The Tropopause Structure of Hurricanes Nadine (2012) and Patricia (2015)

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Introduction and Motivation

- Theoretical models implicate tropopause structure as an important parameter in determining the intensity of tropical cyclones (TCs).
- Until recently, a dearth of upper-level observations in TCs precluded thorough analyses of TC tropopause structure. .
- Two recent field campaigns – the NASA Hurricane and Severe Storm Sentinel (HS3) and the Office of Naval Research Tropical Cyclone Intensity Experiment (TCI) – revealed dramatic spatial and temporal variability of the tropopause in TCs.

Hurricane Nadine (2012)

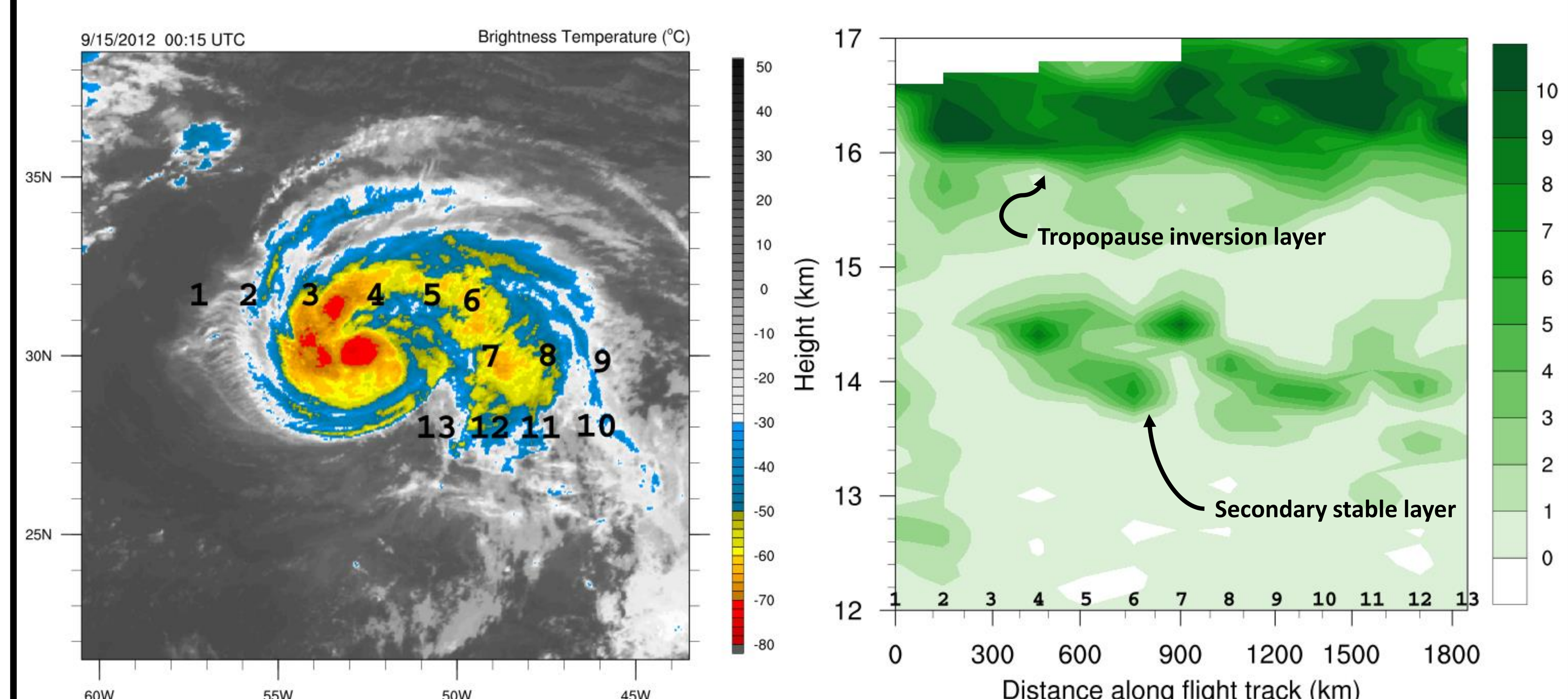
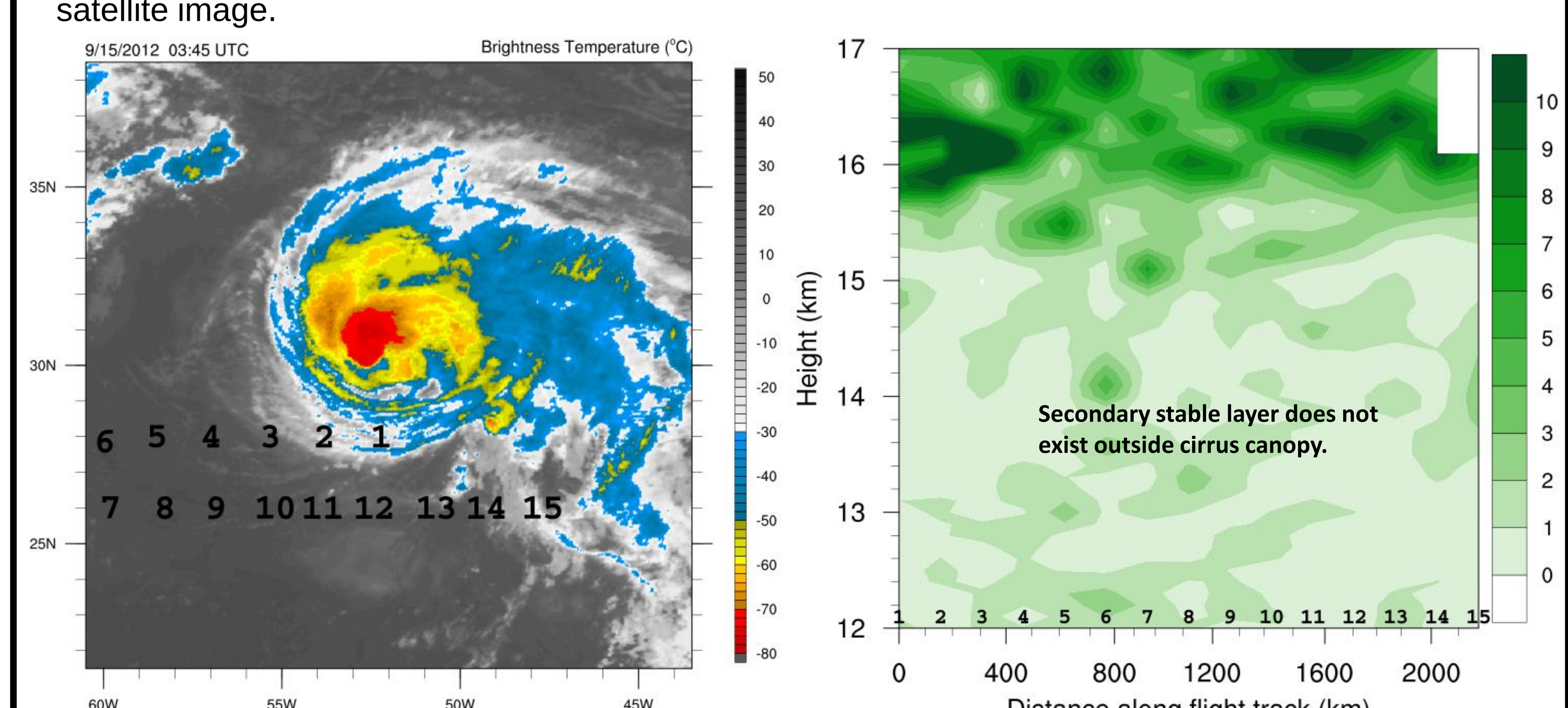


Fig. 1: (Left panels) Infrared brightness temperature images of Hurricane Nadine during the overnight hours of 14-15 September 2012 with HS3 dropsonde deployment locations indicated by digits. (Right panels) vertical cross-sections of Brunt-Väisälä frequency squared (10^{-4} s^{-2}) constructed using the HS3 dropsondes shown. Digits along the bottom of the cross-sections correspond to digits on the satellite image.



- Within Nadine's cirrus canopy (top panels), two distinct static stability maxima were present: one between the 14 and 15 km altitudes and another above 16 km.
- Outside of the cirrus canopy (bottom panels), the stable layer between 14 and 15 km was not present.
- The static stability maximum present above 16 km in both cross-sections – the tropopause inversion layer (TIL) – is slightly stronger within the cirrus canopy than outside.

Hurricane Patricia (2015)

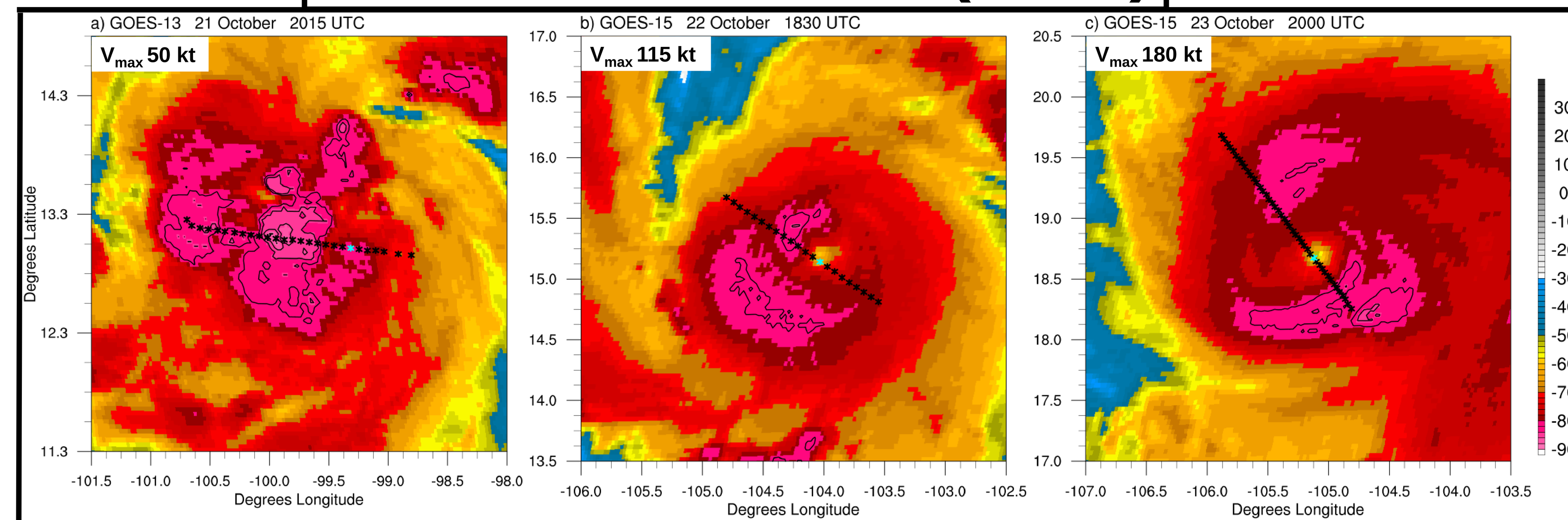


Fig. 2:Infrared brightness temperature images of Tropical Storm Patricia at (a) 2015 UTC 21 October, and Hurricane Patricia at (b) 1830 UTC 22 October and (c) 2000 UTC 23 October 2015. Black stars represent TCI dropsonde deployment locations, with a cyan star marking the center location used for each cross-section shown below and to the right. Black contours delineate the coldest brightness temperatures, with a contour interval of 2°C starting at -82°C.

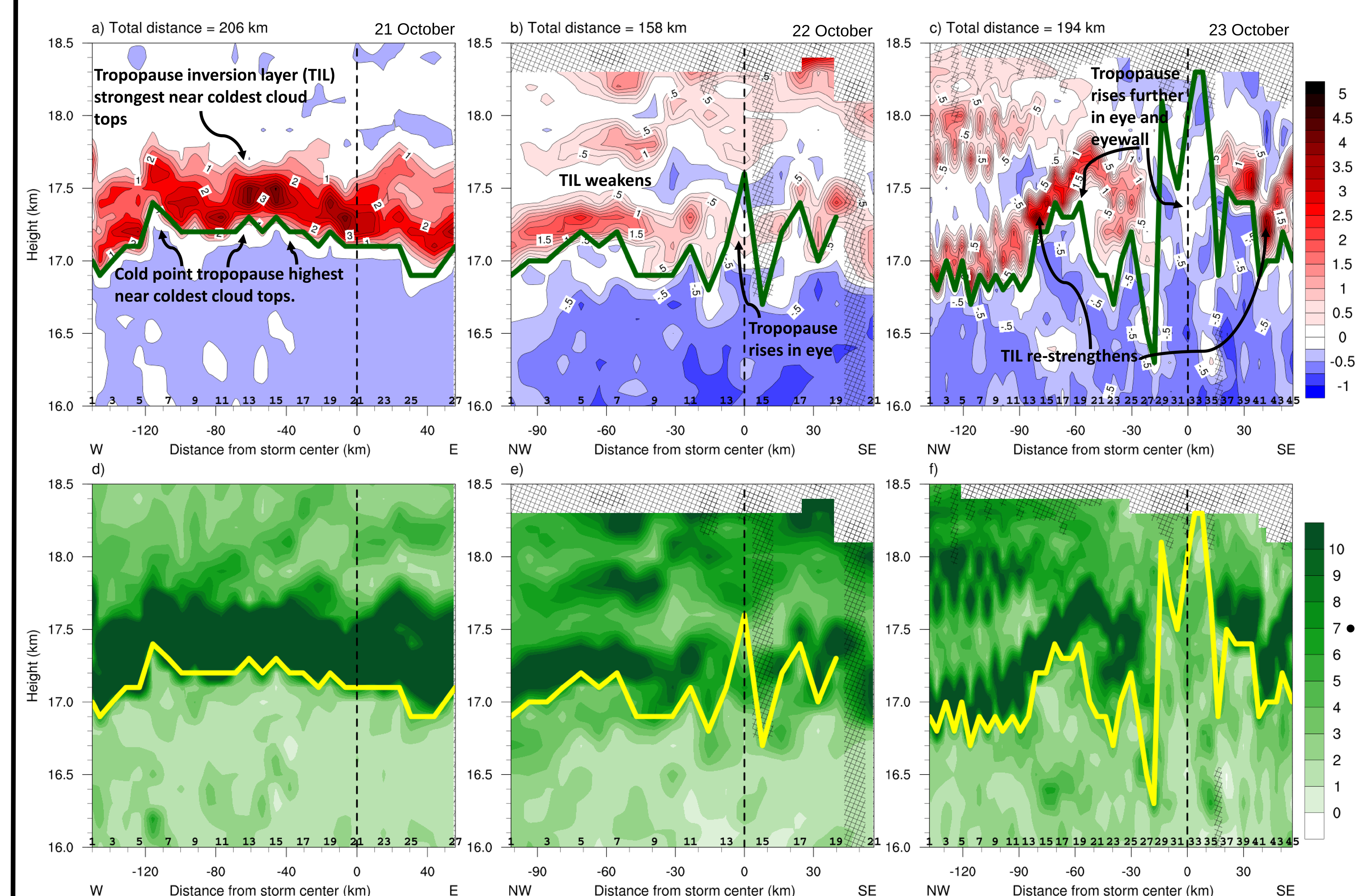


Fig. 3 top panels: Vertical cross-sections of the vertical temperature gradient (K/100 m; filled contours) and cold point tropopause height (green lines) along the transects shown in Fig. 2 on (a) 21, (b) 22, and (c) 23 October 2015. Numbers along the bottom of each cross-section represent the dropsonde deployment locations shown in Fig. 2, with number 1 corresponding to the westernmost dropsonde. Dashed vertical lines mark the storm center and hatching indicates regions of missing values. where interpolation is performed in the radial direction.

Fig. 3 bottom panels Vertical cross-sections of Brunt-Väisälä frequency squared (10^{-4} s^{-2}; filled contours) and cold point tropopause height (yellow lines) on (d) 21, (e) 22, and (f) 23 October 2015.

- Tropical Storm Patricia (left panels above) exhibited a strong tropopause inversion layer, with a 2-5 K/100 m temperature inversion over a broad region of the storm.
- At category 3 strength, (middle panels), this inversion layer weakened considerably and the tropopause height began to increase near the storm center.
- Just after reaching its peak intensity (right panels), the inversion layer re-strengthened in the vicinity of the eyewall but completely disappeared within the eye.
- The cold point tropopause reached its peak altitude within the eye and over the eyewall.

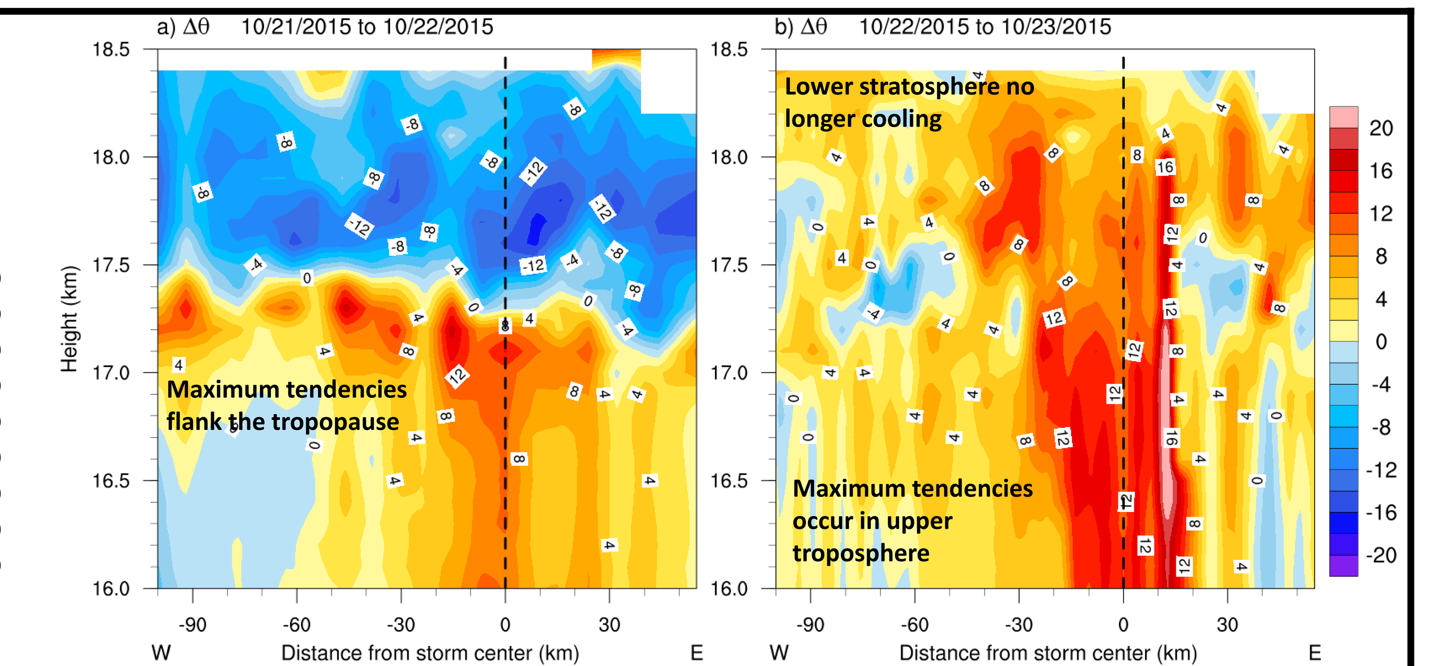


Fig. 4: 24-hour changes in potential temperature in Patricia between (a) 21 and 22 October and (b) 22 and 23 October.

- Early in the period (Fig. 4a), potential temperature changes were maximized just above and just below the tropopause.
- Later in the period (Fig. 4b), the maximum potential temperature changes occurred below the tropopause (between 16 and 17 km).

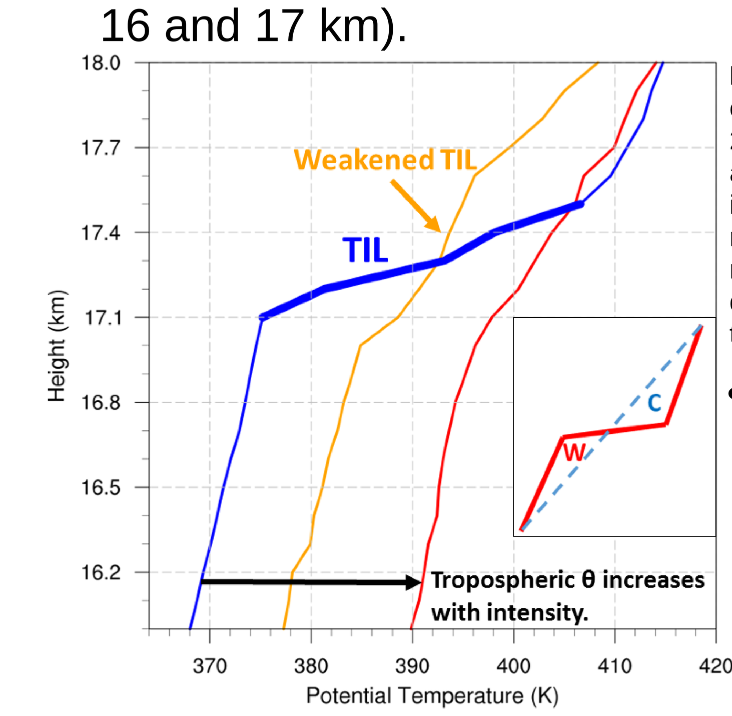


Fig. 5: Vertical profiles of potential temperature at the center of Patricia on (blue) 21, (orange) 22, and (red) 23 October. Inset is an idealized schematic of mixing across a strongly stable layer, with the solid red line indicating the initial profile and the dashed blue line representing the profile after a period of mixing. W represents a layer of increasing potential temperature during mixing and C a layer of decreasing potential temperature.

- Below 17 km as Patricia intensified, potential temperature increased nearly uniformly in the vertical as the storm's warm core developed.
- Above 17.3 km, however, the vertical profile of potential temperature changed dramatically.
  - This evolution is consistent with mixing across the tropopause, as illustrated by the schematic in Fig. 5.
    - Mixing across a highly stable layer will force potential temperature tendencies that maximize just above and below the stable layer, evidence for which is seen in Fig. 4a.
- **These results suggest that both mixing and warm core development contributed to the elimination of the tropopause inversion layer over Hurricane Patricia's eye.**

Some Open Questions

- What caused the double stable layer structure observed within Hurricane Nadine's cirrus canopy?
- What were the relative roles of turbulent mixing and subsidence warming in eliminating the tropopause inversion layer over Hurricane Patricia's eye?
- Does the static stability structure at the tropopause determine whether or not a warm core forms in the upper troposphere?

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