10.1 ECHO CLIMATOLOGY, IMPACT OF CITIES, AND INITIAL CONVECTION STUDIES: NEW HORIZONS OPENED USING 17 YEARS OF CONTERMINOUS US RADAR COMPOSITES

Frédéric Fabry[1], Quitterie Cazenave[2], and Radhakrishna Basivi[1]
[1]McGill University, Montreal, Quebec, Canada [2]Ecole Nationale de Météorologie, Toulouse, France

1. OLD DATA, NEW INVESTIGATIONS

In the early 1990s was deployed the U.S. WSR-88D radar network, the first national Doppler radar network in the world. More importantly, a framework and process for monitoring and maintaining radar data quality was implemented and adhered to since. From 1996 onwards, the reflectivity data has been composited into a national mosaic by a variety of actors, including private companies, research institutes, and the National Weather Service itself. A unique dataset now exists to study radar echoes collected by the same radars over a period of more than 17 years (and counting) over the contiguous United States.

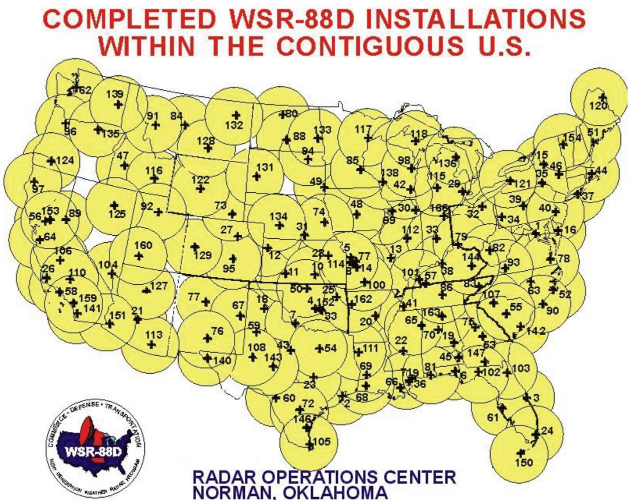


FIG. 1: WSR-88D Radar sites in the contiguous US. Circles have a 230 km radius. Figure courtesy of NOAA ROC.

Radar data offer information on precipitation climatology that is simply not available or archived elsewhere: how often does it rain at any particular location? At what time? And with what intensity distribution? What are the geographical and temporal patterns of precipitation occurrence, formation, and decay? What is the climatology of severe weather? Answers to these questions invariably trigger more questions about the processes causing these patterns as well as suggest some answers. These tend to be of a different nature than those arising from individual case studies because the specificity of atmospheric conditions leading to one storm instead of another are being washed out. What are left are the persistent features that often or always influence precipitation occurrence which, in the end, are the most important to get right both in the context of process studies and of numerical modeling. It may be hard to imagine for researchers in this field that thrive too much on individual case studies what can be achieved by combining more than a decade of radar data, but imagination is truly the limit, and what can be discovered can be mind boggling. A tiny subset of that will be presented in this contribution.

But before we can reach that point, one has to build and look at such climatology, and this has been rarely done. Though radar climatologies have been attempted early on in radar meteorology (Riggs and Truppo 1957) and on and off since (e.g., Wilson 1977), it is only thanks to the work of Rit Carbone and colleagues that it has achieved a timid rebirth (Carbone et al. 2002, Carbone and Tuttle 2008).

The field is hence open, and it makes the exercise even more interesting to undertake. A radar echo climatology for the conterminous U.S. was therefore built, and its initial analysis is presented here.

Of course radar data processing and interpretation is fraught with complications. Are all radars properly calibrated? Have the data been properly cleaned of ground echoes, of insects, of birds? Is radar coverage sufficient everywhere? Are there range or topography dependent biases? These questions both complicate the interpretation of a radar echo climatology and also can be partially answered by it.

2. TO BUILD A CLIMATOLOGY: HARD LESSONS

For reasons of simplicity, and because we did not have access to the raw radar data for the whole U.S. over such a long period, we have chosen to build the radar echo climatology from existing mosaics. But while the radars collecting the data have not changed much since the mid-1990s, the process of cleaning radar data and compositing it into a national mosaic certainly has. And because the interest in radar echo climatology has been small until now, there has been no reanalysis effort undertaken. We must hence contend with radar mosaic maps whose recipe has changed over the years (Table 1). To complicate matters, the early maps we have access to were made by a private company that treats its mosaic making process as a trade secret and will not share it with us.

Corresponding author address: Frédéric Fabry, Dept. of Atmospheric and Oceanic Sciences, McGill University, Montreal, QC, H3A 2K6 Canada; frederic.fabry@mcgill.ca

TABLE. 1: Composite radar maps used in this study.

Period	Source	Resolution	Processing
10/1995-12/2001	Weather Services International (WSI)	5 dB(Z); 2 km * (≤2 km); 15 min	Unknown
02/2002-08/2007	Weather Services International (WSI)	1 dB(Z); 2 km * (≤2 km); 15 min	Unknown
09/2006-03/2011	NSSL / WDSSII via Weather Decision Technologies	5 dB(Z); .9 km * (~1 km); 5 min	Lakshmanan et al. (2006, 2007) 2D composite
03/2011-07/2013	NSSL / WDSSII via Weather Decision Technologies	.33 dB(Z); 1 km * (~1 km); 5 min	Lakshmanan et al. (2006, 2007) US low altitude

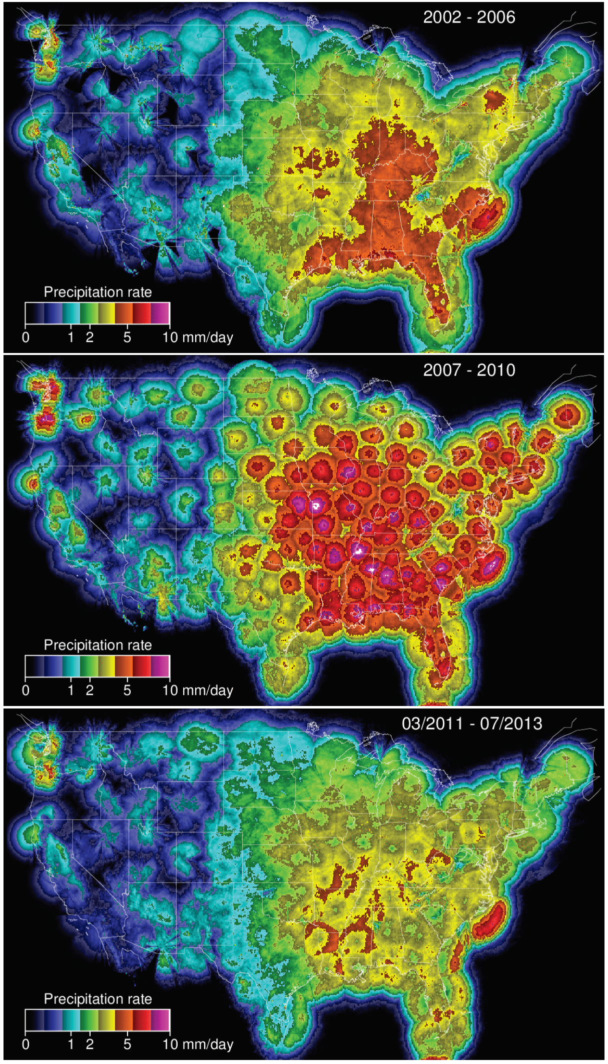


FIG. 2: Average precipitation rates derived from WSI (top), WDSSII 2D (center), and WDSSII US Low-Alt (bottom) radar composites over different time periods.

Let us contrast the average daily accumulations computed by using a single Z-R relationship ($Z=300R^{1.5}$) over years of maps produced by WSI and WDSSII (Fig. 2). They are over different time periods, but long-term accumulations have the power to reveal the weaknesses of each processing approach, and it is on those that we will focus.

It is fairly clear that the three methods of generating composites are qualitatively different. Focusing on the weaknesses, the first has remaining clutter and is slightly biased high when compared to raingauges; the second is strongly biased high, especially near radars; and the third has minima at radar sites and show bright band contamination at far ranges, particularly for the southern radars. It is hard to imagine how one should combine the statistics from these three data sets.

In light of this finding, we have taken the radical decision to eliminate for now the period from September 2007 to February 2011 until we can figure out how to replace or fix the data from that period. Using the two remaining periods, we can almost reproduce with radar the precipitation climatology deduced using gauges (Fig. 3), except in mountainous areas where blockage remains a problem. With these limitations in mind, it looks as if these composites can therefore be used to derive meaningful information.

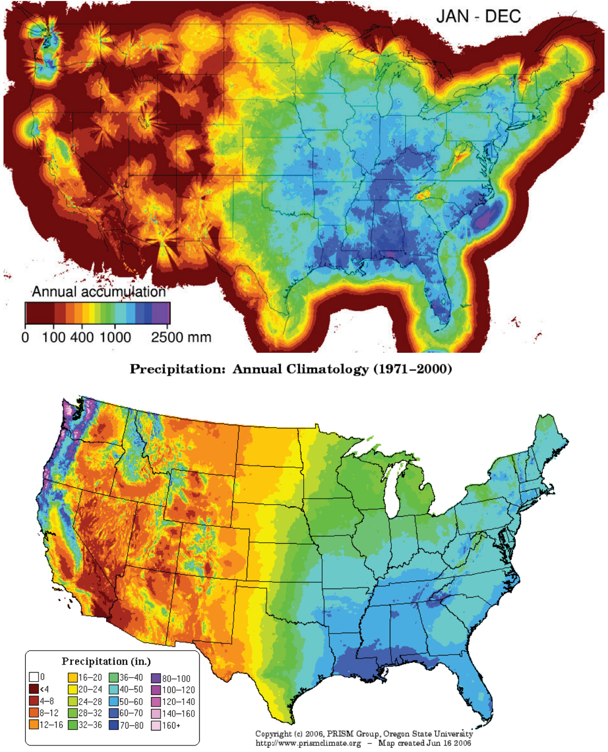


FIG. 3: Average radar-derived precipitation accumulation (top) compared to a gauge-based climatology (bottom).

Two important lessons to be learned from this experience: To the users of products such as radar composite maps, make a few basic checks to ensure that these products will satisfy your needs. To the producers of products, although we really appreciate your efforts, some more information on the strengths and weaknesses of the products is badly needed.

If instead of accumulations we focus on the probability of exceeding a certain reflectivity threshold (Fig. 4), we find that the “footprint” of individual radar coverage is more visible for weaker thresholds, less so for stronger thresholds.

3. PRECIPITATION OCCURRENCE V. THRESHOLD

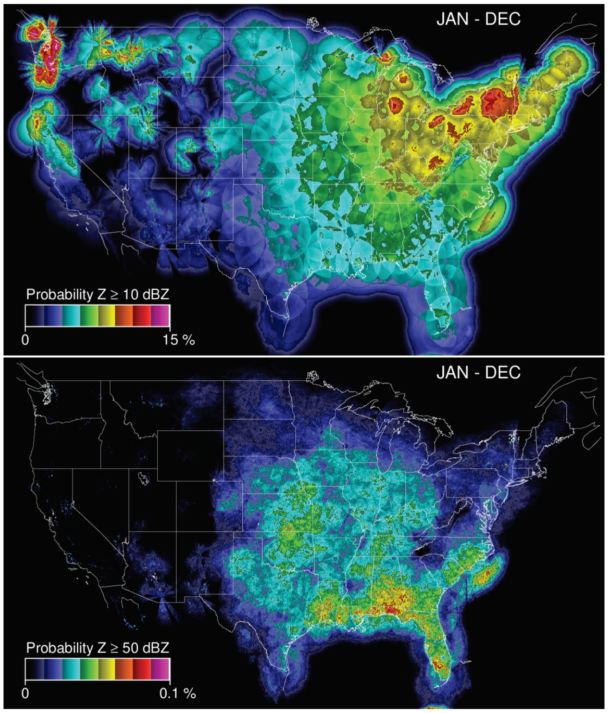


FIG. 4: Probability of observing echoes of at least 10 dBZ (top) and at least 50 dBZ (bottom). Artifact-wise, we can see more artificial transitions at low reflectivity than at high reflectivity. Meteorology-wise, precipitation is more frequent in the mid-latitudes (West Coast & north east). Heavy rain occurrence is highest on the Gulf Coast and southern Atlantic Coast where sea breezes often play a major role in convection initiation, and lowest on the West Coast bathed by cold ocean water. Note how the two images are anticorrelated.

A first set of illustrations of the kind of information retrievable by years of radar data is a set of maps of the likelihood of observing precipitation with different reflectivities. Precipitation (Z ≥ 10 dBZ, Fig. 4) is most frequent in mid-latitude regions to the north, especially near the oceans or the Great Lakes area. Precipitation is observed on average 2 hrs a day in Buffalo (43° N) and 3.5 hrs a day just east of Seattle (47° N) on the foothills of Mount Rainier, but 30 mins a day in Los Angeles (33° N) and 1 hr in Miami (26° N). As we increase the reflectivity threshold, the area of higher occurrence shifts southward. Heavy convection (≥ 50 dBZ) is essentially never observed on the West Coast, detected 0.005 % of the time (30 min per year) in Buffalo, but 6 hrs per year in Miami. If we further increase the threshold to 60 dBZ (Fig. 5, top), a reflectivity associated with hail, the peak of occurrence shifts towards the west of the Central Great Plains, peaking near Amarillo TX (15 minutes per year). Interestingly, the map compares well with that of severe hail occurrence made by the Storm Prediction Center (Fig. 5, bottom), except that it shifts the hail capital away from Norman OK where the SPC is located and where careful weather observers tend to be concentrated.

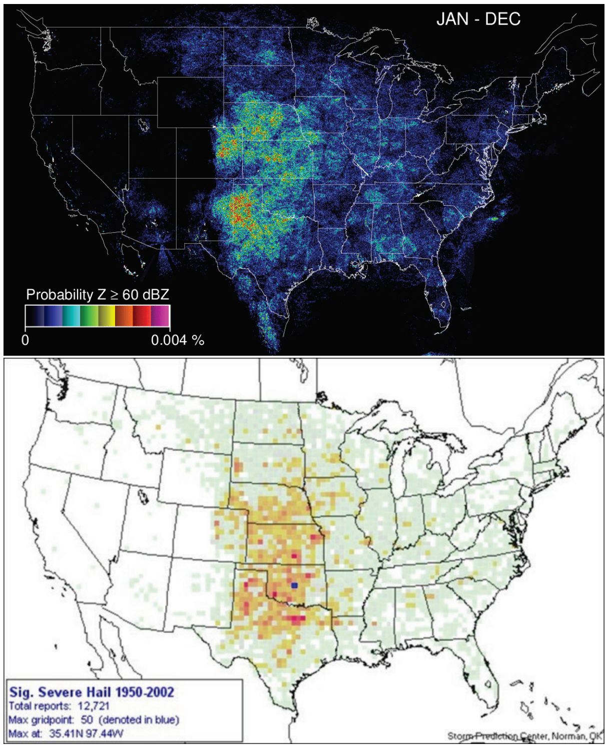


FIG. 5: Probability of observing echoes of at least 60 dBZ (top) compared with the SPC climatology of severe hail (bottom).

While no truly surprising results came out of this exercise, this section illustrates the power of using radar composites for meteorological teaching purposes. Similar exercises could be done by looking at the annual cycle of precipitation; however, we will instead shift our attention towards convection occurrence.

4. CONVECTION: DAILY CYCLE, INITIATION SITES

The Poster Child of radar-based climatology since Carbone et al. (2002) has been the daily cycle of summer convection in the continental United States (Fig. 6): it illustrates how convection forms at various locations during daytime, in particular over the Rockies, and later on the Great Plains, convection that then travels eastward during the night. This process shapes the average time at which convection is observed (Fig. 7): Morning over the warm waters of the south, early afternoon on the southern coasts and over the mountains, late afternoon in the east, in the night in the Central Plains and over the Great Lakes, with no strong daily maxima being observed in the Midwest. In addition of being of meteorological interest, this information could have practical importance, such as for hazard preparedness purposes: for example, if flash flooding is more likely to occur at night in some areas, this may be the time of the day when the most experienced flood management crews should be assigned.

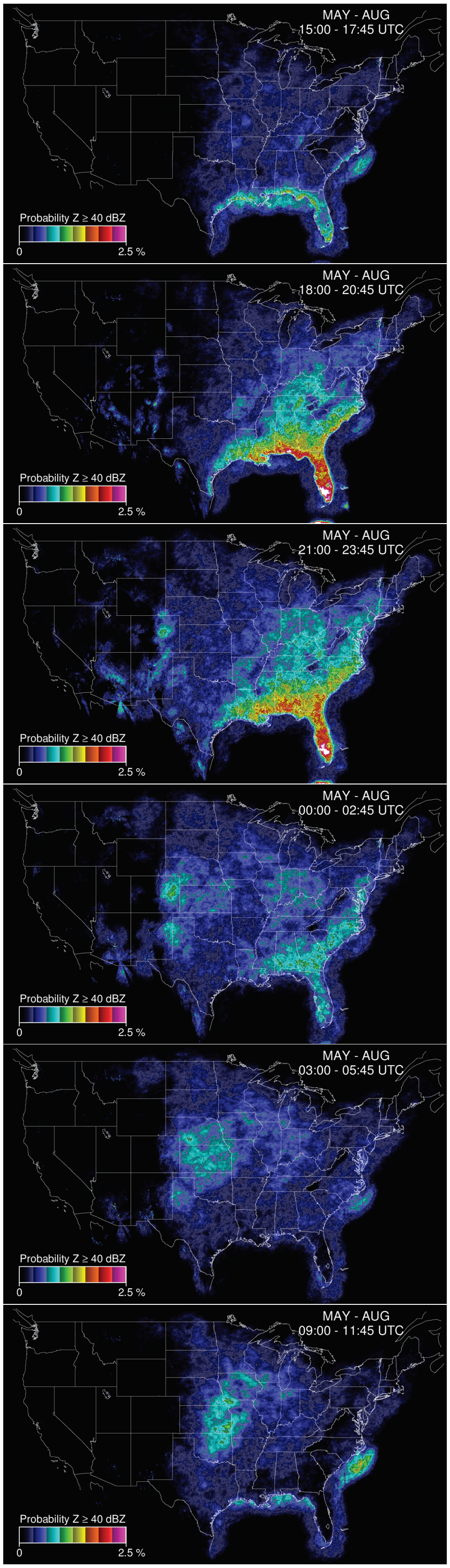


FIG. 6: Likelihood of summer convection: a time sequence.

Convection occurrence is, among others, driven by convection initiation (CI), and it is the spatio-temporal of CI that determines the observed daily cycles in convection occurrence. CI patterns is determined by the timing when and location where air parcels become unstable, and this is strongly determined by surface properties. Because CI is one of the hardest forecasts to make, we were curious to see whether the analysis of many years of data over the continental United States would provide information of value concerning these phenomena.

It is possible to extract events of CI from the radar composites, though it requires a detection algorithm that is more complex than counting the frequency with which echoes exceed a certain threshold reflectivity. In this case, we looked for set of pixels exceeding 40 dBZ that were not present previously. We chose to limit our search to “new” convection events and not to expanding existing convection. As a result, to declare a CI event, we computed the velocity of the cell, and went back in time to ensure that at least one of the two following conditions was met:

I) No pixels above 25 dBZ was observed 30 min prior to the convection event within 30 km of the expected position of the cell; or,

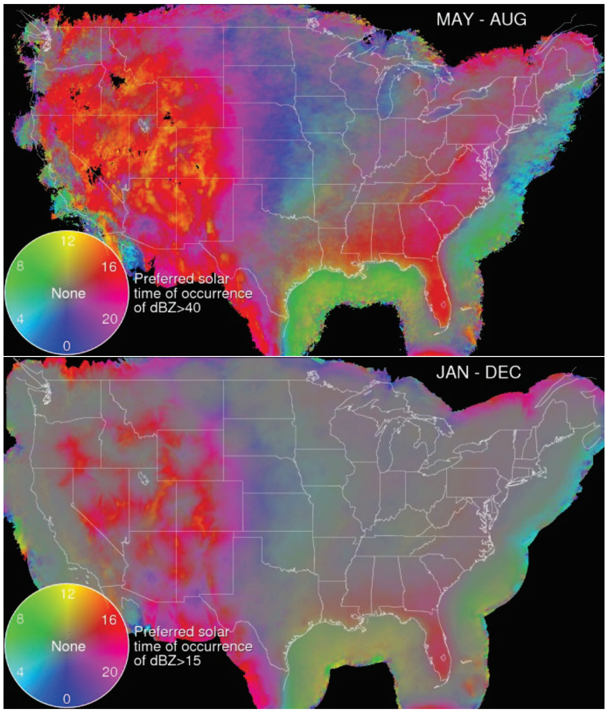


FIG. 7: Map of the solar time at which echoes with reflectivity greater than 40 dBZ can be observed in the summer season (May-August, top) contrasted with the time at which echoes with reflectivity greater than 15 dBZ can be observed throughout the year (bottom). While the hue of the color used indicates the average time at which echoes are observed (e.g., reds indicating peak of occurrence in the afternoon), its saturation (or lack of dullness) illustrates the extent with which echo occurrence is concentrated at one time (bright colors) or spread throughout the day (gray-dominated colors).

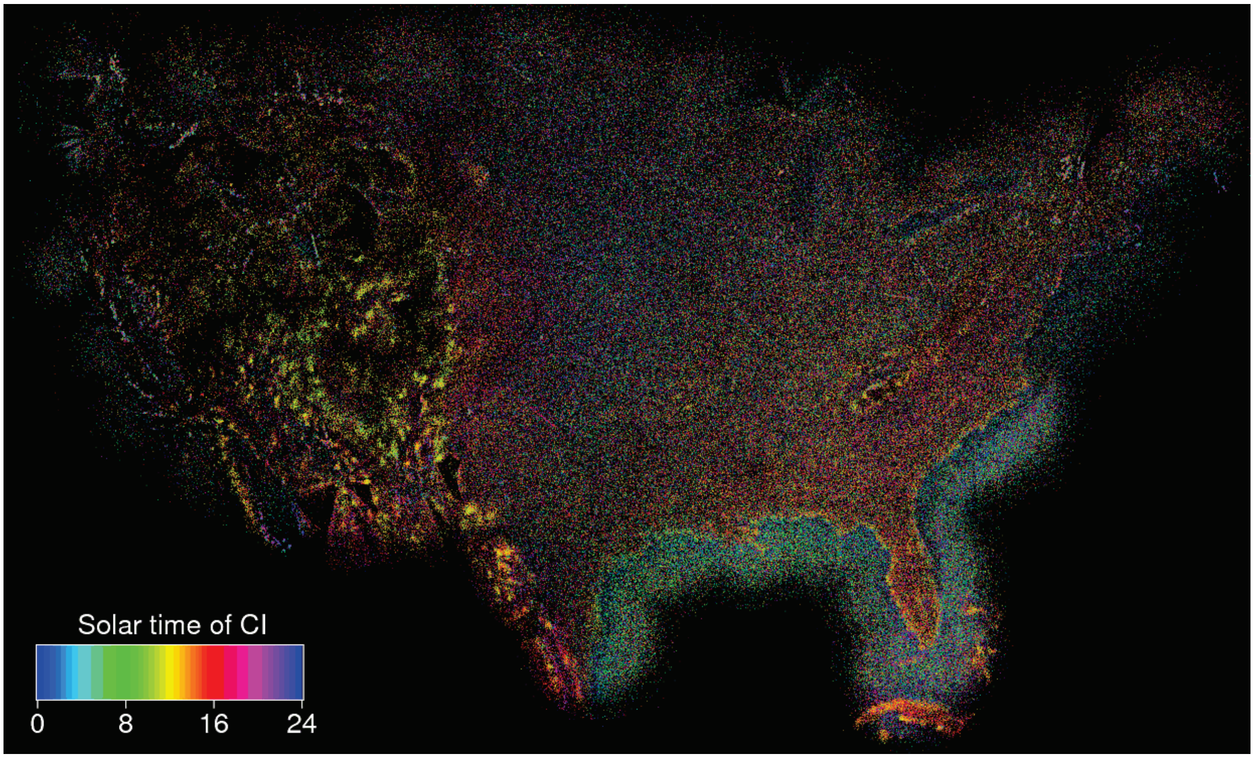


FIG. 8: Location and time of day of the 634010 events of isolated convection initiation identified in the dataset. Each small dot indicates the location of a CI event while the color of the dot is a function of the solar time at which it occurred.

II) No pixels reaching 35 dBZ was observed 30 min prior the convection event within 30 km of the expected position of the cell, and no pixels exceeding 25 dBZ was observed 60 min prior the convection event within 50 km of the expected position of the cell.

These conditions reject a lot of valid initiation events, but we were more curious to see what spatial and temporal patterns would be revealed by this processing rather than getting accurate statistics on the rate of CI events observed at different locations. But, via this process, thanks to the many years of radar data over the whole conterminous United States, 634010 events were logged. Their location and time of occurrence is plotted in Fig. 8.

Somewhat to our surprise, larger number of CI events can be observed over the warm waters of the Gulf of Mexico and of the Gulf Stream, as well as over the peaks of the Rocky Mountains, than over other land areas. This may be partly due to the algorithm used to detect CI that privileges isolated and disorganised convection more typical in these areas. Over land, areas of high number of CIs tend to be areas with more early daytime events, for example on southern coastlines and over peaks of the Rockies and Appalachian mountains. Many of the Great Lakes stand out because fewer events are observed and peak CI occurs at night. And it may be only now that you realize that I did not put any geographical overlay on Fig. 8: one can rely solely on CI timing and occurrence to reveal the geographical features on which these events depend.

5. THE MISSISSIPPI VALLEY SIGNATURE

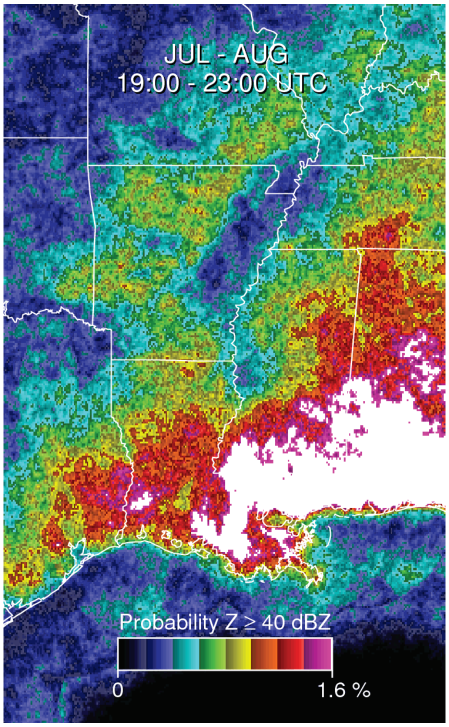


FIG. 9: Likelihood of occurrence of observing echoes stronger than 40 dBZ in the afternoons of July and August (between 19:00 and 23:00UTC) in the Mississippi Valley.

FIG. 10: Natural color satellite imagery of the Mississippi Valley (source: Google Maps).

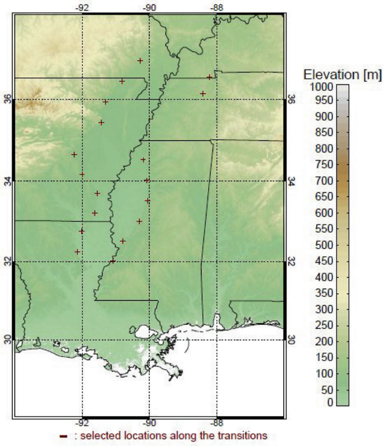
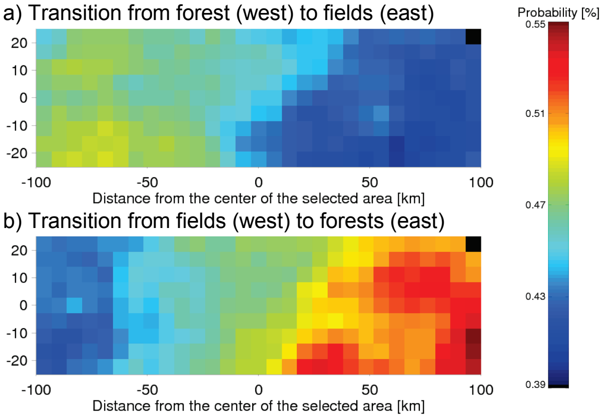


FIG. 11: Topography of the Mississippi Valley. On this map, the crosses indicate the points that were selected to represent the west and the east borders of the valley and whose convection characteristics will be combined.


a) Transition from forest (west) to fields (east)

b) Transition from fields (west) to forests (east)

FIG. 12: Mean occurrence of convection (reflectivities greater than 40 dBZ) around the selected points on the a) western edge and b) eastern edge of the valley. Systematically, more convection is observed over the forest than over the fields.

A feature that attracted our attention in the maps of convection occurrence was the presence of a signature that seemed to match the pattern of the Mississippi Valley. In the afternoon, particularly in the middle of the summer, a pattern of relative minimum in convection occurrence can be observed (Fig. 9). As seen on Fig. 10, the Mississippi Valley is an agricultural area with relatively light surface colors surrounded by darker forests. We then wondered: could the difference in solar energy absorbed and/or evapotranspiration between the two regions drive a change in convection occurrence?

There is, however, a confounding effect: as with all valleys, the agricultural region of the Mississippi is at somewhat lower levels than the forests that are on hilly terrain (Fig. 11). This difference in elevation of the order of 100-200 m might also be sufficient to drive a mountain-valley circulation that could enhance convection over the forested area.

Before one can explore the attribution problem, we chose to document this feature a bit more. Along the valley edges, a set of “anchor points” were selected, displayed as crosses on Fig. 11. Around each of these data points, the occurrence of convection was computed. Then, the data computed for each of these points were averaged for the western edge and for the eastern edge of the valley. The result of that analysis is shown in Fig. 12. When averaging day and night, the difference in convection occurrence between fields and valleys is around 20%. In parallel, whatever convection does occur in the valley in the summer afternoon happens later in the day than over forests (Fig. 13). Hence, it appears that conditions leading to convection occur more easily over the forest in the hills than over the fields in the valley. Whether topography and/or terrain cover are important drivers of that difference remains an open question.

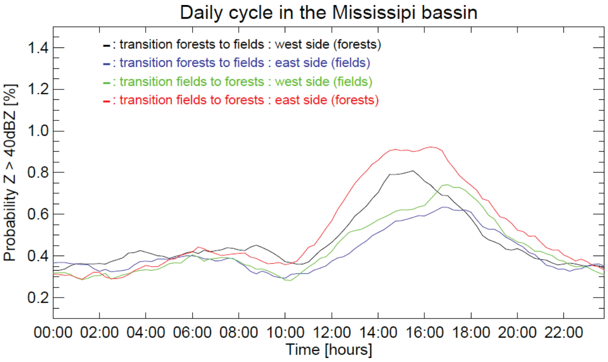

Daily cycle in the Mississipi bassin

FIG. 13: Daily cycle of occurrence of convection in solar time around the Mississippi Valley contrasting the timing of convection over the forest area to the west (black line) and to the east (red line) of the valley with those over the adjacent fields in the valley.

6. EFFECTS OF CITIES ON CONVECTION

Since surface properties clearly play a key role on convection timing and occurrence, we wondered whether the influence of cities on the occurrence of convection could be detected on radar maps. And because we did not entirely trust the radar data because of the tendency of radars to be located in urban areas, we used lightning data in comparison.

Here too, we combined the 40 dBZ exceedance statistics centered on 11 cities. These cities were all the cities above 1,000,000 inhabitants that were away from the Rockies or of coastal regions where poor data quality and other forcing may influence convection statistics. The result, shown in Fig. 14, suggests that cities do have an influence on convection occurrence.

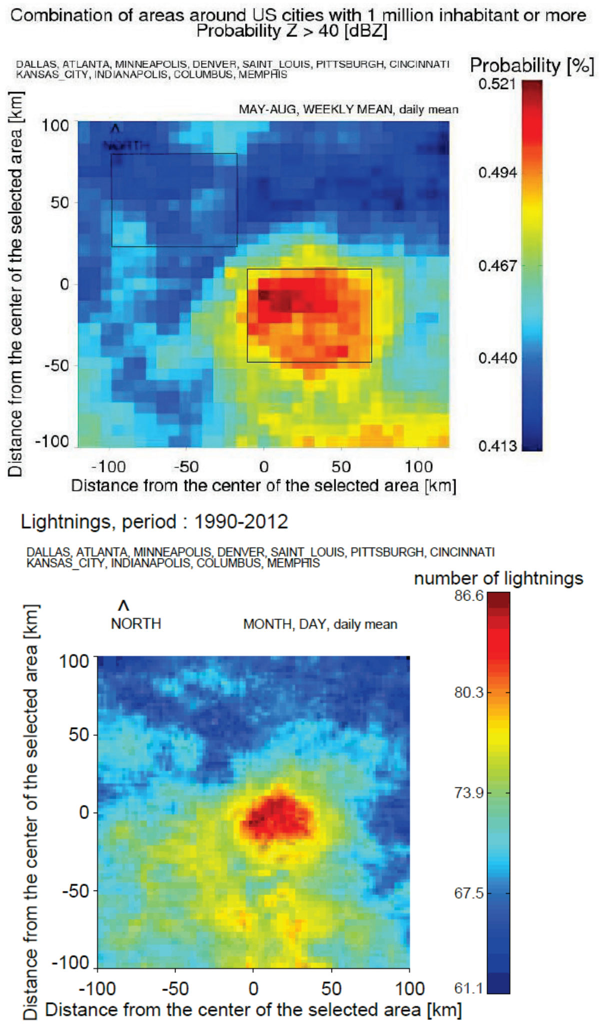


FIG. 14: Top: Occurrence of convection around major urban centers that are away from coastlines. Bottom: Occurrence of lightning around the same cities.

7. WEEKDAY-WEEKEND CONTRASTS

Emboldened by these findings, and tired of hearing from atmospheric chemistry colleagues that aerosols are key drivers of precipitation, we then decided to see whether one could detect a difference in precipitation characteristics between weekdays, when human activity and aerosol emissions peak, and weekends. One of the results of this exercise, show in Fig. 15, shocked us.

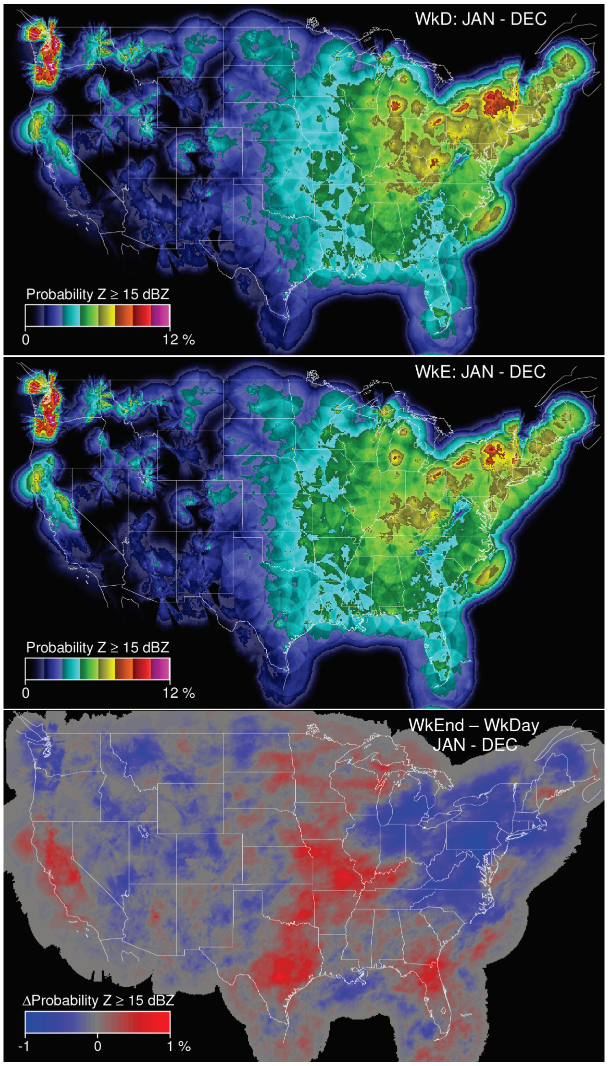


FIG. 15: Probability of observing echoes of at least 15 dBZ on weekdays (Tuesdays-Fridays, top) and on weekends (Saturdays-Mondays, middle), and the difference between the two (bottom).

There is a difference! And over the NE, where combustion-related emissions peak, it is statistically significant! But though such human-activity signals are typically looked for in convective storms, it is in winter precipitation that the difference between weekdays and weekends seems to be most significant, at least in the NE.

What is not entirely clear is the extent with which the difference in reflectivity occurrence between weekdays and weekends is due to a change in rainfall or a change in drop size distributions (imagine this horror movie scenario: DSDs and Z-R relationships as a function of the day of the week…).

8. IMAGINATION IS THE LIMIT

As mentioned before, this is a small sample of what is possible to do when having 15 years or radar data over the whole US at your disposal. We have barely scratched the surface. Imagination is the limit. What will you do with it?

9. ACKNOWLEDGEMENTS

This project was undertaken with the financial support of the Government of Canada provided through the Department of the Environment. But the views expressed herein are solely those of McGill University.

REFERENCES

Basivi, R., F. Fabry, J. Braun, and T. Van Hove, 2014: Precipitable water from GPS over the continental United States: Diurnal cycles, intercomparisons with NARR, and link with convection initiation. *Journal of Atmospheric and Oceanic Technology*, to be submitted.

Carbone, R.E., J.D. Tuttle, D. Ahijevych, and S.B. Trier, 2002: Inferences of predictability associated with warm season precipitation episodes. *Journal of Atmospheric Sciences*, **59**, 2033–2056.

Carbone, R.E., and J.D. Tuttle, 2008: Rainfall occurrence in the U.S. warm season: the diurnal cycle. *Journal of Climate*, **21**, 4132–4146.

Lakshmanan V., T. Smith, K. Hondl, G.J Stumpf, and A. Witt, 2006: A real-time, three dimensional, rapidly updating, heterogeneous radar merger technique for reflectivity, velocity and derived products. *Weather and Forecasting*, **21**, 802–823.

Lakshmanan, V., A. Fritz, T. Smith, K. Hondl, and G. Stumpf, 2007: An automated technique to quality control radar reflectivity data. *Journal of Applied Meteorology and Climatolology*, **46**, 288–305.

Riggs, L.P, and L.E. Truppi, 1957: A survey of radar climatology. *Proceedings of the Sixth Weather Radar Conference*, Cambridge, MA, March 26-28 1957, 227-232.

Tuttle, J.D., and R.E. Carbone, 2011: Inferences of weekly cycles in summertime rainfall. *Journal of Geophysical Research*, **116**, D20213, doi:10.1029/2011JD015819.

Wilson, J.W., 1977: Effect of Lake Ontario on precipitation. *Monthly Weather Review*, **105**, 207–214.