel, but it is weaker, and not at all apparent in the Aviso data product.

[18] The mesoscale signals propagating into the channel as well as their seasonal cycle seem to be related to variability at the same time-scales in the SEC north of Madagascar. Comparing the weekly transports and vorticities from HYCOM (Figure 2a), there is good correlation between the two data, $r = 0.48$ and statistically significant at the 95% confidence level. Similarly, the correlation coefficient between the Aviso U velocity and vorticity (Figure 2c) is 0.57, indicating that strong westward volume fluxes in the SEC north of Madagascar are quite often associated with

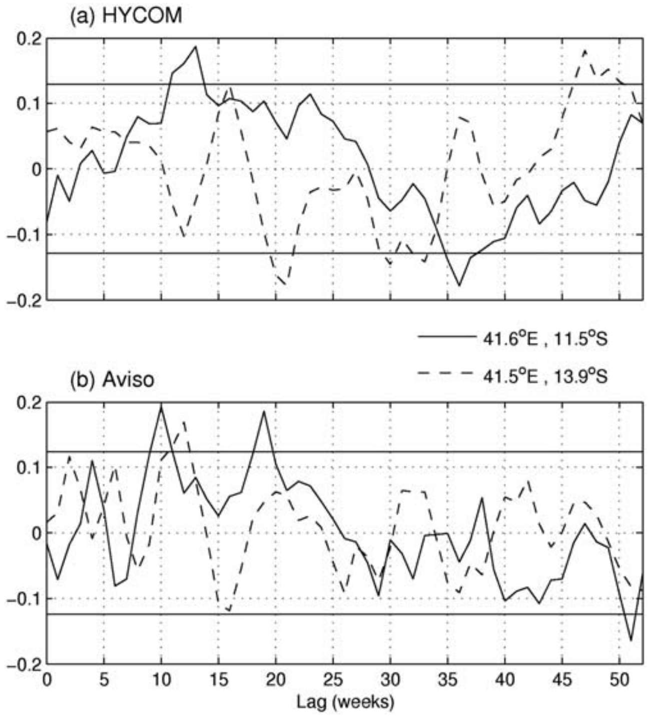

Figure 3. (a) Lagged cross-correlation sequence of HYCOM transports north of Madagascar and vorticity at 41.6°E, 11.5°S (solid line) and 41.5°E, 13.9°S (dashed line). (b) Lagged cross-correlation sequence of Aviso U velocities and vorticity for the same locations. The horizontal lines represent the 95 percentiles.

positive vorticity features which then propagate westward to the MZC.

[19] At the seasonal time-scale (Figures 2b and 2d), there is very close agreement between the westward transport fluctuations calculated in the SEC north of Madagascar and vorticity propagating toward the Mozambican coast. This agreement indicates that the seasonal cycle of the SEC is transmitted into the MZC, with maximum (minimum) currents and vorticity occurring during the austral winter (summer), and suggests that eddy formation in the MZC has a seasonal cycle, which has also been previously documented [*Hermes et al.*, 2007].

[20] The cross-correlation sequence of the transport in HYCOM north of Madagascar and the vorticity near the Mozambican coast (Figure 3a) at 41.6°E, 11.5°S (solid line) and 41.5°E, 13.9°S (dashed line) shows peaks at 13 and 16 weeks. These peaks are in relatively good agreement with the signal propagation velocity estimates from the Hovmöller analysis. The latter peak is however not statistically significant, indicating a weaker relationship between the transports of the SEC north of Madagascar and vorticity near the narrows of the channel.

[21] For the cross-correlation sequence of the Aviso U velocities and vorticity at the northern location near the Mozambican coast, statistically significant peaks are observed at 10 and 19 week lags, while for the southern location a statistically significant peak is observed at a lag of 12 weeks. These peaks are in good agreement with the signal propagation velocity estimates of 6–10 km.d^{-1}.

[22] Using both model and altimetry data, it is shown that positive vorticity features propagate into the MZC and that these are associated with transport fluctuations of the SEC north of Madagascar. Wavelet analyses of the currents north of Madagascar, and the vorticities in the narrows of the MZC (auxiliary material[1]) confirm that while the dominant mode of variability in the SEC north of Madagascar is seasonal, some higher frequency variability (~8 weeks) occurs north of Madagascar, which agrees with the eddy formation frequency of 6 yr^{-1} (about every 8 weeks) in the channel. Furthermore, the ~8 week periodicity of the SEC indicates that the 19 week lag of the Aviso data cross-correlation (Figure 3b) is due to the arrival of the next vorticity signal at the Mozambican coast.

[23] To identify the time-scale with which mesoscale pulses north of Madagascar transmit into the channel a composite analysis of the HYCOM current and vorticity fields was performed (Figure 4). It shows that 20 weeks prior to an eddy being formed in the narrows of the MZC, a positive vorticity anomaly extends westward from the northern tip of Madagascar (Figure 4a). Subsequently, 5 weeks later (T_{-15}, Figure 4b) the vorticity anomaly has moved westward toward the Mozambican coast with the background flow. Upon approaching the Comoros Island at 43.5°E, 11°S, coastal shear effects cause the vorticity anomaly to intensify and expand southwestward (T_{-9}, Figure 4c), and 13 weeks later (in agreement with the cross-correlation sequence) the vorticity anomaly reaches the Mozambican coast, where it acts to intensify the poleward currents (T_{-7}, Figure 4d). In the now enhanced poleward flow, conservation of potential vorticity generates additional anticyclonic flow curvature and serves to further intensify the positive vorticity anomaly (T_{-5}, Figure 4e), and an anticyclonic eddy begins to form. The poleward moving eddy experiences an increasingly negative f (Coriolis parameter) and thus, to conserve potential vorticity, its relative vorticity (ζ) must become increasingly positive (anticyclonic). We assume that the depth of the fluid is constant which is reasonable for the MZC. Between 14° and 16°S the magnitude of f and ζ increases by about 40%. This increase explains the intensification of MZC eddies in their southward passage toward the narrows (T_{-5} and T_{-0}, Figures 4e and 4f).

[24] In conclusion, combining output from an eddy resolving model and satellite altimetry data, it is shown that eddy formation in the MZC is related to variability of the SEC north of Madagascar and the increasing magnitudes of f and ζ, during the southward propagation of the positive vorticity anomaly. The model composite analysis indicates that eddies form in the channel approximately 20 weeks following a vorticity anomaly north of Madagascar associated with a strong westward transport pulse in the SEC. Also, a seasonal signal occurs in the channel and evolves downstream, accounting for the seasonal changes in the eddy activity previously noted.

[25] A connection between the large-scale variability of the Indian Ocean and MZC eddies is significant, because it implies a downstream connection to the Agulhas leakage, which is the main pathway through which warm, saline water, critical for maintaining the meridional overturning

[1]Auxiliary materials are available in the HTML. doi:10.1029/2009GL041950.

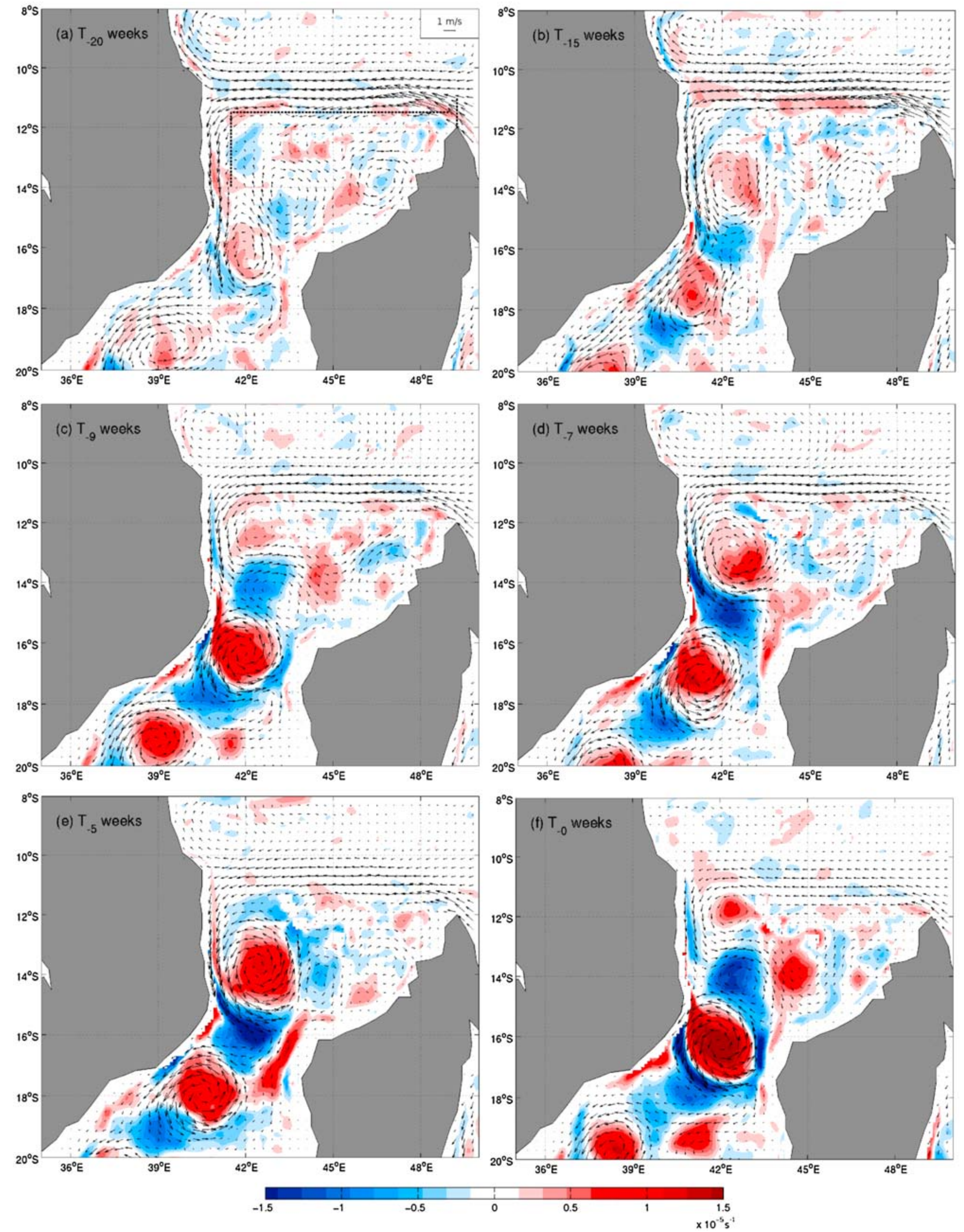

Figure 4. HYCOM vorticity (s^{-1}) and current ($m.s^{-1}$) composites for vorticity events in the narrows higher than the 95th percentile (T_{-0}; f). Composite maps of 20, 15, 9, 7 and 5 weeks before the events are included as (a) T_{-20}, (b) T_{-15}, (c) T_{-9}, T_{-7} and (d) T_{-5}. The dashed black lines in (a) indicate the coordinates of the sections along which data was extracted.

circulation, enters the South Atlantic Ocean. Thus interannual modes of variability such as the El Niño Southern Oscillation and the Indian Ocean Dipole may influence the thermohaline circulation and hence global climate in a different way to what is presently known.

[26] **Acknowledgments.** We would like to acknowledge the reviewers for their constructive review of our work. This work has been supported by the Mohn-Sverdrup Center for Global Ocean Studies and Operational Oceanography, through a private donation from Trond Mohn C/O Frank Mohn AS, Bergen, Norway, and the National Research Foundation, South Africa. CPU time came from the Norwegian Super-computing project, and the altimetry data came from Aviso.

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