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Key Points:
- The meridional flux of zonal momentum associated with intraseasonal variability acts to maintain lower frequency varying zonal currents in the equatorial ocean, in particular the equatorial deep jets
- The mechanism is demonstrated using both an idealized primitive equation model and using momentum fluxes computed from mooring data on, and either side of, the equator at 23°W in the Atlantic
- Analysis of the mooring data shows that the same mechanism also supports the seasonal cycle in the equatorial Atlantic Ocean

Supporting Information:
- Supporting Information S1

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Evidence for the Maintenance of Slowly Varying Equatorial Currents by Intraseasonal Variability

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Abstract Recent evidence from mooring data in the equatorial Atlantic reveals that semiannual and longer time scale ocean current variability is close to being resonant with equatorial basin modes. Here we show that intraseasonal variability, with time scales of tens of days, provides the energy to maintain these resonant basin modes against dissipation. The mechanism is analogous to that by which storm systems in the atmosphere act to maintain the atmospheric jet stream. We demonstrate the mechanism using an idealized model setup that exhibits equatorial deep jets. The results are supported by direct analysis of available mooring data from the equatorial Atlantic Ocean covering a depth range of several thousand meters. The analysis of the mooring data suggests that the same mechanism also helps maintain the seasonal variability.

1. Introduction

It has long been known that atmospheric Rossby waves associated with storm systems have their shape distorted by the jet stream in such a way as to feed momentum into the jet and support it against frictional and other dissipative processes (Eady, 1957; Marshall & Plumb, 2008; Starr, 1968). There is also evidence that such a mechanism operates in the ocean to maintain the Gulf Stream (Greatbatch et al., 2010; Wang et al., 2017; Webster, 1961). Intraseasonal waves in the equatorial oceans, with time scales of tens of days, are similar dynamically to atmospheric Rossby waves and therefore also have the potential to be distorted by zonal flows with longer time scales in such a way as to feed momentum into these zonal flows and maintain them against dissipation. It is also a remarkable feature of the variability in zonal currents in the equatorial Atlantic that, on a broad range of time scales from semiannual to interannual, this variability is close to being resonant with equatorial basin modes (Brandt et al., 2016; Claus et al., 2016; see Figure 1b and Thierry et al. (2004) for the semiannual cycle). Furthermore, being close to resonance, the forcing required to maintain the zonal current variability is relatively small (Claus et al., 2016) and convergence in the flux of momentum associated with the intraseasonal variability is a candidate for providing this forcing.

Aside from the annual and semiannual variabilities, the equatorial deep jets are the dominant feature of zonal flow variability below the upper few hundred meters of the equatorial Atlantic (see Figure 1; Brandt et al., 2011; Claus et al., 2016). The equatorial deep jets, which are found in all ocean basins (Youngs & Johnson, 2015), are vertically stacked zonal jets with zonal extent close to the basin scale, alternating in direction with depth along the equator, with, in the Atlantic Ocean, a time scale of close to 4.5 years and a vertical scale of between 300 and 700 m, corresponding to roughly the 16th vertical normal mode (Brandt et al., 2011; Claus et al., 2016). The jets are well described by the gravest resonant basin mode for the dominant vertical normal mode so that the time scale of 4.5 years corresponds to the time taken by an equatorial Kelvin wave to cross the basin from west to east and then be returned as a reflected long Rossby wave to the western boundary (Cane & Moore, 1981). Realistic ocean models have difficulty reproducing deep jets (Ascani et al., 2015; Eden & Dengler, 2008), although they are found in idealized nonlinear primitive equation model setups where they are also well described by an equatorial basin mode (Ascani et al., 2006, 2015; d'Orgeville et al., 2007; Matthießen et al., 2015, 2017). It has been shown that the forcing for the deep jets in one such simulation is through the meridional advection term in the zonal momentum equation, with the zonal advection term acting as an energy sink (Ascani et al., 2015). The forcing was shown to arise from the interaction of two intraseasonal Yanai waves, one with vertical scale much larger than that of the deep jets and one with a vertical scale that is roughly the same as that of the deep jets (Ascani et al., 2015). The exact nature of this forcing was,

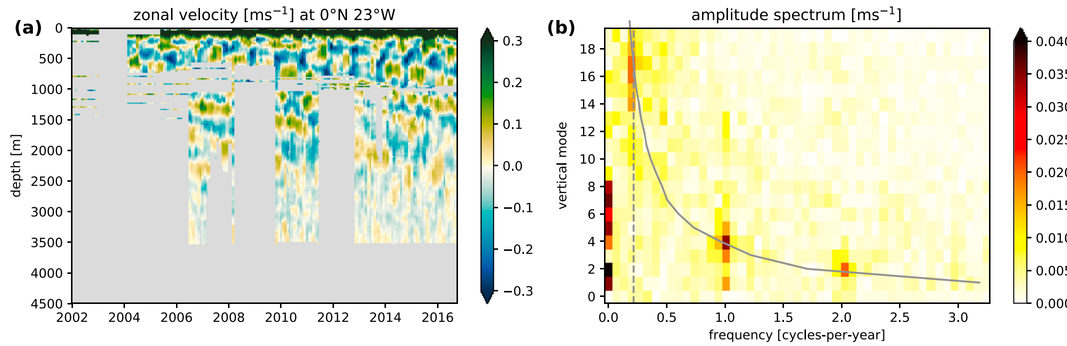

Figure 1. Zonal velocity from moored observations at 23°W on the equator. (a) Zonal velocity as measured using different instrumentation from 2002 to 2016 (see Brandt et al., 2011; Bunge et al., 2008; Claus et al., 2016). The labeling on the *x* axis indicates 1 January of the indicated year. (b) The amplitude spectrum of the zonal velocity shown in (a) for each vertical mode, as described in Claus et al. (2016), here also including the mean flow. The solid line marks the resonance frequency of the gravest equatorial basin mode, and the dashed line indicates a period of 1,691 days, corresponding to the deep jets, for which most of the energy is found around mode 16.

however, not explained, nor was it explained how the intraseasonal variability interacts with the deep jets to generate a wave with vertical scale the same as that of the deep jets.

It is instructive to start by thinking about an intraseasonal wave with a vertical scale comparable to the ocean depth. The simplest example is a barotropic wave for which the horizontal velocity components are vertically uniform. Such waves are known to exist in the equatorial ocean and to be excited by tropical instability waves near the surface (Farrar, 2011). Such a wave, having a large meridional scale, will interact with and be advected by the deep jets that have a smaller meridional scale. The horizontal structure of the wave is distorted by the deep jets in such a way that zonal momentum can be fluxed into the jets and used to maintain them against dissipation (see Figure 2). The flux of zonal momentum, $\overline{u'v'}$, where here the overbar denotes a low-pass filter, appears in equation (S3) in the supporting information, that is,

$$\frac{\partial \overline{u}}{\partial t} \approx -\frac{\partial\left(\overline{u'v'}\right)}{\partial y} - \frac{1}{\rho_0}\frac{\partial \overline{p}}{\partial x} + dissipation \tag{1}$$

and takes place meridionally, that is, toward the equator from the flanks of the jets (see the supporting information for the details), and can therefore appear as a forcing through the meridional advection term, as in the idealized model study of Ascani et al. (2015).

In section 2, we demonstrate the mechanism first using an idealized model setup, as in Ascani et al. (2015) and Matthießen et al. (2015, 2017), and then using mooring data from the equatorial Atlantic Ocean. The details of the model setup and also the treatment of the mooring data can be found in the supporting information. Section 3 provides a summary and discussion.

2. Results

The model is setup in an idealized configuration that is known to support deep jets (Ascani et al., 2006, 2015; Matthießen et al., 2015, 2017; see the supporting information for the details of the model setup). Starting from a state of rest and horizontally uniform density stratification, the model is spun-up using a time-independent wind stress field derived from observations. The model develops a mean wind-driven circulation, tropical instability waves near the surface, and deep jets at depth, as shown in Figure 3. Since the wind forcing is time independent, and since the model setup does not support a Deep Western Boundary Current (see d'Orgeville et al. (2007) and note that the Deep Western Boundary Current can be a source of intraseasonal variability in the equatorial oceans), the tropical instability waves are the only source of intraseasonal variability in the model (Ascani et al., 2015). Figure 4a shows the convergence of the meridional flux of intraseasonal zonal momentum, given by $-\frac{\partial\left(\overline{u'v'}\right)}{\partial y}$ in equation (1) above, superimposed on the time evolution of the deep jets at the point in the center of the model domain along the model equator. It can be seen that the

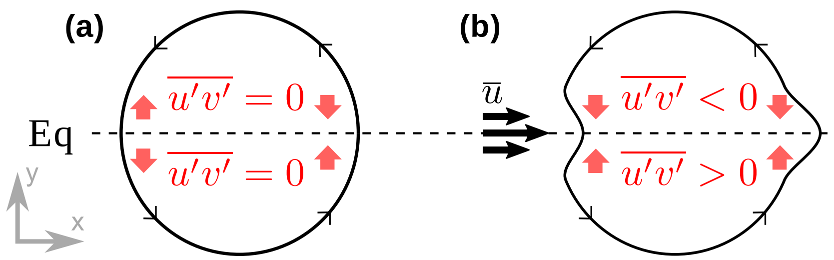

Figure 2. The distortion of intraseasonal waves by the deep jets shown schematically for the horizontal plane. An initially circular wave of large meridional scale, here shown to represent an intraseasonal Yanai or short Rossby wave, is distorted by a zonal jet (shown by the straight black arrows) of smaller meridional scale. Whereas in (a) there is no net flux of intraseasonal zonal momentum toward the equator, in (b) the distortion ensures a net flux of zonal momentum toward the equator that acts to support the jet.

convergence of the meridional flux of intraseasonal zonal momentum tends to be positive, thereby providing an eastward forcing, when the zonal jets flow eastward, and negative, thereby providing a westward forcing, when the zonal jets flow westward, as anticipated theoretically. This behavior is also seen in Figure 4b, where an independent estimate of the forcing for the jets is shown, as inferred by Claus et al. (2016) from the mooring data shown in Figure 1 using a linear multimode model (see Claus et al., 2016 for the details). The magnitude of the forcing shown in Figure 4b is comparable to that deduced from the

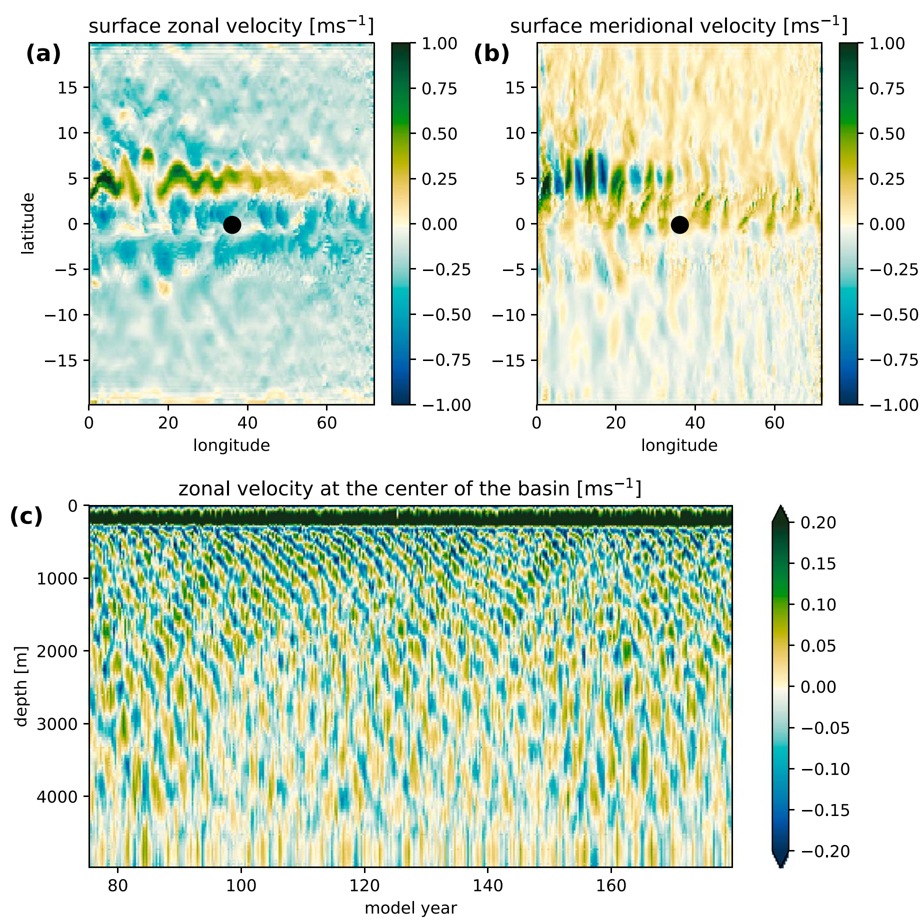

Figure 3. The velocity from the model run. The top panels show (a) a snapshot of the surface zonal velocity and (b) the surface meridional velocity. Note the meandering of the zonal currents, especially between the equator and 5°N, that is characteristic of tropical instability waves. These waves can also be seen in the alternating sign of the meridional velocity as a function of longitude. The tendency to have northward/southward surface velocity north/south of the equator is an indication of the surface Ekman transport due to the wind forcing. (c) A Hovmoeller diagram of the zonal velocity as a function of depth and time at the location on the equator of the black dot shown in (a) and (b). Note the downward propagating bands of eastward and westward velocity that are characteristic of the deep jets in the model. The band of strong eastward velocity in the top few hundred meters corresponds to the Equatorial Undercurrent.

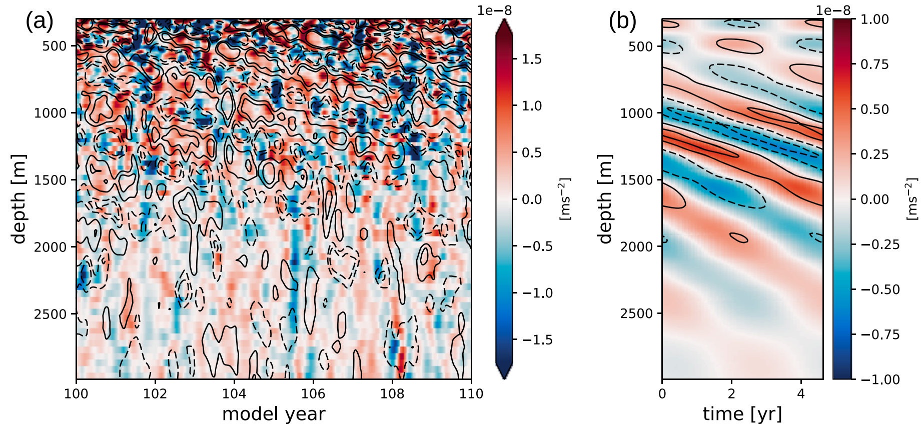

Figure 4. The forcing for the deep jets. (a) The color shading shows the convergence of the meridional flux of intraseasonal zonal momentum in the model at the point marked by the black dot in Figure 3 (see the supporting information for the details). The contours show the 70 day low-pass filtered zonal velocity at the same location, with the time mean removed, and with contours drawn at −0.1, −0.05, 0.05, and 0.1 ms^{-1}. Negative contours are dashed, while positive contours are solid. Note how the momentum forcing propagates downward with the jets and is such as to maintain the jets (red/blue shading generally coinciding with solid/dashed contours, respectively). (b) A reconstruction of the forcing for the deep jets derived from the mooring data shown in Figure 1, as described in Claus et al. (2016). The contours show the corresponding low-pass filtered zonal velocity as in (a) but here covering only one deep jet cycle. It should be noted that what is shown in (b) is a reconstruction, using a linear, multimode model, that is independent of the analysis used to produce Figure 5 and using only the mooring at the equator. As in (a), the forcing propagates downward with the jets and acts to maintain the jets at any given depth.

model (Figure 4a), although it should be remembered that the forcing shown in Figure 4b depends on the level of dissipation that is specified in the linear multimode model (the case shown here is for what Claus et al. (2016) argue is a realistic level of dissipation—see their Figure 5 for comparison with a weaker dissipation case). The relationship between the jets and the convergence of the momentum flux in the model is even more clearly shown in Figure 5 (blue line) where the positive regression slope over most of the depth range indicates that momentum is being fluxed into the deep jets by the intraseasonal variability.

We can also break down the convergence of the intraseasonal momentum flux in the model into its different wave constituents (Figure S1 in the supporting information), showing that not only barotropic ($m = 0$) waves are involved but actually, to good approximation, any two waves whose vertical mode numbers either add up to, or differ by, 14, the dominant vertical mode number associated with the deep jets in the model (see the supporting information for the details). The special case of a barotropic wave ($m = 0$) interacting with a wave of the same vertical scale as the deep jets ($n = 14$) is consistent with previous work (Ascani et al., 2015), where it was suggested that the wave with the vertical scale of the deep jets arises in situ as part of the interaction process. We can understand the generation of the second wave as being a consequence of the advection of an initially barotropic wave by the deep jets, analogous to Figure 2, but this time leading to a distortion in the vertical direction (see Figure S2).

Next we turn to the mooring data for confirmation from observations of the theoretical and modeling results described above. We are fortunate to have mooring data not only from the equator at 23°W but also from either side of the equator at 0.75°N and 0.75°S at 23°W (see Figure S3 for the data availability and note that below 1,000 m we only have a short period available [about 18 months in 2010 and 2011] to compute the convergence of the momentum flux and then only using the moorings on and to the south of the equator —see Figure S3D). The results are shown in Figure 5 and are found to be consistent with the model. In the upper few hundred meters, the negative regression slope indicates that the intraseasonal momentum flux is removing momentum from the Equatorial Undercurrent consistent with the generation of intraseasonal waves by barotropic instability (von Schuckmann et al., 2008). Lower down, the regression slope changes sign in both the estimate from observations and the model, indicating that momentum is being fluxed into the slowly varying flow (in particular, the deep jets) by the convergence of the meridional flux of intraseasonal zonal momentum. In the model, this picture holds all the way to the bottom, whereas in the observations, the sign of the regression slope changes below 2,000 m depth (see Table S1 in the supporting information). It is possible that the change in sign is related to the presence of the Mid-Atlantic Ridge (missing from the

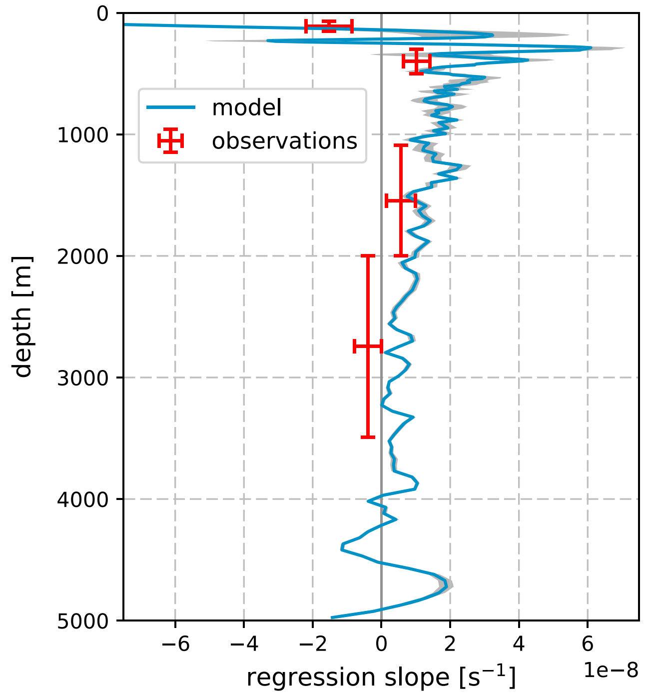

Figure 5. Regression of the convergence of the meridional flux of intraseasonal zonal momentum on the slowly varying zonal velocity at the equator. The blue line shows the regression slope from the model at the point in the center of the model domain shown by the black dot in Figure 3. The gray shading shows plus/minus the standard error for the regression slope computed, as described in the supporting information, following Bretherton et al. (1999). Also shown are the corresponding regression slopes estimated directly from the mooring data for the 70–150 m, 300–500 m, 1,090–2,000 m, and the 2,000–3,490 m depth ranges. See Table S1 for the details and note that, where possible, the difference between moorings north and south of the equator has been used to compute the convergence shown in the plot. The vertical error bars show the analyzed depth range, and the horizontal error bars show the standard error of the regression slope (see the supporting information for the details). Note that while a 20 day low-pass filter has been applied to the velocity components from the mooring data before the analysis (to remove tides, for example), no such filter has been applied to the model output. It should also be noted that below 1,000 m, only 1.5 years of mooring data are available and this only from the moorings on and to the south of the equator (see Figure S3D).

model which has a flat bottom) which extends up to 2,000 m depth at the equator. The change in sign of the regression slope across the Equatorial Undercurrent is consistent with earlier estimates of the momentum flux convergence from the upper 250 m at a location in the equatorial Pacific (Bryden & Brady, 1989) and also with an early indication of upgradient momentum fluxes in the upper water column of the equatorial Pacific (Lukas, 1987). The present study provides the first such estimates for the whole water column and for the equatorial Atlantic.

We noted earlier that, like the EDJs, the annual and semiannual cycles in the equatorial Atlantic Ocean are also associated with basin mode resonance (Brandt et al., 2016). The theory we developed above applies to any low frequency zonal current variability along the equator and so applies just as well to the seasonal cycle as to the deep jets. The positive regression slopes for the seasonal component shown in Table S1 support this conclusion and imply that the convergence of the meridional flux of intraseasonal zonal momentum acts to reinforce the seasonal cycle in the depth range 300–500 m. The forcing is of similar magnitude to that which supports the interannual variability. This offers a new insight into the dynamics of the seasonal cycle (Busalacchi & O'Brien, 1980; Philander & Pacanowski, 1984; Brandt et al., 2016). Not only is direct wind forcing important for the seasonal variability of zonal currents; there is also a role for the positive feedback from the convergence of the meridional flux of intraseasonal zonal momentum.

3. Summary and Discussion

We have shown that the convergence of the meridional flux of zonal momentum at the equator, which arises from the intraseasonal variability in the ocean, can maintain zonal jets in the ocean and, in particular, the equatorial deep jets in the Atlantic, and presumably in other ocean basins (Youngs & Johnson, 2015). The mechanism we have described supports the interpretation of the equatorial deep jets as a series of vertically stacked zonal jets, analogous to the jet stream in the atmosphere, each distorting the intraseasonal waves in such a way as to provide a positive feedback in which zonal momentum is fed into the jets in order to maintain them against dissipation. Since in the Atlantic, the deep jets, and also the annual and semiannual cycles, are close to resonance with equatorial basin modes, the required forcing from the convergence of the flux of intraseasonal zonal momentum is relatively weak compared to the forcing required to maintain variability that is not resonant (Claus et al., 2016). We have demonstrated the mechanism in an idealized model setup that supports deep jets and also using multiyear mooring time series from the equatorial Atlantic (Figure S3 shows the available data). For the deep ocean, below 1,000 m, we only have roughly 18 months of data and also only from moorings on and to the south of the equator. Nevertheless, the estimated convergence of the flux of intraseasonal zonal momentum onto the equator is consistent with theoretical expectations and with the model, except that below the summit of the Mid-Atlantic Ridge, there is a sign reversal in the flux convergence estimated from the moored data. We suggested that this is due to the presence of the Mid-Atlantic Ridge, missing from the flat-bottomed model setup. The mooring data also suggest that the convergence of the flux of intraseasonal zonal momentum at the equator plays a role in maintaining the annual and semiannual cycles in the tropical Atlantic Ocean.

The mechanism we have presented here can explain how the deep jets are maintained against dissipation, but it cannot explain their existence in the first place. Indeed, one important feature of the deep jets we have not discussed is their vertical scale and, in particular, how the vertical scale of the jets is selected. To answer these questions some additional theory is required. The most promising idea comes from noting that intraseasonal waves can be barotropically unstable and, in closed basin geometry, can break down into a series of stacked zonal flows resembling deep jets (d'Orgeville et al., 2007; Hua et al., 2008). An intraseasonal Yanai wave of relatively large vertical scale can also interact with a second intraseasonal Yanai wave and a longer period Kelvin wave, both of much shorter vertical scale, through a resonant triad interaction (Hua et al., 2008). This resonant triad mechanism somewhat resembles the mechanism identified in the idealized primitive equation model study of Ascani et al. (2015) and also the mechanism described here, as exemplified by Figure S1.

The failure of climate, and even high-resolution ocean models, to support the equatorial deep jets represents a serious shortcoming. One reason is that the deep jets are known to influence the atmosphere and hence are important for seasonal and interannual forecasting, in particular of rainfall in continental Africa, an issue of great socioeconomic importance (Brandt et al., 2011). Another is the role played by the deep jets and the neighboring zonal current system in transporting tracers such as oxygen along the equator from the western boundary (Brandt et al., 2012; Dietze & Löptien, 2013; Getzlaff & Dietze, 2013; Duteil et al., 2014) and in facilitating the transport of North Atlantic Deep Water, that is, the Atlantic Meridional Overturning Circulation, across the equator (Weiss et al., 1985; Gouriou et al., 2001; Eden, 2006). The insight we provide here into the dynamics of these jets is therefore of fundamental importance when considering how to improve realistic models used for climate projections and seasonal to interannual forecasting, for example, the model used by Scaife et al. (2014). Representing the deep jets in ocean models is a challenge for future research. Having deep jets in a model should also lead to an improvement in the representation of the neighboring flanking jets (Ascani et al., 2015). However, from what we have presented here, likely factors in the failure of realistic models to represent deep jets are (i) the complete lack of intraseasonal variability in the models due to a lack of horizontal resolution, (ii) inadequate vertical resolution in ocean models (a problem even with the current generation of models that have high horizontal resolution), and (iii) too weak intraseasonal wave energy in the models at depth, all topics for further investigation.

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