The Extratropical Transitions of Hurricanes Felix and Iris in 1995

CHRIS THORNicroFT
Department of Meteorology, University of Reading, Reading, United Kingdom

SARAH C. JONES
Meteorologisches Institut, Universität München, Munich, Germany

(Manuscript received 28 October 1998, in final form 19 March 1999)

ABSTRACT

The extratropical transitions of Hurricanes Felix and Iris in 1995 are examined and compared. Both systems affected northwest Europe but only Iris developed significantly as an extratropical system. In both cases the hurricane interacts with a preexisting extratropical system over the western Atlantic. The remnants of the exhurricanes can be identified and tracked across the Atlantic as separate low-level potential vorticity (PV) anomalies. The nature of the baroclinic wave involved in the extratropical transition is described from a PV perspective and shown to differ significantly between the two cases.

The role of vertical shear in modifying the hurricane structure during the early phase of the transition is investigated. Iris moved into a region of strong shear. The high PV tower of Iris developed a marked downshear tilt. Felix moved into a vertically sheared environment also but the shear was weaker than for Iris and the PV tower of Felix did not tilt much.

Iris maintained its warm-core structure as it tracked across relatively warm water. It moved into the center of a large-scale baroclinic cyclone. The superposition of the two systems gave rise to strong low-level winds. The resulting strong surface latent heat fluxes helped to keep the boundary layer equivalent potential temperature ($\theta_e$) close to the saturated equivalent potential temperature of the underlying sea surface temperature. This high equivalent potential temperature air was redistributed in the vertical in association with deep convection, which helped maintain the warm core in a similar way to that in tropical cyclones.

Felix did not maintain its warm-core structure as it tracked across the Atlantic. This has been shown to be linked to its more poleward track across colder water. It is argued that negative surface fluxes of latent and sensible heat decrease the boundary layer $\theta_e$, resulting in low-cloud formation and a decoupling of the cyclone boundary layer from the deep troposphere.

In order to forecast these events there is a need for skill in predicting both the nature of the large-scale baroclinic wave development and the structural evolution of the exhurricane remnants.

1. Introduction

Considerable attention is focused on tropical cyclones, in particular those that threaten to make landfall. Much less notice is taken of tropical cyclones that transform into extratropical weather systems. Such systems can in fact be characterized by strong winds and heavy rains and, like tropical cyclones, can cause loss of life and damage to property. Extratropical transition is not always well forecast by numerical models. A recent example of this was the case of Hurricane Lili in 1996 (Browning et al. 1998), which transformed into a deep extratropical system over northwest Europe; neither the operational U.K. Meteorological Office (UKMO) nor the European Centre for Medium-Range Weather Forecasts (ECMWF) model was able to predict the intensity to within 24 hPa in the 48-h forecast.

Extratropical transition occurs in all basins where tropical cyclones recurve. Previous work on extratropical transition has included case studies of events in the northwest Pacific (e.g., Sekioka 1956), near Australia and New Zealand (e.g., Foley and Hanstrum 1994; Sinclair 1993a,b), and over the United States (e.g., Palmén 1958; Kornegay and Vincent 1976; DiMego and Bosart 1982a,b; Bosart and Lackmann 1995). In all of the cases that affected the United States, transition either occurred over land or the system moved over land soon after transition. However, a large number of tropical cyclones become extratropical over the ocean, some of which track eastward. This type of system, which can affect northwest Europe, is the focus of the present study.

Most of the early work on extratropical transition was concerned with northwest Pacific tropical cyclones and...
was based mainly on surface data (e.g., Sekioka 1956, 1970; Matano and Sekioka 1971a,b; Mohr 1971; Brand and Guard 1979). Matano and Sekioka (1971a,b) suggested that recurring tropical cyclones that interact with extratropical systems form two types of systems: a complex system or a compound system. A complex system forms when the tropical cyclone approaches a preexisting front and induces a frontal cyclone that subsequently develops as the tropical cyclone decays. A compound system forms when the tropical cyclone approaches a preexisting extratropical cyclone. They suggest that the extratropical cyclone develops during this interaction and that the tropical cyclone decays. From this viewpoint neither the complex nor the compound system that develops is actually an ex–tropical cyclone.

Further understanding of extratropical transition was gained in more recent case study work on systems over the United States. In particular, studies of Tropical Storm Agnes in 1972 (DiMego and Bosart 1982a,b; Bosart and Dean 1991) and Hurricane David in 1979 (Bosart and Lackmann 1995) have highlighted processes not addressed in the earlier work on northwest Pacific storms. Agnes was a large tropical storm that weakened rapidly after making landfall over Florida and reintensified a few days later as it interacted with a midlatitude trough. DiMego and Bosart (1982a) suggested that the reintensification was analogous to a Petterssen type-B development (Petterssen and Smeybe 1971) that was aided by the presence of warm moist tropical air and modified by the low-level remnants of Agnes. David was a major hurricane that also weakened rapidly after making landfall over Georgia and reintensified in a weakly baroclinic environment. In contrast to the redevelopment of Agnes, there was no prominent upper-level trough involved in the redevelopment of David. Bosart and Lackmann (1995) suggested that, in addition to the presence of warm moist tropical air and the low-level remnants of David, an important factor in the reintensification was the upper-level anticyclonic outflow from David, which strengthened an upper-level jet.

Insight into the nature of David was gained by Bosart and Lackmann (1995) using a potential vorticity (PV) approach (Hoskins et al. 1985). Using this approach the transformation problem can be viewed in terms of the interaction of different PV anomalies. In this framework it is important to consider the nature of the different PV anomalies involved. The structure of a tropical cyclone is characterized by a strong deep cyclonic PV anomaly with a broad but shallow anticyclonic anomaly at upper levels (Shapiro and Franklin 1995). Observations of tropical cyclones show a broad range of structures and intensities suggesting that the nature of these PV anomalies is likely to vary significantly from storm to storm. Unfortunately, the only calculations of PV derived from a high resolution dataset are those presented in Shapiro and Franklin (1995), which means that our knowledge of the PV structure of tropical cyclones is limited. We have a much better knowledge of the PV structure of extratropical weather systems. Potential vorticity anomalies are associated with undulations of the tropopause or perturbations on a surface baroclinic zone (e.g., Hoskins et al. 1985). They can arise also through diabatic or frictional processes (e.g., Thorpe and Clough 1991; Davis and Emanuel 1991; Hoskins et al. 1985).

Hoskins et al. (1985) describe baroclinic development in terms of the interaction between upper-level PV anomalies and surface temperature anomalies. They include in this description the case where a large-amplitude upper-level PV anomaly interacts with a surface baroclinic zone to give strong development. This view needs to be modified for the case of extratropical transition due to the presence of the tropical cyclone. There are several characteristics of the tropical cyclone that should be considered. First, the large-amplitude tropospheric cyclonic anomaly can interact with both the upper-level PV gradients and the surface baroclinic zone. Second, the upper-level anticyclonic anomaly can interact with the upper levels. Bosart and Lackmann (1995) suggested that the anticyclonic anomaly acted to steepen the tropopause in the vicinity of David resulting in an enhanced upper-level PV gradient. A similar modification to the upper levels by Hurricane Floyd (1987) was noted by Hoskins and Berrisford (1988) but this occurred downstream of the hurricane. They hypothesized that this modification of the upper levels was important in the development of the October storm that devastated southern England in 1987. It should be recognized that the anticyclonic anomaly can also interact with surface features (Shapiro 1992; Wu and Emanuel 1993; Flatau et al. 1994). However, this has not been considered in previous work on extratropical transition.

In all previous case study work on the extratropical transition of Atlantic tropical cyclones, the transition has taken place over land. However, in a significant number of cases extratropical transitions occur over the Atlantic Ocean. Transitions that occur over the ocean are likely to be characterized by stronger surface fluxes of heat and moisture, and by weaker surface friction than those that occur over land. The aim of the present study is to investigate extratropical transition that occurs over the North Atlantic Ocean. We focused on the Atlantic tropical cyclones in 1995 due to the large number of tropical cyclones that recurved that year (e.g., Lawrence et al. 1998). The National Hurricane Center (NHC) classified 9 out of the 19 named storms as extratropical systems. Three of these deepened by 10 hPa
or more. The classification as extratropical indicates a modification of the tropical cyclone structure as it moves into a nontropical environment. This modification may be characterized by an increase in the size of the system, a decrease in the maximum wind speed and by the development of asymmetries in the wind, temperature, and rainfall fields (Neumann et al. 1993). It should be noted though that such a classification is qualitative and future work should address this problem. One reason for this is that extratropical transition, as the word suggests, is a gradual process that may vary significantly from case to case. In this paper we use the NHC best track data to define the time when the tropical cyclones became extratropical.

All but two of the transitions noted by NHC in 1995 occurred over the ocean. The strongest extratropical development occurred in the case of Iris, which became extratropical over the ocean, deepened by 38 hPa, and affected Europe. In this study we present the extratropical transition of Hurricane Iris and contrast it with the case of Hurricane Felix, which also became extratropical over the ocean and reached Europe but did not deepen as an extratropical system.

The paper is organized as follows. Section 2 and section 3 describe the extratropical transitions of Iris and Felix, respectively, using mainly U.K. Meteorological Office model analyses (Cullen 1993). We use the analyses from the limited area model version \((0.442° \times 0.442°, 19 \text{ levels})\). Section 4 considers the role of vertical shear during the early phase of the transition and section 5 compares the thermodynamic structure of Iris and Felix. A summary and conclusions are included in section 6.

2. Iris

a. Synoptic overview

Iris formed from a tropical wave that began moving over the Atlantic on 16 August and intensified to tropical storm strength by 22 August. Figure 1 shows the NHC best track position of Iris at 12-hourly intervals. After a period of westward motion Iris turned northward on 26 August. The overall motion remained northward until about 3 September when Iris started to accelerate north-eastward. According to the NHC Iris became extratropical at 1200 UTC 4 September well to the southeast of Newfoundland (cf. Fig. 1) and continued to track eastward across the Atlantic, reaching the English Channel at 1200 UTC on 7 September.

Figure 2 shows a time series of the minimum mean sea level pressure (mslp) of Iris taken from the NHC best track data. Iris reached maximum intensity as a hurricane at 0600 UTC 1 September located at 25.6°N, 59°W with a central pressure of 965 hPa. It then filled until 0000 UTC 5 September by which time it had been classified as extratropical. During the next 48 h the extratropical storm deepened by 42 hPa. The deepening rate on 5 September exceeded 24 hPa in 24 h and so the extratropical cyclone can be classified as a bomb (Sanders and Gyakum 1980). The minimum mslp of the extratropical cyclone was 957 hPa, which was actually lower than the minimum central pressure of Hurricane Iris.

The transition of Iris from a tropical cyclone to an extratropical system between 0000 UTC 3 September and 0000 UTC 7 September is first described using a sequence of 1000-hPa geopotential height \((Z)\) analyses (Fig. 3). The shading included in this figure indicates 900-hPa PV values greater than 1 PVU (1 PVU is \(1 \times \))
At 0000 UTC 3 September Iris is located around 31°N, 59°W on the western side of the Azores high. A significant feature is an extratropical low pressure region north of Newfoundland. During the next 24 h Iris moves rapidly northeastward around the Azores high and approaches the extratropical low. By 5 September exhurricane Iris and the extratropical low are contained within the same 80-m Z contour and so appear to have merged, resulting in a low pressure region of large meridional extent. However, the exhurricane can still be identified as a separate feature. The next 48 h are when the strong extratropical development occurs (see Fig. 2). By 0000 UTC 7 September a very large region of low pressure dominates the eastern Atlantic. In the region of the low pressure minimum there is a circular core characterized by strong pressure gradients. The strongest pressure gradient is south of the low center. Consistent with this is a ship observation at 47°N, 13°W with a 17 m s⁻¹ surface wind at 0000 UTC 7 September. Surface winds of 20 m s⁻¹ were observed at La Rochelle at around 46°N on the French Atlantic coast at 1200 UTC 7 September. It should be noted that...
neither of these observations were in the region of strongest pressure gradients and so stronger winds would have been expected closer to the low center (see Fig. 7b below). In addition, surface observations at Brest showed winds gusting above 20 m s⁻¹ throughout the period from 1200 UTC 6 September to 0000 UTC 8 September.

A prominent feature of the analysis in Fig. 3 on 7 September is a circular region of high PV at 900 hPa with a peak value of 2.1 PVU. This PV anomaly is collocated with the surface pressure minimum. Perhaps unexpectedly this PV feature can be tracked back to the core of Hurricane Iris on 3 September. Although it is likely that the low-level PV would have been modified during this period, the coherence of the low-level PV anomaly as it moves across the Atlantic is striking. This suggests that a remnant of the PV of Hurricane Iris is central to the extratropical development near western Europe, which contrasts greatly with the view of Matano and Sekioka (1971a, b) that the tropical cyclone vortex decays during transition. For clarity in the subsequent discussion, we will continue to refer to the remnants of the hurricane as Iris even when it has been classified as extratropical by NHC. It should also be noted that whereas Iris and the extratropical low may have appeared to have merged, based on 1000-hPa Z, in the more dynamically significant PV field Iris is tracked as a separate coherent feature.

The role of the upper levels in the extratropical development is described first using a sequence of 200-hPa Z analyses (Fig. 4). Isotachs are shaded for values greater than 40 m s⁻¹ and Iris is marked as a black dot. The 200-hPa Z field at 0000 UTC 3 September shows a very deep trough over the eastern United States. Iris is situated in weak southwesterly flow ahead of this trough in a region of weak pressure gradient. During the next few days Iris moves through the long-wave pattern and across the jet axis. The trough that steered Iris poleward develops an equatorward cutoff low over the southeast United States (not shown) leaving a more mobile poleward trough that moves eastward across the Atlantic. This poleward trough develops between 5 and 6 September. During this time Iris moves toward the left jet exit region, a synoptically favorable location for development and by 0000 UTC 7 September Iris is clearly situated on the poleward side of the jet. At the same time as Iris moved poleward, the main 200-hPa jet moved equatorward as the upper-level trough developed. The movement of Iris across the axis of jet exit between 5 and 6 September is clearly an important synoptic development. On 5 September one might have envisaged that Iris would have been steered southeastward toward the Iberian Peninsula, which would have resulted in a very different development, but as can be seen on 6 September, the upper-level ridge weakened and Iris was steered northeastward. The reason for this can be seen more clearly by considering the evolution of the upper-level PV discussed in the next section.

Note that during most of this period the jet stream is located quite far south around 45°N, consistent with a period of enhanced cyclonic activity in NW Europe. This cyclonic regime has important consequences for the nature of the upper-level developments as will be discussed further in the next section.

b. PV-θ view

An important aspect of the extratropical transition of Iris is the midlatitude baroclinic wave development, which will be illustrated by considering the evolution of the upper-level PV distribution together with the low-level potential temperature (θ). Figure 5 shows the PV evolution on the 325-K isentropic surface together with the 900-hPa θ between 0000 UTC 3 September and 0000 UTC 7 September. The 325-K isentropic surface was chosen as this most clearly illustrates the upper-level baroclinic wave developments. This surface generally slopes downward from about 10 km near 60°N to about 6 km near 30°N. The 900-hPa θ is shown to illustrate the low-level frontal regions together with the low-level thermodynamic structure of Iris.

At 0000 UTC 3 September (Fig. 5a) the Atlantic has marked baroclinic wave activity associated with pronounced longitudinal variations in low-level θ and upper-level PV. A north–south-oriented cold front downstream of Iris is well marked in the central Atlantic. Upper-level troughs are characterized by high PV values over western Europe and also over the United States. It is this high PV over the United States that is later responsible for the poleward steering of Iris and is also associated with the subsequent extratropical development. At this time Iris is located southeast of both the upper-level trough and a low-level baroclinic wave zone that is just off the U.S. coast in the region of strong Gulf Stream temperature gradients. Iris has high values of low-level θ relative to its surroundings. During the next two days (see Figs. 5b,c) the high upper-level PV trough originally over the United States moves eastward into the Atlantic. Iris similarly moves eastward during this time and also poleward. In Fig. 5b Iris is manifested as a small positive PV anomaly on the 325-K isentropic surface around 41°N, 54°W (cf. Fig. 16a). By 0000 UTC 5 September the northern edge of the low-level warm air associated with Iris has impinged on the low-level frontal zone of the baroclinic wave near 46°N, 38°W. At 0000 UTC 6 September Iris, characterized here by high low-level θ, and the upper-level PV anomaly are now in close proximity. This is the time when Iris moves into the left jet exit region as discussed above suggesting an increased likelihood of development. From a PV perspective Iris is steered poleward in association with the large-scale cyclonic wrap-up of the upper-level PV. The poleward advection is linked to a southerly wind (not shown) at the end of the high-PV tongue located around 50°N, 20°W on 6 September (Fig. 5d).

Between 6 and 7 September (Figs. 5d,e) the upper-
level PV wraps up cyclonically and moves equatorward resulting in a distinctive PV structure at 0000 UTC 7 September with cyclonically spiraling high and low PV air. It is striking how similar the upper-level development is to that in the LC2 baroclinic life cycle described in Thorncroft et al. (1993, henceforward THM), which wraps up cyclonically. Interestingly, as noted in THM, the LC2-type life cycle is also characterized by a large and deep surface low pressure system. In the present case, as the upper-level PV wraps up cyclonically, the low-level warm core of Iris is advected around into the center of the upper-level trough. The wrapping-up of low-level warm air in this manner is a characteristic of many midlatitude cyclones and has been termed a seclusion process (e.g., Shapiro and Keyser 1990). In the present case we argue that the warm air that is secluded has a history linked with the remnants of Iris. It should be noted that from a PV perspective the magnitude of the warm anomaly is also determined by the background temperature. In the present case this may have been lower due to the downstream cyclone development and associated equatorward cold advection seen very clearly.
The analyses presented suggest that the extratropical cyclone that develops during this period is associated with an LC2-type baroclinic life cycle, which gives rise to a large-scale deep surface low and large-scale cyclonic wrap-up of upper-level PV. We suggest though that extra deepening and extra strengthening of low-level winds in the center of the low are associated with the superposition of the low-level remnants of Iris, which is advected into the center of the low during the cyclonic wrap-up. In this view it is likely that a large-scale low pressure system would have developed without Iris but would presumably have been weaker. From a PV perspective we can view the development as an LC2-type development but with a low-level small-scale PV anomaly superimposed to give a more intense core. We cannot rule out the possibility though that Iris may have influenced the nature of the large-scale baroclinic life cycle itself. In particular the low-level warm air

Fig. 5. The 900-hPa potential temperature with a contour interval of 4 K and PV on the 325-K isentropic surface (light shading indicates values greater than 2 PVU, darker shading indicates values greater than 4 PVU) for Iris at 0000 UTC 3–7 Sep 1995.
ahead of the upper-level trough in Fig. 5a may have been enhanced by strong poleward advection of warm subtropical air east of Iris.

The marked LC2-type development between 0000 UTC 5 September and 0000 UTC 6 September (see Figs. 5c,d) was also clearly very important in steering Iris poleward and across the upper-level jet axis (see Fig. 4c,d); without it Iris may have been steered toward the Iberian Peninsula in the downstream ridge–trough system. We must rely on numerical weather prediction models to predict these upper-level trough developments well, in order to achieve the correct exhurricane tracks. Badly predicted upper-level trough developments may lead to large errors in these tracks resulting in very different types of transition.

c. Mature structure

The mature system at 0000 UTC 7 September can be thought of as a large-scale cyclonically wrapping-up PV trough with an embedded smaller-scale warm-core cyclone. This will be illustrated further here. The large-scale cyclonic nature is first confirmed in the visible satellite image at 0800 UTC 7 September in Fig. 6. Note the broad-scale region with cyclonically wrapping-up bands of cloud. There is also some indication of a separate convective region in the center of this region around 8°W. This is where we observe the seclusion in Fig. 5e and the 900-hPa PV maximum in Fig. 3e and is the feature we have tracked as exhurricane Iris.

The vertical structure and superposition of the warm-core cyclone and large-scale baroclinic wrap-up in PV are well illustrated in the north–south cross sections along 8°W shown in Fig. 7. The PV structure is characterized by a vertically stacked PV tower beneath a low tropopause with prominent folds, especially on the equatorward flank. The winds associated with these PV anomalies are shown in Fig. 7b. There is a well-defined low-level core of strong winds with maximum winds greater than 36 m s⁻¹ around 900 hPa. The strongest winds are on the equatorward side at low levels, which is probably associated with the superposition of the winds linked to the upper-level PV structure. This feature was also found in Browning et al. (1998) and is clearly associated with the large-scale cyclonic wrap-up poleward of the mean zonal jet in an LC2-type life cycle (cf. THM).

The thermodynamic structure is illustrated using vertical sections of θ and equivalent potential temperature (θe) (see Figs. 7c,d). A pronounced warm core can be seen in the θ section, between the surface and the tropopause in the region of the PV tower. Comparing this with the θe section we see that this region of the warm core is characterized by relatively high θ values. The equivalent potential temperature is well mixed in the vertical consistent with a deep convecting region (see satellite image in Fig. 6). A comparison with the saturated equivalent potential temperature (θes) (not shown) confirms that this region is saturated. The closed contours on either side of the warm core at midlevels are minima. It thus qualitatively takes on the appearance of a hurricane that has a warm core with elevated θe values distributed in the vertical in association with deep convection. In a hurricane the high θe values arise in association with surface fluxes of latent and sensible heat. The role of the surface fluxes and the evolution of the θe structure of Iris will be further discussed in section 5.

3. Felix

a. Synoptic overview

Felix formed from a tropical wave that moved off the African coast on 6 August. It was named on 8 August and reached hurricane intensity (based on satellite intensity estimates) at 0000 UTC on 11 August. Figure 8 shows the NHC best track position of Felix at 12-hourly intervals. The best track shows that Felix moved initially west-northwestward. The northward component started to increase after 1200 UTC on 11 August when Felix crossed 20°N. On 13 August it moved almost due north; the following day the motion was northwestward toward the Carolinas. Felix remained a few hundred kilometers off the U.S. coast moving anticyclonically in a loop until 21 August when it started to move northeastward. According to the NHC, Felix became extratropical on 22 August at 1800 UTC when it was located at 49°N, 46°W. It eventually passed between Iceland and Scotland on 24 August.

Figure 9 shows a time series of the minimum mslp of Felix taken from the NHC best track data. Felix reached maximum intensity at 1800 UTC 12 August located at 24.3°N, 61°W, with a central pressure of 929
Fig. 7. North–south vertical sections of Iris at 0000 UTC 7 Sep 1995 at 8°W between 35° and 60°N. (a) Potential vorticity with a contour interval of 0.5 PVU, (b) zonal wind with a contour interval of 4 m s$^{-1}$, (c) potential temperature with a contour interval of 4 K, and (d) equivalent potential temperature with a contour interval of 4 K.

Fig. 8. NHC best track for Felix. Symbols show 12-hourly positions of Felix. The $\lambda$ symbol is used after Felix was defined as being extratropical.
decreased during these interactions (cf. Fig. 9). The second of these systems can be seen on 20 August in the northern central Atlantic in Fig. 10a.

At 0000 UTC 20 August Felix is clearly identifiable as a separate low with high PV at its center. The extratropical system that Felix interacts with is located to the northwest of this and has a prominent PV signature characteristic of a strong warm front. By 22 August at 0000 UTC Felix and the extratropical system share the same $Z = 40$ m contour but Felix can still be recognized as a region of separate high low-level PV and therefore has not merged with the extratropical low. During the next day the extratropical low deepens slightly. At the same time Felix fills (cf. Fig. 10) but can still be seen as a separate feature at 0000 UTC 23 August. Between 0000 UTC 23 August and 0000 UTC 24 August the analyses suggest that low-level PV associated with Felix was deformed in the horizontal, resulting in the approximately west-east elongated PV anomaly in Fig. 10e although some PV merger may also have occurred. In summary, as in the case of Iris a feature in the low-level PV associated with the exhurricane could be tracked across the Atlantic. However, in the case of Felix there is no explosive extratropical development and the low-level signature of the exhurricane is lost.

The role of the upper levels is described briefly using a sequence of 200-hPa $Z$ analyses with 200-hPa isotachs (Fig. 11). At 0000 UTC 20 August the trough associated with the second extratropical system that passed poleward of Felix is at around 50°W and northeast of Felix. During the next few days this trough elongates meridionally and forms a cutoff cyclone at 0000 UTC 22 August.

Between 0000 UTC 21 August and 0000 UTC 22 August the trough that eventually steers Felix poleward develops and moves equatorward at around 70°W. At 1200 UTC 21 August Felix is located around 66°W and thus the trough is in a favorable position to steer Felix poleward. During the subsequent two days Felix continues to move poleward and across the main jet axis.

It is of interest to note that the two upper-level troughs that did not steer Felix poleward (first one not shown), elongated meridionally to the east of Felix and were thus in an unfavorable configuration for steering Felix poleward. The third trough elongated meridionally, closer to the North American coast and was thus in a more favorable position for steering Felix poleward. This was in a similar location to the trough that steered Iris poleward (cf. Fig. 4a). Clearly, the precise timing of the meridional extension of the troughs as well as the longitude where this occurs are crucial in determining when the ex-tropical cyclones are accelerated poleward.

### b. PV–θ view

Figure 12 shows the 325-K PV evolution from 0000 UTC 20 August to 0000 UTC 24 August together with the corresponding 900-hPa $\theta$. The second trough that passed by Felix can be seen just to the east of Newfoundland as a prominent broad feature and has a long trailing cold front. Felix can be seen as a 325-K cyclonic PV anomaly southwest of this trough as well as in the low-level $\theta$ as a warm core. The upstream trough that eventually steers Felix poleward can be seen just entering the area of interest around 90°W. The strong warm front mentioned in section 3a is also seen.

During the next few days the trough downstream of Felix thins markedly and elongates meridionally eventually resulting in a cutoff in high PV and a frontal cyclone very much like the LC1 life cycle discussed in THM. This trough only moved significantly equatorward after passing Felix and was thus unable to steer Felix poleward. It is possible that Felix may have enhanced the equatorward movement of the trough. Ferreira and Schubert (1999) have suggested that Felix played a role in enhancing the equatorward penetration of the first trough, which passed close to Felix around 14 August. They argue that the southerly flow associated with the cyclonic PV of Felix interacts with the midlatitude PV gradients to force a Rossby wave response to the east; with first a ridge and then a trough. We would argue that a more likely scenario would be for the upper-level diabatically forced anticyclonic PV of Felix to enhance the preexisting upper-level midlatitude anticyclone that would encourage more directly the equatorward penetration of high PV. Then, rather like the LC1 life cycle of THM, the downstream trough moves equatorward and thins. A similar development
was observed in a study of transitioning northwest Pacific typhoons by P. Harr (1998, personal communication).

Between 0000 UTC 20 August and 0000 UTC 21 August the high PV over north America moves equatorward to the west of Felix surrounding a region of anomalously low PV, around 60°N, 100°W, as it does so. This results in quite a complicated PV structure for the upper-level trough. As the high PV moves equatorward, Felix moves poleward ahead of it. The fact that Felix still remains visible on the 325-K surface suggests that the deep PV anomaly of Felix is maintained across the Atlantic despite being in a vertically sheared environment. This is consistent with the study of Jones (1995) who showed that strong PV anomalies are less susceptible to vertical shear than weaker anomalies.

Felix can also be tracked in the low-level θ field as a warm-core feature until 22 August. Between 22 and 23 August Felix becomes cold core at low levels as it moves over colder water (see section 5). During all of
this time Felix remains in the developing warm sector of the large-scale baroclinic wave. On 24 August Felix moves into the warm frontal zone of the extratropical system where it is horizontally deformed.

c. Mature structure

The mature structure of Felix is illustrated using north–south vertical sections through the 900-hPa PV maximum at 0000 UTC 24 August (see Fig. 13). At this time the ex-hurricane has been deformed horizontally and appears to have merged with the extratropical warm front. Despite this the remnants of Felix can still be identified and some important differences between Felix and Iris are apparent. A PV tower is still evident at this time with a slight tilt toward the north. The PV tower is situated below a low tropopause as in the case of Iris. Unlike Iris the winds and $\theta$ are more characteristic of a strong warm front with no well-defined separate low-level circular warm core. The $\theta$ section is of particular
interest though. A northward sloping maximum with values around 328 K is seen clearly aligned with the PV maximum. This high $\theta_e$ tower can be tracked backward with the PV maximum of Felix. Unlike Iris though, the high $\theta_e$ values are not vertically uniform and do not reach low levels. A comparison with $\theta_{es}$ (not shown) indicates that the column is mostly unsaturated. This suggests that the high $\theta_e$ tower of the exhurricane has become decoupled from the sea surface in a way that was not seen in the case of Iris. This point will be discussed further in section 5.

Although the extratropical transition of Felix is not accompanied by such a spectacular extratropical surface development as Iris, the extratropical system associated with Felix is still a fairly deep Atlantic system for the time of year. Felix appears to have contributed, in particular, to the deep warm-frontal structure, seen clearly in Figs. 13c,d. The marked warm front (around 59°N)
can also be seen in the visible satellite image at 1416 UTC 23 August shown in Fig. 14. It is likely that the extratropical development would have been weaker without the presence of Felix although future work is needed to show this.

4. Interaction with vertical shear during early phase of transition

From a PV–θ view of extratropical transition the PV structure of the tropical cyclone must be considered. For example, we might expect a strong deep cyclonic PV anomaly to interact differently with a baroclinic wave than a shallow low-level anomaly. The 900-hPa PV anomaly associated with both Felix and Iris can be tracked from the hurricane stage to the extratropical stage. However, we expect the PV structure to change considerably during this time. One environmental factor present during extratropical transition that influences the PV structure of a tropical cyclone is vertical shear. Jones (1995) showed that tropical cyclone–like vortices in vertical shear undergo structural changes that depend not only on the strength of the shear but also on other factors including the strength and size of the vortex. The fact that Iris was a weaker hurricane than Felix suggests that Iris and Felix might respond differently to a vertically sheared environment.

Satellite imagery is often used to detect whether a tropical cyclone is affected by shear. One characteristic of a tropical cyclone in vertical shear is an exposed low-level circulation. Figure 15 shows a sequence of infrared satellite images between 2 and 5 September. On 2 September (see Fig. 15a) Iris has a characteristic eye surrounded by a much broader expanse of outflow cirrus. Although Iris is weakening at this stage (see Fig. 2), it still has the appearance of a hurricane. By 3 September (see Fig. 15b) Iris has lost its eye consistent with its continued decay. On 4 September (see Fig. 15c) the
Figure 14. Meteosat infrared satellite image of Felix at 1416 UTC 23 Aug. Image courtesy of the University of Dundee.

The satellite image indicates a marked change in the structure of Iris with clear loss of axisymmetry. By this time the cirrus shield has been displaced northeastward relative to the surface cyclone center exposing the low-level cloud to the southwest. This could be an indicator that Iris is in a vertically sheared environment. On 5 September (see Fig. 15d) Iris appears even more asymmetric in the satellite image with a distinctive wedge of cirrus to the northeast. However, a region of low-level cloud southwest of the cirrus is suggestive of a low-level circulation, seen more clearly in the visible image (not shown). A noteworthy feature at this time is a sharp western edge to the cirrus that is consistent with a low tropopause to the west of this cirrus region (see Fig. 5c).

The satellite imagery sequence suggests that Iris becomes influenced by vertical shear during the period shown. The vertical shear diagnosed from the UKMO analyses is presented in Fig. 16 for the same period. In order to eliminate the contribution from Iris, the winds at each level are averaged over a circle of radius 600 km centered on the storm center (DeMaria 1996). At 0000 UTC 2 September and at 0000 UTC 3 September (Figs. 16 a,b) the vertical shear is weak, of the order 0.8 m s\(^{-1}\) (100 hPa\(^{-1}\)). At 0000 UTC 4 September the vertical shear is stronger with a value of 2.0 m s\(^{-1}\) (100 hPa\(^{-1}\)) and the horizontal wind veers slightly with height. The increase in shear between 3 and 4 September occurs at the same time as we see the cirrus shield being displaced from the low-level center (cf. Fig. 15c). Although the cirrus is displaced to the northeast of the surface cyclone, the shear vector is almost due east.

Jones (1995) showed that there is not always a simple relationship between the direction of the shear vector and the direction of the vortex tilt. However, her study was confined to the cyclonic part of the tropical cyclone vortex. Studies of the upper-level anticyclone in vertical shear have shown that a complicated structure may develop (Shapiro 1992; Wu and Emanuel 1993). Thus we might not necessarily expect a simple relationship to exist between the direction of the shear vector and the asymmetries in the outflow cirrus. At 0000 UTC 5 September (Fig. 16d) the shear is very strong with a value of 5.3 m s\(^{-1}\) (100 hPa\(^{-1}\)) consistent with the analyzed position of Iris beneath the upper-level westerly jet (see Fig. 4c). At this time the wind direction is constant with height.

The structural changes of Iris as it becomes influenced by the vertical shear will be illustrated by showing vertical cross sections of PV at 0000 UTC 4 September and 0000 UTC 5 September centered on the 900-hPa PV anomalies in Figs. 3b,c. The sections are oriented west–east so as to lie close to the direction of the shear vector (cf. Figs. 16c,d), which is predominantly west–east on these days. On 4 September (Fig. 17a) Iris is characterized by a vertically oriented positive PV anomaly with almost no vertical tilt. In the upper troposphere negative PV anomalies can be seen that are probably associated with the anticyclonic outflow layer of Iris. At 0000 UTC 5 September when the vertical shear is much stronger (cf. Fig. 16d) the positive PV tower is much more tilted. Figure 17b shows the cross section close to the direction of maximum tilt, which is predominantly in the direction of the shear vector. Figure 17b indicates that relative to the 900-hPa PV maximum the PV maximum at 600 hPa has moved about 300 km. It should be noted that if the PV anomaly was sheared out passively between 0000 UTC 4 September and 0000 UTC 5 September, the displacement would have been about three times as large. This is consistent with Jones (1995) who showed that positive PV anomalies in idealized models are not sheared passively. Instead, the destructive action of the vertical shear is reduced due to the vertical interaction of PV anomalies and the development of a secondary circulation. It should be noted that the tilt of the cyclonic PV anomaly may be reduced also by diabatic modification of PV (Flatau et al. 1994; Wang and Holland 1996). These different mechanisms require further investigation in the context of extratropical transition.

In the satellite imagery for Felix (not shown) we observe a similar transition from the typical axisymmetric structure associated with a hurricane to a more extratropical appearance. The vertical shear was calculated for the case of Felix in the same way as that for Iris (not shown). On 20 August both the average wind speed and the shear are weak with no preferred direction. On 21 August the wind and shear are still both weak but there is now a preferred direction from the southwest indicating the approach of the upper-level trough. Dur-
ing the next two days as Felix moves poleward the shear increases significantly with values of approximately 1.6 m s\(^{-1}\) (100 hPa\(^{-1}\)) and 3.3 m s\(^{-1}\) (100 hPa\(^{-1}\)) on 22 and 23 August, respectively. It is during this time that Felix loses its tropical cyclone character. Note that the shear experienced by Felix is significantly weaker than that experienced by Iris on 5 September. Since Felix was much stronger than Iris and experienced weaker shear we might expect its structure to be less strongly influenced by the vertical shear. This can be seen in Fig. 13a where the tilt of the PV tower is considerably smaller than that seen for Iris in Fig. 17b.

5. A comparison of the thermodynamic structures of Iris and Felix

Comparing the \(\theta_e\) structures of Iris and Felix at the mature stage shown in Figs. 7d and 13d we notice a fundamental difference between the two systems. Iris has a well-defined warm core in association with a deep convecting layer characterized by a region of relatively high \(\theta_e\) between the surface and the tropopause. The convecting region has a \(\theta_e\) value of around 328 K. The sea surface temperature (SST) in this region, (see Fig. 18a below) is 290.1 K. With a surface pressure minimum of 957 hPa the saturated equivalent potential temperature at the SST (\(\theta_{es}\)) is 328 K suggesting that the deep convecting region is closely linked to the local SST. The idea that the boundary layer is in equilibrium with the local SST, and that the warm core forms in association with the convective transport of high \(\theta_e\) in the vertical, overlaps with current ideas on tropical cyclone structures and maximum potential intensity (e.g., Emanuel 1986; Holland 1997). A comparison with tropical cyclones was also made by Gronas (1995) in a study on seclusion intensification.

In contrast to Iris, Felix does not have a well-defined warm core at the mature stage and is not characterized by a deep convecting \(\theta_e\) tower in equilibrium with the local SST. Instead the high \(\theta_e\) tower is tilted in an association with the warm front and appears to be decoupled from the SST. Below the tower is a stable layer not seen in the Iris case.

One obvious reason for some of the difference in thermodynamic structure is the difference in the track across the Atlantic of the two systems. Figure 18a shows
the tracks of both cyclones across the August–September mean SST. The graph shows the SST at the center of Felix and Iris as a function of time, based on the August mean SST and September mean SST, respectively. Iris moves across colder water early on but then tracks mainly eastward above water with a fairly constant SST of around 18°C. In contrast Felix tracks much farther poleward and consequently moves over colder water. By 24 August the SST below Felix is only 13.5°C. It is very likely that this had a detrimental effect on the warm-core structure of Felix.

Based on this discussion we hypothesize that an important factor in the extratropical transition of Atlantic hurricanes into deep extratropical systems in the eastern Atlantic is the maintenance of a warm-core system across the Atlantic. This is associated with an adjustment from a deep convecting core characterized by \( \theta_e \) values determined by tropical SSTs to one characterized by lower \( \theta_e \) values that are determined by extratropical SSTs. The superposition of this warm-core system and a broad-scale cyclonic system can result in the strong winds that characterize the strongly developing systems. In this case the deep troposphere remains controlled by the boundary layer \( \theta_e \) and is in this sense coupled to the ocean like a tropical cyclone. If the system moves over much colder water as in the case of Felix the deep troposphere can become decoupled from the ocean due to the development of a stable layer.

In order to illustrate the changes in the vertical profiles of \( \theta_e \) in the core of Felix and Iris as they track across the Atlantic, time–pressure sections have been produced of the \( \theta_e \) averaged over a circle of radius 200 km centered on the 900-hPa PV maximum (see Fig. 19). Although there are errors involved in doing this due to the nonaxisymmetry of the cyclones a clear overview of the evolution is obtained. Also shown are time–pressure sections showing the difference between \( \theta_e \) averaged over a radius of 200 km and averaged over 600 km. We use this as a measure of the strength of the warm core that is valid for the deep convective case of Iris. The same diagnostic is included for Felix for comparison.

Focusing on Iris first we see clearly that throughout the track across the Atlantic \( \theta_e \) generally decreases at all levels consistent with the adjustment to lower SSTs discussed above. Interesting points to note include the large decrease in midlevel \( \theta_e \) values between 2 and 3 September. Between 3 and 4 September the low-level
$\theta_e$ decreases. This is the time when Iris first moves over colder water. Around 4 September the profile becomes approximately well mixed in the vertical indicating a convective period. After this there is again a rapid decrease in $\theta_e$ at midlevels followed by a second vertical mixing event in association with convection on 6 September. Between 6 and 7 September the low-level $\theta_e$ actually increases. In summary, the low-level $\theta_e$ decreases steadily as Iris tracks across the Atlantic but the midlevel $\theta_e$ changes in a sporadic way, in association with lateral advection, radiational cooling, and deep convective events. Figure 19b shows that, despite the decreasing $\theta_e$, relative to the environment a warm core is maintained. After 7 September when Iris moves over land finally this warm core weakens.

The evolution of averaged $\theta_e$ in the case of Felix is quite different. Between 20 and 22 August there is very little change with the core characterized by high tropical values and with the warm-core signature even increasing (see Fig. 19d). But as Felix tracks across the colder water (see Fig. 18b) $\theta_e$ decreases in a dramatic fashion and in this case more rapidly at low levels than at midlevels so that a stable layer develops. Above 800 hPa the $\theta_e$ values steadily decrease and are relatively well mixed, but are much larger than the low-level values, consistent with the decoupling discussed above. Associated with the rapid decrease of low-level $\theta_e$ is a loss of the warm-core signature below about 800 hPa verified by an examination of $\theta$ (see Figs. 12d and 13c).

Since the evolution of $\theta_e$ is important and differences between Iris and Felix are marked, it is worth considering what processes contribute to changing $\theta_e$. The boundary layer $\theta_e$ budget has been examined in detail by several authors in the context of tropical cyclones and tropical convection (e.g., Raymond 1995; Rotunno and Emanuel 1987). As they discuss, the processes that change the boundary layer $\theta_e$ are entrainment from the mid troposphere, downdrafts, surface fluxes of $\theta_e$, and radiative cooling. In midlatitudes horizontal advection of $\theta_e$ is also important. In the case of extratropical transition we expect the midlevel $\theta_e$ to decrease through advection and radiative cooling and this to be communicated to the boundary layer through entrainment and downdrafts. The surface fluxes will oppose this
change if boundary layer $\theta_e$ is greater than $\theta_{\text{eq}}$ but since the surface fluxes also depend on the low-level winds the fluxes are likely to vary in a complicated way as the hurricanes track across extratropical SST gradients. To illustrate how these fluxes change, the surface latent heat fluxes together with the 900-hPa $\theta_e$ are presented for Iris between 2 and 7 September (Fig. 20). Although both sensible and latent heat fluxes contribute to the $\theta_e$ fluxes, for brevity only the latent heat fluxes are shown. In the case of Iris the latent heat fluxes are typically 4–5 times larger than the sensible heat fluxes but in the case of Felix the fluxes are more comparable. Generally the pattern and sign of the sensible and latent heat fluxes are similar.

It is first worth noting that as with the 900-hPa PV and $\theta_e$, a well-defined 900-hPa $\theta_e$ maximum can be tracked across the Atlantic. Consistent with Fig. 19a and the discussion above though, the peak value of $\theta_e$ decreases from 351 to 334 K. On 2 September the situation is very similar to that expected of a mature tropical cyclone. There is a high-$\theta_e$ core with strongest low-level winds around it collocated with the strongest fluxes, which at the time are greater than 350 W m$^{-2}$. It should be noted that asymmetries are already evident at this time. On 3 September Iris is characterized by very marked asymmetries in the surface fluxes with the strongest fluxes clearly located on the eastern side. This is consistent with stronger winds on this side of the cy-
clone, which, comparing with Fig. 3a, is associated with the strong pressure gradient between the cyclone and the large-scale anticyclone that it is tracking around.

When a tropical cyclone moves poleward across a strong north–south SST gradient such as that seen in Fig. 18a we would expect to see the development of north–south asymmetries in surface fluxes with stronger fluxes on the equatorward side and weaker fluxes on the poleward side in association with the differences between the $\theta_e$ of the overlying air and $\theta_{es}$. This is indeed the case for Iris on 4 September (see Fig. 20c). Also seen at this time is a region of negative fluxes on the northeastern side of the cyclone. This implies that the $\theta_e$ of the boundary layer air is actually greater than $\theta_{es}$, which must be associated with low-level cloud formation or fog. This is seen more dramatically in the case of Felix below. Since hurricanes are usually characterized by high-$\theta_e$ values at low levels in their core, we would expect fog formation to be a general feature of these systems when they track across the strong SST gradient associated with the Gulf Stream.

On 5 September a similar pattern in the surface fluxes is present but now there is clear evidence of equatorward advection of low-$\theta_e$ air and, linked to this, positive sur-
A PRIL 2000 967THORNCROFT AND JONES

FIG. 19. Time–pressure sections of the equivalent potential temperature in K area averaged over a circle with radius 200 km centered on the 900-hPa PV maximum (based on UKMO analysis) of (a) Iris between 2 and 7 Sep 1995 and (c) Felix between 20 and 24 Aug 1995. (b) and (d) The difference in equivalent potential temperature area averaged over a circle with radius 200 km and that area averaged over a circle of 600 km.

Figure 21 shows the surface latent heat flux together with the 900-hPa $\theta_e$ for Felix between the 21 and 24
Fig. 20. Surface latent heat fluxes (shaded), and contours of 900-hPa $\theta_e$ with a contour interval of 4 K and 900-hPa wind vectors for Iris 0000 UTC 2–7 Sep 1995.
August (n.b., a different scale for the fluxes is used compared with Fig. 20). As in the case of Iris there are west-east asymmetries in the fluxes initially (Fig. 21a) followed by north-south asymmetries a day later as Felix crosses the Gulf Stream SST gradients. However, Felix tracks farther poleward and the negative fluxes resulting from the difference between the high-\(\theta_e\) core and \(\theta_e\) are larger and are much more collocated with the core region (see Fig. 21c). This results in lower \(\theta_e\) values in the core than in the environment by 23 August (also seen in \(\theta_e\) see Fig. 12d). These \(\theta_e\) values are lower than \(\theta_e\) and are thus associated with low cloud or fog (confirmed by ship reports on 22 and 23 August). By 24 August a well-defined \(\theta_e\) signature can no longer be seen, consistent with the merger in PV seen at this time (see Fig. 10).

The thermodynamic structures of Iris and Felix develop quite differently during extratropical transition. This we believe is linked strongly to the different SSTs they feel. Iris tracks across warmer water than Felix. We suggest that the surface fluxes maintain a boundary layer \(\theta_e\) that is close to the \(\theta_{es}\) and, in association with deep convection, the \(\theta_e\) of the tropospheric column of air above adjusts to this \(\theta_{es}\). In this sense Iris behaves like a mature tropical cyclone; however, the surface fluxes in the case of extratropical Iris are enhanced through a superposition of the winds associated with the large-scale baroclinic wave and upper-level PV (see Fig. 7) and do not develop purely in association with the development of a warm-core vortex. In contrast, Felix moves over colder water resulting in negative surface fluxes that decrease the boundary layer \(\theta_e\) resulting in a decoupling of the boundary layer from the troposphere above. Rough estimates of the boundary layer \(\theta_e\) tendencies associated with the surface latent heat fluxes can be made.

Following Raymond (1995), assuming that the fluxes are distributed over a boundary layer depth of 500 m, a latent heat flux of \(+100\) W m\(^{-2}\) would be associated with a boundary layer \(\theta_e\) tendency of about \(+17\) K.
The fluxes in the vicinity of Iris as it tracked across the Atlantic were typically +50 to +100 W m$^{-2}$ (see Fig. 20) giving a typical positive contribution to the boundary layer $\theta_e$ tendency of about +10 K day$^{-1}$. Despite this, the low-level $\theta_e$ continued to decrease until 0000 UTC 6 September (see Fig. 19a,b) due to other more dominant physical processes opposing the action of the surface fluxes. The pronounced midtropospheric $\theta_e$ minimum in Fig. 19 suggests that convective downdrafts contributed to this. In contrast to this the fluxes in the vicinity of Felix at 0000 UTC 23 August are around $-100$ W m$^{-2}$ resulting in a strong negative boundary layer $\theta_e$ tendency. Without the positive surface fluxes seen in the case of Iris the boundary layer $\theta_e$ in the vicinity of Felix decreases rapidly (see Figs. 19c,d and 21b,c) resulting in the decoupling discussed above. A more detailed analysis of the low-level $\theta_e$ budget of tropical cyclones as they become extratropical is recommended in order to understand the maintenance or not of the warm-core structure.

6. Summary and conclusions

Tropical cyclones that undergo extratropical transition can develop into severe weather systems that can affect high latitudes. The present study has contrasted two such cyclones that affected northwest Europe in 1995.

Iris was a weak tropical cyclone that maintained its warm-core structure as it tracked across relatively warm water. It was advected into the center of a large-scale baroclinic wave. The superposition of the two systems resulted in strong low-level winds. These winds resulted in strong surface latent heat fluxes that helped to keep the boundary layer $\theta_e$ close to the $\theta_e$ of the underlying SST. In this sense the processes that maintained the warm-core structure of Iris and enhanced it near the United Kingdom are similar to those processes that determine tropical cyclone growth.

Felix was a much stronger tropical cyclone than Iris but did not maintain its low-level warm-core structure as it tracked across the Atlantic. This has been shown to be consistent with its more poleward track across colder water. Negative surface fluxes of latent heat decreased the boundary layer $\theta_e$ resulting in low-cloud formation and a decoupling of the cyclone boundary layer from the deep troposphere. Felix may have influenced the warm frontal structure of the extratropical low that it interacted with.

The contrasting cases of Iris and Felix highlight the problem of defining exactly what is meant by extratropical transition. One possible definition might be that the warm-core tropical cyclone changes into a cold-core extratropical system. However, in the case of Iris the system never developed a cold core but baroclinic processes played a dominant role in the subsequent extratropical development. In the case of Felix a cold core developed at low levels but a weak warm core was still observed above 600 hPa when the system was certainly extratropical.

As in the studies of extratropical transition over the mainland United States (DiMego and Bosart 1982a,b; Bosart and Dean 1991; Bosart and Lackmann 1995) we consider that the role played by the warm, moist air in the inner core of the exhurricane is crucial to the extratropical development. However, in contrast to cases where extratropical transition occurs shortly after landfall, in the case of Iris, the core of warm, moist air was maintained due to a favorable track over relatively warm water. In this sense we believe that Iris behaves similarly to exhurricane Lili in 1996 (Browning et al. 1998).

In both Felix and Iris a low-level PV feature could be tracked across the Atlantic from the hurricane to the extratropical stage. This suggests that the remnants of the tropical cyclone play an important role in extratropical development following transition. This contrasts with the view presented in earlier studies (e.g., Matano and Sekioka 1971a,b) that suggested that the hurricane vortex decays during transition.

Extratropical transition could be viewed as an initial value problem where the PV of the tropical cyclone interacts with a baroclinic wave. In this case the structure of the tropical cyclone remnants could play an important role in the nature of the development. Both Iris and Felix interacted with vertical shear during the early phase of the transition, which modified their structure. Iris was a weak hurricane that experienced strong shear. Thus the PV structure of Iris was modified considerably. Felix was a stronger hurricane and not as strongly sheared as Iris. Thus it did not develop as strong a vertical tilt as Iris.

A significant difference between the cases of Felix and Iris was the nature of the extratropical trough that finally steered the exhurricanes poleward. THM have discussed two types of baroclinic wave development: an LC1-type, which is associated with predominantly northeast–southwest-orientated thin upper-level troughs, and an LC2-type, which is characterized by less equatorward movement and a cyclonic wrap-up of high PV in a broad-scale upper-level trough. In this study, Felix is steered poleward in association with an LC1-type baroclinic wave development while Iris is steered into the center of an LC2-type baroclinic wave development. It is clear from this that a forecast model must correctly handle the baroclinic wave development in order to correctly forecast extratropical transition.

As well as the baroclinic wave development the forecast models must be able to predict the thermodynamic structure of the tropical cyclone remnants correctly. This is a severe test for forecast models since this involves the complicated interactions that occur between the surface fluxes, boundary layer, radiation, and convection. Poor representations of any of these will result in a poor forecast of the core of the exhurricane and associated development. Indeed Rabier et al. (1996), in an examination of ECMWF forecasts of exhurricane Floyd,
which reached the United Kingdom in 1993 as an extratropical system, found strong sensitivity to the convection scheme. From the above arguments it is likely that the boundary layer $\theta$ in the core of Floyd will have been different in the different forecasts. Future work should consider more closely the thermodynamic budget in the core of the exhurricanes. In addition, there is a need for idealized studies of extratropical transition, which consider the modification of the tropical cyclone during the early phase of transition and the interaction of the tropical cyclone remnants with different types of baroclinic waves.

Acknowledgments. This study benefited from discussions with Pat Harr, Daniel Keyser, and Martin Miller. We are most grateful for the comments of Lance Bosart, Pat Harr, and an anonymous reviewer on an earlier version of this paper. We would also like to thank Ed Dicks for programming support for analyzing the UKMO data. The collaboration was made possible by a grant from the British Council and the DAAD. Sarah Jones received some support from the U.S. Office of Naval Research under Grant N00014-95-1-0394.

REFERENCES


Sinclair, M. R., 1993a: Synoptic-scale diagnosis of the extratropical


