4A.2

NUMERICAL MODELING OF ATLANTIC HURRICANES MOVING INTO THE MIDDLE LATITUDES

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1. INTRODUCTION

The Meteorological Service of Canada (MSC), in partnership with Dalhousie University in Halifax, Nova Scotia, Canada**,** has recently been conducting numerical simulations of hurricanes migrating into the middle latitudes of the North Atlantic. The MSC's Mesoscale Compressible Community (MC2) model is being used to study and predict the structural changes that take place when tropical cyclones (TCs) undergo extratropical transition (ET).

Here we present some results from selected case studies of storms that have affected Eastern Canada since 2000. The case studies include Hurricane Michael (2000), Hurricane Karen (2001) and Hurricane Juan (2003). Hurricane Michael intensified in a strongly baroclinic environment and evolved into an intense extratropical storm over Newfoundland. Karen also underwent ET, but weakened quickly while approaching Nova Scotia, while Hurricane Juan struck Nova Scotia as a category-two hurricane, experiencing only marginal weakening over anomalously-warm sea surface temperatures (SSTs). In essence, these cases represent a cross section of the behavior of many tropical cyclones in this part of the world.

2. METHODOLOGY

2.1 *Atmospheric Model*

The MC2 model (V4.9.6) (Benoit et al. 1997) is a non-hydrostatic, fully compressible limited area model, which employs three-dimensional semi-Lagrangian advection, and semi-implicit time discretization to solve the primitive Euler equations on terrain-following height coordinates. Version 4.0 of the Canadian Meteorological Center (CMC) Physics Library is used for the parameterization of physical processes. A kinetic energy closure scheme described by Benoit et al. (1989) is used in the boundary layer to parameterize turbulent transports. Monin-Obukhov similarity theory is used in the atmospheric surface layer to determine the vertical profile of the wind field and sea surface fluxes. Deep convective processes are handled with Kain and Fritsch (1990) convective parameterization in the control simulations on a coarse (12 km) grid, but solved explicitly on a fine (3 km) grid, described below. Shallow convective processes are solved explicitly in all the experiments. Stratiform condensation (cloud microphysical) schemes are given by Tremblay et al. (1996) for the 12 km simulations and Kong and Yau (1997) for the 3 km runs.

The model is piloted by regional analyses or forecast fields every six hours from the Global Environmental Multiscale (GEM) numerical weather prediction model. The MC2 model is run on two grids, one is a 12 km (0.108^{o}) latitude-longitude grid with 25 computational levels (7 in the atmospheric boundary layer (BL)), and another on a finer 3 km (0.027^{o}) grid with 40 computational levels (12 in the BL). The lowest computational level (for momentum) in the 3 km version is 40 m. A time step of 120 seconds is used in the 12 km simulations and 30 seconds for the 3 km simulations.

Ensembles of experiments are run for each case study to diagnose the sensitivity of the simulations to different initial conditions, model configurations and boundary conditions such as SST. In this short paper, we will focus on some individual runs.

2.2 *Synthetic Storm Vortex*

Normally, the hurricane is not adequately resolved in the initial analysis fields used by the operational model. To solve this problem, a synthetic TC vortex (bogus) is inserted into those fields near the time when the storm is most intense prior to ET. The vortex construction follows Davidson et al. (1993). The vortex is constructed using key observational data from the National Hurricane Center (NHC) best track and operational forecast advisory archives. Control parameters for the vortex include: (a) the minimum central sea level pressure, (b) storm center position, (c) size (radius of 15 m s^{-1} surface winds, R_{15}) and (d) the percent of the environmental flow used for the initial wind field asymmetry.

3. CASE STUDY RESULTS

3.1 *Hurricane Juan*

As Hurricane Juan moved northward toward Nova Scotia, Canada in September 2003, it moved over much warmer than normal SSTs south of Nova Scotia (3 to

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5°C above normal) on the Scotian Shelf. A map of the pre-storm SST anomaly field is shown below in Fig. 1.

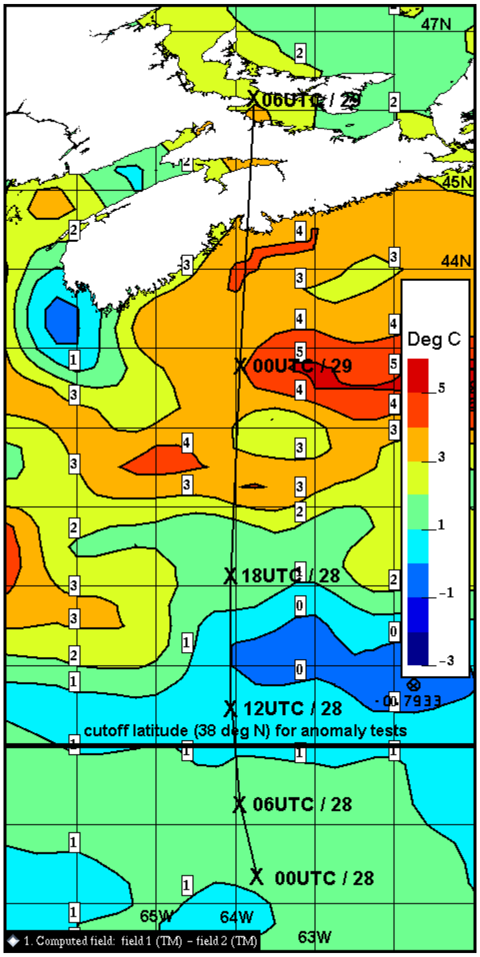

Figure 1. *Pre-storm SST anomaly (degrees Celsius) for Hurricane Juan. The storm track segment is also indicated by the solid curve with 6-hourly nodes marked with an "X".*

The primary focus of the numerical modeling of Juan was to assess the role of these warmer SSTs on the weakening rate of the hurricane leading up to landfall. Juan struck the province as a category-two hurricane. Most of the hurricanes that move toward Nova Scotia weaken to category-one or tropical storm strength.

Figure 2 shows results from the 12- and 3-km simulations using observed SSTs (JUAN) and climatological SSTs (CLIM). In terms of maximum surface winds, the rate of pre-landfall weakening in the 3-km CLIM run was more pronounced than the JUAN control run. The landfall intensity was 45.4 m s^{-1} (88 kts) for the control run but only 37.6 m s^{-1} (73 kts) for the CLIM run. In terms of the power associated with the maximum winds, which goes as the 3rd power of the wind speed (Emanuel 2005), the CLIM storm was only 60% as destructive as the control.

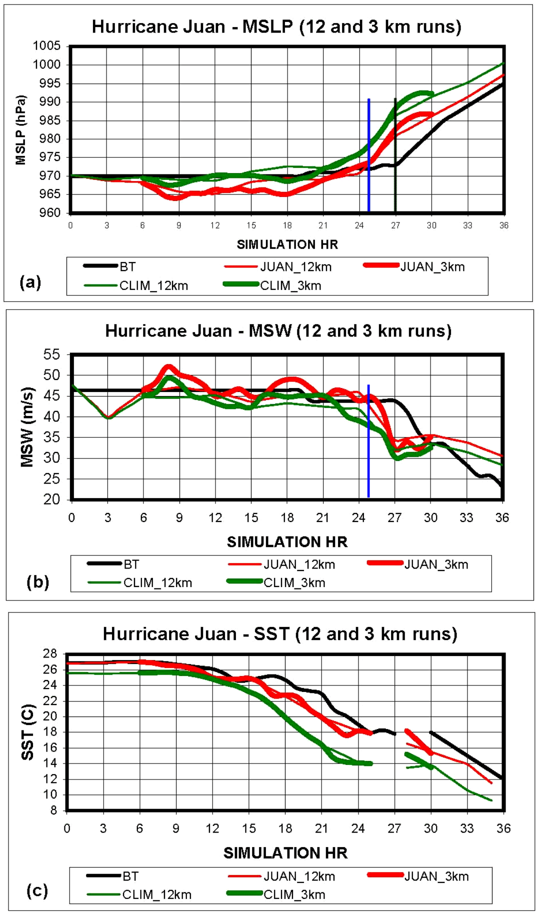

Figure 2. *Time traces for the Hurricane Juan control simulations: (a) evolution of minimum sea level pressure (MSLP) for 12 km JUAN (thin red line), 12 km CLIM (thin green line), 3 km JUAN (thick red line), 3 km CLIM (thick green line) and the best track (BT) (black line); (b) maximum surface winds (MSW); and (c) sea surface temperature (SST) beneath the storm center (defined by the location of the MSLP) as a function of model simulation time (hours). The vertical lines denote the approximate model landfall time (blue) and observed landfall time (black).*

3.2 *Hurricane Karen*

Hurricane Karen made landfall in southern Nova Scotia as a tropical storm with maximum sustained winds near 23.2 m s^{-1} (45 kts) in October 2001. Several experiments were run for Karen, including sensitivity tests on the initial intensity of the prescribed hurricane vortex. These tests include the control run with initial intensity equal to a category-one storm, and two others at category-two and category-three strength. The results of those runs are shown in Fig. 3.

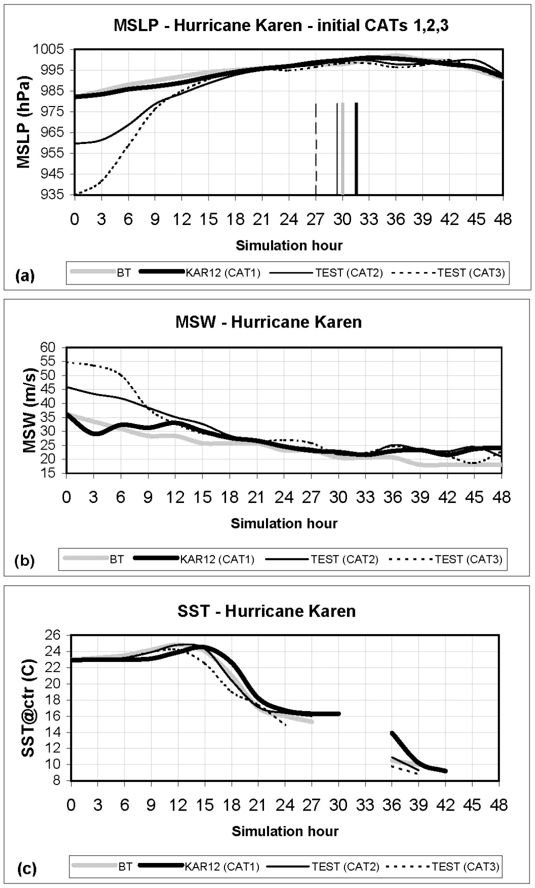

Figure 3. *Model results for the category-one control (KAR12), category-two test (CAT2), and category-three test (CAT3) simulations: (a) evolution of minimum sea level pressure (MSLP) for KAR12 (thick black curve), CAT2 (thin black curve), CAT3 (thin dashed curve), and the best track (thick grey curve); (b) maximum surface winds (MSW); and (c) sea surface temperature (SST) beneath the storm center as a function of model simulation time (hours). The vertical bars in (a) denote the approximate model landfall times (same line style as curves) and observed landfall time (grey).*

The landfall intensity for each run is generally insensitive to the initial intensity of the storm prior to exiting the warm waters of the Gulf Stream. The initial decay rate appears to be proportional to the storm's intensity, similar to the results of Kaplan and DeMaria (2001) for landfalling TCs, but with a slower rate of decay.

As Tropical Storm Karen underwent ET while tracking toward Nova Scotia, heavy rainfall associated with the storm fell primarily to the west of the track. Near 2" or 50 mm fell over western Nova Scotia. Simulated cumulative rainfall from the 12-km control run is shown in Fig. 4. Upwards of 50 mm is shown along the southwestern coast of Nova Scotia which is similar in amount to what was observed. Note how the rainswath migrates from right-of to left-of-track. This is a hallmark of ET.

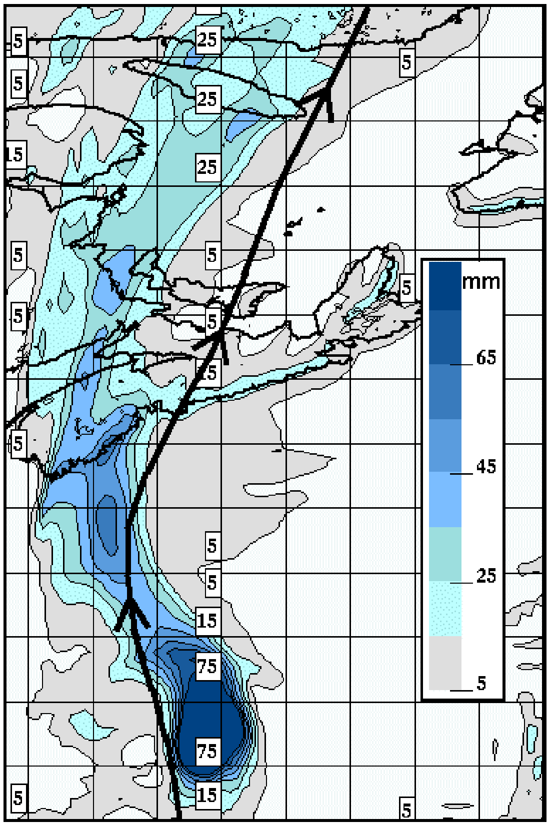

Figure 4. *Control simulation of rainfall during the ET of Tropical Storm Karen. Rainfall amounts are shown in grey and blue (5, 15, 25, 35, 45 mm, etc). The modeled storm track is indicated by the thick black line.*

3.3 *Hurricane Michael*

Unlike Hurricane Juan, Hurricane Michael underwent vigorous ET to the south of Newfoundland in October 2000 and struck the island as a large "hybrid" hurricane with maximum winds of 40.5 m s^{-1} (75 kts). We conducted various simulations with and without the TC bogus and compared with observations and the operational GEM model forecast. Those comparisons are shown in Fig. 5 near the time of landfall in Newfoundland.

The most realistic numerical representation of the storm is from the vortex-initiated run (Fig. 5d). When the TC vortex is not applied in the initial conditions, the compact center of the storm (and associated high winds) is not depicted (Fig. 5b and 5c).

Time series of vertical cross sections of equivalent potential temperature (θ_e) and horizontal wind speeds from the 3-km control experiment of Hurricane Michael provide a summary of the thermodynamic and dynamic changes in the storm structure during ET in Fig. 6. The cross sections run from west to east through the center of the storm along a distance of 500 km. Panel (a) shows the structure of the initial prescribed storm vortex. By 12 UTC 19 October (12/19) in Fig. 6b, ET has already begun as seen by the jet of low θ_e air on the west side of the storm. Drier air also intrudes into the mid levels of the storm (~500 hPa). As ET continues, the warm core tilts toward the west and the strong wind jet encircling the storm contains increasingly cooler/drier air, in effect "secluding" the warm core from the cooler airmass to the north. This pattern was observed to a certain extent in dropsonde data during a research flight into the storm (Abraham et al. 2004). The jet on the east side of the storm becomes elevated to near the 700 hPa level by 19/19 (Fig. 6d) and the warm core becomes thermodynamically decoupled from the cooler SSTs (~14^{o}C) as shown by the cool θ_e air in the lower boundary layer. In the hours leading up to landfall, drier air intrudes into the mid-levels of the storm, imparting an eastward tilt to the warm core and then destroying the upper part of it (Fig. 6e). Immediately prior to landfall (Fig. 6f) very low θ_e air (< 310 K) floods in from the west and the storm becomes frontal, although an elevated warm core remains.

4. SUMMARY

The MC2 model has been a useful research tool for studying the ET of TCs when a suitable synthetic hurricane vortex (bogus) is used in the initial conditions. We have also been running the model in forecast mode with positive results. The hurricane configuration of the model has been tested experimentally during the 2005 hurricane season. The output allows forecasters to obtain a better picture of how the wind and moisture fields may evolve as the hurricane or tropical storm moves into the middle latitudes and undergoes ET. Selected case studies have been completed by running multiple sensitivity simulations for Hurricanes Michael, Karen and Juan affecting Eastern Canada since 2000.

The unusually strong landfall intensity of Hurricane Juan in Nova Scotia in September 2003 was due partly to anomalously-warm SSTs along the storm track. In the cases of Hurricanes Michael and Karen (October 2000 and 2001 respectively), SSTs were slightly warmer than normal, but the effect on landfall intensity was small.

Sensitivity tests on initial storm intensity for Hurricane Karen revealed that the weakening *rate* of the storm was extremely sensitive to the initialized intensity. On the other hand, the *landfalling* intensity was essentially insensitive to the intensity prior to the storm traversing cool water south of Nova Scotia.

Simulations of Hurricane Michael confirmed aircraft observations of a strong low-level wind jet entraining extratropical air and encircling the storm during the vigorous extratropical transformation. The model also indicated the presence of the storm's warm core, decoupled from the cold boundary layer after transition over Newfoundland.

Additional information on these case studies can be found on the research website located at:
http://projects.novaweather.net/work.html

5. REFERENCES

Abraham, J., W. Strapp., C. Fogarty, and M. Wolde, 2004: Extratropical transition of Hurricane Michael: an aircraft investigation. *Bul. Amer. Meteor. Soc.*, **85,** 323–1339.

Benoit, R., M. Desgagné, P. Pellerin, S. Pellerin, S. Desjardins and Y. Chartier, 1997: The Canadian MC2: a semi-Lagrangian, semi-implicit wide-band atmospheric model suited for fine-scale process studies and simulation. *Mon. Wea. Rev.*, **125**, 2382-2415.

Benoit, R., J. Coté, and J. Mailhot, 1989: Inclusion of a TKE boundary layer parameterization in the Canadian regional finite-element model. *Mon. Wea. Rev.,* **117**, 1726-1750.

Davidson, N. E., J. Wadsley, K. Puri, K. Kurihara, and M. Ueno, 1993: Implementation of the JMA typhoon bogus in the BMRC tropical prediction system. *J. Met. Soc. Japan,* **71**(4), 437-467.

Emanuel, K. A., 2005: Increasing destructiveness of tropical cyclones over the past 30 years. *Nature*, **436**, 686-688.

Kain, J. S., and J. M. Fritsch, 1990: A one-dimensional entraining/detraining plume model and its application in convective parameterization. *J. Atmos. Sci,* **47**, 2784-2802.

Kaplan, J., and M. DeMaria, 2001: On the decay of tropical cyclone winds after landfall in the New England area. *J. Appl. Meteor.*, **40**, 280–286.

Kong, F., and M. K. Yau, 1997: An explicit approach of microphysics in MC2. *Atmosphere-Ocean*, **35**, 257-291.

Tremblay, A. A., W. Yu, and R. Benoit, 1996: An explicit cloud scheme based on a single prognostic equation. *Tellus.,* **48A**, 483–500.

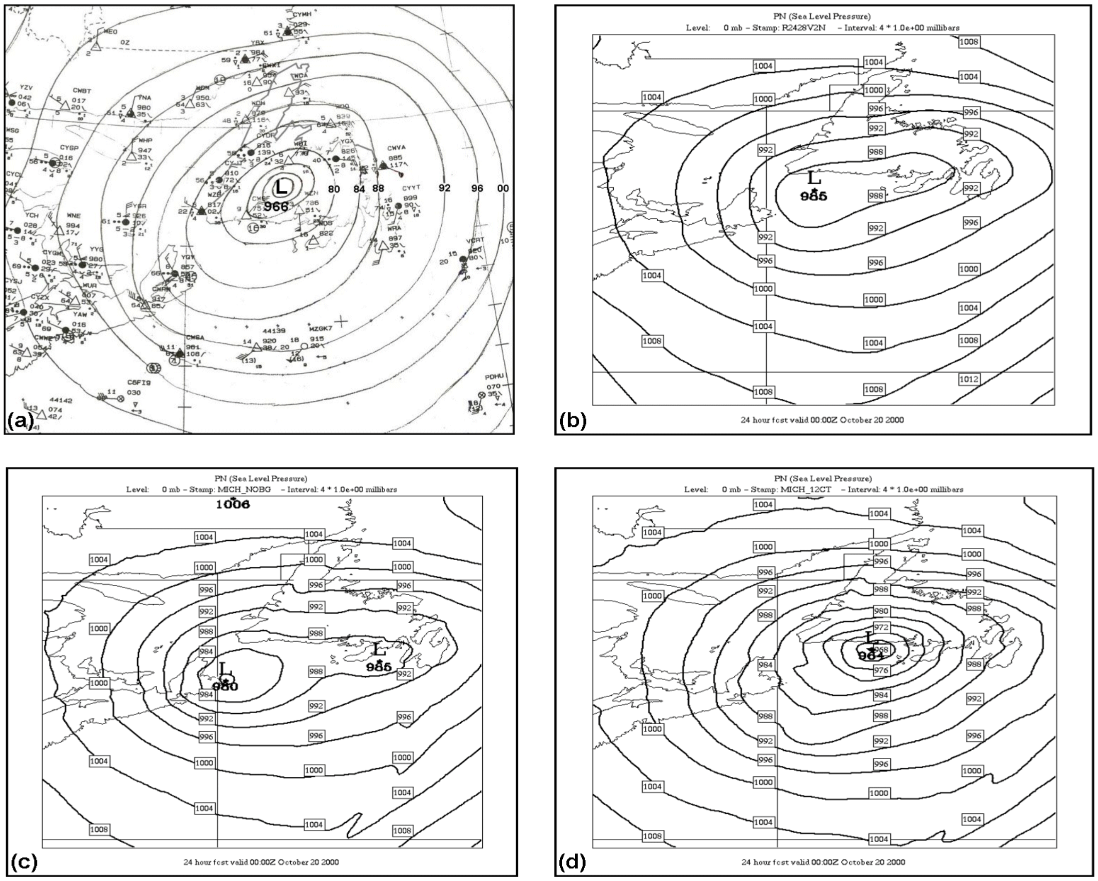

Figure 5. *Sea level pressure (every 4 hPa) valid at 00 UTC 20 October 2000 based on (a) manually drawn (subjective) analysis, (b) 24-hour GEM regional forecast, (c) 24-hour "no-vortex" simulation of the 12-km MC2 model, and (d) 24-hour simulation of the control run of the MC2 model with vortex insertion employed (MICH12). Standard synoptic weather plots are shown in (a).*

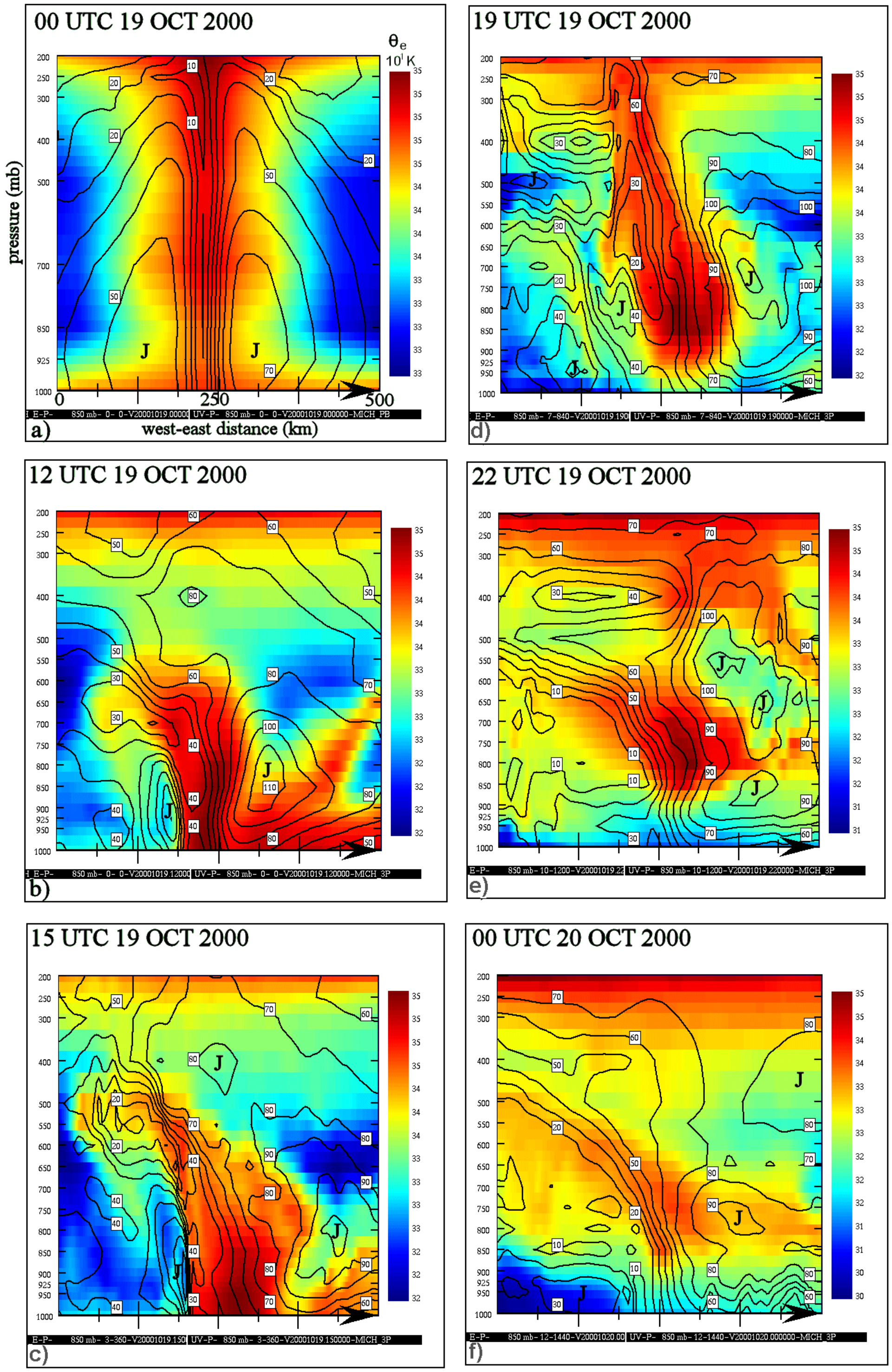

Figure 6. *Time series of simulated vertical cross sections of equivalent potential temperature and wind speed for Hurricane Michael. Equivalent potential temperature is denoted by the colored field and horizontal wind speed magnitude is denoted by solid contours every 10 knots (1 knot = 0.515 m s*$^{-1}$*) from the 3 km control simulation (MICH3) at selected times during extratropical transition. The cross sections are taken along a west to east line through the storm center. Panel (a) shows the structure of the synthetic vortex at 00/19.*