Role of Equatorial Basin-Mode Resonance for the Seasonal Variability of the Angola Current at 11°S

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ABSTRACT

Multiyear moored velocity observations of the Angola Current near 11°S reveal a weak southward mean flow superimposed by substantial intraseasonal to seasonal variability, including annual and semiannual cycles with distinct baroclinic structures. In the equatorial Atlantic these oscillations are associated with basin-mode resonances of the fourth and second baroclinic modes, respectively. Here, the role of basin-mode resonance and local forcing for the Angola Current seasonality is investigated. A suite of linear shallow-water models for the tropical Atlantic is employed, each model representing a single baroclinic mode forced at a specific period. The annually and semiannually oscillating forcing is given by 1) an idealized zonally uniform zonal forcing restricted to the equatorial band corresponding to a remote equatorial forcing or 2) realistic, spatially varying Fourier components of wind stress data that include local forcing off Angola, particularly alongshore winds. Model-computed modal amplitudes are scaled to match moored velocity observations from the equatorial Atlantic. The observed annual cycle of alongshore velocity at 11°S is well reproduced by the remote equatorial forcing. Including local forcing slightly improves the agreement between observed and simulated semiannual oscillations at 11°S compared to the purely equatorial forcing. However, the model-computed semiannual cycle lacks amplitude at middepth. This could be the result of either underestimating the strength of the second equatorial basin mode of the fourth baroclinic mode or other processes not accounted for in the shallow-water models. Overall, the findings underline the importance of large-scale linear equatorial wave dynamics for the seasonal variability of the boundary circulation off Angola.

1. Introduction

The Angola Current represents a major feature of the boundary circulation in the southeastern tropical Atlantic, connecting the equatorial Atlantic with the coastal upwelling systems of Angola and Benguela (Peterson and Stramma 1991; Rouault et al. 2007; Ostrowski et al. 2009). In the past, based exclusively on synoptic observations, the Angola Current had been assumed as a continuous poleward current, yet seasonally varying in strength, thereby advecting warm tropical waters southward (Moroshkin et al. 1970; Dias 1983a,b). Since July 2013, two current meters have been in place on the continental slope near 11°S to investigate both advective and coastally trapped wave (CTW) signals in the Angola Current (Kopte et al. 2017). These direct velocity observations revealed a strongly
variable alongshore flow in the depth range between 45 and 450 m with periodically alternating poleward and equatorward velocities in the range of ±40 cm s⁻¹ on submonthly to intraseasonal time scales. A weak southward mean flow was found in the upper 200 m, representing the Angola Current with core velocities of 8 cm s⁻¹ at about 50-m depth and an associated southward mean transport of 0.32 Sv (1 Sv = 10⁶ m³ s⁻¹; Kopte et al. 2017). Transport variability caused by the semiannual and annual harmonics was determined to be of the same order as the mean Angola Current transport. The Angola Current converges with the northward-flowing Benguela Current at about 16°S, where a sharp, yet highly variable, thermal front is formed known as the Angola–Benguela frontal zone (ABFZ; Meeuwis and Lutjehars 1990).

The ocean circulation off southwestern Africa is highly sensitive to equatorial wave dynamics. Eastward-propagating equatorial Kelvin waves (EKWs) are initiated by wind stress modulations in the equatorial Atlantic. Upon reaching the African coast, EKWs are reflected as westward-propagating Rossby waves. Additionally, part of the EKW energy is transmitted into poleward-propagating CTWs. Downwelling CTWs are associated with poleward intrusions of warm tropical waters across the ABFZ, eventually causing severe warm events in the northern Benguela (Florenchie et al. 2003; Lübbeke et al. 2010; Bachêlery et al. 2016). Owing to their similarities to the El Niño phenomenon in the Pacific Ocean, these intermittent warm events are referred to as Benguela Niños (Shannon et al. 1986) and are known to have a severe impact on the local marine ecosystem and rainfall variability, affecting both fishery and agricultural sectors of the neighboring countries (Gammelsrød et al. 1998). Based on regional modeling studies excluding the seasonal cycle in the analysis, Bachêlery et al. (2016) attributed intraseasonal variability in the upwelling system mainly to local forcing, which is in agreement with an observational study of submonthly to intraseasonal sea surface temperature (SST) variability in the central Benguela upwelling region (Goubanova et al. 2013). Nonetheless, continuous and recurrent propagation of EKWs and CTWs from intraseasonal (Polo et al. 2008) via seasonal (Schouten et al. 2005; Rouault 2012) to interannual time scales (Bachêlery et al. 2016) are well documented from satellite altimetry data. Passages of these waves also imply modulations of the Angola Current strength through thermocline displacements (Ostrowski et al. 2009). Likewise, in the Pacific, semiannual oscillations of the Peru–Chile Undercurrent in the south and the California Undercurrent in the north have been associated with the passage of semiannual CTWs that are induced by semiannual EKWs (Pizarro et al. 2002; Gómez-Valdivia et al. 2017). Thermocline displacements associated with CTWs have been verified as far south as 21°S off the coast of Chile (Ramos et al. 2006).

The main focus of the present study is the seasonal cycle of the Angola Current as observed by the moored current meters near 11°S. As the equatorial and coastal waveguides are well connected, a question to be addressed is whether the variability observed in the Angola Current is linked to equatorial Atlantic variability particularly on seasonal time scales. A large fraction of the observed variability in the equatorial Atlantic circulation is concentrated near resonance frequencies associated with equatorial basin modes (Claus et al. 2016; Brandt et al. 2016). Equatorial basin modes (Cane and Moore 1981) represent low-frequency standing equatorial modes in a zonally bounded basin and are composed of EKWs and long equatorial Rossby waves. While EKWs propagate eastward at a gravity wave speed associated with a particular baroclinic mode, long equatorial Rossby waves propagate westward at a speed 3 times slower than the corresponding EKW. Depending on the basin width $L$ and the gravity wave speed $c_n$ of the $n$th baroclinic mode, the resonance periods of the respective basin mode are given by $T_{n,m} = 4L/(m c_n)$, where $m$ is a positive integer, and $m = 1$ corresponds to the gravest basin mode, while $m = 2$ describes a second basin mode having one midbasin nodal point (e.g., Cane and Moore 1981; Han et al. 2011). Despite weak wind forcing at the semiannual time scale in the equatorial Atlantic, a considerable semiannual cycle in equatorial circulation is found, which is attributed to the gravest basin mode of the second baroclinic mode excited by the resonance of this mode with the semiannual wind forcing (Thierry et al. 2004; Ding et al. 2009; Brandt et al. 2016). Likewise, the resonance period of the gravest basin mode for the fourth baroclinic mode is very close to the annual period, indicating resonance of this baroclinic mode with the annual wind forcing (Brandt et al. 2016). On interannual time scales, equatorial zonal flow variability is dominated by equatorial deep jets (EDJs), and EDJs have been interpreted as equatorial basin modes for higher baroclinic modes (Ascani et al. 2006; d’Orgeville et al. 2007; Greatbatch et al. 2012; Claus et al. 2016).

The large-scale structure of the basin modes themselves, but also their role in exciting CTW propagation, suggests an impact of basin-mode-related dynamics on the boundary circulation off Angola. This topic is investigated in the present study by employing multimode shallow-water simulations to reconstruct the observed seasonality of the Angola Current. A decomposition of moored zonal velocity observations acquired at 0°, 23°W [Brandt et al., 2016] and at around 0°, 35°W [Send et al., 2002; Hormann and Brandt, 2009] into baroclinic modes is aimed to describe the gravest and second equatorial
basin modes. Furthermore, these observations provide valuable information to scale model-computed modal amplitudes for each baroclinic mode at annual and semianual frequencies.

The paper is organized as follows: In section 2, the observational datasets used in this study are introduced, while section 3 briefly describes an ocean general circulation model that will be compared to both observations and shallow-water model simulations. Section 4 introduces the basic equations, setup, and forcing of the shallow-water model experiments. Section 5 is devoted to the model validation and baroclinic-mode analysis in the equatorial band. In section 6, observed and simulated annual and semianual cycles at 11°S off Angola (hereinafter described as 11°S–Angola) will be compared for various model experiments to examine the role of equatorial and local forcing for the seasonality of the Angola Current. A summary with a discussion of the results is presented in section 7.

2. Observational data

Off Angola, direct velocity observations are available from two successive deployment periods of an ADCP mooring from July 2013 to October 2016 (Fig. 1). For each deployment, the mooring was located on the continental slope at ~1200-m water depth (10°50.0′S, 13°00.0′E), constituting the offshore component of a mooring array monitoring the boundary current flow off Angola (Kopte et al. 2017). The inshore component, a bottom shield deployed at ~500-m depth (10°42.7′S, 13°11.0′E), was lost during the second deployment period presumably caused by fishing activities. Therefore, in the following we primarily use ADCP data from the offshore mooring for a more robust description of the seasonality in the alongshore flow. The mooring configuration was identical during both deployment periods. An upward-looking 75-kHz Teledyne RDI’s Workhorse Long Ranger ADCP was mounted to the mooring cable at 500-m depth. The instrument measured velocity in the water column up to about 45 m below the sea surface with a vertical resolution defined by a 16-m bin size.

As a proxy for near-surface velocities we use the delayed-time multimission (all-sat-merged) product of absolute geostrophic velocities from AVISO. The dataset is provided with daily resolution on a 0.25° × 0.25° grid [details on the mapping algorithm of the altimetric observations can be found in Pujol et al. (2016)]. The data are distributed by the EU Copernicus Marine Service Information (http://marine.copernicus.eu/). We extract the velocity time series from the closest data point (10°52.5′S, 13°07.5′E) to the mooring position (Fig. 1).

Additionally, for this study we make use of the ocean velocity time series acquired along the equator at 23° and 35°W. The 0°, 23°W time series comprises a multiyear record of equatorial zonal velocity obtained from current meters deployed between 2004 and 2016. Merging nine successive deployment periods, this product is an updated version of the one presented in Brandt et al. (2016). It is composed of moored ADCPs profiling the upper 600–900 m of the water column, a few single-point current meters between 600- and 1000-m depth, as well as a McLane Moored Profiler (MMP) sampling between 1000- and 3500-m depth [for further details on the mooring setup see Brandt et al. (2016)]. The time series used here also incorporates lowered ADCP profiles taken during the mooring service cruises near the mooring position. Significantly fewer measurements are available at 0°, 35°W. Here, the merged time series of zonal velocity contains moored ADCP data covering the upper 550-m depth between August 2004 and June 2006 (Hormann and Brandt 2009) as well as data from three single-point current meters deployed at 652-, 809-, and 1107-m depth during the
same period. Furthermore, deep velocity data are available at 0°, 36°W, recorded by four single-point current meters at 1290-, 1490-, 1690-, and 1890-m depth between October 1992 and June 1994, that previously have been used to study the space–time structure of the EDJs (Send et al. 2002) and that are incorporated into the 35°W dataset. To improve the vertical coverage, we incorporate nine lowered ADCP as well as eight Pegasus profiles that were acquired between 1°N and 1°S at 35°W during several cruises and cover the seasonal cycle.

A 40-h low-pass filter was applied to all available ADCP data (temporal resolution ranging from 2 to 8 h) as well as to single-point current meter data (temporal resolution of 2 h) to eliminate tidal currents. The MMP executed two successive profiles, an upcast followed by a downcast, every 4 or 6 days, with the two profiles separated by 6 h. Here, no temporal filter was applied.

Finally, ADCP data from 11°S–Angola were linearly interpolated on a 1 day × 5 m grid, while the velocity data acquired by different instrument types at 0°, 23°W and 0°, 35°W were gridded onto a regular 15 day × 10 m grid. Note the different total lengths of the velocity time series obtained at the mooring locations, with the 0°, 23°W mooring providing at least 5 years of zonal velocity data covering the whole water column and the 11°S–Angola mooring yielding about 3 years of boundary current observations, while at 0°, 35°W about 2 years of zonal velocity observations are available at distinct depth levels (Fig. 2).

3. Ocean general circulation model TRATL01

For comparison with the observations and the shallow-water model experiments, we use the fully forced dynamical ocean general circulation model (OGCM) TRATL01 (Duteil et al. 2014). TRATL01 constitutes a 0.1° resolution nest between 30°S and 30°N in the Atlantic Ocean that is embedded in a global ORCA05 configuration at 0.5° resolution via two-way nesting (Debreu and Blayo 2008). The configuration is forced by interannually varying atmospheric data provided by the Co-ordinated Ocean–Ice Reference Experiments (CORE), version 2, reanalysis data (Griffies et al. 2009) over the period 1948–2007.

4. Shallow-water model simulations

To examine the role of remote equatorial versus local forcing as well as the potential impact of equatorial basin modes on the seasonality of the boundary circulation as observed at 11°S–Angola, we employ a suite of linear shallow-water models, each model representing the solution for a single baroclinic mode (e.g., Gill 1982).
directions, respectively, where \( \eta \) represents the isopycnal displacement. The term \( H_E \) is a depth scale for the surface Ekman layer. The term \((F^u, F^v)\) is the lateral mixing of momentum given by

\[
F^u = \frac{A_h}{\alpha^2} \left[ \frac{1}{\cos^2 \theta} \frac{\partial^2 u}{\partial \lambda^2} + \frac{1}{\cos \theta} \frac{\partial}{\partial \theta} \left( \cos \theta \frac{\partial u}{\partial \theta} \right) \right]
+ u(1 - \tan^2 \theta) - \frac{2 \sin \theta}{\cos^2 \theta} \frac{\partial u}{\partial \lambda}, \quad \text{and} \quad (4)
\]

\[
F^v = \frac{A_h}{\alpha^2} \left[ \frac{1}{\cos^2 \theta} \frac{\partial^2 v}{\partial \lambda^2} + \frac{1}{\cos \theta} \frac{\partial}{\partial \theta} \left( \cos \theta \frac{\partial v}{\partial \theta} \right) \right]
+ v(1 - \tan^2 \theta) - \frac{2 \sin \theta}{\cos^2 \theta} \frac{\partial v}{\partial \lambda}, \quad (5)
\]

where \( A_h \) is the horizontal eddy viscosity coefficient. Furthermore, \( H_n \) is the equivalent depth set by the wave speed \( c_n = \sqrt{gH_n} \) associated with baroclinic mode \( n \). The term \((\tau^p_x, \tau^p_y)\) represents the surface wind stress vector that acts as a body force with \( G_n \) representing the wind stress projection coefficient for each baroclinic mode. Choosing an approach similar to Zhu et al. (2017), we first solve the equations for \( G_n = 1 \) and then obtain realistic projection coefficients by fitting model-computed modal amplitudes to modal amplitudes derived from observed velocities at \( 0^\circ, 23^\circ W \) (see section 5a and section 5c).

b. Model setup and forcing

We set up a model domain for the Atlantic Ocean extending from \( 60^\circ W \) to \( 15^\circ E \) in the zonal and from \( 34^\circ S \) to \( 25^\circ N \) in the meridional direction. The 1000-m isobath represents the coastline. Both model boundaries and coastlines are treated as solid vertical walls. Along the northern and southern boundaries of the model domain sponge layers with \( e \)-folding scale of \( 2.5^\circ \) latitude are applied to inhibit Kelvin wave propagation. The model has a horizontal resolution of \( 0.25^\circ \) both in longitude and latitude. The scale depth \( H_E \) is chosen to be 500 m, which is an arbitrary choice, as the actual value of \( H_E \) will only affect the scaling factor \( G_n \) in the fitting procedure. Lateral eddy viscosity is set to \( A_h = 300 \text{ m}^2 \text{s}^{-1} \) (Claus et al. 2014; Brandt et al. 2016).

Model simulations are carried out with varying gravity wave speeds representing the first five baroclinic modes.

Either annually or semiannually oscillating forcing is applied to the momentum equations with each shallow-water model being run for 11 years, which is sufficient for the model to reach equilibrium near the equator. The oscillating solution of the eleventh integration year is stored for further analysis. To distinguish between the role of the equatorial forcing that eventually excites resonant equatorial basin modes and the role of local forcing off Angola, we carry out two sets of simulations that differ in the applied forcing.

In the first set of model simulations, the forcing is derived from oscillating wind stress (including both the zonal and meridional components) applied to the entire model domain. These runs therefore include the equatorial forcing (EF), potentially exciting equatorial basin modes as well as any local forcing (LF) that might be relevant at \( 11^\circ S \)-Angola (hereinafter referred to as EF + LF). Equivalent runs are carried out using four different wind products with differing horizontal resolutions (Table 1). For consistency, annual and semiannual wind stress cycles are calculated from wind stress data between March 2007 and June 2016 for each wind product.

In a second set of simulations, the model is forced by a zonally uniform zonal forcing oscillating at either annual or semiannual frequency and restricted to the equatorial band (hereinafter referred to as EF-only). Following Greatbatch et al. (2012), the forcing \( [\tau^p_x \text{ in Eq. (1)}] \) is given by

\[
\tau^p_x = X_\beta e^{-(\beta y/\Delta \phi)} \sin(\omega t), \quad (6)
\]

where \( y = a \theta, \beta = 2.3 \times 10^{-11} \text{ m}^{-1} \text{s}^{-1} \) is the meridional gradient of \( f \) at the equator, \( \omega = 2\pi/T_B \) is the forcing frequency with \( T_B \) being either the annual or semiannual period and \( X_\beta \) being the amplitude. The results are independent of the choice of the amplitude, as the model-computed modal amplitudes (as well as the phases) from the EF-only runs are adjusted to reach agreement with the EF + LF runs at \( 23^\circ W \)-equator. By excluding the local forcing at the eastern boundary, the EF-only runs assist in evaluating the relative importance of remote equatorial and local forcing for the seasonality of the eastern boundary circulation off Angola.
5. Baroclinic-mode analysis and model validation in the equatorial band

a. Modal decomposition of observed zonal velocity at the equator

As noted in section 4a, the projection coefficients $G_n$ are not assumed a priori but remain to be determined through the fitting of model-computed modal amplitudes to modal amplitudes derived from the time series of top-to-bottom zonal velocity at 23°W–equator. The mooring location at 23°W–equator appears advantageous for estimating the amplitudes of the gravest basin modes (Brandt et al. 2016). Here, we use the vertical structure functions $\hat{p}_n(z)$ of the first five baroclinic modes representing a subset of those derived by Claus et al. (2016) for an ocean depth of $H = 4500$ m (Fig. 3a).

They were calculated from a mean buoyancy frequency profile obtained from 47 shipboard CTD profiles acquired near 23°W–equator during the mooring service cruises. The structure functions of the low baroclinic modes change only marginally when taking into account the variability about the mean buoyancy frequency profile. Note that the structure functions have been normalized so that $(1/H) \int_{-H}^{H} \hat{p}_n(z)^2 \, dz = 1$.

The modal decomposition of observed zonal velocity at 23°W–equator is carried out by consecutively projecting the vertical structures associated with one particular baroclinic mode (Fig. 3a) multiplied with either the annual or semiannual cycle onto the velocity time series. As the time series contains some gaps, particularly at deeper levels, the orthogonality of the projected modes is not ensured. Therefore, the first 20 baroclinic
modes are fitted in random order with the resulting contribution of the corresponding baroclinic mode being subtracted from the velocity signal before fitting the next mode. Repeating this procedure for 10,000 random permutations of the fitting order yields estimates of the most probable mode energies and phases and associated uncertainties (Fig. 3b). To test the robustness, particularly with regard to the phase distribution, the modal decomposition is carried out once for annual and semiannual components derived using the total length of the time series and once using only the 2013–16 period, with the latter corresponding to the mooring observation period at 11°S–Angola. We note the dominance of the fourth baroclinic mode for the annual cycle and the second baroclinic mode for the semiannual cycle as discussed by Brandt et al. (2016) but also the stability of these modes in terms of energy and phase lock when comparing results from different observation periods (Fig. 3b). However, a relative increase of the energy associated with the third and fourth baroclinic mode for the annual cycle of up to 25% is found when considering the 2013–16 period, while the phases remain unchanged. Here, an anomalously deep-reaching Equatorial Undercurrent (EUC) during the second half of 2015 (not shown) most likely results in an enhanced projection of the annual cycle onto these modes. For the semiannual cycle of the second baroclinic mode, the energy varies by about 20% for the limited period relative to the value obtained for the full time series, while the phase stays within less than 8 days. Nevertheless, overall we find a consistent mode energy-phase distribution for both annual and semiannual cycles derived using different reference periods.

A similar study conducted in the Indian Ocean (Han et al. 2011) has indicated the potential importance of second basin modes, which are characterized by a nodal point in the midbasin. In the Atlantic, 0°, 23°W is located in the proximity of this amplitude minimum, which complicates the description of a second basin mode based on velocity data from 0°, 23°W. Therefore, the modal decomposition is also carried out for the velocity time series acquired at 0°, 35°W (Fig. 3c). As the latter is limited both in temporal and vertical coverage, the modal characteristics are determined for the first five baroclinic modes only, based on 120 random permutations of the fitting order. Similar to 0°, 23°W, the fourth and second baroclinic modes are found to be dominating the annual and semiannual cycle, respectively. Interestingly, at 0°, 35°W the second baroclinic mode at the semiannual period exhibits the highest energy, while the dominance of the fourth baroclinic mode at the annual period seems not as striking as at 0°, 23°W. However, given the comparably sparse sampling, particularly of the deep ocean, uncertainties of derived amplitudes and phases are substantially larger at 35°W than at 23°W (Figs. 3b,c).

b. Adjustment of prescribed gravity wave speeds in shallow-water model experiments

As a starting point for the shallow-water model experiments, a first realization of simulations driven by JRA-55 wind stress data (Japan Meteorological Agency 2013) was obtained using gravity wave speeds as in Brandt et al. (2016; Table 2). We then carried out five sensitivity experiments for each baroclinic mode by slightly modifying the prescribed phase speeds, aiming at improving the agreement between observed and model-computed modal phases at 0°, 23°W (Fig. 4; Table 2). Note that $G_n = 1$ for the sensitivity experiments, as the choice of the wind projection coefficients does not influence the model-computed modal phases. The approach of adjusting prescribed gravity wave speeds is justified, as several factors not accounted for in the linear shallow-water model might affect the gravity wave speed, such as background mean flow and nonlinear effects. Moreover, the gravity wave speed is treated as being constant across the basin by our model—a simplification that cannot be met in reality because of large-scale changes in stratification and mean flow. Gravity wave speeds for the first and fifth baroclinic mode remain unchanged. An improved agreement of observed and model-computed semiannual cycle is found for the second baroclinic mode when increasing the gravity wave speed by 0.11 m s$^{-1}$ and for third baroclinic mode when decreasing the gravity wave speed by 0.06 m s$^{-1}$. These adjustments only marginally change the phase differences for the corresponding annual cycles. Likewise, decreasing the gravity wave speed of the fourth baroclinic mode by 0.06 m s$^{-1}$ minimizes the phase difference for the annual cycle (Fig. 4).

c. Scaling of model-computed modal amplitudes and choice of wind-forcing product

Oscillation amplitudes obtained from the modal decompositions at 0°, 23°W (section 5a) are now used to
quantify the wind stress projection coefficients $G_n$ separately for annual and semiannual oscillations. The term $G_n$ is determined as the ratio of modal amplitudes of the zonal velocity derived from observations and the corresponding model-computed modal amplitudes from the EF + LF runs at $0^\circ$, $23^\circ W$. While model-computed modal amplitudes are scaled, modal phases are determined solely by the model, that is, are not fitted to match the observed modal phases at $0^\circ$, $23^\circ W$.

A set of equivalent EF + LF shallow-water model simulations is carried out, differing only by the applied wind-forcing product (Table 1) in order to assess the dependency of the model runs on the chosen forcing product to reproduce the seasonal cycle of zonal velocity along the equator. The derived wind stress projection coefficients $G_n$, which correspond to the scaling factor for model-computed modal amplitudes, provide a measure on how much energy input is needed to reproduce observed amplitudes of annual and semiannual oscillations. Therefore, $G_n$ is not only a function of the wind energy input but also depends critically on how realistically the model reproduces the resonance characteristics (see also Greatbatch et al. 2012; Brandt et al. 2016). The latter depend on several parameters of the model configuration such as basin geometry, dissipation, and gravity wave speeds. A comparison of wind stress projection coefficients depending on the wind-forcing product and the oscillation period does reveal a clustering for coefficients derived from scaling model-computed modal amplitudes at $0^\circ$, $23^\circ W$ for similar baroclinic modes and oscillation periods (Fig. 5a). In general, there is only a weak dependence on the chosen forcing product. However, some larger differences between the products for particular baroclinic modes should be noted. For example, the coefficients for the second baroclinic mode, annual cycle, or the fourth baroclinic mode, semiannual cycle, associated with ERA-Interim forcing are about a factor of 3 smaller or larger compared to the corresponding coefficients associated with the other forcing products. This means that a different energy input is necessary to reproduce the observed amplitudes for the corresponding baroclinic modes when forcing the model with oscillating wind stress derived from ERA-Interim compared to the other wind products. As our EF + LF model simulations differ only in the applied wind forcing, the findings demonstrate the uncertainties in the representation of specific aspects of the equatorial Atlantic circulation when forcing ocean models with one particular wind-forcing product. Similar projection coefficients are derived from scaling model-computed modal amplitudes at $0^\circ$, $35^\circ W$, which can differ significantly from their counterparts at $0^\circ$, $23^\circ W$ (Fig. 5a). These differences might result partly from the less robust modal decomposition at $0^\circ$, $35^\circ W$ and, in case of the gravest basin mode, from the mooring being located in an area of strongly changing and lower modal amplitudes (Figs. 8, 13 (shown below)).

Model-computed phases from EF + LF runs are not fitted to observations. Therefore, the difference of observed and simulated phases represents another indicator of how well the models are able to reproduce observed annual and semiannual oscillations locally at $0^\circ$, $23^\circ W$, depending on the applied wind-forcing product (Fig. 5b). Again, concerning the phase differences only minor dependencies on the applied wind forcing are found at least for baroclinic modes with significant energy at $0^\circ$, $23^\circ W$ (cf. Fig. 3b). Phase differences at $0^\circ$, $35^\circ W$ are generally larger (Fig. 5b), as expected, keeping in mind that gravity wave speeds are optimized for local
agreement at 0°, 23°W. Yet again, the smallest phase differences are observed for the dominant baroclinic modes that are close to basin-mode resonance. For the remainder of the study we decided on comparing simulations forced by annual and semiannual oscillations derived from the JRA-55 wind stress data and scaled locally at 0°, 23°W to our observations from the equatorial moorings and 11°S–Angola, as these simulations generally yield the best phase agreement to the observations at 0°, 23°W (for corresponding projection coefficients, see Table 3). However, we note, although the model-computed modal amplitudes are scaled to match observed modal amplitudes at 0°, 23°W, elsewhere they do depend on several aspects of the model configuration, such as the applied damping or the capture of the resonance characteristics as a function of basin geometry and chosen phase speeds.

To focus on the relative importance of equatorial and local forcing, modal amplitudes and phases from the EF-only runs are fitted to the scaled modal amplitudes and unaltered phases from the EF + LF runs at 0°, 23°W. Following this approach, EF + LF and EF-only runs agree locally at 0°, 23°W, and differences between EF + LF runs and EF-only runs at 11°S–Angola can be related to the impact of local forcing that is retained in the EF + LF runs.

d. Validation of model-computed annual and semiannual cycles of zonal velocity at the equator

As a first test for our chosen set of EF + LF simulations, we compare the observed vertical structure of annual and semiannual cycles both at 0°, 23°W and 0°, 35°W to the sum of corresponding shallow-water model simulations for the first five baroclinic modes (Fig. 6). The observed annual cycle of zonal velocity at 0°, 23°W (Fig. 6a) is characterized by a phase jump at 70- to 80-m depth accompanied by maximum annual amplitudes above and below, mirroring the annual cycle in EUC core depth (Brandt et al. 2016). Deeper in the water column, significant annual amplitudes are found down to about 2500-m water depth. For comparison, we extract zonal velocities at the model grid point corresponding to 0°, 23°W from the EF + LF simulations. The scaled model-computed amplitude for each baroclinic mode is multiplied with the corresponding equatorial vertical structure function. The resulting time series of velocity profiles associated with each baroclinic mode are summed up to reconstruct the annual and semiannual cycles.

TABLE 3. Dimensionless wind stress projection coefficients $G_n$ for EF + LF simulations being forced by Fourier components of JRA55 wind stress data corresponding to annual (middle column) and semiannual (right column) oscillations as obtained from scaling model-computed amplitudes locally at 0°, 23°W. In parentheses corresponding wind stress projection coefficients derived from scaling model-computed amplitudes locally at 0°, 35°W are displayed.

<table>
<thead>
<tr>
<th>Baroclinic mode n</th>
<th>$G_n$, annual cycle</th>
<th>$G_n$, semiannual cycle</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1.39 (1.24)</td>
<td>0.16 (0.33)</td>
</tr>
<tr>
<td>2</td>
<td>0.60 (0.89)</td>
<td>0.21 (0.41)</td>
</tr>
<tr>
<td>3</td>
<td>0.13 (0.17)</td>
<td>0.22 (1.51)</td>
</tr>
<tr>
<td>4</td>
<td>0.16 (0.22)</td>
<td>0.07 (0.09)</td>
</tr>
<tr>
<td>5</td>
<td>0.14 (0.52)</td>
<td>0.02 (0.57)</td>
</tr>
</tbody>
</table>

FIG. 5. (a) Dimensionless projection coefficients $G_n$ for EF + LF simulations being forced by different wind products. Projection coefficients are computed by fitting model-computed amplitudes to amplitudes derived from projecting the corresponding baroclinic mode on annual (AC) and semiannual (SAC) cycles of observed zonal velocity at 0°, 23°W (yellow and red, respectively) and 0°, 35°W (only shown for JRA-55 forcing, green and blue, respectively). Model-computed phases are not fitted but remain solely determined by the applied wind forcing and model characteristics. In (b), local phase differences between EF + LF shallow-water model simulations and observed modal semiannual and annual cycles are shown; colors and symbols are as given in (a).
of zonal velocity. The sum of annually oscillating shallow-water model simulations for the first five baroclinic modes reveals a very similar behavior, showing zero amplitude at 70–80-m depth surrounded by maxima above and below (Fig. 6b), however, not as vertically confined as in the observations (Fig. 6a). According to Fig. 3b the pattern of annual amplitudes is mainly determined by the fourth baroclinic mode. However, because of discrepancies in the model-computed phases, particularly for the third and fifth baroclinic mode (Fig. 5b), a phase shift in the distribution of annual amplitudes is clearly visible compared to the observations. The observed vertical structure of semiannual amplitudes at 0°, 23°W (Fig. 6e) is dominated by the second baroclinic mode (Fig. 3b; Brandt et al. 2016) and accordingly is characterized by near-surface amplitude maxima. Below, compared to the annual cycle, the vertical structure is less baroclinic, consistent with the dominance of lower baroclinic modes. The reconstruction using semiannually oscillating shallow-water model simulations shows a very similar amplitude distribution compared to the observations both in magnitude and phase (Fig. 6f). This is attributable to the precise simulation of the second baroclinic mode, with the remaining modes having only minor influence on the semiannual cycle. In fact, for the semiannual cycle baroclinic modes 1, 3, 4, and 5 are characterized by energies of less than 0.7 cm² s⁻², while the second baroclinic mode exhibits
about 2.3 cm² s⁻² (Fig. 3b). Nevertheless, we note that the reconstructed semiannual cycle from shallow-water model simulations lacks structure and amplitude in the deep ocean below 1500-m depth.

A similar comparison is carried out for annual and semiannual components in zonal velocity at 0°, 35°W (Figs. 6c,d,g,h, respectively). Note again that projection coefficients obtained at 0°, 23°W are used for scaling of model-computed modal amplitudes. For the annual cycle, this results in a weaker simulated annual cycle with maximum near-surface amplitudes about 50% smaller compared to the observations. Despite the deficiencies in the strength of the simulated annual cycle near the surface, observed and model-computed baroclinic structures bear important similarities, particularly in the structure and phasing of the variability at depth. The model-computed semiannual cycle at 0°, 35°W also suffers from a lack of near-surface amplitude (about 20% smaller compared to the observations). Apart from that, the largest differences are found in the depth range between 100- and 500-m depth, where the semiannual cycle reconstructed from observations shows stronger baroclinicity and higher amplitudes. At depth, observed and model-computed semiannual cycles largely agree in terms of the phasing but with weaker model-computed amplitudes. Overall, larger discrepancies are found for the reconstruction of observed and model-computed annual and semiannual oscillations at 0°, 35°W compared to 0°, 23°W. These might partly be explained by generally larger differences between observed and model-computed phases at 0°, 35°W (Fig. 5b). Furthermore, we note the larger uncertainties in the reconstruction of observed annual and semiannual cycles at 0°, 35°W, as it relies on less than 2 years of velocity observations (Fig. 2).

Nonetheless, our findings encourage us to evaluate the models further for their basinwide structures and particularly at 11°S–Angola.

6. Seasonal cycle of the Angola Current

a. Harmonic amplitudes of observed alongshore velocity at 11°S–Angola

While the annual component is the main contributor to the seasonal cycle of zonal velocity at 0°, 23°W (Brandt et al. 2016), at 11°S–Angola the relative importance of the semiannual compared to the annual cycle of alongshore velocity is strongly enhanced (Fig. 7). Furthermore, the periodogram derived by harmonic fits to the velocity data from the first deployment period of the inshore ADCP off Angola reveals a strong component near 120 days. However, this peak is neither as pronounced in the periodogram calculated from the first deployment period for the offshore ADCP (not shown) nor in the periodogram for the offshore ADCP when combining both deployment periods. Here, distinct peaks are found near 90 and 100 days, most likely associated with a period of enhanced intraseasonal variability in the alongshore flow between December 2015 and April 2016 (Fig. 1). In the following, we restrict our analysis to annual and semiannual oscillations, making use of the longer time series obtained from the offshore ADCP. However, a brief discussion of the intraseasonal oscillations is provided in section 7.

b. Horizontal structure of annual and semiannual oscillations

In a next step we explore the horizontal distribution of the amplitude of simulated annual and semiannual oscillations (Fig. 8) in order to identify baroclinic modes relevant at 11°S off Angola. For this purpose, we use the EF-only simulations that show the impact of purely equatorial forcing off the coast of Angola. The horizontal structures are generally characterized by the elongated amplitude maxima along the equator; in the eastern part of the basin regions of enhanced amplitude are partly being deflected to the south. The largest amplitudes are obtained for the semiannual cycle of the second baroclinic mode and for the annual cycle of the fourth baroclinic mode, both showing maximum amplitude of zonal velocity oscillation at the equator in mid-basin. As discussed in Brandt et al. (2016), for these combinations of baroclinic mode and forcing period the equatorial ocean is close to resonance, forming the gravest equatorial basin modes. Similar simulations for a rectangular ocean basin resulted in meridionally
Including a realistic coastline generates asymmetric structures because of the presence of the Gulf of Guinea and the northwestward slanted coastline of equatorial Brazil. The horizontal structures of the amplitude for other combinations of baroclinic mode and forcing period can strongly deviate from the basin-mode structure (see, e.g., patterns of the first baroclinic mode). For the fourth baroclinic mode, semiannual cycle, a different pattern is found, which is characterized by two amplitude maxima along the equator separated by a nodal point in the midbasin. It can be associated with a second basin mode. In any case, enhanced amplitudes of higher baroclinic modes are more confined to the equator in their meridional extent (Fig. 8). Note that Fig. 8 displays the amplitudes of the baroclinic-mode contribution to the surface velocity, where the second baroclinic mode has the largest expression (cf. Fig. 3a). In the subsurface the relative importance of different baroclinic modes varies depending on their vertical structure. Off the coast of southwestern Africa alongshore velocities have a dominant meridional component. Therefore, the amplitude of the meridional velocity is displayed in the southeastern corner of the domain in Fig. 8. Whether a particular baroclinic mode affects the velocity at 11°S–Angola apparently depends on the meridional extent and associated shape of the southward deflection of the amplitude maximum as well as on the mode’s energy as determined at 0°, 23°W. The fourth and second baroclinic modes, being found to
dominate the annual and semiannual cycles in zonal velocity both at $0^\circ$, $23^\circ$W and $0^\circ$, $35^\circ$W, respectively, also appear to dominate the annual and semiannual cycles in meridional velocity at $11^\circ$S–Angola. Simulations for the baroclinic modes closest to basin-mode resonance are generally found to exhibit appropriate amplitudes to influence the meridional velocity near the coast at $11^\circ$S, that is, baroclinic modes 3–5 and 1–3 for the annual and semiannual cycle, respectively. However, for the semiannual cycle the near-coastal amplitude maximum of meridional velocity is located south of $11^\circ$S–Angola for the first and second baroclinic modes, suggesting an even stronger impact of the equatorial forcing farther away from the equator. Particularly, the first baroclinic mode exhibits low amplitude at the semiannual period at $11^\circ$S–Angola. Instead, the second basin mode of the fourth baroclinic mode is likely to play a role.

c. Annual and semiannual cycles of alongshore velocity at $11^\circ$S–Angola

The annual and semiannual components at $11^\circ$S–Angola are derived by fitting annual and semiannual harmonics to the time series of alongshore velocity at each depth level (Figs. 9a,e, respectively). In agreement with Fig. 7, the semiannual cycle on average shows higher amplitudes compared to the annual cycle, along with a reduced baroclinicity. Annual and semiannual components derived from the corresponding time series of altimetry-based geostrophic velocities allow for the interpretation of near-surface baroclinic structures. For the annual cycle the flow reverses direction between the surface and the depth of the uppermost ADCP measurements (about 50 m). The semiannual cycle of the alongshore velocity is instead characterized by a more gradual change with depth, again indicating the dominance of low baroclinic modes. As for zonal velocity along the equator, the annual and semiannual cycles of alongshore velocity at $11^\circ$S–Angola are reconstructed by summing up the individual contributions of the first five baroclinic modes to the alongshore velocity extracted from the shallow-water model simulations. For the purely equatorial forcing, the model-computed annual cycle agrees well with the observations in terms of both amplitude and phase (Fig. 9b; red line in Figs. 10a,b). Thus, the annual cycle of alongshore velocity at $11^\circ$S–Angola appears to reflect primarily the response to the remote equatorial forcing. The purely equatorial forcing also generates a semiannual cycle at $11^\circ$S–Angola with a depth-averaged amplitude comparable to the observations (Fig. 9f). However, the vertical structure and phasing of the model-computed semiannual cycle is substantially different compared to the observed one, characterized by too strong near-surface velocities along with a phase difference of about 2 month and too weak velocities at depth (red line in Figs. 10c,d). This suggests that the remote equatorial forcing alone is not sufficient to set up the baroclinic structure of the semiannual cycle as observed; instead
other driving processes such as local forcing might play a role as well. Therefore, a similar extraction is carried out for the EF + LF simulations that include also the local forcing along the eastern boundary. Again, using the first five baroclinic modes for the reconstruction of the annual cycle, we find a good agreement between the summed-up model output (Fig. 9c; solid blue line in Figs. 10a,b) and the observations (Fig. 9a; black line in Figs. 10a,b). The reconstructed baroclinic structure of the semiannual cycle from the EF + LF simulations (Fig. 9g; solid blue line in Figs. 10c,d) is only marginally improved compared to the EF-only runs (Fig. 9f, red line in Figs. 10c,d), with more realistic amplitudes of near-surface velocity and an improved phasing. Nonetheless, middepth amplitudes are too weak also in the EF + LF runs and particularly do not indicate a local maximum as in the observations. In general, the inclusion of local forcing introduces only small improvements for the model-computed semiannual cycle compared to the runs with purely equatorial forcing. This indicates that additional processes not included in our linear shallow-water model simulations must to some extent control the semiannual cycle at 11°S–Angola. However, the baroclinic structure of the semiannual cycle of the alongshore

Fig. 10. (left) Amplitude and (right) month of maximum northward flow, as function of depth for (a),(b) annual and (c),(d) semiannual cycles of alongshore velocity at 11°S–Angola corresponding to patterns in Fig. 9. Observations (black), EF-only (red), and EF + LF simulations (solid blue: modes 1–5; dotted blue: modes 3–5 for AC, modes 1–3 for SAC). Additionally, corresponding profiles derived from TRATL01 output are shown in green.
velocity at 11°S–Angola in the OGCM TRATL01 also shows similar discrepancies compared to the observations, like too strong near-surface velocity and a vertical phase distribution that agrees better with the shallow-water model runs than the observations (green lines in Figs. 10c,d). Nonetheless, in TRATL01 a middepth maximum of semiannual amplitudes is indicated, although slightly deeper and not as pronounced as in the observations (Fig. 10c). For the annual cycle from TRATL01, we note a slightly deeper depth of both the phase transition (Fig. 10b) and the middepth maximum (Fig. 10a) compared to the observed annual cycle. Overall, we find a general good agreement between observations, shallow-water model simulations, and TRATL01 for the annual cycle. We further note substantial differences in the observed and model-computed semiannual cycle. As the discrepancies are (partly) present in both shallow-water model simulations and TRATL01, potential causes are not easy to assess.

To further evaluate the importance of the remote equatorial forcing particularly for the annual cycle at 11°S–Angola, the amplitude and phase of the individual modal contributions to the oscillation are compared between the simulations driven with equatorial forcing and those simulations driven with full forcing. With few exceptions, modal phase differences for the two sets of simulations are within less than 1 month and modal amplitude differences are smaller than 0.1 cm s⁻¹ (Table 4). These minor differences underline the dominance of the remote equatorial forcing for the annual cycle at 11°S–Angola. The larger discrepancy between the reconstructions of the forcing-dependent semiannual cycles is largely associated with the third baroclinic mode, which is phase shifted by about 1 month, and, more importantly, stronger in amplitude by about 0.23 cm s⁻¹ in the simulation with equatorial forcing only. Multiplied with the corresponding vertical structure function (Fig. 3a), this difference in amplitude is sufficient to explain the intensification near the surface and concurrent reduction at depth in the semiannual cycle reconstructed from simulations based on equatorial forcing compared to the simulations with realistic forcing (Fig. 9f).

As Fig. 8 suggests, in general only baroclinic modes with basin-mode resonance periods close to either the annual or semiannual cycles are likely to influence the alongshore velocity off the coast of Angola. Therefore, we repeat the reconstruction using EF + LF simulations, summing up only selected baroclinic modes, which are modes 3–5 and 1–3 for the annual and semiannual cycles, respectively (Figs. 9d,h). As expected from Fig. 8, the annual cycle is only little changed compared to the reconstruction using five modes, stressing the importance of the fourth baroclinic mode for the annual cycle with contributions from both the third and fifth baroclinic modes, especially in setting up the phases. For the semiannual cycle, the restriction to the first three baroclinic modes results in even less amplitude at middepth. Together with Figs. 8 and 10, this indicates the influence of higher baroclinic modes in generating the observed baroclinic structure of the semiannual cycle in alongshore velocity at 11°S–Angola and thus, besides the gravest basin mode, also a potential impact of the second basin mode for the fourth baroclinic mode.

### Table 4. Amplitude and phase differences between EF-only and EF + LF simulations for individual baroclinic modes at 11°S–Angola.

<table>
<thead>
<tr>
<th>Baroclinic mode n</th>
<th>Annual cycle</th>
<th>Semiannual cycle</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Δ amplitude (cm s⁻¹)</td>
<td>Δ phase (month)</td>
</tr>
<tr>
<td>1</td>
<td>−0.021</td>
<td>+5.6</td>
</tr>
<tr>
<td>2</td>
<td>+0.081</td>
<td>−2.3</td>
</tr>
<tr>
<td>3</td>
<td>+0.043</td>
<td>−0.3</td>
</tr>
<tr>
<td>4</td>
<td>−0.016</td>
<td>−0.4</td>
</tr>
<tr>
<td>5</td>
<td>−0.072</td>
<td>−1.0</td>
</tr>
</tbody>
</table>

7. Summary and discussion

We have analyzed the seasonal cycle of alongshore velocity measured by a moored ADCP at 11°S–Angola between July 2013 and October 2016. Pronounced spectral peaks at annual and semiannual frequencies (Fig. 7) were found to be associated with distinct baroclinic structures (Figs. 9a,e). In the equatorial Atlantic resonant basin modes (Cane and Moore 1981) have been found to represent robust features that are associated with pronounced spectral peaks in zonal velocity time series at the annual and semiannual frequencies (Claus et al. 2016; Brandt et al. 2016; Thierry et al. 2004; Ding et al. 2009). Equatorial basin modes are composed of equatorial Kelvin and long equatorial Rossby waves for a particular baroclinic mode, with basin resonances...
found at characteristic periods depending on both gravity wave speed and basin geometry. Given the link between the equatorial and coastal waveguides, we examine the relative importance of remote equatorial forcing, including potential basin-mode resonances versus the local forcing off Angola for the observed annual and semiannual cycle of alongshore velocity at 11°S–Angola.

A suite of shallow-water model simulations is employed, forced either by zonally uniform oscillating zonal forcing restricted to the equatorial band (EF-only runs) or by the Fourier components of several wind products corresponding to the annual and semiannual periods (EF + LF runs). Model-computed modal amplitudes are fitted to modal amplitudes derived from mooring data at 0°, 23°W (Fig. 5a; Table 3). Note that the resulting wind stress projection coefficients may differ for annual and semiannual frequencies for the same baroclinic mode. As noted earlier, it is crucial how well our simulations capture the resonance characteristics of the equatorial Atlantic (Greatbatch et al. 2012; Brandt et al. 2016). The resonance frequency in the model depends mainly on the combination of chosen gravity wave speed and model boundary geometry. Furthermore, dissipation of wave energy could be different for the annual and semiannual cycle but is prescribed and fixed in the shallow-water model simulations. Therefore, the wind stress projection coefficients do not so much mirror the wind energy input (and are therefore not necessarily similar for different oscillation periods) but rather indicate how much energy input is required to establish similar modal amplitudes as observed at a given oscillation period, given the model-inherent resonance characteristics.

The large-scale horizontal structures of the amplitude of annual and semiannual oscillations for different baroclinic modes suggest their dynamic influence on the boundary circulation off Angola (Fig. 8). In model simulations driven with zonally uniform zonal forcing restricted to the equatorial band (EF-only), the observed annual cycle of alongshore velocity at 11°S–Angola is already well reproduced, suggesting remote equatorial forcing as the major driver for annual oscillations of the eastern boundary circulation off Angola (Fig. 9b). Although the remote equatorial forcing also generates a semiannual cycle of comparable amplitude, the model-computed semiannual cycle is significantly different from the observed one (Fig. 9f). Some improvements in terms of the vertical structure and phase of the reconstructed semiannual cycle are achieved when including local forcing along the eastern boundary (EF + LF runs; Fig. 9g). Furthermore, it could be shown that both simulated annual and semiannual oscillations appear to be primarily determined by those baroclinic modes being close to basin-mode resonance either for the annual or semiannual frequency (Figs. 9d,h).

Nevertheless, while amplitudes of model-derived and observed annual cycles are very similar, the model-derived semiannual cycle lacks amplitude at middepth. Given the vertical structure of the baroclinic modes (Fig. 3a), contributions of higher baroclinic modes seem to be underestimated for the semiannual cycle. Here, we want to note that our approach for scaling model-computed modal amplitudes relies on one particular location in the central equatorial Atlantic, where an observational dataset of top-to-bottom ocean velocities is available to allow for baroclinic-mode decomposition. However, owing to the differences in the spatial distribution of the amplitude for different baroclinic modes, a locally confined scaling might be problematic, as seen, for example, for the fourth baroclinic mode, semiannual cycle. The corresponding basin mode represents the structure of a second basin mode, which is characterized by two velocity maxima along the equator (Fig. 8); 0°, 23°W is located close to the nodal point of the second basin mode, which complicates the determination of the corresponding modal amplitude and thus adds uncertainty to the scaling of model-computed modal amplitudes. By artificially enhancing the amplitude of the fourth baroclinic mode it can be tested whether a larger contribution of this mode improves the model-computed semiannual cycle. More specifically this would require that the model-determined phase of the fourth mode at 11°S–Angola allows for an improvement of the baroclinic structure of the semiannual cycle. Enhancing the amplitude of the fourth baroclinic mode, semiannual cycle, for example, by a factor of 4.5 indeed leads to an improvement of the phasing of the model-computed semiannual cycle (Fig. 11b). However, although the semiannual cycle at middepth is slightly enhanced, amplitudes are still substantially different compared to the observations (Fig. 11a). Overall, this indicates that the phase of the semiannual cycle of the fourth baroclinic mode as determined by our simulation would permit a stronger contribution of this mode, and a limiting factor for a realistic reconstruction of the semiannual cycle at 11°S–Angola appears to be the amplitude of the fourth baroclinic mode. Here, the modal decomposition derived from zonal velocity data at 35°W–equator yields another estimate of the strength of the second basin mode associated with the fourth baroclinic mode, semiannual cycle. Indeed, the mode energy for this particular basin mode is found to be significantly larger at 0°, 35°W compared to 0°, 23°W (0.25 vs 0.08 cm s⁻²). However, the corresponding scaling coefficients for the shallow-water model simulations derived independently at the two locations are very similar (0.09 at 0°, 35°W vs 0.07 at 0°, 23°W; compare Table 3). Hence, the strength of the simulated basin
mode associated with the fourth baroclinic mode, semiannual cycle, would change only marginally, if we scaled our simulations at 0°, 35°W and thus cannot explain the too weak amplitude at 11°S–Angola.

However, several other factors potentially influence the model-computed amplitude at 11°S–Angola. Among them are model-inherent characteristics such as the applied damping and the efficiency of basin-mode resonance depending on model geometry and chosen phase speeds. As noted earlier, gravity wave speeds are kept constant in our simulations. Consequently, large-scale changes in stratification (e.g., because of the eastward shoaling and thinning of the equatorial thermocline) that might cause changing wave speeds as well as scattering of baroclinic waves are not taken into account in the model. According to Clarke and Van Gorder (1986), scattering of baroclinic waves also occurs via frictional coupling, which depends on the bottom topography (in case of CTWs on the shelf slope steepness). However, our model setup does not contain topographic features like the mid-Atlantic ridge and treats coastlines as solid vertical walls. Therefore, the potential transfer of energy between baroclinic modes is not included in our model. Also the interaction of equatorial waves with the mean flow, as discussed by Claus et al. (2014) for high-order baroclinic modes, is not included in our model. Furthermore, linear models also do not include nonlinear processes like a potential nonlinear interaction of the annual cycle with itself that could shift energy to the semiannual cycle. In this way, the dominant basin mode of the annual cycle, being of fourth baroclinic mode, might feed energy into the second basin mode of the semiannual cycle, providing one potential explanation for the missing strength of the fourth baroclinic mode in the semiannual cycle in our linear model. Nevertheless, given the simplicity of our model, it seems even more remarkable how much of the annual and, with some reservations, semiannual oscillations discussed here appear to be governed essentially by linear dynamics.

While investigating the seasonal cycle of equatorial Atlantic circulation, Brandt et al. (2016) compared their shallow-water, basin-mode simulations to the OGCM TRATL01 (Duteil et al. 2014), noting similarities in the representation of the dominant basin modes for the annual and semiannual cycles. As for zonal velocity at 0°, 23°W, annual and semiannual cycles of alongshore velocity at 11°S–Angola bear important similarities between observations and TRATL01 (Fig. 10). However, local maxima/minima or phase transitions are generally found slightly deeper in TRATL01 compared to the observations, pointing to a too strong vertical diffusion in the model (Brandt et al. 2016). Considering baroclinic-mode contributions, this would result in a stronger projection onto the third instead of the fourth baroclinic mode (not shown). Thus, for the semiannual cycle it still supports the potential importance of the fourth baroclinic mode in setting up the semiannual cycle of alongshore velocity at 11°S–Angola. A modal decomposition of zonal velocity from TRATL01 at 0°, 23°W qualitatively confirms the importance of particular
baroclinic modes as seen in the observations; nonetheless, the annual cycle of the fourth baroclinic mode is more energetic, while the semiannual cycle of the second baroclinic mode is less energetic in TRATL01 (Fig. 12b). Similar to 11°S–Angola, the relative contribution of the third baroclinic mode to the annual cycle is larger in TRATL01 compared to the observations at 0°, 23°W. At 0°, 35°W, the third baroclinic mode is the largest contributor to the annual cycle in TRATL01, while the modal decomposition of the observed time series suggests local dominance of the fourth baroclinic mode followed by the second baroclinic mode (Fig. 12a). Considering the semiannual cycle at 0°, 35°W, the large amplitude of the second baroclinic mode derived from observations is mirrored neither by TRATL01 nor by the EF + LF shallow-water model simulations scaled at 0°, 23°W. Overall, mode energy spectra derived from observations, the EF + LF shallow-water model runs, and TRATL01 agree less well at 0°, 35°W compared to 0°, 23°W. As noted earlier, the uncertainties associated with the modal decomposition of the zonal velocity observations at 0°, 35°W are rather large and might be one of the factors accounting for the differences between mode spectra. Furthermore, for a realistic representation of the seasonal cycle of the equatorial circulation by an OGCM, it seems crucial that resonance characteristics are captured correctly. To achieve the latter, a realistic representation of the stratification along the equator is essential, as this specifies corresponding gravity wave speeds. While our shallow-water model simulations assume constant phase speeds across the basin, TRATL01 does account for changes in stratification. Consequently, the basinwide structures of the annual and semiannual cycles for a specific baroclinic mode can look significantly different in TRATL01 compared to our idealized simulations (Fig. 13). Comparably small shifts in the location of local maxima thus can result in rather large discrepancies in the modal amplitude at one particular location, as seen, for example, in the annual cycle of the second baroclinic mode near 35°W (cf. Fig. 8 and Fig. 13). Also the location of local maxima associated with the semiannual cycle of the fourth baroclinic mode is significantly different between the shallow-water model simulations and TRATL01, underlining the problematic nature of correctly scaling modal amplitudes relying on individual locations, where suitable observations are available.

The CTW response of the coastal upwelling regions off Angola and Namibia to the remote equatorial wind forcing has previously been discussed mainly with respect to the intermittent occurrence of warm Benguela Niño events (Florenchie et al. 2003; Florenchie et al. 2004; Rouault et al. 2007; Huang and Hu 2007; Lübbecke et al. 2010; Richter et al. 2010; Bachéléry et al. 2016) developing in the northern Benguela. Carrying out a set of regional model simulations for the southeast Atlantic intentionally excluding the seasonal cycle in the analysis, Bachéléry et al. (2016) noted the dominance of remote equatorial forcing on interannual time scales, while on intraseasonal time scales local forcing prevailed.

![Fig. 12. Baroclinic-mode energy spectra of the annual (AC; solid) and semiannual (SAC; dashed) cycles for (a) 35°W–equator and (b) 0°, 23°W derived from moored velocity observations (blue), EF + LF shallow-water model simulations (red) 0°, 35°W, and the TRATL01 model (green). In (b) mode spectra of the shallow-water model are identical to the one derived from observations as model-computed modal amplitudes are scaled locally at 0°, 23°W.](image-url)
However, for seasonal time scales particularly the importance of the semiannual cycle as contributor to upwelling and downwelling seasons off Angola has been underlined (Ostrowski et al. 2009; Rouault 2012; Kopte et al. 2017). The mooring observations off Angola (Fig. 1) for the first time reveal the baroclinic structures of both the annual and semiannual cycle, and our results appear to confirm that equatorial dynamics play a crucial role for the eastern boundary circulation variability on these time scales.

As noted in section 6a, on intraseasonal time scales a pronounced spectral peak in the velocity time series is found near 120 days for the inshore ADCP (Fig. 7). The persistence of this oscillation cannot be verified with the available data. Nevertheless, elevated energy near 120 days is also found in the zonal velocity time series at 0°, 23°W, which might be associated with resonance of either the gravest basin mode of the first baroclinic mode or the second basin mode of the second baroclinic mode. The vertical structure of the 120-day oscillation at 11°S–Angola indeed suggests the dominance of low baroclinic modes (not shown). Interestingly, a basin resonance at 120-day has been described for the Caribbean Sea (Hughes et al. 2016) that could impact also equatorial Atlantic circulation via CTW and EKW response and potentially even the boundary circulation off Angola. However, the isolation of the corresponding signatures in the velocity data at 0°, 23°W was hindered by several interfering, stronger signals that are associated with a diversity of forcing mechanisms. Thus, the possible equatorial forcing of intraseasonal variability in the boundary circulation off Angola remains an open question.

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