On local and zonal pulses of atmospheric heat transport in reanalysis data

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The present study analyses large values (or pulses) of local and zonally integrated meridional atmospheric heat transport due to transient eddies. The data used is the European Centre for Medium-Range Weather Forecasts ERA-Interim reanalysis with daily, 0.7° latitude and longitude resolution. The domain of interest is the extra-tropics. First, the circulation associated with local pulses of heat transport is described. This is found to match many of the features found in warm conveyor belts, although important regional differences exist. The large values of heat transport are seen to be associated with co-varying meridional velocity and moist static energy anomalies.

Next, it is shown that there exist strong pulses of meridional heat transport when a zonal integral around a given latitude circle is considered. These zonal pulses are only partly driven by the synchronised occurrence of a large number of local pulses. The existence of such pronounced variability in zonally integrated meridional heat transport can have important consequences for the energy balance of the high latitudes.

Key Words: heat transport; atmosphere; transport pulse; extreme events; reanalysis; variability.

1. Introduction

As part of the vast body of literature dedicated to anthropogenic climate change, a great deal of attention has focussed on possible changes in the mechanisms and magnitudes of meridional heat transport (e.g. Hwang and Frierson, 2010; Zelinka et al., 2012). While there is some agreement on general trends, the transport magnitudes forecasted by models are extremely variable, for both pre-industrial and future scenarios (e.g. Donhoe and Battisti, 2012; Zelinka et al., 2012).

In many cases, the attention has focussed on zonally integrated, time-mean transport values. The role of variability on sub-seasonal time-scales has received comparatively little attention.

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At the same time, atmospheric heat transport has been shown to be sensitive to short-lived, very intense heat bursts. Swanson and Pierrehumbert (1997) first highlighted the dependence of atmospheric heat transport by transient motions on extreme events. The authors analysed three points in the Pacific storm track. Messori and Czaja (2013, hereafter MC13; 2014) have generalised this conclusion showing that, at any given location in the extra-tropical regions, only a very few days every season can account for over half of the net seasonal transport, in both winter and summer. The seasonal mean transport by transient motions is therefore effectively set by a few extreme events every season.

These studies focussed on a local view of the transport, whereby the calculations were based on transport values at single grid-boxes. The discussion was centred on statistical features of the transport and local processes; relatively little attention was devoted to analysing the larger-scale circulation associated with these local extremes. If the local events were to be associated with systematic mesoscale, synoptic or larger-scale circulation features, this might lead to a measure of synchronisation between extremes at different longitudes. When adopting a zonally integrated view, the atmospheric transport by transient motions might therefore still be characterised by a fundamentally sporadic nature. That is, the transport might be modulated by strong zonal pulses, due to the simultaneous occurrence of a large number of local extremes at a given latitude, which carry a significant amount of the net seasonal heat transport in a very short period of time. We will refer to this occurrence as a “zonal extreme”.

Anomalies in atmospheric heat transport magnitude and convergence on sub-seasonal scales can have severe impacts on the polar regions (Graversen et al., 2011). The existence of zonal extremes would therefore provide an important new perspective on the study of meridional heat transport under a changing climate.

If zonal extremes were indeed found to exist, the relevant questions to address would be how the local extremes, and the associated circulation, relate to the zonal ones, how the frequency
and intensity of zonal extremes is set to change in the future and how this will influence the polar regions. The present paper will focus on the first of these questions, and aims to:

   a. Provide a simple overview of the circulation features associated with local extremes.

   b. Demonstrate that, in real-world data, the extremes do not exist solely in terms of local transport, but that there exist strong pulses of zonally integrated meridional heat transport across a given latitude circle.

   c. Show that these zonal pulses are partly driven by the synchronised occurrence of a large number of local extremes, and that this is consistent with the circulation features discussed in point a).

The analysis will focus on atmospheric poleward heat transport by time-dependent motions in the ERA-Interim dataset. While it is beyond the scope of this study to include the climate forecasts made by GCMs, it lays out the bases for an investigation on the subject.

First, the circulation associated with local pulses of heat transport is described. This is found to match many of the features found in warm conveyor belts, although important regional differences exist. The second part of the analysis is centred on the largest zonally integrated values of meridional heat transport. It is shown that the top percentiles of the zonally integrated transport distribution are significantly different from other days and can therefore be considered as zonal extreme events. The discussion focuses on the relationship between these zonal extremes and the local pulses.

The structure of this article is as follows. Section 2 describes the data used and outlines the methodology. Section 3 looks at the circulation associated with local extremes. An analysis of the zonally integrated heat transport is discussed in Section 4, with a focus on the nature and role of the extreme events. Section 5 provides a discussion of the zonal versus local extremes. Finally, section 6 presents some further discussion, conclusions and scope for future research.
2. Data and Methods

2.1 The Re-Analysis Data
The present study utilises the European Centre for Medium-Range Weather Forecasts (ECMWF) ERA-Interim reanalysis data (Simmons et al., 2006). Similarly to MC13, 0.7° latitude and longitude resolution, daily (1200 UTC) fields are considered. A subset of the data has been analysed at 6-hourly resolution to verify that the conclusions drawn in the present study are not dependent on the choice of utilising daily values. The period taken into consideration spans from June 1989 to February 2011, thereby providing twenty-two December, January and February (DJF) and twenty-two June, July and August (JJA) time series. Even though ERA-Interim includes additional years of data, this more limited period is selected in order to allow for an easy comparison with the analysis presented in Messori and Czaja (2014).

The analysis of the circulation features (Section 3) uses all available pressure levels between 975mb and 20mb. The statistical analysis of the extreme events (Sections 4 and 5) focusses on the 850mb level. This is the level of peak heat transport by transient eddies, and is often used as a reference level in the literature (e.g. Lau, 1978). MC13 analysed other vertical levels in the data set and found that the 850mb analysis did indeed provide a good indication of the statistics of the transport at other levels.

2.2 Meridional Heat Transport by Transient Motions
The transient-eddy transport is computed as the product of \( v \) (meridional velocity) and \( H \) (moist static energy, hereafter also referred to as MSE) temporal anomalies. These are defined as departures from the linearly detrended seasonal mean, and are denoted by a prime. Velocity is positive polewards in both hemispheres. Moist static energy is defined as:

\[
H = L_s q + C_p T + g\zeta, \quad (1)
\]
where $L_v$ is latent heat of vaporization, $C_p$ is specific heat capacity at constant pressure, $T$ is absolute temperature, $q$ is specific humidity, $z$ is geopotential height and $g$ is gravitational acceleration (e.g. Neelin and Held, 1987). The anomalies are computed at every grid point for 172 latitude bands between 30°N and 89°N and 30°S and 89°S, and the analysis is performed over both land and ocean. Note that, in figures, $H$ is given in Kelvin, after division by the specific heat capacity of dry air (taken to be 1005.7 $\text{JK}^{-1}\text{kg}^{-1}$).

The terminology “local event” simply refers to the transport value at a single reanalysis gridbox. In order to present results in the same units as the zonally integrated values, the local transport in the figures has been multiplied by the circumference of the latitude at which it is located. On the opposite, zonally integrated values are computed by integrating each local $v'H'$ value over the width of the gridbox it refers to. All the values around a given latitude are then summed to obtain the zonal integral. Both local and zonal values are then normalised by layer thickness and the transport is expressed in $\text{W}/1000\text{hPa}$. Values can therefore be interpreted as the transport in $\text{W}$ which would occur if the local flux were realized at all vertical levels and longitudes.

For both the local and zonally integrated analyses, extreme events are defined as values of $v'H'$ which exceed the 95$^{\text{th}}$ percentiles of the respective distributions for the full hemisphere and time period considered. Note that these distributions are computed for the 850mb level only. MC13 have shown that the exact percentile chosen as threshold does not affect the statistical characteristics of the extremes for single-point values. The same is found in the case of the zonally integrated distributions.

Part of the analysis is performed on time-filtered data. The filter used is a 21-point high-pass finite impulse response filter, with a half-power cut-off at 8 days, and is designed to capture the full breadth of baroclinic time-scales. Chang (1993) suggested that filters with a 6 day cut-off lose a key part of the baroclinic variance. Here, we therefore follow Nakamura et
al. (2002) in choosing an 8 day cut-off. Where no filter is applied, the analysis encompasses phenomena covering a wide range of periods, beyond those typically associated with baroclinic timescales. A brief discussion of the sensitivity of the present analysis to filtering is therefore provided in the supporting information (section S2).

The analysis also uses “well-separated” local extremes. These are local extremes which are driven by distinct atmospheric systems as opposed to extremes resulting from a single, zonally elongated region of enhanced transport, which might register as a local extreme at several locations. In order to provide an objective definition of well-separated extremes, a mean decorrelation length for heat transport is computed at every latitude. The decorrelation length is defined as the distance over which the autocovariance function of the transport anomalies crosses zero for the first time. Local extremes which are located at more than one decorrelation length from one another are counted separately. Extremes which are within one decorrelation length are only counted once.

2.3 2-D Heat Transport Cross-Sections

The analysis of the circulation features (Section 3) is based on cross-sectional composites of local extreme events in the zonal and height (pressure) plane. The selection of these extremes is based on the transport values at single data points, with no zonal integration applied. In all of the composite figures, only the extremes corresponding to local maxima are selected. In fact, in choosing a percentile threshold to define extreme events, an extensive region of strong heat transport could contribute with multiple data points to the statistics. This is desirable when computing, for example, a climatology of heat transport bursts. However, it becomes problematic when analysing atmospheric circulation, since it would imply replicating several times the same circulation system associated with a single heat transport peak.

In MC13, the majority of local events were found to have zonal wavenumbers between 6 and 10. In order to capture the full extent of the extremes, including the surrounding circulation features, 50 model grid boxes (corresponding to approximately 35° longitude), are retained on
either side of the selected local maxima. To avoid double-counting data points, if two successive extremes, on the same day and latitude, are less than 100 grid boxes apart, half of the data points in the interval are assigned to one of the extremes and half to the other. The heat transport is then computed across all the selected longitude data points, at all pressure levels. This procedure provides a pressure-longitude transport cross-section of each extreme. All the extremes thus analysed are then composited, and the values found are normalised by the number of data points being composited. Note that, since some extremes are less than 100 grid boxes apart, the normalisation factor will not be a constant across the composite. A similar procedure is applied in order to obtain cross-sectional plots of the wind fields corresponding to the extreme events. Note that no vertical integration is performed. Indeed, the reanalysis estimates might not be accurate for the whole vertical extent between two adjacent pressure levels. As noted by Trenberth (1991), the values archived in the ECMWF reanalyses should be interpreted as the most accurate values available at those levels, but not representative of layers. Such issue has vastly improved in the passage from ERA-40 to ERA-Interim, but is still present in the latter data set and should not be ignored (e.g. Graversen et al., 2011).

Since the atmospheric circulation is analysed in composite plots, one needs to ensure that the mean picture represents individual events well. As first step, statistical significance limits are presented in the cross-sectional plots. The null hypothesis is that the structure of the extreme events does not differ significantly from that of all other poleward transport events. Events above the 75th percentile of the full hemispheric distribution are taken as reference for the average event. A random Monte-Carlo sampling (1000 iterations) is then applied to determine locations where the extreme event composite is not statistically different from the average events at the 99% confidence level. A separate test is performed exclusively on the areas which display equatorward (negative) transport. Here, a non-parametric sign test is applied
with the null hypothesis that the data in these regions comes from an unknown distribution with a positive median. While the first test verifies whether the extreme event composite is statistically different from weaker poleward transport instances, the second test helps to evaluate whether the negative transport is a robust feature of the extremes or whether it is simply part of a near-zero background flow. Again, a 99% confidence threshold is considered. The same procedure is applied to the velocity composites.

In addition to this, two further analyses are carried out. The first analysis separates extreme events depending on the sign of the meridional velocity anomaly driving the heat transport. The second is an analysis focusing on regional domains, selected so as to match the areas in which local extreme events are most frequent. The names of the different regions, and the corresponding geographical domains, are listed in table I. Figure 6a) provides a graphical illustration of the same domains.

### 2.4 Net Meridional Heat Transport

In addition to the transport by transient motions described above, we also briefly analyse the net, vertically and zonally integrated meridional heat transport by all atmospheric motions, expressed as:

$$T_{ATM} = \frac{1}{g} \int_0^1 d\eta \int_0^{2\pi} d\phi \psi \left( \frac{1}{2} \vec{u} \cdot \vec{u} + C_p T + g z + L_s q \right) \frac{\partial p}{\partial \eta}, \tag{2}$$

where $g$ is gravity, $\vec{u} = (u, v)$ is the horizontal wind vector, $p$ is pressure $\phi$ is longitude and $\eta$ is the vertical co-ordinate of the ERA-Interim atmospheric model (Graversen et al., 2011). $T_{ATM}$ provides a value in W for the net northward energy transport across a given latitude circle. A barotropic mass correction to account for the non-conservation of mass in the ERA-Interim dataset is also applied, following Trenberth (1991) and Graversen (2006).
2.5 Probability Density Functions
Finally, the present article discusses several probability density functions (PDFs), and refers to their skewness. This is a measure of the asymmetry of a distribution or, more formally, the distribution’s third standardised moment. Note that a skewness of zero does not necessarily imply symmetry about the mean. Another oft-used indicator is the most likely value (MLV) of the PDF, which is taken to be the central value of the bin with the highest frequency of events. While the exact value of the MLV depends on the choice of bins, the latter is generally a robust indicator if used to compare the order of magnitude of the most frequent value of a variable to the one of its most extreme realisations.

3. Circulation and Local Extremes
Previous studies (e.g. Swanson and Pierrehumbert, 1997; MC13; Messori and Czaja 2014) have highlighted how meridional atmospheric heat transport is sensitive to short-lived, very intense heat bursts. Here, these are referred to as local extreme events (or pulses). The term “local” simply refers to the transport at a single gridbox. When analysing PDFs of local transport, the extremes form a population of events which are one or more orders of magnitude larger than the MLV of the distribution. The present section investigates the atmospheric circulation associated with these local extremes.

3.1 Hemispheric Composite Maps
To investigate the vertical and zonal structure of transient-eddy heat transport extremes, we begin by computing composite transport maps. These take into account extreme events at all available latitude bands (30°-89°) over the full analysis period (1989-2011). Figure 1 shows the composite map for events in the Northern Hemisphere (NH) DJF. The other season/hemisphere combinations (not shown) yield similar maps. As would be expected from the definition of extreme events used here, the peak transport is found around 850mb. The general spatial structure of the extreme events seems to be that of a deep vertical column of
poleward transport, flanked by weaker equatorward transport regions to the east and at high levels. Cross-hatching marks the regions where the composite is not statistically different from heat transport events above the 75th percentile of the distribution. The diagonal striping marks regions of equatorward heat transport. The exact position and intensity of the equatorward flow varies significantly between individual events. Sometimes there is virtually no return transport, while other times a more extended return flow region is seen. Where the cross-hatching is superimposed onto the striped regions, it marks locations where the null hypothesis of non-negative transport cannot be rejected, and the equatorward transport is therefore not significant. Notwithstanding the large variability between events, virtually all of the equatorward transport regions are statistically significant. The whole transport pattern displays a small westward tilt, consistent with the development of a baroclinic system. Even though the area of poleward heat transport is very extensive, the core of the extreme event is quite narrow, covering on average only a few degrees longitude. The spatial scales of the transport are generally in agreement with the conclusions drawn in MC13, which found that the full extent of an extreme event, including the possible recirculation features, typically corresponds to wavenumber 8 (or, equivalently, 45° longitude).

Figure 1 also displays the composite meridional velocity (continuous contours) and MSE (dashed contours) anomalies corresponding to the extremes. The strongest positive anomalies of both variables are seen in correspondence with the peak transport, and the picture across the event core is that of in-phase positive anomalies. As for what concerns the two equatorward transport regions, the upper level one corresponds to negative MSE and positive velocity anomalies, while the one on the eastward flank corresponds to positive MSE and negative velocity ones. The western flank of the extreme events is characterized by a negative MSE anomaly, which is strongest at low levels. Care should be taken in interpreting these results. The contours represent mean values, meaning that the sign of the product of the two
mean anomalies will not always correspond to the sign of the transport, which is the mean of the product.

Next, maps analogous to that in figure 1 are produced for individual velocity components, in order to reconstruct the wind field corresponding to the extreme events. Panels a-c) in figure 2 show the zonal (u) and meridional (v) components of the wind field, as well as the pressure velocity (ω). The figure refers to events in NH DJF. Meridional, zonal and pressure velocities are positive in the polewards, eastwards and downwards directions, respectively. The diagonal striping marks regions of negative velocities. Cross-hatching marks the regions where the composite is not statistically significant; the null hypotheses adopted are the same as for the heat transport.

Extreme events are characterised by a strongly ascending air stream just to the west of the core of the event (ω<0), flanked by two regions of subsiding air. The meridional velocity pattern displays a core of strong poleward velocity at the location of the extreme, surrounded by a strong equatorward flow on the eastern flank and a weaker one on the western flank. This is consistent with the velocity anomalies displayed in figure 1. The zonal flow is eastwards, in agreement with the mid-latitude westerlies. The zonal velocity composite is therefore dominated by the climatological flow rather than by a circulation specific to the extreme events. The statistical significance test, which compares extreme events to average poleward transport days, is therefore not as relevant as for the other plots, where the major features of the velocity patterns are directly related to the extremes.

The large-scale features described above are representative of the majority of events across all four season/hemisphere combinations. However, a composite covering almost a full hemisphere inevitably runs the risk of smoothing out many features, both in the transport and in the anomaly fields. A regional analysis is therefore presented in section 3.2. Further details
concerning the variability of $v'$ and $H'$ signals are also provided in the supporting information (section S1).

### 3.2 Cold Air Advection and Regional Domains

The composite in figure 1 displays a poleward heat transport driven by positive $v'$ and $H'$ anomalies; however, this is not always the case. Indeed, there is a large number of extreme events (approximately 38% of the total in the NH) where both anomalies are negative, corresponding to equatorward advection of cold air. This motivates a further analysis, where the extreme events are divided into ones where the 850mb transport peak is driven by poleward advection and others where it is driven by equatorward advection.\(^2\) Since, by definition, the transport at the location of the extreme is poleward, the MSE anomalies must have the same sign as the velocity ones. For conciseness, this section focusses on the winter seasons in both hemispheres.

Cross-sectional composites of the extremes are shown in panels a) (poleward) and b) (equatorward advection) of figure 3. The markings on the figure match those of figure 1, except for the intervals of $v'$ and $H'$ contours which are now 5 ms\(^{-1}\) and 3 K, respectively. As can be seen, the structure of the transport in the two panels is extremely similar, even though the anomalies driving it are opposite. In turn, both panels bear a strong resemblance to the transport structure seen in the full NH composite in figure 1. This highlights two conclusions. Firstly, that the full hemispheric composite presents a very good representation of the heat transport structure of a typical event, notwithstanding the large domain considered. Secondly, that similar patterns of heat transport can correspond to very different meridional velocity and MSE anomalies. Further details on the analysis of cold-air advection are provided in the supporting information (section S1).

\(^2\) Even though here we are talking about velocity anomalies and not absolute values, for ease of reference we term the instances where $v'$ is negative as equatorward advection and those where it is positive as poleward advection.
The presence of extremes driven by both poleward and equatorward advection suggests that large regional differences in the meridional velocity and MSE anomalies may exist. We therefore present a brief analysis of extreme events in the five regions listed in table I. Panels a)-e) in figure 4 show the meridional heat transport cross-sections and velocity and MSE anomalies for the five domains. The colourbars and markings are identical to those in figure 1. As can be seen, the two NH storm track domains (GS and PS, corresponding to panels a) and b)) display a structure which is almost identical to the one seen in the NH DJF composite shown in figure 1. Even the finer details, such as an upper-level local maximum in meridional velocity anomaly, match quite closely. The two sub-Arctic domains (BS and NS, corresponding to panels c) and d)) display an overall very similar transport pattern but a weaker transport core. The corresponding meridional velocity and MSE anomalies, even though they are on average both positive at the core, are also significantly weaker. Upon closer analysis this is found to be due to the fact that, in the BS and NS domains, just under half of the extreme events correspond to southerly cold-air advection (45% and 44%, respectively). This is in contrast to the GS and PS domains, where the contribution of cold-air advection is significantly smaller (38% and 33%, respectively). As mentioned before, this compares to a hemisphere-wide average of 38%.

In order to illustrate that both hemispheres present similar features, the regional cross-section for the Southern Hemisphere (SH) stormtrack (SO, panel e)) is also shown. As can be seen, the transport pattern is broadly similar to that of its NH counterparts. The only major difference is that none of the equatorward transport is statistically significant. This is mainly due to the fact that the average magnitude of such transport is much smaller than the one seen in the NH.
Regardless of the chosen hemisphere, the regional analysis therefore supports the previous conclusion that, even though the dynamical drivers of extreme heat transport events might be very different, the heat transport pattern is surprisingly robust across the selected events.

3.3 Physical Interpretation

The results from sections 3.1 and 3.2 show that heat transport extremes are characterized by a rapidly ascending airstream, and that for the most part they correspond to positive meridional velocity and MSE anomalies. These features account for more than half of the heat transport events in all of the domains analysed, although their relative importance is lesser in the more northerly regions such as the Bering Strait and the Nordic Seas. These considerations suggest a direct correspondence with precise mesoscale atmospheric features, such as warm conveyor belts (WCBs) associated with extratropical cyclones. WCBs are streams of moist, rapidly ascending air parcels which rise from the boundary layer into the upper troposphere. Both their typical duration of a few days and their sporadic occurrence are consistent with the characteristics of the extreme heat transport events (e.g. Eckhardt et al., 2004).

Taking as reference a typical WCB schematic (see figure 5, corresponding to figure 1 in Catto et al. (2010), adapted from Browning (1997)), the rapid ascent near the location of the extremes would match the warm conveyor itself. The fact that the highest rate of ascent is seen to the west of the 850mb heat transport core is consistent with the flow of the warm conveyor turning anti-cyclonically as it gains height. The descending motion seen in the velocity composites would correspond to the dry air from the upper atmosphere on the western flank of the WCB. Indeed, as shown in figure 1, this flow generally corresponds to a negative MSE anomaly. Such anomaly is particularly intense in the two NH storm track domains. What the WCB schematic does not necessarily explain is the fact that the return heat transport is generally seen only on the eastern flank of the extremes. In fact, idealised simulations of midlatitude cyclones predict two re-circulating branches of the WCB, one to
the east and one to the west of the location of rapid ascent (e.g. Boutle et al., 2010). A further element which is not present in the heat transport composites is the cold conveyor belt (CCB). This is a cold air feature typically seen to the west of the WCB. These discrepancies between the structure of the heat transport extremes and the one of WCBs are consistent with the fact that the latter do not drive the totality of the transport extremes. Indeed, almost 40% of the selected events correspond to cold air advection. Consequently, the exact structure of the velocity and MSE anomalies varies significantly across the different individual events, and some do indeed agree closely with the typical recirculation pattern seen in WCBs. The GS composite (figure 4a), for example, displays a low-level region of negative $v'$ and $H'$ to the west of the extreme event core, consistent with a recirculating CCB-type feature. A comparison of the climatology of local extreme heat transport events (figure 6a) and one of WCBs (figure 6b, originally figure 3f) from Eckhardt et al., 2004), highlights some differences in the geographical distributions. There is a good match between WCBs and extreme heat transport events over the storm track domains, but elsewhere the two distributions do not overlap as closely. Examples of this are over the Bering region and in the Nordic Seas, where relatively few WCBs are detected even though there are significant numbers of heat transport extremes. Indeed, in these regions, the mean structure of heat transport extremes shows fewer resemblances to WCBs than in the storm track domains. A comparison with WCB climatologies from other studies, such as Madonna et al. (2014), presents a very similar picture.

A possible analogue for the negative $v'$ events could be provided by marine cold air outbreaks (MCAOs). These are large-scale outflows of cold air masses over the ocean, and would correspond to negative $v'$ and $H'$ values. The NH MCAOs are particularly intense in three regions: the Nordic Seas, the Labrador Sea and the Northern Pacific (e.g. Kolstad and Breecegirdle, 2008). Two of these regions match the NS and BS domains, where the cold
advectio...advection events are most frequent. In both the full NH domain and the regional composites, these events are fewer than the WCB-type structures, and are therefore smoothed out. Obviously, the $v'$ and $H'$ patterns of the cold-air advection extremes are very different from those of the mean depicted in figure 1. The typical heat transport structure, however, is surprisingly similar, as illustrated in figure 3b.

An important question which has not been fully addressed concerns whether the circulation described above is indeed unique to the highest percentiles of the distribution, or whether the so called “extremes” are not that different from median days in terms of the circulation pattern. Composite cross-sectional plots of the lower percentiles of the distribution (not shown) are found to lack the rapid ascent and return flows seen in the extreme event ones. Even composites of the top 10 percentiles still present some differences compared to figure 1, most notably in the return flows. This is in agreement with the fact that the extreme event composites are statistically different from events above the 75th percentile at most points of the cross-sectional composites. The structure described above is therefore specific to the upper percentiles of the $v'H'$ distribution, and justifies the terminology adopted thus far.

4. The Zonal Mean View

We now shift our attention to extremes (or pulses) in zonally integrated heat transport, which have received less attention in the literature. By zonally integrated transport, what is intended here is simply the sum of all single grid box transport values around a given latitude circle, integrated over grid box width.

4.1 Zonally Integrated Heat Transport PDFs

As first step in the analysis, we verify whether the top percentiles of the zonally integrated heat transport PDF in the ERA-Interim reanalysis data play any relevant role relative to the
The net seasonal transport for a given PDF is taken to be the full integral of the distribution for the full spatial and temporal domains. In constructing the PDFs, the integral of heat transport around a latitude circle, on a given day, is treated as a single data point. All available latitude bands (30°–89°) and time series (1989-2011) are considered. In the interest of conciseness, the resulting distributions are only shown for NH DJFs and SH JJAs (figures 7a and b), respectively.

The PDFs are significantly different from the ones obtained in the local analysis by MC13, which were constructed by treating transport at each gridbox as a single data point. For comparison, the single-point distribution for NH DJF is shown in figure 8a. Its SH counterpart is very similar. Both figures 7 and 8a consider the same data set and geographical domain. As clearly shown in figure 8a, the single-point distributions have a very pronounced MLV and a thin, extended positive tail. This tail represents a very small fraction of the overall data, as shown by the cumulative distribution function (CDF) overlaid onto the PDF. However, it accounts for a significant part of the net seasonal transport. The distributions also have a large skewness (4.8 for NH DJF).

The zonally integrated distributions shown in figure 7 still have a well-defined MLV and long positive tails. However, these tails account for a much larger portion of the events than was seen in the single-point distributions. Furthermore, the skewness values are significantly lower than those of the single-point data (0.83 versus 4.8 for NH DJF), and the two hemispheres present important differences. The strong positive year-round atmospheric heat transport suggests that negative transport values should be almost entirely absent. In this respect it is interesting to note that, in both hemispheres, there are indeed some negative values, albeit with very low frequencies and magnitudes. These events are briefly addressed in section 4.2 below. The MLVs of both hemispheres lie in the smallest positive bin of the respective distributions, centred on zero. The fact that both hemispheres have exactly the
same MLV, and that such MLV is equal to zero, is simply due to the choices of plotting both
distributions over the same bins and of centering a bin on zero. Since the MLV is defined here
as the central value of the bin with the highest frequency of events, as long as both
distributions have similar peaks in frequency, the resulting MLVs will be identical unless the
bins are very narrow. Further analysis shows that the majority of the values in the bins centred
on zero are positive.

Concerning the differences between hemispheres, the most striking one is the bi-modality of
the SH PDF. By splitting the distribution into two latitude bands (30°-60°S and 60°-89° S, not
shown), it becomes clear that the right-hand side peak is due to the lower latitudes and the
left-hand side one to the higher latitudes. This is partly due to the lower relative frequency of
extremes at higher latitudes: the pronounced near-zero MLV of the PDF is driven by the high
latitudes, where very few 850mb extremes are seen. A similar pattern is seen in the NH, but
the split between the two latitude bands is less marked, and thus does not lead to a bimodal
distribution. Further discussion of the differences between the two hemispheres is presented in
section 6. The PDFs for NH JJA and SH DJF share the same qualitative features as their
wintertime counterparts, albeit with some quantitative differences.

4.2 Equatorward Transport Events
As mentioned in Section 4.1 above, the PDFs of the zonally integrated transport display some
negative values. These equatorward transport events correspond to between 6.3% and 8.9% of
the data points, depending on hemisphere and season. The values for all four cases are shown
in table II. While these numbers would not be surprising for single-point transport values,
they are intriguing for the zonally integrated case, where one may expect some measure of
counterbalancing between different longitudes.

Form a dynamics standpoint, it is interesting to try and separate the role of the different
timescales in driving this negative transport. Figure 8b) displays the zonally integrated heat
transport distribution for the high-pass filtered NH DJF data. This can be compared to figure 7a), which displays the same distribution for the unfiltered data, plotted using the same bins. Focussing on the negative portion of the distribution, it can be seen that the negative values in the filtered data are greatly reduced in magnitude, with the lowest filtered values being less than 30% of the magnitude of the lowest unfiltered ones. Indeed, the fully negative bins in figure 8b) are almost completely depopulated, likely reflecting the fact that motions in the high-pass band are the ones “tapping” into the available potential energy of the atmosphere, lowering its center of mass and, as a result, carrying heat polewards. This reduction is much sharper than that seen for the positive tail, and suggests that the zonally integrated equatorward transport is primarily driven by lower frequency motions. The increase in skewness (1.34 versus 0.83) confirms this. In fact, the skewness provides a measure of the asymmetry of a distribution; in this case the higher skewness of the filtered data corresponds to more unequal positive and negative tails. This point is discussed further in section 6.

Returning to the unfiltered data, an obvious question to ask is whether transient motions at other pressure levels act to balance out the negative contribution of the 850mb level. To get an indication of this, equatorward transport data points are identified at the 300mb level, which is the approximate level of the secondary peak in meridional heat transport by transient motions (Peixoto and Oort, 1992). Depending on season and hemisphere, it is found that between 41.6% and 63.6% of the equatorward transport data points identified at 850mb correspond to a negative transport also at 300mb. This means that up to 5.5% of the data points present equatorward transport at both levels. Again, the values for all four hemisphere/season combinations are displayed in table II. This is suggestive of a strong vertical coherence of the transport by transient motions in a zonally integrated sense.

From the point of view of the energetics of the atmosphere, an even more important question concerns the behaviour of the net meridional energy transport. By “net” here we indicate the
zonally and vertically integrated meridional atmospheric energy transport by all motions. It is found that between 12.3% and 23.9% of the data points where the zonally integrated 850mb transport is negative correspond to a negative net transport. This means that typically 1-2% of the data points present equatorward transport both for transient motions at 850mb and net atmospheric heat transport. On this small fraction of days, the atmosphere as a whole, at a given latitude, is carrying energy towards the equator. The higher percentages correspond, as might be expected, to the summer seasons of the two hemispheres, when the climatological poleward transport is weaker (see table II).

4.3 The Contribution of Zonally Integrated Extreme Events
As is evident from a visual assessment of the PDFs in figure 7, the contribution of the largest zonal events to the overall transport is significantly lower than that seen in figure 8a for the local extremes. The contributions of the top 5% of events in the zonal transport PDFs to i) the overall and ii) the poleward-only transports are shown in table III. The values displayed are simply i) the percentage contribution of the selected events to the overall integral of the distribution and ii) the percentage contribution of the selected events to the integral of the positive portion of the distribution. Depending on the season and hemisphere, these values range from about 13% to over 16%. Since almost all of the zonally integrated transport values are positive, the overall and poleward-only contributions are almost identical.

As a point of comparison, the last column in table III shows the contributions found for local extremes relative to the single-point PDFs. Compared to these, the contributions of the zonal case may seem extremely small. However, one should keep in mind that this is somewhat expected. Indeed, the local extremes correspond to specific circulation patterns, which have the ability to effect an enormous heat transport. This can be orders of magnitude larger than the typical values at a given point (MC13). In the zonal picture, however, it is hard to imagine planetary-scale coherent structures which could account for a similar effect.
It is also instructive to compare the values shown in table III to the weight of the corresponding events in a Gaussian distribution. To obtain these values, Gaussian profiles with the same means and standard deviations as the zonal transport distributions are constructed. The role of the velocity and MSE anomalies in driving the transport is not considered here. The portions of the Gaussian distributions above the respective 95th percentiles are then selected, and their weight relative to the integral of the positive portion of the Gaussians is computed as a percentage. The resulting values are shown in the third data column of table III. Even though these values appear to be similar to those found for the reanalysis distributions, a random Monte-Carlo sampling procedure shows that the differences are statistically significant for all four season/hemisphere combinations, at the 99% confidence level. There is therefore some basis for calling the top percentiles of the zonally integrated transport distributions “zonal extremes”.

5. Zonal versus Local Extremes

Having established that there is reason to discuss zonal extremes, the next pertinent question to address is how these zonal events might relate to the local extremes analysed in section 3 of the present paper. The terminology “zonal extremes” refers to the top 5% of events in the PDFs of zonally integrated meridional heat transport.

5.1 A Pictorial Overview

A first overview of the relationship between local and zonal heat transport can be gleaned from a simple comparison of the frequencies of local and zonal extreme events on a given latitude circle over a season. The barplot in figure 9 depicts this in graphical form. The plots for 5 consecutive DJF seasons (1989-1994), are shown. The figure refers to the 50°N latitude
circle. The choice of season, years and latitude are entirely random, as the plot simply serves to illustrate the typical pattern seen throughout the period and domains analysed in the present paper. On a given day, the value of the vertical bar is set to the number of local \( v'H' \) events falling in the top five percentiles of the local distribution for the full NH domain. The vertical lines over the light grey bars mark the days when a zonal extreme occurs at the selected latitude. Again, these are defined as the top five percentiles of the zonal distribution for the full NH domain.

The local extreme events tend to happen in bursts lasting for a few days, during which very significant numbers of events occur. In the context of the circulation features highlighted in section 3, these could correspond, for example, to periods of particularly vigorous synoptic activity in the storm tracks (e.g. Pinto et al., 2014). These bursts are preceded and followed by days with very little activity. In certain years, more extended periods of activity are present. At the same time it is clear that, at least at the selected latitude, there is a continuous background of extremes throughout the season. The intermittency in the frequency of the local extremes is consistent with the link found between local transport extremes and circulation structures typically associated with the storm tracks. Indeed, the intermittent nature of eddy activity in the storm tracks is well known and has been modelled, for example, by Ambaum and Novak (2014).

Shifting the attention to the zonal extremes, it can be seen that they typically match the periods of strong local activity. However, there are occasions when a period with an enhanced local extreme event frequency does not match any zonal extremes, and vice-versa. This visual appraisal of the temporal variability of meridional heat transport therefore suggests a strong link between local and zonal extreme events, but also highlights that there must be other mechanisms at play.
5.2 Local and Large-Scale Drivers

Based on the visual overview provided by figure 9, we formulate the following three hypotheses concerning the origin of large values of zonally integrated heat transport:

a. They are due to synchronised local extremes at several gridpoints around a given latitude. Namely, several single-gridbox extreme events occurring on the same day, at the same latitude. These local extremes might be either:

i. Multiple but well-separated systems or;

ii. Zonally elongated regions of large heat transport values that may register as local extremes at multiple locations.

b. They are due to a larger than average transport across all longitudes, with no significant contribution from the local extremes. That is, to a generalised increase in the transport across large stretches of the latitude circle, without necessarily implying a higher than normal frequency of extreme events at fixed locations.

c. A combination of points a.i) (c.i)) or a.ii) (c.ii)) and b) above.

A pictorial schematic of hypotheses a) and b) is provided in figure 10.

The barplot in figure 9 indicates that both a) and c) are plausible answers. The results from section 3 further suggest that it would be natural for large heat transport bursts to be spread over multiple longitudes (and not single unrelated points). In fact, a large portion of the heat transport in the mid-latitudes is driven by baroclinically unstable waves, and a synoptic or mesoscale eddy will cover several gridboxes. The zonal profiles, such as that shown in figure 1, indeed suggest that the central core of a local heat transport extreme typically covers a few degrees longitude. Therefore, a local extreme will often be part of a larger longitudinal band of strong heat transport, and not an isolated burst. This would correspond to case a.ii). However, several low pressure systems typically coexist around a given latitude circle,
making case a.i) equally credible. Hypothesis c) is essentially a relaxed version of a), and is therefore also plausible following the above arguments.

At the same time, Messori and Czaja (2014) found that long length scales and time periods, beyond those typically associated with baroclinic motions, play an important role in the power spectra of meridional heat transport by transient motions. This points to the possibility that a larger than average transport across a broad range of longitudes might also contribute to the zonal extremes. Moreover, the analysis in section 5.1 confirms that there are instances where the frequency of local and zonal extremes appear to be decoupled. Hence, even though hypotheses a) and c) remain the most likely, it is not possible to exclude \textit{a priori} option b).

5.3 The Role of Local Extremes

To test hypothesis a) robustly, one can first of all verify whether any of the day/latitude data points which are classified as zonal extremes correspond to no local extremes. It is found that for all hemisphere/season combinations, virtually all of the zonal extremes correspond to at least one local extreme. That is, when meridional heat transport around a given latitude on a given day classifies as a zonal extreme, there is at least one location at that latitude where the transport also classifies as a local extreme. For non-extreme zonal days, the picture is very different. Depending on hemisphere and season, between 20\% and 39\% of non-extreme zonal data points correspond to no local extremes. The percentages are systematically higher for the SH where, as illustrated in figure 6a), the bulk of the local extremes is centred on a narrow band in the Southern Ocean, and there are very few extremes in the high latitudes. Hypothesis b) proposed that an increase in the zonally integrated meridional heat transport would not necessarily imply a higher than normal frequency of extreme events at fixed locations. The large discrepancy found between extreme and non-extreme zonal days therefore suggests that hypotheses a) or c) might be more appropriate than b).
The next natural step is to investigate what happens when there are local extremes at a given latitude. To this end one can produce PDFs of the number of local extremes around a full latitude circle on days corresponding to zonal extremes and on all other days, excluding days/latitudes with no local extremes. If the PDFs for the extreme zonal days were to peak at significantly larger values than those for all other days this would suggest that, when local extremes are present, zonal extremes come about because of local extremes. Panels a) and b) in figure 11 show the resulting PDFs for NH DJFs and SH JJAs, respectively. White bars correspond to data for zonal extremes, while grey bars correspond to data for all other days. The data set used has 512 grid boxes around each latitude circle; this number clearly provides an upper bound on the number of simultaneous local extremes that can occur at a given latitude. For NH DJF, the zonal extremes PDF’s MLV and mean are both larger than the non-extreme PDF’s ones by a factor of approximately two. The distributions for SH JJA (figure 11b)), NH JJA and SH DJF (not shown) present a similar pattern. In all four hemisphere/season combinations, the PDFs for extreme and non-extreme zonal days are statistically different under a two-sample Kolmogorov-Smirnov test, with the null hypothesis of the same parent distribution rejected at the 5% significance level.

Hypothesis a) above would imply that the two PDFs have almost no overlap, since local extremes would be the sole drivers of zonal ones. On the opposite, hypothesis b) would correspond to approximately equal PDFs for both extreme and non-extreme zonal days. Even though the distributions in figure 11 are statistically different, there is still considerable overlap between them. To quantify this statement, the overlap between the extreme and non-extreme PDFs in panels a) and b) of figure 11 is 31% and 32%, respectively. These are simply the percentages of data points in the distributions which lie in the overlapping portions of the different bins. They provide an indirect measure of how likely it is for an extreme zonal day to have the same number of local extreme events as a non-extreme zonal day. It should further
be remembered that the distributions only refer to those days on which there are local extremes at a given latitude circle. As already discussed, a significant portion of the non-extreme zonal data correspond to days when no local extremes are seen. In physical terms, we interpret the above results as corresponding to a scenario governed by the number of local events, with a significant contribution from changes in the background flow (hypothesis c) above).

5.4 Clustering of Local Extremes
In terms of local extremes, hypothesis c) considers two options: i) that they are driven by independent atmospheric systems; or ii) that they form part of large-scale coherent transport structures. To distinguish between the two, a decorrelation length for heat transport is computed; local extremes within one decorrelation length of one another are only counted once (see section 2.2 for details). This process reduces the local extremes to around 8% of their original numbers. The severe decrease is partly due to the fact that, as seen in section 3, local extremes extend across several gridboxes. A single local maximum will therefore be counted multiple times if the selection is purely based on the exceedance of a threshold. The rest of the decrease can be ascribed to multiple closely spaced local extreme peaks which form part of a same, extensive band of strong meridional heat transport, and are only counted once. The local extremes therefore present a pronounced clustering, corresponding to hypothesis c.ii). This is in agreement with the well-defined geographical regions of high extreme event frequency shown in figure 6a.

The fact that clusters of local extremes exist, however, does not necessarily mean that they actively drive the zonal extremes. Indeed, the clustering might be a general property of the heat transport, and be completely unrelated to the zonal extremes. We therefore test whether there is any systematic relationship between the additional heat transport seen on extreme zonal days and the size or number of clusters of local extremes. To do this, the PDF analysis described in section 5.3 above is repeated for the new set of well-separated local extremes.
Panels c) and d) in figure 11 display the results for NH DJF and SH JJA. As before, the extreme zonal days display systematically more local extremes than the non-extreme zonal days. The distributions are again statistically different under a two-sample Kolmogorov-Smirnov test, at the 95% level, for all hemispheres and seasons. What is immediately noticeable, however, is that the overlap between the distributions for extreme and non-extreme zonal days is much larger than before. The overlaps are now 55% for NH DJF (panel c)) and 46% for SH JJA (panel d)). If the additional heat transport during extreme zonal days were entirely due to larger clusters of local events, the two PDFs in each of the panels would overlap. In fact, each cluster would be counted only once, regardless of the number of local extremes forming it. The opposite would occur if the additional transport were due to larger numbers of clusters.

5.5 The Weak Synchronisation Hypothesis

The picture that emerges from the above analysis corresponds to a zonally integrated heat transport which is largely, but not exclusively, governed by the number of local extreme events. It is further found that the local extremes driving the transport tend to cluster in zonally elongated bands. This corresponds to hypothesis c.ii) of the original list. If local extremes forming part of the same cluster are only counted once, approximately half of the extreme zonal days have the same number of clusters as non-extreme ones. This indicates that a zonal extreme may come about because of either more frequent or larger clusters of local extremes.

We therefore conclude that the zonal heat transport is characterised by a weak synchronisation effect, whereby zonal extremes do, in part, result from synchronised, zonally elongated bands of local extremes. However, they have a much weaker impact on the overall transport distribution than their single-point counterparts, as shown in section 4.3.

Finally, one should note that there is a caveat to the methodology adopted here. The validity of the hypotheses made above may depend on the exact definition of local extremes in terms
of percentiles of a distribution. Indeed, if the percentile thresholds were to be changed by tens of percentiles, the picture would in turn change. However, the fact that the circulation maps seen in section 3 are specific to only the strongest transport events suggests that the 95\textsuperscript{th} percentile threshold does capture events which are physically different from the norm, and is therefore a suitable selection criterion. While one could argue that the 93\textsuperscript{rd} or 97\textsuperscript{th} percentiles would be equally valid choices, it would be unphysical to choose, for example, the 70\textsuperscript{th} percentile as threshold. Moreover, if the percentiles defining local extremes change, so do the ones defining the zonal ones. For example, if local extremes were to be defined as events within the top 10\% of the single-point distribution, the same definition would then be applied to the zonally integrated distribution in order to select extreme zonal days. This definition is already a limit case since, as discussed in section 3, the events selected by this relaxed criterion lack some of the circulation features seen in figure 1. If such threshold were adopted, the fractional overlap of the PDFs corresponding to those in figures 11a) and b) would rise from 31\% and 32\% to 64\% and 51\% respectively, but the distributions for extreme and non-extreme days would remain statistically different. We therefore conclude that large changes in the chosen extreme event threshold would not be justifiable from a dynamics standpoint, while small changes will not significantly alter the findings discussed here.

6. Further Discussion and Conclusions

The present paper examines zonally integrated meridional atmospheric heat transport due to transient eddies, focussing on low levels in the mid and high latitudes. Previous studies have already shown that the local transport is very discontinuous in nature, and is very sensitive to a few extreme events every season (e.g. Swanson and Pierrehumbert, 1997; MC13; Messori
and Czaja 2014). Here, it is shown that the local extremes can be associated with precise circulation features. In the storm track regions, these correspond primarily to WCB-type structures. Different circulation patterns, such as cold air outbreaks, emerge in other regions. The existence of these circulation analogues for local extremes suggests that there might be a measure of synchronisation between extremes at different longitudes, hence giving rise to large values of zonally integrated meridional transport, or zonal extremes. This is indeed seen to be the case: the zonal extremes in the ERA-Interim data are found to be partly due to numerous local extremes occurring simultaneously around a given latitude circle. The local extremes are found to cluster in zonally elongated bands of high activity, with the clustering more pronounced during extreme zonal days than during other days. In addition to this, the zonal events also have a contribution from increased transport at non-extreme locations. These two features suggest that scales larger than those associated with the extremes act to enhance the transport over wide areas of the latitude circle. Such inference is in agreement with the results of Messori and Czaja (2014), who found that long length scales (zonal wavenumbers ≤ 4) and time periods (periods > 8 days), beyond those typically associated with baroclinic motions, play an important role in the power spectra of meridional heat transport by transient motions.

The percentage contributions of zonal extreme events to the net zonally integrated meridional heat transport are significantly lower than the corresponding values found for local extremes (MC13). They are still, however, significantly larger than those found for Gaussian distributions with the same means and standard deviations as the transport PDFs.

It should also be remembered that the local poleward transport extremes are often associated with a return equatorward transport (see figure 1). Such return transport is highly variable, and might provide an additional explanation as for why days with a large number of local extremes do not always correspond to zonal extremes. As shown in figure 11, a small fraction
of non-extreme zonal days have a very large number of local extremes – larger, in fact, than the most likely value for a zonal extreme day. A realistic hypothesis is that these outlying non-extreme days are characterised by local extremes which have uncommonly strong recirculation features, such that their net transport is smaller than usual.

Extending the analysis of re-circulation features to a global scale, it is interesting to note that, even when considering zonally integrated values, the transport is not always polewards. Indeed, the 850mb zonally integrated transport is negative on a small fraction of the days and latitudes considered. Only a very brief analysis of these events has been performed here. The results suggests that the negative transport is mainly driven by the large-scale motions, associated with timescales beyond 8 days. This is consistent with the picture of baroclinic-scale growing systems accounting for the majority of the transport and lower frequency, decaying waves accounting for weaker or even negative values. It is further found that the transport by transient motions displays a high vertical coherence, meaning that when the transport at 850mb is negative, the transport at upper levels has a significant chance of also being negative. When the net atmospheric energy transport is computed, the other components of the transport (e.g. climatological stationary eddies and/or compensation by a reduced Ferrel cell) often balance out the transient contribution. However, there is still a small fraction of cases (1-2% of the total) where a negative 850mb transport corresponds to a negative net transport, meaning a day on which, at a given latitude, the atmosphere carries energy towards the Equator. A more in-depth analysis, based on existing studies of the co-variability of the different components of the atmospheric energy transport (e.g. Trenberth and Stepaniak, 2003) would be required in order to determine the dynamical drivers of these events.

While the general picture seems coherent, there are some aspects which require further clarification. A first natural question is whether the role of the longer timescales and
lengthscales, mentioned above, is compatible with a direct correspondence between the extremes and the local atmospheric features discussed in section 3. The definition of “extreme” adopted here is based on a numerical threshold. When considering the spectral features of the heat transport, large variations in power at scales consistent with baroclinic motions could be sufficient to determine whether events with high power at larger scales classify as extremes or not. That is, the power in a specific region of the spectrum can determine whether a given event falls above or below the threshold, even though said region may not account for the majority of the net spectral power. One can therefore reconcile the spectral and synoptic analyses, and interpret the extreme events as regionally coherent synoptic features superimposed on planetary-scale variability. This view is further strengthened by the fact that the local extremes, which always show some degree of clustering, tend to form larger clusters during zonal extreme days. In fact, the formation of the clusters could be facilitated by an enhanced heat transport driven by planetary-scale modes.

In this regard a detailed spectral analysis, studying the contributions of the different periods to the vertical and zonal structure of extremes, could prove valuable. Applying a high-pass or band-pass filter to the data, with an upper cut-off around 6-8 days would remove the planetary-scale component and highlight the structure of the local synoptic motions.

A second question concerns the differences seen in terms of the zonally integrated transport distributions between the two hemispheres. It has already been suggested in section 4 that the bimodality seen in the SH distribution is the result of two distinct patterns. One holds for the lower latitudes, where there are larger values of zonally integrated transport. The other holds for the higher latitudes, where the zonally integrated transport is smaller. While, in general, this is also true of the NH, the two hemispheres display a clear difference in the geographical distributions of the local extremes. In the NH, the location of the extreme events is varied, with the two storm tracks playing an important role, but with several other areas of vigorous
activity at higher latitudes (MC13). This is in contrast to the SH, where the vast majority of the extreme events is concentrated in a narrow latitudinal band, providing a much sharper contrast between the lower and higher latitudes (see figure 6b).

Regardless of their differences, both hemispheres display a pronounced variability on a zonally integrated level, which translates into the existence of zonally integrated transport extremes. This is very significant for the energy balance of the high latitudes. The last decade has seen unprecedented sea-ice loss in the arctic basin, which has been underestimated by almost all climate models (e.g. Stroeve et al., 2007). There are studies suggesting that anomalous atmospheric heat transport convergence at high latitudes, driving local long-wave forcing, could be playing a significant role in this process (Graversen et al., 2011). A more systematic analysis and modelling of the variability of zonally integrated meridional heat transport, and a study of the possible changes in variability resulting from climate change, would therefore be crucial in order to better understand the future of the polar regions.

Supporting Information
The supporting information presents a discussion of the role of \( v' \) and \( H' \) in driving transport extremes (section S1) and a short comment on the sensitivity of the analysis to filtering the data (section S2). The following figures are included in the supporting information:

Figure S1: Composite pressure versus longitude \( v' \) and \( H' \) sign combination colourmap for extreme events. The colour bar shows the sign combinations corresponding to the different colours. The data cover NH DJFs from December 1989 to February 2011. All latitude circles between 30° and 89°N are taken into account. The continuous black contours mark regions where 30%, 40%, 50% and 60% of extreme events share the same sign combination. The diagonal striping marks regions of equatorward transport.

Figure S2: Composite pressure versus longitude composite covariance map for meridional heat transport extreme events. The data cover the same range as in figure S1. Darker (redder) colours correspond to larger (more positive) covariance values. The covariance is normalised relative to the maximum. The diagonal striping marks regions of equatorward transport. Note that the colourbar is not symmetric about zero.

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the helpful comments. We are also grateful to R.G. Graversen for providing the vertically integrated heat transport data and for a stimulating discussion on equatorward transport events.
References


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### Extreme Event Regional domains

<table>
<thead>
<tr>
<th>Domain Name</th>
<th>Abbreviation</th>
<th>Boundaries</th>
</tr>
</thead>
<tbody>
<tr>
<td>a. Gulf Stream</td>
<td>GS</td>
<td>30°N-55°N; 265°E-335°E</td>
</tr>
<tr>
<td>b. Pacific Storm Track</td>
<td>PS</td>
<td>30°N-50°N; 150°E-230°E</td>
</tr>
<tr>
<td>c. Bering Strait/Gulf of Alaska</td>
<td>BS</td>
<td>55°N-70°N; 180°E-200°E</td>
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<tr>
<td>f. Nordic Seas</td>
<td>NS</td>
<td>55°N-80°N; 335°E-15°E</td>
</tr>
<tr>
<td>e. Southern Ocean</td>
<td>SO</td>
<td>40°S-70°S; 295°E-275°E;</td>
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Table I: Names, abbreviations and boundaries of the domains used in the analysis of extreme event regional composites.
Incidence of equatorward atmospheric heat transport in the ERA-Interim Reanalysis

<table>
<thead>
<tr>
<th>Hemisphere</th>
<th>Season</th>
<th>850mb</th>
<th>850mb &amp; 300mb</th>
<th>850mb &amp; Full Transport</th>
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<tbody>
<tr>
<td>N</td>
<td>DJF</td>
<td>8.9</td>
<td>4.7</td>
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<tr>
<td></td>
<td>JJA</td>
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<td>2.6</td>
<td>1.4</td>
</tr>
<tr>
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<td></td>
<td>JJA</td>
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<td>3.6</td>
<td>0.8</td>
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</table>

Table II: Frequency of equatorward zonally integrated atmospheric heat transport values. The 850mb column refers to events where the zonally integrated transport by transient motions is equatorward at 850mb. The 850mb & 300mb column refers to events where the zonally integrated transport by transient motions is equatorward at both 850mb and 300mb. The 850mb & full transport column refers to events where the zonally integrated transport by transient motions at 850mb and the vertically and zonally integrated net transport by all motions are both equatorward. The data cover all longitudes and latitudes, from 30°N to 89°N and from 30°S to 89°S over the period June 1989-February 2011.
Contribution of extreme events to meridional atmospheric heat transport in the ERA-Interim Reanalysis

<table>
<thead>
<tr>
<th>Hemisphere</th>
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<th>Zonal integration % weight</th>
<th>Local events % weight</th>
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<td></td>
<td></td>
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<td>JJA</td>
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</table>

Table III: Percentage contributions of the top five percentiles of $v'H'$ events in DJF and JJA to net and poleward-only meridional atmospheric heat transport due to transient eddies. The first three data columns refer to zonally integrated values; the last column to single-gridbox values. The “Gaussian Equivalent” column indicates the positive-only contributions of events above the same percentile thresholds as the extremes in Gaussian distributions with the same means and standard deviations as the reanalysis distributions. The data cover the same range as in table II.
Figure 1: The colourmap displays composite pressure versus longitude meridional heat transport (W/1000hPa) for extreme events. The diagonal striping marks regions of equatorward transport. The cross-hatching marks regions which are not statistically significant at the 99% confidence level. The continuous contours show meridional velocity anomalies every 2.5 ms\(^{-1}\). The dashed contours show MSE anomalies every 1.5 K. Zero contours for both variables are labelled; thicker contours correspond to negative values. The data cover NH DJFs from December 1989 to February 2011. All latitude circles between 30° and 89°N are taken into account. Note that the colourbar is not symmetric about zero.
Figure 2: Composite pressure versus longitude colourmaps of a) zonal, b) meridional and c) pressure velocities for meridional heat transport extreme events. The units are ms$^{-1}$, ms$^{-1}$ and Pas$^{-1}$, respectively. The data cover the same range as in figure 1. The diagonal striping marks regions of negative velocities (westwards, equatorwards and upwards, respectively). The cross-hatching marks regions which are not statistically significant at the 99% confidence level. Note that the colourbars of panels b) and c) are not symmetric about zero, while that of panel a) is positive-only.
Figure 3: Same as figure 1 but for extreme events corresponding to a) positive and b) negative meridional velocity anomalies at the location of the extreme event local maxima. Unlike in figure 1, the contour intervals are every 5 ms$^{-1}$ for meridional velocity anomalies and 3 K for MSE ones.
Figure 4: Same as figure 1 but for extreme events in the five regional domains listed in table I. The letters of the panels match those of the table.
Figure 5: Schematic showing the typical structure of a conveyor belt system, including the warm conveyor, the cold conveyor and the dry air intrusion (from Catto et al., 2010, © American Meteorological Society, used with permission).
Figure 6: a) Map of seasonal mean spatial distribution of local heat transport extreme events for DJF. The data cover DJFs from December 1989 to February 2011. The scale of the colour bar corresponds to the number of data points per season per $0.7^\circ \times 0.7^\circ$ box. The calculation is not applied equatorward of $30^\circ$ latitude. The black boxes correspond to the regional domains used in section 3.2. The exact co-ordinates for each domain are listed in table I. b) Map of seasonal mean spatial distribution of WCB trajectories 24h after genesis for DJF. The data cover DJFs from December 1979 to February 1993. The scale of the colour bar corresponds to the fraction (in percent) of all trajectories that fulfil the WCB criteria (from Eckhardt et al., 2004, © American Meteorological Society, used with permission).
Figure 7: PDFs of zonally integrated atmospheric heat transport due to transient eddies for a) NH DJFs and b) SH JJAs. Both PDFs are plotted over the same bins. The data cover the 850 mb fields from June 1989 to February 2011. All latitude circles between 30° and 89°N and S are taken into account. The skewnesses of the PDFs are a) 0.83 and b) 0.34. The corresponding most likely values are a) 0 W/1000hPa and b) 0 W/1000hPa. The continuous vertical lines show the bins corresponding to the most likely values. The dashed vertical lines show the bins corresponding to the 95th percentiles.
Figure 8: PDFs of a) local and b) high-pass filtered zonally integrated atmospheric heat transport due to transient eddies. The data cover NH DJFs from December 1989 to February 2011. All latitude circles between 30° and 89°N are taken into account. The skewnesses of the PDFs are a) 4.8 and b) 1.34. The corresponding most likely values are a) 0 W/1000hPa and b) 0 W/1000hPa. The continuous vertical lines show the bins corresponding to the most likely values. The dashed vertical lines show the bins corresponding to the 95th percentiles. The continuous black line with circular markers in a) shows the CDF of the data.
Figure 9: Bar plot of local and zonal extreme event frequency along the 50°N latitude circle. The data cover the 850mb fields. Both local and zonal extremes are defined as events in the top 5 percentiles of the respective meridional heat transport distributions for the full NH domain. The five panels correspond to DJF seasons from December 1989 to February 1994. The height of the bars corresponds to the number of longitude gridboxes displaying a local extreme event on a given day; vertical lines over the light grey bars mark days where the 50°N latitude circle displays a zonal extreme event. The abscissa indicate the day of the season.
Figure 10: Schematic illustrating hypotheses a) and b) formulated in section 5.2. The dashed curves in both panels represent a hypothetical baseline meridional heat transport profile at a given latitude. The continuous curve in a) represents an enhanced heat transport (zonal extreme) resulting from strong, localised increases at specific locations (local extremes). The continuous curve in b) represents an enhanced heat transport (zonal extreme) resulting from an approximately uniform increase at all longitudes, without any large local peaks.
Figure 11: PDFs of the number of local extreme events around a full latitude circle for days which are in the top 5% (white) and days which are in the bottom 95% (grey) of the distributions of the zonally integrated meridional atmospheric heat transport due to transient eddies. The PDFs cover a), c) NH DJF and b), d) SH JJA data, over the same temporal and spatial range as figure 7. a) and b) consider all local extremes; c) and d) only count well-separated local extremes. Only days/latitudes with at least one local extreme are considered. The most likely values are respectively a) 60 (extremes, in white) and 28 (non-extremes, in grey), b) 68 and 20, c) 4 and 1 and d) 5 and 2. The corresponding means are respectively a) 64 and 31, b) 70 and 33, c) 4.0 and 2.3 and d) 5.2 and 2.9. The vertical lines show the bins corresponding to the most likely values.
Figure S1: Composite pressure versus longitude $v'$ and $H'$ sign combination colourmap for extreme events. The colour bar shows the sign combinations corresponding to the different colours. The data cover NH DJFs from December 1989 to February 2011. All latitude circles between 30° and 89°N are taken into account. The continuous black contours mark regions where 30%, 40%, 50% and 60% of extreme events share the same sign combination. The diagonal striping marks regions of equatorward transport.

Figure S2: Composite pressure versus longitude composite covariance map for meridional heat transport extreme events. The data cover the same range as in figure S1. Darker (redder) colours correspond to larger (more positive) covariance values. The covariance is normalised relative to the maximum. The diagonal striping marks regions of equatorward transport. Note that the colourbar is not symmetric about zero.