Understanding the thermodynamic evolution of the tropical cyclone warm core during the extratropical transition process

Clark Evans and Bob Hart

Florida State University
Department of Meteorology
What brings about the warm-to-cold thermal transition as a tropical cyclone (TC) undergoes extratropical transition (ET)?
Why study the thermal evolution?

- Thermal structure a key determining factor of cyclone intensity and overall structure
  - Hart et al. (2006) – cold-core versus warm seclusion cyclones
  - Evans and Hart (2008) – cooling inside radius of maximum winds (RMW) leads to its outward movement

- Significant heat energy transport directly or indirectly affects many larger-scale features
  - Impacts upon hemispheric weekly to seasonal weather patterns (e.g. McTaggart-Cowan et al. 2007, Hart 2009)
  - Maintenance or restoration of atmospheric balances
  - Implications toward global energy balance

- Relatively little comprehensive study has been performed upon the topic to date
Main work: Sinclair (1993)
- Thermodynamic budget of ETing S. Pacific TC Patsy (1986) using 2.5° ECMWF analyses
- Diabatic heating (convective heating early, saturated ascent late) almost exactly offset by adiabatic cooling
- Horizontal advection suggested to drive evolution with net cooling due to translation into a colder environment

Other works:
- McTaggart-Cowan et al. (2003, 2004): suggest horizontal advective processes important with preferred advection patterns between the polar jet and TC
- Hart et al. (2006), Evans and Hart (2008): hypothesize about role of adiabatic cooling in observed evolution
Methodology

- Case study analysis: North Atlantic TC Bonnie (1998)
  - Benign cold-core ET
  - No merger, post-ET reintensification, or land interaction

- Analysis method: numerical modeling
  - Used MM5 V3.7.4
  - 36/12/4 km, 30 half-sigma levels
  - 1200 UTC 28 Aug.-1200 UTC 31 Aug. 1998 (before to after ET)
  - Output frequency: 15 minutes
  - Model evolution found to be qualitatively similar to observations (not shown)
Budget Formulation

- Directly obtained thermodynamic time tendency terms (Dudhia 1993) from MM5 during execution:

\[
\frac{\partial T}{\partial t} = - \mathbf{v} \cdot \nabla T + T (\nabla \cdot \mathbf{v}) + \left. \frac{\partial T}{\partial t} \right|_{\text{parameterizations}}
\]

where “parameterizations” accounts for tendencies due to PBL, convective, shallow cumulus, radiational, diffusive, and microphysical processes.

- All terms are directly obtained from MM5 integration every 15 simulated minutes
  - No residuals: all terms are directly computed, including the parameterized terms
  - Uses native model data for analysis, but only as accurate as the model is itself!

- Budgets computed in native model coordinate system following the storm, focusing within 500 km radius
  - Dynamical components: advective and divergence terms (three in total)
  - Physical components: all parameterized terms (six in total)
Evidence of Cooling

Significant cooling observed starting early in the ET process

- ≈10 K day$^{-1}$ maximum along radial band (within 100 km)
- ≈2 K day$^{-1}$ average within 500 km radius
- Primarily observed within the expanding RMW (‘inner’ core)
Net cooling a superposition of opposing factors

Dynamical (parameterized) components produce significant net cooling (warming) at increasingly large radii

Averaged: dynamical: ~8-11 K day$^{-1}$, parameterized: ~6-8 K day$^{-1}$

What are the contributing factors to these fields?
Dynamical Contributors

- Amalgam of opposing factors observed...
  - Horizontal advection: significant cooling (warming) in inner (outer) core (left)
  - Vertical advection: significant warming (cooling) in inner (outer) core (right)
  - Divergence: weaker factor; in phase with vertical advection (not shown)

- Implication of hydrostatic balance given canceling effect between the fields
Parameterized Contributors

- Primary contributors: microphysics (left) and radiation (right)
  - Microphysics - phase changes in primary convection/precipitation banding features
  - Radiation - agrees with commonly accepted values and accounts for approx. 50% of total cooling observed

- Radiation only primary parameterized contributor within the ‘inner’ core
Summary Thus Far

- Primary factors in ‘inner’ core: advection and radiation, both accounting for approx. 50% of the observed 3-4 K day⁻¹ cooling
  - Loss of heat to outer space via radiative processes
  - Net horizontal import of cooler air into near-center volume

- Evolution appears to be in hydrostatic balance given near cancelation of the horizontal and vertical advection terms at all radii

- Inner versus outer core evolution seems to be apparent
  - Near-total cancelation seen outside RMW, but net cooling inside
  - Outer core evolution is perhaps a consequence of the structural evolution of the cyclone
    - Parameterized tendencies maximized near radii of convective features
    - Dynamical tendencies maximized near frontal and conveyor belt features
    - Further analysis is needed, however!

- Next, let’s analyze what happens in the region outside the RMW vertically as well as spatially.
Note: 0-500 km averaged fields

- Dynamical contribution is always cooling (~10-15 K day\(^{-1}\)).
  - Maximized: upper troposphere and PBL
  - Components show very similar results to vertically integrated fields (not shown)

- Parameterized contribution is always warming (~10 K day\(^{-1}\)).
  - Maximized: middle troposphere and PBL

- Net cooling intensifies when parameterized contributions weaken
Parameterized Vertical Evolution

Height–Magnitude Azimuthally and Radially Averaged Temperature Tendency, 12 km, 06Z30AUG1998

Sigma Level vs Temperature Tendency (K day⁻¹)
Spatial Budget Structure

-0.944 K day$^{-1}$ 0-500 km Avg.
12 km: Vertically Integrated Total Temperature Tendency (K day$^{-1}$)
Forecast Time: 12Z29AUG1998

-3.612 K day$^{-1}$ 0-500 km Avg.
12 km: Vertically Integrated Total Temperature Tendency (K day$^{-1}$)
Forecast Time: 12Z30AUG1998
Spatial Budget Structure

-10.637 K day^{-1}

**Dynamical**
Horizontal advection outweighs vertical advection and divergence terms.

+9.693 K day^{-1}

**Parameterized**
Microphysical and convective heating processes drive this downstream evolution.

-9.778 K day^{-1}

+6.166 K day^{-1}
Spatial Budget Structure

Spatial pattern is largely driven by two physical features...

- Dynamical components largely tied to conveyor belts that develop within the transitioning cyclone (left)
- Parameterized components largely tied to heating processes in the ‘delta rain’ warm frontogenetical region (right)

- Like the vertical evolution, this primarily captures the outer core thermodynamic factors and their evolution

(Klein et al. 2000, Fig. 5) (Jones et al. 2003, Fig. 12d)
Conclusions

- ET thermal evolution can be partitioned into inner and outer core components...
  - Inner core: net cooling occurs due to horizontal advection and radiational processes
  - Outer core: thermal balance maintained by dynamical factors counterbalancing microphysical and convective tendencies
  - Results are fairly consistent vertically at all radii

- Evolution largely appears to be hydrostatic in nature

- Some agreement with prior works
  - Results closely resemble those of Sinclair (1993) and affirm hypothesis of McTaggart-Cowan et al. (2003, 2004)
  - No evidence noted to support Hart et al. (2006) hypothesis
Conclusions

- ET thermal evolution is driven by larger-scale structural changes within the cyclone
  - Dynamically: conveyor belt development
  - Physically: precipitation and phase change processes within warm frontogenetical delta rain region
  - Loss of surface heat fluxes and latent heat release during ET allows radiative cooling and advective processes to dominate the evolution

- Results raise some questions regarding model predictability...
  - How well can a model represent the timing and intensity of the non-linear interaction between a TC and the trough that causes it to undergo ET?
  - How well can the model represent important convective and microphysical heating processes that provide a "brake" upon the observed cooling during ET?
  - How well can the model represent the processes that occur within the RMW on short wavelengths?
Future Work

- Further refine physical explanations and linkages detailed here
- Analyze sensitivity of results to horizontal resolution (36 vs. 12 vs. 4 km)
- Refine implications toward predictability on all scales
- Sensitivity to post-transition thermal evolution
  - How do warm seclusion events differ from cold-core ones?
- Understand the impacts of the larger-scale thermodynamic evolution
  - What factors modulate poleward heat transport and energy balance and what are their magnitudes?
- Ultimate goal: how does the inner and outer core thermodynamic evolution modulate our weather-climate system as a whole and how well can we capture it?
References


