2.4 FROM SEVERE WEATHER CLIMATOLOGIES TO THE IMPACT OF CITIES, OR WHAT WE CAN LEARN FROM 17 YEARS OF US RADAR COMPOSITES

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ABSTRACT

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 have value on their own and also invariably trigger more questions about the processes causing these patterns as well as suggest some answers.

Here, U.S. composites of radar data from 1995 to 2013 are used to demonstrate the possibilities offered by such a data set. Three topics are touched: a) daily and annual cycles of precipitation, convection, and severe weather and what they can teach us about precipitation mechanisms; b) the influence of weekly activity cycles and of cities on precipitation and convection, and on the power and challenges of looking for a small signal in even such a large dataset; and c) the spatial and temporal distribution of the appearance of convection, and what it reveals on the importance of surface terrain properties for these events.

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.

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.

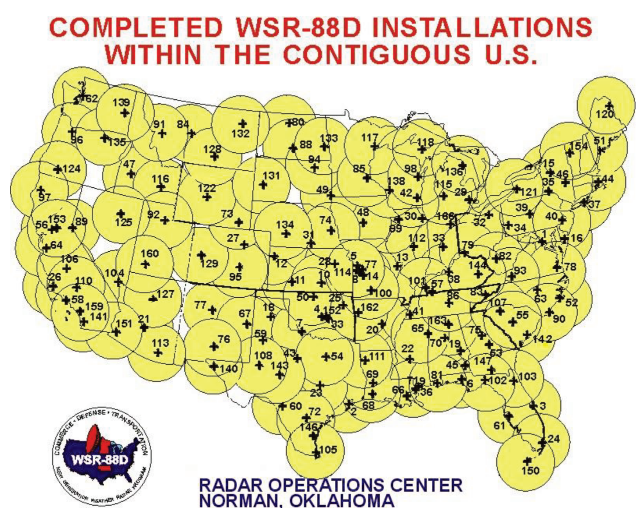

FIG. 1: WSR-88D Radar sites in the contiguous US. Circles have a 230 km radius. Figure courtesy of NOAA ROC.

Of course radar data processing and interpretation is fraught with complications. Are all radars properly calibrated? Have the data been properly cleaned of

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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.

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

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 shows 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.

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.

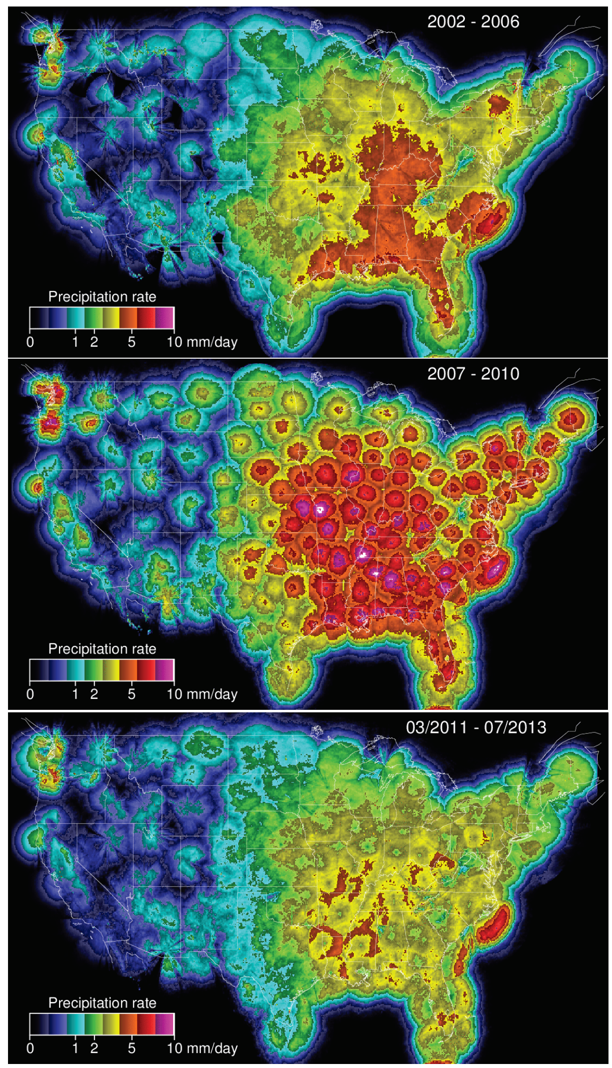

FIG. 2: Average precipitation rates derived from WSI (top), WDSSII 2D (center), and WDSSII US Low-Alt (bottom) radar composites over different time periods.

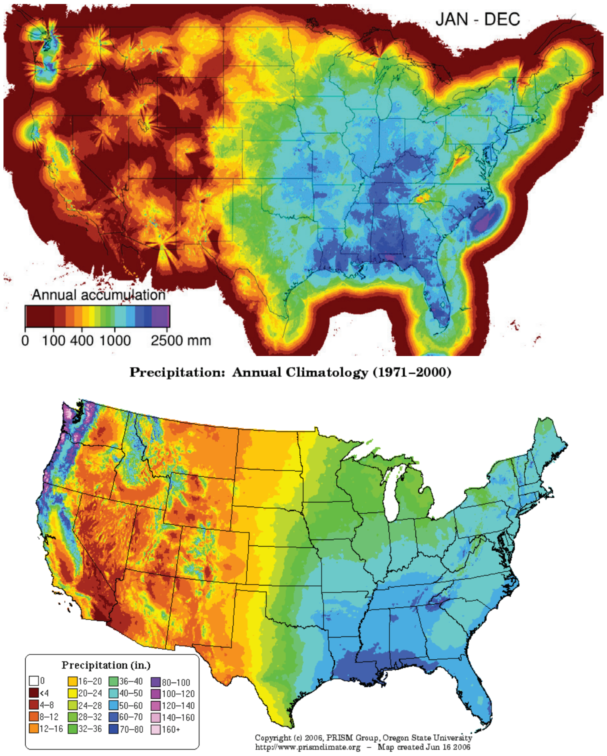

FIG. 3: Average radar-derived precipitation accumulation (top) compared to a gauge-based climatology (bottom).

3. PRECIPITATION OCCURRENCE V. THRESHOLD

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. This figure also illustrates nicely the possibilities offered by radar composites compared to more traditional datasets such as those used by Changnon (1988) to look at the occurrence of thunderstorms and heavy rainfall.

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.

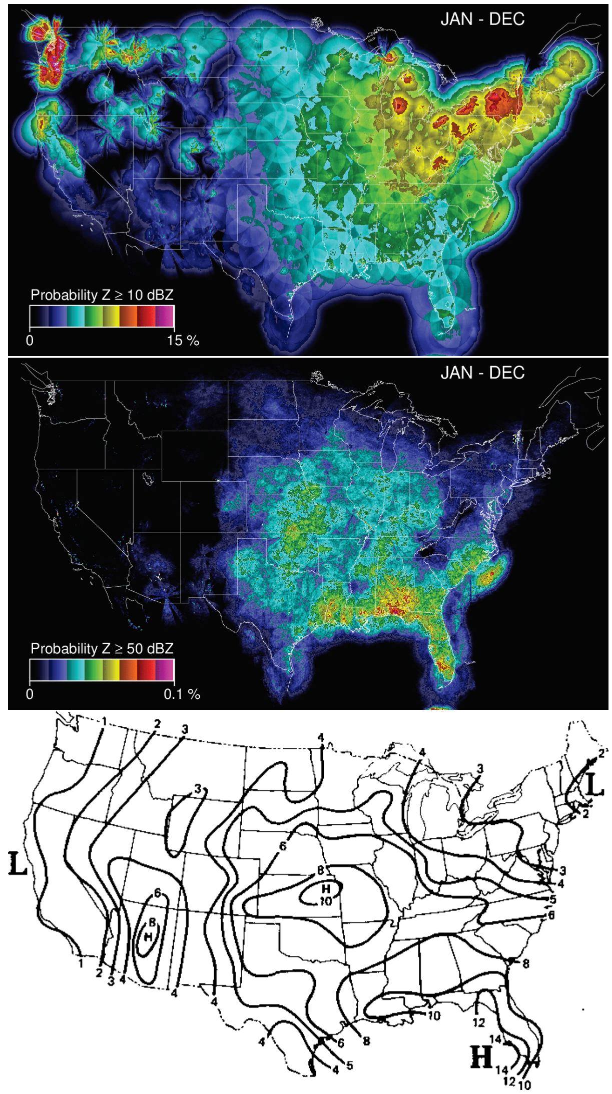

FIG. 4: Probability of observing echoes of at least 10 dBZ (top) and at least 50 dBZ (center). Artifact-wise, we can see more artificial transitions at low reflectivity than at high reflectivity. Meteorology-wise, precipitation is more frequent in the mid-latitudes (West Coast & north east). Heavy rain 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. Bottom: Number of thousands of minutes per year with thunderstorms between 1948 and 1977 (Changnon 1988). Contrast its estimates with those from the 50 dBZ echo occurrence.

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 to a study of more local effects that were at the center of Stanley Changnon's interests.

And this is when the results become interesting.

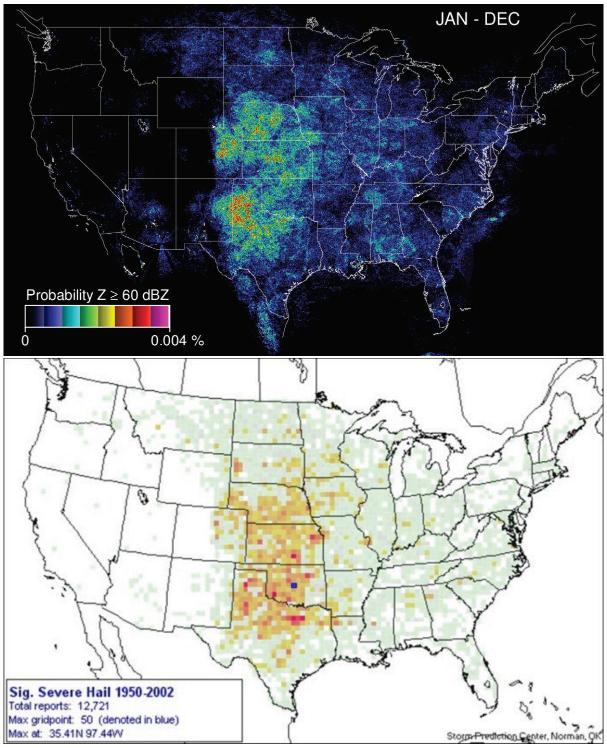

FIG. 5: Probability of observing echoes of at least 60 dBZ (top) compared with the SPC climatology of severe hail (bottom).

4. THE MISSISSIPPI VALLEY SIGNATURE

A first surprise came out in the heavy rain occurrence maps: the presence of a signature that seems 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. 6). As seen on Fig. 7, 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. 7). 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. 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. 8). 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.

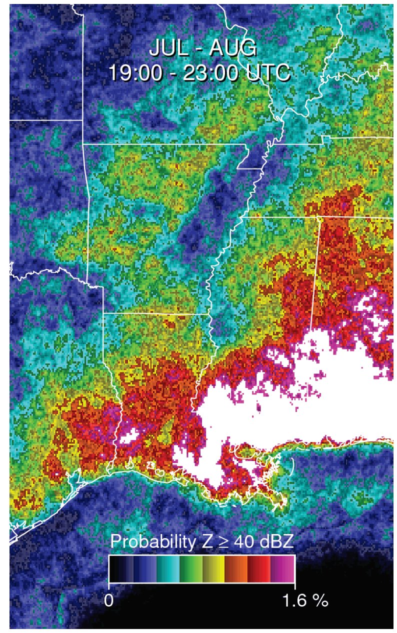

FIG. 6: Likelihood of occurrence of observing echoes stronger than 40 dBZ in the afternoons of July and August (between 19:00 and 23:00 UTC) in the Mississippi Valley.

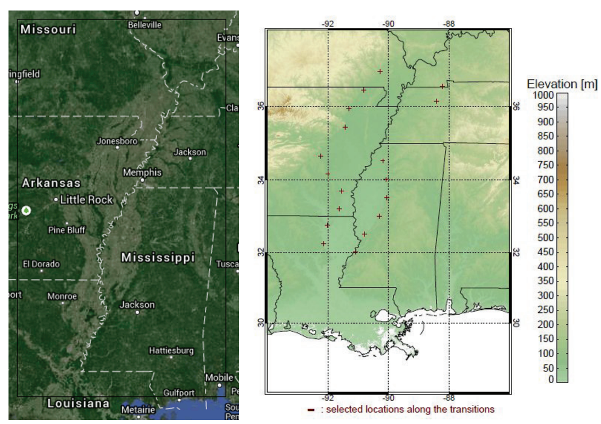

FIG. 7: Left: Natural color satellite imagery of the Mississippi Valley (source: Google Maps). Right: Topography of the Mississippi Valley.

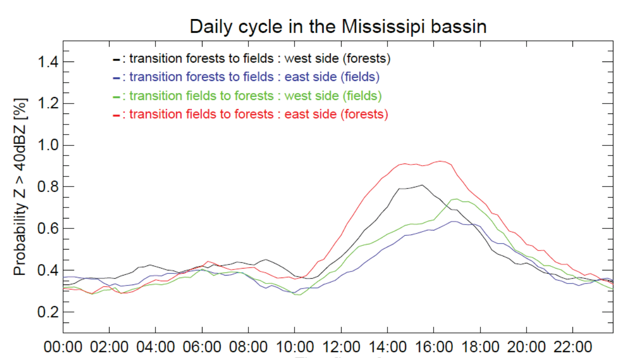

FIG. 8: Daily cycle of occurrence of convection in solar time around the Mississippi Valley contrasting the timing of convection over the forest area to the west (black line) and to the east (red line) of the valley with those over the adjacent fields in the valley.

5. EFFECTS OF CITIES ON CONVECTION

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

In an attempt to reveal the possible signature of urban areas on convection, we combined the 40 dBZ exceedence statistics centered on 11 cities. These cities were all the US cities above 1,000,000 inhabitants that were away from the Rockies or from coastal regions, where poor data quality and more powerful forcings such as those due to water-land contrast may influence convection statistics. The results, shown in Figs. 9 and 10, suggest that cities do have an influence on convection occurrence: in both the radar and lightning imagery, a local maximum can be observed immediately downstream (east) of the city center, and the peak time of convection is also moved earlier, much like the forest did around the Mississippi (Fig. 8). This specific signature is difficult to see for any individual city because of the large variability in convection occurrence over this relatively short time period; but it becomes much more visible when the statistics from many cities are combined. The fact that a similar signature is seen in independent datasets (radar and lightning data), and that the signature seems to have a timing signature (convection downstream of cities speaking earlier than upstream), allude to the fact that this signature is probably not a fluke.

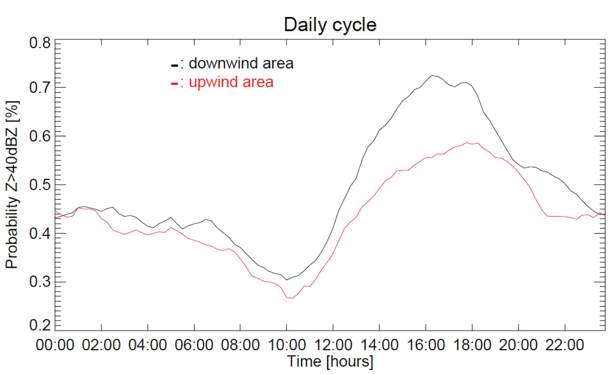

FIG. 9: Daily cycle of occurrence of convection in solar time north-west (upwind, red line) and east-south-east (downwind, black line) of the center of 11 US cities. The areas used to compute those statistics are indicated by rectangles in Fig. 10.

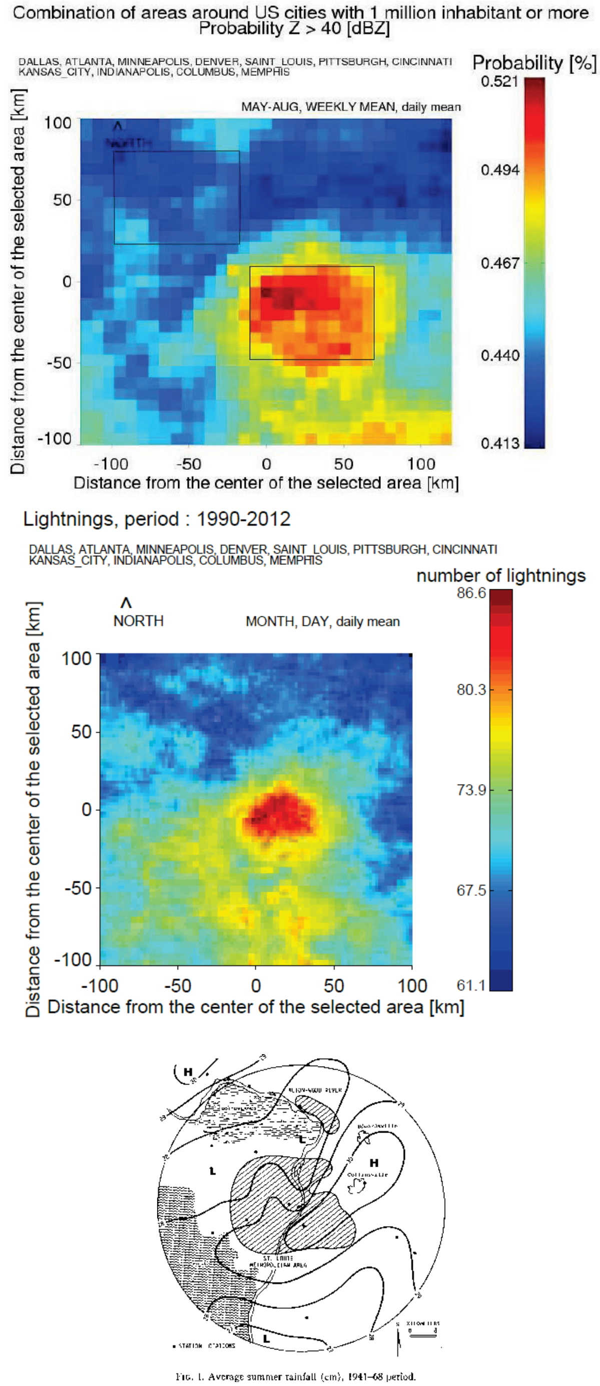

FIG. 10: Top: Occurrence of convection around major urban centers that are away from coastlines and major mountains. Center: Occurrence of lightning around the same cities (units in # of flashes per km^2 over 23 years). Bottom: Average summer rainfall around St-Louis (1941-1968, Changnon et al. 1976).

6. WEEKDAY-WEEKEND CONTRASTS

Emboldened by these findings, and tired of hearing from atmospheric chemistry colleagues without much evidence in terms of examples 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, shown in Fig. 11, shocked us.

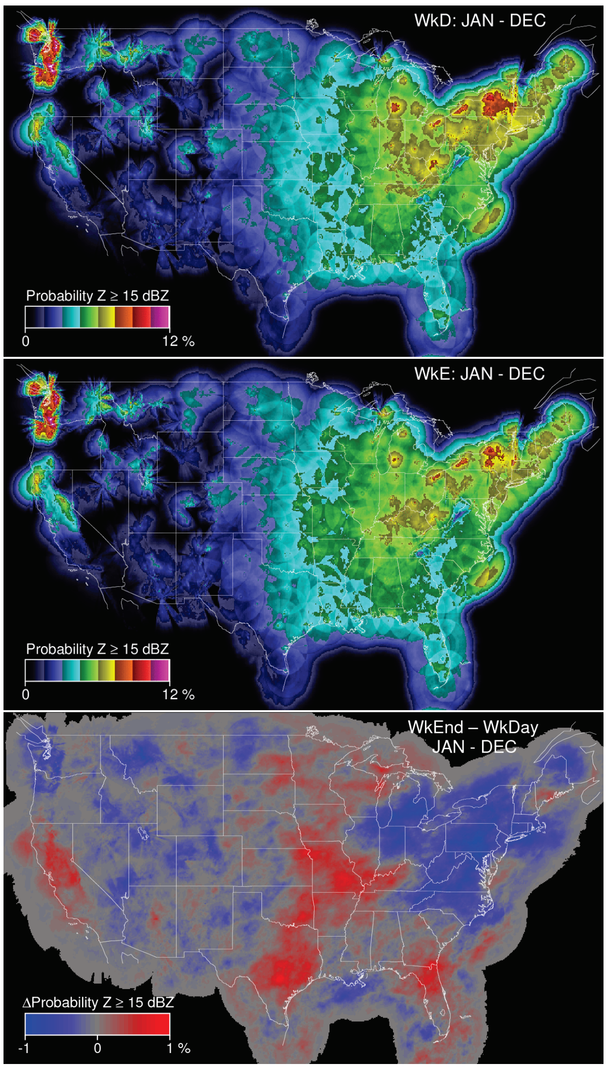

FIG. 11: Probability of observing echoes of at least 15 dBZ on weekdays (Tuesdays-Fridays, top) and on weekends (Saturdays-Mondays, middle), and the difference between the two (bottom).

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.

The three examples above, the Mississippi convection void, the signature of cities, and that of weekday-weekend precipitation, illustrate how, thanks to the distributed data available from radar, we can use a relatively short dataset in climatic terms (15 years for the radar data, 23 years for the lightning) to illustrate processes that were unknown, or have been theorized but not illustrated, or whose existence remains hotly debated.

7. CONVECTION: DAILY CYCLE, INITIATION SITES

The Poster Child of radar-based climatology since Carbone et al. (2002) remains the daily cycle of summer convection in the continental United States (Fig. 12): 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. 13): 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.

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:

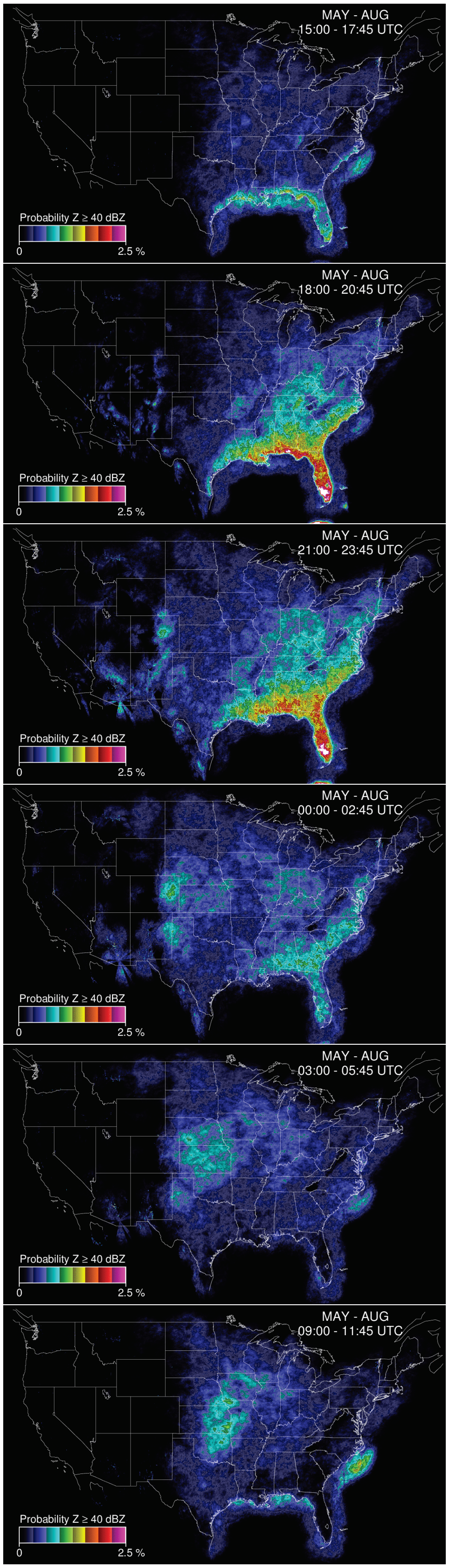

FIG. 12: Likelihood of summer convection: a time sequence.

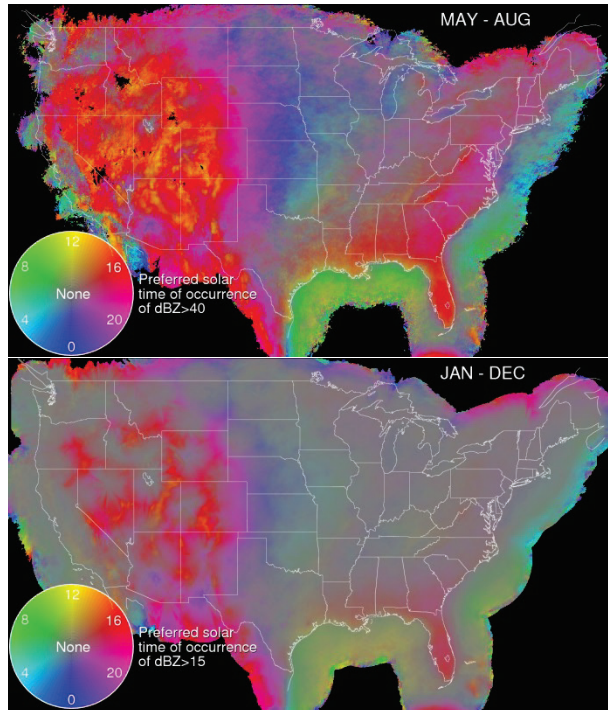

FIG. 13: Map of the solar time at which echoes with reflectivity greater than 40 dBZ can be observed in the summer season (May-August, top) contrasted with the time at which echoes with reflectivity greater than 15 dBZ can be observed throughout the year (bottom). While the hue of the color used indicates 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).

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,

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. 14.

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 we did not put any geographical overlay on Fig. 14: one can rely solely on CI timing and occurrence to reveal the geographical features on which these events depend.

8. IMAGINATION IS THE LIMIT

As mentioned before, this is a small sample of what is possible to do when having 15 years of 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

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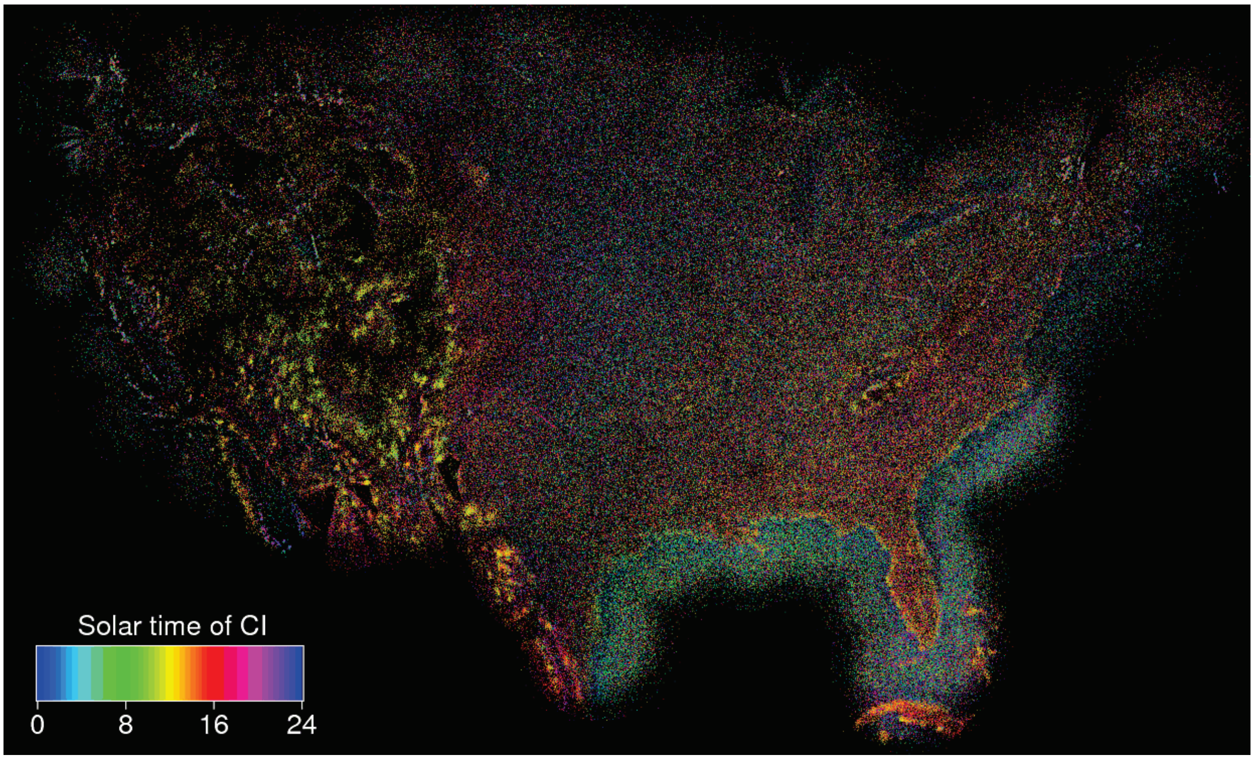

FIG. 14: Location and time of day of the 634010 events of isolated convection initiation identified in the dataset. Each small dot indicates the location of a CI event while the color of the dot is a function of the solar time at which it occurred.

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.

Changnon, S.A. Jr., R.G. Semonin, and F.A. Huff, 1976: An hypothesis for urban rainfall anomalies. *Journal of Applied Meteorology*, **15**, 544–560.

Changnon, S.A. Jr., 1988: Climatology of thunder events in the Conterminous United States. Part I: Temporal aspects. *Journal of Climate*, **1**, 389–398.

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.