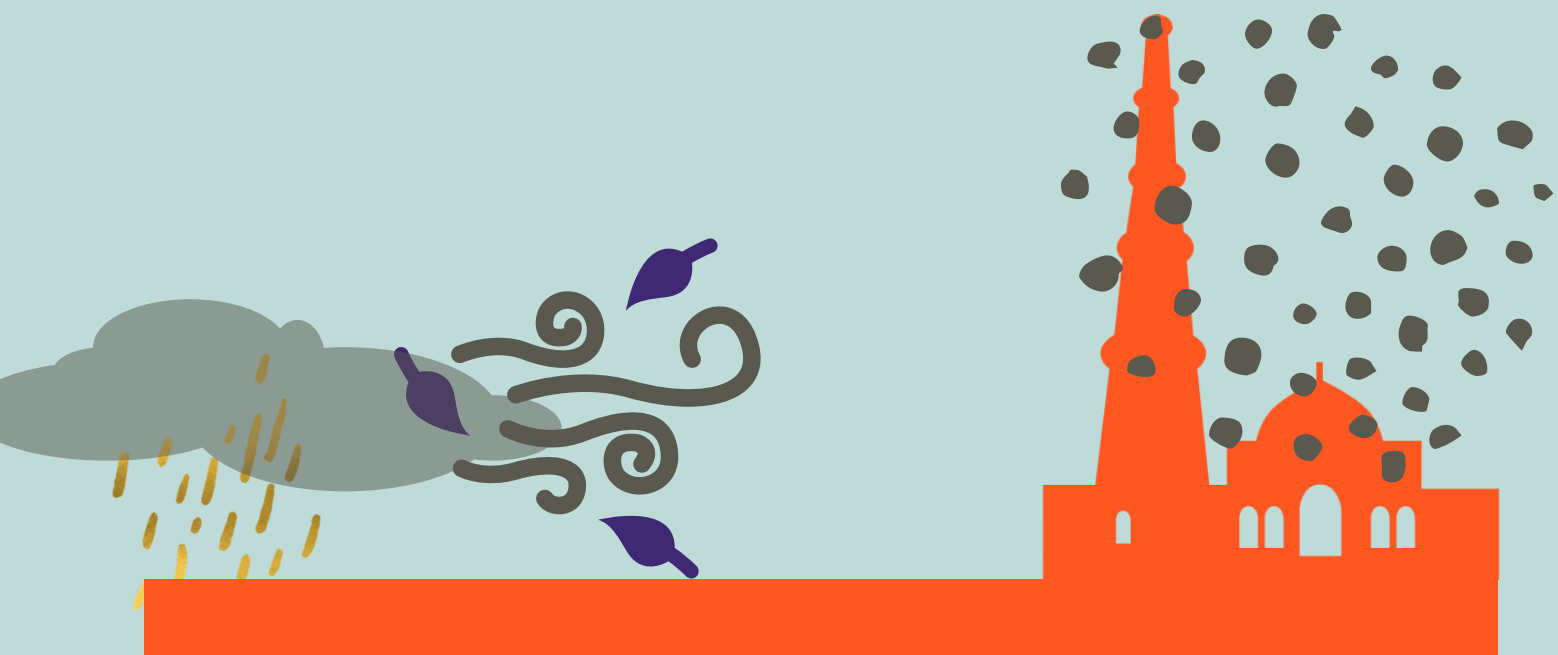




Role of Meteorology on Urban Air Pollution Dispersion

A 20yr Analysis for Delhi, India





(UEinfo) was founded in 2007 with the vision to be a repository of information, research, and analysis related to air pollution. There is a need to scale-up research applications to the secondary and the tertiary cities which are following in the footsteps of the expanding mega-cities. Advances in information technology, open-data resources, and networking, offers a tremendous opportunity to establish such tools, to help city managers, regulators, academia, and citizen groups to develop a coordinated approach for integrated air quality management for a city.

UEinfo has four objectives: (1) sharing knowledge on air pollution (2) science-based air quality analysis (3) advocacy and awareness raising on air quality management and (4) building partnerships among local, national, and international airheads.

This report was conceptualized, drafted, and designed by the members of UEinfo.

All the working papers and more are accessible @ www.urbanemissions.info/publications

Send your questions and comments to simair@urbanemissions.info

Role of Meteorology on Urban Air Pollution Dispersion: A 20 Year Analysis for Delhi, India

Dr. Sarath Guttikunda, New Delhi, India (Email: sguttikunda@urbanemissions.info)

Air we breathe originates from many places and the science (and physics) of meteorology has great bearing on how the air and its constituents move in an urban environment. While the emissions from a region tend to contribute primarily to the local air pollution, depending on the meteorological conditions and the pollutant in discussion, the impact levels can vary.

Typically, the emissions are released from (a individual point or an area) source, which after entering the atmosphere, depending on the meteorological conditions like wind speed, wind direction, pressure, temperature, moisture content, etc., interacts with other pollutants, and depending on the local canopy, either deposits on a surface (as dry or wet) or lingers in the air in the form of pollution, which we breathe (**Figure 1**).

It is given that the air pollution can only be controlled at the source and the limiting factor is most often the balance sheet of costs and associated benefits (like health). However, in some cases, the possible reductions in emissions are a direct function of the geographical location and prevalent meteorological conditions. For example, in cities like Los Angeles or Ulaanbaatar, which form a valley terrain, irrespective of the wind patterns, the emissions tend to stay in the area longer and contribute more to the local air pollution problems. On the other hand, in cities like Bangkok, Beijing, Delhi, Dhaka, and Manila, with flat terrains, the meteorology tends to have higher impact on either dispersing or retaining the air pollution.

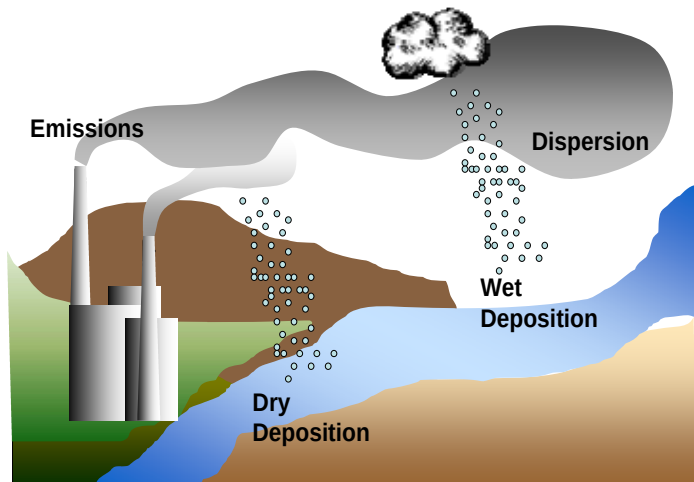


Figure 1: Simulation of air pollution movement

In this regards, a study of air movement over urban areas can help us better understand the movement of pollutants and their respective impact on pollution planning.

Question: How can we assess the seasonality in air pollution? Is there a variation in meteorology which is affecting the measured air pollution levels?

In order to assess the role of meteorology as a diffusing or non-diffusing agent, this paper presents a 20 year analysis of the effects of meteorology on air pollution. The city of Delhi, India is considered for pilot analysis. The study will be extended to 10 more cities in 2010.

Study Methodology

The fundamental parameter in the movement of the contaminants is the wind, its speed and direction, which in turn are interlinked with the vertical and horizontal temperature gradients, both at the regional and local level. In other words, the greater the wind speed, the greater is the turbulence and the more rapid and complete is the dispersion of the contaminants in the air.

The study is designed to evaluate the impact of meteorology on the primary pollutants, released in a dispersion model as a tracer. The movement of the tracer is diagnosed as monthly average relative concentration fields along with the synopsis of local meteorological conditions. The methodology

- is limited to qualitative assessment of the impacts using some quantitative inputs and no attempt is being made to list any working formulae for assessment
- does not list various theoretical approaches to analyzing atmospheric diffusion¹
- is limited to the primary pollutants only. The tracer modeling is conducted assuming no chemical reactions and to study the impact of meteorology only. For example, particulate pollution (PM). It is assumed that the pollutant of concern is PM and dispersion characteristics (dry and wet deposition) used are of PM
- cannot be extended to secondary pollutants like Ozone, which follow a very complex path to the observed concentrations via a series of chemical reactions between Nitrogen Oxides and Volatile Organic Compounds
- is limited to urban scale
- does not attempt to estimate the impact of long range transport. This analysis is limited to studying the impacts of local emissions and their movement based on observed local meteorology.

The study was conducted for a period of 20 years from 1990 to 2008, using the ATMoS² dispersion model and meteorology from the NCEP/NCAR Reanalysis data³.

¹ Refer to the books “Atmospheric Chemistry and Physics” by Seinfeld and Pandis, and “Fundamentals of Atmospheric Modeling” by Mark Jacobson, which provide detailed discussion on the air pollution modeling and involved steps

² For model description and applications, refer to the SIM-air working paper

No.30 “Simplified Atmospheric Transport Modeling System (ATMoS-4.0) for the SIM-air Tool”

@ <http://www.urbanemissions.info/simair/atmos.html>

The outputs of the version 4.0 are customized for use in the SIM-air tool, however the tracer analysis version 3.0 was utilized with gridded meteorology from NCEP Reanalysis data (also available for download upon request)

³ NCEP/NCAR Reanalysis data for a number of meteorological conditions is available for a period starting from 01/01/1948 @ <http://www.esrl.noaa.gov/psd/data/gridded/data.ncep.reanalysis.html>

In the ATMoS dispersion model, the NCEP data is re-gridded and multiple parameters are utilized to establish the mixing layer height. Meteorological parameters utilized are 3D wind and temperature, surface wind, temperature, and pressure, surface heat flux, and precipitation fields. The meteorological processing is conducted before the dispersion modeling.

Study Domain & Dispersion Modeling

The schematics of the model and a representation of the domain are presented in **Figure 2**. The modeling domain consists of a $2^\circ \times 2^\circ$ box ranging from 76°E to 78°E in longitude and 27.5°N to 29.5°N in latitude. The red square indicates the domain in which the tracer emissions were released for this analysis. The $2^\circ \times 2^\circ$ box is sub-divided into 40×40 grid cells and the tracer domain consists of 8×8 grid cells, i.e., 64 cells were assigned tracer emissions.

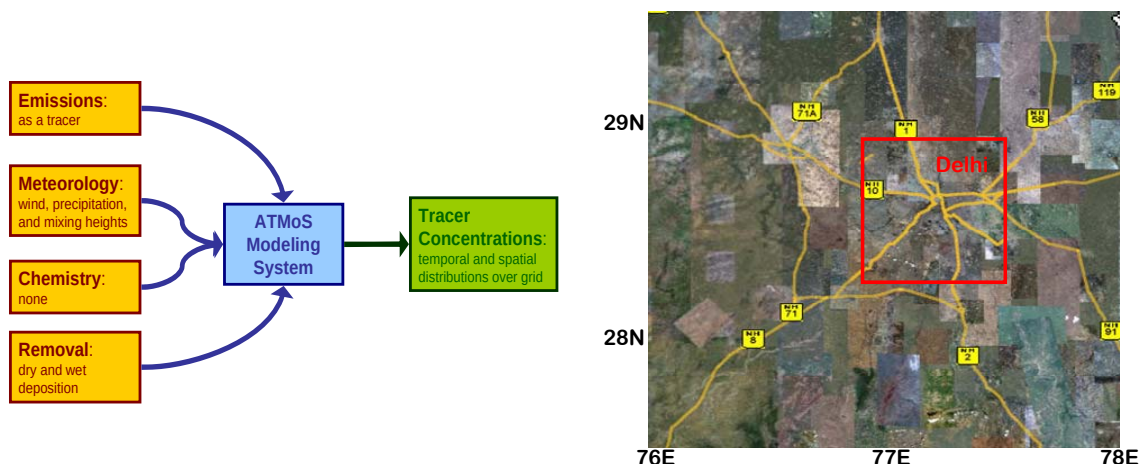


Figure 2: Dispersion model schematics and the modeling domain

The tracer emissions were released at regular intervals (every 3 hr) and advected following lagrangian-puff transport formulation in ATMoS modeling system.

Tracer Modeling Results

Annex 1 presents the results from 1990 to 2008, with 12 panels per page, representing each month. An animation of the 12 month panels and individual monthly results from the 20 year simulation are available

@ <http://www.urbanemissions.info/simair/SIM-31-2010-Met-Impacts-on-AP.html>

NOTE that there is NO legend included in this set of figures, because the results are based on a tracer run and doesn't represent the actual (or modeled) pollution levels in the city.

An important observation is the similarity in the dispersion patterns over the years (1990 to 2008). The same analysis, once substituted with the absolute emissions inventory, will provide a picture for pollution comparisons over seasons.

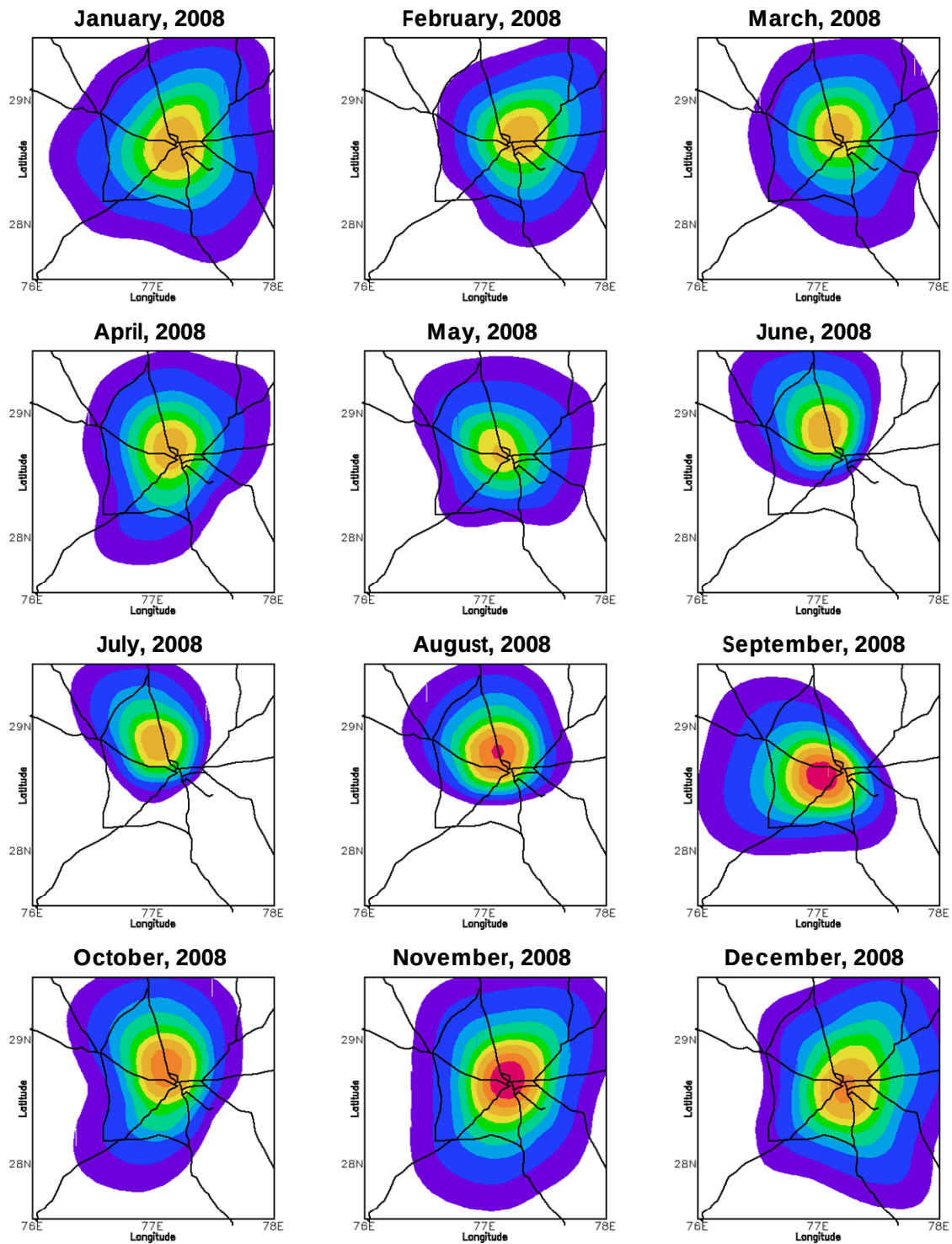


Figure 3: Spatial representation of dispersion of the tracer emissions from Delhi (no legend included for the tracer run)

Monthly Pollution Patterns

A snapshot of results for year 2008 is presented in **Figure 3** and a summary of the variation of the monthly tracer concentrations compared to the annual average for the domain with tracer emissions (red border line domain in **Figure 2**) is presented in **Figure 4**. For convenience only the results from 2001 to 2008 are presented and discussed in this paper. However, the analysis is conducted for the period of 1990 to 2008.

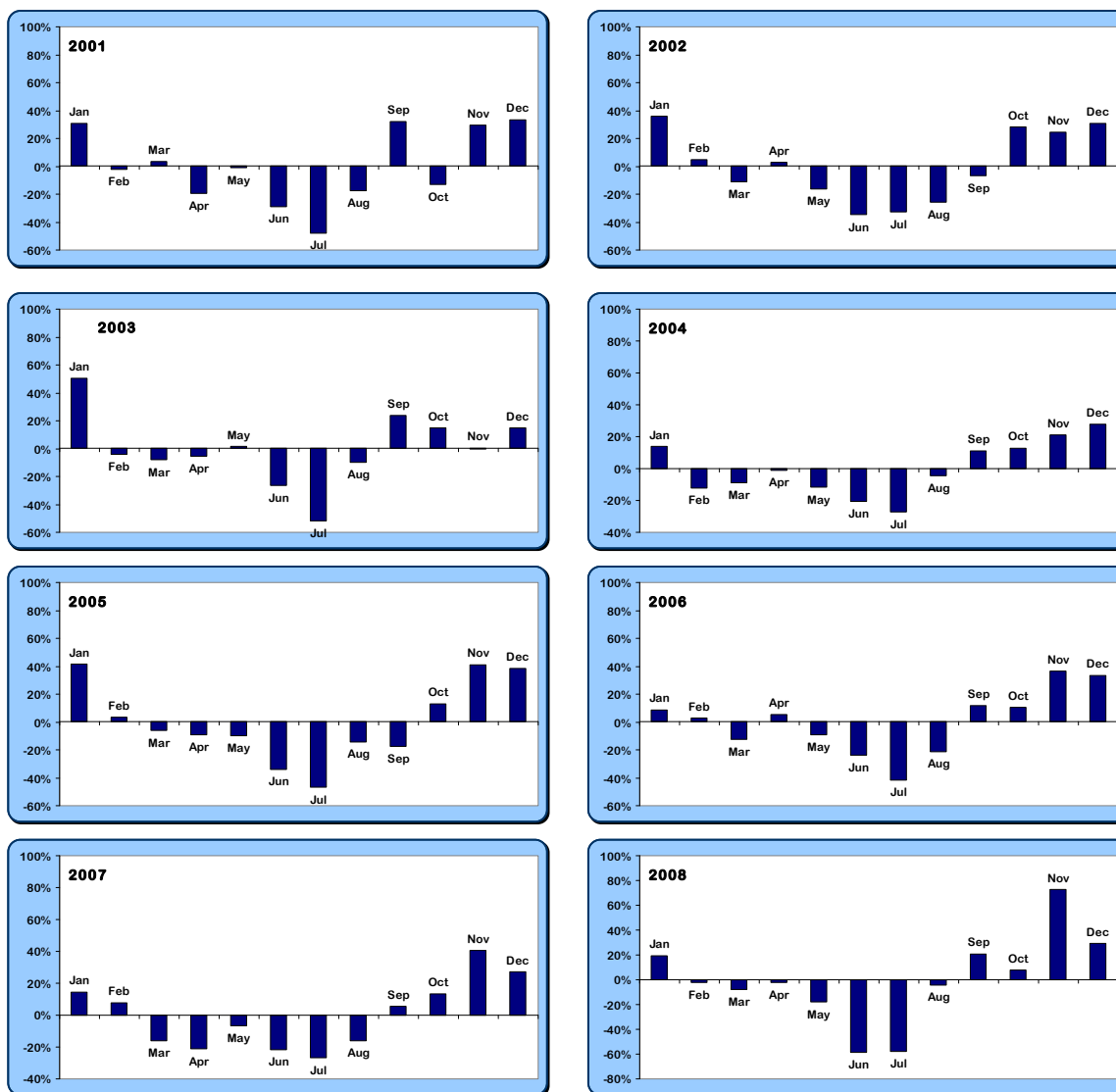


Figure 4: Variation of monthly average tracer concentrations compared to the annual average concentration for the Delhi emission domain

A clear conclusion is that irrespective of the constant emissions over each month, the observed concentrations are invariably 40% to 80% higher in the winter months (November, December, and January) and 10% to 60% lower in the summer months (May, June, and July) when compared to the annual average tracer concentrations for the emissions domain.

The pattern is consistent over the years and the shift is primarily due to the variability in the mixing layer heights and wind speeds between the seasons (and years). During the day, similar patterns are also evident, when the mixing height is routinely lower during the night time compared to the day, irrespective of the seasons.

Mathematically, this is better illustrated in **Figure 5** as a box model. By definition, the ambient concentration is defined as mass over volume. Assuming that the emissions are equally mixed in an urban environment under the mixing layer, for the same emissions, a lower mixing height means higher ambient concentrations.

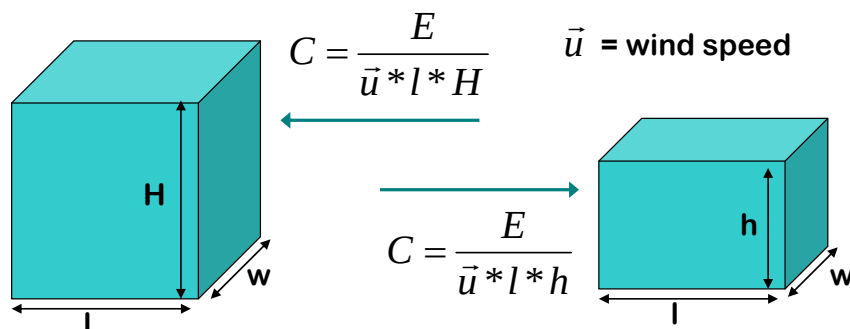


Figure 5: Box model illustration of the impact of the mixing layer height

Similar to the mixing layer height, the wind speed is also very relevant. **Figure 6** presents a summary of the surface layer wind speeds in 2008 from ECMWF for Delhi. The higher wind speeds observed in the summer months are responsible for driving part of the pollution out of the city limits, as evident in the months of June, July, and August (**Figure 3**) when the predominantly southerly winds move the contours more north, and thus reducing the average contribution of the local emissions. The mixing layer height, presented in **Figure 7**, shows the highs in the spring and summer months for the period of 2001-2008.

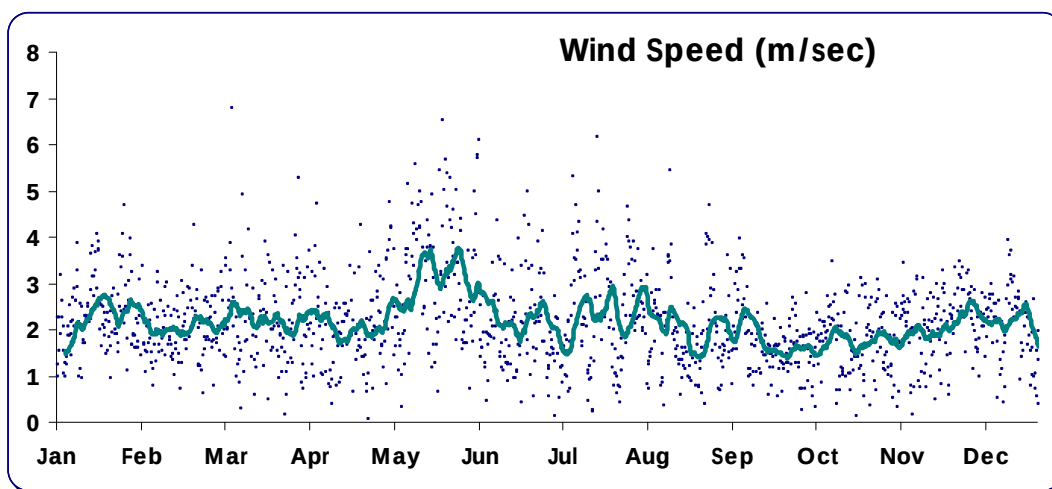


Figure 6: Wind Speed for Delhi domain, estimated from ECMWF

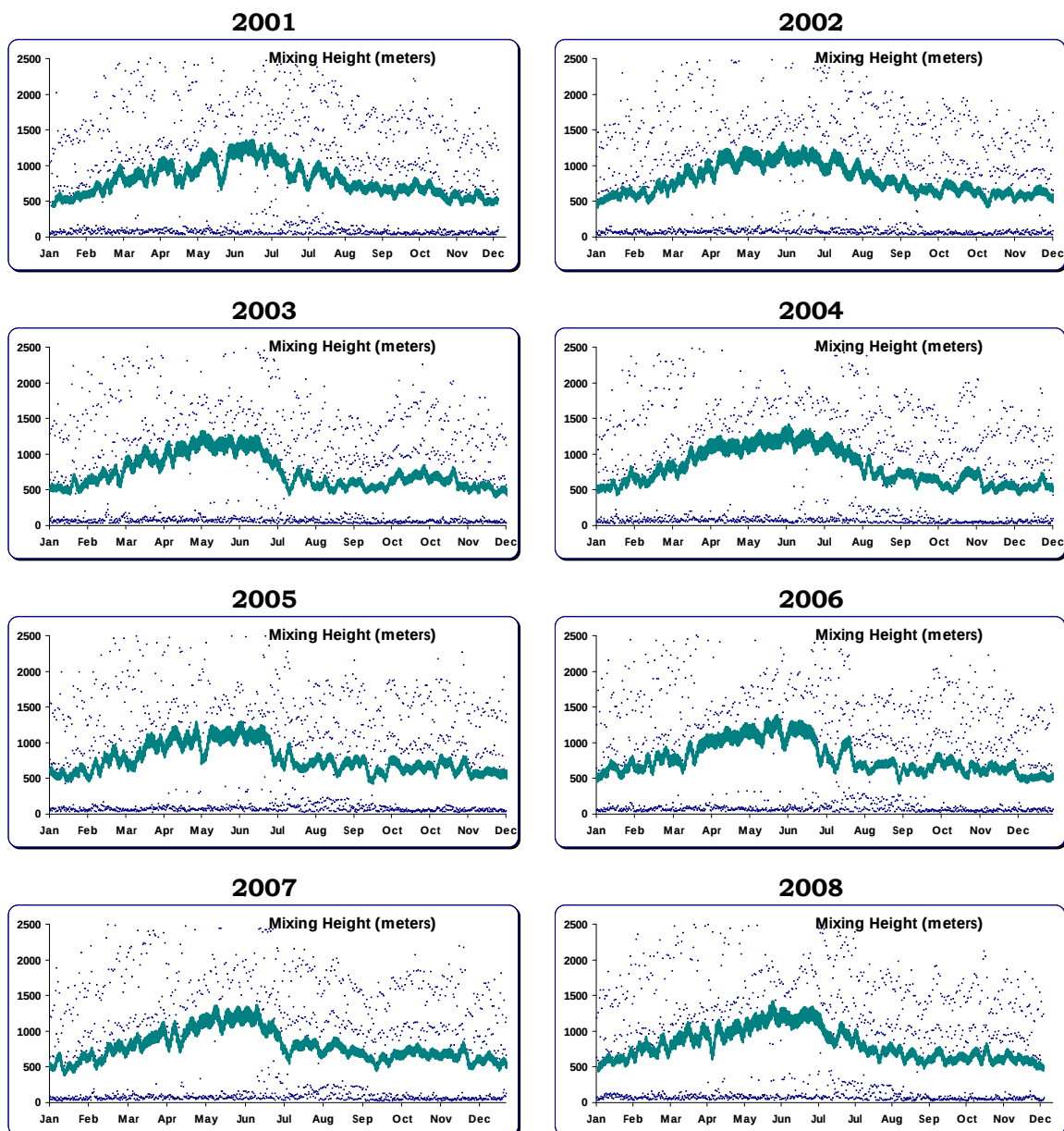


Figure 7: Mixing layer height in Delhi, estimated from NCEP Reanalysis data⁴

It is important to note that while the modeling is conducted using the meteorology pertinent to the city area, the emissions are not. The simulations provide a better understanding of the dispersion of the air pollution in the city, the pollution patterns should be best studied using a local emissions inventory, including the contributions of emissions originating outside the city (transboundary pollution). For example, in case of Delhi, a constant traffic between Delhi and its satellite cities in the south (Gurgaon and NOIDA) is a growing emission source, along with all the industrial estates in the northeast and northwest sectors.

⁴ The thick line indicates a 15 day moving average

Monitoring Data from ITO Monitoring Station in Delhi

The ambient PM_{2.5} (particulates with aerodynamic diameter less than 2.5 µm) levels from one of the traffic junctions in Delhi, the ITO monitoring station, are plotted in **Figure 8** for the period of 2006-09. The monthly variations of PM_{2.5} are very prominent and similar to the estimated influence of the meteorological parameters.

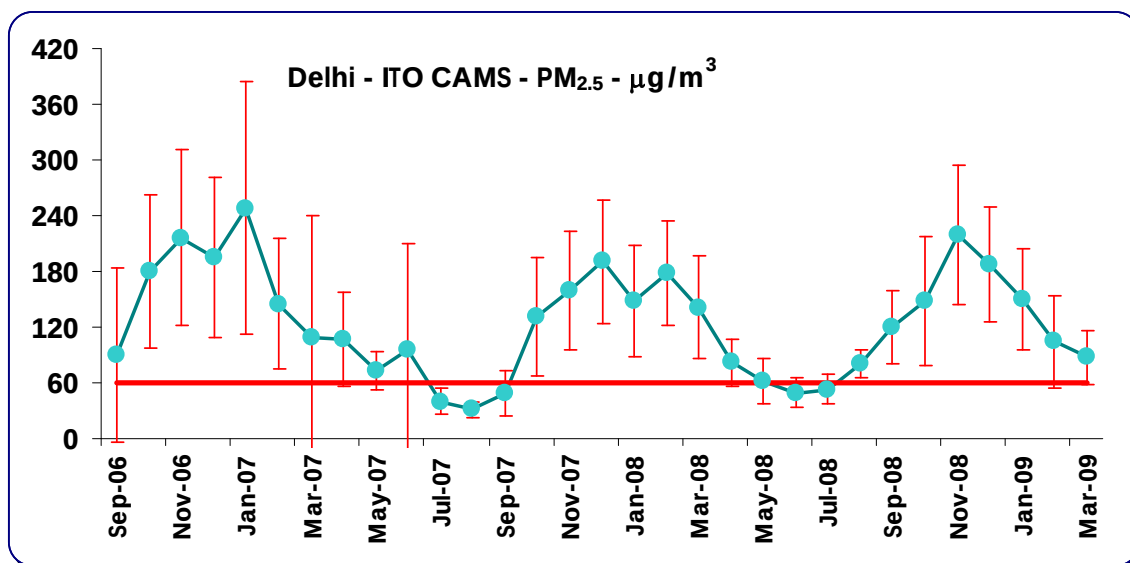


Figure 8: PM_{2.5} monitoring data from the ITO monitoring station in Delhi, India

In 2008, the highs were observed in November and lows in June/July, which coincide with the highest above average tracer concentrations in November and lowest below average in June/July in **Figure 4**.

Similar patterns are evident over the years, with maxima observed over the winter months due to lower mixing layer height and wind speeds and minima over the summer months with higher mixing layer height and wind speeds. See **Annex 1** for monthly variation in the tracer concentrations for the period of 2000 to 2008.

Back-Trajectory Analysis of Meteorological Fields Reaching Delhi

The analysis presented in the previous sections focused primarily on understanding what happens to the emissions originating in the Delhi city limits, but the question of how much is the contribution of emissions outside Delhi to the pollution experienced in Delhi is explored via the back-trajectory analysis.

Similar to the analysis presented in the previous section, the back-trajectory analysis is not aimed at quantifying the contribution of the emissions from the neighboring cities, but to assess the possibility of the contribution of the outside emissions.

The back-trajectory analysis was conducted for the year 2008 using the HYSPLIT (Hybrid Single Particle Lagrangian Integrated Trajectory) model, a web-based portal for trajectory

analysis, utilizing the NCEP Reanalysis data^{5 6}. The trajectories are generated one per day and advected backwards for 24 hours to indicate the meteorological origin of the air parcel⁷. The source point, Delhi, India is assigned at 28.6°N latitude + 77.2°E longitude at 100m above ground level. Each line in **Figure 9** indicates a trajectory for one day.

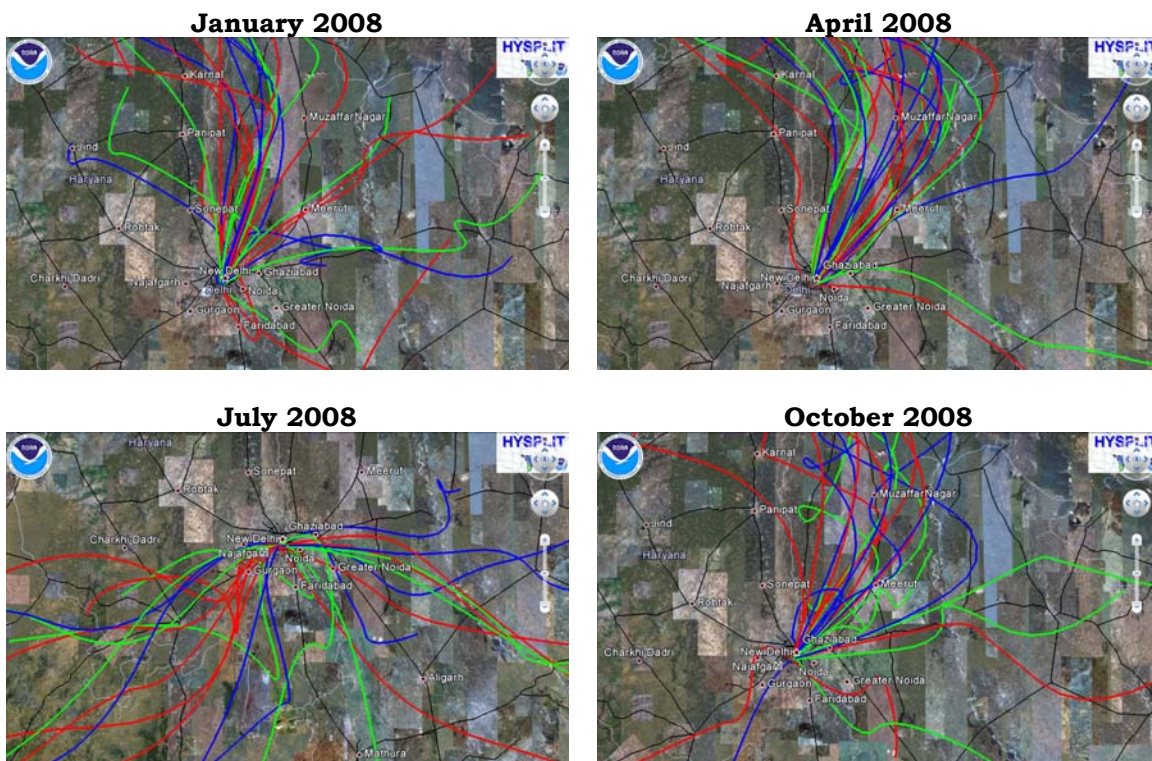


Figure 9: Back trajectories for Delhi, India for four months in 2008

The winter and summer months see a strong influence of northern and northeasterly winds, passing cold temperatures over the city and the resultant low mixing layer heights. The summer and late fall months experience a mix of southern winds, increasing the possibility of pollution entrainment from the southern satellite cities.

⁵ HYSPLIT - Hybrid Single Particle Lagrangian Integrated Trajectory. The details of the model, instructions to generate forward and backward trajectories, and resources should be referred to Draxler, R.R. and Rolph, G.D., 2003, via NOAA Air Resources Laboratory (ARL) website, Silver Spring, MD @ <http://ready.arl.noaa.gov/HYSPLIT.php>

⁶ For convenience, maps from only four months are presented in this paper. Download the google earth kmz files for each month @ <http://www.urbanemissions.info/simair/SIM-31-2010-Met-Impacts-on-AP.html>

⁷ The HYSPLIT model can be used to generate trajectories every 6 hours, since the meteorological data exists at 6 hour intervals

Discussion

The month of October is crucial for the city of Delhi, due to the upcoming Commonwealth Games in 2010. While the infrastructure needs are being taken care by various ministries, the air quality, which is already high among the Indian cities⁸, is a crucial subject for discussion.

Lessons from 2008 Olympic Games in Beijing, China

Air pollution in Beijing received significant attention in 2008 before (and after) the Olympic Games. A number of interventions were implemented in domestic, industrial and transport sectors, to achieve the target air pollution reductions and improve the number of clean air (blue sky) days in Beijing¹⁰.

During the Games, because of the pollution control policies in place, the levels of NO_x (primarily from the cars, trucks, and power plants) plunged ~50 percent. Likewise, levels of PM fell ~20 percent (**Figure 10**).

The traffic restrictions included shutting down 50% of the passenger vehicles (depending on the registration number) every day. And at the industrial level, a number of small and large scale industries were shut down. Most importantly, a number of industries were also shut down in the neighboring cities, to cut down the long-range transport of primary pollutants.

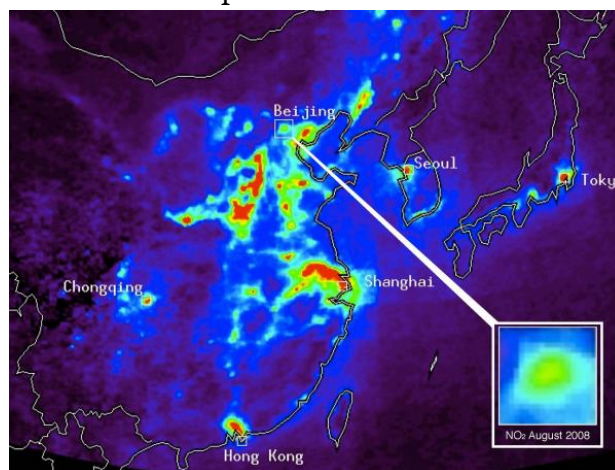


Figure 10: Averaged change in the levels of NO_x during the Olympic Games⁹

Wind Blown Dust & Smoke

Natural phenomena also causes a considerable amount of air pollution. One of the major natural sources of air pollution is volcanic activity, which at times spews large amounts of ash and toxic fumes into the atmosphere, but do not exist in the vicinity of Delhi. Though seasonal, dust storms from the Thar desert (to the west) and arid regions and smoke from

⁸ A detailed analysis of the particulate pollution in India is presented in the SIM-air working paper No.27 "PM Pollution in India in 2007" @ <http://www.urbanemissions.info/simair/atmos.html>

⁹ Science Daily, "Olympic Pollution Controls In Beijing China" December, 2008 @ <http://www.sciencedaily.com/releases/2008/12/081216131016.htm>

¹⁰ UN news center, "Beijing Olympics raises bar on eco-friendly sporting events", on February 18th, 2009 @ <http://www.un.org/apps/news/story.asp?NewsID=29935&Cr=sport&Cr1=environment>

UNEP's independent environmental assessment of Beijing Olympics Games 2008 @ http://www.unep.org/sport_env/Activities/BeijingReport08/

A photo summary and statistically analysis of blue sky days in Beijing @ <http://www.asiasociety.org/beijingair/#statistically-speaking>

forest and grass fires contribute substantially to PM pollution. Due to the magnitude of the impact of these events, pollution due to natural phenomena is more of a regional concern than an urban issue. **Figure 11** presents satellite images from two recent episodes in Northern India, experiencing the long range dust and smoke.

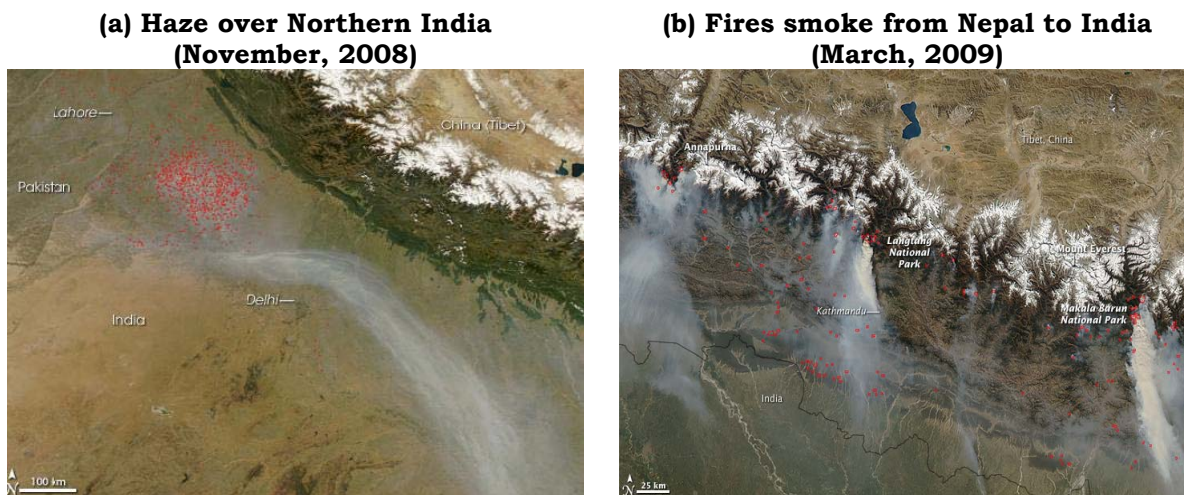


Figure 11: Haze and forest fire smoke reaching Northern India¹¹

The dust events can only be predicted using satellite and modeling data, but cannot be prevented. However, the smoke due to forest fires can be prevented, following cautionary measures during the burning seasons. The dust events are known to raise the PM levels in the cities above WHO guidelines¹².

It should be noted that dust storms and burning are not necessarily natural phenomena. Desert crusts and vegetation can be destroyed via construction activities in the cities, thereby creating a reservoir of suspendable dust during high winds. These with anthropogenic activities, compound the impact of what might otherwise be viewed as purely natural phenomena, and they may change the importance of these pollution sources within the context of an air quality management program.

In Conclusion, similar to Beijing, China, the interventions in the transport sector like newer buses and metro rail will be crucial in reducing the air pollution, but more is required from the industrial sector (either shutting down or relocation) to achieve the clean air norms in the city. At the same time, given the proximity and the synoptic meteorological analysis, the interventions introduced in the satellite cities and a regional pollution control program will be critical in decision making for clean air during the Commonwealth Games in October 2010.

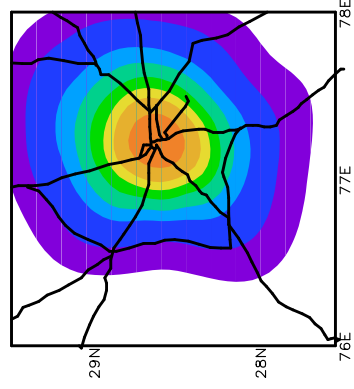
¹¹ Haze over Northern India – Observations of November 5th 2008, http://www.nasa.gov/mission_pages/fires/main/world/indiafire_20081105a.html

¹² During these dust storm periods, PM measurements of over 1000 $\mu\text{g}/\text{m}^3$ were recorded in Northeast China and Mongolia.

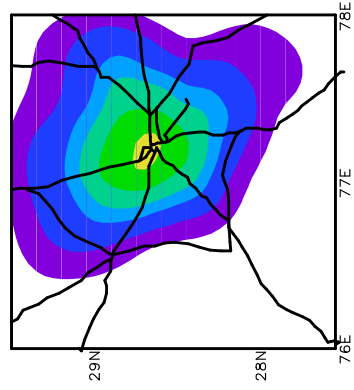
Annex – 1

**12 month panels
Tracer run results for the period of 1990-2008
for Delhi, India**

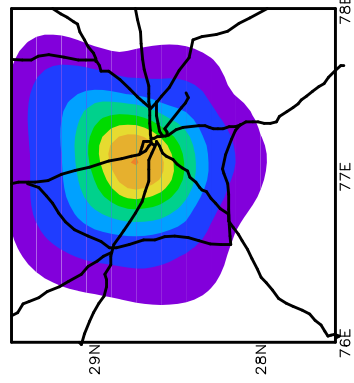
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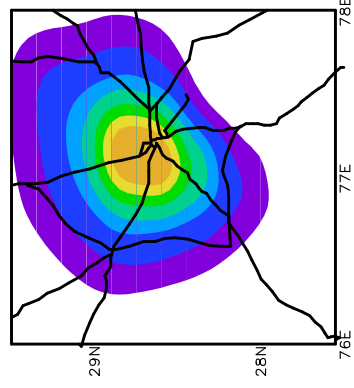
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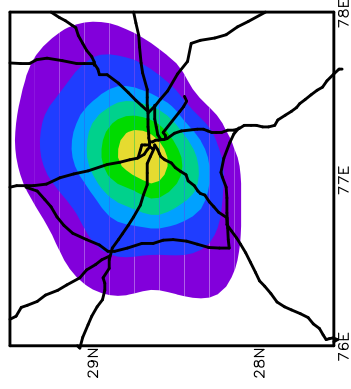
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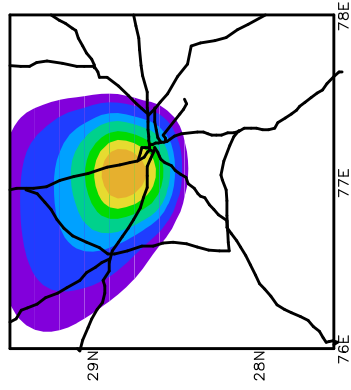
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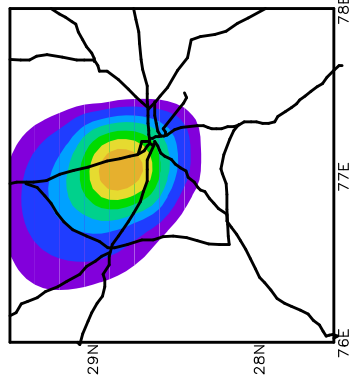
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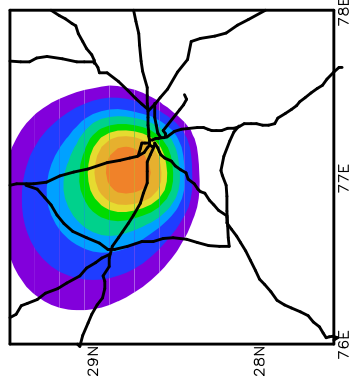
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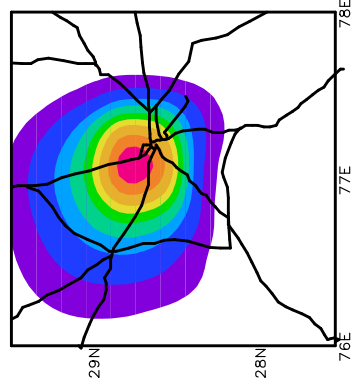
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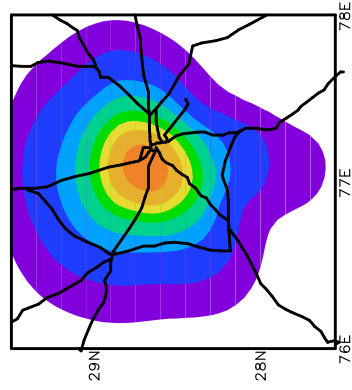
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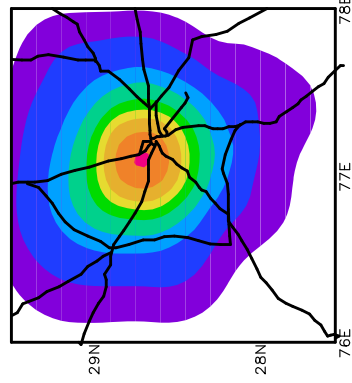
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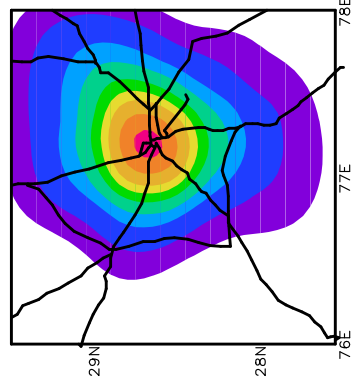
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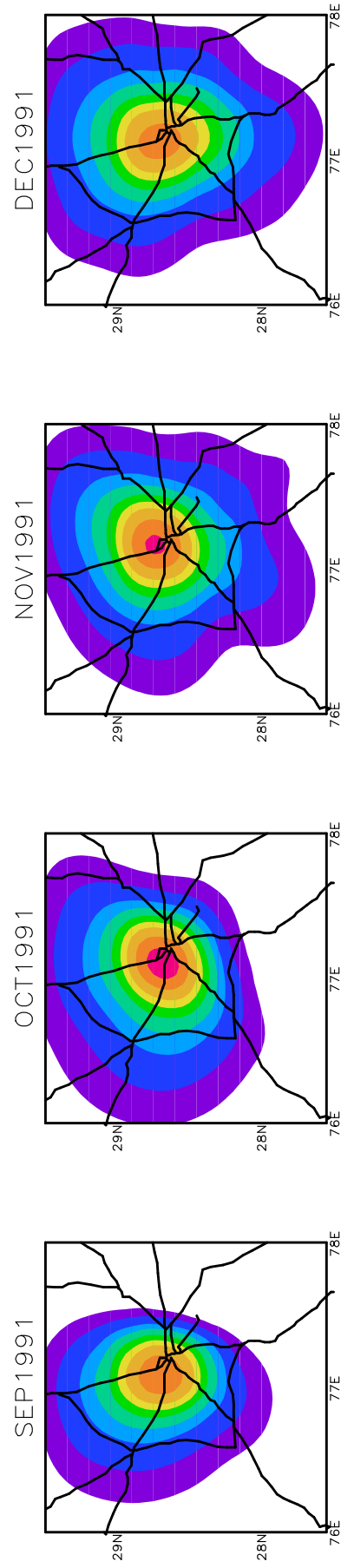
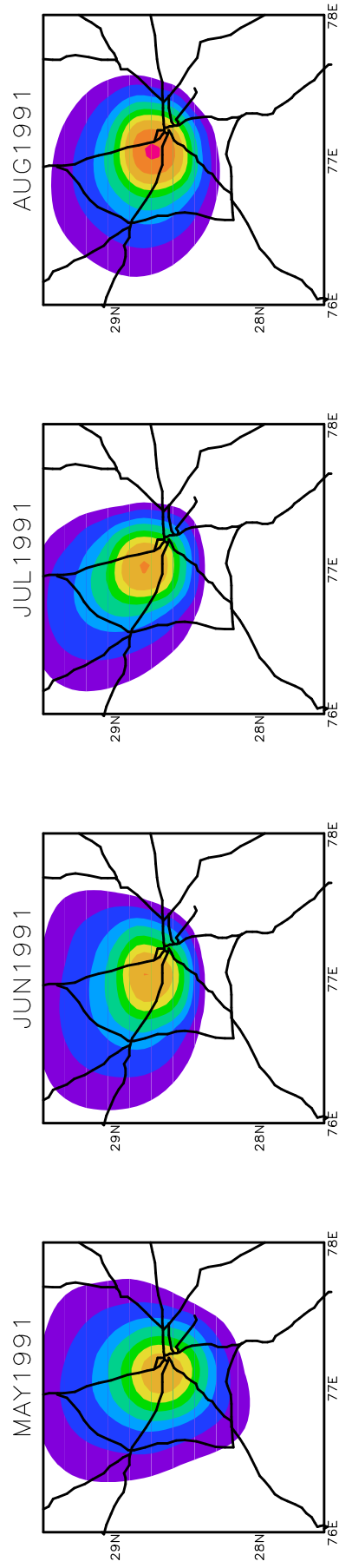
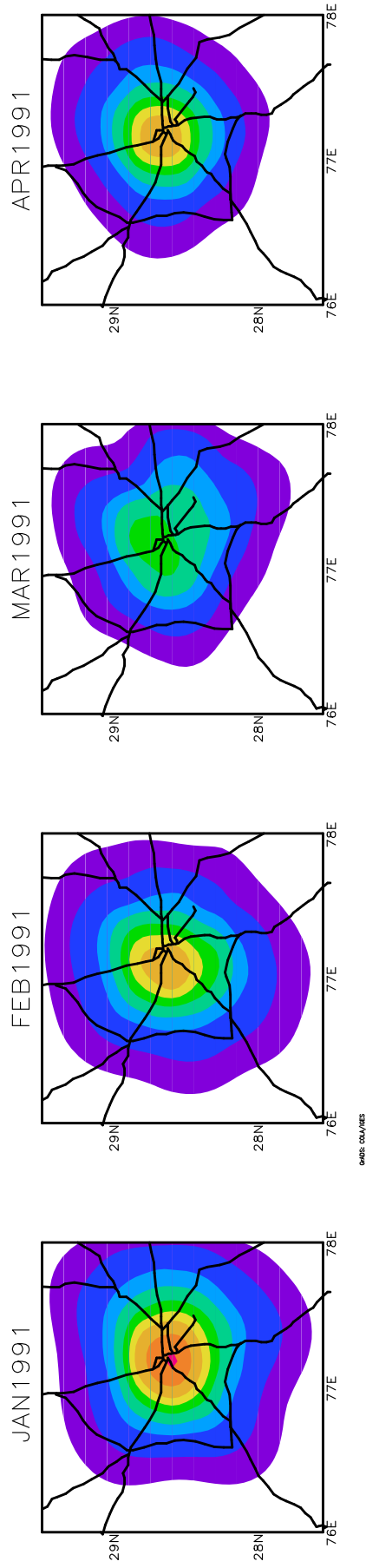
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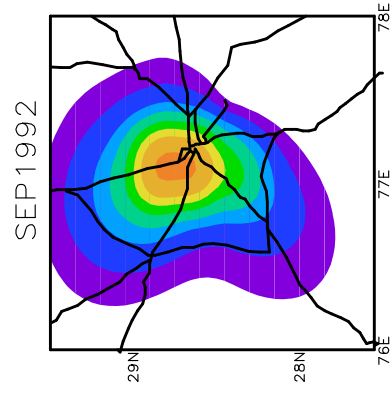
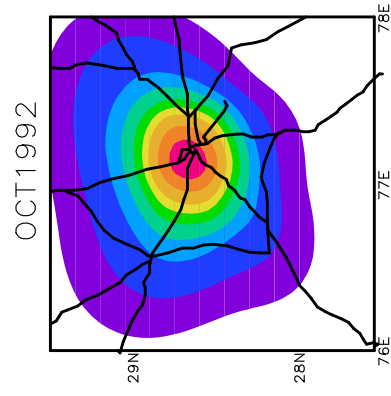
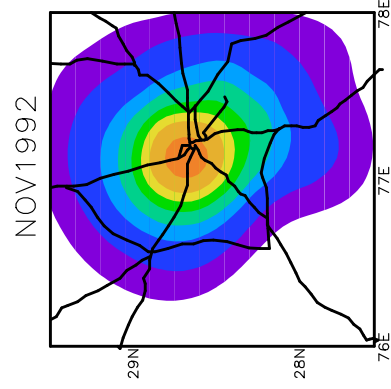
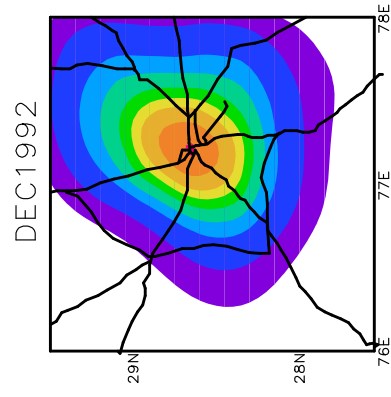
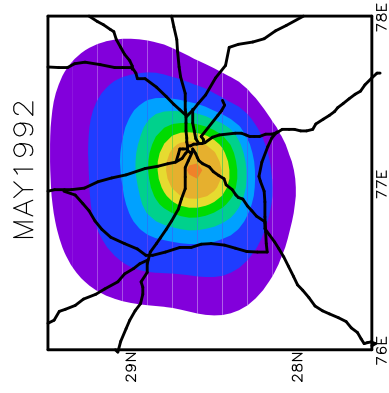
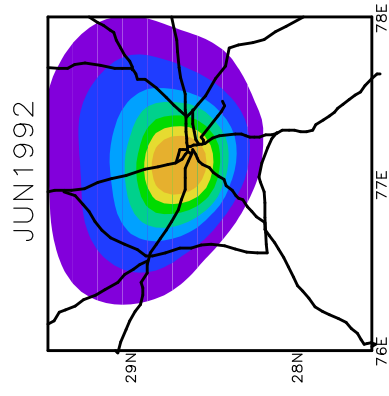
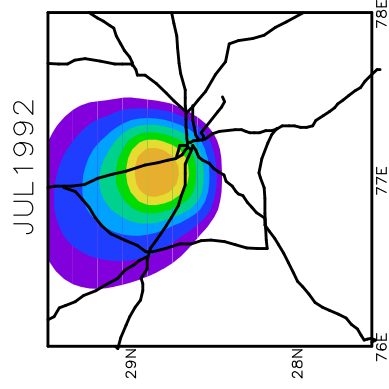
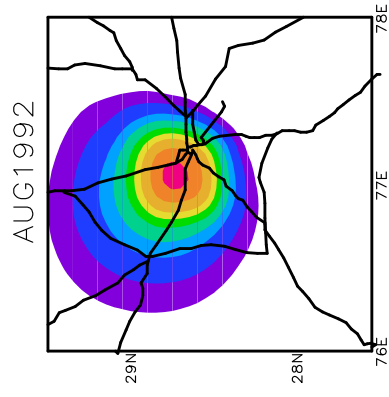
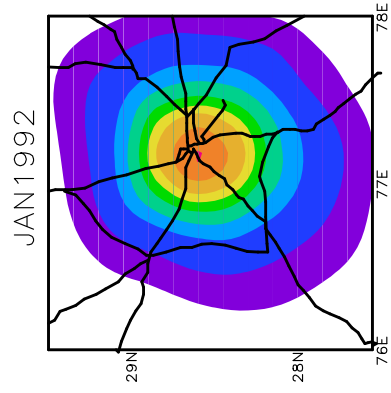
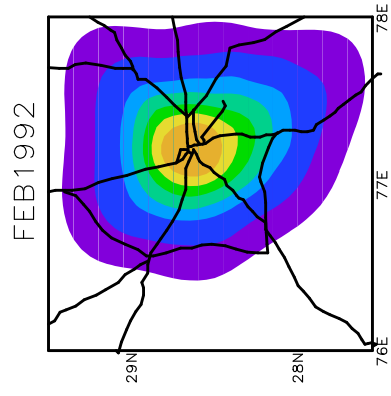
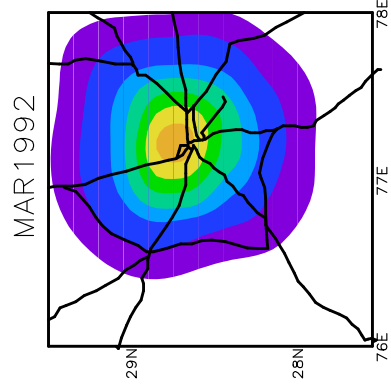
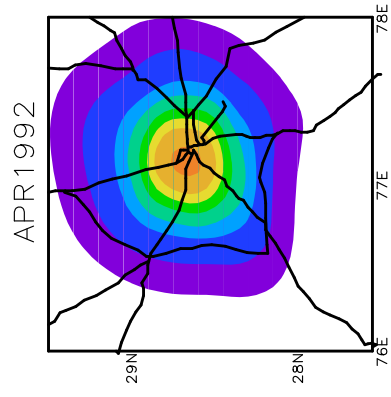


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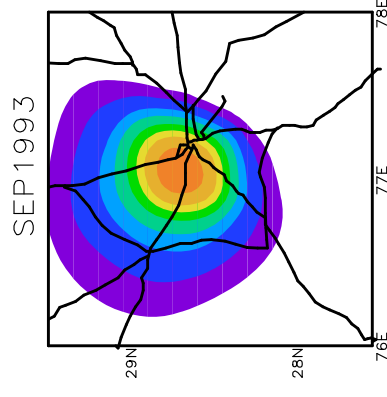
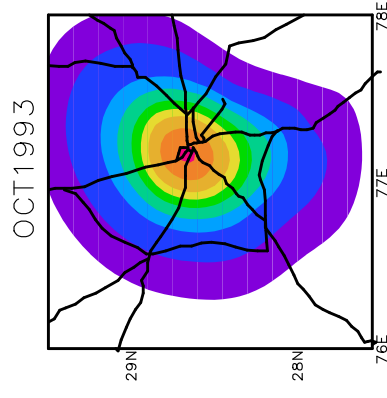
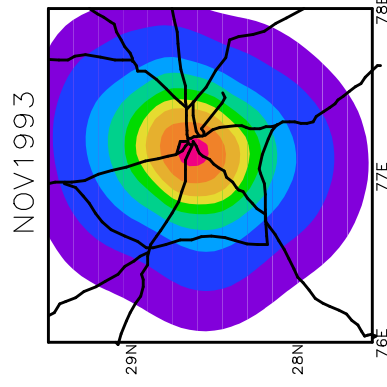
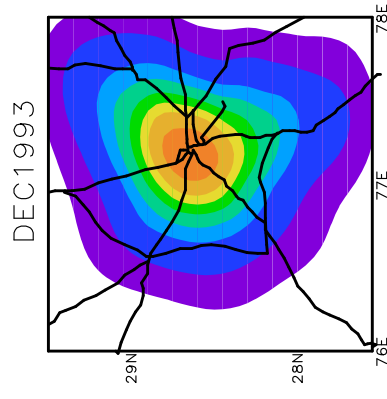
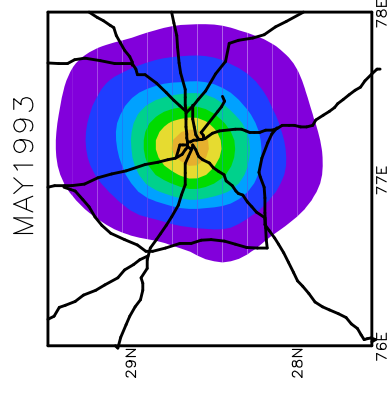
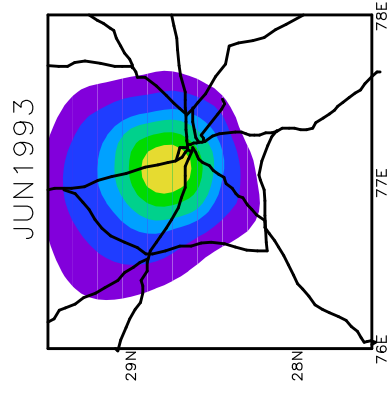
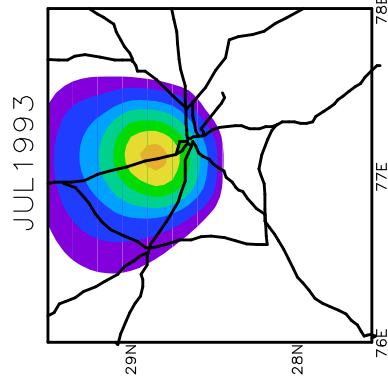
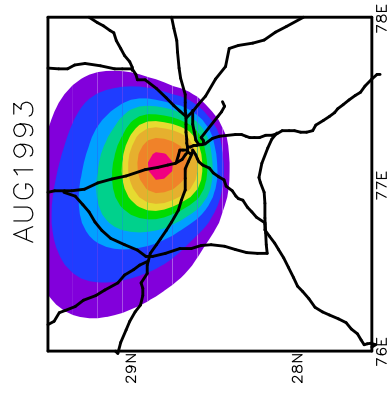
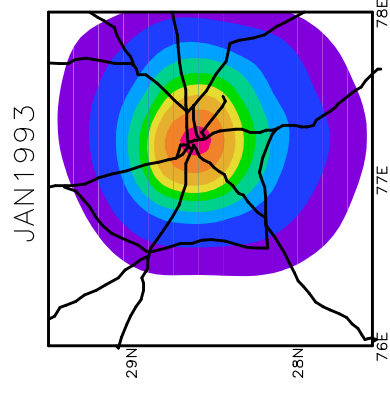
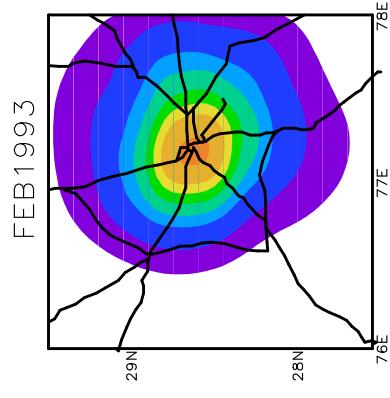
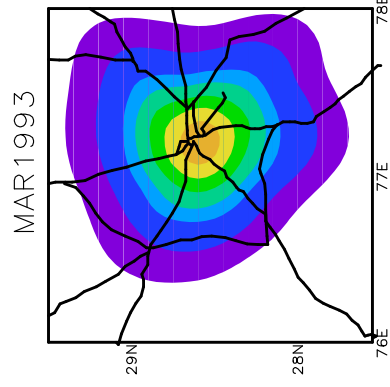
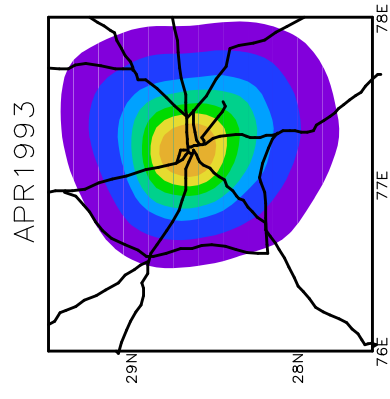


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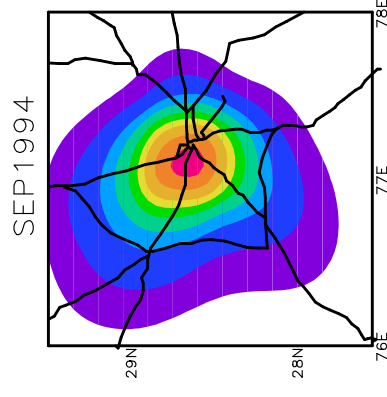
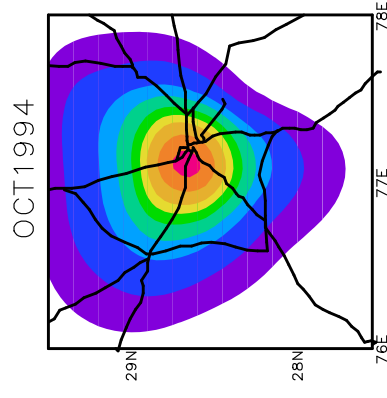
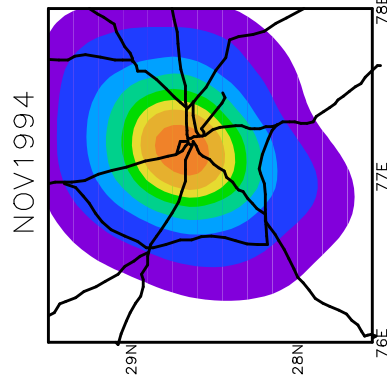
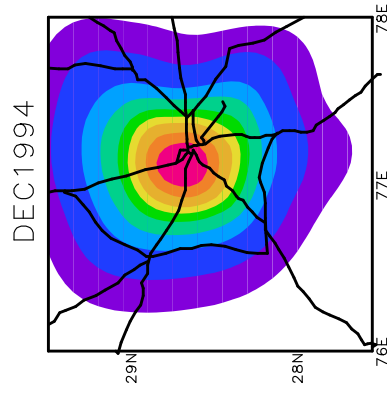
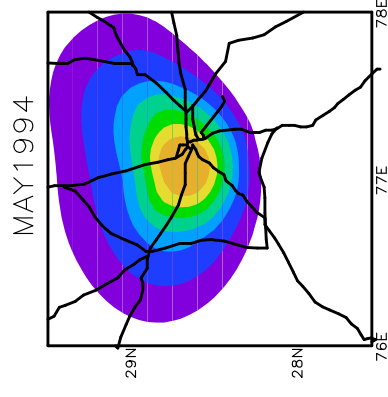
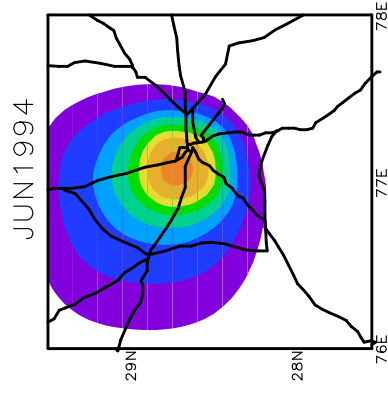
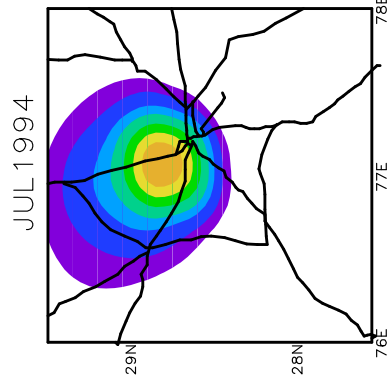
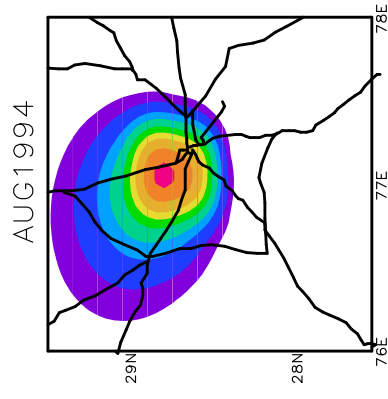
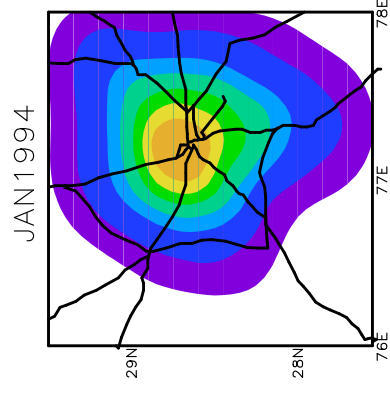
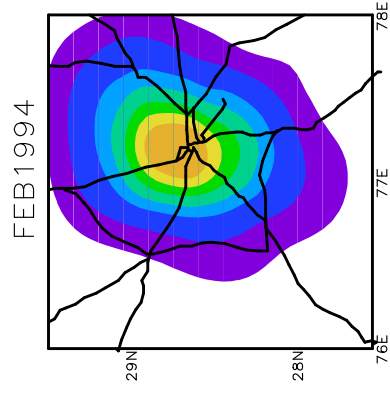
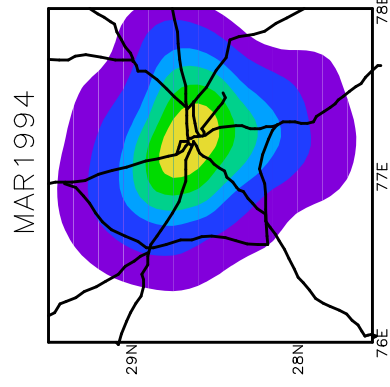
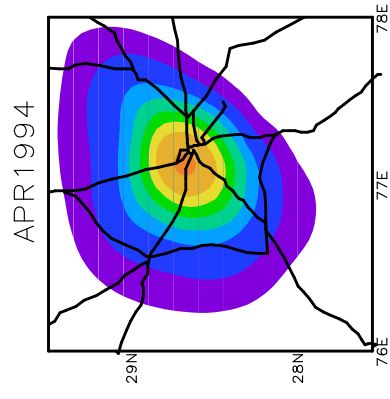




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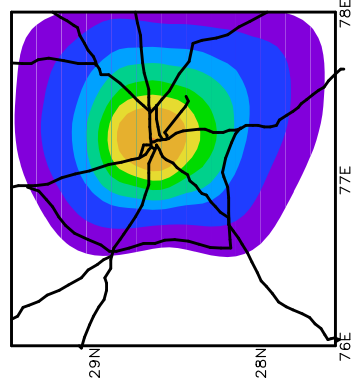


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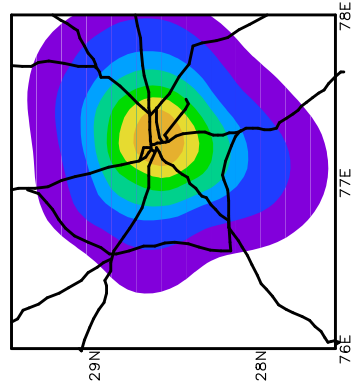


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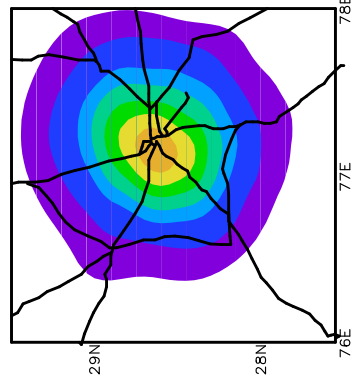
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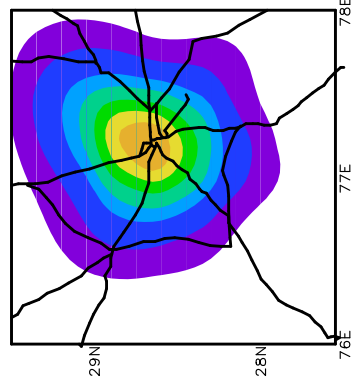
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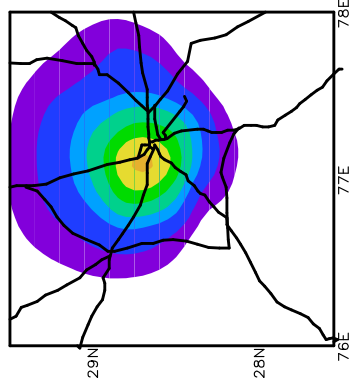
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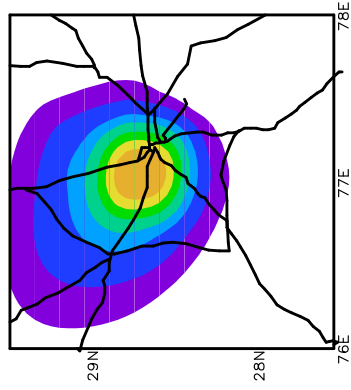
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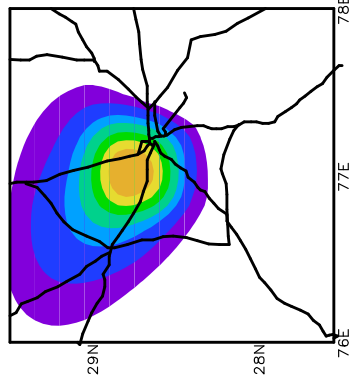
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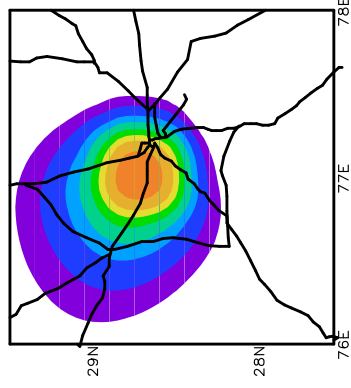
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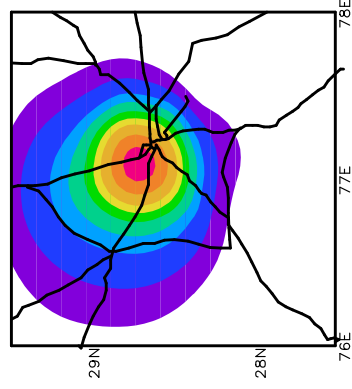
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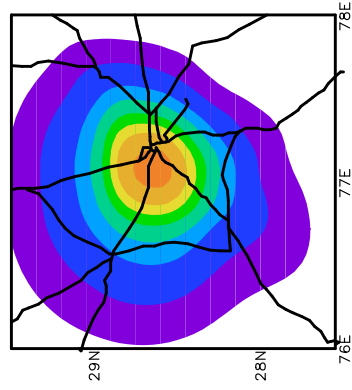
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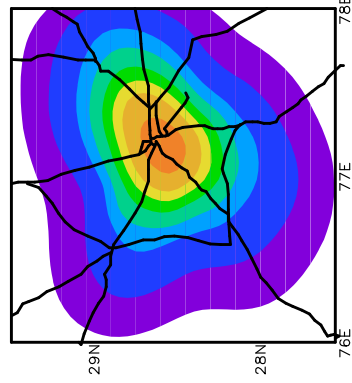
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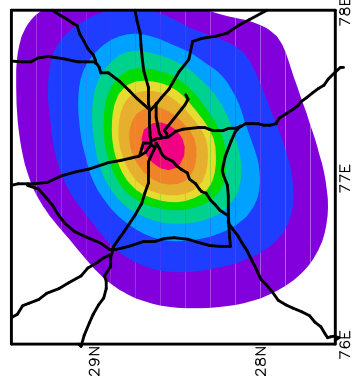
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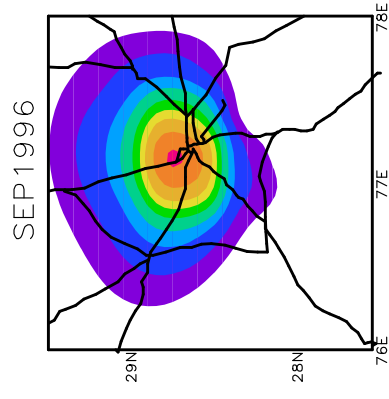
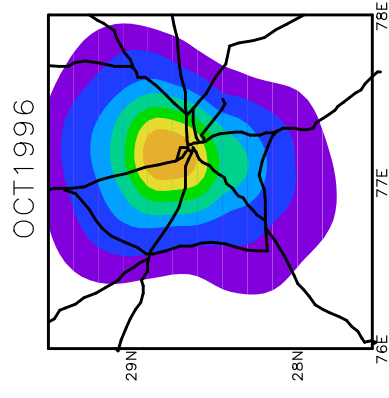
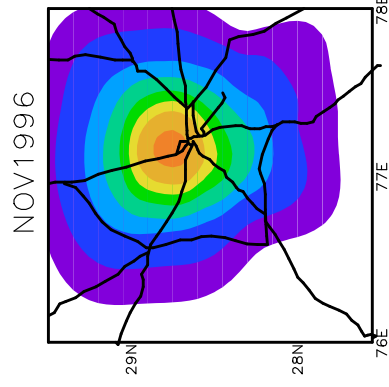
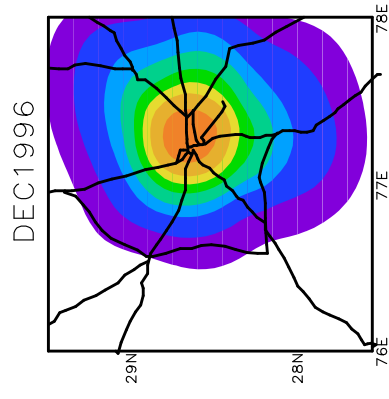
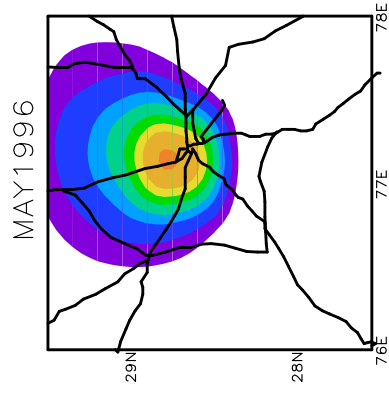
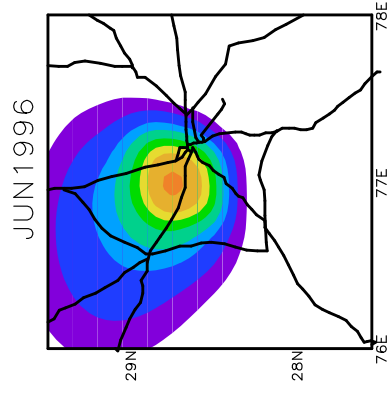
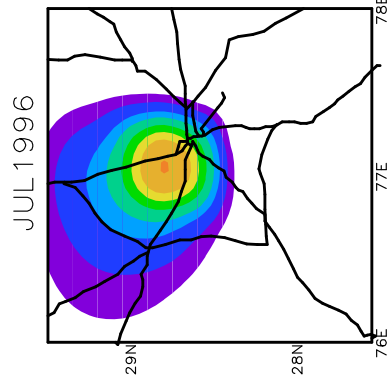
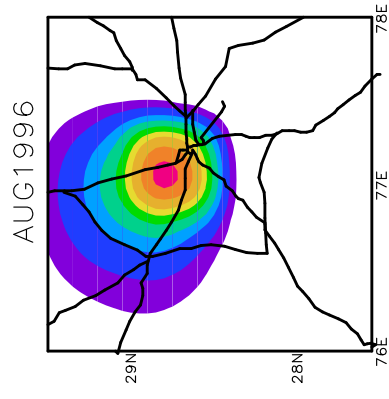
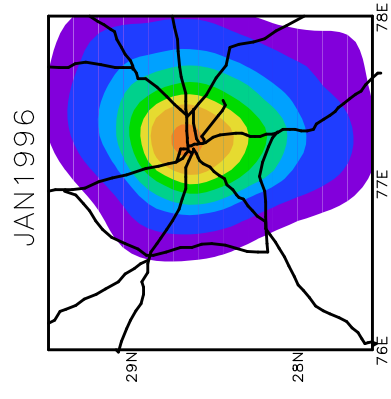
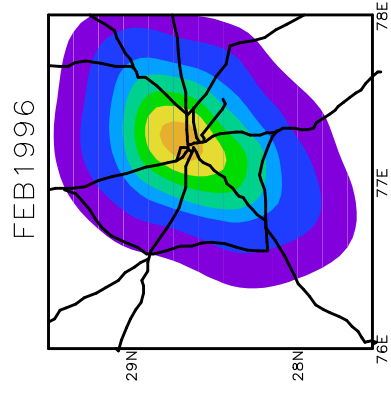
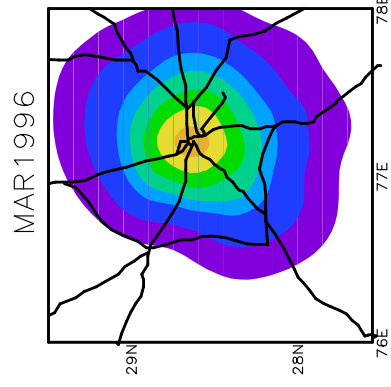
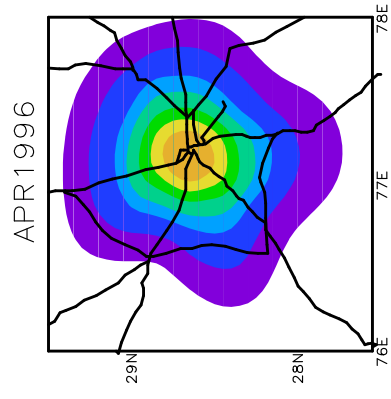
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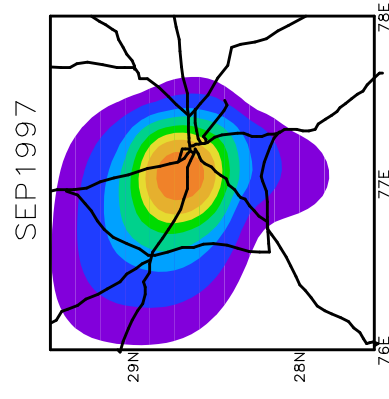
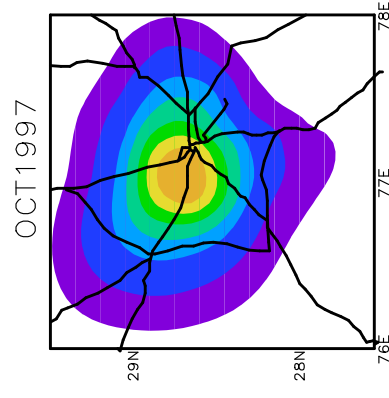
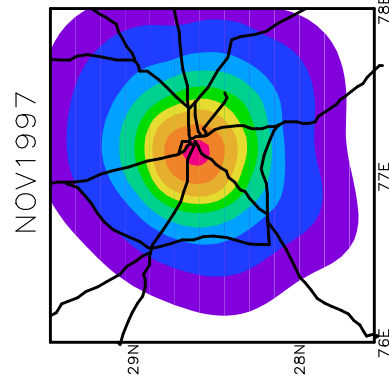
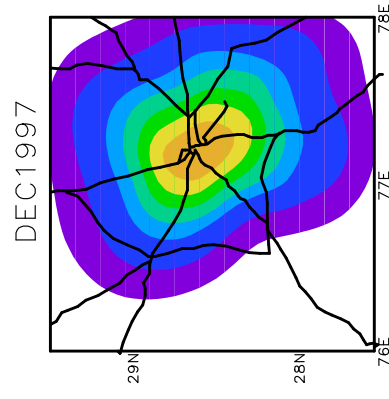
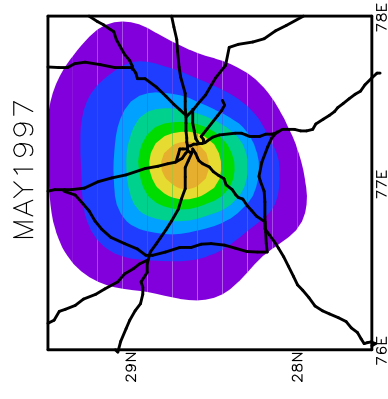
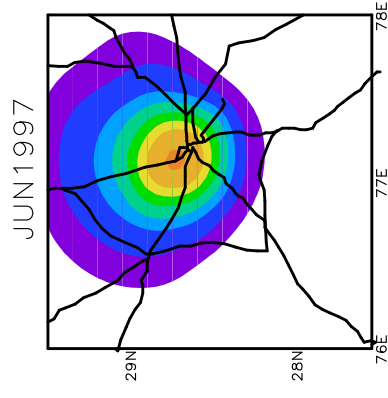
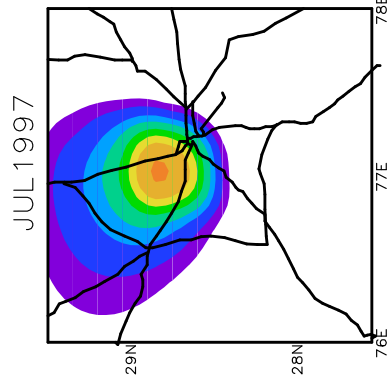
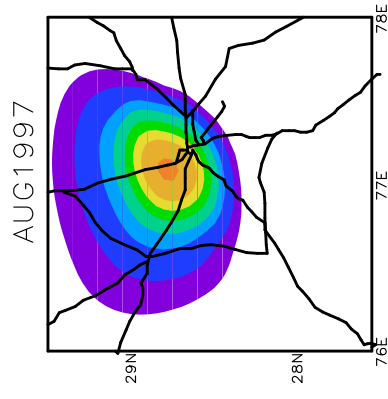
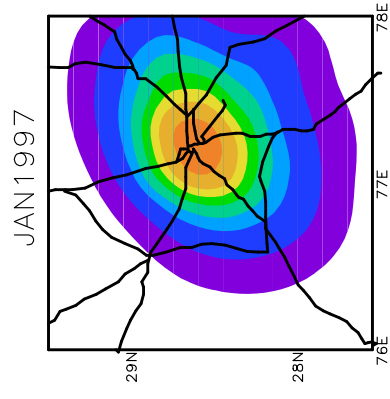
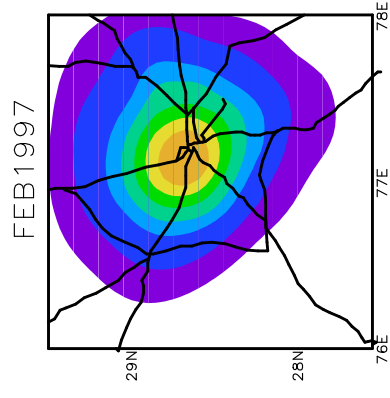
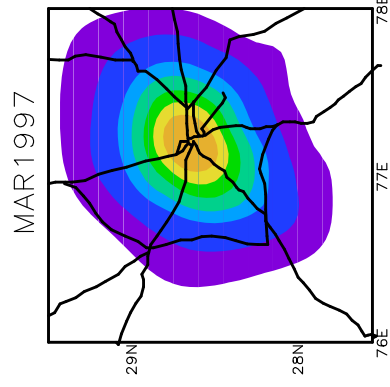
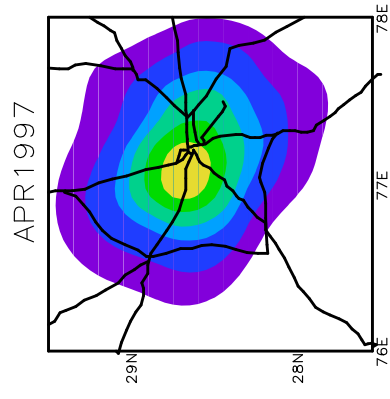
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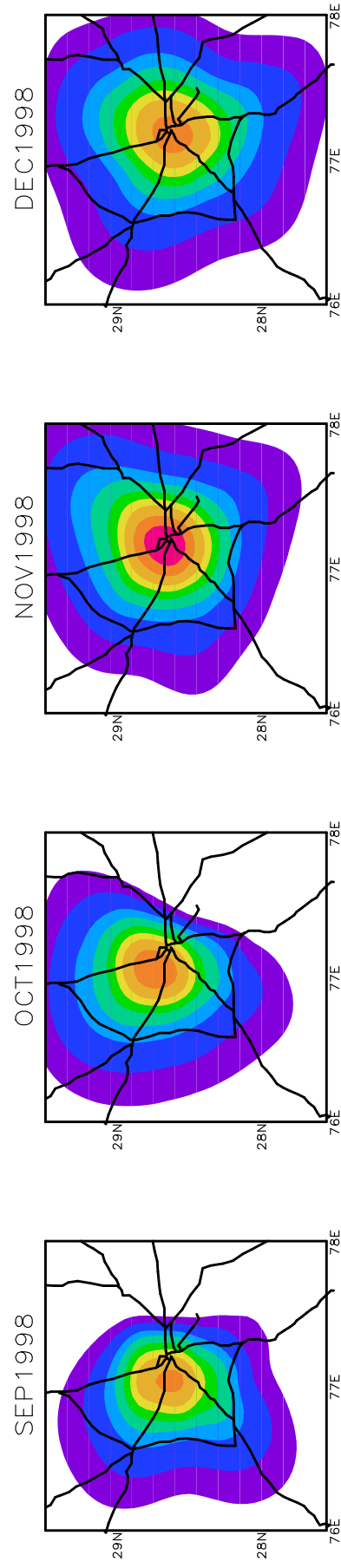
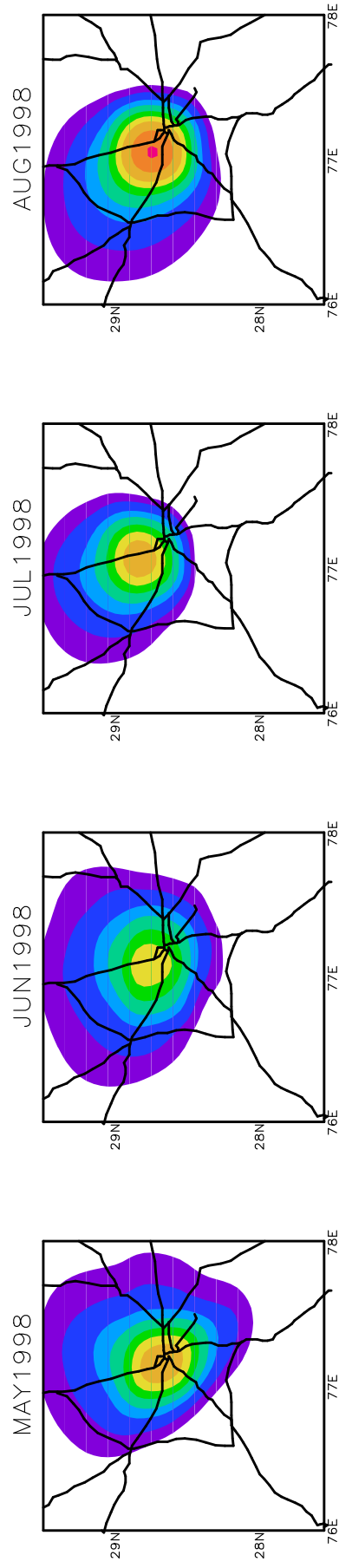
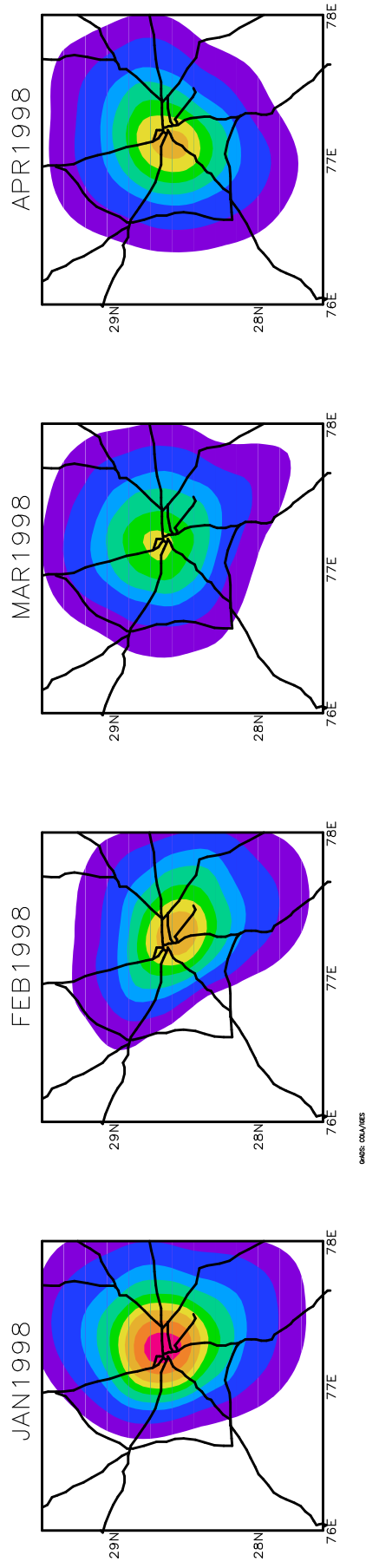
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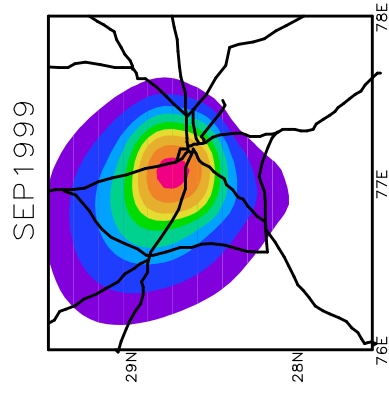
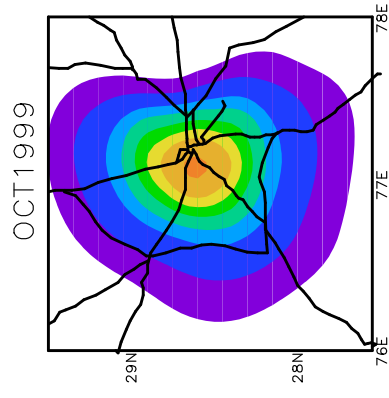
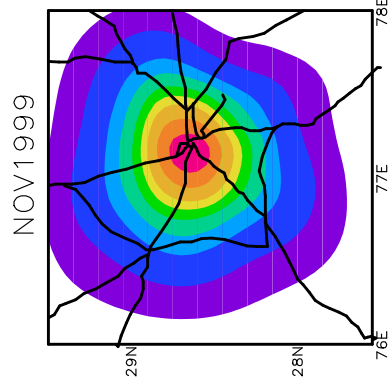
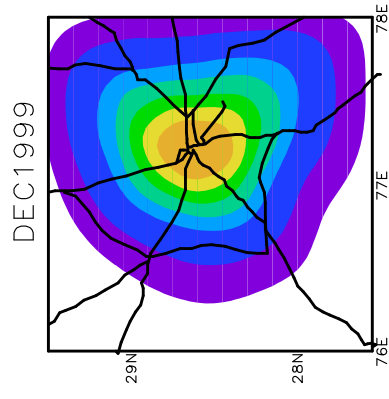
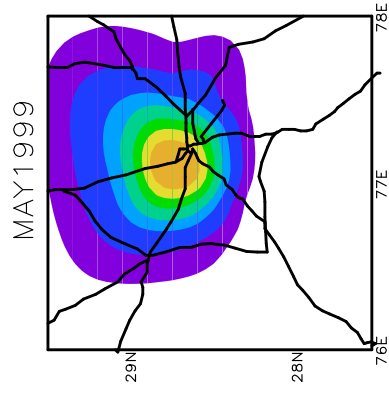
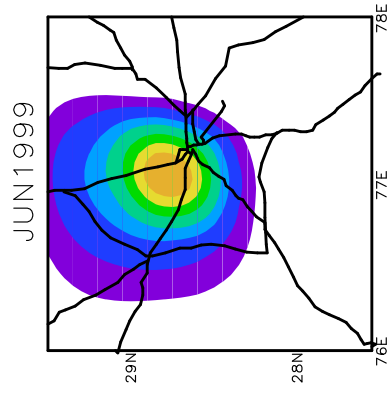
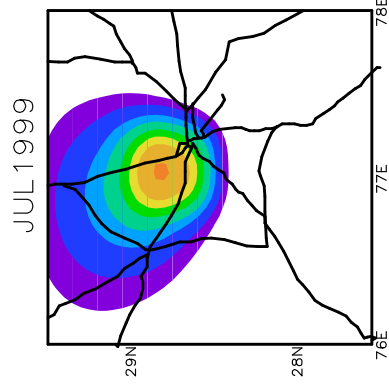
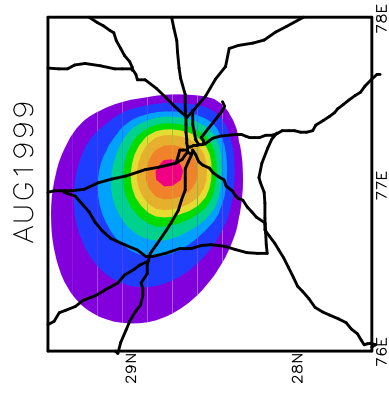
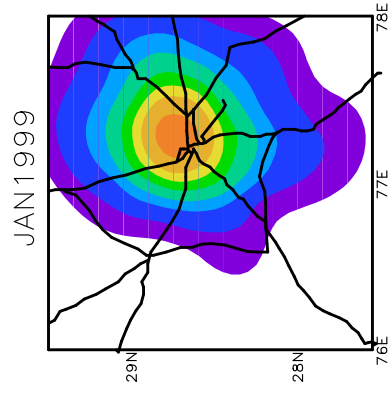
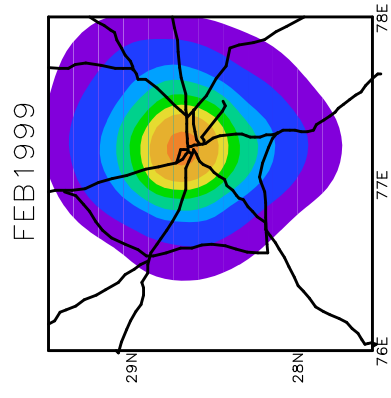
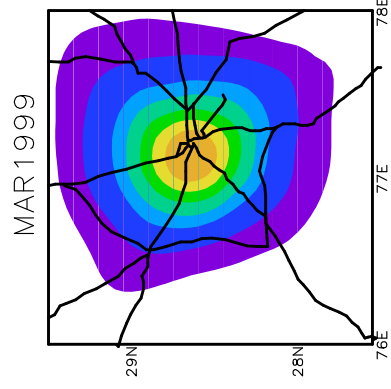
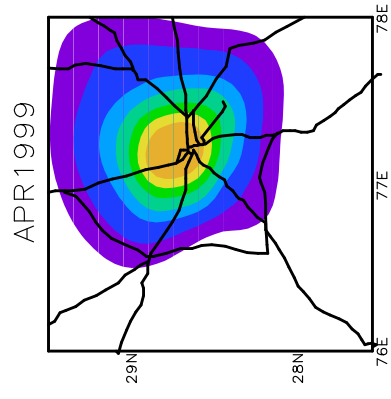


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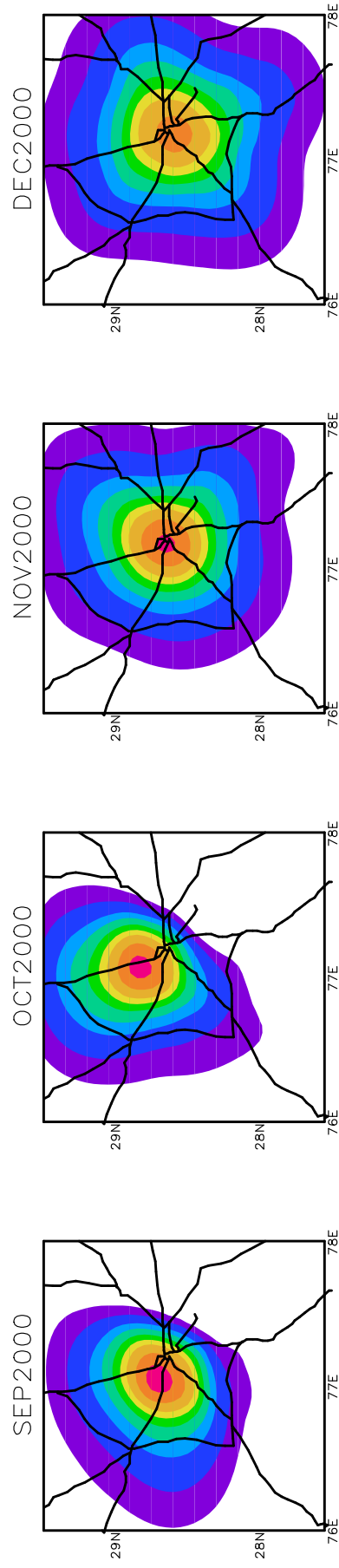
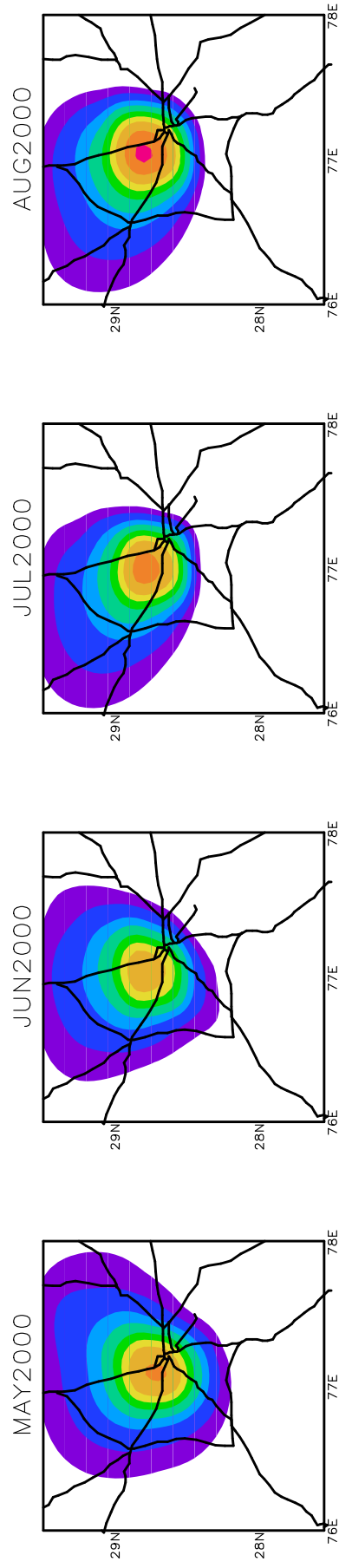
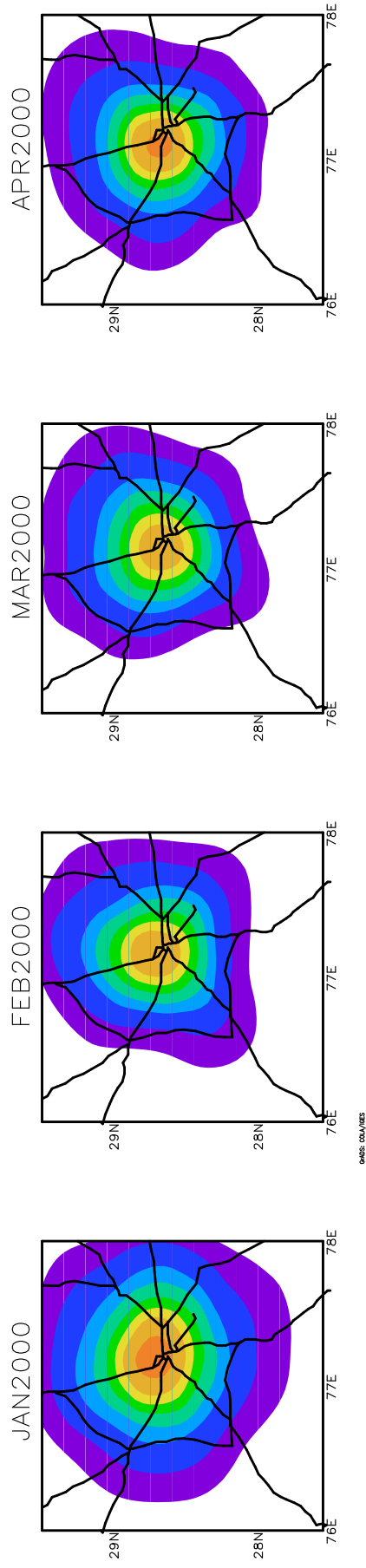


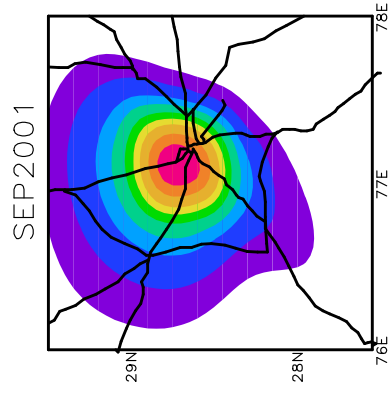
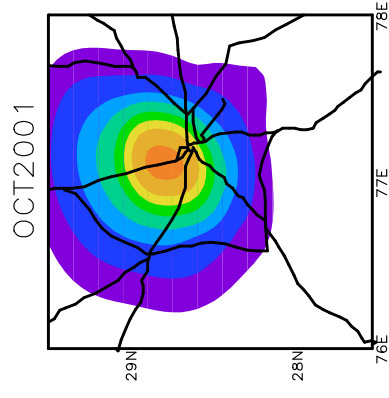
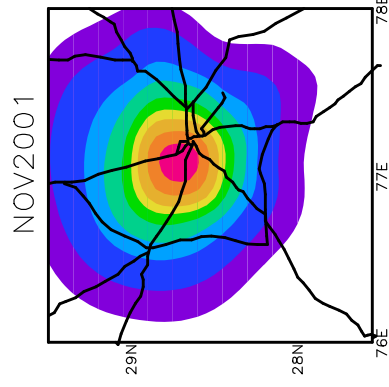
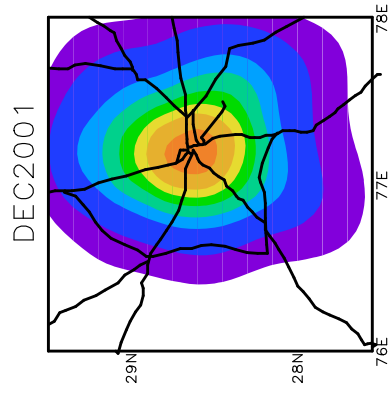
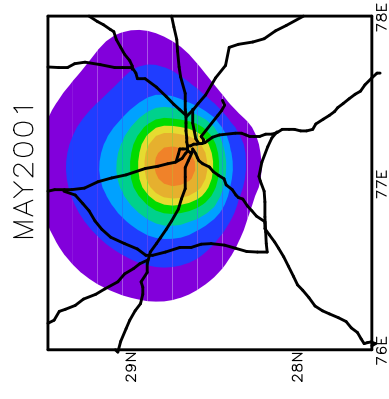
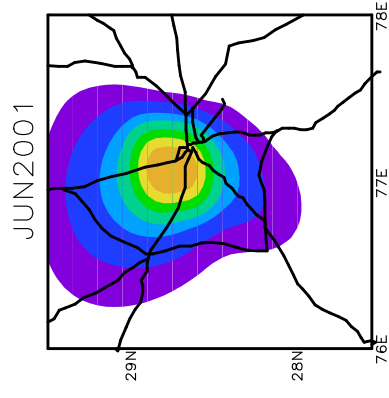
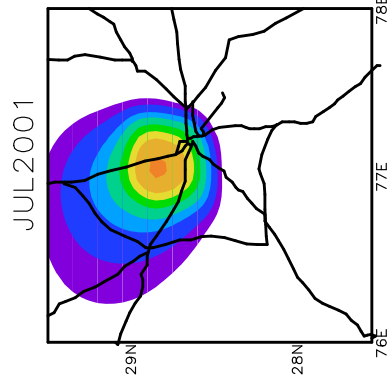
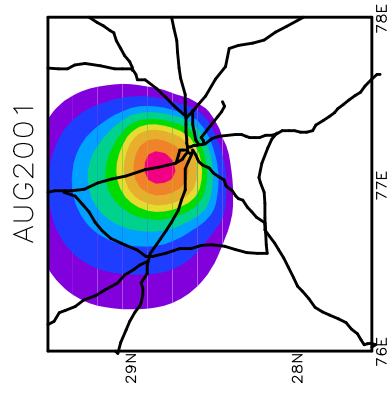
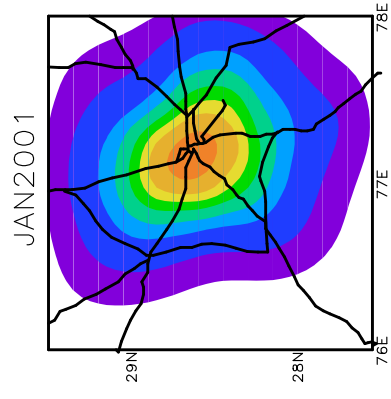
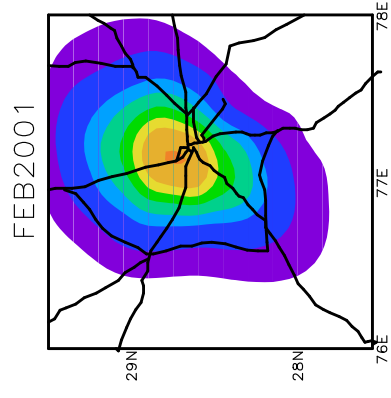
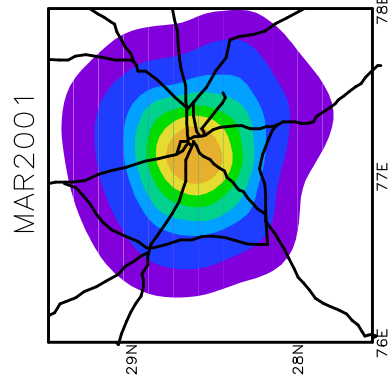
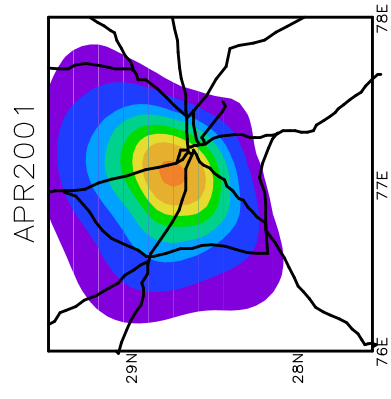
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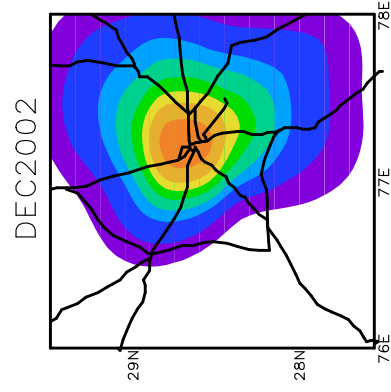
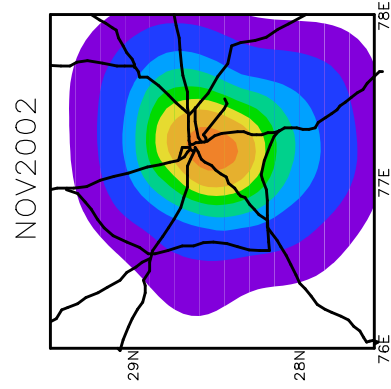
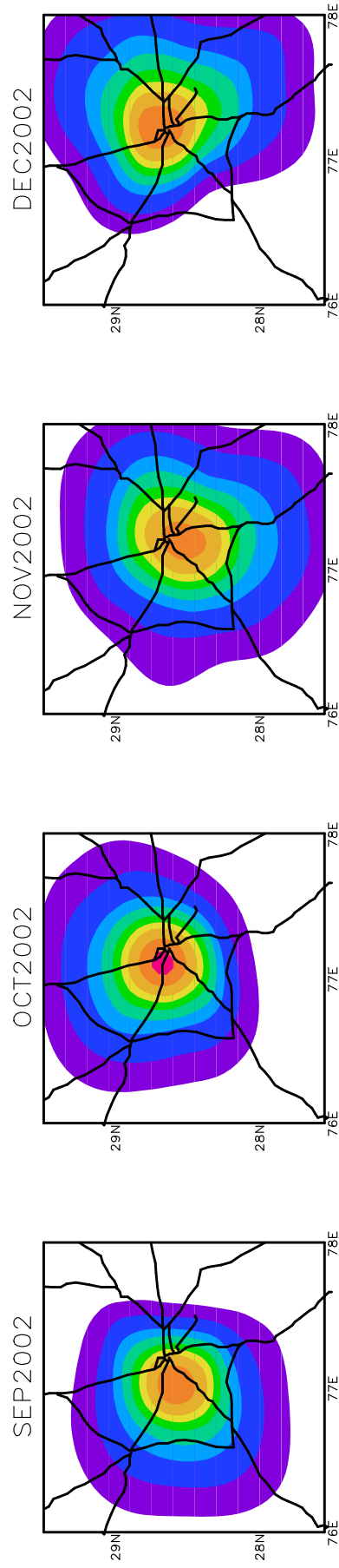
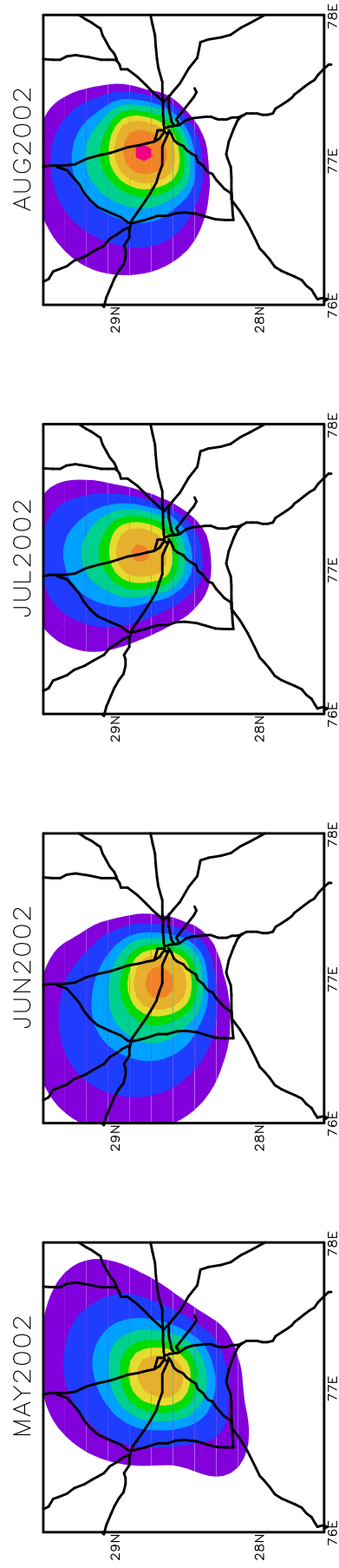
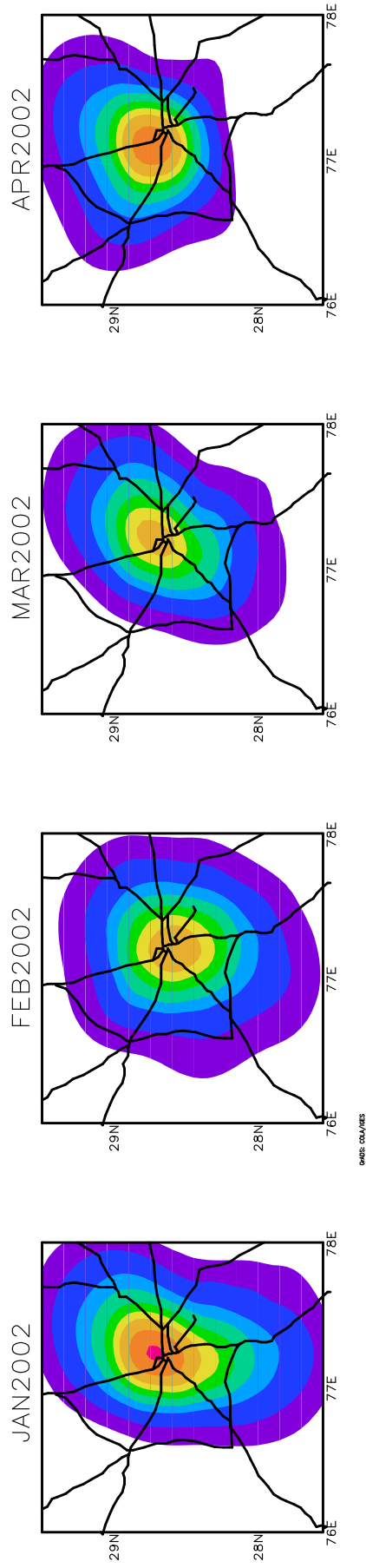


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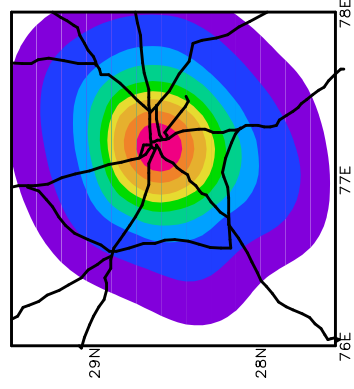




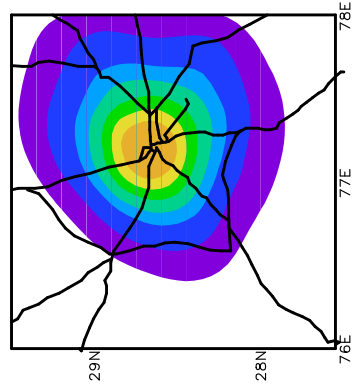
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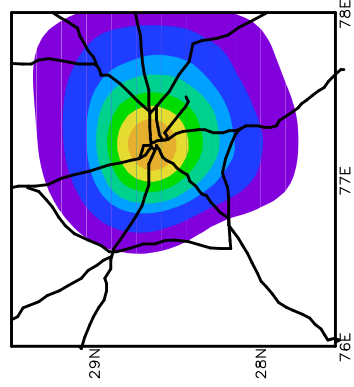
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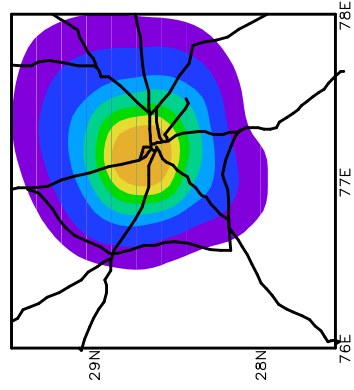
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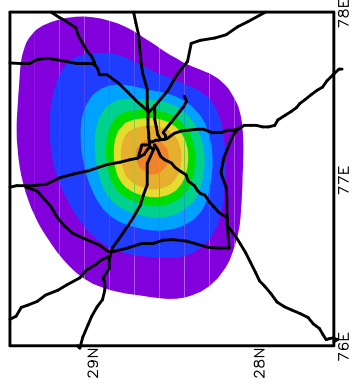
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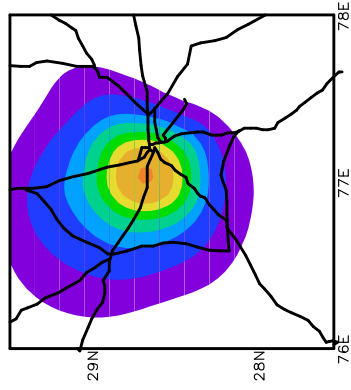
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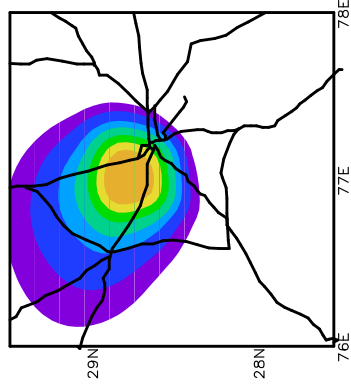
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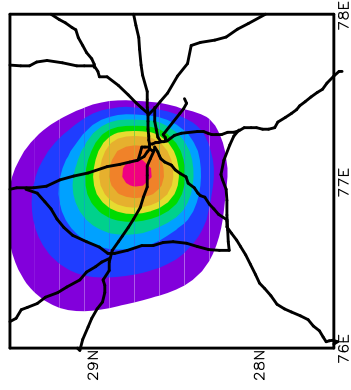
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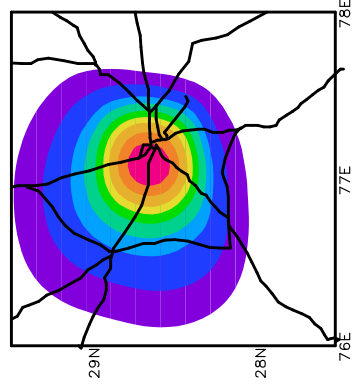
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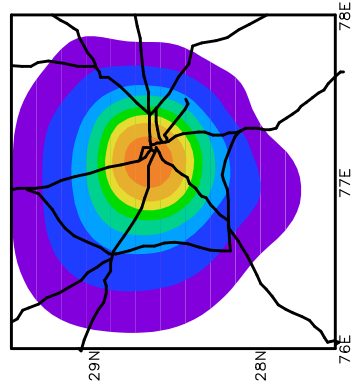
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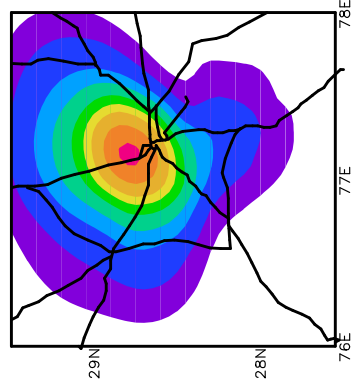
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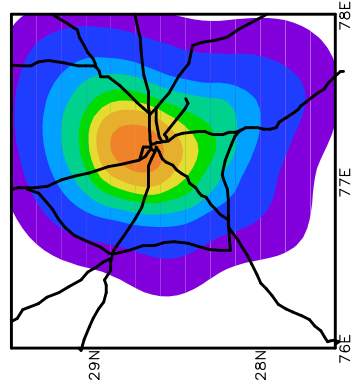
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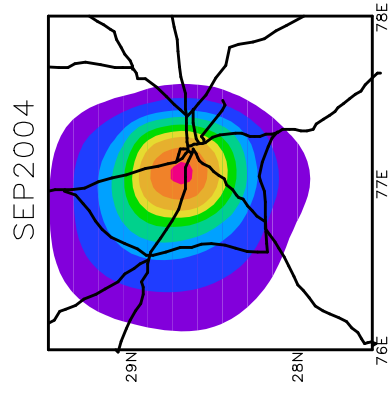
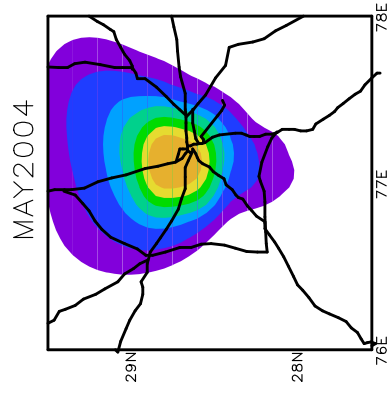
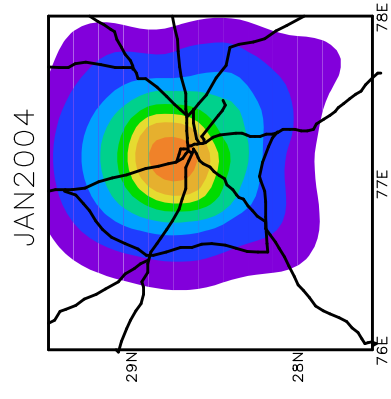
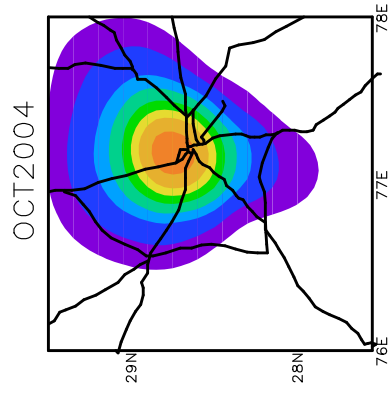
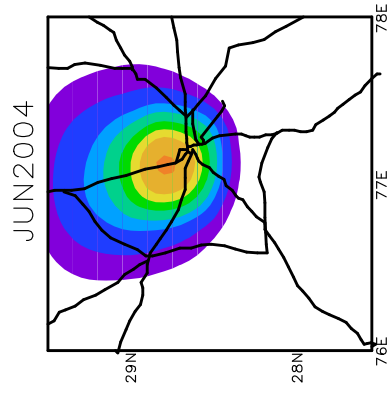
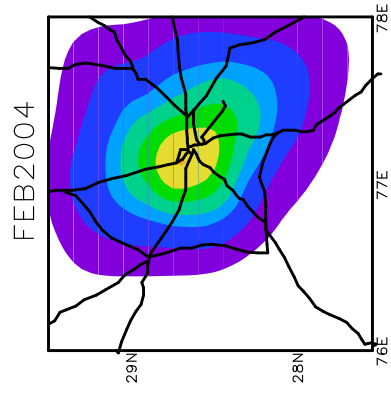
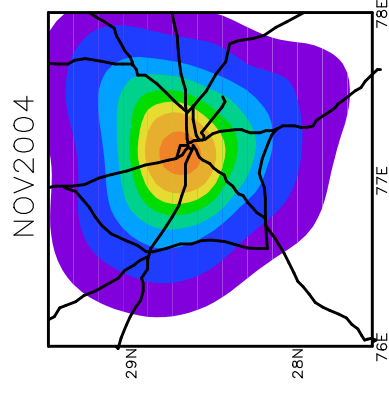
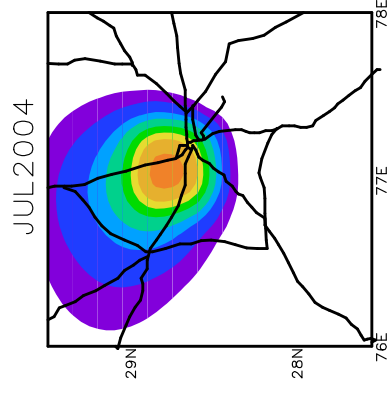
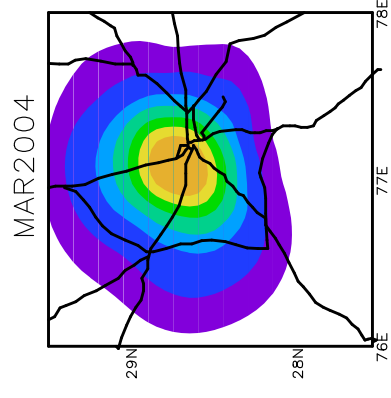
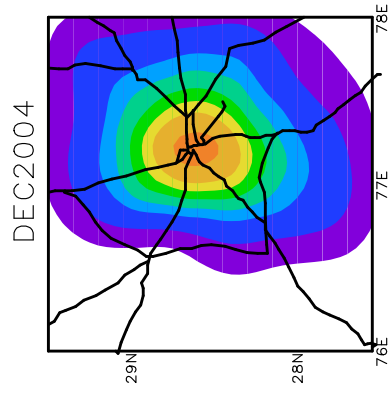
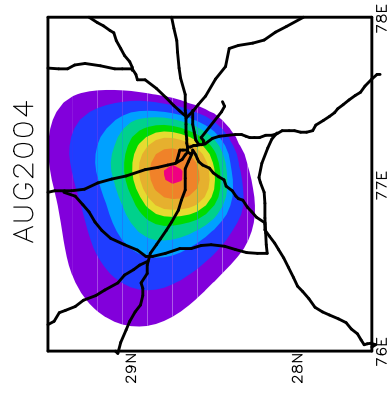
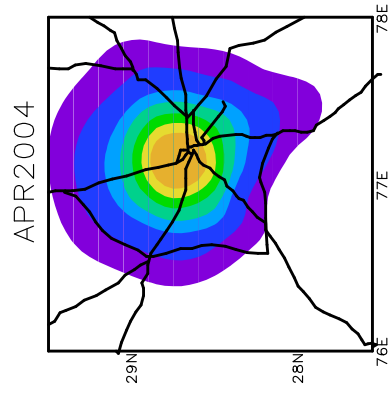
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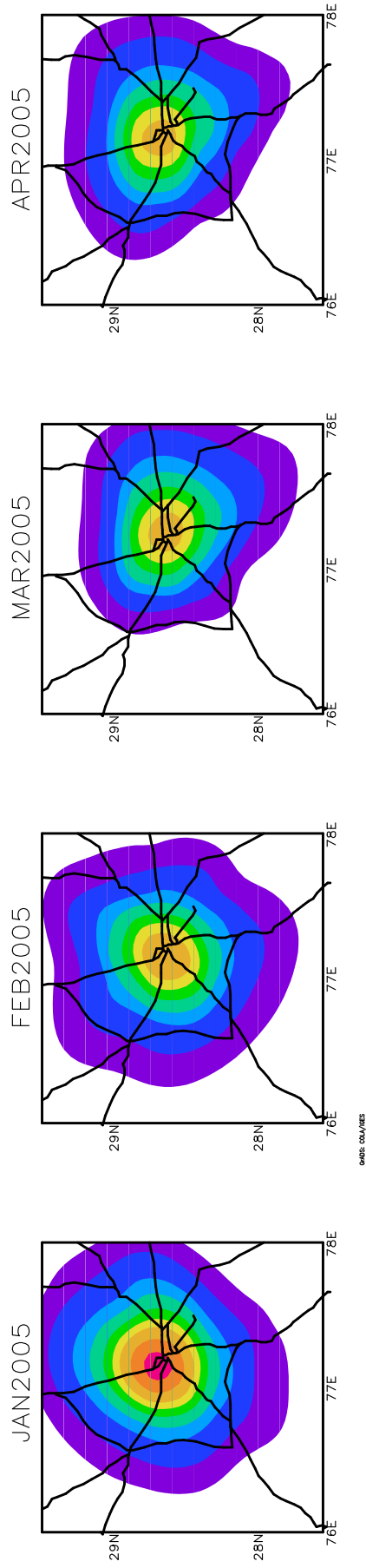
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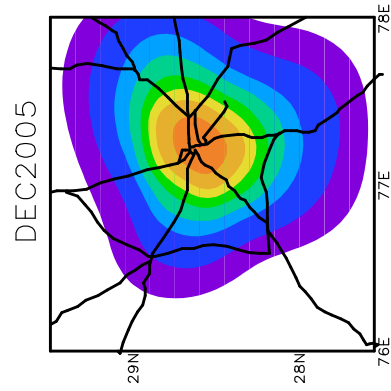
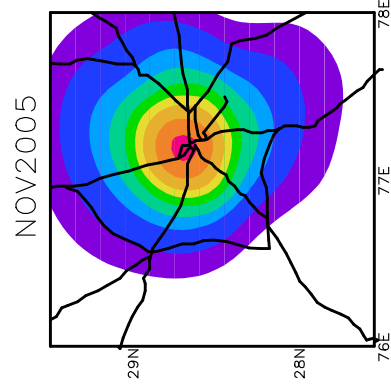
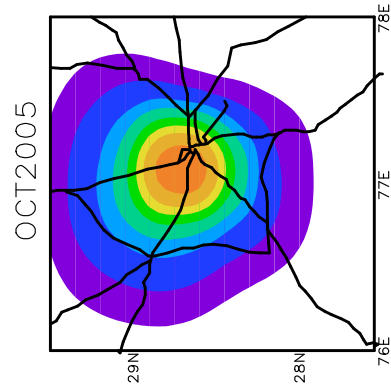
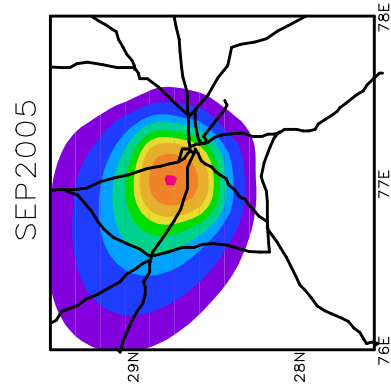
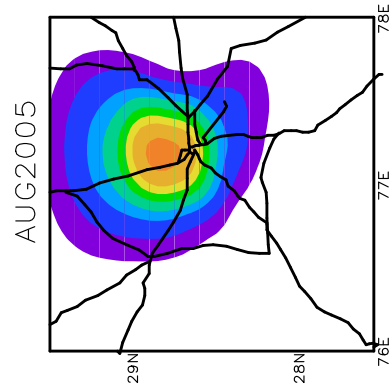
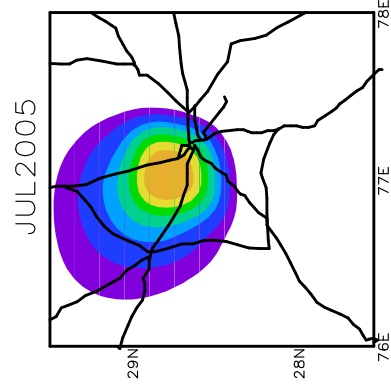
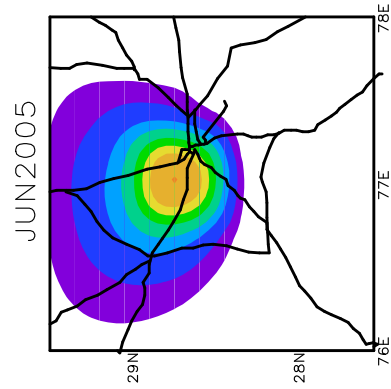
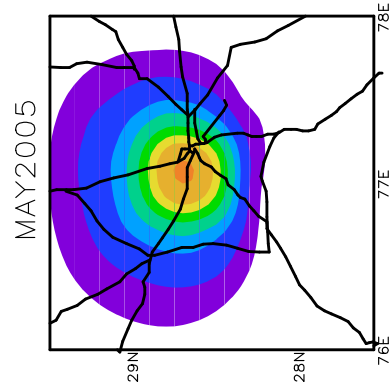
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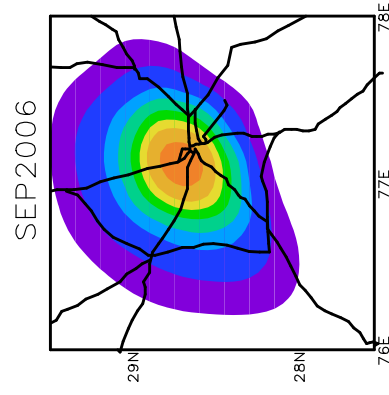
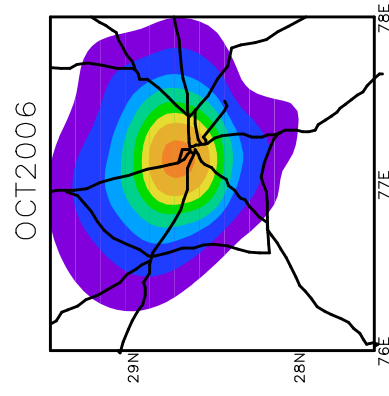
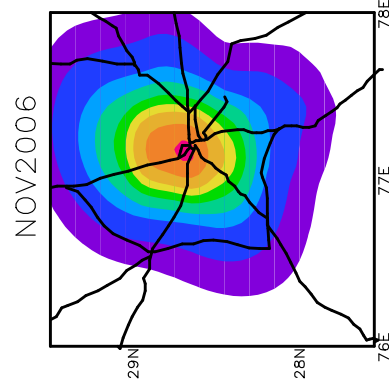
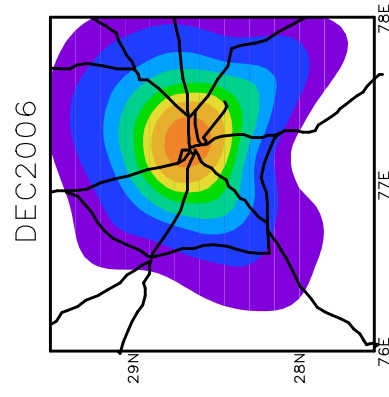
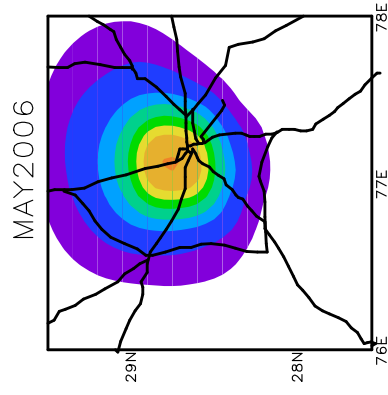
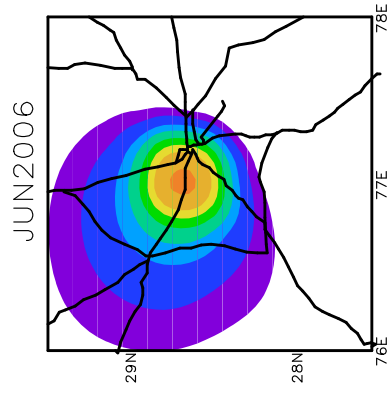
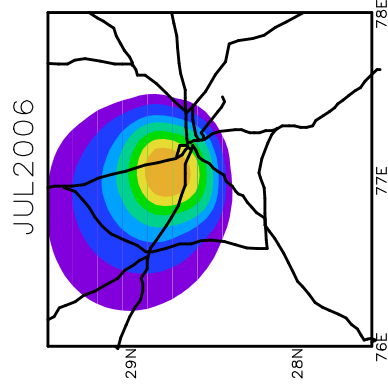
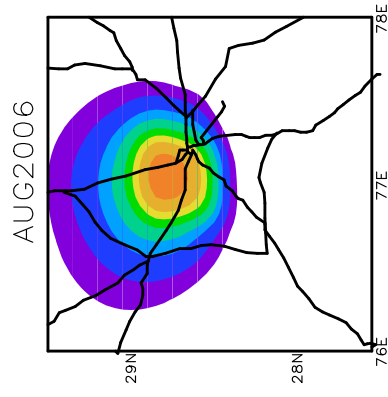
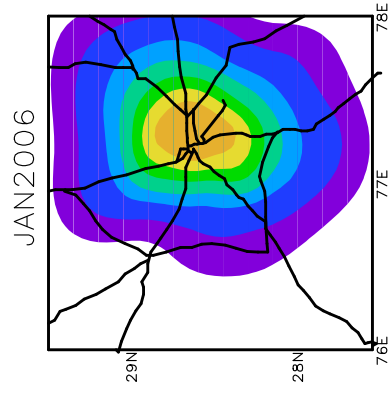
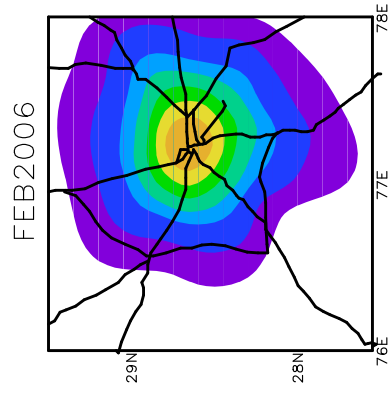
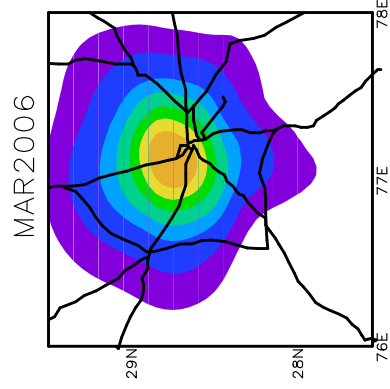
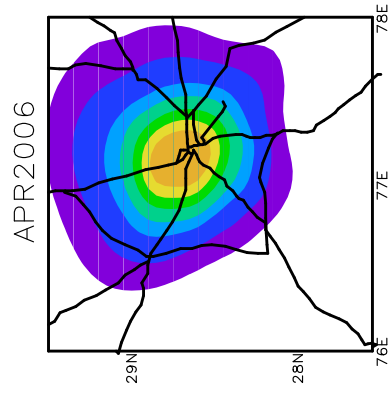


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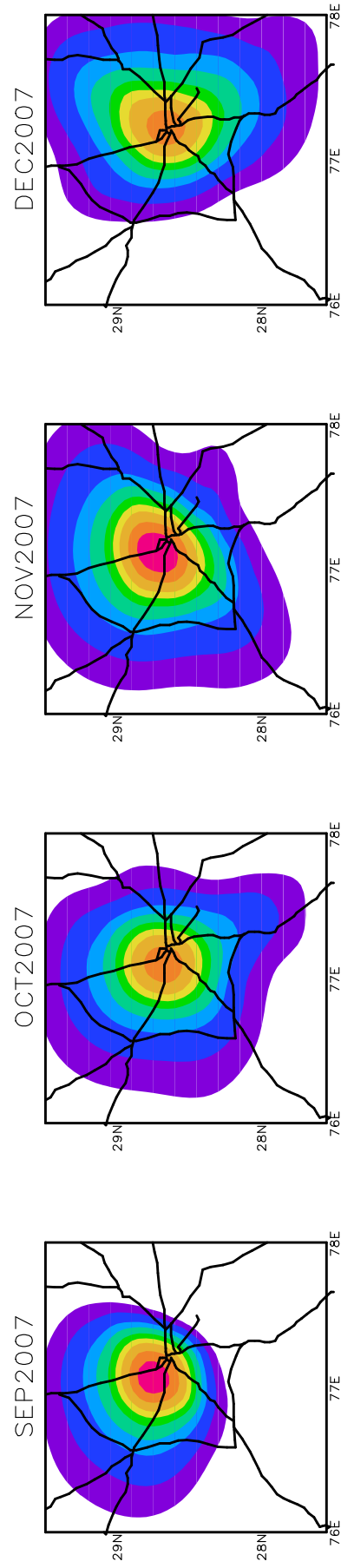
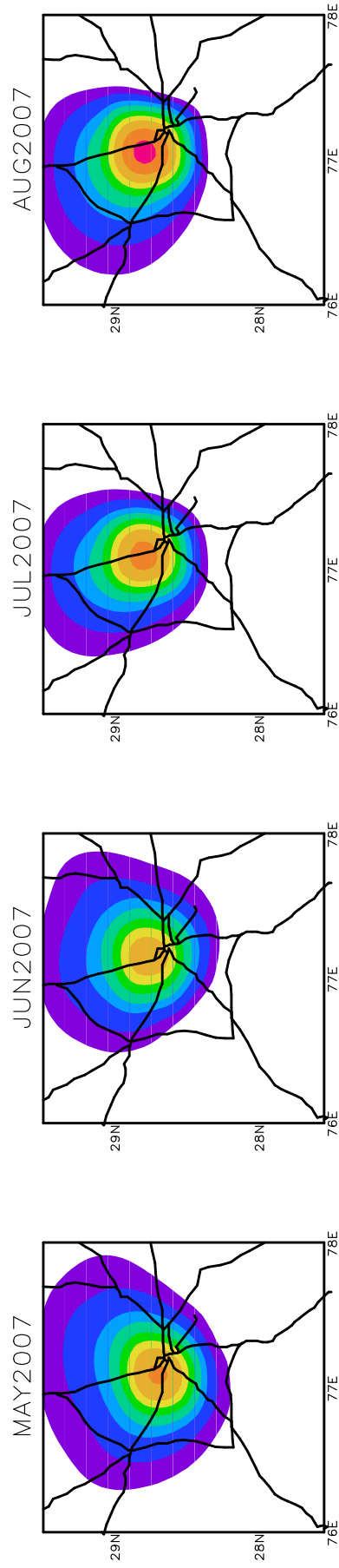
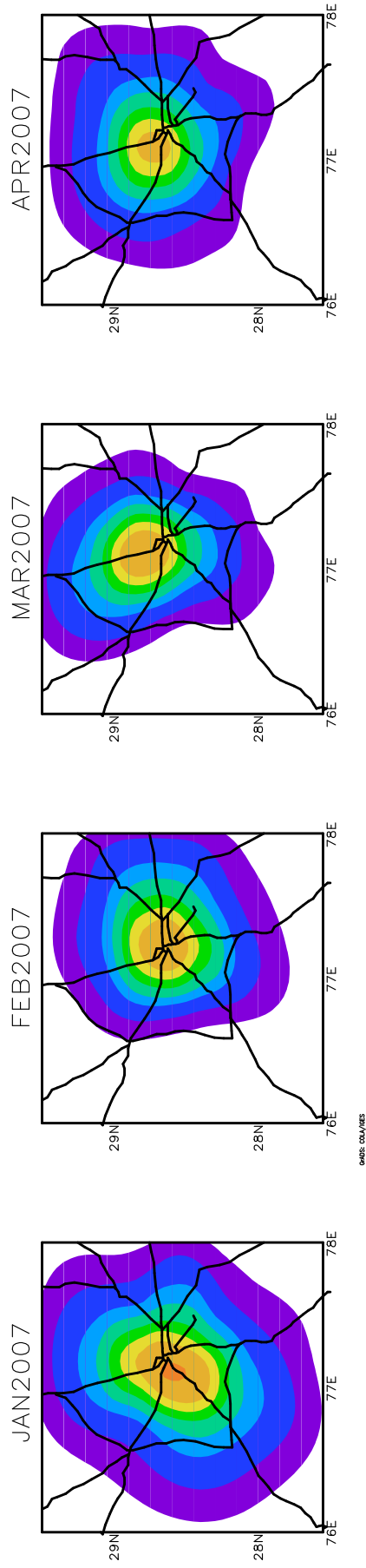


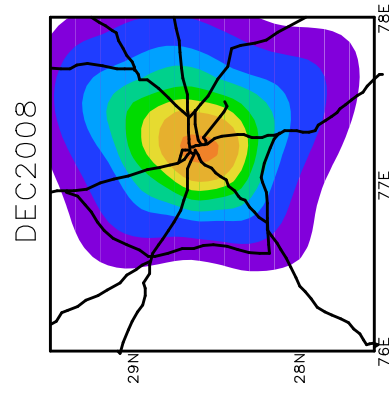
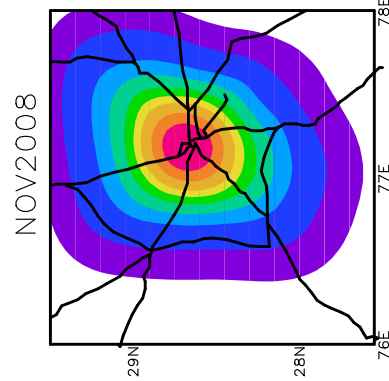
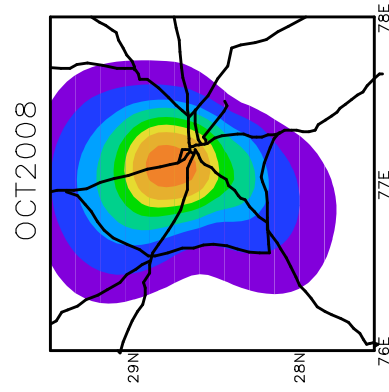
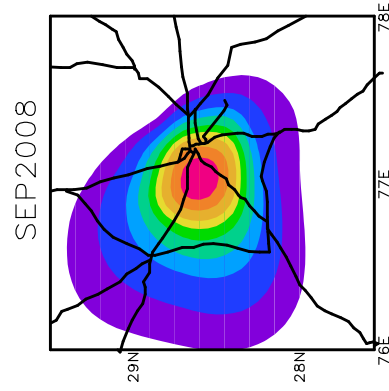
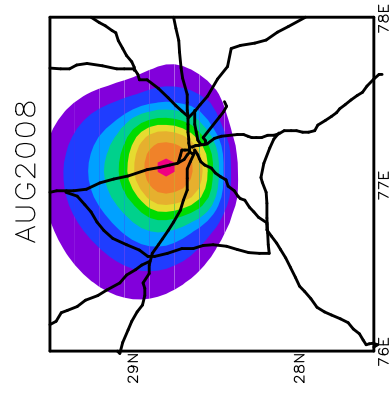
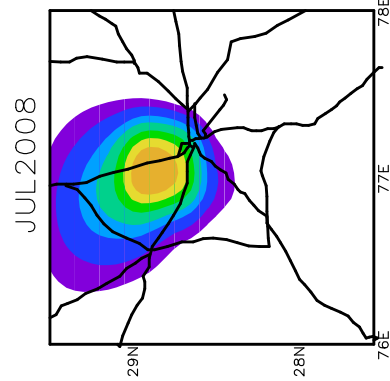
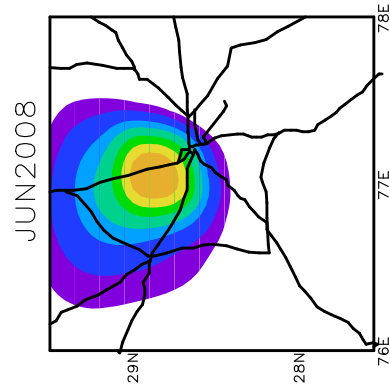
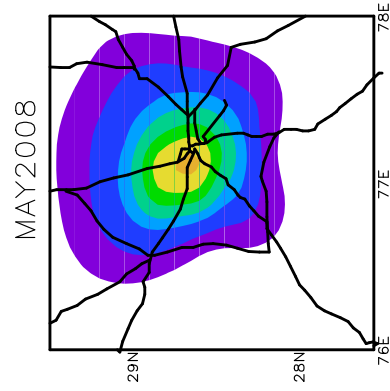
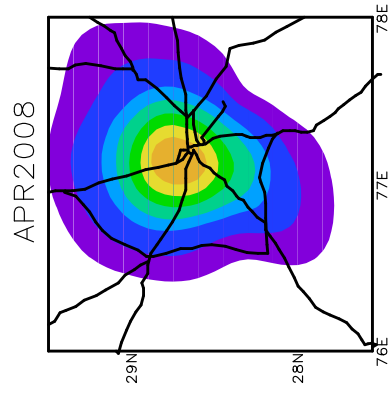
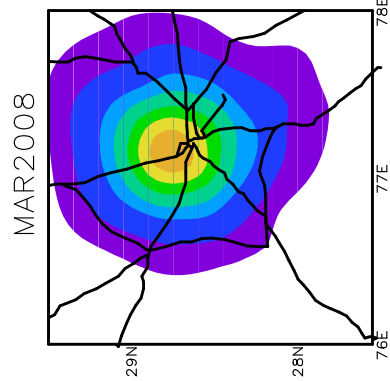
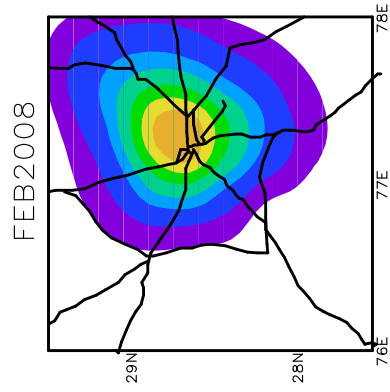
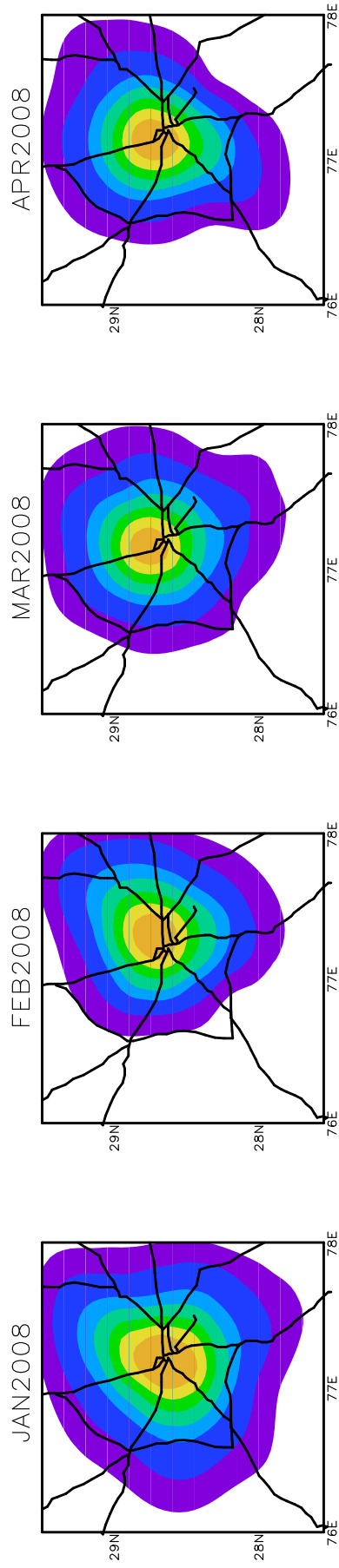
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