



Minerva Access is the Institutional Repository of The University of Melbourne

Author/s:

Pezza, AB;Garde, LA;Veiga, JAP;Simmonds, I

Title:

Large scale features and energetics of the hybrid subtropical low 'Duck' over the Tasman Sea

Date:

2014-01-01

Citation:

Pezza, A. B., Garde, L. A., Veiga, J. A. P. & Simmonds, I. (2014). Large scale features and energetics of the hybrid subtropical low 'Duck' over the Tasman Sea. *Climate Dynamics*, 42 (1-2), pp.453-466. <https://doi.org/10.1007/s00382-013-1688-x>.

Persistent Link:

<https://hdl.handle.net/11343/282940>

Large scale features and energetics of the hybrid subtropical low 'Duck' over the Tasman Sea

Short title: Energetics of the hybrid low 'Duck'

Alexandre Bernardes Pezza¹, Luke Andrew Garde^{1,2}, José Augusto Paixão Veiga³ and Ian Simmonds¹

¹School of Earth Sciences, The University of Melbourne, Victoria 3010, Australia

² Centre for Australian Weather and Climate Research
PO Box 1289K, Victoria 3001, Australia

³ Institute of Technology, Amazon State University, Manaus, Brazil

Revised version submitted to *Climate Dynamics* on 20 Dec 2012

Corresponding authors address:

School of Earth Sciences
The University of Melbourne
Victoria 3010, Australia
e-mail: apezza@unimelb.edu.au

ABSTRACT

New aspects of the genesis and partial tropical transition of a rare hybrid subtropical cyclone on the eastern Australian coast are presented. The ‘Duck’ (March 2001) attracted more recent attention due to its underlying genesis mechanisms being remarkably similar to the first South Atlantic hurricane (March 2004). Here we put this cyclone in climate perspective, showing that it belongs to a class within the 1% lowest frequency percentile in the Southern Hemisphere as a function of its thermal evolution. A large scale analysis reveals a combined influence from an existing tropical cyclone and a persistent mid-latitude block. A Lagrangian tracer showed that the upper level air parcels arriving at the cyclone’s center had been modified by the blocking.

Lorenz energetics is used to identify connections with both tropical and extratropical processes, and reveal how these create the large scale environment conducive to the development of the vortex. The results reveal that the blocking exerted the most important influence, with a strong peak in barotropic generation of kinetic energy over a large area traversed by the air parcels just before genesis. A secondary peak also coincided with the first time the cyclone developed an upper level warm core, but with insufficient amplitude to allow for a full tropical transition. The applications of this technique are numerous and promising, particularly on the use of global climate models to infer changes in environmental parameters associated with severe storms.

Key words: Mid-latitude storms, cyclones, Lorenz energetics, blocking, polar lows.

1. Introduction

Cyclone Duck was a rare westward-propagating low pressure storm that made landfall on the east Australian coast on 8 March 2001 (*Qi et al.*, 2006; *Garde et al.*, 2010). This cyclone had a hybrid thermal structure partially driven by upper level baroclinicity and partially driven by tropical processes in association with strong surface heat fluxes (e.g. *Montgomery et al.* 2009). The low potentially qualified as a subtropical cyclone (*Evans and Guishard*, 2009). In light of its short lived upper level warm core development, the Duck has been regarded as a case of partial tropical transition (TT) (*Garde et al.* 2010).

As noted by *Garde et al.* (2010), the broadscale environment conducive to the intensification and landfall of cyclone Duck was provided by a mid-latitude blocking anticyclone, which was associated with persistent low windshear off the coast. A favorable pattern of positive heat and moisture fluxes over the ocean, and of enhanced moisture convergence into the area of development were also key ingredients leading to the development of this system.

The role of blocking on the development of rare hybrid (subtropical) cyclones undergoing tropical transition (*Hart*, 2003) has been recently demonstrated for the South Atlantic (*Pezza and Simmonds*, 2005; *Veiga et al.*, 2008). A persistent, near-record blocking high was central to the development of the first known South Atlantic hurricane, ‘Catarina’ (*Pezza and Simmonds*, 2005). Atmospheric blocking has also been suggested as an important mechanism in the development of mid-latitude maritime cyclones on the eastern coast of Australia, often called East Coast Lows (*Holland et al.*, 1987). Frequently cyclones forming on the equatorward edge of a blocking ridge may develop into severe (explosive) storms, in some cases producing hurricane-force winds (average winds greater than 120 km/h) and undergoing explosive development (*Lim*

and Simmonds 2002; Allen *et al.*, 2010 and references therein). The Duck produced wind gusts of at least 39 m/s to the south of Byron Bay (around 29°S), causing locally heavy thunderstorms with flash flooding and near-record rainfall amounts (Garde *et al.*, 2010).

Classic, non-hybrid extratropical cyclones have been the subject of studies using the Lorenz energetics approach in the past with emphasis on understanding the importance of heat and momentum transfers in mesoscale processes (Wahab *et al.*, 2002; Marquet, 2003; Decker and Martin, 2005; Pezza *et al.* 2010). Recently the technique has been used to study the tropical transition of Catarina from an energy-transfer perspective (Veiga *et al.*, 2008). This was the first time that a dynamic transition (from cold to warm core) of a storm was explained by the environmental energetics, opening a new avenue of exploration of extreme weather events and their connections with climate drivers.

As summarized by Veiga *et al.* (2008), baroclinic and barotropic conversions on the scale of the background environment can be used to explain the onset of the hybrid phase when the signal is above the background noise. Such conditions tend to be observed within blocking highs, where the background energy conversion is ‘settled’ as a result of low vertical windshear, with a dominance of barotropic conversions. The energy transfer is believed to occur indirectly from the environment to the blocking firstly, while the blocking gives dynamical support necessary for the vortex to grow. Once the vortex has been initiated, local processes may become more important.

Other recent papers have explored links between the large scale environment and extreme weather events, including the environmental energetics of severe weather (e.g. Dal Piva *et al.*, 2010; Davis 2010 and Cordeira and Bosart, 2010; Favre *et al.*, 2012). Dal Piva *et al.* (2010), for instance, found that baroclinic conversion dominates the energetics of winter upper level troughs

that enter South America from the Pacific Ocean, while *Gutierrez et al.* (2009) used the Lorenz energy diagnostics to characterize each phase of their monsoonal season. *Cordeira and Bosart* (2010) revisited the “perfect storms” of late 1991 (three high-impact extratropical cyclones affecting the North Atlantic) and found that the downstream baroclinic development was strengthened by a curvature amplification formed by tropical convection. In their analysis it became evident that the baroclinic conversion from eddy available potential into eddy kinetic energy was a key factor in the maturation of the extratropical cyclones.

Harr and Dea (2009) also conducted an eddy kinetic energy analysis for North Pacific tropical cyclones undergoing extratropical transition, showing that for all cases there was an evolving peak in the volume-integrated kinetic energy. *Favre et al.* (2012) studied the relationship between cut-of-lows and the Semi-Annual and Southern Oscillations via an automated tracking scheme, finding that the meridional temperature gradient, as expected by the baroclinic instability theory, remained the most important ingredient for the genesis of those systems. When assessing the energetics, this is one of the factors which helps explain the vigorous conversions in the energy cycle of baroclinic storms.

We here explore how the Lorenz energetics present a very informative perspective on the onset and development of the Duck episode, analyzing several implications of the energy exchange in terms of dynamical processes that were fundamental to the development of this storm.

Data and methodology are discussed in section 2. In section 3a we introduce the Dvorak signature and the large scale environment associated with the Duck, highlighting the combined participation of the turbulent heat fluxes and the extratropical influences via the persistent

blocking poleward. This is followed by an energy analysis in section 3b, revealing the fundamental barotropic and baroclinic conversions over two domains specifically chosen to represent I) the environment surrounding the cyclone's trajectory as well as the blocking over the Tasman; II) the remote influences from the extratropics. This novel approach is then followed by a climatological discussion of thermal changes in cyclones that satisfy a condition similar to the Duck, defining a filter that reveals the global signature of lows undergoing a similar 'transition'. We conclude in section 4 with a discussion of future avenues of exploration, particularly in light of climate change prediction of large scale patterns leading to blocking and extreme storms worldwide.

2. Data and Methodology

The methodology employed to calculate the fundamental energy transfers associated with the Duck cyclone follows from *Veiga et al.* (2008) and references therein. A traditional and compact form of energy computations was initially derived in the classic work of *Lorenz* (1967), where the available potential energy was partitioned into zonal available potential energy (AZ) and eddy available potential energy (AE). Similarly, the kinetic energy was partitioned into zonal (KZ) and eddy (KE) components.

The energy budget equations for an open area can be given as (see, e.g., *Pezza et al.* (2010)):

$$\frac{\partial KZ}{\partial t} = CK + CZ + BKZ + B\phi Z - DZ \quad 1a$$

$$\frac{\partial KE}{\partial t} = CE - CK + BKE + B\phi E - DE \quad 1b$$

$$\frac{\partial AZ}{\partial t} = -CZ - CA + BAZ + RGZ \quad 1c$$

$$\frac{\partial AE}{\partial t} = CA - CE + BAE + RGE \quad 1d$$

where CK, CE, CZ and CA are the conversion terms between the different energy forms. From equations 1a-1d we can see that CK appears in 1a and 1b (with opposite signs), implying that this term represents a conversion between zonal kinetic (KZ) and eddy kinetic (KE) energies. Similarly, it can also be seen that the remaining conversion terms are also present with opposite signs in two equations, implying a conversion between the remaining energy forms. In short: CE converts available eddy into kinetic eddy, CA converts available zonal into available eddy and CZ converts available zonal into zonal kinetic energy. CK is the only term which is regarded as barotropic because it involves only kinetic energy, relying entirely on horizontal wind shear for its expression.

To complete the sources and sinks of each energy form, AZ and AE are also produced by generation processes named RGZ and RGE (generation of AZ and AE). In an open area the budget is complicated by the presence of energy fluxes across the horizontal boundaries. To account for these we include four new components representing the transport of AZ, AE, KZ and KE (BAZ, BAE, BKZ and BKE, respectively). In addition, KZ and KE are associated with the work done at the boundaries (BØZ and BØE, respectively).

The last terms in 1a and 1b, namely DZ and DE, represent dissipation processes. Those terms are here combined and computed in the form of residuals (*Wahab et al.*, 2002). In a similar

fashion, the errors resulting from the numerical estimations for the remaining terms in 1c and 1d are also included as residuals. In the interest of brevity and clarity we do not include the energy box diagrams showing the transport, boundary and dissipation terms, as the energy conversions discussed in section 3 are at least one order of magnitude greater than those terms.

Six-hourly data from the ERA interim reanalysis ($1.5^\circ \times 1.5^\circ$ resolution (*Dee et al.*, 2011)) were used for the gridded energy calculations. ERA interim was chosen because of its high quality, this being of particular importance in the Southern Hemisphere where surface observations are sparse. Horizontal integrations were performed over the areas of domain 1 ($50^\circ\text{S} - 20^\circ\text{S}$; $150^\circ\text{E} - 170^\circ\text{E}$, hereafter D1) and domain 2 ($50^\circ\text{S} - 35^\circ\text{S}$; $135^\circ\text{E} - 170^\circ\text{E}$, hereafter D2), both indicated in figure 4a.

Two separate domains were chosen based on the principle that the environment sampled should be sufficiently large that the budget calculations are not unduly influenced by the presence of the vortex itself. While D1 covers the main environment incorporating the whole track as well as the Tasman blocking which gave dynamical support to the system, D2 represents the extratropical influences which maintained the blocking, remotely contributing to the genesis and evolution of the Duck (*Garde et al.*, 2010). Tests were performed for several variations of the domains proposed and the results are robust.

While the Lorenz energetics approach here employed can only be used over a sufficiently large domain where the energy and conversion terms are robustly expressed by area integrals, our choice of presenting the results for two domains is a novel approach adding value to the analysis. The combination of domains 1 and 2 provide an excellent overall perspective on the key aspects of the dynamics and thermodynamics taking place. To test the sensitivity our calculations were

also performed using the NCEP/NCAR reanalysis, and we found our main results to be essentially unchanged.

The average temperature difference between the cyclone core and an environmental ring, set at a distance corresponding to the cyclone's size, is calculated throughout the troposphere during the life cycle of a cyclone, as a metrics of the core temperature anomaly. This difference represents the thermal index or 'thermal phase' of the cyclone relative to its immediate environment, and is here referred to as the General Cyclone Transition (GCT) index. The word 'transition' is employed here in a sense of exploring how the thermal signature of a cyclone's core may evolve in time regardless of its latitudinal shift (see section 3c for more details, including the application of a climatological filter to detect cyclones that have evolved similarly to the Duck).

The GCT is defined as: $GCT = T_c - T_{env}$, where T_c is the temperature at the centre of the cyclone. The 'environmental' temperature, T_{env} , is the average temperature over the circle of radius R and centered on the cyclone centre. The radius is taken to be the radius of the cyclone, the calculation of which is explained in detail in Lim and Simmonds (2007). The GCT has been added by one of the authors (L. A. Garde) as an extension to the existing Melbourne University Cyclone Tracking Scheme (PhD thesis at The University of Melbourne).

It is important to take care when sampling the upper level temperatures to calculate the GCT, as the stratosphere may give a distorted picture of the thermal signatures (Hart 2003). This becomes an issue when dealing with cyclones at high latitudes, where the tropopause is naturally lower. The approximate height of the tropopause is identified by evaluating the vertical gradient of potential temperature at every cyclone location, using 0.23 K hPa^{-1} as an empirical threshold

considering a standard atmosphere (Bluestein, 1993). As our analysis will show (see section 3c), only a very small fraction of the cyclones identified by our filter were ‘contaminated’ by stratospheric influences.

We also note that the GCT does not explicitly take into account the possibility of vertical tilts in the cyclones. In our climatological analysis (section 3c), the adoption of a ‘vertically-aligned’ core temperature index gives a true representation of the thermal signature at the lower levels. At the upper levels the accuracy of the index would depend on how vigorous the baroclinic tilt is as well as on cyclone size. Our tests have shown the index (above 0.5°C magnitude) to be a true representation of the sign of the thermal core for synoptic scale cyclones, which are the aim of this analysis. Furthermore, the filter employed in section 3c uses the relative temperature evolution over 48 hours and is therefore unaffected by small asymmetries. This is also not a problem in the case of the Duck, which had very little tilt for the levels in which the GCT was calculated (Garde et al. 2010).

The ERA-interim (1989-2009) data is also used to derive the cyclone track and to calculate the environmental dynamical and thermodynamical properties that help understand why the Duck was formed. We note that while Garde et al. (2010) presented a mesoscale analysis based on high resolution datasets our aim here is to address the large scale, with energy conversions pertaining to the synoptic environment. For this purpose the ERA-interim has adequate resolution to resolve the processes of interest, noting that this is one of the strengths of the Lorenz technique. We start the analysis in the next section with an overview of the large scale blocking and bulk fluxes (*Reale and Atlas, 2001*) before proceeding on to using the selected domains for the environmental energetics.

3. Results

(a) Overview of Dvorak signature, air-sea interaction and blocking properties

Figure 1 shows (a) a color-enhanced GMS-5 Infra red image of the Duck at its developing phase prior to landfall and (b) the evolution of the central MSLP and radius as given by the Melbourne University automatic tracking scheme (Simmonds, 2000). Panel (a) depicts key geographical locations in Australia. The Duck's location at 2200 UTC 7 March 2001 is marked with an L. The areas with enhanced surface heat fluxes (marked by an asterisk) as well as the position of the upper level and surface blocking highs to be discussed in this section are also indicated (the latter features are also shown in figure 2). The storm appears cut-off from the old frontal structure to the northeast, with a maturing self-sustained cyclonic vorticity center. At the time depicted in the image the cyclone had a vertically aligned (barotropic equivalent) structure, being warm-cored at the surface and cold-cored at mid and upper levels (Garde et al., 2010). It satisfied the basic subtropical criteria (*Evans and Guishard, 2009*), suggesting at least some participation of convective heating.

The color enhancement, which is the physical principle of the Dvorak technique used to remotely identify the intensity of tropical cyclones (Dvorak, 1984), indicates moderate cloud top temperatures of about -60°C . This suggests that the latent heat release of the storm alone would have been too small to cause its observed growth into a near category-I wind-equivalent in the Saffir-Simpson scale. The Duck did not present a very marked drop in pressure (figure 1b), but the MSLP remained below 1005 hPa during most of the lifecycle increasing just before landfall, while the radius decreased throughout the lifecycle. This combination helps explain the increase in intensity towards landfall as the Duck became a mesoscale system with tighter gradients,

producing locally strong winds. (Note that a zig-zag pattern, of amplitude of 1-2 hPa appears in the pressure trace. This is associated with the atmospheric semi-diurnal tide (see, e.g., Covey et al. (2011)). At landfall, the minimum pressure measured by a meteorological station was about 992 hPa, which was unsurprisingly lower than the reanalysis data estimates in figure 1a.

Figure 2 shows the MSLP (colour scheme) and the 300 hPa geopotential anomalies (contours) from day minus 5 (12Z 3 March 2001, top left) to day zero (12Z 8 March 2001, bottom right). The genesis and landfall positions of the Duck are indicated on the first panel as a reference. Day zero (bottom right) corresponds to the approximate time of landfall. We note the presence of a low in the western Pacific just to the west of the date line, TC Paula, on day minus five. That pre-existing tropical cyclone projected a trough to the west (light blue shading on top left panel) which may have partially contributed towards the genesis. However, the overall development of Duck was also supported by a cyclonic upper level potential vorticity (PV) anomaly propagating from mid-latitudes on day minus three as shown by figure 10 of *Garde et al.* (2010).

From the evolution of the Duck we can appreciate that the small initial surface disturbance is separated from the parent trough on day minus four, losing intensity on day minus three but regaining upper level support on day minus two while approaching the coast. This recovery coincided with the earlier PV anomaly findings by *Garde et al* (2010). As we will discuss shortly, the heat fluxes also played an important role in the Duck's enhancement. Hence it is clear that the Duck required a combination of many conditions to evolve. Our findings about the influence of the pre-existing TC in its embryonic stage had not been noted by *Garde et al.*, but our analyses confirm their view that without the PV injection the system would have been left with very little upper level support (figure 2, day minus three).

The overall scenario in figure 2 shows a persistence of very high MSLP to the south of Australia at all longitudes. The blocking conditions (H_{500} and H_{MSL}) were also summarized in figure 1a, where the key areas are noted. The small H_{MSL} between Australia and New Zealand (figures 1a and 2a) indicates the average position of the surface anticyclone during the Duck's lifecycle (3-8 March). The position of this high was key for the generation of the cold advection which enhanced the oceanic heat fluxes to the south of the Duck's center, as discussed below.

The large H_{500} (figures 1a and 2a) refers to the average 500 hPa geopotential anomaly that manifested as a continuous injection of anticyclonic vorticity feeding the surface anticyclone to the east. As shown by Garde et al. (2010), the blocking created the ideal set up to allow the Duck to grow at the expense of the favorable thermodynamic energy in a low sheared environment. It can be easily observed throughout the temporal sequence provided in figure 2 how these areas experience an intensification of the MSLP and geopotential anomaly, characterizing the overall strength of the blocking. This was very similar to the underlying development of the first South Atlantic hurricane (*Pezza and Simmonds, 2005; Veiga et al., 2008*).

The asterisk shows the origin location of the air parcels reaching the vicinity of the Duck at 200 hPa. This feature remarks the notable extratropical connection that helped form the Duck, with air parcels originating far in the Indian Ocean within a week of the landfall date. A zoomed-in plot of the 3D air parcel trajectory associated with this feature will be discussed in detail in the energetics chapter in section 3b.

An overview of how the large scale dynamics acted in concert with the air-sea fluxes is now described. Figure 3 shows the anomalous large scale conditions averaged over the week leading to landfall. The following fields are shown: (a) mean and anomalous sea surface

temperature (SST), (b) mean and anomalous 2m air temperature, (c) SST minus air temperature, (d) 10 m wind anomalies, (e) anomalous sensible heat flux and (f) mean latent heat flux. The SST field (figure 3a) shows a pattern dominated by warming over mid and high latitudes with a suggestion of a wave four structure. This bears some resemblance with the SST response normally observed during the positive phase of the Southern Annular Mode (SAM) (*Lovenduski and Gruber, 2005*), except that the anomalies are also positive around Antarctica.

Of relevance here is that over the Tasman Sea the anomalous warming extends well into the tropical region where the precursor to the Duck was first identified. The 2m air temperature anomalies (figure 3b) also reflects the hemispheric wave four pattern, promoting a reduced north-south temperature gradient inland Australia. This pattern was a catalyst for the maintenance of the blocking structure over the Australian sector via forcing barotropic conditions.

Panel 3c shows that for most of the hemisphere the SST was warmer than the air temperature, including the western Pacific Ocean, and the Tasman and Coral Seas. Immediately east of New Zealand this positive difference is maximized, enhancing the thermodynamic instability. An analysis of backtrack trajectories (figure 5 of *Garde et al. (2010)*) shows that this area was the main origin of the parcels reaching the Duck from the lower levels. Figure 3(d) shows that the wind anomalies were cyclonic over the area where the Duck formed, with easterly anomalies to the south of Australia contributing to the maintenance of the blocking.

A strong easterly anomaly is also observed to the east of New Zealand in connection to the enhanced sea-air gradient region discussed before. Figure 3e shows the anomalous surface sensible heat flux. As expected, the highlighted areas above experienced a greater than normal flux uptake into the atmosphere, contributing towards the build up of the convection. *Garde et al.*

(2010) argued that only for a short time the convection eventually sustained what they referred to as ‘partial transition’ of the Duck, with a small upper level warm core forming on March 5th before disappearing and reappearing again at landfall (their figure 2) .

We also note the positive anomalies around New Caledonia, close to where the cyclone was first observed. The latent heat flux shows a similar pattern, and the mean field is shown in figure 3f to highlight the actual observed values. The structure confirms that the Tasman Sea and the west Pacific to the north of New Zealand had fluxes amongst the largest in the Southern Hemisphere, indicating that the persistent moistening of the atmosphere in the lead up to the event was an additional ingredient that favoured the formation and maintenance of the convective structure accompanying the Duck.

Garde et al. (2010) also noted that the final enhancement as the cyclone approached the coast was also associated with the evaporative effects over the ocean (e.g., Wind-induced surface heat exchange: Montgomery et al., 2009). This agrees well with the persistent areas of positive sensible and latent heat fluxes discussed above. We note that the wind anomalies induced the thermal anomalies via advection in the first place, being fundamentally driven by the anticyclonic circulation of the blocking high. Hence it is evident that both the blocking and the thermodynamics acted in concert to intensify the Duck during its lifecycle, allowing it to draw energy simultaneously from the baroclinic wave as well as the heat fluxes. The overall cyclone trajectory as derived by the University of Melbourne automatic Cyclone Tracking Scheme (*Simmonds et al.*, 2003) is shown in figure 4(a). We discuss in the next section how the environmental energy conversions reveal that the blocking created a marked barotropic source from which the cyclone drew energy in its pre-genesis phase.

(b) Lorenz energetics

As discussed earlier we conduct our energetic analysis over the two domains shown in Fig. 4a (D1 and D2). This provides insights on both the thermodynamics and dynamics of the underlying mechanisms associated with Duck's transition. As we will see, from an energetics perspective both areas exerted key influences that help explain how the environment contributed to the genesis and partial tropical transition of this hybrid cyclone indirectly, via providing energy barotropically (i.e, primarily via barotropic conversions) to the blocking high.

Fig. 4(a) shows the cyclone track (in blue) and the 3D Lagrangian trajectory (*Barras and Simmonds, 2009*) for an air parcel arriving two degrees to the south of the cyclone center at about the time of landfall, at 200 hPa (in orange). This level is representative of the baroclinic region supporting the cyclone. A slightly southward location was chosen because this is where the maximum wind speeds and convergence were observed (*Garde et al., 2010*). Figure 4a shows that the trajectory originated to the southwest of Australia and crossed D2. This agrees with the PV anomaly noted by *Garde et al. (2010)*, further clarifying the influence of D2 on the formative process.

Figure 4b shows the time series of the vertically-integrated (925 - 100 hPa) energy terms over D1. It is evident that KZ and AZ participate with strong manifestations during all the key phases of the Duck's lifecycle, *viz.* genesis, partial tropical transition and landfall. The genesis is preceded by a strong peak in AZ. This energy is 'drained' as the cyclone forms (see point G marked on the figure) while the eddy available potential and kinetic energy terms (AE and KE) increase above the background about 24 hours before genesis. We note that the strong peaks observed in the mean kinetic and available potential energies are well above the climatology, and

hence are not reflecting meridional vacillations of the mid-latitude jet near the peripheries of D1. The whole domain was indeed engulfed by the blocking system which remained virtually unchanged throughout the entire lifecycle as seen in figure 2.

While we will see that the conversions at genesis are more revealing for D2, the signal at landfall for D1 is mainly associated with conversion from zonal available potential energy to zonal kinetic energy (CZ) due to the overturning circulation. This reflects the build up of a strong meridional thermal gradient in the box particularly at landfall when the cyclone brought cold advection and cloudiness inland.

Figure 4b also shows that KZ peaks for the first time when the cyclone briefly acquired a modest warm core (partial TT, see figure 2a of *Garde et al.* (2010)). The strong kinetic energy manifestation at this phase is associated with a combined pattern with barotropic (CK) and baroclinic (CZ) conversions (not shown). The eddy kinetic energy, KE, had only a modest peak about 12 hours before the TT phase, slightly smaller than the maxima observed at genesis. Strong energy conversions are also seen at landfall (LF) when the available potential energy peaks and is quickly converted as the cyclone touches land.

The energetics for D2 are shown in figure 4c, and they indicate that the extratropical influences responsible for sustaining the blocking are different from those for D1. When the extratropical influence is considered alone the contribution from AZ is much more modest, and KZ dominates the environment throughout most of the lifecycle with a strong, sustained maximum starting just before the TT phase. The conversion terms for D2 show that the fundamental exchange was barotropic (CK) and given by a sharp peak a few hours before genesis (figure 4d). This peak in barotropic conversion suggests that the air parcels crossing the domain

(as shown in figure 4a) drew kinetic energy from the environment via momentum transport (horizontal shear). Hence, the energetics over D2 contributed to the maintenance of the vortex, helping explain the teleconnection with the extratropics.

Figure 5 shows the time evolution of the vertical structure of the (a) baroclinic conversion term CZ for D1, (b) barotropic conversion term CK for D2, (c) omega vertical velocity averaged over D2 and (d) omega vertical velocity averaged over a radius of 300 km around the storm center following the cyclone. The panels show strong responses and similarities during the key phases associated with the Duck's development. D1's CZ becomes positive after genesis (figure 5a) with a marked signature extending through the troposphere, and peaks between 250 and 400 hPa just before LF. This conversion can be thought of partially resulting from the enhanced horizontal temperature gradients and the corresponding vertical motions within the environment (overturning circulation), suggesting that this baroclinic process facilitated the Duck's development just before landfall, helped by the pronounced sensible and latent heat fluxes near the coast noted earlier. While the heat flux anomalies are only modest, they do occur over an area which already has one of the highest rates of latent heat release in the whole hemisphere during this time of the year (figure 3f).

The outstanding contribution of the barotropic conversion just before genesis is very clearly seen in figure 5b for D2. The pattern is vertically organised, extending all the way from the surface to the stratosphere, with a maximum slightly above 300 hPa. The sharpness of this barotropic pulse suggests that without the underlying presence of the blocking the Duck would not have formed, similar to what was hypothesized for the first South Atlantic hurricane (*Veiga et al.*, 2008). We draw attention to the fact that this pulse is symmetric (about 250 hPa) with height, whereas the maximum in CZ discussed earlier tends to abruptly dissipate above 200 hPa. This

fundamental difference reflects the fact that CK does not rely on the thermal structure, but rather on the horizontal (barotropic) shear.

Figure 5c shows that D2 experienced pronounced subsidence before genesis, as well as in the period between genesis and TT and just before landfall. Those were key periods of development for the storm. As the parcels that reached the Duck at the upper levels crossed D2 while the peak in barotropic conversion unfolded (figures 4a and 4d), we can argue that the blocking may also have acted as an energy source feeding the storm. Physically, the parcels would have gained increased kinetic energy via positive CK conversion while being anticyclonically deflected from the blocked area D2. The parcels would then acquire an upper level cyclonic turning when exiting the blocking and approaching the cyclone (figure 4a), still conserving their increased kinetic energy. This explanation adds a new energetics perspective to the classic synoptic view of cut-off-low equatorward of blockings (Holland et al., 1987; Garde et al., 2010).

Figure 5d shows that the ascending motion following the cyclone center largely resembles the other features discussed, with enhanced values between genesis and TT and also at landfall. In particular, this pattern strongly resembles the signature of CZ (compare panels a and d), reflecting the overall modulation of the energetics during the development of the Duck. Note that the time domain of panel d is slightly shorter than the remaining of figure 5 because the calculation of the Lagrangian tracer requires the existence of a cyclone by definition. It extends just slightly prior to genesis and beyond landfall as the cyclone was still captured as open (weak) depression by the automatic software, highlighting how the transition of the omega field unfolded. It can also be seen from the omega field (figure 5d) that the demise occurred from the upper levels towards the ground.

(c) GCT and climate perspective

The Duck was a rare system, but how rare? In order to put this cyclone in climate perspective our automatic cyclone tracking scheme has been enhanced to also track the evolution of the thermal properties of any given cyclone's core. This concept is here explored unconstrained by the traditional notion of transition involving a large latitudinal displacement (for example when a cyclone moves from the tropics towards mid-latitudes). Instead, our approach highlights how the thermal nature of cyclones can evolve and change even when the latitudinal shift is small or inexistent. In this sense, the idea of the 'general core transition' to be discussed below is to investigate how cyclones evolve thermally, and to eventually diagnose the links between the large scale environment and specific types of thermal evolution. While this is part of a larger project (to be communicated in a future publication), we present here the results relevant to diagnose the thermal evolution of the Duck and compare it with a sub-sample of SH cyclones which satisfy similar conditions, unconstrained by whether they are tropical, extratropical or classical transitions.

Figure 6 shows the 'general core transition index' (GCT) of the Duck during its lifecycle. An index above $+0.5^{\circ}\text{C}$ indicates that the cyclone is warm-cored, while a cold-cored cyclone is indicated by a GCT of less than -0.5°C . We can see that the Duck was primarily cold cored in the upper levels (300 hPa), briefly exhibiting a warm core just before landfall. The lower level signature was the reverse, starting as warm cored and becoming cold cored before landfall (850 and 925 hPa). This tracking agrees well with the partial transition concept discussed in this paper, and with the significant participation of the barotropic conversion associated with the blocking.

It is of significant interest to display the climatological characteristics of systems similar to the Duck. We performed an analysis over the ERA-interim climatological period of reference, showing that the Duck marginally falls within a filter containing only 0.84% of all SH cyclones found by the tracking scheme on an annual basis. The signature of such a filter is displayed in figure 7, where the red parts of the trajectories correspond to areas where a thermal core ‘transition’ (or evolution) similar to the one observed for the Duck is measured. The blue parts show the remaining of the same trajectories, during the period in which no thermal changes were observed.

The majority of the tracks have a net movement from the west towards the east, as expected. The Duck does not appear in this plot because its ‘thermal transition’ into warm core was only partial, with the core temperature change falling just under the standard threshold which was applied to the GCT filter as a reference. This filter (called filter A for simplicity, and as a reference for future work) displays trajectories where the upper level part of a cyclone is observed to change from negative (i.e., GCT less than -0.5°C) to positive-cored (i.e, GCT greater than $+0.5^{\circ}\text{C}$) over a period of 48 hours, while the inverse occurs at the lower levels. This metrics was chosen in order to identify cyclones whose overall energetics evolved towards a greater contribution from latent heat release processes throughout their life cycles.

Filter A shows that most subtropical tracks tend to follow a more baroclinic path towards the southeast, while the subtropical Tasman Sea and western Pacific appear as a one of the favored world-wide genetic areas for this type of cyclones at relatively low latitudes. Many cyclones that pass the test of this filter are also seen around Antarctica, showing many vigorous extratropical lows will also present a thermal evolution consistent with latent heat release processes (e.g. explosive cyclones and polar lows) in the absence of pronounced latitudinal shifts.

Hence, as discussed earlier, those are not ‘classic’ transition types, but rather a class that evolves thermally in a very specific way responding to surface heat fluxes and latent heat release. Tracks that might have been influenced by tropopause undulation (TU) in the calculation of the GCT are given by dashed lines. Amongst all 199 tracks only 13 might have been influenced by TU in the calculation of the GCT, showing that the interpretation for ‘Filter A’ is robust.

The filter conveys a specific temporal evolution of the thermal properties of each cyclone caused by various dynamical and thermodynamical processes such as intake of turbulent heat fluxes when crossing large bodies of relatively warm water, or via latent heat release resulting from convective processes. Figure 7 also shows that the parts of the trajectories that satisfy filter A (shown in red) experience much greater meridional displacement than the remaining periods (in blue). There is also a noticeable concentration of such tracks around the Ross Sea and the Eastern part of the Antarctic Peninsula, suggesting that processes associated with the formation of polar lows (Rasmussen and Turner, 2003) can also fall within the same thermal evolution as depicted in filter A as noted earlier. These results further highlight that overall the cyclones that obey a similar thermal evolution as the Duck are mostly associated with the high latitudes, indicating that the Duck was indeed very rare particularly at the relatively low latitude in which it was formed.

Figure 8 shows the climatological average cyclone GCT index per 5 degree latitude band for different levels for filter A. From this figure we can assess the average behavior of transitioning cyclones similar to the Duck as a function of their latitude. For the subtropical latitudes where the Duck underwent partial transition (25-30°S) there is a tendency for neutral to slightly warm cored systems at both lower and upper levels. This is slightly different to the Duck, for which the core signature averaged over its lifecycle would imply a somewhat colder average

(figure 6). When the cyclones retained in filter A are observed at higher latitudes they tend to have significantly warmer cores at lower levels with neutral to cold cores at higher levels.

4. Concluding remarks

In this article we discussed the environmental conditions associated with the formation and decay of a severe cyclonic storm that battered the east coast of Australia in March 2001. The ‘Duck’, as dubbed by operational meteorologists at the time, attracted attention as a system in the ‘gray’ area in what would be considered a cyclone with combined tropical and extratropical dynamical and thermodynamical signatures. The interest in this storm grew considerably when it became evident that its large scale precursors were similar to the ones observed during the first South Atlantic hurricane later developed in 2004 (*Pezza and Simmonds, 2005; Garde et al. 2010*).

The new analyses presented here reveal important aspects of the tropical-extratropical interaction not addressed before, such as the influence of a pre-existing TC in the very early stages, and the combined participation of the blocking and heat fluxes to re-intensify the system during the partial TT. A climatological filter shows that the Duck belongs to an overall class of cyclones which is very rare, corresponding to less than 1% of their annual occurrence in the SH. Our ‘transition filter’ highlights for the first time how cyclones evolve thermally in the SH within a sub-range where latent heat processes become progressively important at some stage during the trajectory. This view is unconstrained by the latitudinal shift classically associated with the traditional notion of ‘tropical or extra-tropical transition’, and adds to the recent global climatology provided by *Ulbrich et al., 2009*.

The environmental energetics was associated with a sharp barotropic conversion maxima just prior to the genesis, while a weaker peak occurred at the time the system first acquired an upper level warm core. The landfall is also seen to produce intense energy manifestations via baroclinic conversions associated with thermal dissipation inland. Overall, the conversions during the developing phase were modest and not exclusively barotropic, explaining why the cyclone did not attain hurricane status although it had formed under similar conditions as the South Atlantic hurricane Catarina. During Catarina's unfolding the combination of strong blocking and low shear was measured to be a long-term, unprecedented record during the satellite era, whereas during the Duck's lifecycle neither the blocking nor the low windshear were sufficiently prominent. The Duck moved faster and consequently spent little time over the favorable heat fluxes area.

Recently there has been increased interest in exploring links between the large scale environment and extreme weather events, including the environmental energetics of severe weather (e.g. *Dal Piva et al.*, 2010; *Cordeira and Bosart*, 2010; *Favre et al.*, 2012). Our results point to the value of considering multi domains in this approach in the pursuit of combined conversions that were available for the cyclone to draw energy from. The energetics was also complemented by our range of 'traditional' analyses, highlighting a sound physical model that now clarifies the most important aspects of this cyclone and how it connects with the larger climate.

The results highlight that the Lorenz technique has the potential to accurately portray a connection between severe storms and their formative environment. While high resolution datasets and satellite observations are fundamental to characterise the mesoscale properties intrinsic to the vortex, the ERA-interim has given a robust diagnostic of the large scale

conversions and blocking properties. This technique may be used on a wide range of applications involving severe weather systems, which would be of particular interest to better understand how those will behave in the future climate.

This technique has particular appeal in areas where blocking occurrence is high and where air-sea interaction tends to enhance the development of dangerous synoptic features. In particular, while global climate models do not have enough resolution to capture the full aspect of single synoptic storms the energetics offers promise in identifying how the predicted changes in large scale parameters, which do not require as high resolution data, can translate into changes in the probability of occurrence of blocking and extreme cyclones globally.

Acknowledgements

We would like to thank Kevin Keay (The Centre for Australian Weather and Climate Research, Australian Bureau of Meteorology) for technical guidance with the use of the Lagrangian Advective Tracking Scheme and Noel Davidson (The Centre for Australian Weather and Climate Research, Australian Bureau of Meteorology) for input and discussions during an earlier stage of this work. ABP would like to thank the Australian Research Council for funding parts of this work.

References

- Allan, J.T., A.B. Pezza and M.T. Black (2010), Explosive cyclogenesis: A global climatology comparing multiple reanalysis. *Journal of Climate*, **23**, 6468-6484, doi: 10.1175/2010JCLI3437.1
- Barras, V., and I. Simmonds (2009), Observation and modelling of stable water isotopes as diagnostics of rainfall dynamics over southeastern Australia. *Journal of Geophysical Research*, **114**, D23308, doi:10.1029/2009JD012132.
- Bluestein, H.B., 1993. Synoptic-dynamic meteorology in midlatitudes, vol. 2. Oxford University Press, New York, USA. 594 pp
- Cordeira, J.M. and L. Bosart (2010), The antecedent large-scale conditions of the ‘perfect storms’ of late October and early November 1991. *Mon. Wea. Rev.*, **138**, 2546-2569.
- Covey C, Dai A, Marsh D, Lindzen RS (2011) The surface-pressure signature of atmospheric tides in modern climate models. *J. Atmos. Sci.* 68: 495-514 doi: 10.1175/2010jas3560.1.
- Dal Piva, E., Gan, M.A. and V. B. Rao (2010), Energetics of winter troughs entering South America. *Mon. Wea. Rev.*, **138**, 1084-1103.
- Davis, C. A. (2010), Simulations of subtropical cyclones in a baroclinic channel model. *J. Atmos. Sci.*, **67**, 2871-2892.
- Decker S. G. and J. E. Martin (2005), A local energetic analysis of the life cycle differences between consecutive, explosive deepening, continental cyclones. *Mon. Wea. Rev.*, **133**: 295-316.
- Dee, D. P. Uppala, S. M., Simmons, A. J., Berrisford, P., Poli, P., Kobayashi, S., Andrae, U.,
 Balmaseda, M. A., Balsamo, G., Bauer, P., Bechtold, P., Beljaars, A. C. M., van de Berg, L.,
 Bidlot, J., Bormann, N., Delsol, C., Dragani, R., Fuentes, M., Geer, A. J., Haimberger, L., Healy,

- S. B., Hersbach, H., Hólm, E. V., Isaksen, L., Kállberg, P., Köhler, M., Matricardi, M., McNally, A. P., Monge-Sanz, B. M., Morcrette, J.-J., Park, B.-K., Peubey, C., de Rosnay, P., Tavolato, C., Thépaut, J.-N. and Vitart, F. (2011), The ERA-Interim reanalysis: configuration and performance of the data assimilation system. *Quarterly Journal of the Royal Meteorological Society*. **137**: 553-597. doi: 10.1002/qj.828.
- Dvorak, V. F., 1984: Tropical cyclone intensity analysis using satellite data. NOAA Tech. Rep. NESDIS 11, 45 pp.
- Evans, J.L. and M. P. Guishard (2009), Atlantic subtropical storms. Part I: Diagnostic criteria and composite analysis. *Mon. Wea. Rev.*, 137, 2065-2080, DOI: 10.1175/2009MWR2468.1.
- Favre, A., Hewitson, B., Tadross, M., Lennard, C. and R. Cerezo-Mota (2012), Relationships between cut-off lows and the semiannual and Southern Oscillations. *Clim. Dyn.*, **38**, 1473-1487.
- Garde, L. A., A. B. Pezza and J. A. T. Bye (2010), Tropical transition of the 2001 Australian Duck. *Month. Wea. Rev.*, **138**, 2038-2057.
- Gutierrez, E.R., Silva Dias, P. L., Veiga, J.A., Camayo, R. And A. dos Santos (2009), Multivariate analysis of the energy cycle of the South American rainy season. *Int. J. Climatol.*, **29**, 2256-2269.
- Harr, P. A. and J. Dea (2009), Downstream development associated with the extratropical transition of tropical cyclones over the western north Pacific. *Month. Wea. Rev.*, **137**, 1295-1319.
- Hart, R. E. (2003), A cyclone phase space derived from thermal wind and thermal asymmetry. *Mon. Wea. Rev.*, 131, 585–616.

Holland, G. J., A. H. Lynch and L. M. Leslie (1987), Australian east coast cyclones. Part I: Synoptic overview and case study. *Month. Wea. Rev.*, **115**, 3024-3036.

Lim E-P, Simmonds I (2002) Explosive cyclone development in the Southern Hemisphere and a comparison with Northern Hemisphere events. *Mon. Wea. Rev.* 130: 2188-2209.

Lim, E.-P., and I. Simmonds (2007): Southern Hemisphere winter extratropical cyclone characteristics and vertical organization observed with the ERA-40 reanalysis data in 1979-2001. *J. Climate*, **20**, 2675-2690.

Lorenz E. N. (1967), *The Nature and Theory of the General Circulation of the Atmosphere*. World Meteorological Organization, 161 pp.

Lovenduski NS, Gruber N. 2005. Impact of the Southern Annular Mode on Southern Ocean Circulation and biology. *Geophysical Research Letters* **32**: L11603 DOI:10.1029/2005GL022727

Marquet P. (2003), The available-enthalpy cycle. II: Applications to idealized baroclinic waves. *Q. J. R. Meteorol. Soc.*, **129**: 2467-2494.

Montgomery MT, Van Sang N, Smith RK, Persing J (2009) Do tropical cyclones intensify by WISHE? *Quart. J. Roy. Meteor. Soc.* 135: 1697-1714.

Pezza A.B. and I. Simmonds (2005), The first South Atlantic hurricane: Unprecedented blocking, low shear and climate change. *Geophys. Res. Lett.*, **32**: L15712, doi:10.1029/2005GL023390.

Pezza AB, Veiga JAP, Simmonds I, Keay K, Mesquita MdS (2010) Environmental energetics of an exceptional high-latitude storm. *Atmos. Sci. Lett.* 11: 39-45.

Qi, L., L. M. Leslie and M. S. Speer (2006), Climatology of cyclones over the southwest Pacific: 1992–2001. *Meteor. Atmos. Phys.*, **91**, 201–209.

Rasmussen, E. A. and J. Turner, 2003: Polar lows. Mesoscale weather systems in the polar regions. *Cambridge University Press*, 612 pp.

Reale, O., and R. Atlas, 2001: Tropical cyclone-like vortices in the extratropics: Observational evidence and synoptic analysis. *Wea. Forecasting*, **16**, 7–34.

Simmonds I (2000) Size changes over the life of sea level cyclones in the NCEP reanalysis. *Mon. Wea. Rev.* 128: 4118-4125.

Simmonds, I., K. Keay and E.-P. Lim (2003), Synoptic activity in the seas around Antarctica. *Monthly Weather Review*, **131**, 272-288

Ulbrich, U., Leckebusch, G.C. and Pinto, J.G., 2009: Extra-tropical cyclones in the present and future climate: a review. *Theor Appl Climatol*, **96**:117–131

Veiga J.A.P., A. B. Pezza, I. Simmonds and P. L. Silva Dias (2008), An analysis of the environmental energetics associated with the transition of the first South Atlantic hurricane. *Geophys. Res. Lett.*, **35**: L15806, doi:10.1029/2008GL034511.

Wahab M. A., H. A. Basset and A. M. Lasheen (2002), On the mechanism of winter cyclogenesis in relation to vertical axis tilt. *Meteorol. Atmos. Phys.*, **81**: 103-127.

Figure Captions

a) Color-enhanced GMS-5 image of the Duck in its developing phase prior to landfall at 1:32 UTC 7 March 2001. The color scale indicates brightness temperature, with tones given in degrees Celsius. Key features of the circulation are identified on the image: the Duck is seen approaching the eastern coast of Australia as given by L; The asterisk just to the south of the storm indicates the area with averaged strong positive sensible and latent heat fluxes over the period corresponding to the storm's life cycle (3-8 March); The large H_{500} on the southwestern corner indicates the approximate position of the averaged 500 hPa geopotential anomaly responsible for the constant injection of anticyclonic vorticity anomaly over high latitudes; The small H_{MSL} between Tasmania and New Zealand indicates the average position of the surface anticyclone associated with the blocking structure. Both upper level and surface features are averages for the period 3-8 March. Note the old frontal structure to the northeast, and the relatively cut-off environment in which the storm was developed. Satellite picture courtesy of New Zealand Meteorological Service. Key geographical locations are also indicated. (b) Central mean sea level pressure (hPa) and radius (km) time series of the Duck and as calculated from the ERA-interim 6 hourly reanalysis. Estimated central pressure minimum (18UTC 4 March 2001) is 999.94 hPa and maximum and minimum cyclone radii of 926 and 392 km respectively. Dashed vertical bars mark the time in which Partial TT (12UTC 5 March 2001) and Landfall (12UTC 8 March 2001) occurred

Figure 2: Daily Mean Sea Level Pressure (shading, hPa) and 300 hPa geopotential anomalies (contours, metres) from day minus five to day zero (landfall) in southern polar stereographic projection. The position of the genesis and landfall points is indicated by G and LF respectively in the first panel (top left). For the sake of comparison, the position of the H_{500} and H_{MSL} weekly average features indicated in figure 1 are also shown on the first panel. The asterisk indicates where the 200 hPa air parcels arriving in the vicinity of the Duck originated from at the time shown in panel a. Six hourly ERA-Interim data used. See text for further details.

Figure 3: Average surface conditions for the week leading to landfall. Using 6 hourly ERA-interim data, the panel shows the (a) SST Anomaly ($^{\circ}\text{C}$, shaded) and actual average SST (contour), (b) 2m air temperature anomaly ($^{\circ}\text{C}$, shaded) and average 2m air temperature ($^{\circ}\text{C}$, contour), (c) the actual difference between the SST and the 2m air temperature ($^{\circ}\text{C}$), (d) 10m wind speed anomaly (km/h), (e) bulk sensible heat flux anomaly (Wm^{-2}) and (f), the actual latent heat flux (Wm^{-2}). Bulk sensible and latent heat equations are as used by Reale and Atlas (2001) and Garde et al., (2010).

Figure 4: (4a) Full trajectory depicting the life cycle of the Duck, and Lagrangian backward trajectory arriving in the vicinity of the Duck's center at 200 hPa with shown time steps of 24 hours (by closed circles), indicating the respective domains 1 and 2 relevant for the analyses; time series of the vertically integrated (925 – 100 hPa) energy terms for (4b) domain 1 and (4c) domain 2 and (4d) conversion terms for domain 2. The relevant phases of the Duck's lifecycle are indicated in all panels (G for genesis, TT for partial tropical transition and LF for landfall). The units of the energy terms (4b and 4c) are in 10^5 J/m^2 , while the energy conversion terms (4b) are given in W/m^2

Figure 5: Time evolution of the vertical cross section of the (5a) baroclinic conversion term CZ for the domain 1, (5b) barotropic conversion term CK for domain 2, (5c) the time evolution of the omega vertical motion averaged over domain 2 and (5d) omega vertical motion averaged over a radius of 300 km around the storm center following the cyclone. The units of the energy conversion terms (5a and 5b) are in $\text{W/m}^2 (100 \text{ hPa})^{-1}$ and omega (5c and 5d) is given in Pa/s . The relevant phases of the Duck's lifecycle are indicated in all panels (G for genesis, TT for partial tropical transition and LF for landfall). Note that in panel 5d the time domain is bounded by the existence of the cyclone by definition, hence the domain is shorter. The slight extension prior to genesis and after landfall takes into account the open (weak) cyclone phase (i.e. a trough) as given by the tracking scheme. See text for further details.

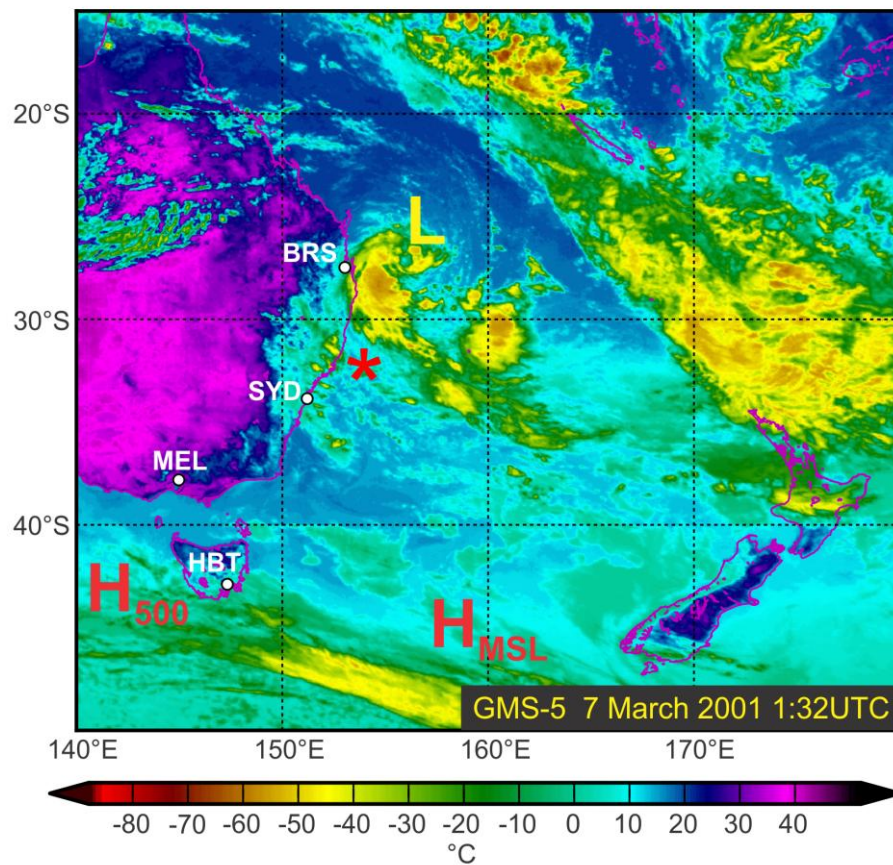
Figure 6: GCT index ($^{\circ}\text{C}$) time series for the Duck analyzing the 300 (dark red curve), 400 (red curve), 850 (blue curve) and 925 hPa (dark blue curve) levels. Red and blue horizontal dashed

lines denote warm and cold core boundaries. Black vertical dashed lines indicate the time in which Partial TT (12UTC 5 March 2001) and Landfall (12UTC 8 March 2001) occurred.

Figure 7: All cyclone tracks satisfying the thermal conditions set by Filter A for the 1989 – 2009 period using six hourly ERA-Interim data. Red parts of tracks correspond to areas where a thermal core transition similar to that observed for the Duck is detected. Filter A thermal conditions are set such that upper levels change from a negative to positive-cored while the inverse occurs to the lower levels.

Figure 8: Average GCT index ($^{\circ}\text{C}$) for each 5 degree latitude band for cyclones that satisfy Filter A. Six hourly ERA-Interim data used.

a



b

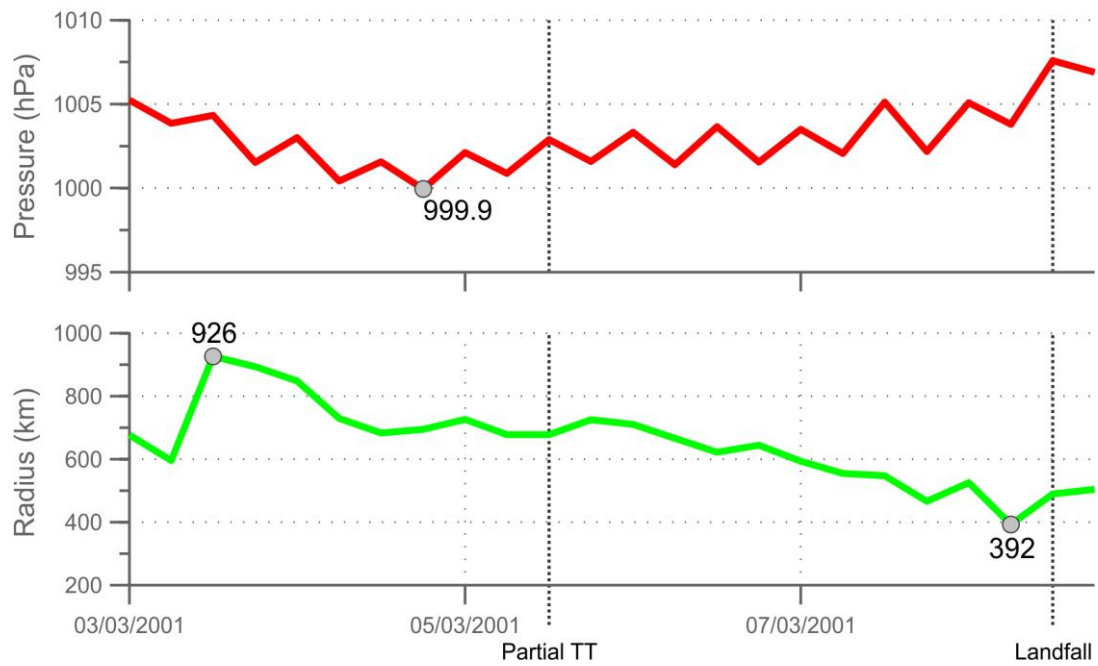


Figure 1

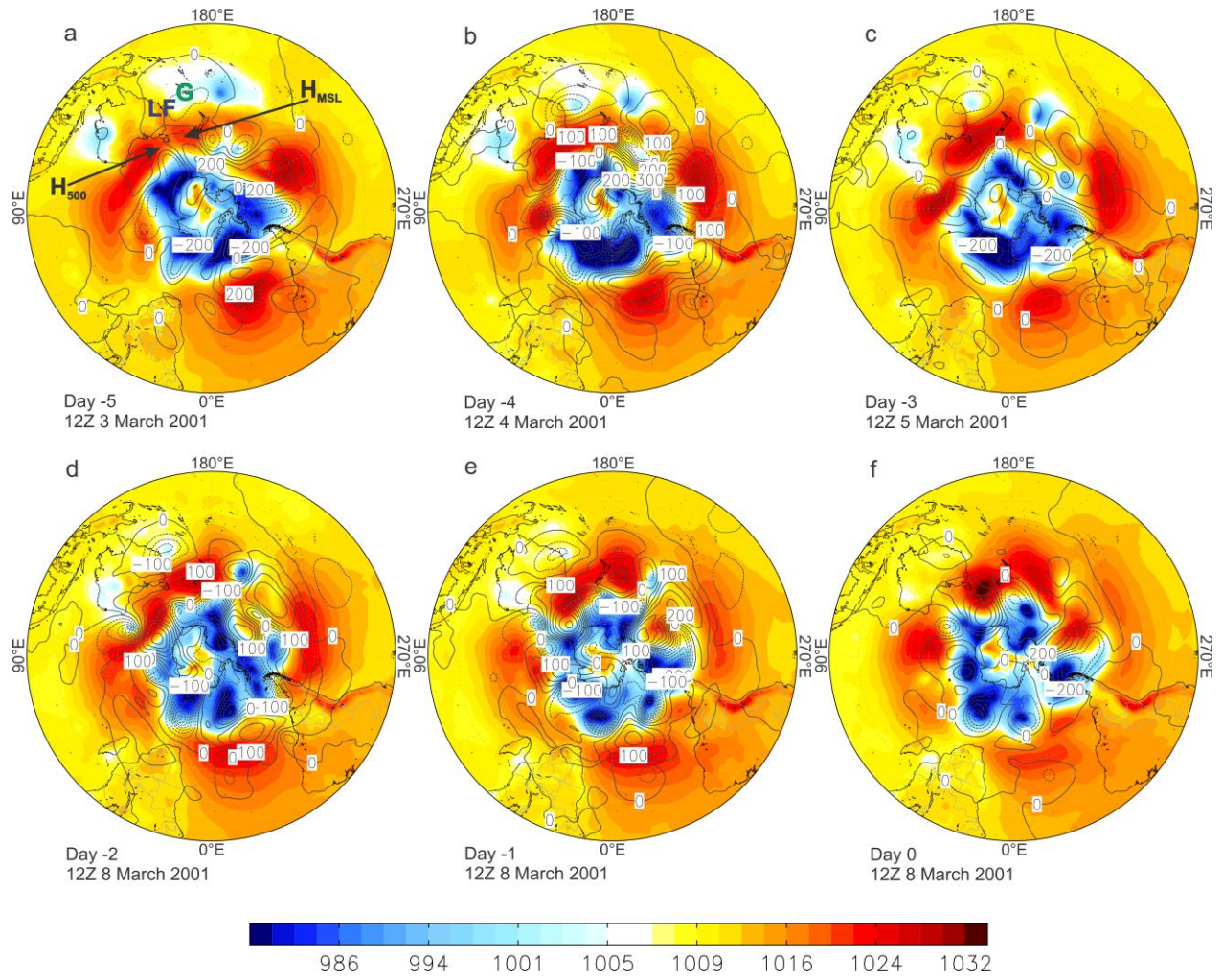


Figure 2

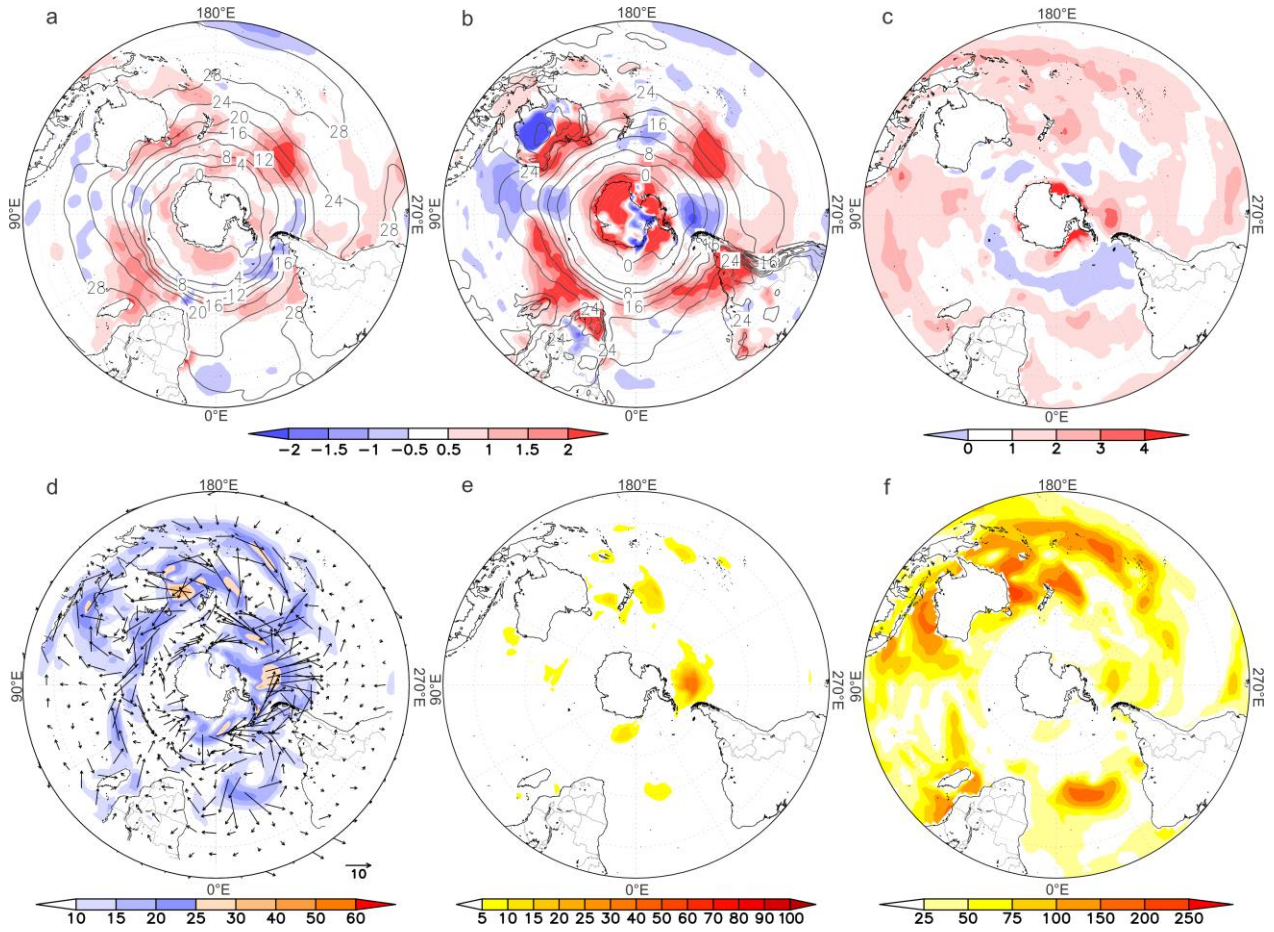


Figure 3

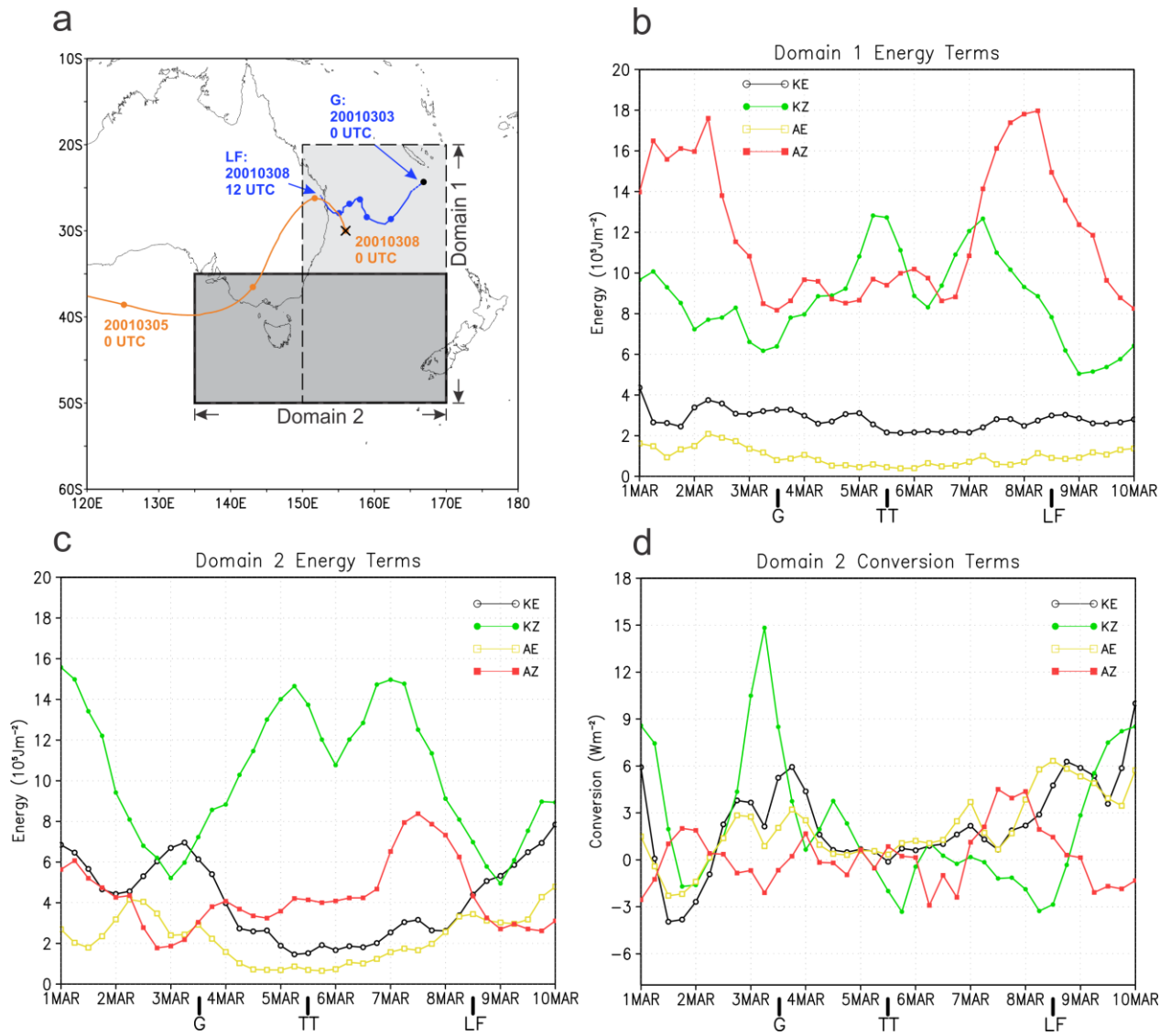


Figure 4

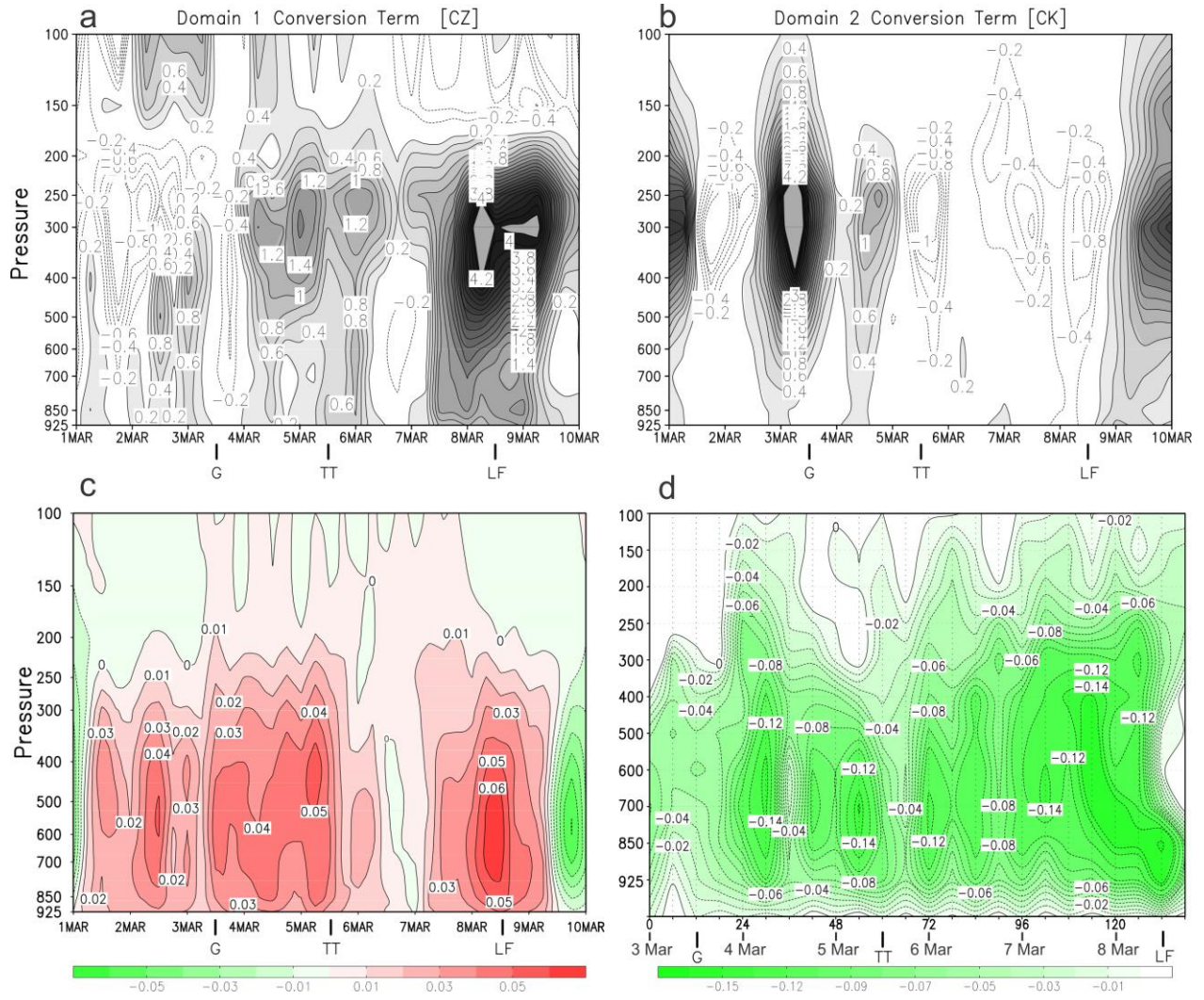


Figure 5

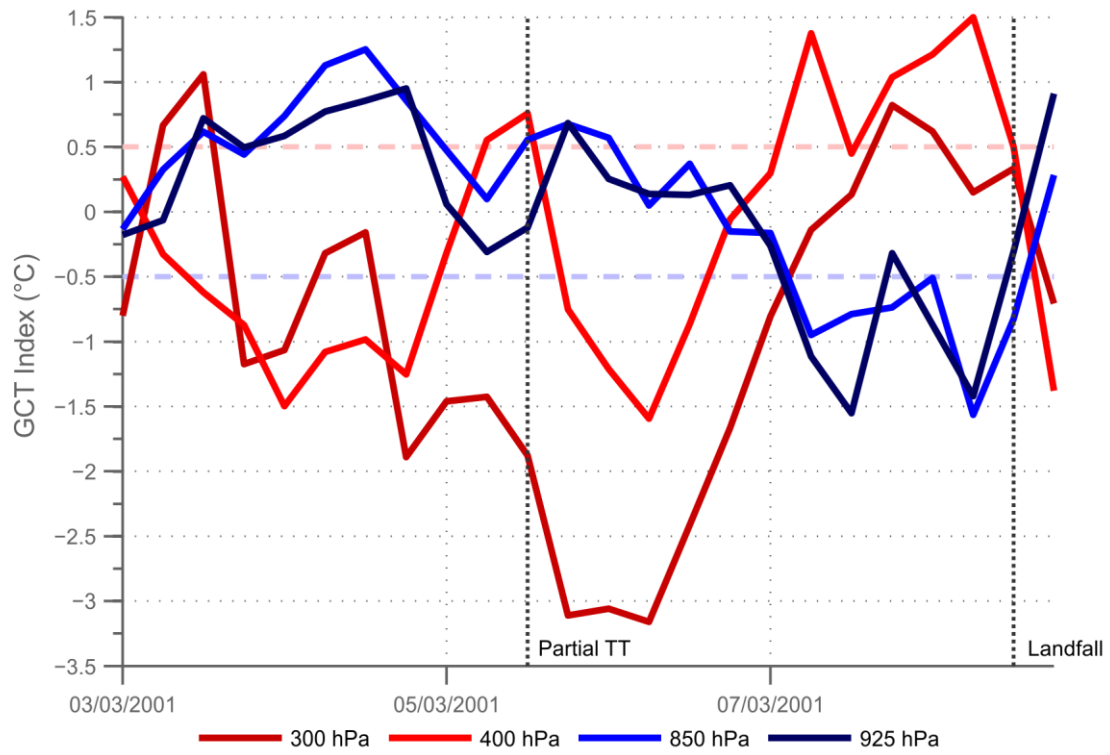


Figure 6

Year: 1989 - 2009 Period: ANN Type: Transition
Tracks: 199 (0.84%) Filter: A Trop Lev > 300 hPa

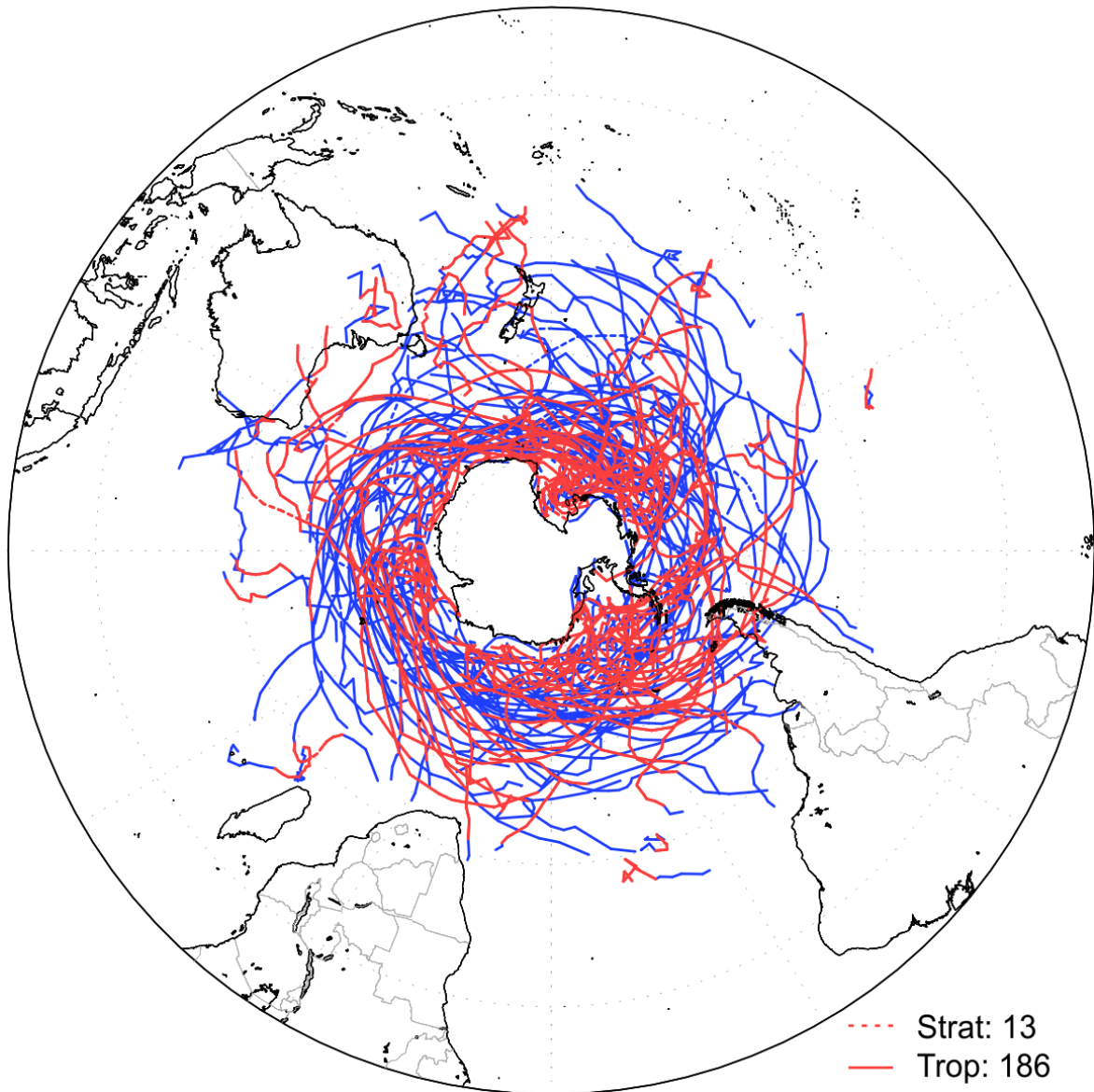


Figure 7

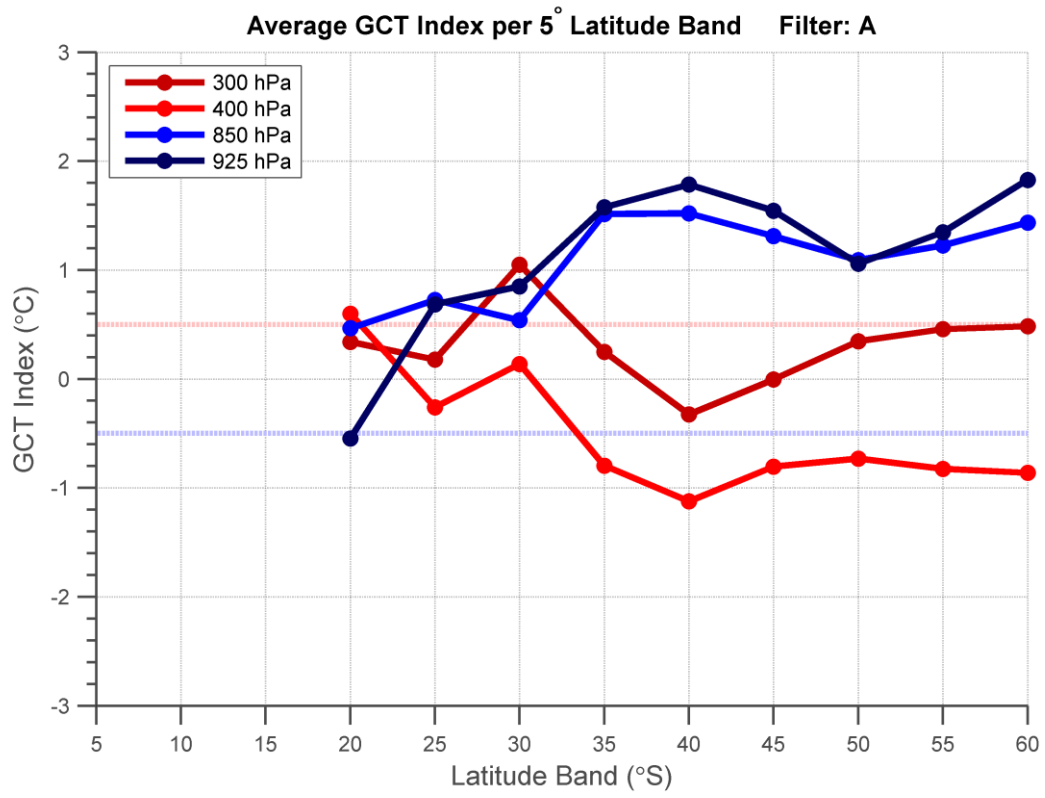


Figure 8