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1. Introduction

Cold lows, also called tropical upper tropospheric trough (TUTT, Sadler 1967), are the antithesis of tropical cyclones. Their structure is displays a nearly vertical cold core low structure with warm anomalies located in the local stratosphere and colder anomalies in the troposphere below. Cyclonic winds are strongest at rather large radii and at the level of zero horizontal temperature gradient moving toward the center and maximize just below the local tropopause, which is sloped upward from the center. The structure of cold lows have long fascinated tropical meteorologists, as they often dictate the local vertical wind shear variations over the trade wind regions of the planet and sometime interact with low-level weather systems. These have been hypothesized to be the foci of the atmospheric sinking within the subtropical ridge, and thus are likely important for stratospheric/tropospheric exchange. There are also documented linkages between seasonal variations of cold lows, variations in tropical cyclone activity, and the seasonal variability and strength of the subtropical highs. Nonetheless, there are not many climatological studies detailing the movement and inter-annual variability nor satellite presentation of these systems.

To provide a short-term climatology of cold lows in and around the Atlantic tropical cyclone basin, this study constructs subjectively analyzed tracks of cold lows over a 10-year period (2007-2016) during June-October using the GOES-East satellite's water vapor channel, which has remained at the same central wavelength and covers a 140W to 10W domain. Using these tracks, I construct mean monthly cold low frequencies and trajectories, and cold low and environmental diagnostics via model analyses. Finally, using the GOES-E satellites water vapor channel, I construct mean water vapor structure of these systems in a motion following framework created and decompose the resulting variance structures, which may provide forecaster insight and the possibility of subjectively forecasting cold low intensification and dissipation. In the following sections the TUTT tracks and their trajectories, and climatological features of cold lows based on satellite imagery and/or derived from operational GFS analyses are presented.

2. Cold Low/TUTT Tracks and Trajectories

Cold lows were visually tracked in water vapor imagery using a 3-hourly archive of GOES-E imagery from 2007 to 2016. This method, while time consuming, also allowed the analyzer (me) to become accustom to how cold lows form and track. Cold lows, like tropical cyclones, seem to form in groups. These groups often form along a shear line in the atmosphere where the horizontal winds change rapidly or on the downstream end of the anticyclonic side of the summertime polar jet. The tracking was started using 2007, followed by 2011, 2012, 2008, 2013, 2008, 2009, 2014, 2016, and 2015 over the course of nearly two years. The hope was that any biases in the tracking methodology would not cause trends.

Figure 1 shows all the tracks in this study and Figure 2 shows the individual tracks for each year. Figure 3 then shows the annual number of tracks and Figure 4 shows the number of TUTT days that existed in each year.

These cold lows seem to move down the climatological mid-oceanic trough (MOT) and are likely the related to the position and strength of this feature as discussed in Frank (1970) and in Sadler (1967). There is also measurable inter-annual variability in the number of cold lows and the number of days they existed. It is likely that the number of TUTT days is better related to the strength and position of the MOT. This is a topic we wish to explore more, as previous research has shown how the MOT is related to basin wide sea level pressure anomalies and vertical wind shear in the Caribbean (Knaff 1997) – factors that are related to seasonal hurricane activity.

Trajectories that are based on these tracks are shown for each year in Figure 5 and each month in Figure 6.

Figure 5 clearly shows that the placement and motion of cold lows changes by year. One remarkable characteristic is that years with relatively few or no Atlantic major hurricanes are associated with years when cold-lows move slowly through the tropics or have a noticeable slowing in the tropics.

The monthly trajectories, Figure 6, show that the cold lows trajectories move poleward from June to August and then move back toward the equator. The anticyclonic trajectories have their maximum poleward extent in the months of August and September. These months also correspond to the most rapid movement of cold lows through the tropical Atlantic.

3. Water Vapor Image Archive

Using the tutt tracks, a water vapor imagery archive was constructed that contains every image that covers a 70% of a 3200 x 3200 km image centered on the storm. Some 137000 images. Examples of this imagery is shown in Figure 7, where 10 images were randomly selected from the data set.

From this imagery, principle component analysis was conducted on a polar grid that has been rotated so that the cold low motion is to the top of the image. The resulting EOFs are shown in Figure 8. These EOFs are remarkably similar to those associated with tropical cyclones (see Knaff et al. 2015).

4. Average Structures

GFS operational analyses were used to construct the composite view of the GOES-East cold lows. These structures are shown in Figure 9.

The kinematic structure of the cold lows that were tracked show central warm anomalies of 5^{o} C vs environment (at 900 km radius) at the 150 hPa level and cold anomalies of -2^{o} C at 400 hPa. In the innermost core of the cold low relative humidity is slightly enhanced and slopes toward the left quadrant. The highest RH is in the edges of the upper level cyclone. Very dry mid-levels are evident in all quadrants but the left. The largest height anomalies (-60m) are near the core at 250 hPa, and the radial gradient of height anomalies is greater front-to-back. This warming maximum is above 250 hPa – the local tropopause. It is interesting that the warm anomalies extend to the 250 hPa in the mean and RH values near 45% allow for cooling to space - maintenance mechanism (Frank 1970). There is clear signs that cold lows are to some degree baroclinic with sloping features (RH, Vt) with higher features on the left. Radial flow seems opposite of motion with a maximum of convergence in the lower statosphere. It looks the line environment blows through cold lows with convergence on the back side maximizing to the rear. Comparing the mean cold low to the Dunion (2011) tropical Atlantic sounding one clearly see how the cold low has much warmer conditions in the upper troposphere and cooler temperature in the lower troposphere (Figure 10). However, the cold-lows, at least in the mean seem to, as hurricanes, favor a low vertical wind shear environment (lower stratosphere, to the bottom of the cold low ~700 hPa).

Another way of looking at the structure is combined EOF analysis that contains the variations of the mean cold low's temperature, relative humidity, height, tangential and radial wind (at 500 km). These structures suggest that cold lows vary primarily in background (tropopause height), then by strength and then by depth, Figure 11.

5. Discussion

When I started this work I had several goals in mind. Some of the goals were questions as follows:

- Are current forecast systems able to maintain and forecasts cold lows?
- Do climate models produce cold lows?
- Can current models produce a similar climatology and track them in a similar manner as nature?

- Are cold lows the focus of sinking in the subtropics (Ricks, 1959)?
- Are they important to the general circulation?
- Since these are special cases of Rossby wave breaking, do they have a larger role in transport of ozone?
- Can a satellite-based tracking be automated?
- Can we use simple hurricane models to learn more about cold low evolution and structure?
- Are variations of cold-low activity and associated movement related to hurricane variability?

I have made some progress with the climatological aspects of these cold lows, but many of these questions remain completely unaddressed or unanswered and require more study by the community.

Other goals were motivated by a general lack of understanding of this phenomenon. To my knowledge very little is known about how to interpret the water vapor imagery when a cold low is identified by eye. For instance, do certain features in the imagery related to strength, depth and size of these features. I have begun to address this problem, but only a couple subjective observations are relevant here. These are:

1. The warmer the overall WV temperatures (in the whole scene) associated with the deeper the circulation, and
2. Stronger cold lows often have an accumulation of moisture nearer the center and cooler temperatures near the center.

There is also some evidence that the seasons with stagnant cold-low trajectories are also seasons with reduced major hurricane activity. However, the monthly nature of this analysis precludes any firm conclusions.

The vertical structure of cold lows is both similar and different from a hurricane. Warm anomalies in the stratosphere force the height fields downward forming a in the upper troposphere that weakens with height. The secondary circulation shows maximum inflow above the maxima in tangential wind in the cross track directions and inflow ahead and outflow behind the cold low in the along-track direction. This implies uplift on the back and left side of these lows, and subsidence elsewhere. From the radial winds it is pretty clear that sinking would be occurring near the center, but maybe not right at the center.

Thus far, and despite decomposing both imagery and analyses into variance structures, there seems to be few easy-to-understand relationships between the kinematic structures and those in the imagery.

Going forward, I would ask the tropical meteorology and climatology if there should an effort be made to create annual tracks of cold lows to improve our understanding and provide another metric for NWP and short-term weather forecasts? Obviously, this is a question of resources versus potential payoff. In the meantime, I will try to focus on the original goals of this study. In this endeavor, I will happily work with anyone that wants to answer the goal related questions. Obvious low-hanging items are forecast model comparisons, climate model cold-low climatology comparisons, transport studies (ozone, high-pv), and air back trajectories centered on cold lows. Collaboration and help is both needed and appreciated.

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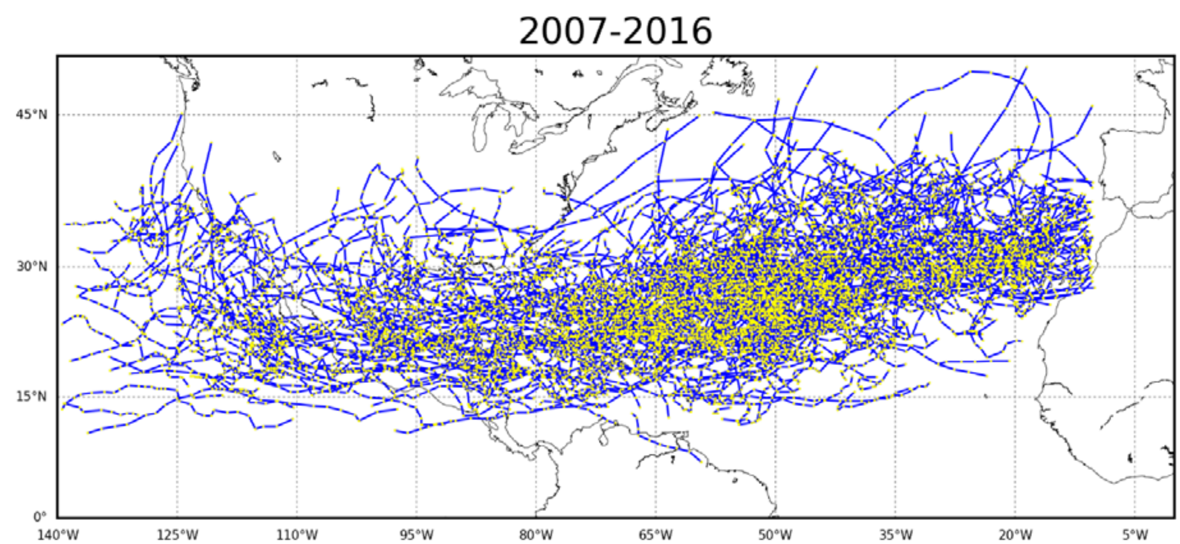

Figure 1. Tracks of all cold lows used in this study 2007-2016. Yellow points are six-hourly positions.

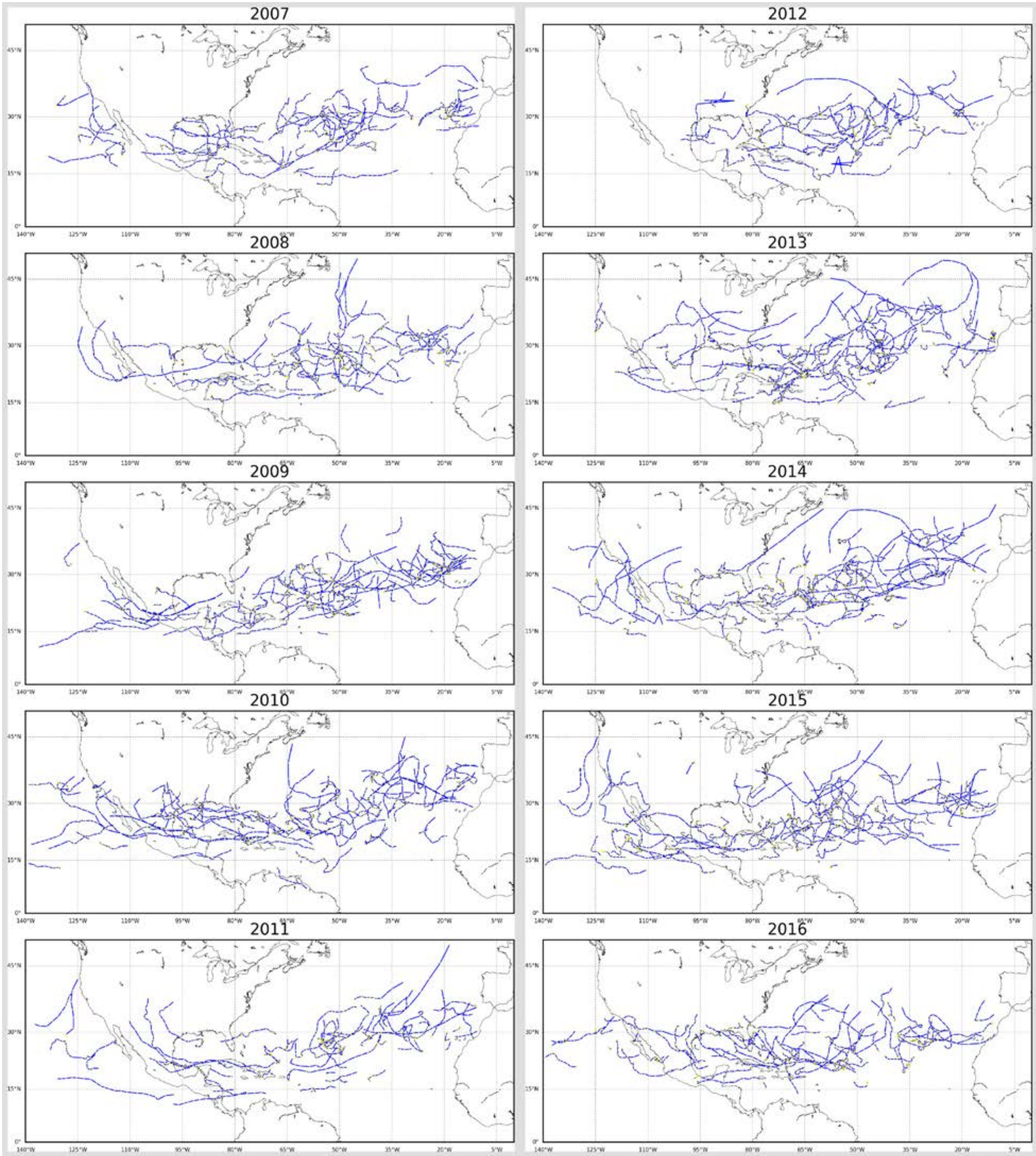

Figure 2. Cold low tracks for individual years 2007 through 2016. Yellow points are the six-hourly positions.

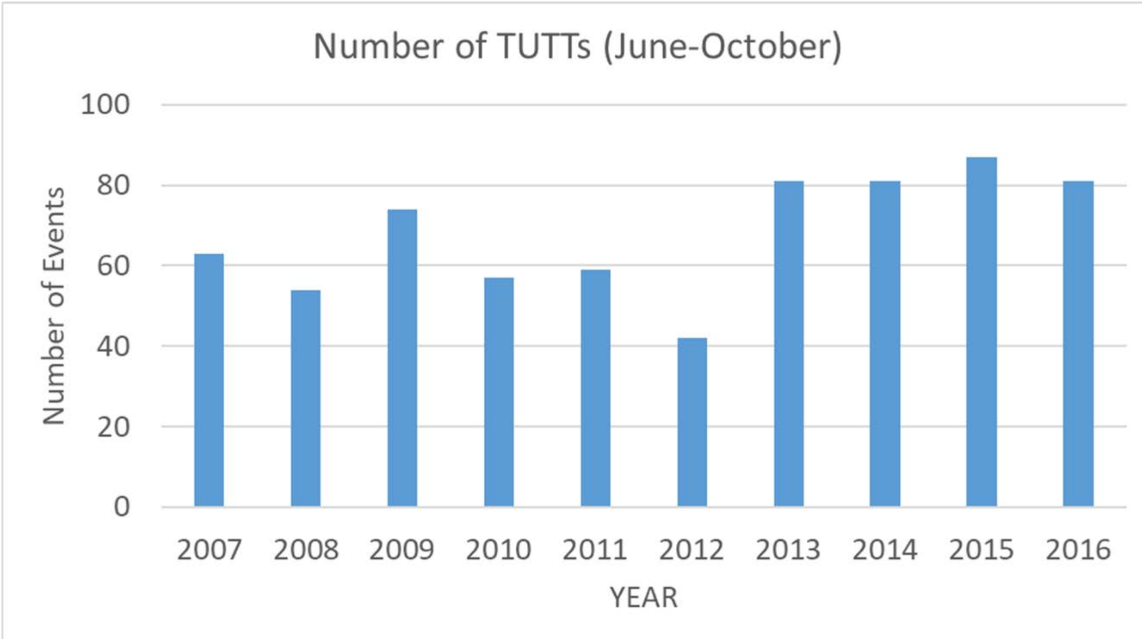

Figure 3. The annual number of cold lows (TUTTs) June to October.

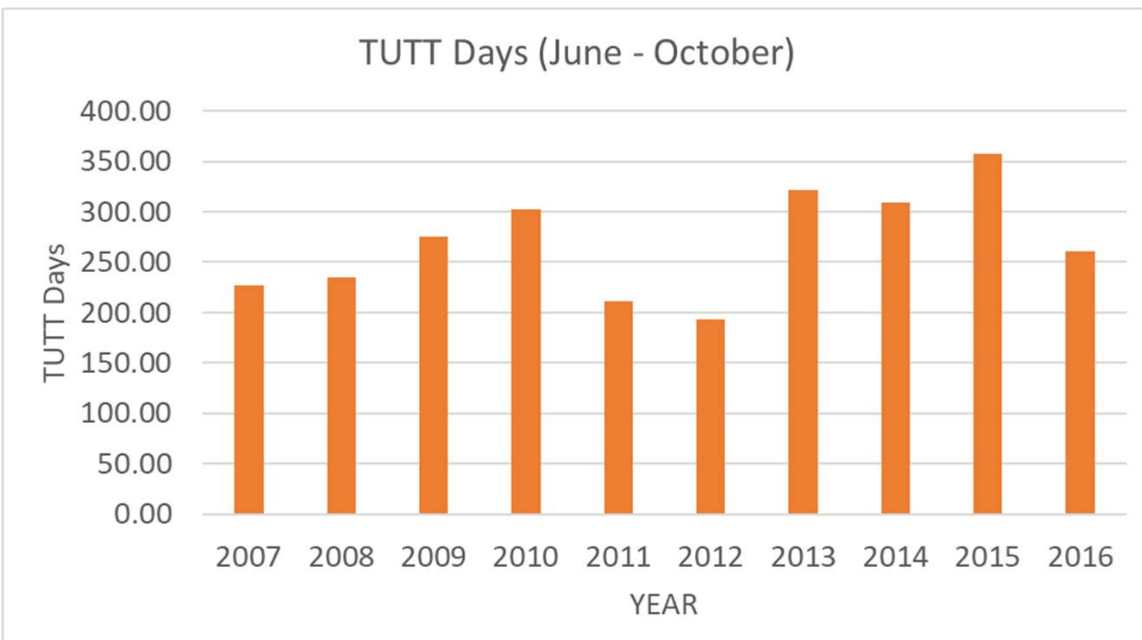

Figure 4. Number of annual TUTT/cold low days, which is the annual number of 6-hourly observations of a cold lows converted to days.

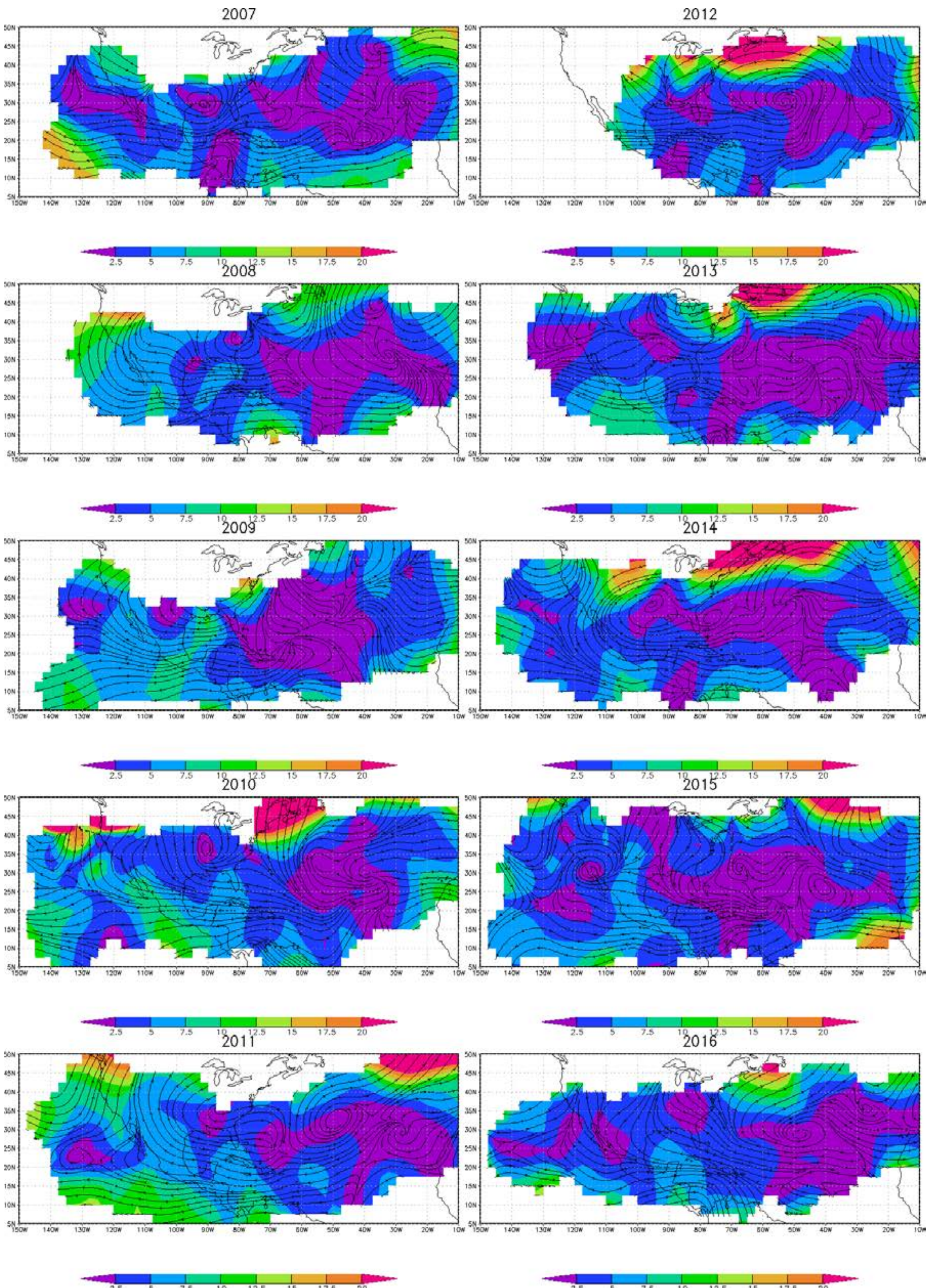

Figure 5. Cold low trajectories based on average cold low movement in years 2007 through 2016. Speeds have units of m/s.

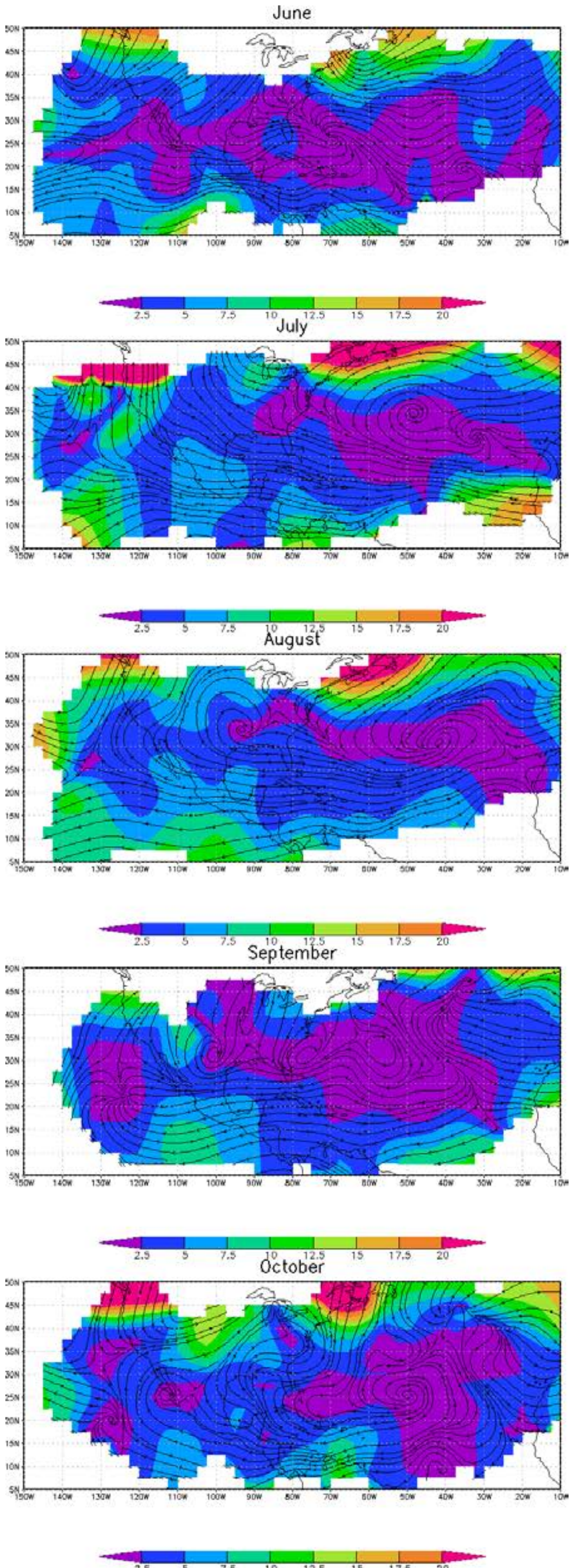

Figure 6. Monthly mean cold low trajectories base on average motions of cold lows 2007-2016.

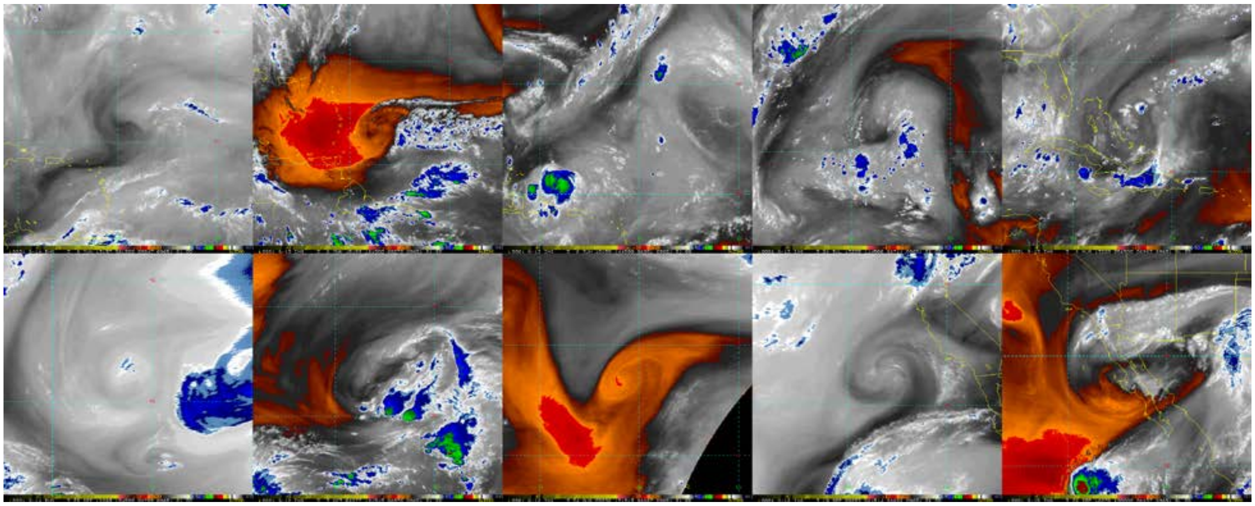

Figure 7. Ten randomly sampled images of cold lows contained in the water vapor image archive. Images are centered on the cold lows.

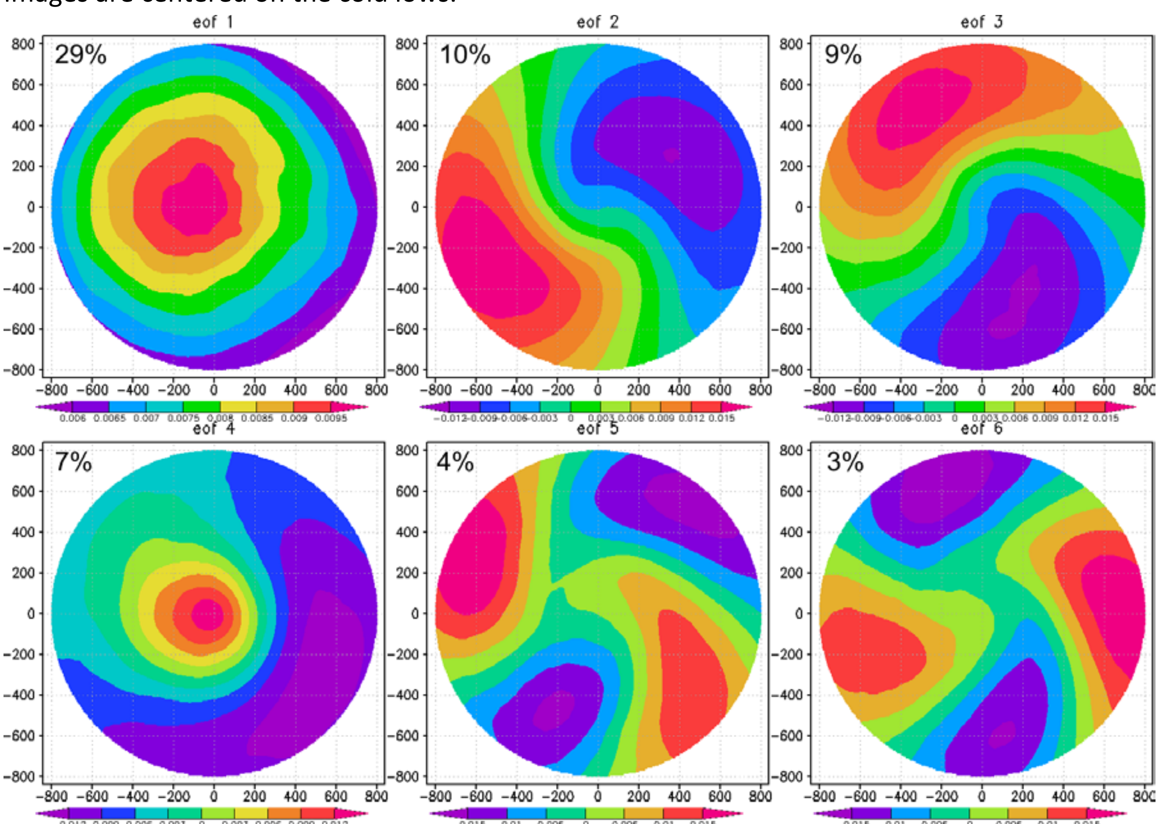

Figure 8. Variance structures (EOFs) of storm-motion relative water vapor imagery. Motion is toward the top of the page and the percent variance explained by each pattern is in the upper left corner of each panel.

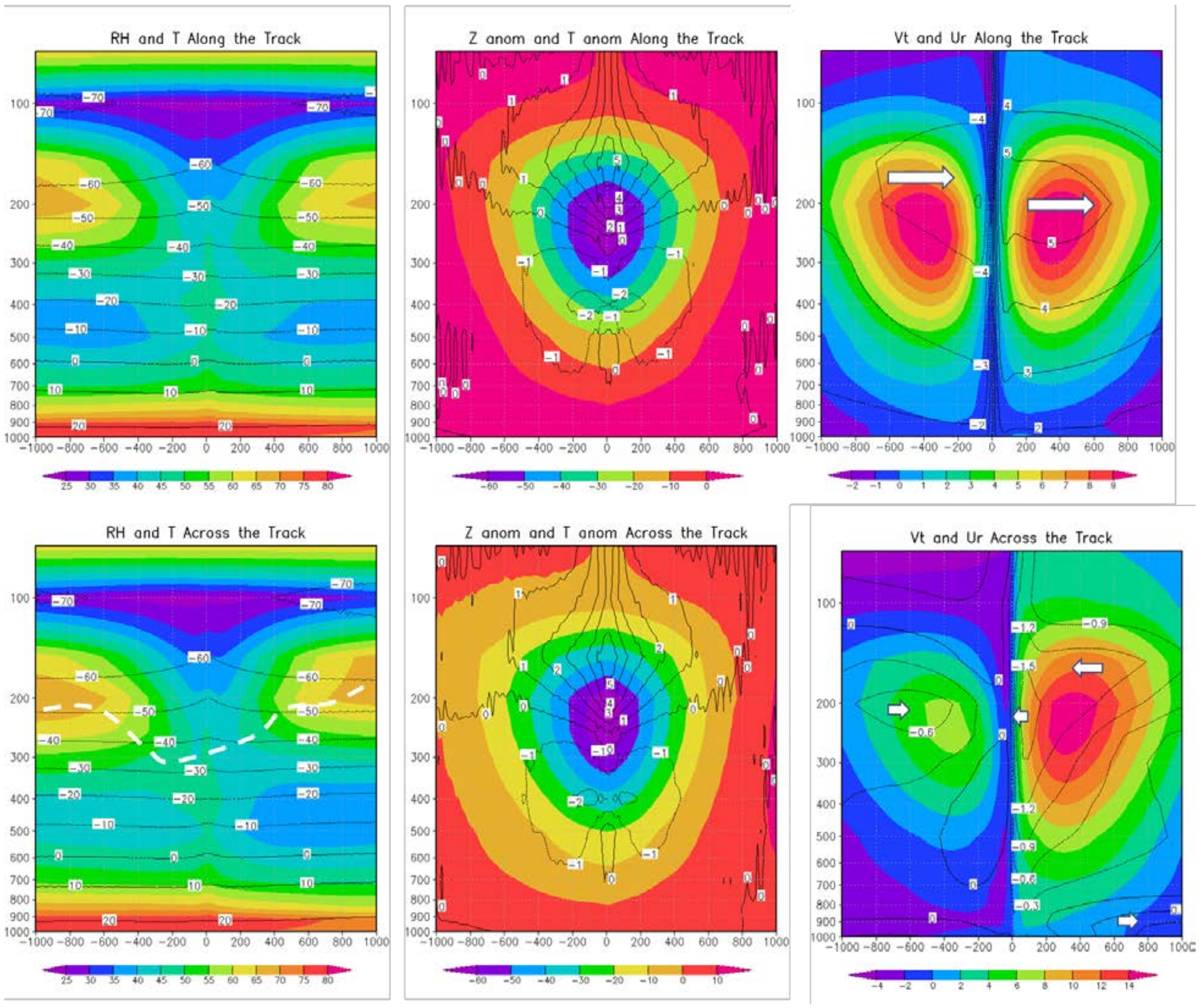

Figure 9. Along-track (top) and cross-track (bottom) GFS-based composites of cold lows. Right most panels show temperature and relative humidity (shaded), middle panels show temperature anomalies and height anomalies (shaded) and the right-most panel shows radial and tangential winds (shaded), where white arrows show the secondary circulation.

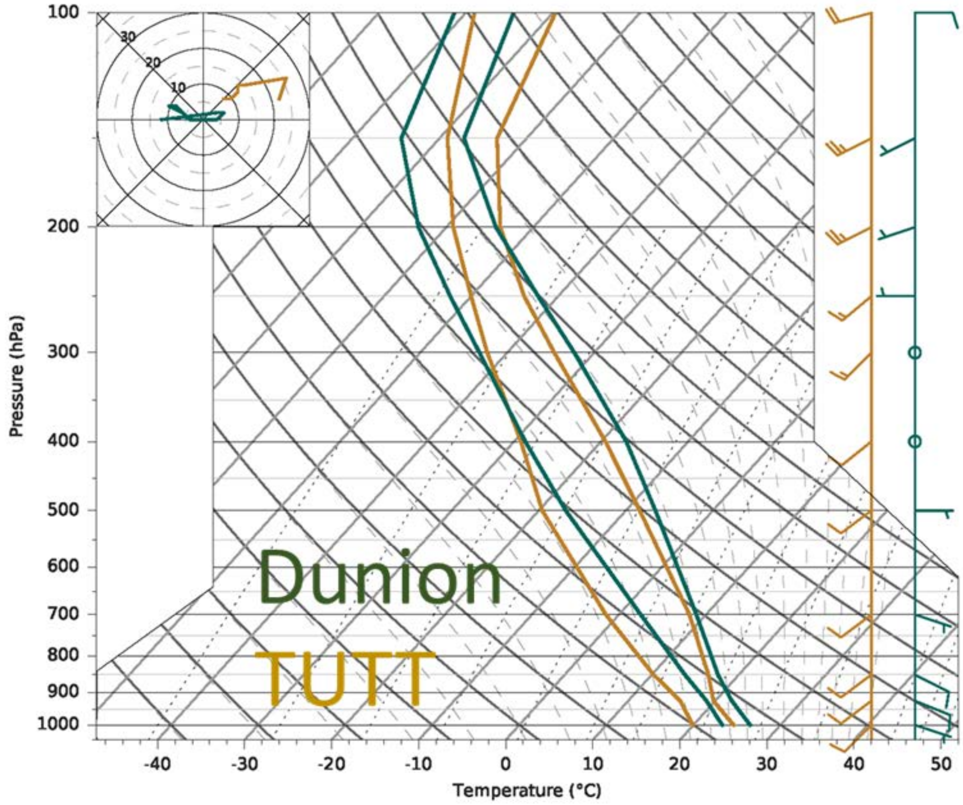

Figure 10. Dunion (2011) tropical sounding (green) and the cold low / TUTT mean sounding (yellow).

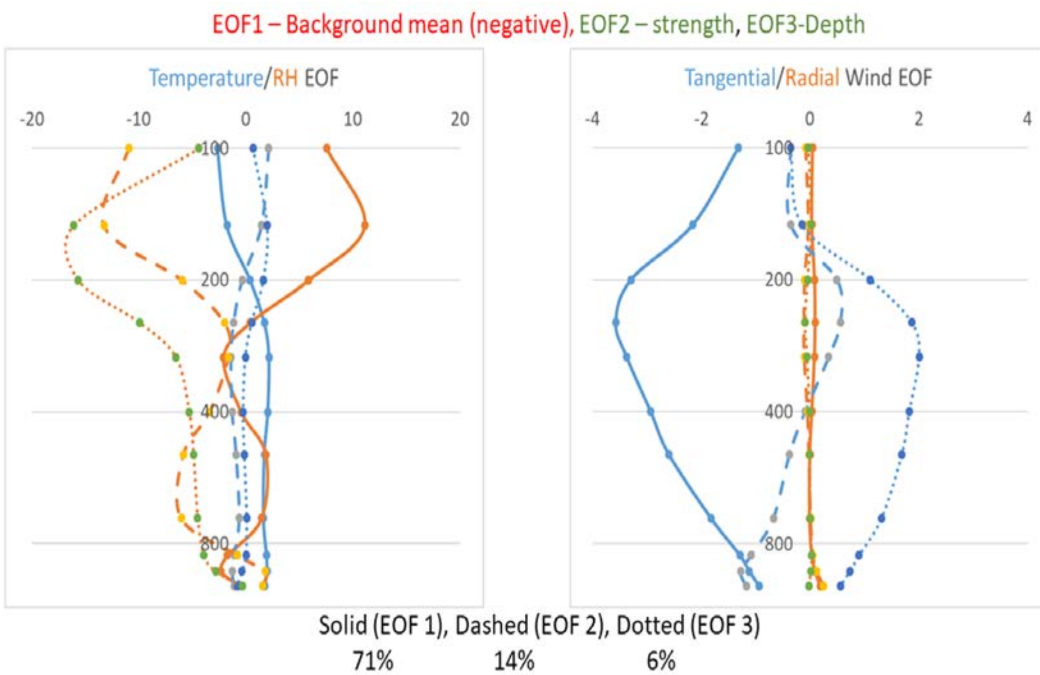

Figure 11. Combined EOF analyses of the mean cold low sounding (at the center) and the tangential and radial winds at 500 km radius.