The anomalous merging of the African and North Atlantic jet streams during Northern Hemisphere winter of 2010. *

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Abstract

The North Atlantic jet stream during winter 2010 was unusually zonal, so that the typically separated Atlantic and African jets were merged into one zonal jet. Moreover, the latitude-height structure and temporal variability of the North Atlantic jet during this winter were more characteristic of the North Pacific. This work examines the possibility of a flow regime change, from an eddy-driven to a mixed eddy/thermally-driven jet. A monthly jet zonality index is defined, which shows that a persistent merged jet state has occurred in the past at the end of the 1960s, and during a few sporadic months. The anomalously zonal jet is found to be associated with anomalous tropical pacific diabatic heating and eddy anomalies similar to those found during a negative NAO state. A Lagrangian back trajectory diagnosis of eight winters suggests the tropical Pacific is indeed a source of momentum to the African jet, and that this source was stronger during the winter or 2010. The results suggest that the combination of weak eddy variance and fluxes in the North Atlantic, along with strong tropical heating, act to push the jet towards a merged eddy/thermally-driven state. We also find significant SST anomalies in the North Atlantic, which reinforce the anomalous zonal winds, in particular in the Eastern Atlantic.

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1 Introduction

One of the main characteristics of the midlatitude atmospheric flow is its organization into zonally oriented jet streams. Meteorologists have long noticed two types of jet streams- subtropical jets which form due to meridional advection of angular momentum by the Hadley cells (e.g. Schneider, 1977; Held and Hou, 1980), and polar front jets, also referred to as eddy-driven jets, which form due to the convergence of momentum by baroclinically unstable eddies as they propagate away from their source region (e.g. Held, 1975; Rhines, 1975; Panetta, 1993; Held, 2000). noted that these processes force both jets simultaneously, but under certain forcing conditions eddy generation is close enough to the subtropical jet so that a single merged jet evolves (see also O'Rourke and Vallis, 2013). Son and Lee (2005) further showed that a merged jet forms preferentially when the tropical heating is strong enough for the resultant subtropical jet to influence the growth of midlatitudes eddies, while a double jet forms when tropical heating is weak enough to allow mid-latitude eddies to grow more poleward and form a separate eddy-driven jet. The type of jet stream strongly affects the weather and correspondingly the climate in a given region. Eichelberger and Hartmann (2007) showed that the different jet types have very different temporal variability. While eddy-driven jets tend to meander latitudinally, due to the nature of wave-mean flow feedbacks, the thermally-driven or merged jets hardly shift in latitude and instead their variability is associated more with a pulsation of the jet.

While the above studies were all tested using models with zonally symmetric surface conditions, the main jet categorization and implied jet characteristics seem to apply to the real atmosphere when considering specific zonal sectors. In particular, the North Pacific jet has a vertical structure and temporal variability characteristic of a merged thermally/eddy-driven jet while the North Atlantic jet is eddy-driven, and it coexists with a subtropical jet which starts over the Eastern Atlantic and extends over Africa and Asia (e.g. Son and Lee, 2005; Eichelberger and Hartmann, 2007). Recently, Li and Wettstein (2012) explicitly showed in reanalysis data that the Atlantic jet is mostly eddy-driven, while the Pacific jet is both thermally-driven and eddy-driven.

In models, the transition from a single to a double jet occurs quite abruptly when external forcing parameters are gradually varied (e.g. Lee and Kim, 2003; Son and Lee, 2005). In particular, in Son and Lee (2005) the jet changed from an eddy driven state to a merged eddy-thermally driven state when the tropical forcing was strengthened or the midlatitude baroclinicity weakened. Recently, Lachmy and Harnik (2014) showed that the important factor by which the midlatitude baroclinicity affects the jet stream type is the strength of the eddies. Moreover, a change in jet type can be induced by changing eddy damping while keeping the mean flow forcing fixed.

In the real atmosphere, jet type transitions have been noted to occur as part of the seasonal cycle, and might occur in the future as the climate changes (e.g. Son and Lee, 2005). It is possible that such changes may also occur inter-annually, in response, for example, to the regular inter-annual variability in tropical heating. Indeed, an examination of the inter-annual variability in the Atlantic jet structure suggests that during some years, a single rather than double jet forms (Woollings et al., 2010b). Most striking is the winter of 2010 (hereafter, winter refers to Dec-Mar months with the year referring to Jan-Mar), which exhibited an unusually strong and persistent negative phase of the North Atlantic Oscillation and unusually cold and wet conditions over North America and Europe (Wang et al., 2010; Seager et al., 2010; Cattiaux et al., 2010; Vincente-Serrano et al., 2011; Santos et al., 2013). As shown below, during this winter, the Atlantic and African jets merged into one zonally oriented jet, with structure and variability more characteristic of the Pacific.

In this study we propose that while the NAO phases are a manifestation of the eddy-driven jet meandering in latitude, some of the extremely negative NAO winters correspond to a change in the type of jet stream, from an eddy-driven jet to a mixed thermally/eddy-driven jet, as is found in the Pacific. We will show that besides negative NAO conditions, a weakening of midlatitude eddies as well as anomalously strong tropical diabatic heating were involved. After presenting the data and analysis methods (Sec. 2), we characterize the anomalous conditions of the Atlantic jet during the winter of 2010, define an appropriate index to identify other months during which the jet was unusually zonal, and show that indeed during such winter months the Atlantic and African jets merged (Section 3). We then examine the change in eddy and thermal driving (Secs. 4.1 and 4.2 respectively), and the possible role of the ocean, given large sea surface temperature (SST) anomalies in the Atlantic and Pacific (Sec. 5). In Sec. 6 we examine the relation between jet zonality and different atmospheric indices. We conclude with a discussion in Sec. 7.

2 Data and analysis methods

For much of the analysis we use daily and monthly mean wind and temperature fields from NCEP re-analysis data for 1949-2012 (Kalnay et al., 1996) (the results were unchanged when using 1958-2012). For some of the eddy diagnostics, in particular a Lagrangian trajectory analysis, we used the ECMWF ERA40 (Uppala et al., 2005) and ERA Interim (Dee et al., 2011) data sets. To examine thermal forcing we use NCEP and ERA Interim radiative and sensible heat fluxes and precipitation, to calculate total atmospheric column diabatic heating. We also use precipitation rates from the Global Precipitation Climatology Project (GPCP) version 2.2 (Adler et al., 2003), which is the combined precipitation data developed and computed by the NASA/Goddard Space Flight Center's Laboratory for Atmospheres as a contribution to the GEWEX Global Precipitation Climatology Project. We note that NCEP radiative fluxes only exist since 2002, while

ERA Interim and GPCP data sets start in 1979. We used the NOAA Climate Prediction Center (CPC) North Atlantic Oscillation (NAO) index (based on the method developed by Barnston, 1987) and the Nino3.4 index, calculated by CPC from the NCDC Extended Reconstructed Sea Surface Temperature (ERSST, Smith and Reynolds, 2004; Smith and Lawrimore, 2008). The ERSST data was also used to examine Atlantic sea surface temperatures.

To study the contribution and influence on synoptic scale eddies we divide the main daily mean NCEP fields into short and long time scales, using a simple top-hat filter with a cutoff of 10 days, so that eddies are defined as the 10 day high pass filtered data, while the mean flow is defined as the 10 day low passed filtered data. We then calculate eddy fluxes as the low passed covariances between high-passed fields. Examining meridional wind variances using a 24 hour difference filter which spans 2-8 day periods gave similar results. A Lagrangian analysis of the momentum sources of the jets in the Atlantic basin and over Africa is done by calculating back-trajectories up to one week back (see Martius and Wernli, 2012, and Martius, 2014, for details). To examine possible causes and effects of an anomalously zonal jet state, we calculate composites of various fields, by averaging monthly data over subsets of the Dec-Mar winter months. Statistical significance is calculated from the anomaly field composites using a standard two-sided T-test against climatology, with anomaly defined as the deviation from a monthly climatological seasonal cycle. Regions for which the anomalies are significant are shaded, both on plots of the full field and of anomaly field composites. Unless otherwise noted, the results we present will be from NCEP reanalysis, for the years 1949-2012, but we verified that the main features of the composite analyses hold also for ERA40 and ERA Interim.

3 The unusually zonal Atlantic-African jet state

3.1 The anomalous conditions during winter 2010

One of the anomalous features of the Northern winter 2010 in the Atlantic, which has not received much attention so far, is the merging of the Atlantic and African jets. Fig 1 shows the upper and lower level jet during this winter, alongside climatological winds. For this part of the analysis we use daily and monthly mean winds from NCEP re-analysis, for 1949-2012 (Kalnay et al., 1996). We see that during 2010 the Atlantic jet became zonally oriented, while the African jet shifted a bit poleward, so that the two jets merged into one. An examination of the latitude-height structure of the Atlantic jet during this winter, in comparison to the climatological Atlantic and Pacific jets (Fig. 2) shows more similarity to the Pacific which has a single jet with strong baroclinic and barotropic components. Consistent with Eichelberger and Hartmann (2007) the anomalous jet configuration during this winter was unusually persistent, and its temporal variability was more characteristic of the jet variability in the Pacific than in the Atlantic (Fig. 3).

3.2 The Zonal Jet Index (ZJI)

The main feature which characterizes the merged Atlantic and African jets is their unusual zonality. We therefore define a Zonal Jet Index (ZJI), which will allow us to objectively identify other such periods. Looking at the 300 hPa zonal wind field (we used either monthly or seasonal averages), we first find the latitude of the jet axis ($\varphi_{ja}(\lambda)$), defined at each longitude λ as the latitude φ with maximum zonal wind values (thick black lines in Fig. 1), and calculate its zonal derivative ($\frac{d\varphi_{ja}}{d\lambda}$). This derivative will have the largest magnitude (large negative values) at the point where the jet axis jumps from the Atlantic to the African jet. During years when the jet is very zonal, as in Figure 1a, this gradient will be small (in absolute value) everywhere.

Using the monthly or seasonal averaged winds, we calculate the maximum absolute value of the zonal gradient of the latitude of the jet axis, and define the ZJI as the monthly anomaly of this quantity from its climatological seasonal cycle. Defined this way, the ZJI will be anomalously negative during months with an unusually zonal jet. Fig. 4a shows the corresponding ZJI time series using monthly mean zonal mean winds at 300 hPa. The figure shows all months, but we marked with solid dots those Dec-Mar months for which the ZJI anomaly (of both signs) exceeds one standard deviation (dashed lines). Note that anomalously zonal jet configurations (negative ZJI anomaly) have occurred during all seasons but we only concentrate on winter months. We see that the ZJI during the winter of 2010 is negative and anomalously persistent, with all 4 winter months being strongly negative. This is highlighted when we examine the ZJI calculated from the Dec-Mar mean 300 hPa zonal wind (Fig. 4b). We also see that there are other months and winters with a negative ZJI index, with more such months occurring in the earlier half of the time series, and other very anomalous ZJI winters occurring only prior to 1971.

3.3 The characteristic negative ZJI jet structure

Figure 5a shows a composite of monthly mean 300 hPa winds for winter months with strongly negative ZJI values, based on a 1 standard deviation threshold (the dots below the lower dashed line in Fig. 4a). We see that indeed during months with anomalously negative ZJI values the Atlantic and African jets merged to one unusually zonal jet. The corresponding zonal wind anomaly composite (Fig. 5b), plotted along with the composite jet axis (thick black line) show an equatorward shift of the Atlantic jet, and a poleward shift of the jet over eastern-central Africa. In contrast, the composite for anomalously positive ZJI (the dots above the upper dashed line in Fig. 4a), shown in Fig. 5c, shows a strongly slanted Atlantic jet which is well separated from the African jet, but the pattern is not statistically significant. This is due to the large variability in split-jet structures, which partly reflects the trimodal structure of the distribution of Atlantic jet latitudes (Woollings et al., 2010a). Also shown, for reference, is the corresponding composite for negative NAO months (based on 1 standard deviation, Fig. 5d). We see that while the Atlantic jet is similar between the negative NAO and negative ZJI composites, the African jet does not shift poleward as much for the negative NAO, so that the two jets are not connected as in the winter of 2010. In what follows we only examine the negative ZJI state, and note that the index was only tested for the monthly and winter mean Atlantic-African jets, so that it does not necessarily work as an indication of jet merging in other regions and on other time scales.

4 Dynamical characteristics of anomalously zonal jet months

In this section we examine the characteristics of various circulation features during months with an unusual zonal Atlantic jet configuration, with the aim of understanding what drove the jet to shift to a merged state and what maintains it. In particular, we examine changes in eddy and thermal driving, and how they related to the changes in the mean flow. We start by calculating negative ZJI composites of various fields. These composites consist of averaging monthly data over those Dec-Mar months for which the ZJI index is negative by more than 1 standard deviation (the dots below the lower dashed line in Fig. 4a).

4.1 Eddy driving

One of the main sources of variance to the Atlantic jet structure is a change in the synoptic scale eddies, which nonlinearly interact with the jet. Fig. 6a-c shows the negative ZJI composites of eddy meridional wind variance, chosen to represent the midlatitude storm track, alongside its climatological field. As expected, the storm track is more zonally oriented during zonal jet years, with its eastern edge reaching Spain rather than Great Britain. Apart for an equatorward shift, however, the eddies weaken during zonal jet years (this is despite the ZJI composite being an average over much fewer months than climatology). This is most evident from the anomaly composite (Fig. 6c). This overall weakening is also evident in the anomalous eddy heat and momentum fluxes (Fig. 6d,e). While in the climatology, the eddy heat fluxes are mostly positive and assume the North-Eastward slant of the Atlantic jet, during zonal jet months, the eddy heat flux anomaly (Fig. 6d) is mostly negative over the central and Eastern North Atlantic and positive over Europe, suggesting eddy growth is greatly suppressed but extends further eastwards, consistent with less efficient baroclinic growth in a more zonal storm track. Eddy momentum fluxes, which are typically directed polewards over most of the storm track region, are significantly weaker during zonal jet years (Fig. 6e), with small increases in the subtropics over the Eastern Atlantic and Africa, due to the equatorwards shift of the eddies. This decrease results in an anomalous eddy momentum flux convergence (Fig. 6f) which accelerates the flow south of $40^o N$ and decelerates it poleward of $40^o N$, reinforcing the observed zonal wind anomaly (Fig. 4b)[1].

It is important to note that the analysis presented shows instantaneous effects, indicating consistency, and not causality. We do not expect to be able to establish causality from observations since the eddies and the jet feedback on each other and the time scales are sub monthly. The above results are however consistent with a transition to a merged jet state, as follows. In the eddy-driven jet regime, the tropical thermally-driven direct mean meridional circulation which continuously forces westerly winds at the subtropics is weak, so that the eddy momentum flux convergence dominates and forces a jet in midlatitudes. When the midlatitude eddies and their

[1]We also examined the contribution of zonal momentum flux convergence and found it to be negligible compared to the meridional component.

associated eddy momentum flux convergence are weaker, as is observed to be the case during zonal jet years, the thermal driving of the jet can play a more significant role. The equilibrated jet in this case is more equatorward and is affected by both thermal and eddy driving (c.f. Son and Lee, 2005; Lachmy and Harnik, 2014). At the same time, the transition to a merged jet state will also weaken eddy amplitudes, by trapping the upper level disturbances equatorwards of the latitude of strongest surface baroclinicity and making baroclinic growth less efficient (Nakamura and Sampe, 2002).

4.2 Thermal driving

Son and Lee (2005) showed that stronger tropical heating leads to a single merged jet, while weaker heating leads to a strong eddy-driven jet alongside a weaker subtropical jet. Li and Wettstein (2012) examined observed monthly mean Northern Hemisphere winter data and showed that in the Pacific, monthly variations in the jet stream correlated strongly both with midlatitude eddy momentum flux convergence and with various proxies of thermal driving. In the Atlantic, on the other hand, they found a strong correlation only with the eddy momentum flux convergence. Given the similarity between the Atlantic and Pacific jets during negative ZJI months, we expect thermal driving to play a larger role during such months. Following Li and Wettstein (2012) we use total column integrated diabatic heating calculated directly from the monthly reanalyses products by summing the net short and long wave radiative fluxes into the atmospheric column (top of atmosphere and surface fluxes), the surface vertical sensible heat flux, and the latent heat released by local precipitation (Eq. 5 of Trenberth and Solomon, 1994). Since radiation data in NCEP reanalysis are only given since 1992, we also use ERA Interim, which starts in 1979.

Fig. 7a,b shows the negative ZJI monthly anomaly composites for both reanalyses. We see a significant Atlantic tripole pattern, with anomalous heating over the midlatitude Atlantic, a large negative anomaly in the northern part of the Atlantic just south of Greenland, and a weak anomalous diabatic cooling in the subtropical Atlantic, which is stronger in NCEP than in ERA Interim, similar to what is found for a negative NAO. In the tropics, however, we do not see a significant signal over the Atlantic, but we do see significant anomalous heating in the equatorial Pacific. These anomalies are consistent with El Nino conditions, which were observed during winter 2010. These results suggest that anomalous tropical Pacific heating forces a stronger Atlantic subtropical jet, strong enough to cause it to transition from a double to a single jet during these months. This is actually consistent with Fig. 2 of Li and Wettstein (2012) which shows a zonal wind anomaly in the mid-latitude Atlantic in composites of extreme tropical Pacific diabatic heating, but not in composites of tropical Atlantic diabatic heating.

Since latent heat release is a major component of the diabatic heating fields (e.g. Romanski, 2013), but this field is highly dependent on the analysis model parameterizations, we also examine monthly GPCP precipitation fields (Adler et al., 2003). The precipitation rate ZJI anomaly, shown in Fig. 7c, looks quite similar to the diabatic heating anomalies, though there is no clear negative anomaly in the subtropical Atlantic, and the positive midlatitude anomaly is only over the Eastern half of the Atlantic. As with diabatic heating, there is a significant positive anomaly over the Central and Eastern Pacific, and even a hint of a midlatitude Eastern Pacific dipole.

We note, from Fig. 4, that a significant number of the negative ZJI months occurred prior to 1979, thus the diabatic heating and precipitation composites consist of only 10 negative ZJI months after 2002, and 3 more between 1979-2001. To extend the composite analysis back in time and include the zonal jet months prior to 1979, we examine vertical pressure velocity (ω) using NCEP reanalysis for the period 1949-2012. As was shown, for example by Li and Wettstein (2012), the climatological ω pattern captures the diabatic heating and precipitation fields well. The negative ZJI ω anomaly composite is shown in Fig. 7d. For clarity, we plot negative values (upward motion) which indicate diabatic heating, in solid. We see anomalous ascent over the tropical Pacific, and a tripole anomaly pattern over the Atlantic. As with the precipitation anomalies, the significant midlatitude ascent occurs only over the Eastern half of the Atlantic. To examine causality, we calculate time lagged composites of all the above fields. Fig. 7e shows a composite of the ω field 2 months prior to the anomalously negative ZJI months. We see a significant tropical Pacific anomaly (with the anomaly starting to be significant already in month -3, not shown), suggesting the Tropical Pacific heating at least partially drives the anomalous jet state. The time lead of tropical Pacific heating is also evident from the SST anomalies which at time lag of -2 months (Fig. 7f) show a very clear positive anomaly which is maximal in the central tropical Pacific, and consistent with El Nino conditions. This tropical Pacific anomaly develops as early as 3 months before the jet becomes zonal, and diminishes only after the peak negative ZJI month (not shown).

The El Nino conditions during winter 2010 prompted Santos et al. (2013) to examine the role of the tropical Pacific in forcing the variability of the Atlantic jet. They did not, however, find a significant signal, suggesting this was a coincidence which occurred during winter 2010. To further verify the robustness of our results, we repeated the composite calculations using subsets of the data. Figure 8a shows the composite of ω anomalies at 0 time lag, for 1949-2011 excluding the four winter months of winter 2010. We see significant ascent in the tropical Pacific (with anomalies being significant as early as month -3), suggesting the tropical Pacific forcing is not unique to winter 2010. We also repeat the analysis for 1979-2012 (Fig 8b,c), and find much weaker anomalies with no significant signal when we remove the winter 2010 months, similar to Santos et al. (2013) (who used ERA interim from 1979). To more closely examine the monthly signals, we define a Tropical Pacific Ascent Index (TPAI) as the average of ω (weighted by cosine latitude) in a tropical box extending from $200^oW - 100^oW$, $15^oS - 15^oN$ (marked in blue on Fig. 8a), and plot it against the monthly Dec-Mar ZJI time series, with the winter months up to 1978 in red and the rest in blue. For reference, we mark the line of -1 ZJI standard deviation, and mark the 2010 winter months by large circles. We see that about two thirds of the negative ZJI months also have negative TPAI values (anomalous ascent), with more negative ZJI months with negative TPAI before 1979. The winters of 2010, 1970, 1969 and 1958, which had a negative ZJI for a few consecutive months (Fig. 4), had anomalously negative TPAI values. Overall, the results support our notion that the tropical Pacific contributes to the anomalous merging of the Atlantic and African jets during a few very anomalous months.

To further examine the role of tropical Pacific heating on the Atlantic jets, we use a back trajectory calculation similar to Martius and Wernli (2012) and Martius (2014). The subtropical jet is forced to first order by the export of angular momentum from the tropics into the subtropics. The angular momentum is modulated in the subtropics by eddies. However, the role of the eddies is of secondary importance during the winter (e.g. Bordoni and Schneider, 2010; Martius, 2014). The back trajectories thus indicate where the transport of angular momentum from the tropics into the subtropics happens. Here we use this analysis to examine the tropical Pacific contribution to air flowing into the Atlantic jet entrance (90^oW-45^oW) and African jet (30^oW-30^oE) regions. Since the analysis is very computationally intensive, it has only been carried out for 8 winters (Dec-Feb, year corresponding to Jan-Feb), using ERA Interim. Based on Fig 4b, we chose 1996, 2005 and 2010 as representative negative ZJI winters, while 1997 and 2006-2009, which were not negative ZJI years, were chosen for comparison. For each day during a given winter, the back trajectory calculation first picks the grid points which constitute the jet, based on characteristics of a subtropical jet - wind velocities above $40m/sec$ and the vertical shear concentrated at upper-levels (see Koch et al., 2006). These grid points serve as starting points for the back-trajectory calculation which is run for 7 days (168 hours). Fig. 9 shows the fraction of the total number of trajectories which cross each grid point over the entire seven day period, as well as the region from which the calculation is started (thick black contour), calculated for the negative ZJI winters of 1996, 2005 and 2010, and an average over 5 other winters (1997, 2006-2009). Also shown is the difference between the two plots. During the years when the jet has a more typical structure, the air parcels that end up in the wintertime subtropical jet over Africa typically ascend into the upper troposphere and hence enter the northward directed branch of the Hadley cell over South America (Martius, 2014). During the negative ZJI winters, a smaller than usual fraction of trajectories reached the subtropical jet over Africa and the Atlantic from South America. In contrast an anomalously large fraction of the air parcels moved northwards from the equator into the subtropics from the tropical Pacific, in particular over the Eastern part $(120^oW - 90^oW)$[2]. In addition, more air flows into the jet from the subtropics, consistent with a strongly zonal flow, and less comes from mid latitudes, South America, or the Tropical Atlantic. The African jet also shows a greater contribution from far upstream sources (Asia and the Pacific and even the eastern subtropical Atlantic), compared to closer upstream air (the western subtropical Atlantic) during the negative ZJI winters, consistent with the merged jet structure.

5 Connection to Atlantic SST

The winter of 2010 was also characterized by strong North Atlantic SST anomalies (Taws et al., 2011; Buchan et al., 2014, and Fig.. 7f). Fig. 10a,b shows the composites of SST anomalies and

[2] We note that 1996 and 2005 were chosen since their ZJI values were the most negative, however, these may not be the most optimal years for detecting a tropical Pacific role since their TPAI values were positive. An examination of the winter of 2010 back trajectories separately from the winters of 1996 and 2005 shows an increase in the number of trajectories coming from the tropical Pacific, but this increase was larger during 2010, in particular in the western part (between $120^oE - 150^oW$).

their meridional gradients in the North Atlantic region, for the anomalously negative ZJI winter months, using monthly ERSST data (Smith and Lawrimore, 2008) ranging from 1949-2012. We also show the line of peak positive lower level wind anomalies (thick black line in Fig. 10a,b), calculated from the negative ZJI composite of $925 - 700$ hPa zonal wind anomalies[3]. We see a significant North Atlantic tripole anomaly, with warm SSTs in the tropics and just south of Greenland and cold water in between, with the line of maximum lower level westerlies slightly equatorwards of the peak cold SST anomalies. This SST anomaly pattern is quite typical of the ocean response during negative NAO conditions (e.g. Visbeck et al., 2003). The tropical warm anomaly extends from the Eastern Tropical Atlantic, where variability was found to be strongly correlated to ENSO (Enfield and Mayer, 1997), all the way to the western coast of Africa. The meridional SST gradients are enhanced (more negative) in the subtropics (Figs. 10b). In the Eastern Atlantic, the anomalous negative gradients coincide with the line of maximum anomalous lower level westerlies, suggesting there is a possible positive SST-wind feedback in this region. The SST anomalies last more than a month, with the high latitude and midlatitude anomalies starting to diminish at lag 2 months and the subtropical warm anomaly lasting even 3 months (not shown). While the SST anomaly pattern is quite typical of negative NAO conditions (e.g. Visbeck et al., 2003), a closer examination shows that during the more persistent negative ZJI winters, the SST gradients in the Eastern Subtropical Atlantic are anomalous even with respect to typical negative NAO conditions. Fig. 10c shows the winter mean time series of the anomalous meridional SST gradients averaged over a box in the Eastern subtropical Atlantic ($20W - 50W$, $24N - 34N$, the blue box marked on Fig. 10b), in the region where the SST gradients are aligned with the anomalous strong surface winds. We see two pairs of consecutive winters with very negative gradients - 2010/2011 and 1969/1970 in which negative gradients are stronger during

[3]The 10 m wind anomalies give similar results.

the first winter. Taws et al. (2011) showed using subsurface ocean data that the SST anomalies during 2010 were strong enough to affect the more persistent subsurface ocean and reemerge the following winter. They further suggested that this reemergence contributed to the anomalously negative NAO during early winter 2011. Though we do not have early subsurface observations, the time series suggest this reemergence mechanism could also have occurred during 1969 and 1970, with the anomalous SST contributing to the anomalous jet state during the winter of 1970. Examining the winter-mean ZJI time series (Fig. 4b), we see that indeed these winters were all characterized by a negative ZJI (though in 2011 it lasted only during Nov-Dec). Moreover, we see a clear coincidence between negative winter mean ZJI and strongly negative winter mean SST gradient index (e.g winters of 1964, 1969, 1970, 1996, 2010). This suggests that anomalously persistent zonal wind anomalies during zonal jet years acts to induce large Eastern Subtropical Atlantic SST anomalies. These large SST anomalies, in turn, could also strengthen the wind anomalies (c.f. Nakamura et al., 2004, 2008). While more studies need to be done to establish it, a positive SST-jet feedback could explain the strong persistence of the zonal mean wind anomalies during some of the negative ZJI episodes. Recently, Buchan et al. (2014) examined the role of Atlantic SST anomalies in forcing the negative NAO during winters 2010 and early winter 2011 using a coupled GCM, and found a significant role only for the early winter 2011. They however emphasized the role of SSTs in initiating the negative NAO conditions, and did not examine their role in increasing NAO persistence, thus their results are not inconsistent with our findings.

6 Connection of ZJI to other atmospheric indexes

The results of previous sections suggest El Nino conditions contributed to the onset of the anomalously zonal jet state, by strengthening the thermal forcing of the jet. We also saw a strong resemblance of negative ZJI months to a negative NAO state. In this section we examine the statistical relation between the ZJI, the NAO index and ENSO. Fig. 11 shows a scatter plot of monthly Nino 3.4 index values with the colors marking the NAO index (negative NAO in blue and positive in red). We see that except for one month, jets with a strongly negative ZJI are in a negative NAO state, while positive ZJI months occur more with a positive NAO. This explains the similarity between the negative ZJI composites and NAO composites. On the other hand, not all negative NAO states are characterized by a zonal jet.

We also see that with the exception of one month, anomalously zonal jets (ZJI smaller than $-1std$) have not occurred during a strong a Nina, suggesting La nina conditions are detrimental to the merging of the Atlantic and African jets. This is consistent with the notion that the merging of these jets is due to the eddy and thermal jet forcings both playing a role in forcing the jet during these years. The relation between ENSO and the ZJI, however, is complex. In particular, it seems to be different during positive and negative NAO months, with ENSO and ZJI being slightly positively correlated during positive NAO months (correlation of 0.17, 92% significance), and slightly (but not significantly) correlated during negative NAO months (correlation of -0.96). This is consistent with the picture that under the right conditions of weak enough eddies which have not shifted the jet too far poleward (a negative NAO), tropical heating during can zonalize the Atlantic jet by inducing a merged thermally/eddy-driven jet state.

7 Summary and conclusion

We have shown that the Northern winter of 2010 (Dec 2009 - Mar 2010) was characterized by an anomalously zonal jet, in which the Atlantic jet shifted slightly southward and assumed a more zonal position, while the African subtropical jet shifted slightly poleward so that the two jets connected to form one elongated zonal jet. Moreover, the latitude-height structure and temporal variability of the Atlantic jet were more characteristic of the Pacific than the Atlantic during this winter. In the context of characterizing the jet stream types (e.g. Son and Lee, 2005), it seems that during this winter, the jet changed from being eddy-driven to being a mixed eddy/thermally-driven jet. This paper examines the possible transition of the Atlantic jet stream from an eddy-driven to a merged jet, as part of the large inter annual variability in the Atlantic. We defined a Zonal Jet Index (ZJI) which characterizes the zonal gradient in the latitude of the jet axis, with anomalously negative values representing anomalously zonal jets. Calculating this index for monthly data allows us to identify zonal jet months. We find that while an unusually zonal state occurs occasionally for a month, it is quite rare for it to be dominant for a whole winter, with the last occurrence before 2010 being the winters of 1969 and 1970. A composite analysis of various eddy quantities in comparison to the climatology shows a picture similar to a negative NAO state, with eddies and eddy fluxes being weaker, and shifted anomalously south. A composite analysis of various quantities related to diabatic heating, including total atmospheric column heating, precipitation, vertical velocities and anomalous SSTs, show anomalous heating in the tropical Pacific. This suggests the combination of weaker eddies and enhanced tropical heating, with positive eddy-mean flow feedbacks, push the jet from being eddy-driven to being partly thermally-driven as in the Pacific (Li and Wettstein, 2012). A Lagrangian back-trajectory analysis of the African and Atlantic jets shows that indeed the tropical Pacific is one of the sources of momentum for both jets, and that during negative ZJI years this source is enhanced relative to other years.

A composite of SST anomalies shows a typical Atlantic tripole pattern (with a phase characteristic of a negative NAO pattern) but with particularly anomalous meridional gradients in the eastern subtropical Atlantic, where the surface wind is anomalously westerly. Previous studies found a strong SST feedback over the Gulf stream region (e.g. Ciasto and Thompson, 2004). We find that when the anomalous meridional gradients become negative enough in the Eastern subtropical Atlantic, an anomalously zonal jet state persists, suggesting a positive SST feedback, but in the Eastern subtropical and mid-latitude Atlantic. Moreover, the SST gradient anomalies in the observational record appeared in pairs of two consecutive winters: 1969/1970 and 2010/2011, with the earlier winters showing stronger anomalies, suggesting these strong anomalies reach the deep waters and reemerge to strengthen the zonal jet state during the following winter (as in Taws et al., 2011).

Thus the picture which emerges is that the Atlantic jet undergoes typical variations associated with eddy-mean flow interactions, which give rise to the typical Atlantic variability associated with the NAO. During a few winters when an anomalously equatorwards jet coincides with anomalous tropical heating, the jet can undergo a transition to a mixed thermally/eddy-driven jet state, which is more characteristic of the Pacific. Woollings et al. (2010b) examined the distribution of NAO phases, and attributed the observed skewness to the existence of two different flow regimes- a "Greenland Blocking" pattern more characteristic of a negative NAO, and a "sub-polar jet" state more characteristic of a positive NAO, each of which exhibits variability with a Gaussian distribution. The relation between Greenland Blocking and the type of jet stream is left for a future study.

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and visualization of geophysical data (http://www.goat-geo.org).

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Figure captions

Fig. 1. 300 hPa zonal wind: a) Dec 2009 - Mar 2010 mean. b) Dec-Mar climatology (1949-2012). c,d) as in a,b) but for $925 - 700$ hPa. The jet axis (latitude of maximum zonal wind) is marked by the thick black lines. Contour intervals are $10m/sec$ and $3m/sec$ for the upper and lower level winds, respectively. In plots (a)(b) contour values of $10m/sec$ and less are dashed, while in plots (c)(d) values of $3m/sec$ and lower are dashed.

Fig. 2. Latitude-height plots of the Dec-Mar mean zonal wind. a) Climatological values, averaged zonally over the Pacific (120W-120E). b) Climatological values, averaged zonally over the Atlantic (100W-0E). c) Dec 2009-Mar 2010 mean over the Atlantic (100W-0E). The contour interval is $5m/sec$, zero line is marked by a thick line, and negative values are dashed.

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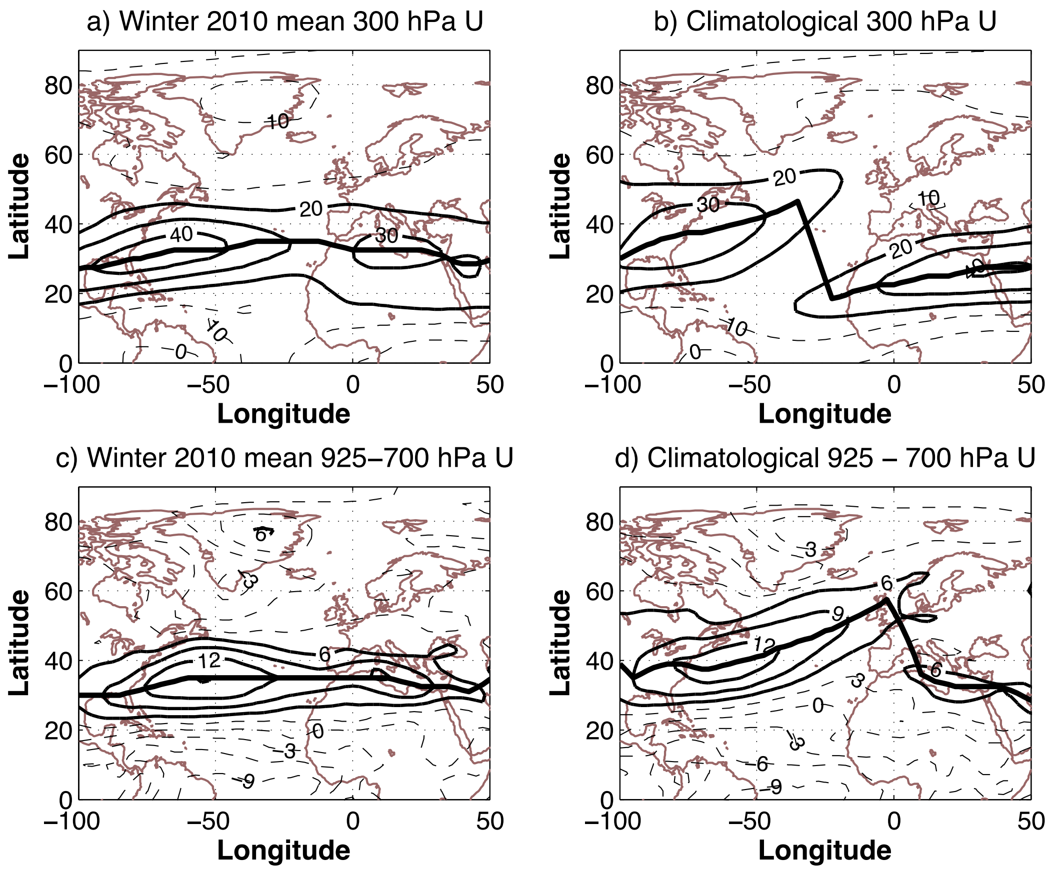

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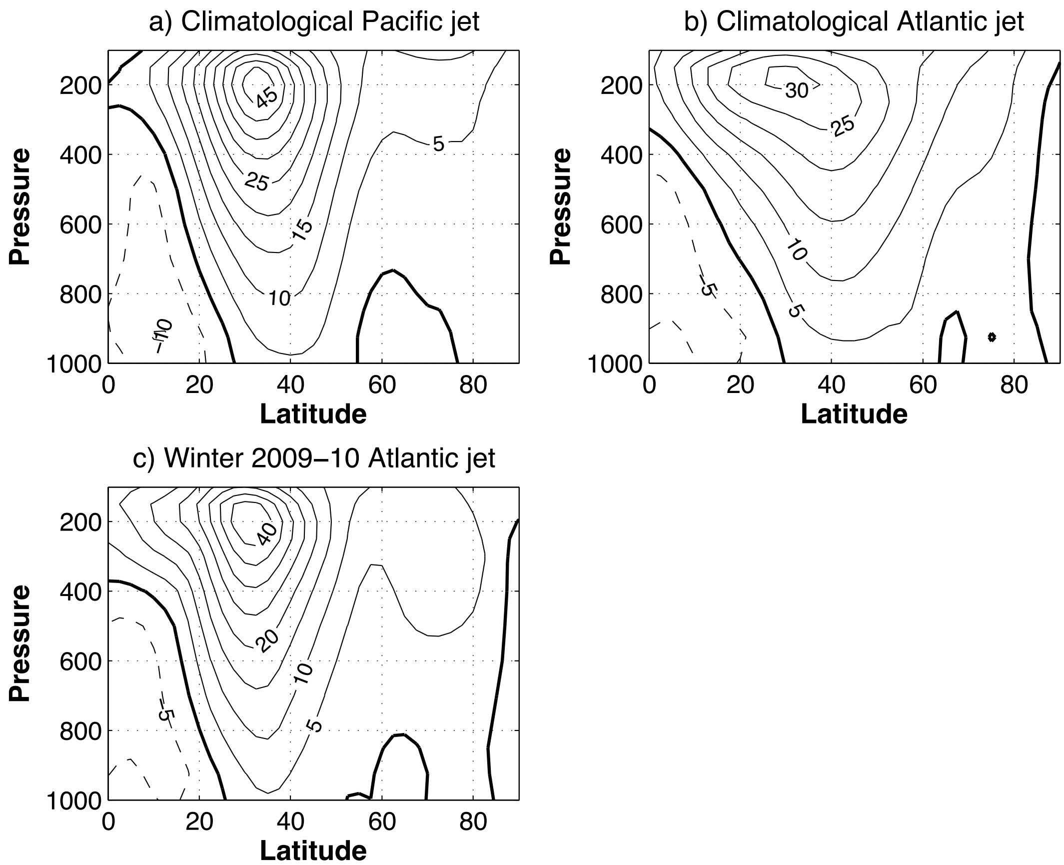

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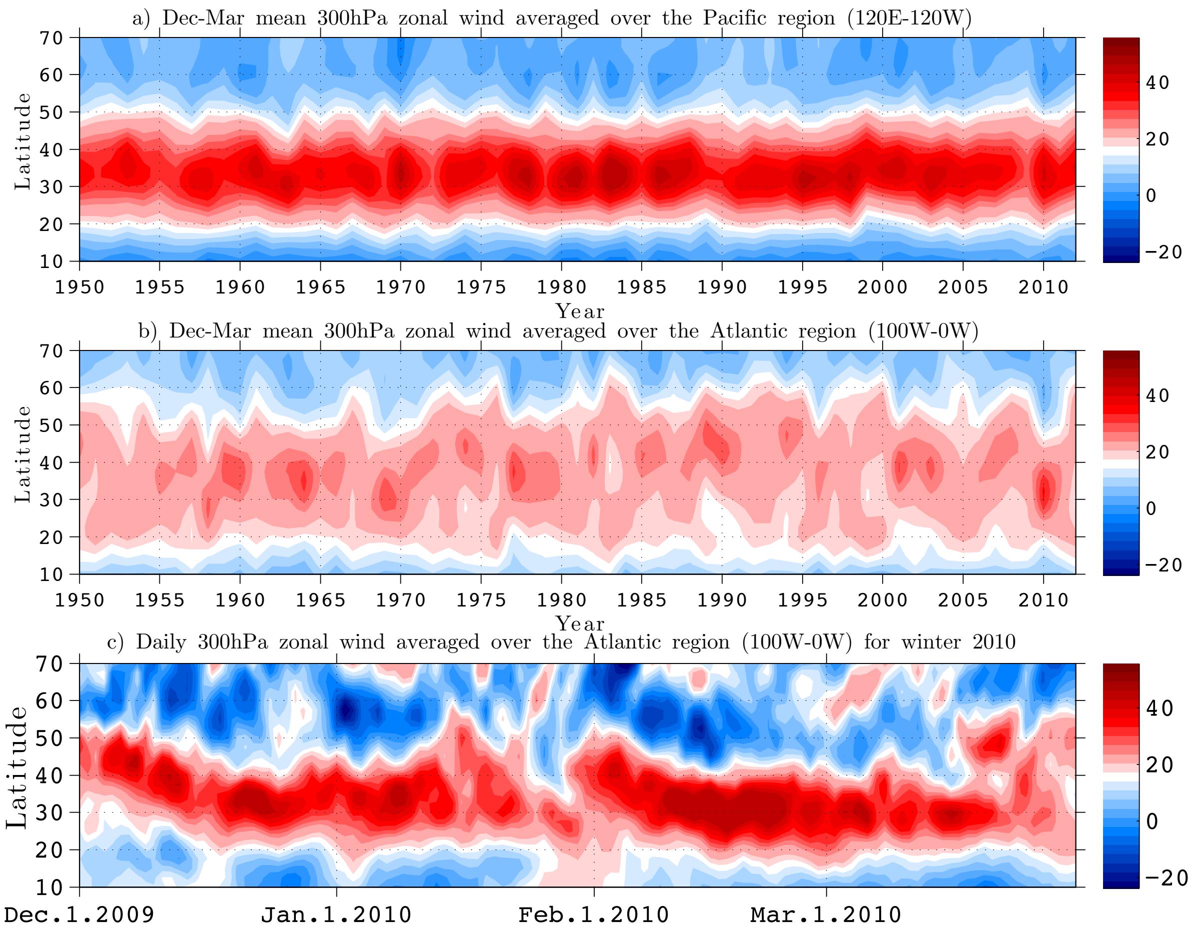

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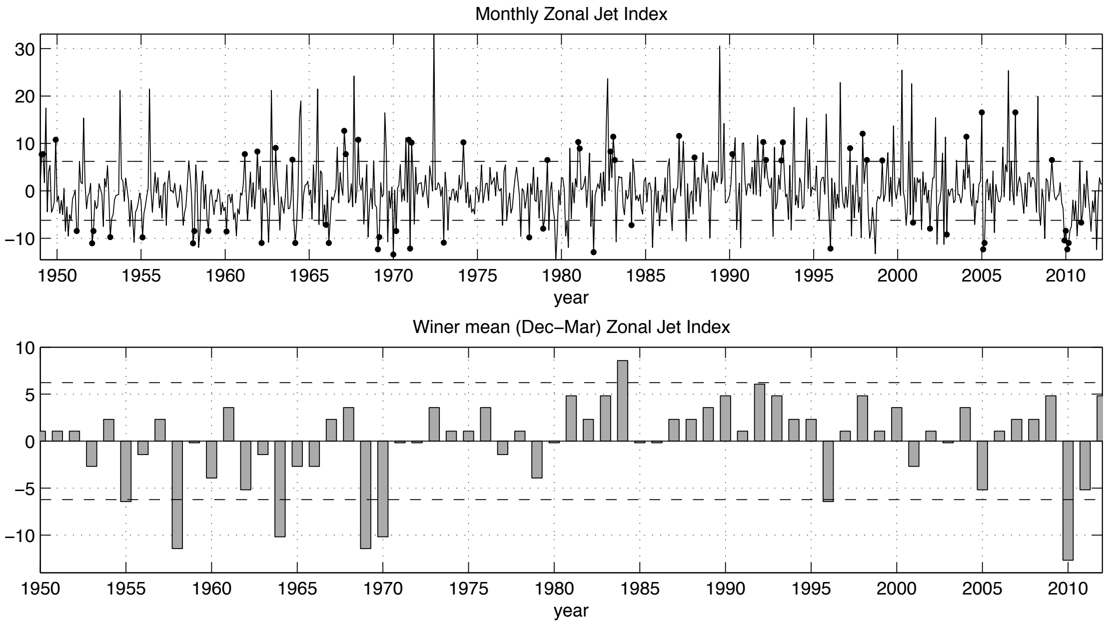

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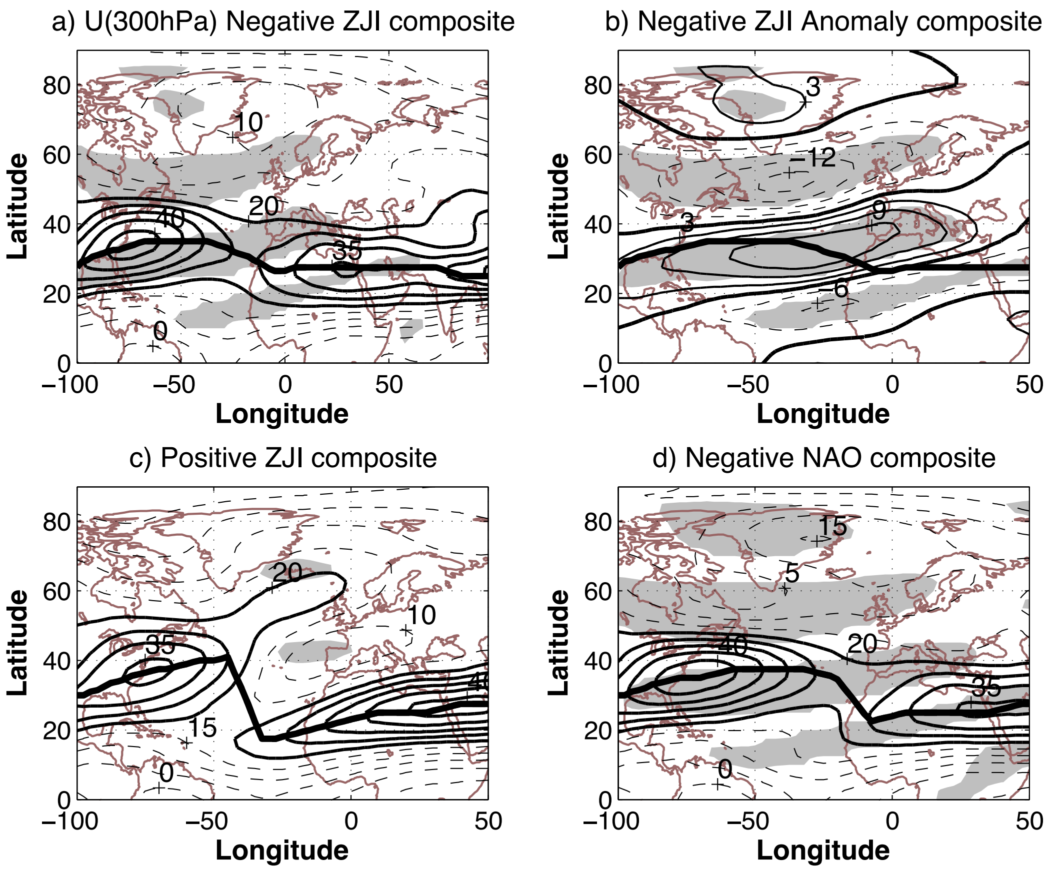

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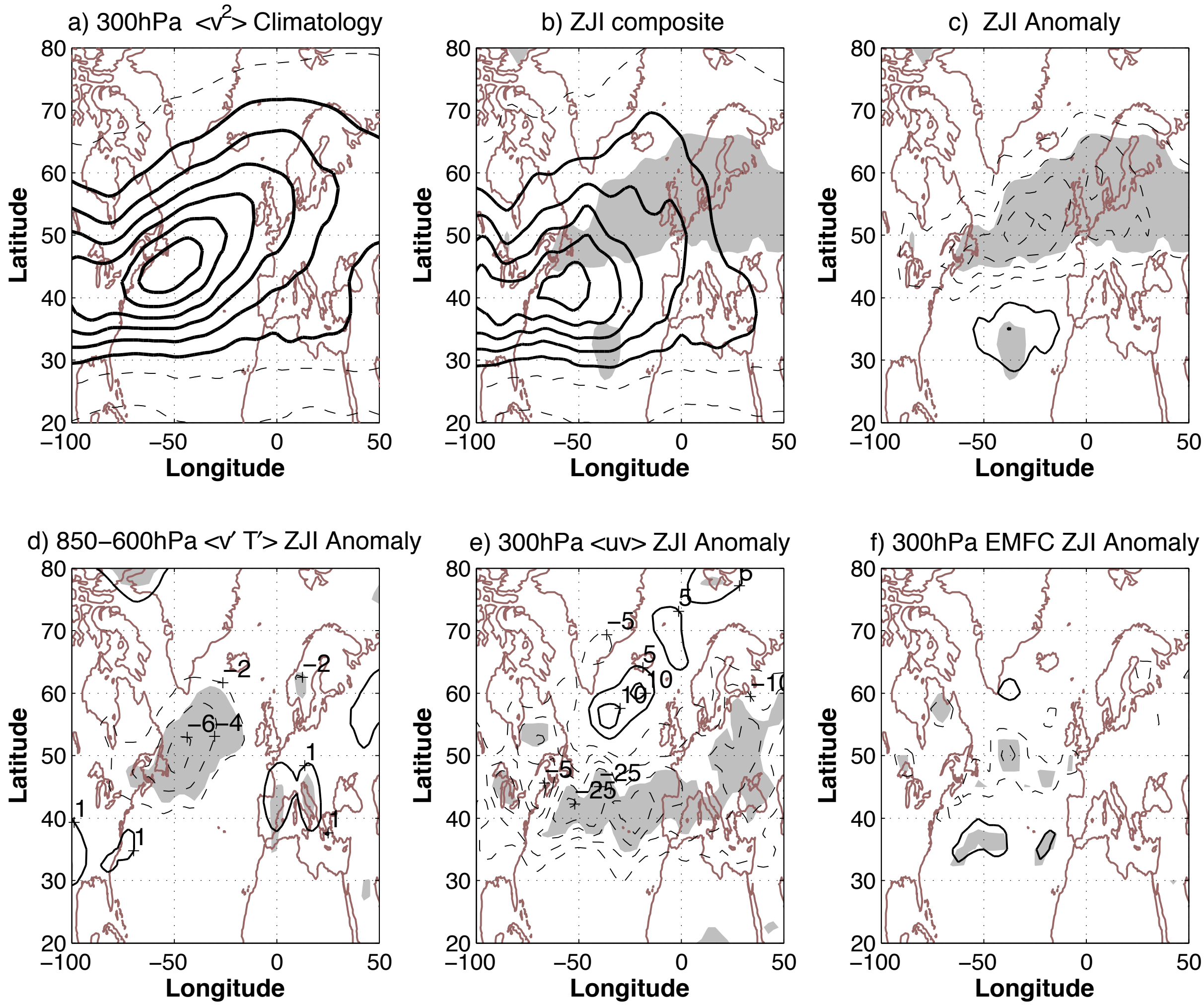

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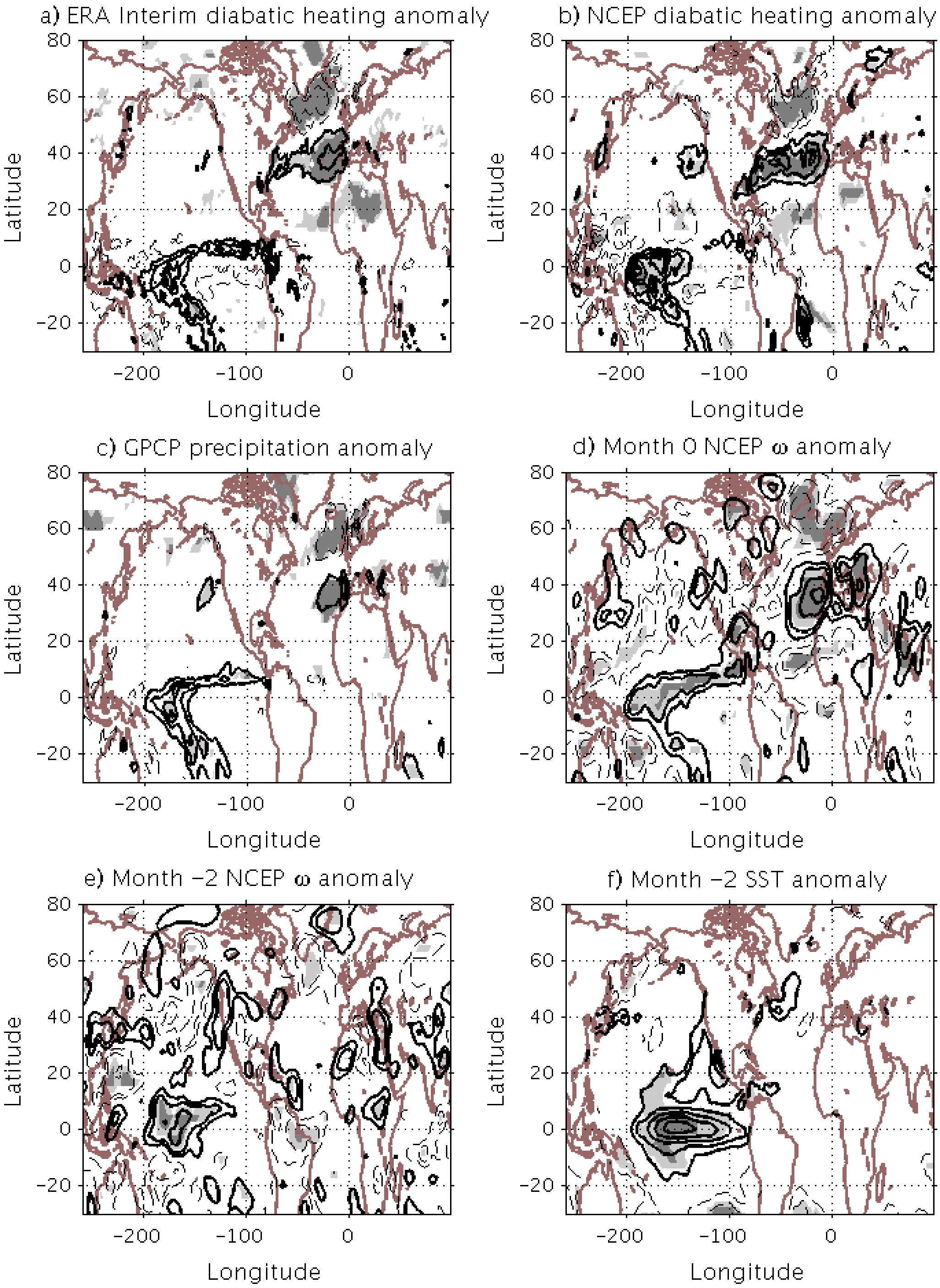

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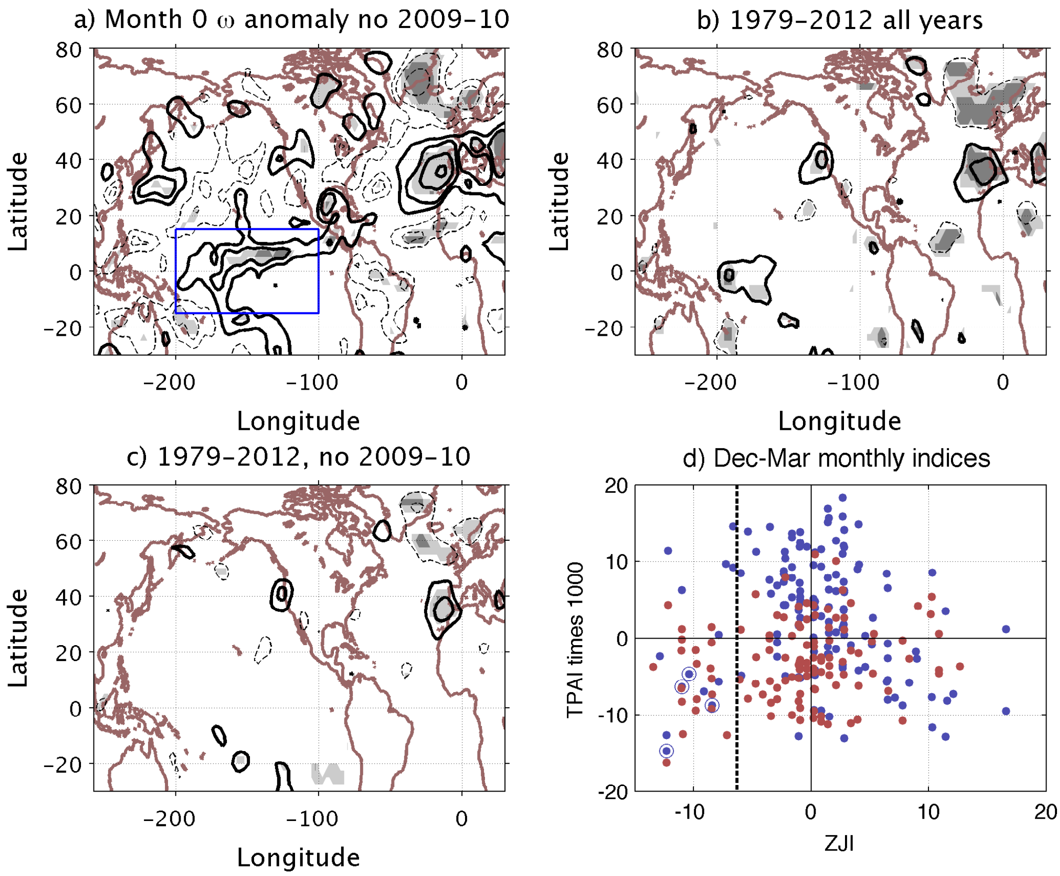

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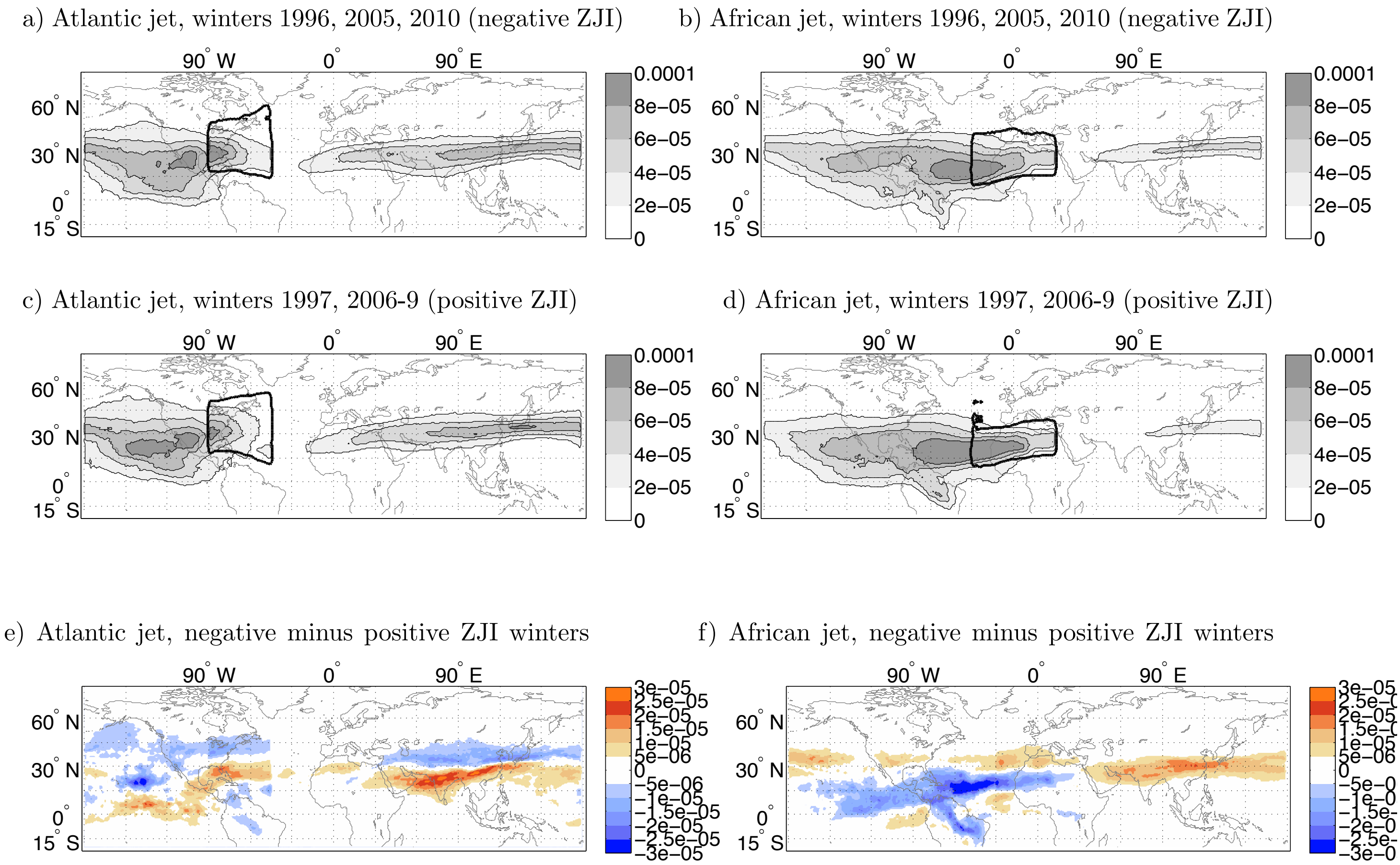

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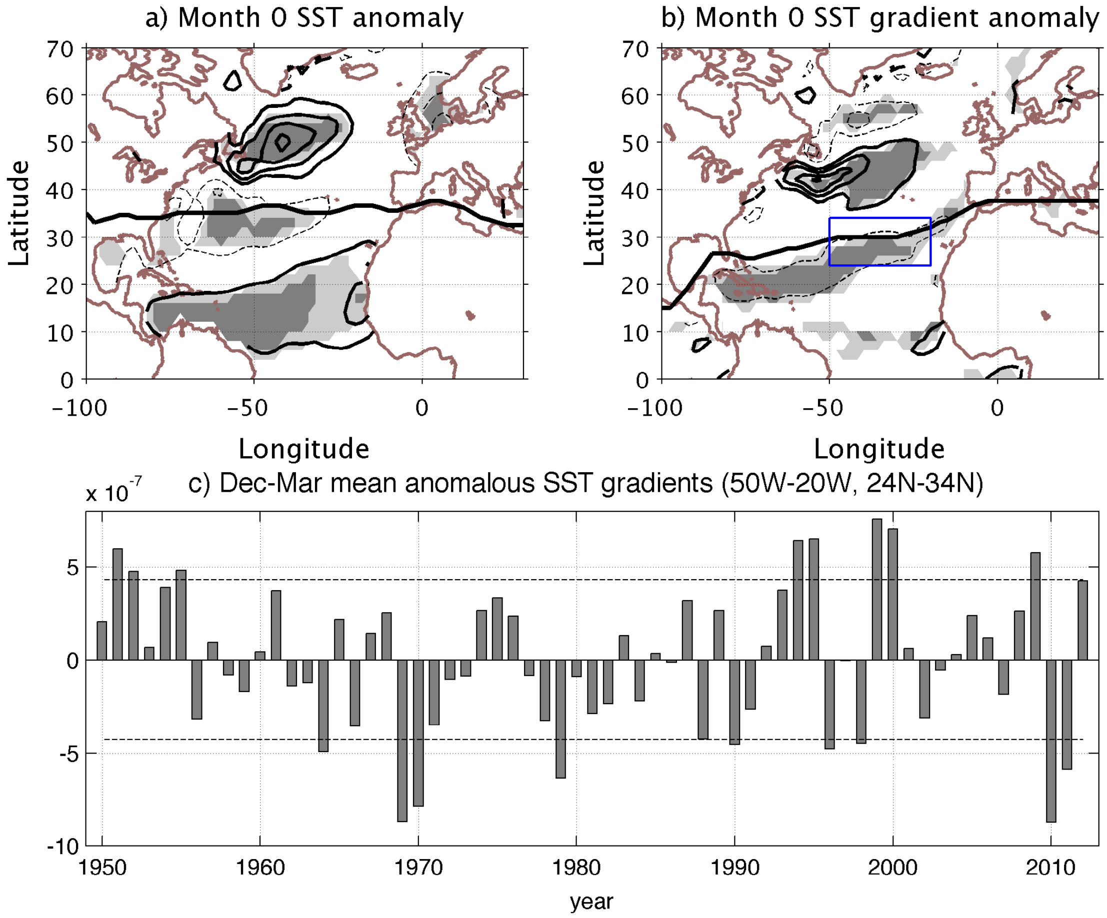

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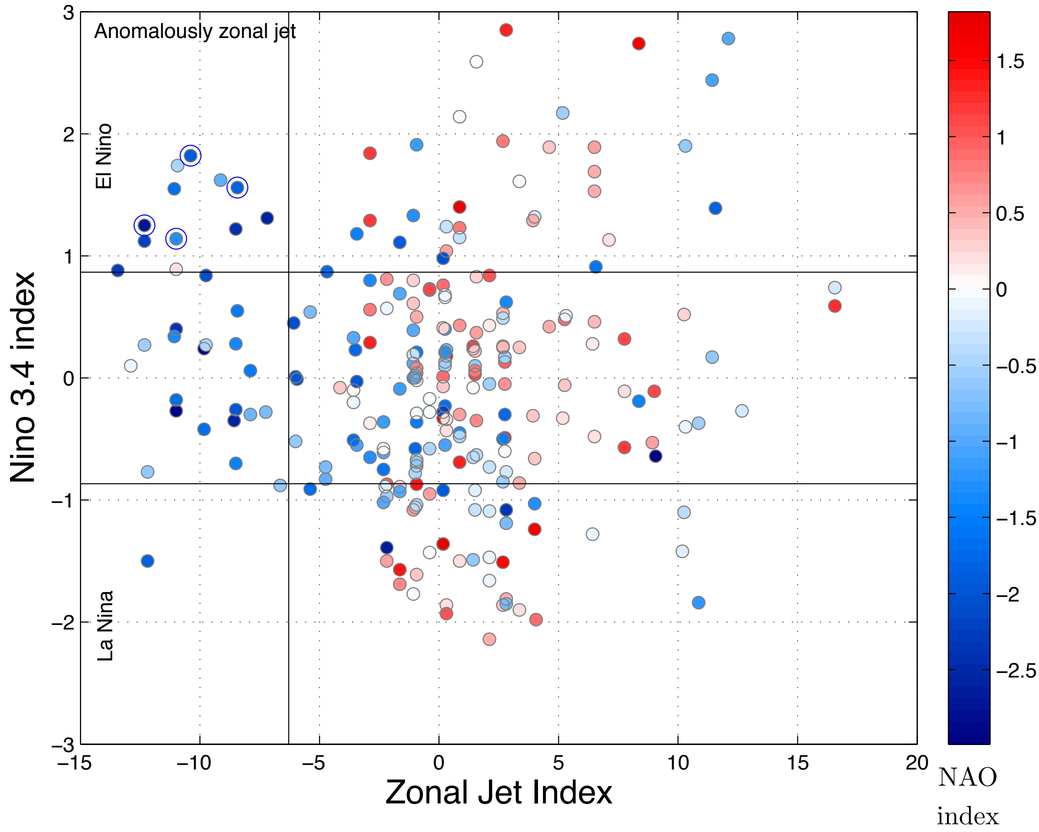

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