Supporting Information for “Equatorial deep jets and their influence on the mean equatorial circulation in an idealized ocean model forced by intraseasonal momentum flux convergence”

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Contents of this file

1. Texts S1 to S4
2. Figures S1 to S7

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April 19, 2020, 1:58pm
Introduction

This Supporting Information contains a more detailed description of the model parameters used in the study than it was possible to give in the main article, and a detailed description of the analysis of the Argo data. Additionally, a brief comparison of the modelled EDJ and EDJ observed at a current meter mooring at the equator at 23°W is given to justify our analysis of EDJ in a simplified model study. Finally, two figures that show the robustness of the generated mean flow pattern for different EDJ amplitudes are included.
Text S1. Extended model description

Our model is set up as an idealized tropical Atlantic basin. It is rectangular, with a uniform depth of 5000 m, extending from 20°S to 20°N and over 55° longitude, mimicking the width of the Atlantic at the equator which is an important factor for simulating the Atlantic EDJ because of their resemblance to an equatorial resonant basin mode. The horizontal resolution is set to 0.25° in both latitude and longitude. The vertical resolution is higher than usually employed in ocean models – we use 200 model levels that are spaced 5 m apart close to the surface and 50 m apart close to the bottom. The level spacing in the entire water column can be seen in Figure S1.

The vertical mixing formulation is Richardson number dependent, following Pacanowski and Philander (1981); in the horizontal, biharmonic diffusivity is used for both tracers and momentum. For a complete list of parameters used see the model namelist that is provided as part of the supplemental dataset (URL in Acknowledgments in the main text). Most of our parameter choices follow Ascani et al. (2015) and Matthießen et al. (2015).

The model is initialized with basin-averaged vertical profiles of temperature and salinity from the World Ocean Atlas (WOA) 2018 (Locarnini et al., 2019; Zweng et al., 2019). Given as in-situ temperature and practical salinity in the WOA, they are converted into conservative temperature and absolute salinity using the TEOS-10 Gibbs Sea Water library Python implementation (gsw 3.3.1) to be compatible with the NEMO implementation of the equation of state. Throughout the simulations, temperature and salinity at the model ocean surface are restored towards the initial values with a time scale of 30 days to at least partly sustain the original density stratification in the water column.
fact, the model thermocline does diffuse a little in the course of our simulations, but over the time of a little less than 150 years over which we run the model the change is small enough that the effect can be neglected.

All simulations are started from rest and run until a quasi-steady circulation has developed, which takes about 60 years in the Sim-WIND case and less than 10 years in the Sim-IMFC case. After this spin-up phase, the model is run for 80 years, and these 80 years are then analyzed.

Text S2. Argo analysis

The dataset of velocities from Argo float data that we used for this study is the YoMaHa’07 dataset (Lebedev et al., 2007). It is updated regularly; our version has been downloaded on November 4, 2019 (covering a time period of approximately 20 years, from 2000 to October 2019). The velocities at the floats’ parking depth have been calculated from the positions of the float’s descent, ascent and the time it spent at depth. For more details on this please see Lebedev et al. (2007) directly.

From this dataset, we used only the zonal velocity, and we chose only the data points that are located in the tropical Atlantic and at a nominal float parking depth of 1000 m, i.e. well inside the main depth interval of the EDJ. Luckily for us, 1000 m is the most abundant parking depth in the Argo float data; although other depths are available, the data coverage is much sparser there. A first impression of the data coverage and the time mean zonal velocity field (binned spatially into $0.1^\circ \times 0.1^\circ$ areas) can be seen in Figure S2. Although the resulting field has a lot of regions with missing data, it gives a
generally good first impression of what the time mean velocity field looks like. Away from the equator, the zonal velocity is arranged in narrow zonal bands, alternately flowing to the west and to the east with increasing distance from the equator. These current bands have been termed the Equatorial Intermediate Current System and have been described in many other studies (cf. e.g. Ascani et al., 2010; Cravatte et al., 2012). Very close to the equator, however, in the region that is of interest in the context of this study, the structure of the mean velocity field is not very clear - the noise due to the periodically reversing EDJ is strongly apparent.

If we look at the temporal coverage of the data, the sampling is generally not evenly distributed over positive and negative EDJ phases, leading to a potential bias in the time mean. Hence, if we want to find the structure of the time mean zonal flow close to the equator, we have to remove the harmonic associated with the EDJ before taking the time average. However, the sampling is not only unevenly distributed, but even at 1000 m depth still relatively sparse, such that we have to spatially smooth the time mean field to be able to fit temporal harmonics to the data, and also to clearly see the dominant structures. For this purpose, we first calculate the spatial decorrelation scales of the raw time mean zonal velocity field, such that we do not apply smoothing on scales larger than those on which the velocity field can be assumed to be coherent.

To calculate the decorrelation scales of the mean velocity field, we use the technique of correlation slotting (Edelson & Krolik, 1988). This is a technique to obtain an estimate of the autocorrelation function of irregularly sampled data. First, the product of every possible combination of two data points is calculated, to be then binned according to the
temporal lag or spatial separation of the two data points (in our case this is applied in
two spatial dimensions). The resulting autocovariance field can be normalized, yielding
the estimated autocorrelation as a function of spatial distance in latitude and longitude
(shown for the Argo zonal velocity data from 1000 m depth in Figure S3). We calculated
the spatial autocorrelation of the mean velocity field from all data points between 7°S and
7°N, i.e. all data shown in Figure S2.

As we only look at points that are less than 7° away from the equator, we calculate the
spatial separation in degrees and neglect the changing length of one degree of longitude
with increasing latitude, the scaling factor with the maximum deviation from one being
\[ \cos(7°) \approx 0.99. \]

In Figure S3, the e-folding scale of the autocorrelation is indicated with the black line.
The field is too noisy to obtain an exact estimate, but it seems safe to assume that
the decorrelation scales are at least 7.5° in the x-direction and 0.3° in the y-direction,
consistent with the much larger zonal than meridional coherence of the zonal flow field.

In order to remove the EDJ harmonic and smooth the resulting time mean field, we
first bin the Argo velocity data into spatial bins of 0.1° × 0.1° and temporal bins of 7 days.
Taking such relatively small bin sizes ensures that we do not lose too much information.
We then construct a time series for every point \((x_0, y_0)\) on a 0.2° × 0.2° grid by, for each
time step, calculating the weighted average of the velocities over a spatial influence ellipse
\(w(x, y)\) defined by a two-dimensional normal distribution with standard deviations of half
our estimated decorrelation scales, i.e. \(\sigma_x = 3.75°, \sigma_y = 0.15°:\)

\[
w(x, y) = \exp \left( - \left( \frac{(x - x_0)^2}{2\sigma_x^2} + \frac{(y - y_0)^2}{2\sigma_y^2} \right) \right) \cdot \frac{1}{W}
\]  (1)

April 19, 2020, 1:58pm
The edge of the influence ellipse is defined by \( w(x, y) = \exp(-3) \approx 0.05 \); values that lie outside this are not considered for the average. The weights are given by the Gaussian function \( w(x, y) \) itself, such that measurements are given less weight the further they are away from the point \((x_0, y_0)\). To retain the physical amplitude of the average, \( w \) has to be normalized at each point separately, because due to the sparsity of our dataset the number and distribution of measurements available for the average varies. \( W \) is the sum of values of \( w \) at all points where \( w > \exp(-3) \) and the velocity field \( u \) is defined. The spatially averaged velocity \( u_{\text{smoothed}} \) at \((x_0, y_0)\) and at time \( t \) is then just given as

\[
  u_{\text{smoothed}}(x_0, y_0, t) = \sum_{x,y} (u(x, y, t) \cdot w(x, y)) \tag{2}
\]

We now have a spatially smoothed zonal velocity field, and with this also time series at every point that are much less sparse than in the unsmoothed data, enabling us to fit harmonics to the velocity field. For this, we use a Python implementation (from astropy 3.2.3) of the Lomb-Scargle periodogram (Lomb, 1976; Scargle, 1982), which fits sinusoidal curves at frequencies corresponding to a discrete fourier transform to unevenly sampled time series. The EDJ, here at a period of 4.57 years, appear as the dominant interannual peak in the spectrum.

At every point \((x_0, y_0)\), we apply the Lomb-Scargle harmonic fit to the smoothed time series and remove the EDJ harmonic before calculating the final time average.

In Figure S4, the effect of the smoothing with the help of the spatial influence ellipse can be seen in Panel a. There, the EDJ harmonic has not been removed. The time mean velocity field without the EDJ harmonic is shown in Panel b. Panel c shows the time mean (non-zero due to the effect of irregular sampling) of the removed EDJ harmonic.
We have additionally tried a different method to remove the bias in the time average due to irregular sampling of the EDJ phases, where we calculated the ratio of measurements taken during positive EDJ phases to measurements taken during negative EDJ phases for each point. We then used this ratio to upweight measurements taken during the undersampled phase and downweight measurements taken during the oversampled phase. This method, however, increases the amount of noise in our data, so that we do not use it here. Nevertheless, we obtained very similar results as those shown in Figure S4, increasing confidence in our resulting time mean velocity field.

Text S3. Validation of model EDJ against observations

Because our model setup is highly idealized, we think it important to show a comparison of the main characteristics of the EDJ in our model to the EDJ measured in the real ocean, justifying our choice of a simplified model for studying the EDJ. Figure S5 shows Hovmöller diagrams and normal mode spectra for our two model experiments (Sim-WIND and Sim-IMFC, as also shown in the main text), as well as for observations from 23°W, obtained from different moorings and shipboard measurements (cf. Bunge et al., 2008; Brandt et al., 2011; Claus et al., 2016). The analysis of the observational data is updated from e.g. Claus et al. (2016); Greatbatch et al. (2018).

Overall, the EDJ in the model simulations exhibit similar characteristics as the observed EDJ, both being the dominant interannual peak in the spectrum at a period of roughly 4.5 years, and lying approximately on the equatorial basin mode resonance curve. However, the observed EDJ peak at mode 17, whereas the simulated EDJ have their maximum at

April 19, 2020, 1:58pm
mode 19. Also, the modal distribution is much broader in observations, where the EDJ peak in the spectrum spans at least modes 14 to 20, if not 10 to 20, than in the model runs, where the EDJ are only comprised of modes 18 to 20. The amplitude of the EDJ in the models is a bit too small compared to observations. This might pose a problem in the analysis of the nonlinear effects of the EDJ, as discussed in the main text. In the observations, there is a clear annual signal (as well as a semi-annual signal, not shown in the spectrum), both of which are not present in the model simulations. This is due to the steady, time averaged wind forcing applied to Sim-WIND, and it is intentional, since we are only interested in the interannual flow variability in this study.

Text S4. Dependence of generated mean flow strength on EDJ amplitude

We have done an additional model run where we changed the amplitude of the IMFC forcing. Although this is not the focus of the main article (where we deliberately did not tune the strength of the IMFC forcing but kept it at the amplitude that we diagnosed from Sim-WIND), we show two figures here because they add some confidence to the mean zonal flow field at intermediate depths that is generated by the EDJ in Sim-IMFC.

Figure S6 shows the mean zonal flow field at 1000 m depth from Sim-IMFC, as shown in the main article, as well as from the additional model run (Sim-doubledIMFC) that we forced with doubled IMFC amplitude, resulting in an approximate doubling of the EDJ amplitude. As in Sim-IMFC, no other forcing (e.g. wind) has been applied to Sim-doubledIMFC. The structure of the generated mean flow stays the same with increasing EDJ amplitude.
The amplitude of the generated mean flow, however, obviously depends strongly on the EDJ amplitude. Figure S7 shows the mean zonal flow along the equator, averaged over all depths between 500 and 1800 m (the structure of the mean flow is very similar on all depths over this range) from the two model runs. One can see that the increase is considerably larger than linear, in some places exceeding quadratic. This is not surprising given that the energy transfer from the EDJ to the mean flow happens through $-\overline{\partial (u'u')/\partial x}$ (the overline denoting the time mean, the prime denoting deviations from the time mean), as shown in the main article.

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Figure S1. Setup of the vertical axis. In the left panel, the placement of each model level along the depth axis is shown (each level indicated by a black dot). In the right panel, the resulting vertical grid spacing is shown.
Figure S2. Time mean zonal velocity at 1000 m depth from Argo data, binned into 0.1° × 0.1° spatial bins
Figure S3. Spatial decorrelation scales of time mean zonal velocity at 1000 m depth in the tropical Atlantic between 7°S and 7°N from Argo data. The color shading shows the autocorrelation (details see text), the black contour at a value of 0.37 indicates the e-folding scale.
Figure S4. Effects of the removal of the EDJ bias on the time mean field of zonal velocity at 1000 m depth from Argo data. For details see text.
Figure S5. Comparison of observed Atlantic EDJ and the simulated EDJ. (Cont. next page)
**Figure S5.** (previous page.) Panels a, c, and e show Hovmöller diagrams of zonal velocity at 23°W. Panels b, d and f show amplitude spectra of the zonal velocity after its decomposition into vertical normal modes. The dashed black lines indicate the dominant EDJ frequency, the solid black line the resonance curve of equatorial basin modes (see main text, Eq. 1). The difference in frequency resolution between mooring data and model output is due to the fact that we only have 14 years of observational data compared to 80 years of model output. Panels a and b are updated from e.g. Claus et al. (2016); Greatbatch et al. (2018).

**Figure S6.** Time mean zonal flow at 1000 m depth generated by EDJ in a model forced by different amplitudes of IMFC (details see text). The EDJ in Sim-doubledIMFC have approximately twice the amplitude of the EDJ in Sim-IMFC.
Figure S7. Increase of mean flow generated by EDJ when IMFC forcing amplitude is doubled. Shown is the time mean zonal flow along the equator, averaged over all depths between 500 and 1800 m. The dashed respectively dotted line are twice respectively four times the Sim-IMFC mean flow, meaning linear respectively quadratic increase of mean flow with increasing EDJ amplitude.