The Impact of air-sea interaction on the extratropical transition of tropical cyclones

Sarah Jones

Institut für Meteorologie und Klimaforschung
Universität Karlsruhe / Forschungszentrum Karlsruhe

1. Introduction

Tropical cyclones moving polewards into the midlatitudes and undergoing extratropical transition are frequently associated with a significant decrease in predictability. This can be associated both with the system undergoing ET and with the flow downstream of the system (Harr et al. 2008; Anwender et al. 2008). Forecast errors are not only associated with strong ET events. For example, the medium-range forecast for Hurricane Philippe (2005) predicted a strong storm developing out of the tropical cyclone (Fig. 1a) whereas in fact Philippe did not undergo ET but was absorbed by a larger-scale and more intense midlatitude system and decayed (Fig. 1b). An example of low predictability of the downstream flow is seen for the ET of Typhoon Nabi (2005). The downstream system was weaker and located further west in the medium range forecast (Fig. 1c) than in the analysis (Fig. 1d). There is a growing body of evidence indicating that such errors arise because an ET system can trigger or modify Rossby wave. Examples such as those illustrated in Figure 1 can be found in forecasts from all operational numerical weather prediction centres.

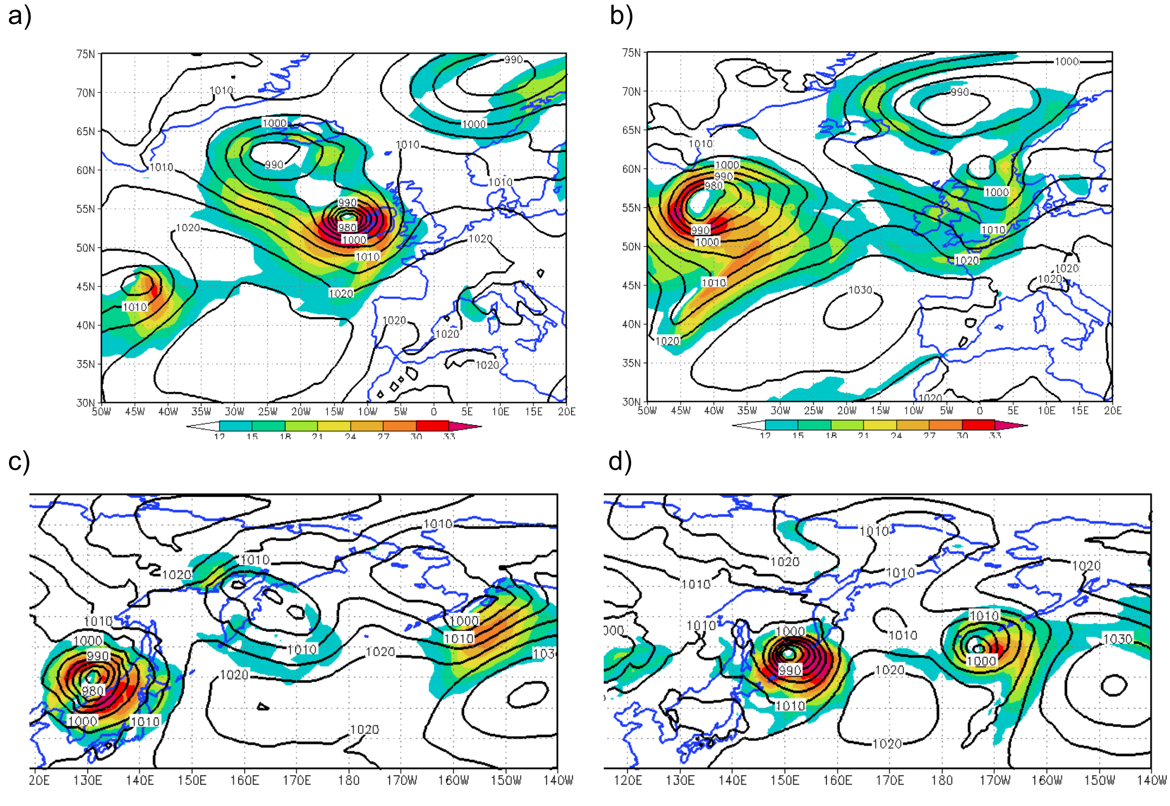

Figure 1:Surface pressure (contours) and 850 hPa wind (colours) from ECMWF analyses and forecasts. (a) 6 day forecast verifying 12 UTC 29 September 2005 predicting Hurricane Philippe to develop into an intense midlatitude low seen here approaching Ireland (b) analysis for 12 UTC 29 September 2005 in which the remnants of Hurricane Philippe are located at (45W, 40N) in the cold front of a midlatitude system (c) 6 day forecast verifying 12 UTC 08 September 2005 for Typhoon Nabi located over China and a downstream low at 165E (d) analysis for 12 UTC 08 September 2005 with Nabi to northeast of Japan and a more intense downstream low at 170W.

As a tropical cyclone transforms into an extratropical system a number of environmental factors change (Jones et al. 2003). One of these is that a system undergoing ET over the ocean experiences decreasing sea surface temperatures (SSTs) and frequently moves over a region with strong SST gradients. However, although considerable effort has been devoted to studying ocean–atmosphere interaction for both tropical and extratropical cyclones, there have been relatively few studies of the impact on ET and on the downstream predictability. In this article we review the characteristics of ET relevant for ocean – atmosphere interaction, describe some of the studies that contribute to our knowledge of the role of this interaction during ET, and conclude with a discussion of open questions.

2. Characteristics of ET

The changing environmental conditions influence the track, structure and intensity of a tropical cyclone moving into the midlatitudes. As the tropical cyclone comes under the influence of the midlatitude westerly flow its forward speed can increase from values of about 5 m/s to speeds in excess of 20 m/s. If the timing of this increase in speed is not captured in NWP models, large position errors of the ET system can result. The intensity of a tropical cyclone typically decreases in the transformation stage of ET but reintensification can occur as an extratropical system. In some cases this reintensification can be classified as explosive cyclogenesis. The major structural changes during ET are associated with increased asymmetry of cloud and precipitation fields (Klein et al. 2000), with a dry slot appearing to the west of the tropical cyclone centre and enhanced precipitation polewards (Fig. 2). The wind field becomes asymmetric also, with strongest winds to the left of the track in the Northern Hemisphere. The ET system increases in size so that, although the maximum winds typically decrease, the areal coverage of strong winds often increases. The interaction of the circulation of the ET system with a midlatitude baroclinic zone leads to strong warm frontogenesis (Harr and Elsberry 2000) and enhanced latent heat release. During this phase the asymmetric vertical mass flux can be stronger than the symmetric mass flux (Davis et al. 2008). Definitions of ET often use the transformation from a warm to a cold core system to define the completion of ET (Evans and Hart 2003), although in some cases the warm core is retained in the midlatitudes (e.g. Thorncroft and Jones 2003).

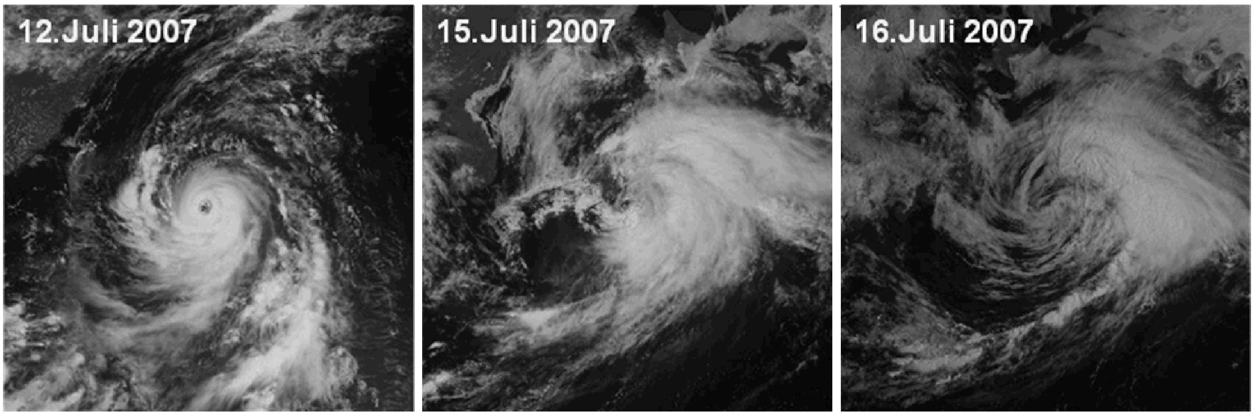

Figure 2: Visible satellite imagery for the extratropical transition of Typhoon Man Yi in 2007. Imagery shows the increasing asymmetry in the cloud field. Images courtesy of Digital Typhoon (http://agora.ex.nii.ac.jp/digital-typhoon/)

An indication of the importance of SST for ET can be found in the climatological study of Hart and Evans (2001). They considered how the energy source for a tropical cyclone undergoing ET changes during the transition. In the tropics, the warm ocean temperatures are essential to maintain the tropical system. The area in which tropical intensification is supported is defined as a region for which the maximum potential intensity theory (Emanuel 1988) predicts a central pressure for a tropical cyclone of below 960 hPa (Fig. 3, dotted line). In the midlatitudes the system can maintain its intensity through baroclinic conversion of available potential energy to kinetic energy. The area in which this is possible is defined using an Eady growth rate in excess of 0.25 / day (Fig. 3, shaded region). The system undergoing ET generally has to pass through a region in which environmental conditions are neither conducive to tropical nor to extratropical reintensification (Fig. 3). During the months with the highest ET frequency the geographic separation of the two favourable regions is smallest.

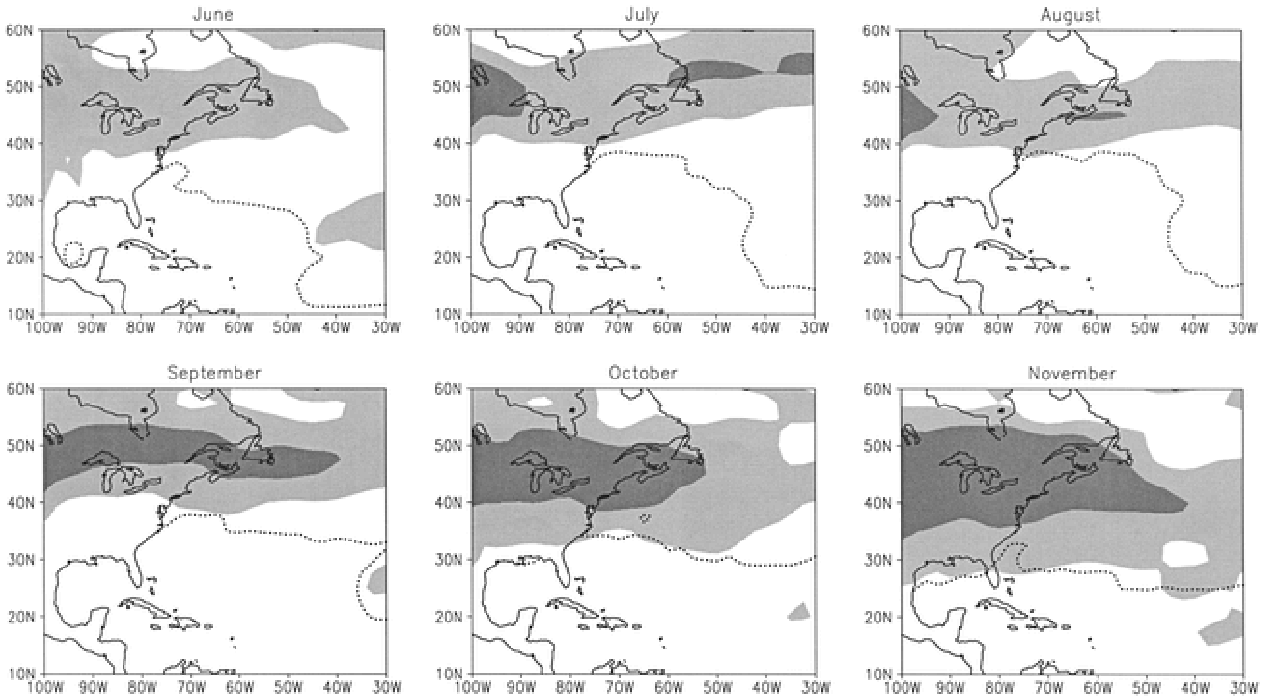

Figure 3: Explaining the seasonal cyclone in frequency and location of extratropical transition. Dotted line denotes climatological regions of support for tropical intensification (minimum pressure of 960 hPa from MPI theory). Shading is the Eady baroclinic growth rate parameter (σ) from 1985 monthly mean 700-hPa ECMWF 2.5° reanalyses (light and dark shaded at 0.25 and 0.5 day^{-1}, respectively). Here $\sigma = 0.31fU_zN^{-1}$, f = Coriolis parameter, U_z = vertical derivative of the horizontal wind, N = Brunt–Väisälä frequency. Taken from Hart and Evans (2001).

3. Studies of interaction of ET with the underlying surface

In a comparison of two ET cases Thorncroft and Jones (2000) showed that the track of the ET event relative to the underlying SST (Fig. 4) influenced the structure and intensity of the midlatitude system after ET. Hurricane Felix (1995) moved over cold water early in the ET so that the boundary layer stabilized and the surface circulation decayed. After ET the remnant core of the tropical cyclone is still seen through the potential vorticity (PV) tower and an elevated warm core, but the system otherwise has lost its tropical characteristics (Fig. 5). Hurricane Iris (1995) moved over cooler water early in the ET, at which time it was influenced by strong vertical shear and thus decreased in intensity. Subsequently, the remnant tropical cyclone moved parallel to the SST gradient and as part of a favourable interaction with an upper-level trough reintensified as an extratropical system. The air-sea interaction was undoubtedly important for this reintensification as exemplified by the resulting tropical-cyclone-like structure – an upright PV tower and a deep region in the inner core of the system in which the equivalent potential temperature is equal to the saturated equivalent potential temperature at the SST (Fig. 6). The modeled surface latent heat fluxes for the two cases confirmed the different behavior. For Felix strong downward fluxes occurred as the ex-tropical cyclone moved over colder water (Thorncroft and Jones 2000, Fig. 21). For Iris the surface flux distribution changed from tropical to extratropical but during the reintensification had elements of both (Thorncroft and Jones 2000, Fig. 20).

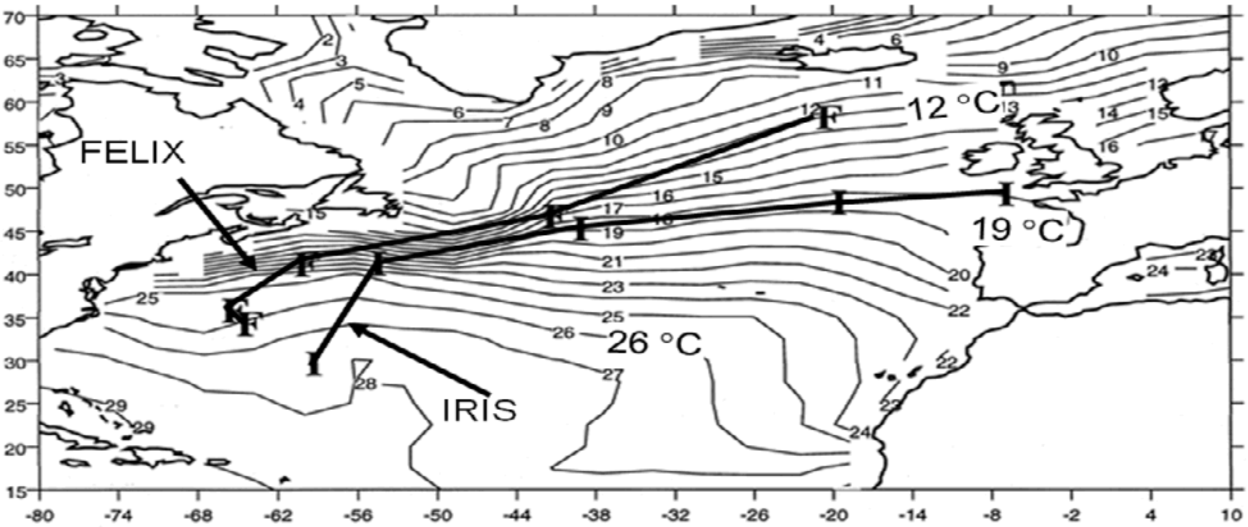

Figure 4: Track of Hurricanes Iris and Felix during their Extratropical Transition superimposed on the average sea surface temperature during the period of both ET events. Modified from Thorncroft and Jones (2000).

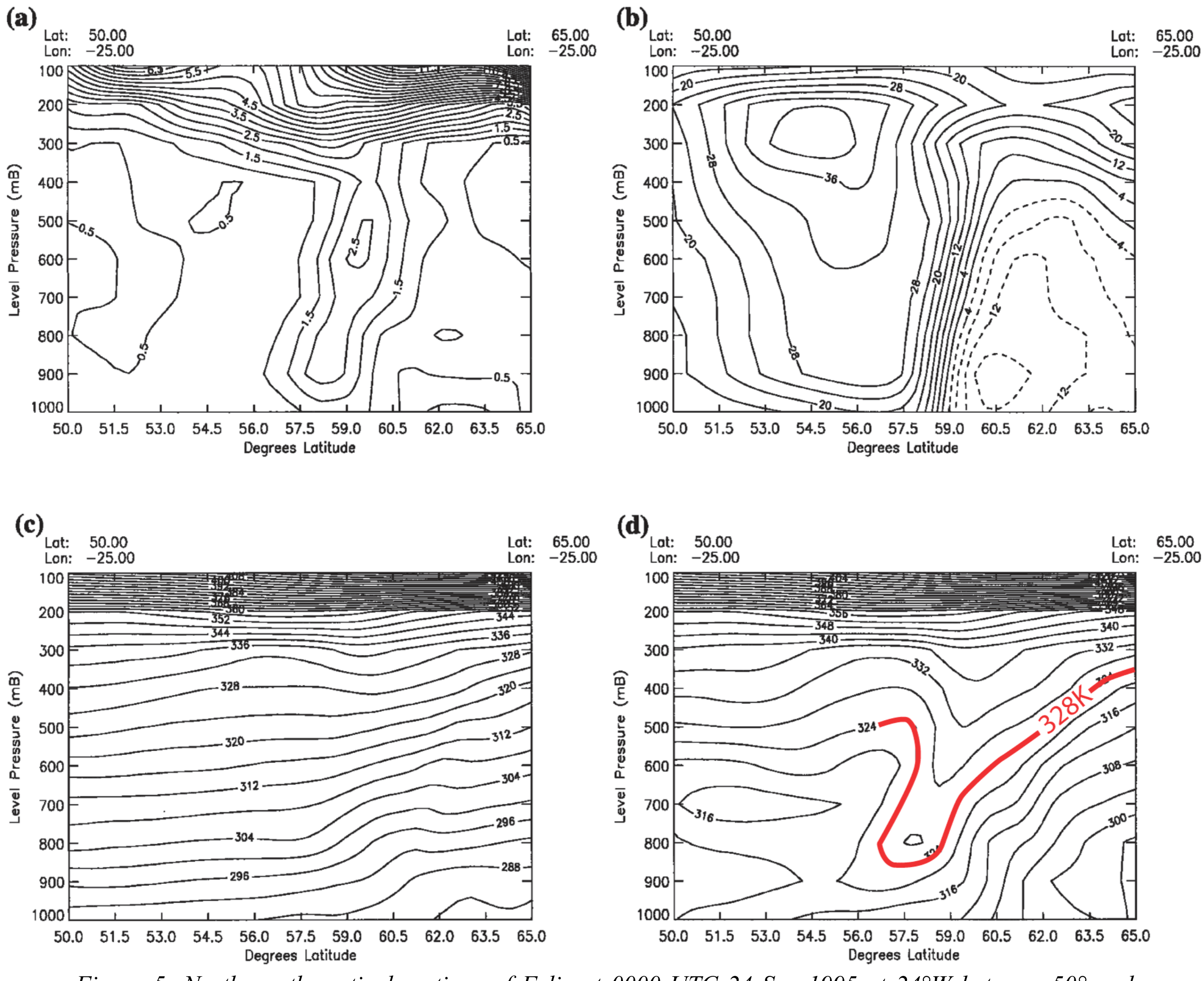

Figure 5: North–south vertical sections of Felix at 0000 UTC 24 Sep 1995 at 24°W between 50° and 65°N. (a) Potential vorticity with a contour interval of 0.5 PVU, (b) zonal wind with a contour interval of 4 m s^{-1}, (c) potential temperature with a contour interval of 4 K, and (d) equivalent potential temperature with a contour interval of 4 K. Taken from Thorncroft and Jones (2000).

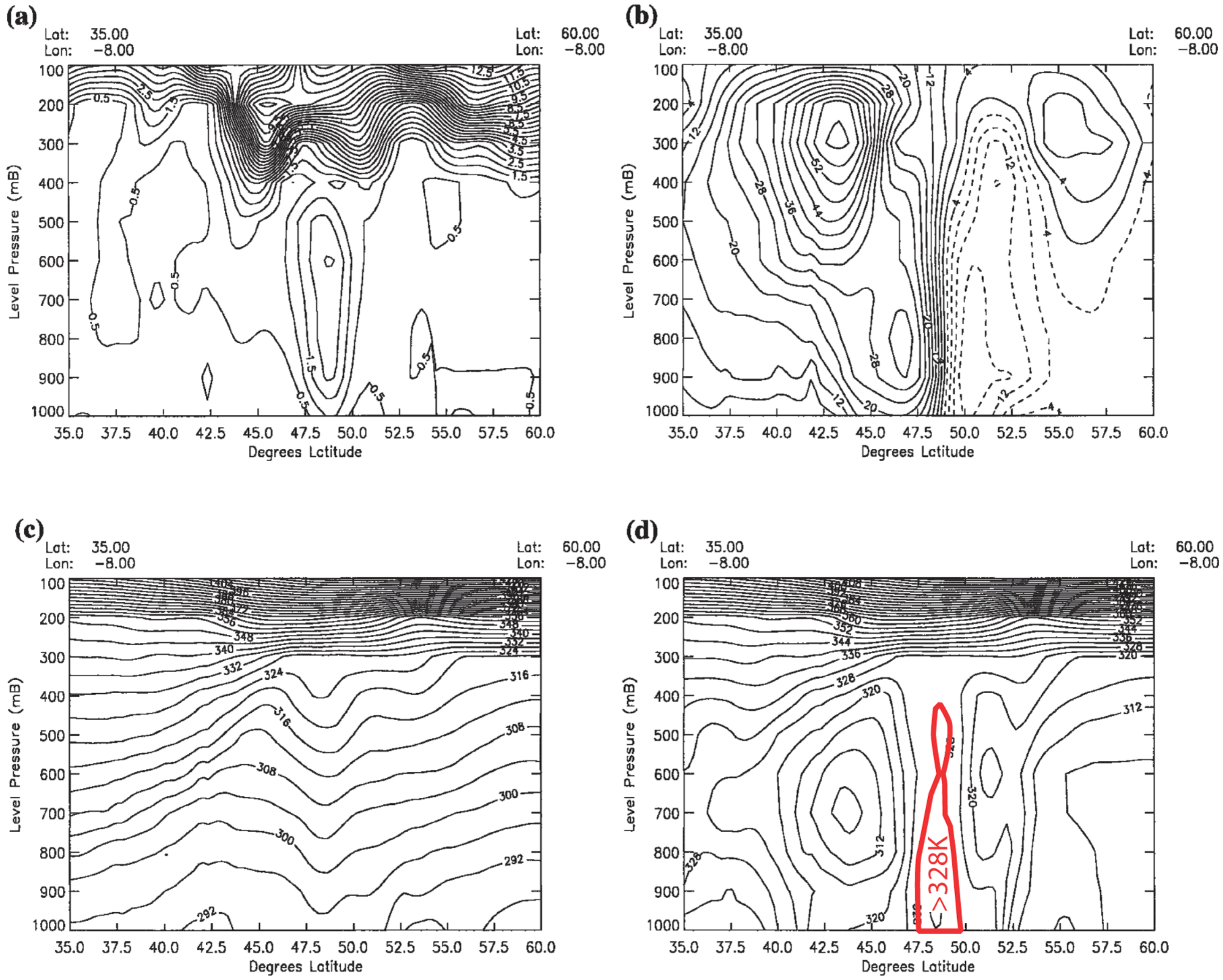

Figure 6: North–south vertical sections of Iris at 0000 UTC 7 Sep 1995 at 8°W between 35° and 60°N. (a) Potential vorticity with a contour interval of 0.5 PVU, (b) zonal wind with a contour interval of 4 m s^{-1}, (c) potential temperature with a contour interval of 4 K, and (d) equivalent potential temperature with a contour interval of 4 K. Taken from Thorncroft and Jones (2000).

Further studies of the impact of SST on extratropical transition include an idealized modeling study (Ritchie and Elsberry 2001) and an observational study of Hurricane Karen (Fogarty, personal communication, http://projects.novaweather.net/work.html). These studies suggest that it is important to consider on the one hand the increasing asymmetry in surface fluxes during ET and on the other hand the decay of the tropical cyclone when it moves over colder water. The spin down of a tropical-cyclone-like vortex was studied using an axisymmetric model by Jones and Thorncroft (2004). They showed that although frictional processes lead to a rapid decay of the low-level circulation, the tropical cyclone vortex in the mid and upper troposphere retains its strength for many days.

4. Wave growth during ET

It has been recognized only recently that the acceleration of a tropical cyclone during ET can lead to the rapid growth of ocean waves (Bowyer and MacAfee 2005; MacAfee and Bowyer 2005). As the tropical cyclone accelerates into the midlatitudes a trapped fetch situation develops leading to the development of large waves that are not preceded by leading swell (Fig. 7). Thus there is little prior warning of the hazard associated with such waves.

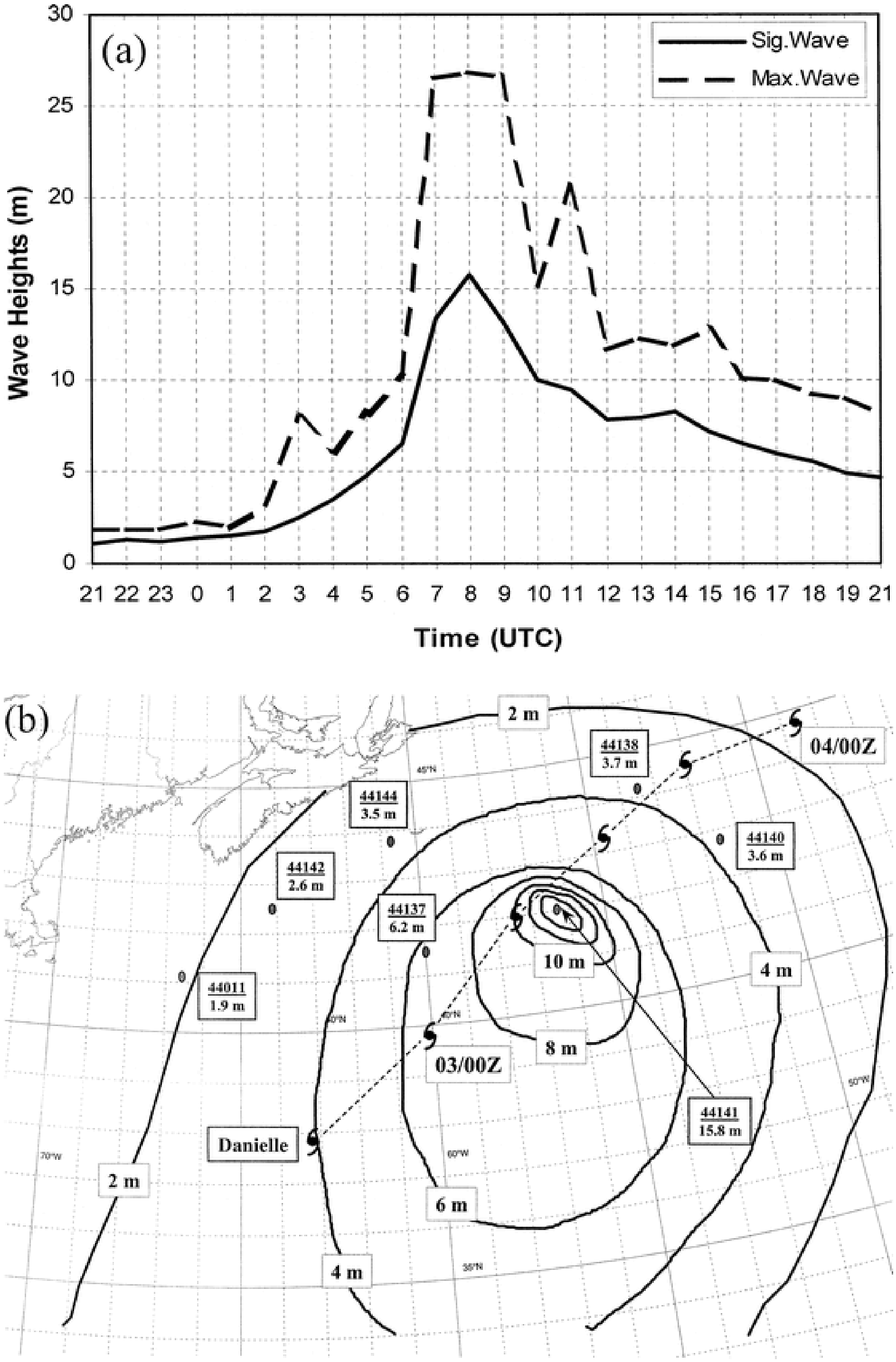

Figure 7: (a) Significant and maximum wave heights reported from Canadian NOMAD buoy 44141 during the passage of Hurricane Danielle (1998). The largest waves were reported at the point when the storm was nearest the buoy indicating strong resonance between the storm and waves. Significant wave heights grew 9 m in only 2 h, indicating little advance warning of approaching waves. (b) Significant wave height field associated with the extratropical transition of Hurricane Danielle (1998). The positions of the buoys are marked. Tight gradients at the leading edge of the maximum significant wave heights are typical for storms undergoing extratropical transition. Taken from Jones et al. (2003).

5. Open questions and future directions

In this article I have introduced the characteristics of ET that are important for the interaction with the ocean and given an overview of studies which have treated some aspects of this interaction. It is clear that there is an enormous potential for further studies in this area. Some of the questions that should be addressed are given below.

i. An accurate track forecast is essential in order to forecast ET but how well do we need to know TC intensity and structure directly before ET in order to forecast the downstream impact? An important factor in answering this question will be the determination of how structure and intensity change as a tropical cyclone moves over SST gradients

ii. How well do we need to know the structure of TC remnants after ET? What determines the spin down of a tropical cyclone when it moves over cold water?

iii. Does ocean-atmosphere interaction for an ET system differ from that of a typical extratropical system? How is the ocean-atmosphere interaction modified by the tropical cyclone remnants, for example by the PV tower and the warm and moist inner core of the ex-tropical-cyclone?

iv. Is there a need for coupled modeling or is an accurate representation of SST sufficient to capture the most important processes?

v. What is the impact of ET on the ocean?

These questions can be addressed using operational analyses and forecasts, through modeling studies and through investigation of real cases from field programs.

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