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

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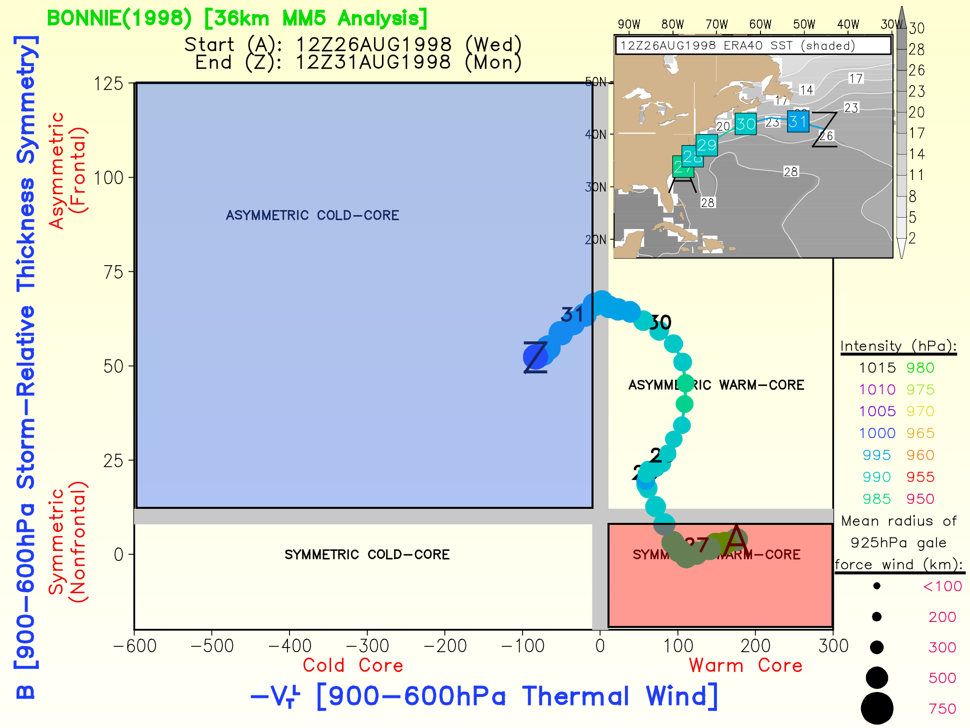
Statement of Research

Displayed: cyclone phase space diagram (Hart 2003) of lower tropospheric thermal wind ($-V_t^L$) versus lower tropospheric thickness asymmetry (B) for North Atlantic TC Bonnie (1998).



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
  - Degradation of model forecasts (Jones et al. 2003, Harr et al. 2008, Anwender et al. 2008)
  - 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

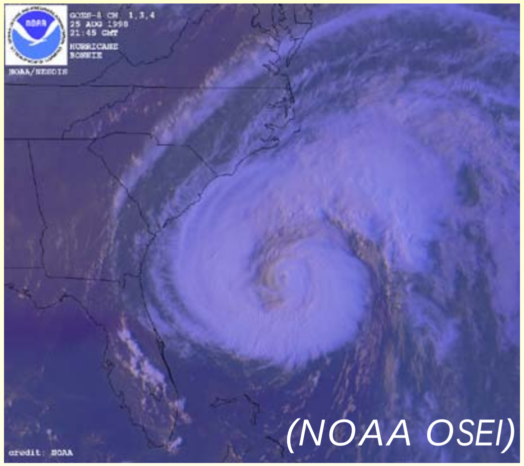
- Relatively little comprehensive study has been performed upon the topic to date

Previous Works and Hypotheses

- 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

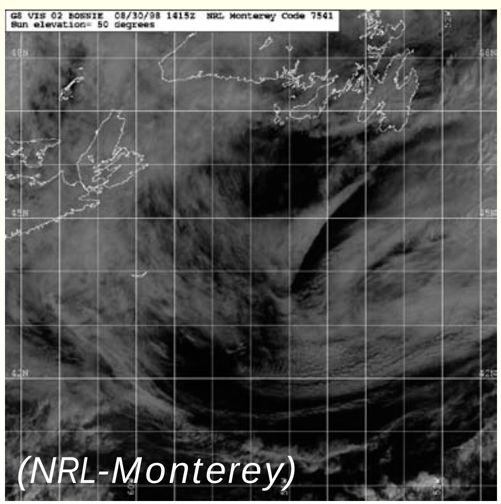
Methodology



(NOAA OSEI)

Peak TC

Near ET



(NRL-Monterey)

- 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:

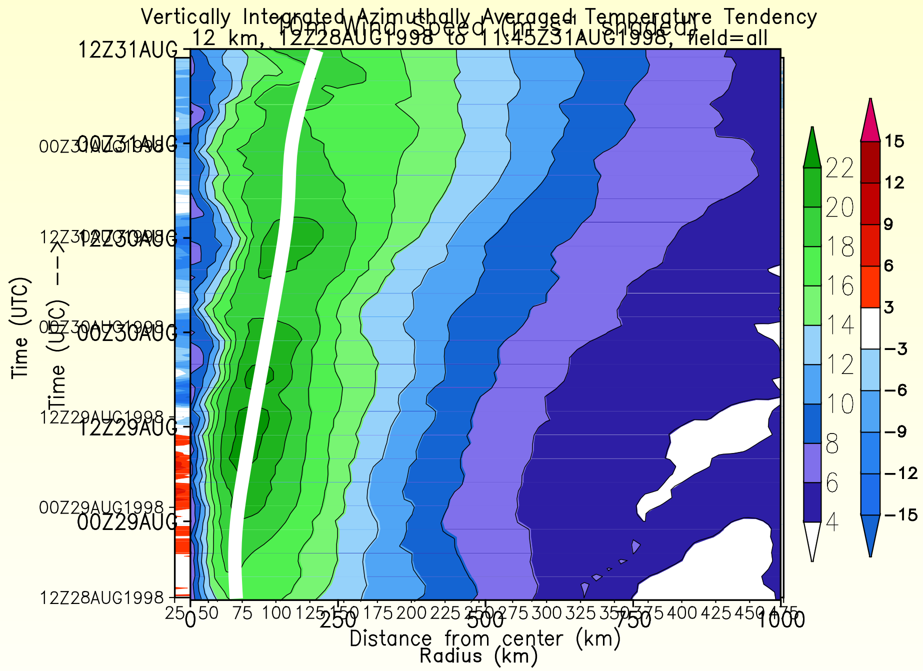
$$\frac{\partial T}{\partial t} = -v \cdot \nabla T + T(\nabla \cdot v) + \left.\frac{\partial T}{\partial t}\right|_{parameterizations}$$

  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

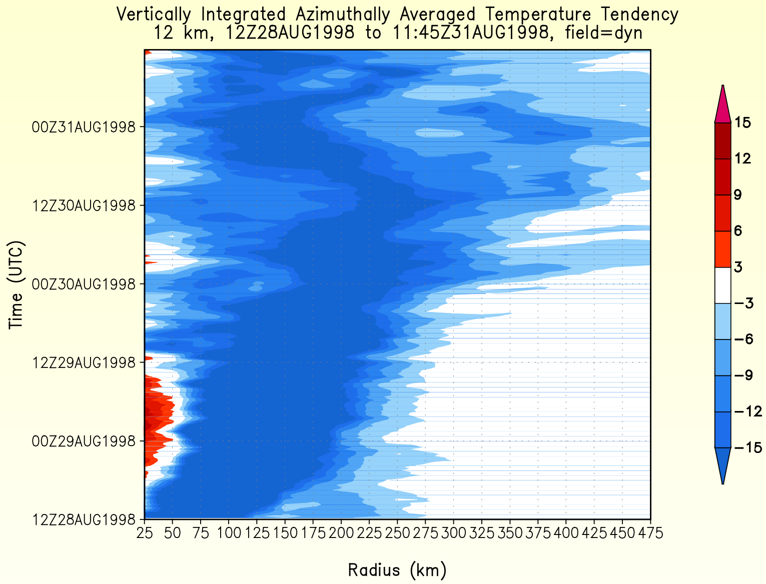


Significant cooling observed starting early in the ET process

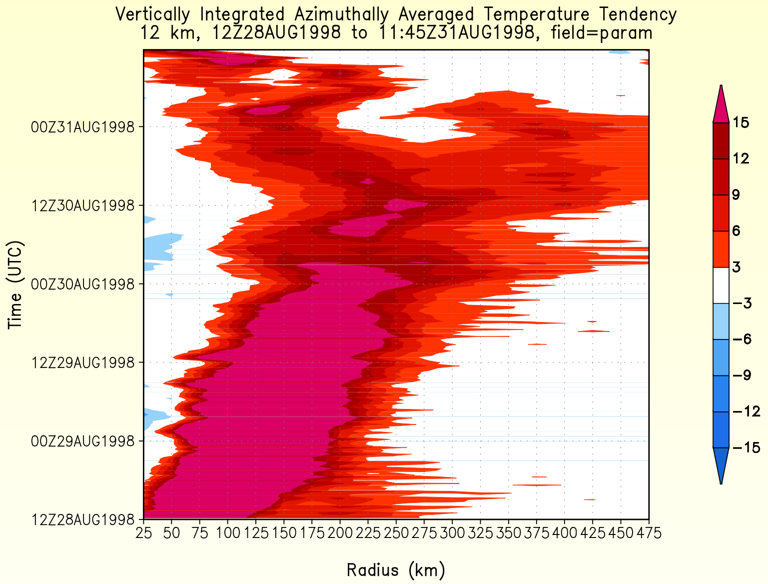
- ~10 K day^{-1} maximum along radial band (within 100 km)
- ~2 K day^{-1} average within 500 km radius
- Primarily observed within the expanding RMW (‘inner’ core)

Contributors to Cooling

Dynamical



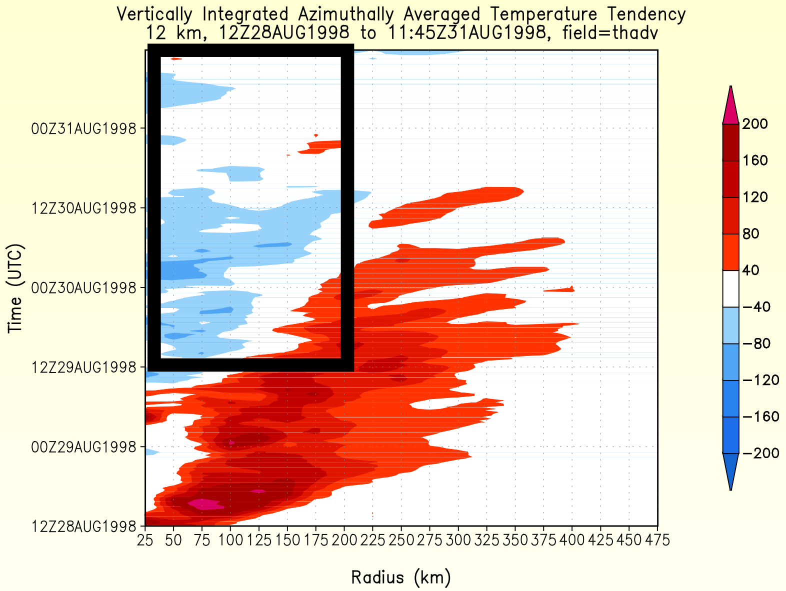
Parameterized



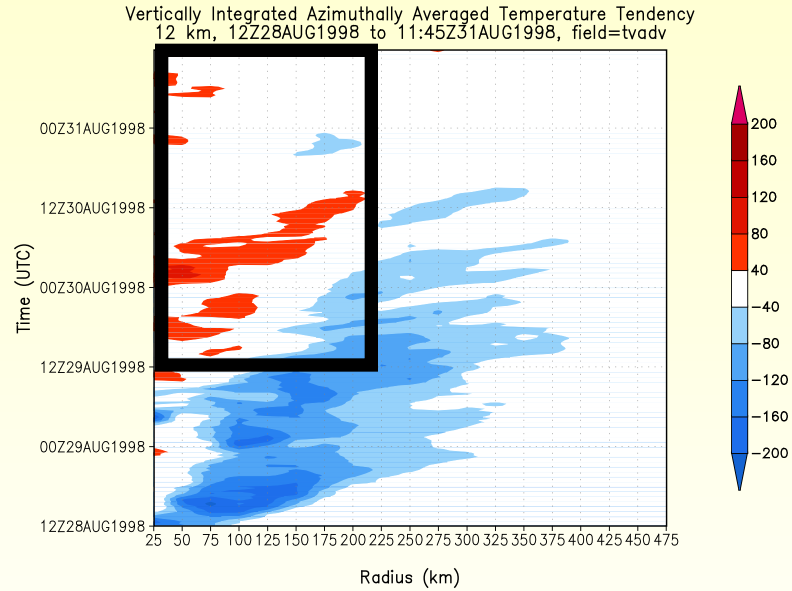
- Net cooling a superposition of opposing factors
- Dynamical (parameterized) components produce significant net cooling (warming) at increasingly large radii
  - Averaged: dynamical: ~8-11 K day^{-1}, parameterized: ~6-8 K day^{-1}
- What are the contributing factors to these fields?

Dynamical Contributors

Horizontal Advection



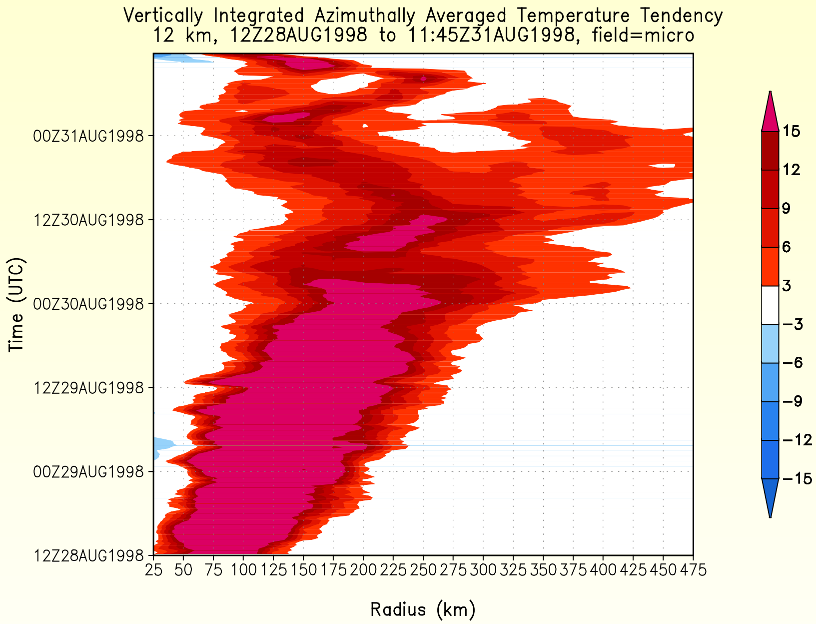
Vertical Advection



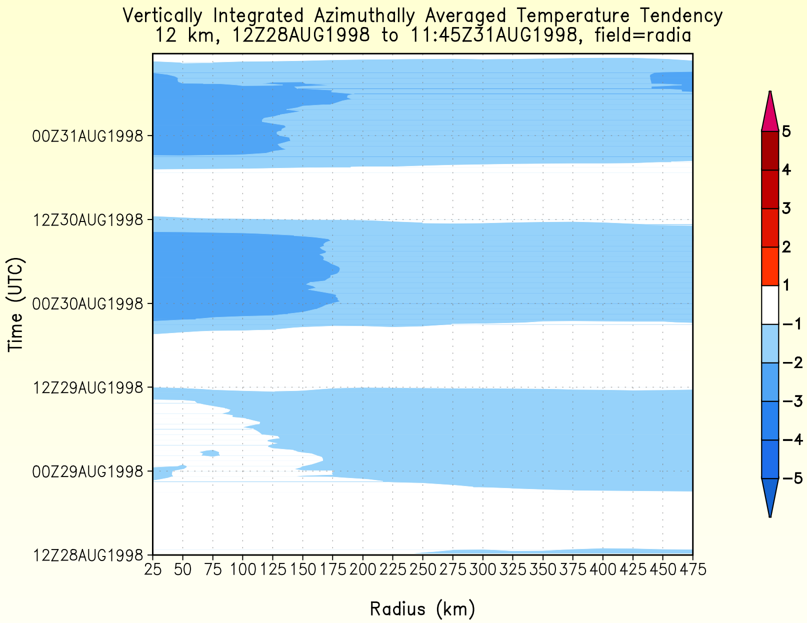
- Amalgam of opposing factors observed…
  - Horizontal advection: significant cooling (warming) in inner (outer) core (left)
  - Vertical advection: significant warming (cooling) in inner (outer) core (right)
  - Divergence: weaker factor; in phase with vertical advection (not shown)
- Implication of hydrostatic balance given canceling effect between the fields

Parameterized Contributors

Microphysics



Radiation



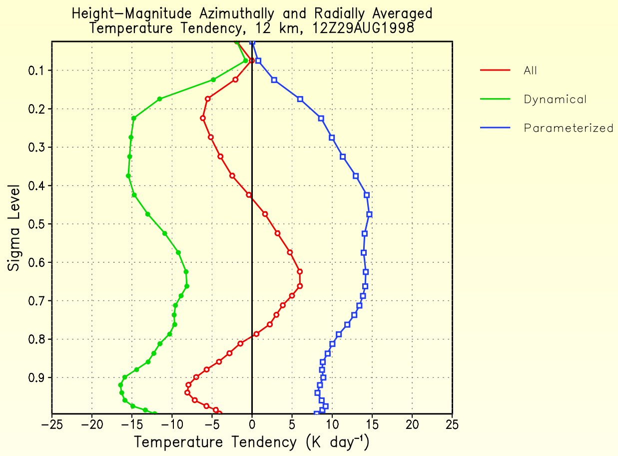
- Primary contributors: microphysics (left) and radiation (right)
  - Microphysics – phase changes in primary convection/precipitation banding features
  - Radiation – agrees with commonly accepted values and accounts for approx. 50% of total cooling observed

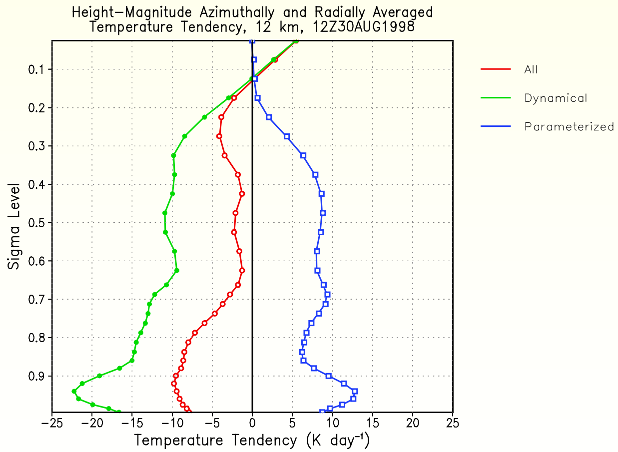
- Radiation only primary parameterized contributor within the ‘inner’ core

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.

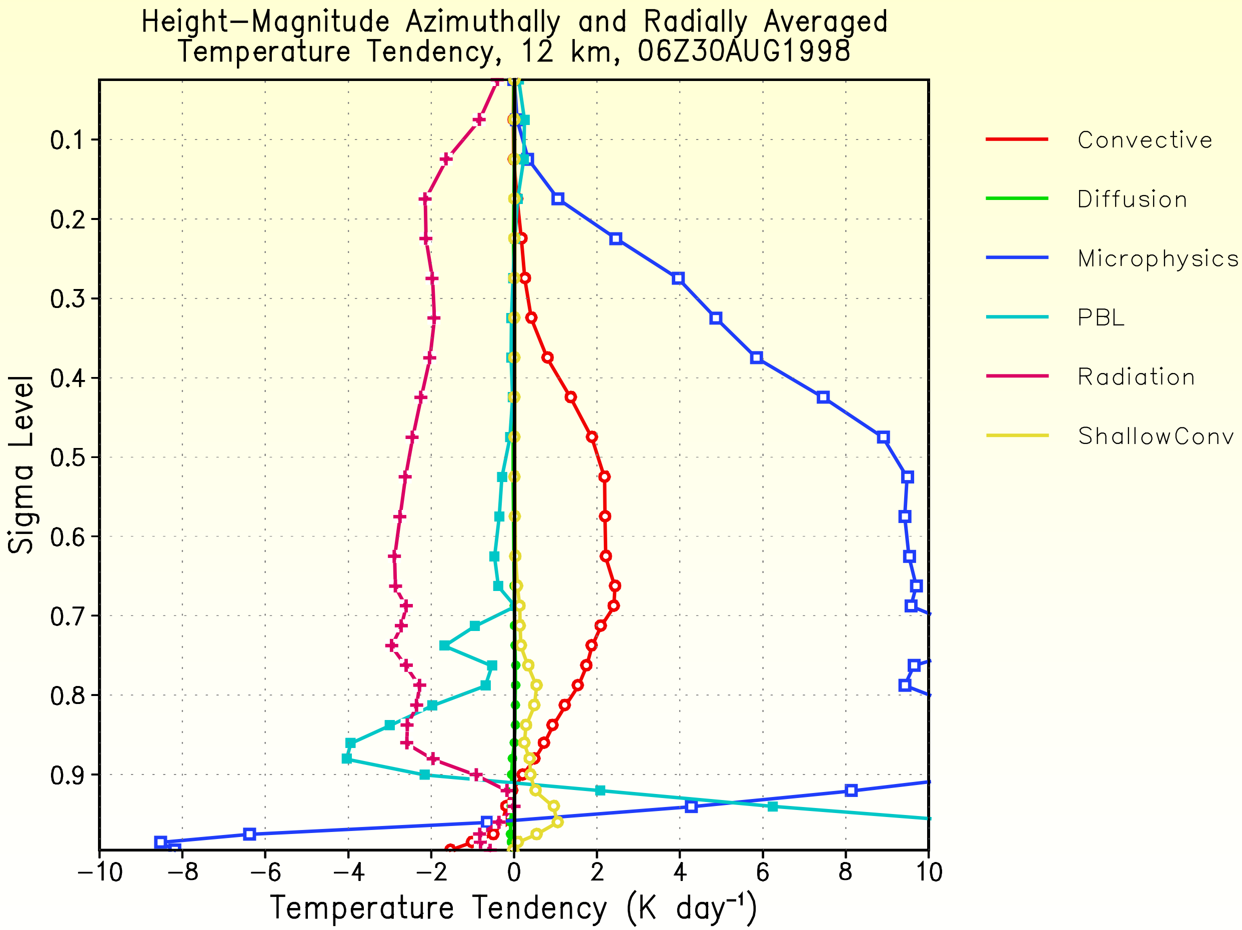
Vertical Budget Structure





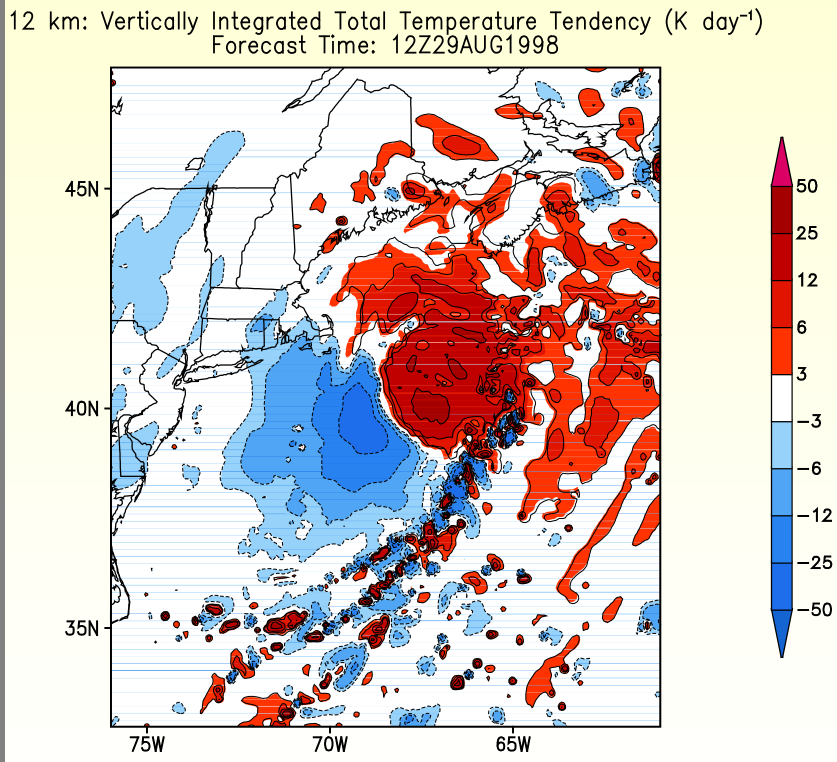
- Note: 0-500 km averaged fields
- Dynamical contribution is always cooling (~10-15 K day^{-1}).
  - Maximized: upper troposphere and PBL
  - Components show very similar results to vertically integrated fields (not shown)
- Parameterized contribution is always warming (~10 K day^{-1}).
  - Maximized: middle troposphere and PBL
- Net cooling intensifies when parameterized contributions weaken

Parameterized Vertical Evolution

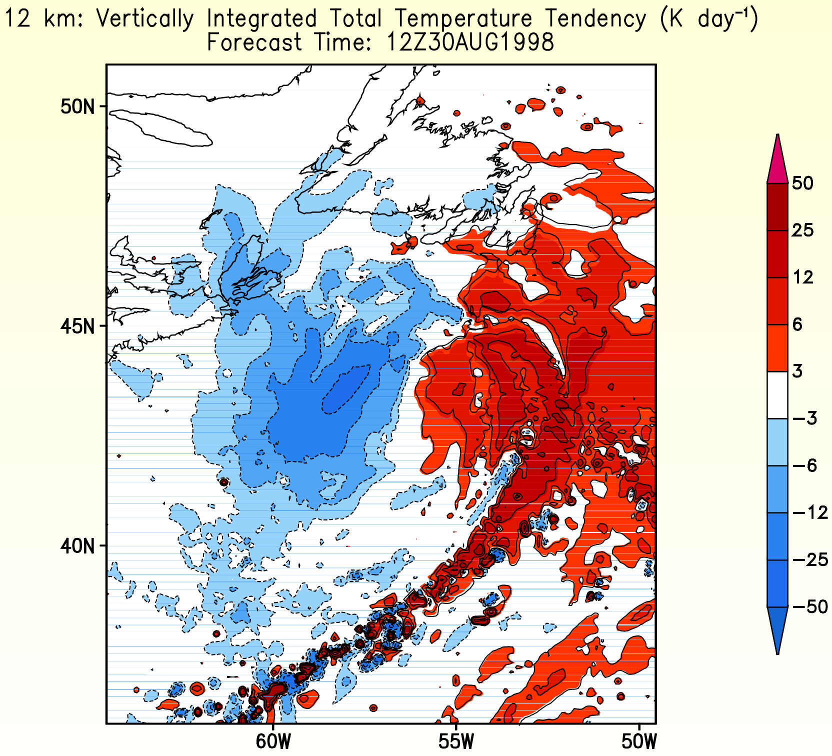


Spatial Budget Structure

-0.944 K day^{-1} 0-500 km Avg.

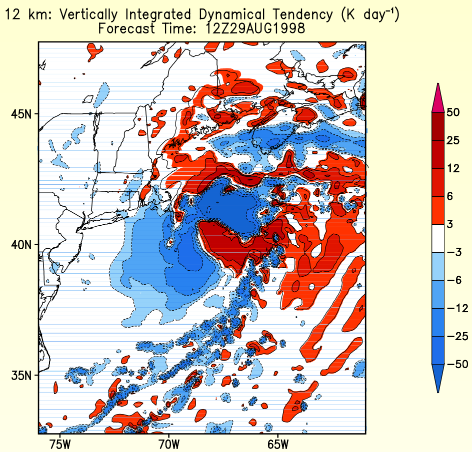


-3.612 K day^{-1} 0-500 km Avg.



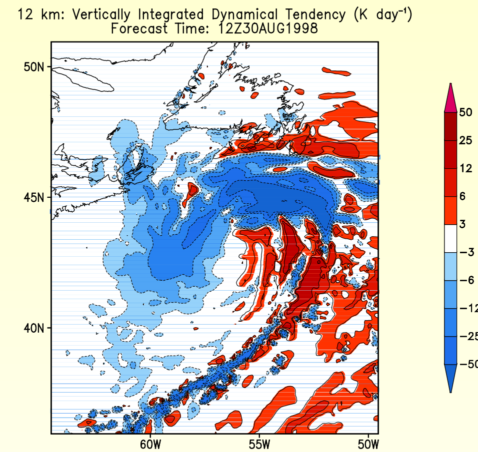
Spatial Budget Structure

-10.637 K day^{-1}



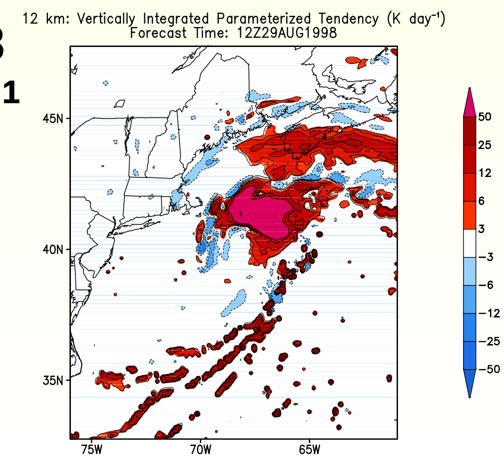
Dynamical

Horizontal advection outweighs vertical advection and divergence terms.



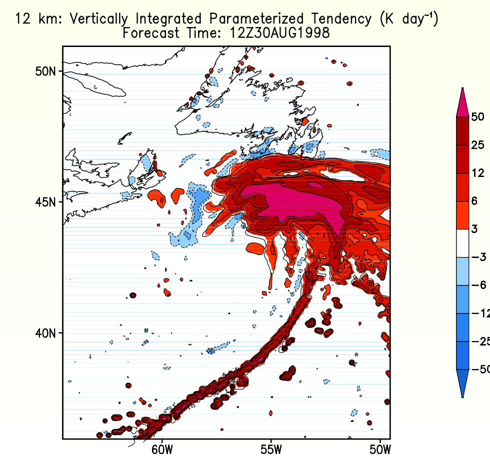
-9.778 K day^{-1}

+9.693 K day^{-1}



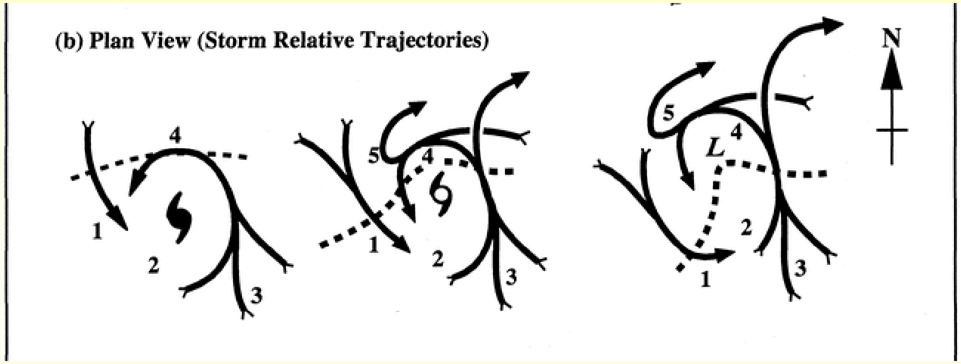
Parameterized

Microphysical and convective heating processes drive this downstream evolution.

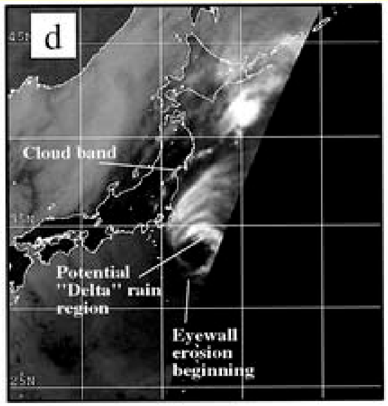


+6.166 K day^{-1}

Spatial Budget Structure



(Klein et al. 2000, Fig. 5)



(Jones et al. 2003, Fig. 12d)

- 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

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

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