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Diabatic heating and jet stream shifts: A case study of the 2010 negative North Atlantic Oscillation winter

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Key Points:
- In the eastern North Atlantic, latent heating shifted south along with the jet in the 2010 winter
- However, in the west the heating remained anchored over the Gulf Stream
- Diabatic feedbacks on jet shifts may be different in the two regions

Supporting Information:
- Supporting Information S1
- Figure S1

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Abstract The role of extratropical diabatic heating in the variability of storm tracks and jet streams remains an important open question. This paper analyzes the role of diabatic heating in observationally constrained analysis data for the 2010 winter, which was notable for an extreme southward shift of the North Atlantic eddy-driven jet. An isentropic slope framework is employed by which the contribution of diabatic terms to the maintenance of seasonal mean baroclinicity can be quantified. This reveals a striking contrast between the eastern North Atlantic, where the latent heating shifted south along with the storm track in 2010, and the western North Atlantic, where the latent heating remained fixed over the Gulf Stream. This motivates the hypothesis that the latent heating may contribute to the anchoring of the storm track entrance over the Gulf Stream but provide a very different feedback on the jet variability downstream.

1. Introduction

Variability of the eddy-driven jet streams and associated storm tracks is the dominant agent of climate variability in midlatitudes and, as such, is responsible for widespread environmental and socioeconomic impacts [*Hurrell et al.*, 2003]. The jet streams vary in strength and position on timescales from days to decades [*Feldstein*, 2000; *Woollings et al.*, 2014], and these variations are commonly described by indices such as the North Atlantic Oscillation (NAO) which describes variability of the Atlantic jet. Deepening our understanding of the mechanisms of jet stream variability is essential for improving the skill of seasonal-decadal forecasting systems in predicting variations in the jets [*Smith et al.*, 2016].

Dynamical feedbacks are known to be important for jet stream variability. These typically involve the faster, transient atmospheric eddies feeding back on to the slower jet stream perturbations through changes in the structure and life cycle of these eddies [e.g., *Robinson*, 2006; *Vallis and Gerber*, 2008]. These feedbacks are generally thought to act in a positive sense, as anomalous eddy momentum fluxes reinforce the zonal wind anomalies [e.g., *Lorenz and Hartmann*, 2003; *Barnes and Hartmann*, 2010], although diagnosis of this feedback from observational data can prove problematic [*Byrne et al.*, 2016]. It has long been known that diabatic effects play an important role in the large-scale circulation [e.g., *Ferrel*, 1889; *Danard*, 1964; *Reed et al.*, 1992; *Pfahl et al.*, 2015], and the potential for these to feed back on jet variability is the focus of the current paper.

While localized storm tracks can be simulated in dry models [e.g., *Gerber and Vallis*, 2009], idealized modeling studies consistently identify midlatitude diabatic heating as a key process responsible for the maintenance of baroclinicity along the observed boreal winter storm tracks [*Hoskins and Valdes*, 1990; *Held et al.*, 2002; *Chang*, 2009a]. The localized storm tracks can then be considered to be self-maintaining to some extent, with diabatic heating organized by the cyclones acting to restore the potential energy available for subsequent systems. This balance was recently detailed in analysis data by *Papritz and Spengler* [2015, PS15 hereafter] by quantifying the impact of diabatic processes on the slope of isentropic surfaces as a proxy for baroclinicity. Storm track eddies grow by adiabatically reducing the slope of isentropic surfaces, but this slope is restored by the action of the diabatic processes associated with these eddies. Sensible heat transfer from the ocean is the key contributor to the diabatic slope restoration near the surface [*Hotta and Nakamura*, 2011], but the latent heating due to condensation of water vapor dominates in the free troposphere (PS15).

If the diabatic heating plays a leading order role in shaping the mean state of the storm tracks, it likely also plays some role in their variability. *Xia and Chang* [2014] investigated this potential feedback on Southern Hemisphere flow using a range of experiments with an idealized general circulation model.

In their experiments the diabatic heating acts to maintain the baroclinicity along the time mean position of the storm track, hence acting as a negative feedback on shifts of the storm track. These interesting modeling results appear in conflict with the literature discussed above, which motivates further examination of the diabatic heating in observationally constrained analysis data. The key questions we address here are how the distribution of latent heating changes as the jet moves and how this relates to the storm track. In particular, it remains an open question how the latent heating may feed back onto the jet variability in a localized storm track such as in the North Atlantic, with clearly separated regions of preferred cyclone growth and decay [e.g., *Hoskins and Hodges*, 2002].

A related feature of the localized North Atlantic and Pacific storm tracks is the presence of strong local sea surface temperature gradients associated with the oceanic western boundary currents. These are known to organize diabatic heating [*Minobe et al.*, 2008; *Hotta and Nakamura*, 2011] and to anchor the upstream end of the storm tracks [e.g., *Inatsu et al.*, 2002; *Nakamura et al.*, 2008; *Kwon and Joyce*, 2013; *Booth et al.*, 2010]. However, the precise mechanisms responsible for this anchoring remain a matter of debate. Cloud radiative feedbacks, which are also a potential negative feedback on jet variability [*Li et al.*, 2014; *Ceppi and Hartmann*, 2015], add more complexity. However, these play a relatively minor role in restoring the mean baroclinicity over the North Atlantic (PS15), perhaps partly because they generate weaker gradients in heating.

In this paper we build on the work of PS15 who diagnosed the maintenance of the baroclinicity in the North Atlantic sector as defined by the slope of isentropic surfaces. They used 2 years of diabatic temperature tendency data generated as part of the YOTC project (Year of Tropical Convection). The data covered the winters of 2008/2009 and 2009/2010 (referred to as 2009 and 2010 hereafter). The 2010 winter has been widely studied as a case of extremely negative NAO, when the Atlantic jet was displaced far to the south of its usual position [*Cattiaux et al.*, 2010; *Santos et al.*, 2013]. In contrast, the 2009 winter was very similar to climatology over the Atlantic; hence, there is an opportunity to compare the two winters as a case study of how the diabatic heating relates to a strongly shifted storm track. We present diagnostics of the two winters, focused on the questions of how the latent heating differs between them and how this difference affects the maintenance of the isentropic slope.

2. Methods

We use the data derived by PS15 from 6-hourly analyses for the YOTC period prepared by the European Centre for Medium-Range Weather Forecasts. Short forecast temperature tendencies arising from the different physics schemes in the model were archived during this 2 year period and were manipulated by PS15 to determine the instantaneous tendency of the slope of isentropic surfaces. The isentropic slope is given by $S = |\nabla_\theta p|$, the horizontal gradient of pressure on a potential temperature surface. Note that in contrast to PS15, we define the slope in terms of pressure instead of height on an isentropic surface. This does not make any changes to the results presented by PS15, but it makes the formalism closer to the Available Potential Energy framework [*Lorenz*, 1955]. The tendency equation for S on a pressure surface can then be written as

$$\left.\frac{\partial S}{\partial t}\right|_p = \mathrm{TILT} + \mathrm{RAD} + \mathrm{MP} + \mathrm{TUR} + \mathrm{ADV} + \mathrm{RES}. \quad (1)$$

Here the terms on the right-hand side represent the effect on the local isentropic slope of adiabatic tilting of isentropic surfaces (TILT), radiation (RAD), microphysics (MP), turbulence (TUR), adiabatic advection of the slope (ADV), and a residual (RES) accounting for numerical errors in the diagnostic calculation of the slope. The latent heating is contained within MP and dominates the diabatic terms above the boundary layer. For example, the radiation is generally a small term in this local budget, even though the baroclinicity is ultimately driven by the planetary-scale radiative imbalance (see PS15 for further details). The slope and slope tendencies are shown here as vertical averages over the 900–200 hPa layer. Averaging over the smaller 900–500 hPa layer was found to give very similar results (see Figure S1 in the supporting information).

We complement the slope tendencies with other flow diagnostics derived from the ERA-Interim reanalysis [*Dee et al.*, 2011]. These include filtered variance metrics of the storm track using a 2–6 day spectral band-pass filter, such as the eddy kinetic energy (EKE), dry static energy ($c_pT + gz$), and moisture fluxes, all integrated between 900 hPa and 200 hPa to match the tendency analysis. Other diagnostics are cyclone and cold air outbreak frequencies derived from the YOTC analyses. Cyclone frequency is obtained from identifying cyclone areas in sea level pressure following the method by *Wernli and Schwierz* [2006]. The cold air outbreak frequency

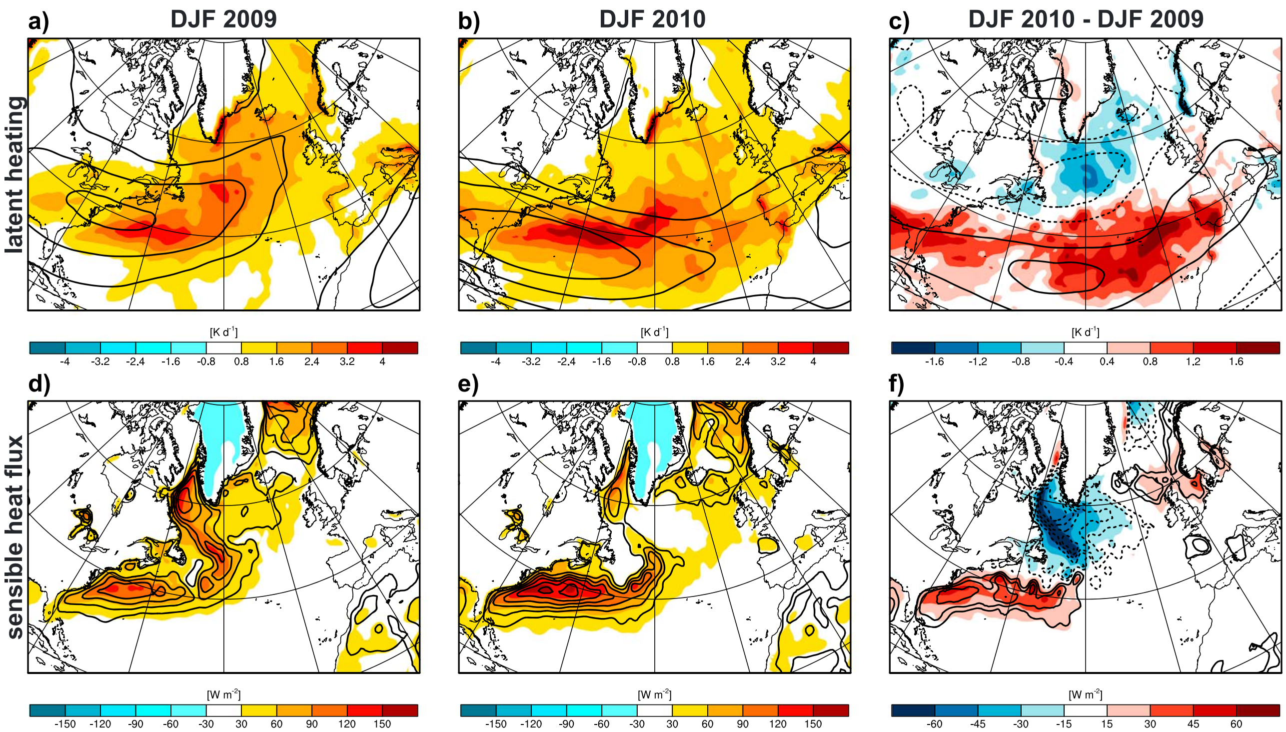

Figure 1. Vertically averaged (a–c) latent heating and (d–f) surface sensible heat fluxes for the two winters. Contours in Figures 1a and 1b are zonal wind at 300 hPa from 20 m s^{-1} in intervals of 10 m s^{-1}, and differences in Figure 1c are in intervals of 10 m s^{-1} with the zero contour omitted. Contours in Figures 1d and 1e are cold air outbreak frequency in intervals of 10%, and differences in Figure 1f are in intervals of 5% with the zero contour omitted. Negative contours in Figures 1c and 1f are dashed.

is given by the fraction of time the air-sea potential temperature difference ($\theta_{SST} - \theta_{850}$) exceeds 4 K [cf. *Papritz et al.*, 2015]. The Hadley cell extent is defined as the latitude at which the global Eulerian mass stream function changes sign at the pressure level poleward of where it attains its extreme value [*Mbengue and Schneider*, 2013]. All diagnostics are presented as averages over the December–February period.

3. Results

We begin by presenting some general characteristics of the flow during the two winters. Figure 1 shows the jet stream over the North Atlantic as wind contours at 300 hPa. This shows the strong difference between the two winters, with the jet axis passing to the north of the British Isles in 2009 but over northern Africa in 2010. The upstream end of the jet also shifted south in 2010, though to a much lesser extent. According to the eddy-driven jet latitude index of *Woollings et al.* [2010], the jet was located at 47.9°N in 2009, which is close to the climatological position, but shifted south to 38.6°N in 2010, one of the southernmost seasonal means on record. In contrast, the jet speeds, as identified by the 850 mb wind, were both very similar to the climatology (speeds were 13.3 and 13.8 m s^{-1} compared to an observed range of 10–17 m s^{-1}). Circulation anomalies, in general, were very weak over the North Atlantic in 2009 (e.g., according to the geopotential height, not shown). The comparison of the two winters thus cleanly isolates the effect of the jet shift, from a very typical winter in 2009 to an extreme southward shift in 2010.

The Hadley cell terminus shifted south along with the jet and storm track in 2010 (thick dashed line in Figures 2a and 2b). This result is consistent with the shifts of the annual mean Hadley cell terminus seen across several reanalysis data sets between 2009 and 2010 [*Adam et al.*, 2014]. Furthermore, a hierarchy of models have shown tandem shifts between the storm tracks and the Hadley cell terminus [*Kang and Polvani*, 2011; *Ceppi and Hartmann*, 2013; *Mbengue and Schneider*, 2013]. The stream function-based definition is generally conservative; we found larger Hadley cell terminus shifts using other metrics, for example, the zero crossing of near-surface zonal winds [*Levine and Schneider*, 2011], and even larger shifts if the zero crossing is computed

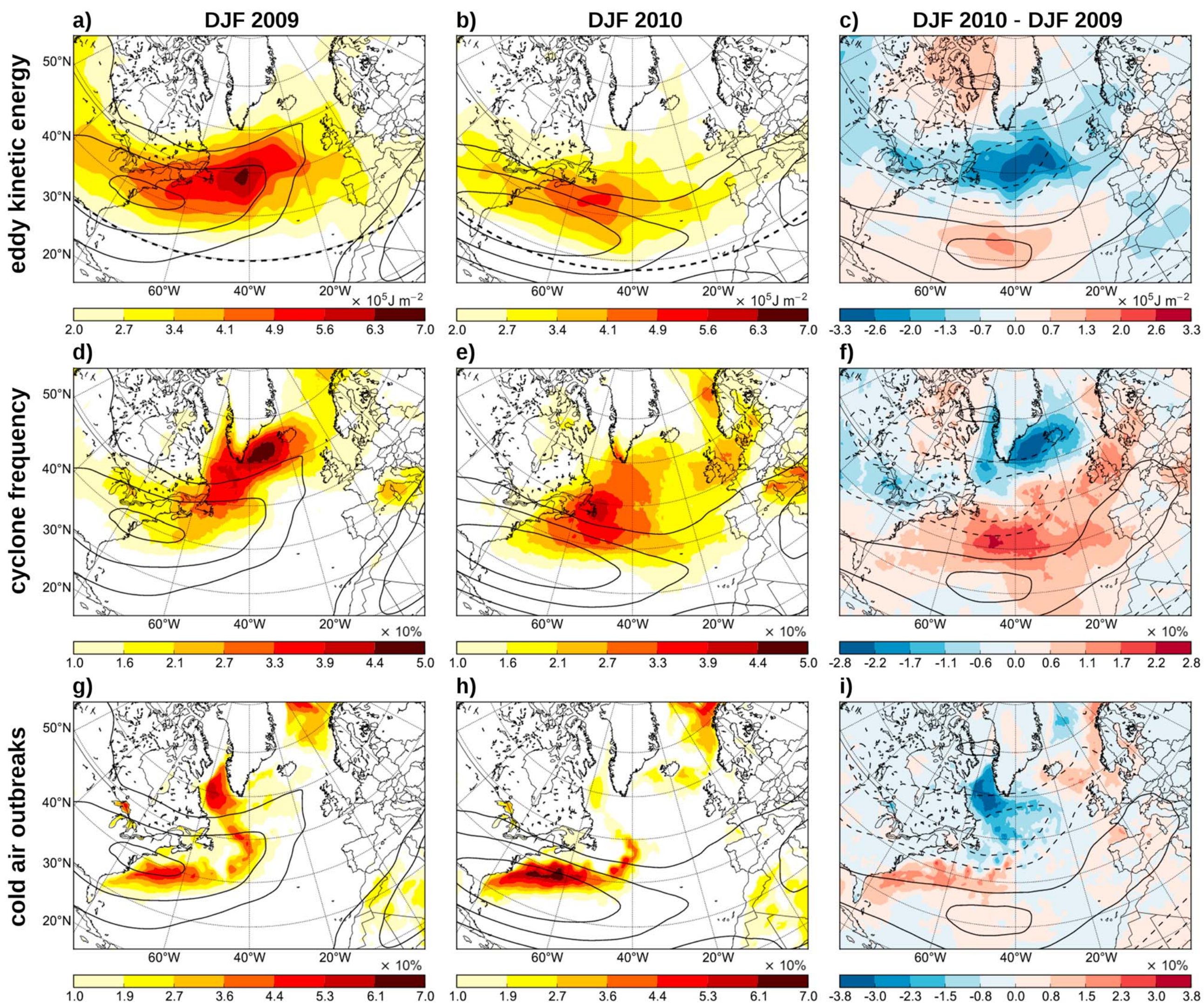

Figure 2. (a–c) EKE, (d–f) cyclone frequency, and (g–i) cold air outbreak frequency for the two winters. Contours are the 300 hPa zonal wind as in Figures 1a–1c. The thick dashed line in Figures 2a and 2b shows the Hadley cell terminus.

using an Atlantic Basin zonal mean. We note that in addition, there are other global circulation features, for example, the signals of El Niño and quasi-biennial oscillation in 2010 which may have acted as drivers of the jet shift [*Fereday et al.*, 2012].

Figure 1 also contrasts the latent heating (a–c) and surface sensible heat flux (d–f) in the two winters. Like the zonal wind, the latent heating shifted south and became more zonally oriented in 2010, although the shift was largely restricted to the eastern half of the basin. In the west the latent heating maximum instead strengthened but remained fixed over the Gulf Stream, whose location is indicated by the band of elevated surface sensible heat flux off the North American coast. Hence, the latent heating over the Gulf Stream lay south of the jet axis in 2009 but north of it in 2010. In the east the southward shift of the heating maximum was slightly weaker than that of the jet, so that while the two were aligned in 2009, the heating maximum lay on the northern flank of the jet in 2010. In line with the latent heating, the surface sensible heat flux also strengthened in 2010 over the Gulf Stream region, whereas it reduced in the Labrador and Irminger Seas. However, the changes in the eastern Atlantic remained small.

The storm track activity in the two winters is contrasted in Figure 2, using both variance-based and feature identification perspectives. In 2010 there were dramatic shifts of cyclone activity away from the Labrador Sea toward Newfoundland, and south in the eastern North Atlantic, with far fewer cyclones over Iceland and more over the British Isles. In both winters the distributions of eddy kinetic energy (EKE) are displaced to the south of

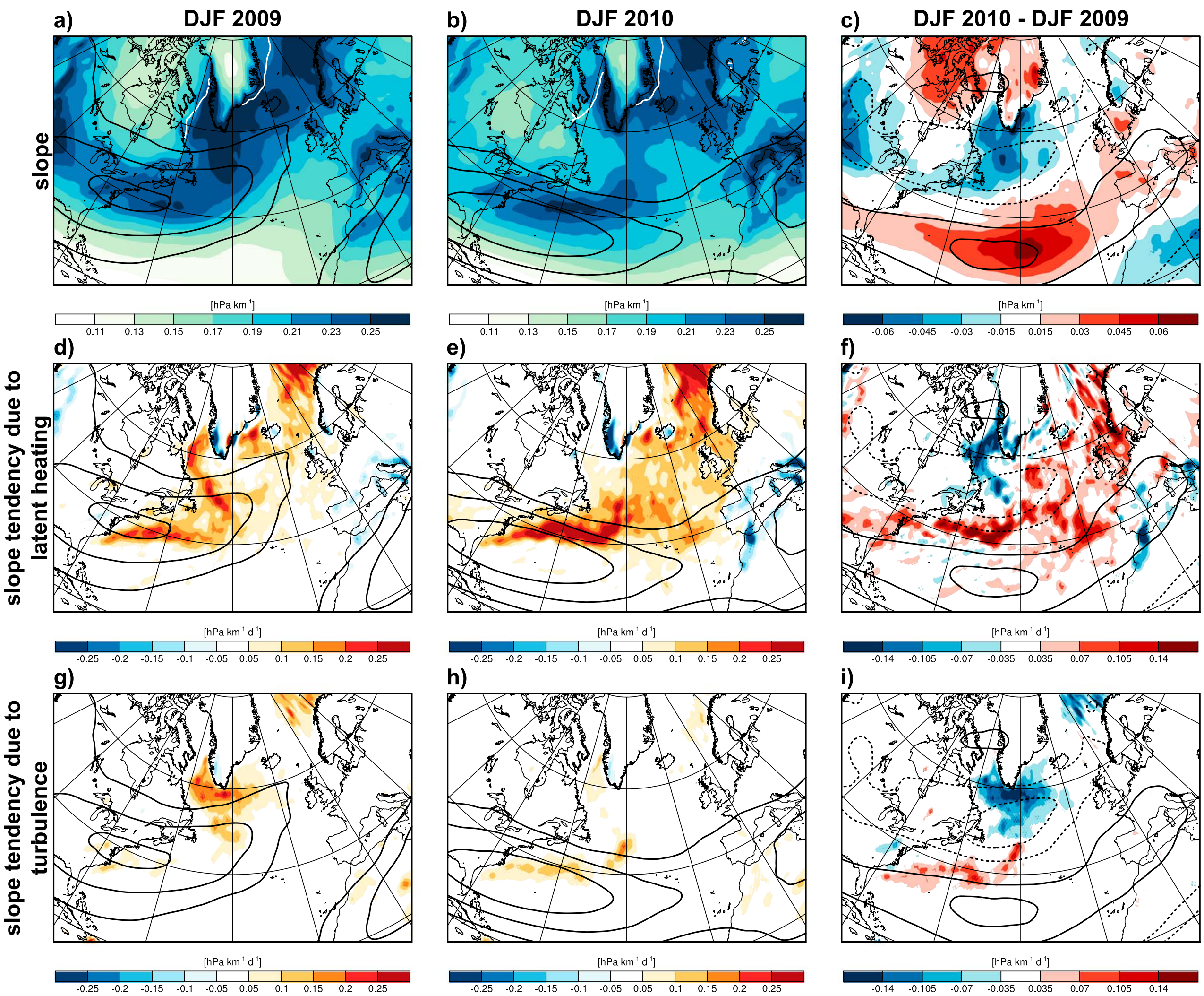

Figure 3. Vertically averaged slope and slope tendency due to latent heating and turbulence, respectively, for the two winters. Contours are the 300 hPa zonal wind as in Figures 1a–1 c.

the cyclone frequency maxima, as expected due to the relative southward propagation of anticyclones which contribute to the EKE [*Wallace et al.*, 1988]. However, consistent with the cyclones, the EKE also shifted south in 2010 and additionally weakened in general. These features are in agreement with other studies of storm track behavior associated with the NAO [*Chang*, 2009b; *Wettstein and Wallace*, 2010]. Comparison with Figure 1 shows that the latent heating lay on the southern flank of the cyclone counts in both winters, consistent with the conceptual picture of latent heating often occurring in the warm conveyor belts of cyclones [*Browning*, 1990]. The heating also lay south of the EKE maxima for much of the upstream part of the storm track. As for the heating, the storm track shift is much weaker upstream, with relatively small changes in both cyclone counts and EKE over the Gulf Stream. The changes in surface sensible heat fluxes coincide with corresponding changes in the frequency of cold air outbreaks. The latter is largely linked to the southward transport of cold air masses in the cold sector of extratropical cyclones. Hence, the enhanced cyclone frequency in 2010 off Newfoundland lead to the more frequent transport of cold air off the American continent across the Gulf Stream front, whereas the smaller number of cyclones east of Cape Farewell lead to the dramatic reduction in the number of cold air outbreaks and surface sensible heat fluxes in the Labrador Sea.

To assess the impact of the diabatic heating anomalies on the maintenance of baroclinicity, we consider the isentropic slope and diabatic slope tendencies as presented in Figure 3. Figures 3a–3c contrast the seasonal mean isentropic slopes in the two winters, showing changes akin to those in latent heating. While the strongest isentropic slopes veered northward around Newfoundland in 2009, they shifted south and

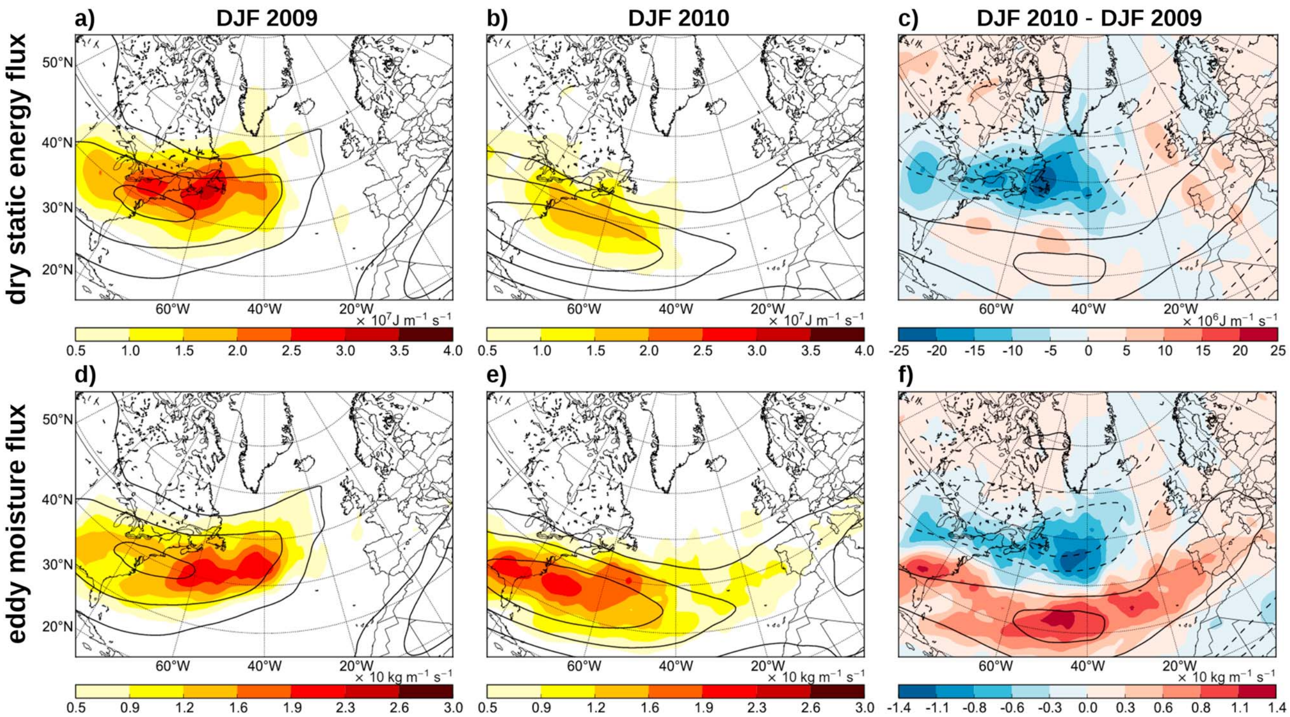

Figure 4. Meridional eddy (a–c) dry static energy and (d–f) moisture fluxes averaged over the two winters. Contours are the 300 hPa zonal wind as in Figures 1a–1c.

proceeded more zonally across the Atlantic in 2010. These changes are locally consistent with the changes in storm track diagnostics in Figure 2, which are located over or downstream of the slope changes. Once again, the change in position over the Gulf Stream is minimal, reflecting the anchoring of the mean state baroclinicity there.

The seasonal mean slopes were maintained by the diabatic terms, and these were dominated by the tendencies due to latent heating (Figures 3d–3f) and turbulence (Figures 3g–3i), which predominantly reflects the upward transport of the surface sensible heat input by the boundary layer parameterizations. The slope tendencies due to latent heating follow closely along the northern edge of the latent heating distribution in Figures 1a–1c, as heating acts to depress isentropic surfaces locally and hence increase the isentropic slope to the north (see Figure 2 in PS15). Interestingly, there is not a corresponding negative slope tendency to the south of the heating. As described in section 3.2 of PS15, this is potentially due to near-surface effects or to increased stability downslope of the level of maximum heating. The increased stability means that a weaker change in isentropic slope is needed to balance the heating there as compared to the region where the slope increases. The overall effect of heating is therefore a net increase in the isentropic slope. It is also possible for heating to generate no local change in isentropic slope depending on the vertical gradient of the heating or the relative slopes of the heating and the isentropes [*Butler et al.*, 2011, PS15]).

The tendency due to latent heating generally dominates the tendency due to turbulence and hence strongly follows the mean slopes in the two winters, tracking around Newfoundland and into the Labrador Sea in 2009 but extending across the Atlantic in 2010. Again, there is a clear contrast between the east, where the slope tendency due to latent heating shifted along with the jet, and the west, where it strengthened but remained anchored over the Gulf Stream. The tendency due to turbulence, while weaker, also shows a clear shift in location from the Labrador region in 2009 to over the Gulf Stream in 2010. When combined, these two diabatic tendencies largely cancel the adiabatic tendencies (not shown). In 2010, the shifted storm track weakened the slope in its anomalous position through the TILT term but also replenished the slope in this anomalous position through the diabatic terms, with both of these opposing tendencies originating in the displaced cyclones.

One distinct feature of both the latent heating and surface sensible heat fluxes, and their slope tendencies, is a strengthening along the Gulf Stream in 2010. PS15 showed that in the lower troposphere (900–600 hPa), over 50% of the diabatic slope tendencies over the Gulf Stream occur during cold air outbreaks, in an interplay between surface heat fluxes, turbulence, and latent heat release. Hence, it is likely that the strengthening of diabatic tendencies along the Gulf Stream in 2010 resulted at least in part from an increase in cold air outbreaks. As these cold air outbreaks are the result of cold air masses advected off the American continent over the Gulf Stream front in the wake of extratropical cyclones, the enhanced cold air outbreak frequency is itself likely a consequence of the southward shifted and more zonally oriented storm track.

Given the changes in latent heating and eddy activity between the winters, it is of interest to examine some energetic aspects of the storm track. Figures 4a–4c show the meridional flux of dry static energy, which shifted south and also weakened overall in 2010, in much the same way as the EKE (although centered to the west of the EKE, as that is where the temperature gradients are strongest). In contrast, the moist static energy flux did not weaken overall (not shown), due to an increase in the meridional eddy moisture flux across the width of the subtropics in 2010 (Figures 4d–4f). These changes are reminiscent of the compensation between dry static energy and latent energy transports in climate change experiments [e.g., *Hall et al.*, 1994]. The moisture flux seems to be increased because of the large-scale circulation anomalies, which in the subtropics comprise an increase in the meridional gradient of temperature and hence also of moisture. The southward shifted storm track is also able to extract moisture from deeper in the subtropics, as indicated by the consistent location of the moisture fluxes to the southwest of the cyclone frequencies (Figures 2d–2f).

4. Conclusions and Discussion

This paper aimed to determine how the diabatic heating changed during the extreme NAO winter of 2010 and how these changes affected the isentropic slopes. In general, the latent heating term was found to dominate the total effect of diabatic heating on isentropic slope tendencies (Figure 3), with the exception of the Gulf Stream region, which also received strong contributions from surface sensible heat fluxes. Each of the winters separately exhibited a close balance between the tilting and diabatic slope tendencies.

The results reveal a striking contrast between the Gulf Stream region and the eastern North Atlantic. Over the eastern basin the latent heating shifted along with the jet, so that the heating still occurred on the southern flank of the storm track even when the jet was displaced south (Figures 1 and 2). In the west, however, the latent heating was anchored to the Gulf Stream along with the storm track. There are two potentially distinct ways in which the 2010 storm track could be considered more diabatic in nature. First, there was a strengthening of the tropospheric latent and surface sensible heating which maintain baroclinicity over the Gulf Stream. Second, the meridional transports across the basin shifted in balance, with weaker dry static energy transports and increased latent heat transports (Figure 4).

Our results show that the diabatic tendencies, primarily due to latent heating in the free troposphere, act to maintain the baroclinicity in each individual winter, as they do in the climatology. The diabatic heating shifts with the storm track and therefore restores baroclinicity in the anomalous, rather than climatological position of the storm track. Hence, the storm track maintains its own baroclinicity wherever it is, and so in this case the diabatic heating may not act to damp storm track shifts. Instead, it may even contribute to enhancing the persistence of these shifts, alongside potential influences of remote drivers and dry dynamical feedbacks. For example, in the region to the west of Iberia the latent heating tendency acted to strengthen the slope anomaly in 2010 rather than weaken it (compare Figures 3c and 3f).

Xia and Chang [2014] argued for the following typical evolution for a zonally symmetric flow (the signs are reversed from their paper to match the 2010 winter): First, an anomalous weakening of the meridional eddy heat transport leads to an equatorward jet shift under the action of upper level momentum fluxes. The latent heating distribution then shifts equatorward along with the jet, resulting in anomalous heating equatorward and cooling poleward of the climatological jet axis. This acts to strengthen the meridional temperature gradient across the climatological jet axis which encourages stronger meridional eddy heat fluxes, hence opposing the initial anomaly.

Our regional observational analysis for winter 2010 reveals a subtly different picture. The meridional eddy heat transport was indeed weakened during this winter, although this was compensated energetically by an increase in the meridional moisture transport. The latent heating did shift equatorward but so did the storm track, so that the heating remained largely on the equatorward side of the storm track and hence acted precisely to balance the anomalous adiabatic destruction of baroclinicity by cyclone intensification.

One important difference from the modeling study of *Xia and Chang* [2014] is that the Atlantic storm track is localized, with clearly separated regions of preferred eddy growth and decay. Baroclinic eddy growth at the storm track entrance is known to be enhanced by the sharp sea surface temperature (SST) gradient over the Gulf Stream [e.g., *Brayshaw et al.*, 2011; *Small et al.*, 2014], where surface sensible heat fluxes act to maintain the surface baroclinicity [*Hotta and Nakamura*, 2011]. Our results suggest that, in addition, the tropospheric latent heating is also fixed over the Gulf Stream during even the strongest shifts of the jet stream and hence makes a contribution to maintaining the baroclinicity and anchoring the upstream end of the storm track. The dynamical mechanisms by which the latent heating is anchored over the Gulf Stream require further investigation. This is a region of large moisture uptake by warm conveyor belts [*Pfahl et al.*, 2014], so these are likely important factors. Convection occurring in the cold sector of cyclones may also play a role by anchoring a band of precipitation over the Gulf Stream [*Vannière et al.*, 2016].

These considerations lead to a hypothesis for the feedback of latent heating on jet shifts in the presence of the localized Atlantic storm track: Across much of the basin the heating moves with the storm track to its anomalous position and maintains the baroclinicity there. In that sense it is unlikely to damp meridional jet shifts there and may even be a positive feedback, contributing to their persistence. In contrast, the latent heating at the entrance of the storm track is anchored to the tight SST gradients of the Gulf Stream. Here it generally restores the baroclinicity in its climatological position, hence damping storm track shifts and contributing to the observed weak jet variability. Diabatic effects might therefore contribute to the observed nature of Atlantic jet variability, which is more pronounced at the exit of the jet than the entrance [e.g., *Novak et al.*, 2015].

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