Near-Surface Frontogenesis and Atmospheric Instability along the U.S. East Coast during the Extratropical Transition of Hurricane Matthew (2016)[1]

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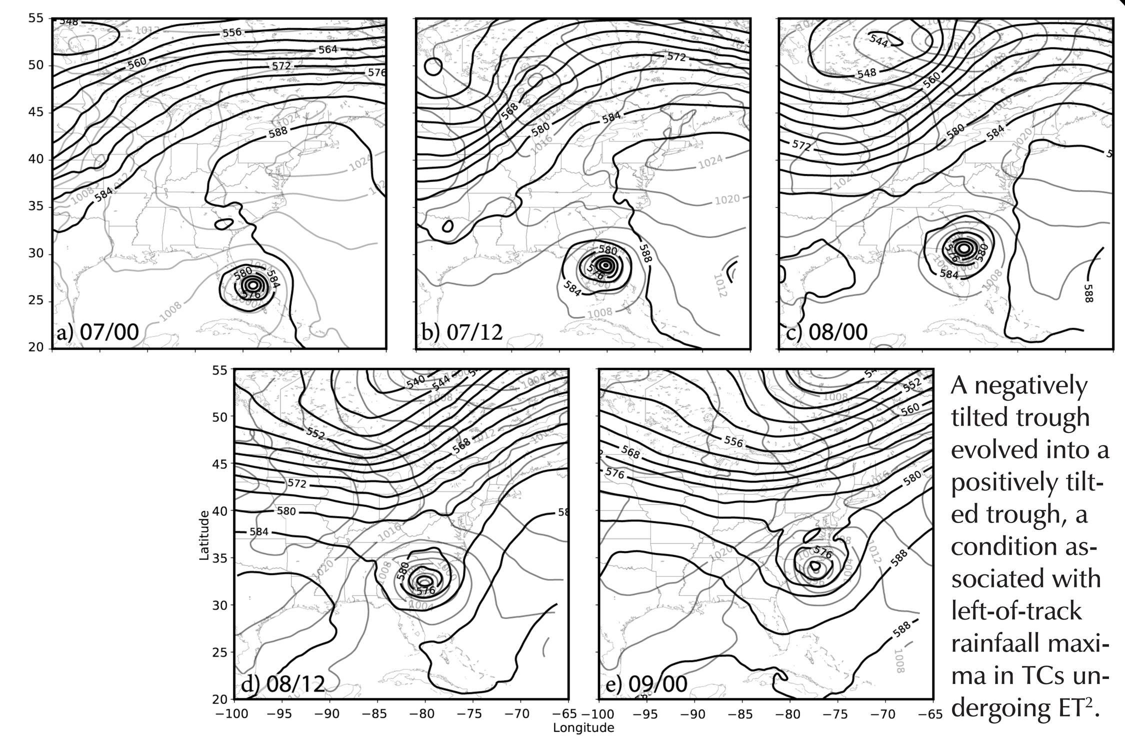
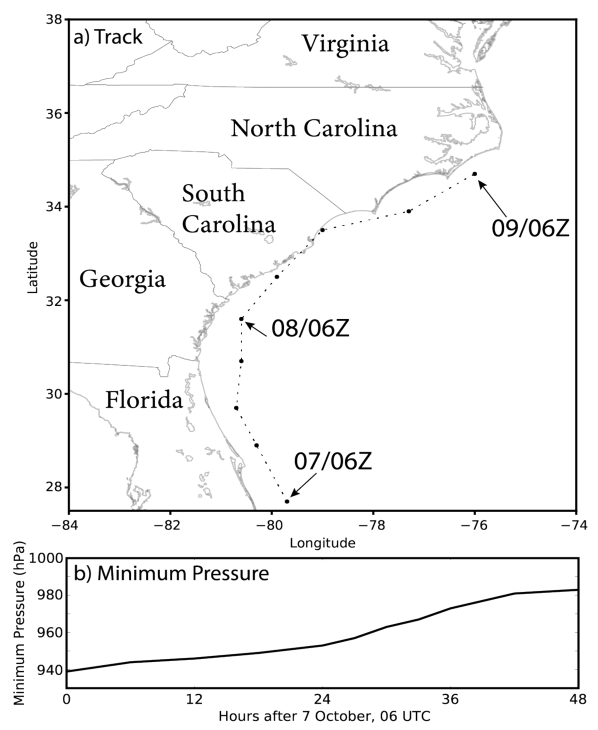
1. Introduction

- Hurricane Matthew paralleled the southeastern U.S. coast on 7-9 October 2016. On 8 and 9 October, it dumped over 250 mm of rain--and up to over 400 mm locally--along a swath located in the coastal plain of South and North Carolina and Tidewater Virginia. The heaviest rain was focused along a surface front that developed to the north and west of Matthew's center as the cyclone underwent extratropical transition (ET).



A negatively tilted trough evolved into a positively tilted trough, a condition associated with left-of-track rainfall maxima in TCs undergoing ET[2].



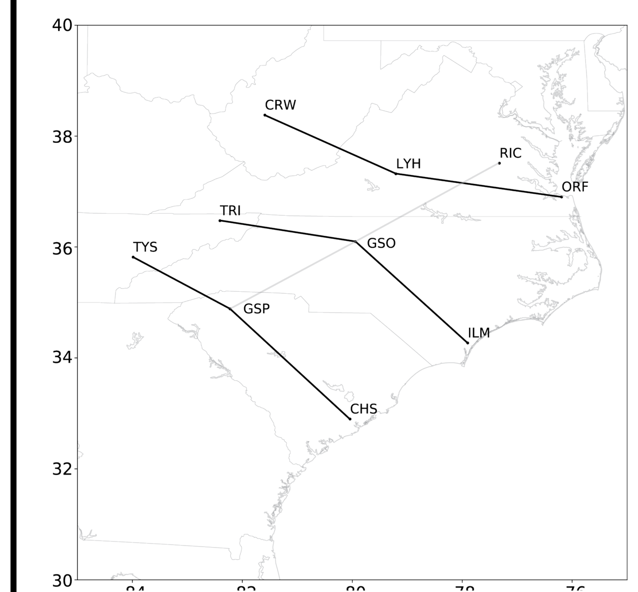
Left: a) Track and b) minimum pressure of Hurricane Matthew from 7-9 October 2016 from NHC best track.

Top right: 500 hPa geopotential height (dam; black contours) and mean sea level pressure (hPa; gray contours) over the eastern United States and western Atlantic from RAP analysis every 12 hours from a) 0000 UTC 7 Oct to e) 0000 UTC 9 Oct.

- Some prior studies[2-4] have raised the possibility that cold air damming east of the Appalachian Mountains could enhance rainfall along the frontal boundary, presumably by making the cross-frontal temperature gradient larger.

- Release of conditional symmetric instability (CSI) as air rides isentropically over surface frontal boundary developed by the cyclone may also play an additional role in enhancing precipitation[5].

2. Cold air damming was probably unimportant in this case.



Cold air damming was objectively identified[6].

Algorithm requirements:
1. ASOS stations at centers of west-to-east segments (LYH, GSO, GSP) must have pressure greater than at ends of segment.

2. Pressure must increase from north (RIC) to south (GSP).

Based on this (see Table 1 below), only weak cold air damming occurred, and only before 0600 UTC 8 Oct, before the heaviest rainfall occurred over NC, SC, and VA.

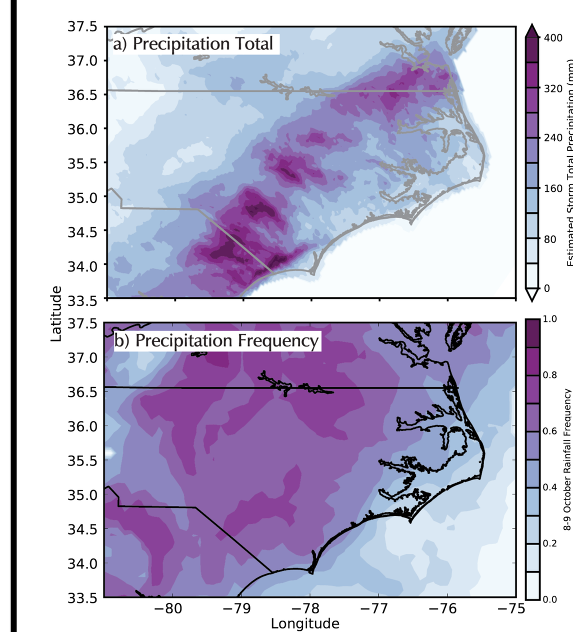
Top: ASOS stations used in Bailey et al. (2003) cold air damming detection algorithm.

Bottom: Table containing reported surface pressures at the stations shown in the above figure every 6 hours from 7-9 October.

TABLE 1. Mean sea level pressure (hPa) at Automated Surface Observing Systems (ASOS) stations used for Bailey et al. (2003) cold-air damming detection algorithm.

Station/time	0000 UTC 7 Oct	0600 UTC 7 Oct	1200 UTC 7 Oct	1800 UTC 7 Oct	0000 UTC 8 Oct	0600 UTC 8 Oct	1200 UTC 8 Oct	1800 UTC 8 Oct	0000 UTC 9 Oct
CRW	1022.0	1020.3	1021.1	1019.3	1017.8	1016.6	1016.8	1017.3	1020.4
LYH	1024.6	1022.8	1022.0	1021.3	1019.3	1017.6	1015.9	1013.6	1013.3
ORF	1022.3	1021.0	1020.8	1020.0	1018.5	1016.2	1014.0	1009.3	1005.1
RIC	1024.3	1022.8	1022.5	1020.9	1019.7	1017.8	1015.9	1012.8	1011.6
TRI	1020.4	1018.7	1019.1	1017.0	1015.8	1013.8	1013.4	1012.2	1017.7
GSO	1022.0	1020.0	1018.9	1018.2	1016.2	1014.5	1011.4	1008.8	1009.4
ILM	1017.8	1016.1	1015.7	1014.7	1012.5	1009.4	1001.7	994.1	992.7
TYS	1018.5	1017.0	1019.0	1015.9	1014.8	1013.9	1013.9	1014.6	1018.3
GSP	1020.4	1018.6	1017.4	1016.2	1013.8	1011.7	1008.1	1007.9	1011.8
CHS	1016.7	1014.7	1012.7	1010.1	1004.5	995.8	984.1	996.2	1007.3

3. Observed rainfall and radar reflectivity

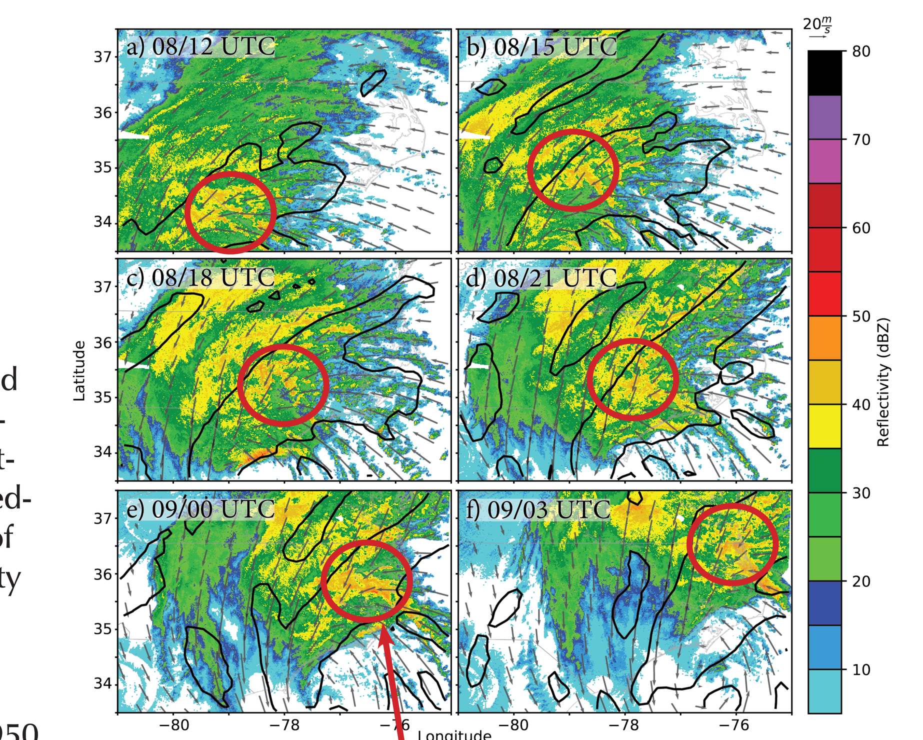


- A corridor of heavy rainfall about 100-200 km inland is clearly visible.

- The heaviest rainfall did not occur because rain lasted longer; rather it happened because the rain there was more intense. This is seen in radar data (below) by the high reflectivity located well inland.

Top left: a) Total precipitation observed during Hurricane Matthew over northeastern SC, eastern NC, and southeastern VA. Maximum rain amounts exceeded 400 mm (15.75 in.) b) Frequency of rainfall (determined by radar reflectivity exceeding 7 dBZ) for 8-9 October.

Bottom right: Reflectivity observed by WSR-88D at 2.5 km above sea level. 950 hPa wind vectors are shown, and the black contour indicates where frontogenesis (see next section) exceeded 1.5 K 100 km^{-1} 3 h^{-1}.



Red circles indicate locations where the primary spiral rainband intersected a more meridionally oriented region of heavy rainfall.

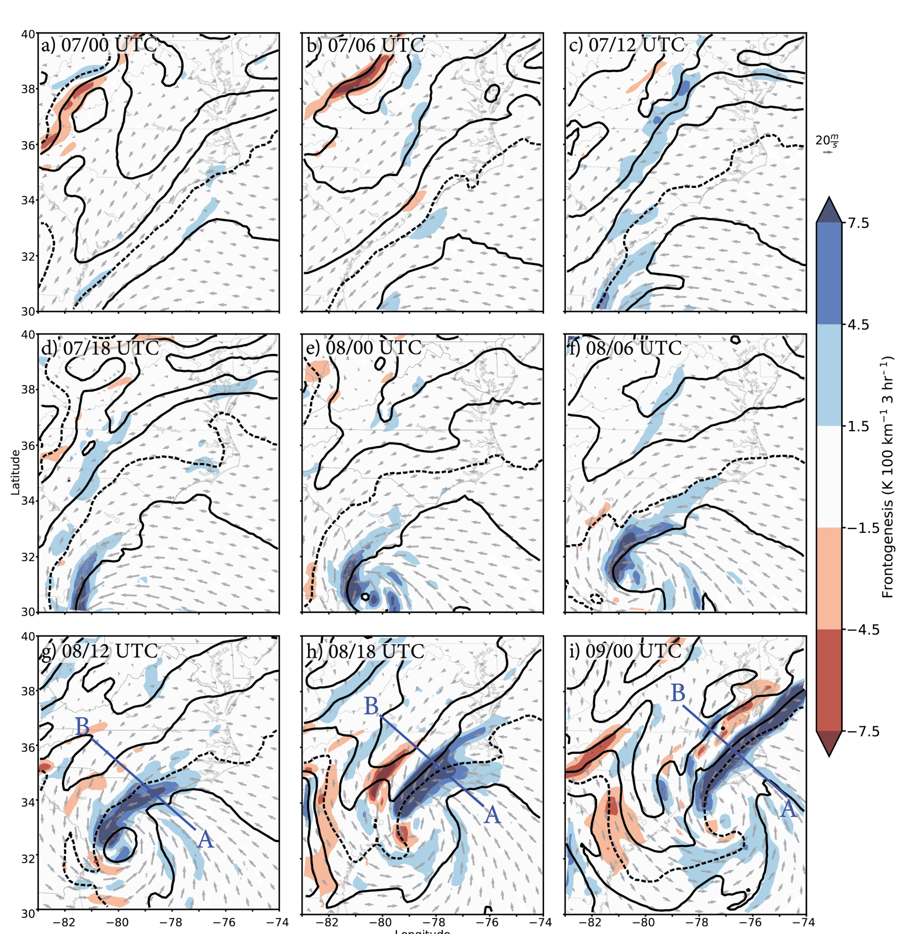
4. Frontogenesis in RAP version 3 analysis

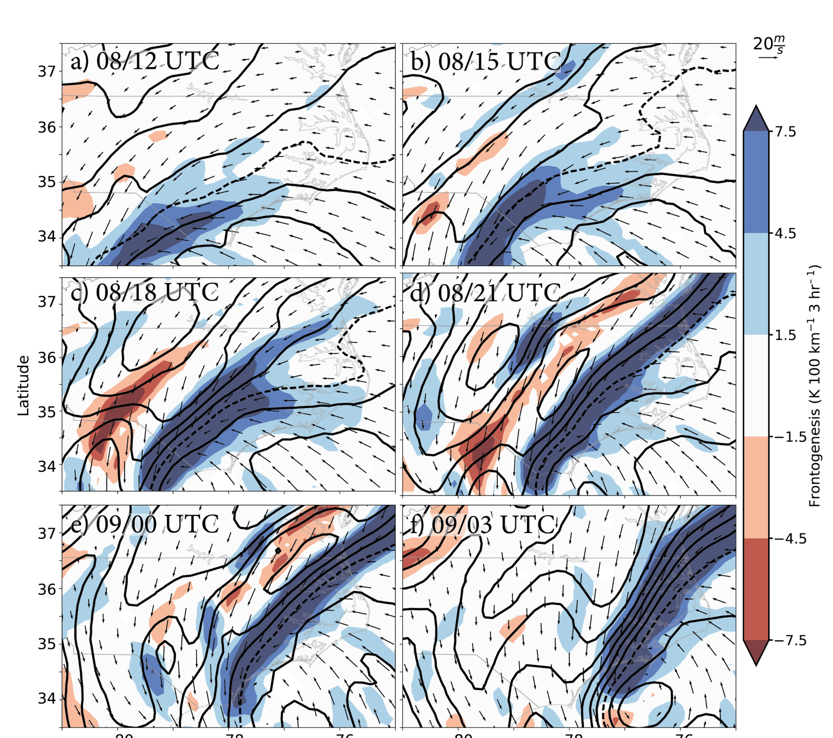
All variables plotted on this poster (except for rainfall and radar data) are derived from Rapid Refresh (RAP) v3 analysis. Pettersen frontogenesis was computed as

$$F \approx -\frac{1}{|\nabla_h \theta|}\left\{\left[\left(\frac{\partial\theta}{\partial x}\right)^2\frac{\partial u}{\partial x}+\left(\frac{\partial\theta}{\partial y}\right)^2\frac{\partial v}{\partial y}\right] + \left[\frac{\partial\theta}{\partial x}\frac{\partial\theta}{\partial y}\left(\frac{\partial v}{\partial x}+\frac{\partial u}{\partial y}\right)\right]\right\}.$$

Top right: 950 hPa potential tempertaure (black lines; intervals of 2 K), wind (vectors) and frontogenesis between 0000 UTC 7 October and 0000 UTC 9 Oct. Dasahed line is the 298 K potential temperataure isoterm. The A to B cross-section is referred to in Section 5.

Bottom left: Same as top right, but zoomed in over eastern NC and displayed between 1200 UTC 8 October to 0300 UTC 9 October. Potential temperature contour (black lines) is 1 K.





Frontogenesis increased in a band extending toward the northeast of the low-level center. The spiral primary rainband (Section 3) intersected a region of enhanced precipitation roughly located along the area of high frontogenesis.

A secondary region of enhanced frontogenesis also developed around 2100 UTC 8 October to the rear of the main feature. The two regions of frontogenesis presumably helped to force more intense convection. This occurred because of the pre-existing temperature gradient between cool air inland of Matthew and relatively warm air over the ocean; however, this gradient was not enhanced by cold air damming (Section 2).

5. Instabilty and Moisture Convergence

Atmospheric instability within and around Matthew was assessed. For each column of RAP analysis, conditional instability (CI) was determined based on the vertical gradient of θ_e.

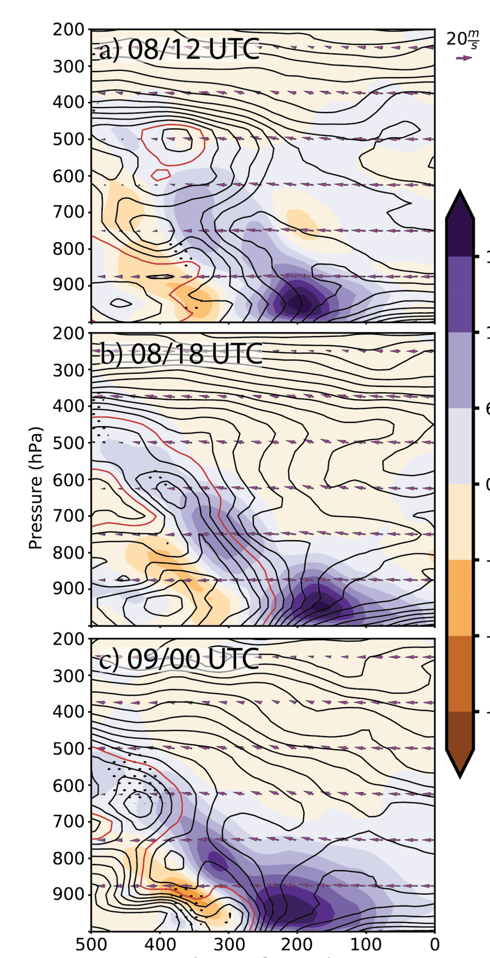
Conditional symmetric instability (CSI) was assessed based on the vertical gradient of saturated equivalent potential temperature, θ_{es}, and the sign of Ertel PV, P:

$$\mathcal{P} = g\boldsymbol{\eta}\cdot\nabla\theta_{\mathrm{es}}$$

$$\mathcal{P} \approx -g(\zeta+f)\frac{\partial\theta_{\mathrm{es}}}{\partial p}$$

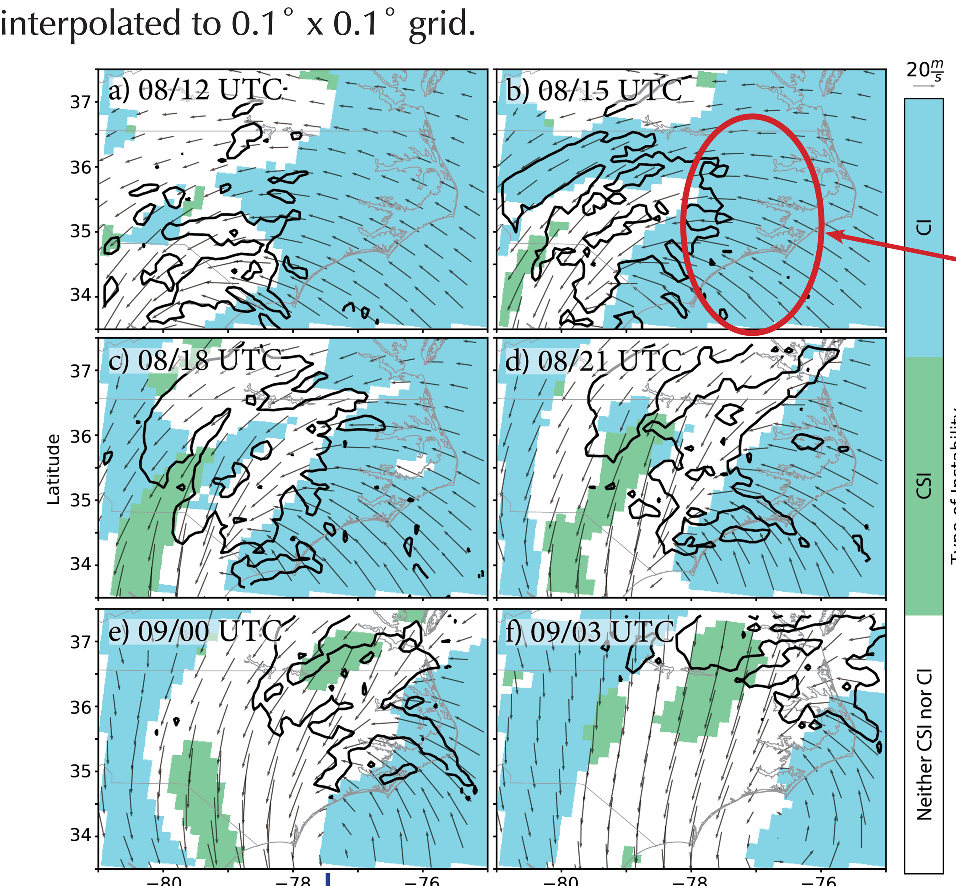
If P was negative, meaning that the absolute vorticity and vertical gradient of saturated equivalent potential temperature were the same, then CSI was present if CI was not.

Below: Maps of atmospheric stability at 925 hPa. Blue (green) indicates CI (CSI). Black contour encloses observed 35 dBZ contour interpolated to 0.1° x 0.1° grid.



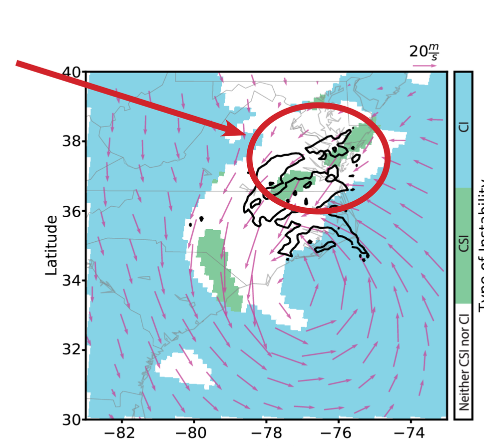
Left: Southeast to northwest cross-section as shown from A to B in figure in upper right of Section 4. Plotted are moisture convergence (shaded), wind along the cross section with vertical motion mulitplied by 10 (vectors), and saturtaed equivalent potential temperature (K; 2 K contour interval). Red contour denotes the 332 K isotherm. Black strippled areas on the figure represent areas of CSI.

Moisture convergence below 850 hPa was largest just upstream of the region of strongest near-surface frontogenesis.



Flow entering rainbands is mostly convectively unstable. CSI mainly prevalent downstream of heavy rain.

Some CSI was present upstream of heaviest rain over NE NE and SE VA.



Zoomed out version of panel (e)

6. Conclusions

- Cold air damming had no apparent impact on the intensity of rainfall along a frontal boundary that developed across eastern NC during the ET of Matthew.

- The heaviest rainfall occurred where the primary spiral rainband of Matthew intersected a broad region of heavy precipitation forced by low-level convergence inland.

- Most of the simulated rainfall over NC during Matthew occurred near a region of intense frontogenesis, where a temperature gradient of O(1 K 10 km^{-1}) developed. Extemely intense low-level moisture convergence (locally in excess of 50 g kg^{-1} hr^{-1}) was likely also a primary driver for the rainfall.

- The moist flow entering the rainbands was generally conditionally unstable and was lifted as it approached the region of frontogenesis. Conditional symmetrically unstable air may have entered the region of heaviest rainfall from the north over northeastern NC and southeastern VA late on 8 October into 9 October.

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[1]Powell and Bell (2019), MWR, 719-732. [2]Atallah and Bosart (2003), *MWR*, 1063-1081. [3]Atallah et al. (2007), *MWR*, 2185-2206. [4]Croke (2005), *M.S. Thesis, NCSU* [5]Colle (2003), *MWR*, 2905-2926. [6]Bailey et al. (2003), *WAF*, 641-661.