4C.8 INVESTIGATING THE ROLE OF THE UPPER LEVELS IN TROPICAL CYCLOGENESIS

John Sears[1] and Christopher Velden
University of Wisconsin - Cooperative Institute for Meteorological Satellite Studies (CIMSS) Madison, WI

1. INTRODUCTION

Tropical cyclone genesis (TCG) remains difficult to forecast for a number of reasons: 1) The interaction between organizing convection associated with pre-TCG systems and the surrounding 3-dimensional environmental flow fields are less understood compared with mature TCs, in part due to the relative lack of routine reconnaissance aircraft data and dedicated TCG research campaigns; 2) Competing theories for the fundamental processes that transform a stochastic cluster of thunderstorms into an organized TC (Tory and Frank, 2010); and 3) TCG has traditionally not been well handled by numerical models.

TCG was the focus of an NSF-sponsored Atlantic field experiment in 2010 called PREDICT (PRE-Depression Investigation of Cloud systems in the Tropics), which was designed to study pre-depression systems and test TCG hypotheses. PREDICT builds on NASA's TCSP (Tropical Cloud Systems and Processes Experiment, Halverson et al., 2007) conducted in 2005 by adding new TCG cases to study, and also by sampling non-developing systems. The primary focus of PREDICT was to observe and better understand the lower-tropospheric marsupial pouch theory processes (Dunkerton et al., 2008; Montgomery et al., 2006). The role of the upper-levels in TCG is uncertain for pre-depression systems, as it has received very little attention in the literature. TCG forecasting (Schumacher et al., 2009; Tory et al., 2007) and pouch diagnostics tend to downplay upper-level conditions aside from vertical wind shear (Bell and Montgomery, 2010).

In this study we employ the collected PREDICT observations along with enhanced satellite datasets to examine the characteristics and potential influence of the upper-tropospheric flow in the near-storm environment prior to and during TCG. Using various analysis techniques that rely heavily on enhanced satellite-derived wind products and dropwindsonde observations, we show that in certain situations the upper-tropospheric environmental conditions may play an important role in the TCG process.

2. DATA SETS

The datasets and analyses employed in this study are derived from several sources, some of which were a result of the PREDICT field campaign. Satellite-derived atmospheric motion vectors (Velden et al. 2005), produced by UW-CIMSS, are used extensively both as observations and integrated into 3-dimensional analyses. The vectors are assimilated by a recursive filter objective analysis using global model background fields, with heavy weight given to the satellite wind observations. Fields of U and V wind components at 1 degree resolution are produced at hourly intervals during PREDICT, but this study uses only 6-hourly datasets to reduce serial correlation between analyses. The domain used for the 502 pouch track locations analyzed in this study is 10°N to 50°N and 120°W to 20°W, running from 00UTC on July 16th 2010 to 18UTC on Sept. 20th 2010.

Dropwindsonde data from the G-V aircraft during PREDICT are first used to verify the quality of the CIMSS satellite-derived wind

---

Corresponding author: John Sears
E-mail: john.sears@ssec.wisc.edu

vectors and analyses. A separate validation study (Sears and Velden, submitted to JAMC) finds that the satellite-enhanced analyses compare quite favorably to the dropwindsonde observations, providing faith to employ the CIMSS satellite-derived winds and analyses more extensively.

The dropwindsondes are also included in storm-relative 3-Dimensional variational analyses produced by the New Mexico Technical University (NMTU) for selected cases centered on GV missions during PREDICT. These high spatial resolution analyses allow for a more precise and detailed study of the upper-level flow structure and evolution for our selected case studies.

Finally, GFS analysis fields are used to initialize the University of Wisconsin Numerical Model Simulations (UW-NMS) regional model to compute isentropic analyses. A diagnostic variable called Inertial Available Kinetic Energy (IAKE) is produced and offers insight into inertial stability characteristics along outflow trajectories (Mecikalski and Tripoli, 1998). IAKE values are generally negative and should only approach zero when environmental winds present weak inertial stability in relation to convective plumes. It can be viewed as a horizontal analog for CAPE, where high CAPE is representative of available buoyant energy (buoyant instability), and high IAKE is representative of available inertial energy (typically from low inertial stability).

The pre-TCG cases examined in this study were tracked (courtesy of Mark Boothe of the Naval Postgraduate School) by manually identifying lower-tropospheric “Pouches“ that are embedded in North Atlantic easterly waves in NWP global model fields (Wang et al. 2010). Pouch centers were identified in 00z runs from analyses of four models: ECMWF, GFS, NOGAPS and UKMET. Linear interpolation was then used to create positions for the 6-hourly analyses investigated in this study.

3. RESULTS

3.1 *Composite Analyses*

Composite analyses (21x21 degree pouch/disturbance-centered boxes at 6 hr intervals derived from the CIMSS wind analyses) of upper-level divergence were broken into three categories: the 36-hours period prior to TCG, non-developing systems, and already-developed (TD or greater) systems. The dominant category is the non-developed systems, representing 60% of all pouches in our sample. Correspondingly, the 36-hours-before TCG category constitutes 15% of the dataset, leaving 25% to be represented by TCs in the already-developed category. Thirteen of the 35 systems achieved TD or greater intensity in this dataset, representing 37.1% of pouches during the PREDICT period in 2010. Systems ceased to be followed upon hurricane declaration by the NHC; therefore, ‘already-developed systems represent entirely TD or TS systems, although some continued on to hurricane intensity, while others subsequently made landfall or weakened due to other adverse conditions.

Composite divergence analyses for the full dataset and the 3 sub-categories were created for the primary upper levels: 150hPa, 200hPa, 250hPa, and 300hPa. Associated composite Lagrangian wind fields were also derived. The 200hPa composite analyses for the 36hrs prior to TCG (Fig. 1b), and non-developers (Fig. 1a) are quite revealing. The developing analysis shows a swath of strong divergence in excess of $8x10^{-6}$ s^{-1} from the southwest to the northeast quadrants, a feature only weakly present in non-developing cases in the southwest quadrant. The accompanying wind fields suggest these divergence “arms” represent outflow channels to the environment. Developing cases also have a stronger divergence maximum near the center relative to the non-developers; a feature that is also found in the other levels (not shown).

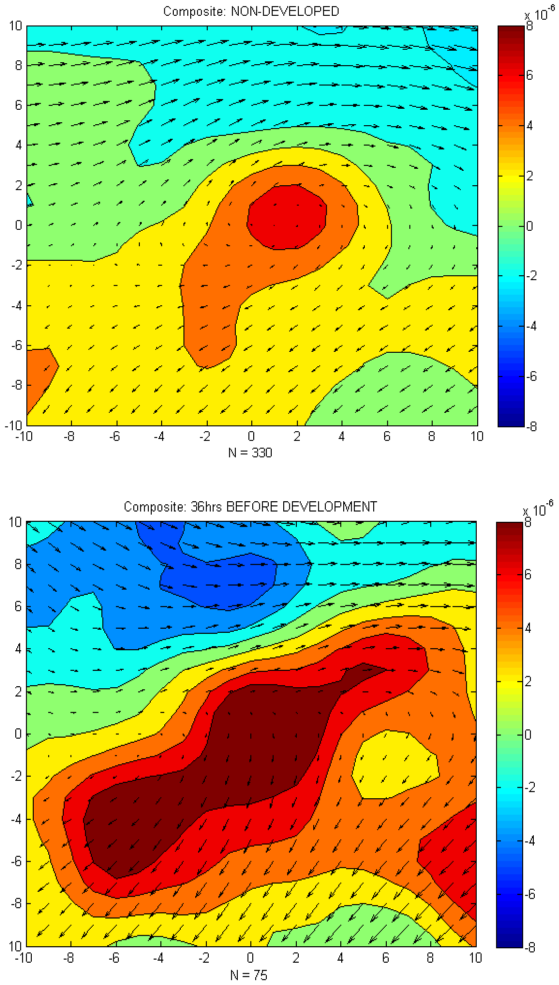

Figure 1. Composite, pouch-centered divergence analyses [color fill, s^{-1}] and Lagrangian wind vectors at 200hPa for a) non-developing pouches, and b) the 36 hour period before TCG.

Is the enhanced divergence aloft over the developing sample simply a response to more convectively-active pouches? Understanding the complex relationship of the ambient upper level environment and persistent convective activity associated with an organizing disturbance is difficult, since some of the upper-level divergence (particularly over the pouch) is naturally driven by the convection itself. However, weak inertial stability may have a role in its horizontal extent, and it is hypothesized that a pre-existing favorable ambient upper-level divergent environment can promote the expansion of the convectively-driven divergence through outflow ducts that eventually link up with environmental flow to vent the mass well away from the developing storm's secondary circulation.

We further hypothesize that this linkage typically occurs 1-2 days prior to TCG. This is supported by a storm-centered composite analysis of upper-level horizontal mass flux at 10 degree radius, as a function of time to TCG, for all 13 developing cases (Fig. 2). The analysis clearly shows a maximum that develops at this outer radius in the ~40hrs before TCG.

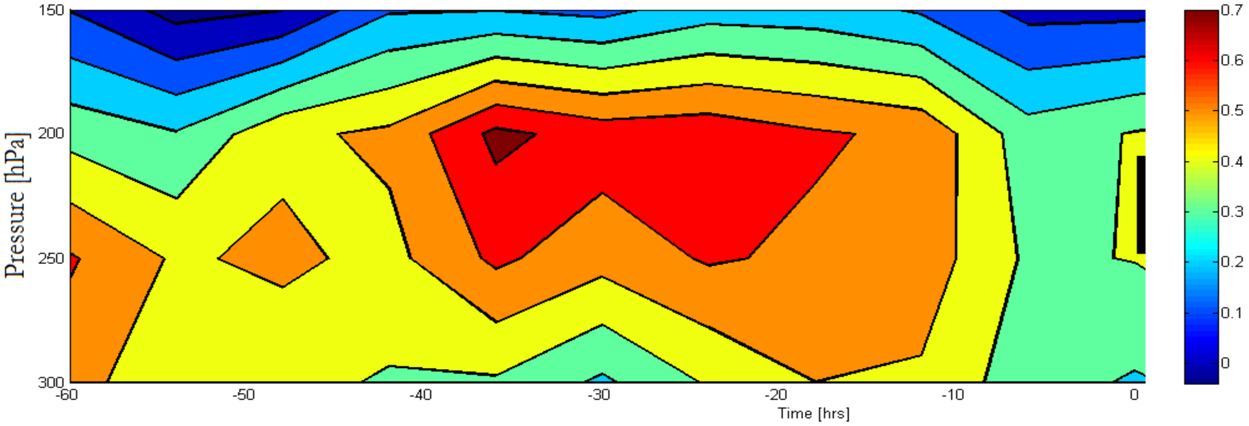

Figure 2. Genesis-time-relative x-section of composited upper-level, radially-averaged horizontal mass flux [kg/m^2s] for the 13 developing cases in our sample. Time 0 = genesis time, and negative time values indicate pre-genesis.

3.2 *Example Case Study*

An event that occurred during PREDICT and best illustrates the concepts and observations forwarded in this study is TC Karl. Pre-TCG Karl was an example of “all systems go” in terms of low-level pouch characteristics, but despite model and official forecasts to strengthen, the system took 5 days to finally achieve TCG.

A significant periodic pulsing is evident in the inner radii (3 degrees) 200hPa horizontal fluxes calculated from the satellite-enhanced wind analyses in the 3-4 days leading up to TCG on Sept. 14th (Fig. 3). This pulsing appears to be associated with diurnally forced inner pouch convection cycles. However the mass flux at the outer radii (10-degrees) doesn’t increase significantly until 13th, coinciding with an earlier maximum on the 13th at the 3 degree radius. This coupling of strong inner and outer mass flux observations reflects the signature of an outflow channel being established to the environment, which is also supported by the satellite-derived winds (Fig. 5). TCG occurred 24-hrs after this linkage.

Further evidence of this linkage is provided in Fig. 4, which shows vertical profiles of quantities based upon the 3-D variational objective analyses (López and Raymond, 2011). These analyses show the trends over the 4-day period leading up to TCG. On Sept. 10th, about 4 days before TCG, there is weak upper-level outflow evident, but it is restricted to the middle radii and short-lived, as by Sept 12th, there is no dominating flux signal aloft (Fig. 4 bottom). However, the outward flux picks up on the 13th, about 24-30hrs before TCG, and extends from the center out to 10 degree radius. This signal persists on the 14th when TCG takes place.

Figure 4 (middle) shows the matching vertical motion profiles during this period. Note the deterioration of subsidence adjacent to the system core (5-10 degrees radius) that slowly gets eroded as the outflow develops. This suggests that the establishment of outflow not only acts to ventilate mass, but at the same time directs the subsiding branch of the system’s developing secondary circulation well away from the pouch core, thereby diminishing locally-produced subsidence and dry air which could hinder sustained inner core convection. The radially averaged tangential wind analyses (Fig. 4 top) show the growth of the vortex during the analysis period. Once the upper-level anticyclone aloft develops, the lower vortex grows in height, eventually reaching 11-12km. This spin-up is identified in the pouch hypothesis as a crucial mechanism for genesis, but in this case it would appear the process is modulated by the ventilation characteristics in the upper levels, allowing the transition of the convection from pulsating to persistent in nature.

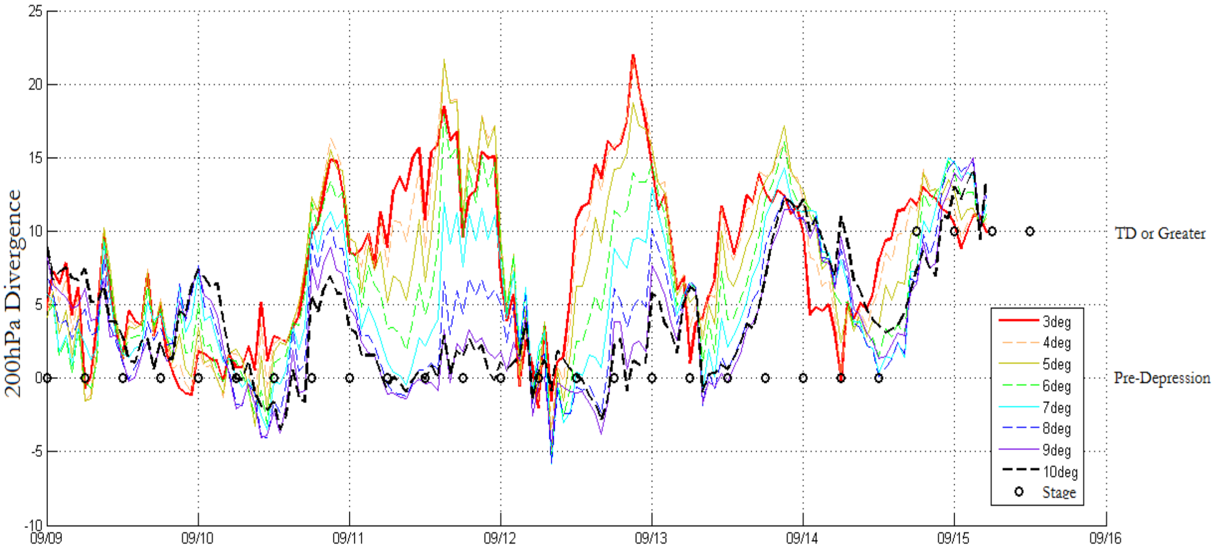

Figure 3. A time-series of radially averaged horizontal mass flux [kg/m^{2}s] at 200hPa at various radii from the pouch center for pre-TCG Karl. Dots indicate TCG on Sep. 14th, 12 UTC.

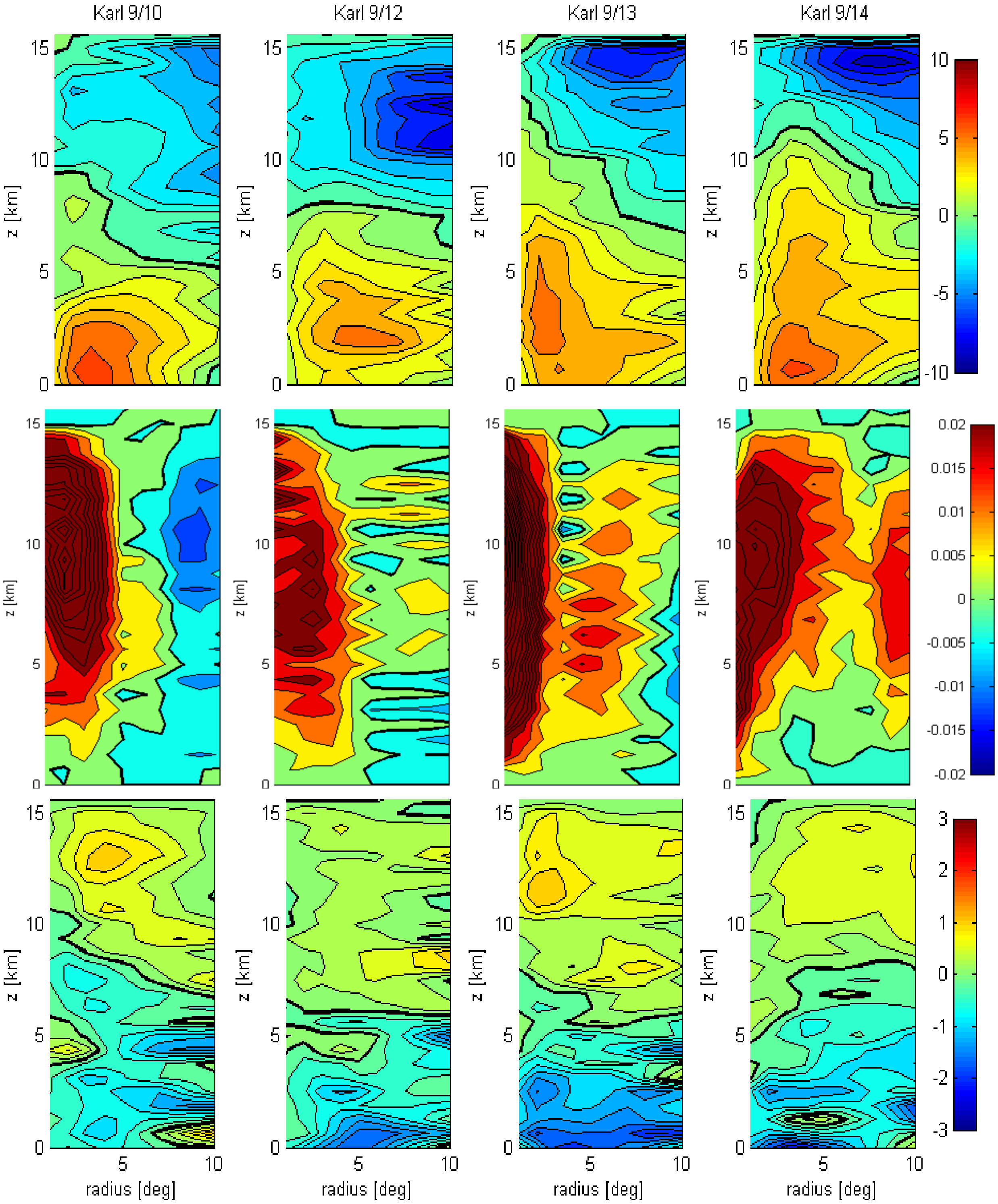

Figure 4. Vertical profiles at various radii from pre-TC Karl of: top) radially averaged tangential wind flux, middle) radially averaged vertical motion, and bottom) radially averaged horizontal mass flux.

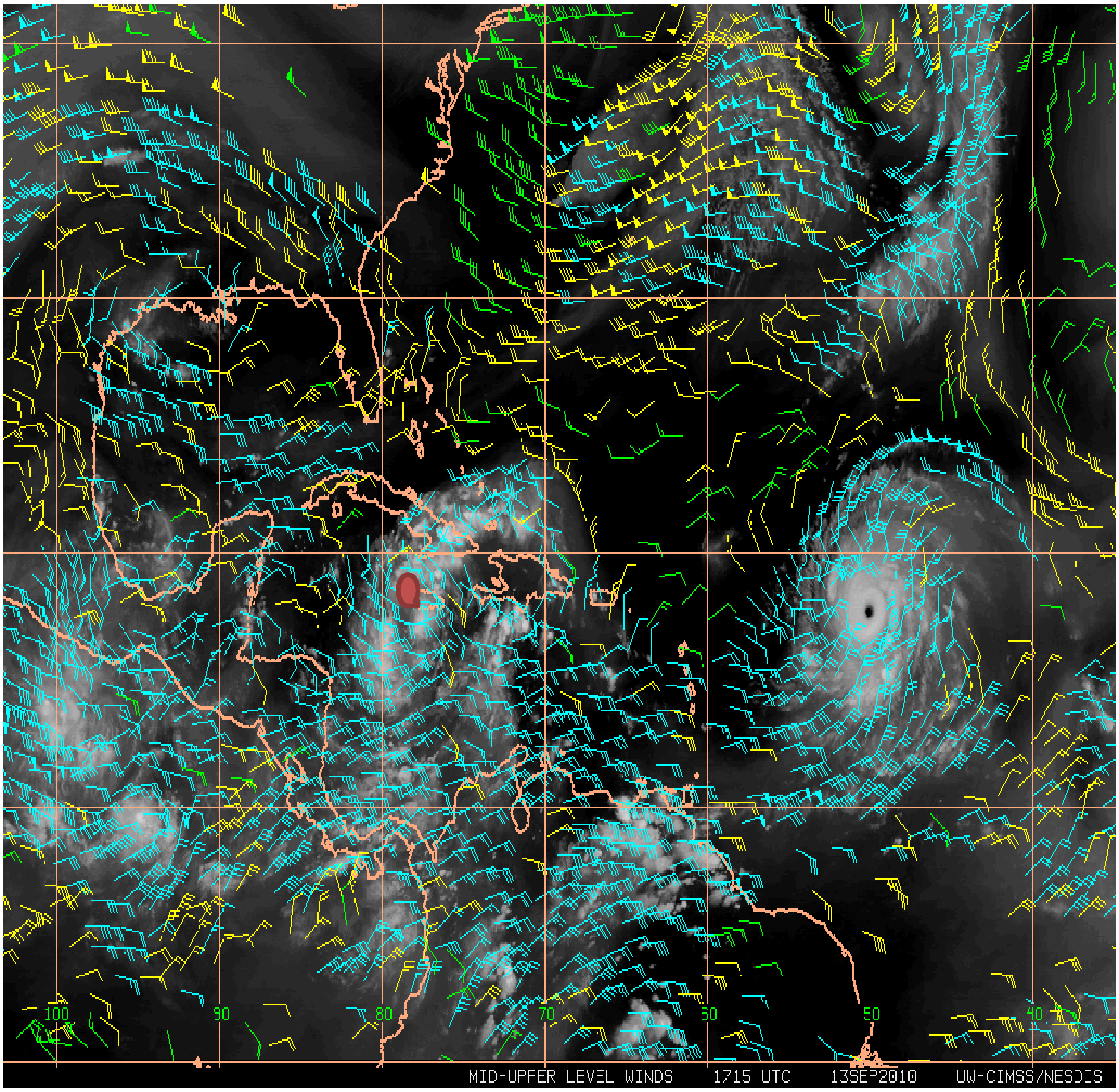

Figure 5. Upper-level (150-500hPa) satellite-derived winds overlain on GOES WV imagery for pre-TCG Karl on Sept. 13th at 1715 UTC. Vectors (kts): Cyan 150-250hPa, Yellow 251-350hPa, Green 351-500hPa. Red dot is pre-TCG Karl pouch position at 12 UTC.

Finally, the trends in IAKE also support the developing favorable environment over the pre-TCG Karl period. The IAKE analysis for the 11th at 12Z features a weakly positive or neutral signal near the storm core at 355K (Fig. 6 top), with a ribbon of low IAKE just to the north associated with a narrow, weak PV streamer also evident in the water vapor imagery at this time. As the PV streamer weakens and moves off to the northeast, it allows for a region of higher IAKE mainly to the east and northeast to settle in over the storm by the 13th at 12Z (Fig. 6 bottom). This encourages the establishment of the outflow before TCG about 24 hours later.

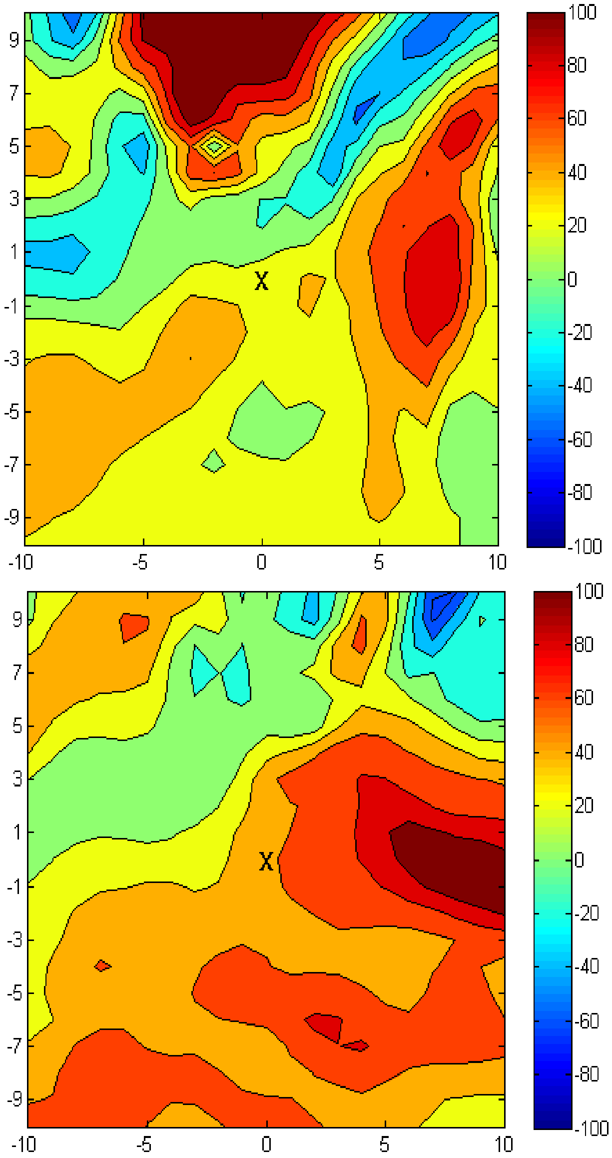

Figure 6. Storm-centered IAKE [m^2/s^2, colored analysis] on the 355K surface at: top) 12 UTC, Sept. 11th, and bottom) 12 UTC, Sept. 13th.

4. DISCUSSION

This study emphasizes the flow patterns and thermodynamic conditions in the upper levels between developing and non-developing systems, identifying upper–tropospheric flow regimes specific to enabling the establishment of outflow and mass evacuation. We find upper-level conditions that promote the establishment of outflow channels that are connected to the environment appear to be important in some cases to allow the TCG processes to flourish. Upper-level IAKE analyses point to regions of low inertial stability, providing “soft spots” for potential mass evacuation from intense core convection. The low inertial stability means less work needs to be done by the evacuating mass as it spreads horizontally upon reaching the tropopause. This allows for a greater acceleration away from the inner core secondary circulation, and once linked to environmental flow, provides an effective “mass transit” from the developing low-level disturbance. In turn, higher mass evacuation promotes a lowering of the surface pressure as well as helping to maintain the secondary circulation driving (and sustaining) the pouch convection.

The establishment and pattern of these outflow channels is strongly dependent on ambient and evolving upper-tropospheric environmental conditions. There are several variations on efficient outflow patterns relative to the pouch center; the most common type being multiple channels to the north turning northeast and south turning southwest. The northern channel setup is often aided by upper level troughs in the westerlies that feature southwest flow ahead of them that can help link the developing pouch system outflow to the environment. Divergent patterns in the upper levels of the ITCZ can similarly help establish channels for outflow to the south. Unfavorable environments are the kind that beset other PREDICT cases, such as ex-Gaston, despite favorable low-level pouch conditions. Or during TS Fiona, where the developing dominant outflow channel was disrupted by converging outflow (and eventually strong vertical wind shear) from nearby Hurricane Earl. Dynamic structures such as these can modify the disturbance’s ambient environment and aid or inhibit the upper level branch of the secondary circulation trying to develop. The ventilation of heat/mass away from the core may also prevent core stabilization, a theory promoted by Merrill (1988) in intensifying TCs.

We recognize the symbiotic nature of upper-level divergence driven by vigorous convection and that associated with larger-scale patterns is often difficult to separate. There will indeed be cases when the pouch processes and forcing are the predominant mechanisms in TCG, and in these events the disturbances may well dictate their own upper-level environments. However, examination of the time evolution of the upper-level mass flux patterns in many cases suggests that the ambient conditions preceding the disturbance (and associated convective component) can play a major factor in the overall ability of the pouch processes to flourish. Although the case-by-case configuration of outflow may vary, enhanced mass flux through organized outflow is shown to be associated with sustaining the inner core deep convection in developing tropical cyclones.

This work does not attempt to represent, infer or suggest a new perspective on “top-down” genesis, but serves to emphasize the role of the upper levels as a potential facilitator for TCG forcing processes that occur below 500hPa. Our study indicates that upper-tropospheric conditions may sometimes regulate those processes, and in some cases unfavorable configurations can act to suppress TCG in promising pouch systems, along with other well-known environmental factors such as strong vertical wind shear, dry-air entrainment, or cold sea surface temperatures.

The findings in this study are not to be considered conclusive or globally applicable given the limitations of the short Atlantic-based dataset studied, but are significant for a number of reasons. Primarily, while the process of TCG should continue to focus on convective forcing mechanisms and generation of vorticity, it is shown the upper level flow environment can provide a modulating effect and should not be ignored. Future research should include the use of idealized high-resolution TC modeling studies where trajectory analyses can be used to track the behavior of core parcels as they engage in amalgamated VHT activity before eventually emerging at upper levels and emanating into the outflow.

References

Bell, M. M., and M. T. Montgomery, 2010: Sheared deep convection in pre-depression Hagupit during TCS-08. *Geophys. Res. Lett*., **37**, L06802, doi: 10.1029/2009GL042313.

Dunkerton, T. J., M. T. Montgomery, and Z. Wang, 2008: Tropical cyclogenesis in a tropical wave critical layer: Easterly waves. *Atmos. Chem. Phys. Disc*., **8**, 11,149-11,292.

Halverson, J., and Coauthors, 2007: NASA's Tropical Cloud Systems and Processes Experiment. *Bull. Amer. Meteor. Soc.*, **88**, 867–882.

López Carrillo, C. and Raymond, D. J., 2011: Retrieval of three-dimensional wind fields from Doppler radar data using an efficient two-step approach, *Atmos. Meas. Tech.,* 4, 2717-2733, doi: 10.5194/amt-4-2717-2011.

Mecikalski, J. R., and G. J. Tripoli, 1998: Inertial Available Kinetic Energy and the Dynamics of Tropical Plume Formation. *Mon. Wea. Rev.*, **126**, 2200–2216.

Merrill, R. T., 1988: Characteristics of the Upper-Tropospheric Environmental Flow around Hurricanes. *J. Atmos. Sci.*, **45**, 1665–1677.

Montgomery, M. T., M. E. Nicholls, T. A. Cramm, and A. Saunders, 2006: A vortical hot tower route to tropical cyclogenesis. *J. Atmos. Sci*., **63**, 355-386.

Schumacher, A. B., M. DeMaria, and J. A. Knaff, 2009: Objective Estimation of the 24-h Probability of TC Formation. W*ea. Forecasting*, **24**, 456–471.

Sears, J., and C. Velden, 2012: Tropical Validation of Satellite-Derived Atmospheric Motion Vectors*. J. Appl. Meteor. Climate. (submitted)*

Tory, K. J., N. E. Davidson, M. T. Montgomery, 2007: Prediction and Diagnosis of Tropical Cyclone

Formation in an NWP System. Part III: Diagnosis of Developing and Nondeveloping Storms. *J. Atmos. Sci.*, **64**, 3195–3213.

Tory, K. J., and W. M. Frank, 2010: Tropical cyclone formation. Chap. 2 Global Perspectives on Tropical Cyclones: From Science to Mitigation. World Scientific, Singapore, 55-91.

Velden, C., and Coauthors, 2005: Recent Innovations in Deriving Tropospheric Winds from Meteorological Satellites. *Bull. Amer. Meteor. Soc*., **86**, 205–223.

Wang, Z., M. T. Montgomery, T. J. Dunkerton, 2010: Genesis of Pre–Hurricane Felix (2007). Part I: The Role of the Easterly Wave Critical Layer. *J. Atmos. Sci.*, **67**, 1711–172.