TOWARD AN ANALYSIS OF THE INFLUENCE OF THE URBAN HEAT ISLAND EFFECT ON SINGLE-CELL CONVECTIVE CLOUD TRAJECTORIES

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ABSTRACT

This is an initial analysis of how the Urban Heat Island (UHI) Effect influences convective cloud trajectories. Case studies have been done in the past that demonstrate the observed movement of convective storms around various urban areas like Atlanta and New York City. This analysis uses the GOES-East satellite to track single-cell convective cloud towers (SCCTs) and the algorithm for following the SCCT tracks them using infrared data from satellite observations taken at 15-minute intervals. Matlab was then used to filter and extract suitable trajectories by using thresholds on both speed and direction. Following the filters to determine viable trajectories, another process was developed to determine where along the trajectory there existed a significant deviation in the propagation of the particular SCCT. After these specific perturbations in trajectory angle were found, they were then cross-referenced with locations of urban areas in the domain using a density plot to determine where the highest concentration of significant perturbation points occurred.

1. INTRODUCTION

Urban Heat Islands are created due to the replacement of natural land cover with paved and built surfaces which absorb heat during the daytime hours, and then radiate it back out come nightfall (Oke 1982). Thus, urbanization has a palpable effect on the weather, resulting in higher temperatures than the surrounding suburban areas both during the day and at night. The scope of effects that UHIs have on weather has still yet to be completely explored.

Our research focused on the possible effect UHIs have on convective cell trajectories; studies have been done in the past to describe specific instances where the UHI effect has been seen to possibly influence the movement of convective thunderstorms. Bornstein and Lin (1999) analyzed three specific cases around the Atlanta metropolitan area during the Summer Olympic Games of 1996, yet their focus was on convective initiation associated with the UHI Effect. Studies by Bornstein and LeRoy (1990) around the New York City region showed the effects of the UHI effect during the summer; part of their conclusion stated that thunderstorms propagating toward the city moved bifurcated around the city, resulting in a radar echo minimum over the city. The Bornstein and Lin (1999) study obtained results for two other case studies that were not the focus of their paper that agreed with the results of the previous New York Study. This change in propagation near UHIs is thought to be caused by a "building-barrier" induced divergence effect. This study was conducted using satellite data in order to track specifically single-cell convective cloud towers (SCCTs), monitoring their propagation inside the selected domain.

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2. DATA

The data for this research was obtained from the GOES-East satellite. The methods for differentiating between different cloud towers are discussed in detail in papers released by MétéoFrance (2006) and Morel et al (2001). In summary, parameters were developed to differentiate between different cloud-structure systems using infrared remote sensing. Cells containing cloud systems were determined by "adaptive temperature thresholding" (MétéoFrance 2006) on the infrared data. This method would thus select convective-like cloud tower structures, for their infrared characteristics mimicked that of convective cloud systems. Thus, by using infrared characteristics of the cloud system, discriminatory techniques were used to determine what type of cloud system was being tracked. After convective-like cells are detected, they are tracked using successive infrared images and a "geographical overlapping of cells" method was used to determine the trajectories of specific cloud systems. Once the SCCTs were tracked by methods described above, latitude, longitude, cloud tower area, cloud top temperature, and cloud base temperature were given for the center of the cloud structure. Every fifteen minutes another image was taken by the satellite and the cloud structure tracked. The new latitude, longitude, area, etc were output. If a SCCT was seen to merge with another, or split into separate SCCTs, the track was truncated at that point in the data set and no longer was that SCCT followed. The data analyzed in this study came from the entire month of May, 2009. The domain area was from 34.5^{o}N to 45^{o}N and from 82^{o}W to 73^{o}W.

3. METHODOLOGY

The data obtained was processed using Matlab, in which various thresholds were devised to select suitable and eliminate erroneous trajectories. Firstly, the trajectories were categorized based on their size, or the number of images they contained. Trajectories that were found containing fewer than five images were eliminated; thus, only SCCTs that lasted at least an hour and fifteen minutes were analyzed further. This parameter was selected because a trajectory with fewer than five images would not yield very many angles, and consequently the sample size of data for that particular trajectory was deemed not large enough to constitute a significant statistical relevance if there had indeed been a deviation in the propagation of the SCCT. Any change seen in these small images would have occurred without many other data points to corroborate statistically and firmly establish where the original trajectory was initially headed. After this point, filters for dealing with the biases of the tracking program used to obtain the data were developed. Velocity can be broken down into speed and direction, and thresholds for both were developed to eliminate spurious jumps in trajectory. Certain trajectories were known to have these erroneous jumps because of the operation of the program used to obtain them. The algorithm that tracks the SCCT trajectories, after the SCCT dissipated, would quite possibly pick up on a different SCCT in the vicinity of the previous cloud tower, and continue tracking as if they were a part of the same trajectory, and a part of the same SCCT altogether.

3.1 Filter 1 - Speed

In order to determine and identify these problematic trajectories, in the first filter employed (Filter 1) we computed a velocity differential between successive points; if there was a significant change (significant change was deemed over 50%) in speed between two successive points in the trajectory, the trajectory was truncated before this change occurred and then a new trajectory was initiated following the new SCCT. We calculated speed with the given latitude and longitude data; after a change in latitude and longitude was determined between two successive points in the trajectory, this displacement was converted into kilometers using the standard conversion between degrees of latitude and kilometers, and by approximating the conversion from degrees of longitude to kilometers, as it varies with latitude, based on an approximate average latitude of the two points used to obtain the trajectory speed for that particular leg. After a speed between two successive trajectory images was calculated, we calculated the speed in the next leg of the trajectory. Then, we found a differential between these two speeds, and divided by the original to obtain a percent change. After the truncations occurred, any subsequent trajectory that was fewer than 5-images in length was eliminated from the data set of trajectories, for the same reasons discussed prior to Filter 1. The results of the application of this threshold on two particular trajectories are evident in the figures below.

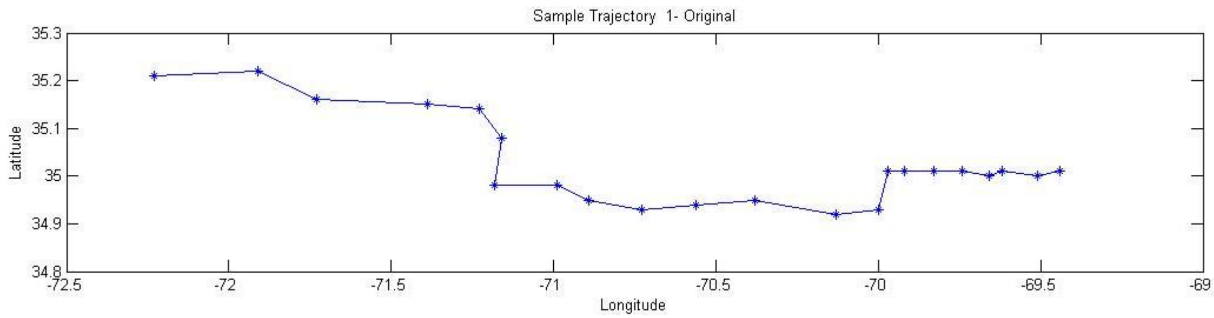

Fig 1: Original Trajectory Sample 2 from Raw Data

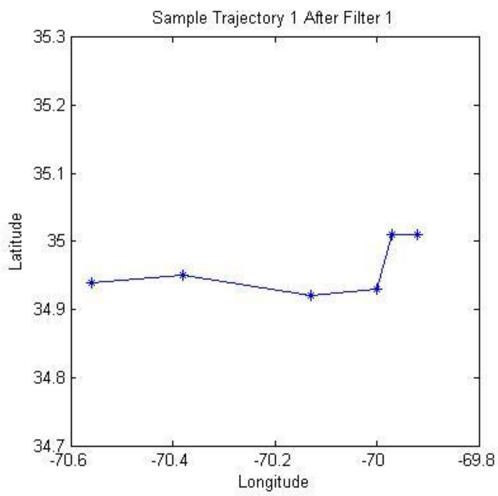

Fig. 2: Sample trajectory 1 zoomed in, after the implementation of Filter 1

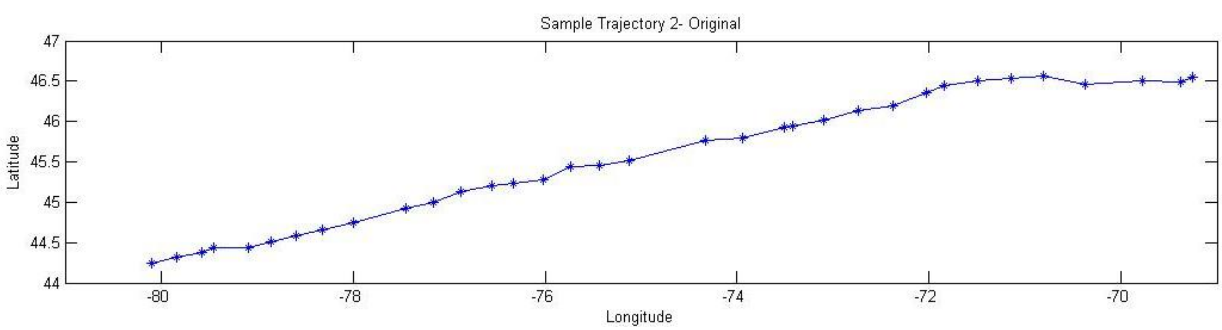

Fig 3: Original trajectory sample 2 from raw data

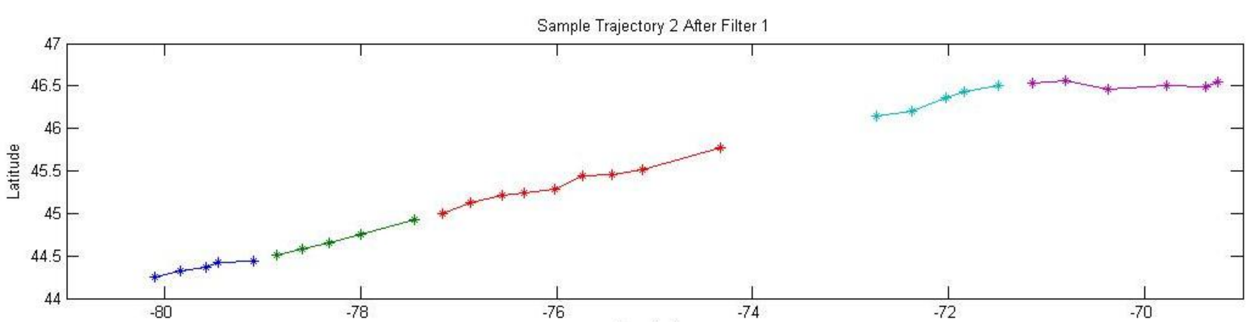

Figure 4: Sample trajectory 2, after the implementation of Filter 1

3.2 Filter Two - Angle

After employing Filter One, a second method (Filter Two) was developed to further eliminate suspected erroneous trajectories. Firstly, angles were calculated using the law of cosines. The diagram below (Figure Five) illustrates its implementation:

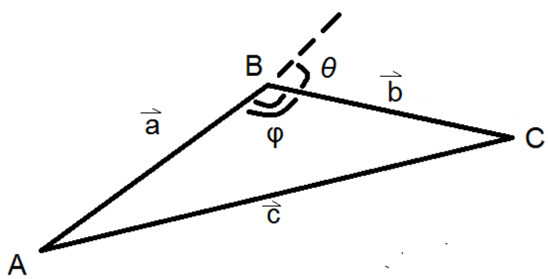

Figure. Five: Vector representation of the trajectory and illustration of which angles were to be computed

In the diagram, φ is the angle calculated between the vectors comprised of points a and b. θ is the angle used as direction for the purposes of this filter, in most cases, as explained later. Once all of these angles were compiled, any angle that was calculated to be over 90^0 was a point where the trajectory was truncated and a new trajectory was started. Then, any newly established trajectory shorter than five-images was eliminated from the pool again, per the same reasons provided earlier. After this method was completed, for each three-point grouping of images, each angle was compared to the following angle in the trajectory (ie. associated with the following three point grouping of images, in this case if the trajectory were extended: B, C, and D). The angles were subtracted and then divided by the initial angle, to obtain a percent change. When the initial angle was calculated as zero, a different method was employed to determine the angle representation of direction. In these cases, a heading with respect to due north was calculated instead. After all of the trajectories that necessitated this additional calculation for angle were processed in this way, percent change was again calculated using the headings to avoid the undefined result when dividing by zero. Any trajectory that deviated more than 50% was chosen to be a statistically relevant perturbation and those three-point groupings in the trajectory were then selected and cross-referenced with the location of nearby urban areas. The method used to do this cross-referencing is the subject of process three. The results after the implementation of Filter two are illustrated in the figures (Figure Six and Figure Seven) below.

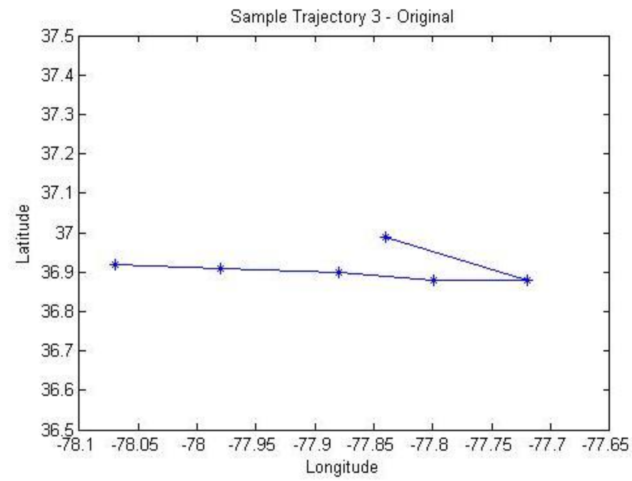

Figure Six: A third sample trajectory, after filter one but before filter two

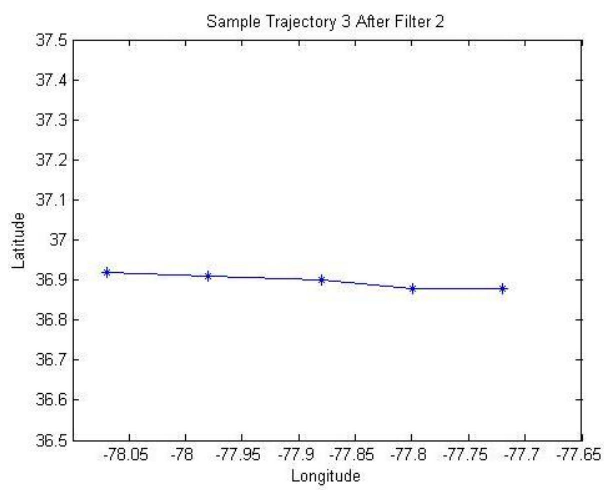

Figure Seven: Sample trajectory three after implementation of filter two

3.3 Density Plot

In order to cross reference this much data over a large domain, covering most of the eastern United States, a way to meaningfully compare the frequency of the location these trajectory perturbations and UHIs, we created a density plot, using a function provided by the Matlab program. Essentially, this function plots a spatial 2D histogram over the domain, calculating a relative (with respect to the entire domain) frequency of data points obtained from the previous Filters. The resulting figure (figure eight) is shown below.

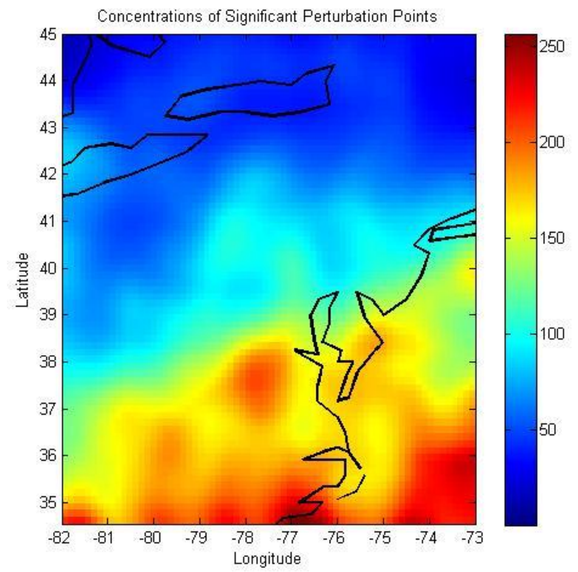

Fig. Eight: Plot of frequency of points in trajectories with over 50% change in angle from one three-point grouping to the next

4. SUMMARY OF METHODOLOGY

Given the cloud trajectory data from the GOES-East satellite, further scrutiny had to be done to account for biases, imperfections, and errors in the tracking of the SCCTs. Filter One was used to find where a significant change in speed occurred from one leg of the trajectory in question to the next. If a certain segment of the trajectory saw a significant change in speed, that was counted as evidence to the effect of an error in detecting and following specific SCCTs, because if the velocity of the cloud tower was changing, it would be most likely accelerate at a constant rate and wouldn't likely see a sudden, abrupt, and significant change in velocity. Secondly, trajectories seen to have an angle greater than 90^0 with respect to the next vector in the trajectory were deemed as erroneous as well because the change in direction from that subdivision of the trajectory to the next was too large to constitute a viable trajectory of an SCCT. After finding the appropriate trajectories, we analyzed each trajectory for points in their movement where their direction changed by more than 50%, a threshold for significance established as statistically relevant for this study. The latitudes and longitudes of these points of significant perturbation were then plotted, and their frequencies calculated by a function already established in the Matlab software.

5. DISCUSSION

From, the results from the implementation of the first two filters developed, it is evident that the selection process was rigorous, and the parameters selected to determine viable and suitable trajectories for this study were stringent, although not all-encompassing. Looking at sample trajectory one, what started out as a wildly varying 22-image trajectory was first shortened and separated by filter one into one smaller, six-image trajectory. Any trajectories that would have otherwise came out of the points from earlier or later in the data set for this particular sample trajectory were eliminated for not containing a sufficient number of data points. It is clear however, that the filter did not eliminate all spurious jumps, as one is evident in figure one. Looking at filter two, any angle larger than 90 degrees was eliminated, however, in any data sets containing angles just under 90 degrees would be ignored, and would not be filtered out. Possible erroneous and random jumps in trajectory, although not evident in figures 6 and 7, consequently, would not be eliminated; as a result, further filters need to be developed to eliminate these jumps.

After the execution of filters 1 and 2, the data set of trajectories was reduced from 288448 to 50631; thus, the performance of Filters 1 and 2 eliminated 82.4% of the original trajectories by marking them erroneous and/or too small statistically. Nonetheless, the trajectories obtained after the execution of the two filters can still be improved upon; spurious jumps in trajectory still exist even after implementing the thresholds in speed and direction.

6. CONCLUSION

Upon plotting the frequencies of the significant perturbation points, there are a few results evident in the image (figure 8). Firstly, on a large scale, there seems to be a latitudinal variation, with larger concentrations of significant perturbation points located in the southern latitudes in the domain. This could be due to the fact that as far as convective cloudiness goes, during the summer a latitudinal temperature gradient persists synoptically due to solar incidence angle. Thus, with uneven heating of the domain, more convective cloudiness would exist in the southern latitudes of the domain. Consequently, as far as frequencies are concerned, any significant patterns that may exist in the northern latitudes of the domain can be washed out by the significant convective cloudiness in the southern latitudes of the domain. Thus, a question remains on how to eliminate this potential bias in a domain of this size. Perhaps one method of eliminating or reducing this bias is to make the domain smaller in order to decrease the latitudinal variation in the domain itself. By, looking at a smaller region around an urban area such as New York City or Washington, DC, a more specific relative frequency of SCCTs particular to that region would be calculated. Subsequently, a relative frequency of SCCTs in that smaller region (perhaps corresponding to an area slightly larger than the metropolitan area of an UHI like NYC) would be more indicative to the number of SCCTs seen in that region in the time period of study. The total number of storms in that smaller regional area would be more effective in calculating a meaningful concentration of significant perturbation points. Another possible way of dealing with this bias may be to take a latitudinal concentration of significant perturbation points. Consequently, concentrations would be plotted at particular longitudes across a specific latitude or latitudes in the domain.

Also evident in the image above (figure 8) is that there is a maximum south of the Potomac River: the urbanized area south of Washington, DC located in Northern Virginia. This result would be consistent with the results seen in the case studies that were discussed earlier in the paper. However, still more questions need to be addressed before any conclusive result is reached because far more factors on movement of SCCTs need to be taken into account, for example: orthographic effects and topographic features such as the Appalachian Mountains. Thus, the result that is evident in the figure above may be consistent with prior case studies, but further questions remain as to how conclusive this consistency is; once other factors that influence SCCT movement are addressed, a more conclusive and significant result and effect could be established.

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