# Real-time, rapidly updating severe weather products for virtual globes

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## ABSTRACT

It is critical that weather forecasters are able to put severe weather information from a variety of observational and modeling platforms into a geographic context so that warning information can be effectively conveyed to the public, emergency managers, and disaster response teams. The availability of standards for the specification and transport of virtual globe data products has made it possible to generate spatially precise, geo-referenced images and to distribute these centrally-created products via a web server to a wide audience.

In this paper, we describe the data and methods for enabling severe weather threat analysis information inside a KML framework. The method of creating severe weather diagnosis products that are generated and translating them to KML and image files is described. We illustrate some of the practical applications of these data when they are integrated into a virtual globe display. The availability of standards for interoperable virtual globe clients has not completely alleviated the need for custom solutions. We conclude by pointing out several of the limitations of the general-purpose virtual globe clients currently available.

**Keywords**: virtual globes; KML; weather; radar; tornadoes; hail

## 1. Virtual globes in severe weather forecasting

A critical role for weather forecasters is to warn of impending severe weather. In the United States, this is accomplished by examining various observed and modeled datasets in real-time. The most critical is Doppler radar, but satellite data, numerical models and surface observations also play a key part. As the number and characteristics of these platforms increase, it has become nearly impossible for a human forecaster to stay abreast of constantly arriving data. Hence, severe weather algorithms have been devised to extract key information from these datasets in real-time so as to provide heads-up guidance to forecasters. These severe weather products have also been found useful in non-real-time mode in order to conduct post-event surveys and research studies. Because a number of industries, such as transportation and electric utilities, can take mitigating action on impending severe weather, severe weather diagnosis products are useful beyond just weather forecasters.

Weather data comes in different spatial and temporal resolutions and in different native coordinate systems. For example, the Doppler radar data used operationally are collected by a rotating instrument placed on the earth's surface. A spherical volume of data is collected every 4-10 minutes (depending on atmospheric conditions) in a "plan" spatial resolution of approximately 0.25km X 0.5 degrees. Geostationary satellites provide full disk scans of the atmosphere once every 15-30 minutes with a spatial resolution of approximately 1-4 km. The data are in a "satellite" projection that has to do with their angle of view from space. Surface observations, meanwhile, are collected in an unsynchronized manner at numerous weather stations located all over the country. All these datasets need to be visualized and analyzed by a severe weather forecaster. It is very important to enable weather forecasters to put severe weather information into a geographic context so that warning information can be effectively conveyed to the public, emergency managers, and disaster response teams. Hence, virtual globe software has been employed since the late 1990s as a data visualization system to assist forecasters with mentally assimilating information from multiple atmospheric sensing platforms (Hondl 2002).

The initial prototypes of severe weather information in virtual globes were developed at the National Severe Storms Laboratory (NSSL) and the University of Oklahoma (OU) to support NSSL's mission of enhancing the capability to provide accurate and timely forecasts and warnings of hazardous weather. These prototypes, consisting of data ingest software, severe weather algorithms, weather analysis products and visualization software were developed to assist National Weather Service (NWS) forecasters with warning decision-making for hazardous weather threats such as blizzards, ice storms, flash floods, tornadoes, and lightning. Subjective and objective analyses of the performance of these prototype systems, using virtual globe applications as the primary method to display data to users, have also been carried out (Adrianto *et al*. 2005).

The original virtual globe for displaying weather data was implemented as part of the Warning Decision Support System – Integrated Information (WDSS-II; Lakshmanan *et al*. 2007). The software, called the WDSS-II Graphics User Interface (GUI; Fig. 1) or "wg", had the ability to visually blend information from multiple Doppler radars, geostationary weather satellites, lightning detection sensors, in situ observations from surface observing systems, numerical weather prediction models, and many other data sources. In the WDSS-II GUI, users could overlay geographic information in ESRI Shapefile format, query data fields, loop images, and generate cross-sections and isosurfaces of three-dimensional (3D) data fields. The WDSS-II GUI was designed to manage a rapid, large, and continuously updating flow of real-time weather data, and because of this ability it was integrated into operational NWS systems as the Four-dimensional Storm-cell Investigator (Stumpf *et al*. 2006).

Although the WDSS-II GUI is fairly robust, supported versions were limited to Red Hat Linux-based computers, which exclude a large potential base of end users from utilizing severe weather diagnosis products. In addition, radar data from proximate radars had to be ingested and the severe weather algorithms had to be run locally by NWS forecasters (see Fig. 2). This required hardware, networking and personnel resources that were beyond the capability of many NWS forecast offices.

With the release of Google Earth and the initial KML specification[1] in 2005 it became possible to generate spatially precise, geo-referenced images for the entire coterminous United States (CONUS) and to distribute these centrally-created products via a web server to a wide audience (Figure 3). This allowed the computationally intensive data processing required to create the severe weather products to be performed centrally. It also permitted accurate, georeferenced display of severe weather information alongside other useful information such as roads, schools and stadia without having to maintain custom software for visualization. Anyone who downloaded Google Earth or other KML-supporting geo-browser would be able to access a

[1]KML 2.2 reference
http://code.google.com/apis/kml/documentation/kmlreference.html

public website[2] and obtain severe weather information. Prior to becoming early adopters of the KML specification, we had been simply making real-time, automated low-resolution snapshot images of severe weather products in the WDSS-II GUI and posting them on a web site. A combination of high-resolution images and KML files that describe those images enables a much more spatially accurate depiction of the locations of severe weather threats.

This manuscript describes the data and methods for enabling severe weather threat analysis information inside a KML framework. Section 2 describes several severe weather diagnosis products that are generated by the WDSS-II system. Section 3 explains how these products are translated to KML and image files that can be distributed via the internet. Section 4 illustrates some of the practical applications of these data when they are integrated into a virtual globe display. Several of the strengths and limitations of current virtual globes for use in weather displays are summarized in Section 5.

## 2. Summary of weather products

The NSSL and the NWS's Storm Prediction Center cooperatively run an experimental WDSS-II system that generates high-resolution three-dimensional radar reflectivity data and other severe weather guidance products for the continental United States (Lakshmanan *et al.* 2006). Internally, WDSS-II maintains the data it generates in widely used, self-describing and extensible data formats, such as Extensible Markup Language[3] (XML) and netcdf.[4] Some

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[2] WDSS-II experimental real-time weather products
http://wdssii.nssl.noaa.gov

[3] Extensible Markup Language (XML) 1.0

sensors, such as lightning detectors and Doppler radars, provide continuous input data streams, while others, such as satellites or numerical weather prediction models may update only every 15 to 60 minutes. The temporal resolution of the various real-time output data sets ranges from 1-minute to hourly updates, while the horizontal spatial resolution is between 0.25 $km^2$ and over 100 $km^2$, depending on the data source (table 1). The vertical resolution of the 3D reflectivity grid from which many products are calculated varies from 0.25 km near the surface to 1 km at 20 km Mean Sea Level. The hardware required to generate the real-time products (as of May 2009) includes 45 dual-processor/dual-core servers, each with 16 GB of memory and multiple internal serial-attached SCSI hard disk drives for fast input/output performance. The temporal update rates and latency for the output of continuously streaming input products may be improved via additional processing hardware.

The products that are generated in the WDSS-II system and translated for viewing in a KML browser are described below.

(a) Reflectivity

A single ground-based radar covers a spherical volume of only about 300 km around the radar. Thus, to obtain a 3D grid that covers the entire country, data from more than 140 radars needs to be blended together in real-time [Lakshmanan et. al 2006]. On average, each radar scans a slice of the atmosphere every 15-20 seconds; the central merging system needs to combine the data as

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http://www.w3.org/TR/xml/

[4] NetCDF User's Guide for C, An Interface for Data Access, Version 3, April 1997. http://www.unidata.ucar.edu/software/netcdf/docs/netcdf/

it arrives and put it into a georeferenced 3D grid.  In addition, the radar reflectivity data that is received from the radars does not all consist of precipitation echoes. The echoes could be due to biological returns (such as bats, birds and insects), anomalous propagation (due to atmospheric conditions, the radar beam may be bent downwards and may end up showing buildings and trees rather than clouds) or such artifacts as sun strobes, terrain occultation or instrument errors. Prior to blending reflectivity from the individual radars into a 3D mosaic of data, the reflectivity data are quality controlled to remove non-precipitating echoes (Lakshmanan *et al*. 2007).

Several radar reflectivity products are generated from the 3D reflectivity field, such as:

- Lowest Altitude Reflectivity:  the reflectivity nearest the ground at each horizontal grid point.  This is computed by marching upwards from the surface height and takes into account beam blockage due to mountains and buildings from the location of the radar. Because of beam-blockage, especially in the Mountain West, the lowest altitude reflectivity at a point may be supplied by a radar that is not the closest.  This product is used by weather forecasters as an estimate of precipitation reaching the ground;
- Reflectivity Composite (Fig. 5): the maximum value of reflectivity in the vertical column above each grid point.  This is used by weather forecasters to view the full horizontal extent of the storm at all altitudes.  High-reflectivity features may be observed in this field that may not appear at the lowest altitude or any one vertical level;
- Reflectivity at isotherm levels:  the reflectivity value at the 0°C, -10°C, and -20°C isotherm, based on the vertical profile of environmental temperature.  Hail growth occurs in the vertical layer between 0°C and -20°C, which is usually 3 to 4 km deep.  These

products provide weather forecasters with a means of identifying intensifying storms that are likely to product hail or lightning in the near future.

A two-dimensional composite reflectivity field without quality control is also produced for comparison purposes. The un-quality-controlled field is used by many forecasters to identify the location of boundaries where new convection is likely.

(b) Echo Tops

The echo top altitude (Fig. 6) is derived from the 3D merged reflectivity grid. At each grid point, this is the highest altitude in the vertical column where the particular reflectivity value is found (18 or 50 dBZ). These products can be useful for quickly identifying rapidly strengthening convection and assessing storm severity. Forecasters use the height of the 50 dBZ echo top as a technique to asses the threat of large hail (Richter *et al.* 2007) The 18 dBZ echo top is used in aviation to determine areas of potentially high turbulence in thunderstorm anvils.

(c) Relative Echo Heights

These products, which are very similar to Echo Tops, represent the difference in height between a reflectivity echo top altitude (50 or 30 dBZ) and the altitude of a specific temperature derived from environmental vertical temperature profiles (253K or -20° C; 263K or -10° C; 273K or 0° C). These fields are calculated by subtracting the height of the given isotherm from the echo top in question. Relative Echo Heights are used by forecasters as another method to estimate the severe hail potential in a thunderstorm (Donavon and Jungbluth 2007). These products can be useful for quickly identifying regions where cloud-to-ground lightning may initiate or become more frequent (MacGorman and Rust, 1998).

(d) Maximum Expected Size of Hail (MESH)

The MESH product is an estimate of hail size that is based on the vertical profiles of radar reflectivity and environmental temperature (Witt *et al.* 1998; Lakshmanan *et al*. 2006). Because the MESH is calculated for each horizontal grid point, the data show the spatial extent and size distribution of hail cores inside of thunderstorms at a given snapshot in time. Forecasters have made use of the MESH field to provide information to the public via Severe Thunderstorm Warnings about the size of hail to expect. It is also useful as a post-event damage assessment tool when accumulated into a Hail Swath product.

(e) Hail Swath

The Hail Swath products (Fig. 6) show the highest observed MESH value for a specific time period, usually 30 minutes or 2 hours, at each grid point. The result is a map of areas that were affected by large hail over that time period. Used in real-time, the Hail Swath shows the past path of the storm and may be used to estimate its direction of movement or to observe changes in direction. Following an event, it may be useful to assess the spatial coverage of potential damage to crops, roofs, and other items that may incur a loss of value when exposed to large hail. Some of the scientific applications of the MESH Hail Swath are discussed in Section 4.

(f) Vertically Integrated Liquid (VIL)

The VIL product (Greene and Clark 1972) is a measure of liquid water content in a cloud, and high values have frequently been associated with severe weather. It is calculated by integrating the vertical reflectivity profile above each horizontal grid point and converting it to mass per unit area ($kg/m^2$). Tall storms with high reflectivity values will result in high VIL values; therefore, VIL is one of several products used by forecasters as a general purpose field to help discriminate between weaker and stronger storms.

(g) Azimuthal Shear Maximum for 0-2 km and 3-6 km Above Ground Level (AGL)

Azimuthal shear is calculated using a Linear Least Squares Derivative method (Smith and Elmore 2004) on radial velocity data from individual radars and then blended into a large multi-radar mosaic for the CONUS. The blending process results in a field of maximum positive cyclonic (counter-clockwise in the northern hemisphere) shear. A near-surface (0-2 km AGL) azimuthal shear product highlights circulations and horizontal shear zones in the low altitudes of storms that may be associated with the strong rotation of mesocyclones or tornadic vortex signatures. High values (greater than 0.01 $s^{-1}$) in the mid-altitude product (3-6 km AGL) may indicate the presence of a deep mesocyclone, indicative of a well-organized supercell thunderstorm that may have a life cycle of up to several hours.

(h) Rotation Tracks

The rotation track products (Fig. 7) plot the highest observed Azimuthal Shear Maxima during a specific time interval (usually either 30 minutes or 2 hours). Two sets of rotation tracks are produced at these two time accumulation intervals, the 0-2 km layer rotation track, and the 3-6 km mid-altitude layer rotation track. This provides a history of the intensity and spatial coverage of strong storm circulations that may be associated with tornadoes or damaging wind. Some practical applications of the Rotation Tracks products are discussed in Section 4.

(i) Geostationary Weather Satellite (GOES) data

Visible, infrared, and water vapor channels are stitched together from GOES-east and GOES-west to make a single image. Forecasters use GOES imagery for a wide variety of purposes, from tracking hurricanes to determining to location of wildfires and observing volcanic ash emissions. In severe storms analysis, the infrared channel is frequently used in conjunction with vertical profiles of environmental temperature to determine the height of to tops of storms and to calculate spatial coverage of cloud cover. The visible channel is used to locate areas where convection is likely to initiate, and to locate “overshooting tops” – cloud tops that are co-located with very strong storm updrafts. Water vapor imagery is useful in assessing the broad distribution of moisture in the atmosphere, and can be used to track large-scale atmospheric waves.

(j) Lightning Density

At every 2D grid point, this product provides the density of cloud-to-ground lightning flashes that have been recorded at the grid point in the previous 5 or 15 minutes. The grid is smoothed in a 3x3 neighborhood. The input data used to generate this field may be obtained from one of several lightning strike data feeds that are commercially available. Lightning strikes may occur several km from where the core of a storm is identified with radar data, and therefore this information very useful as a supplementary meteorological data set to assess the intensity and threat area of storm cells.

(k) Lightning Probability

At every 2D grid point, this product shows the probability of a cloud-to-ground lightning strike in the next 30 minutes. The algorithm uses current lightning density, a storm motion estimate, satellite data, and radar reflectivity fields as input. The probability is computed using a neural network that was trained on historical data from across the United States (Lakshmanan and Smith 2009). This forecast data field provides guidance for people to go indoors to reduce their exposure to lighting strikes, which kill dozens and injure hundreds of people in the United States each year.[5]

(l) Surface Observations

In situ observations from Automated Surface Observing System sites and other surface-based observing systems include measurements of temperature, dew point, pressure, precipitation, wind

[5] National Weather Service Lightning Safety
http://www.lightningsafety.noaa.gov/

speed, and wind direction. These observations are among the most-used meteorological data. They are shown on the local television news, kept for the long-term climate record, and ingested into numerical weather prediction model analyses.

(m) National Weather Service text-based products

Severe convective weather warnings (tornado, severe thunderstorm, flash flood, and special marine) contain both a text description of the threat and a polygon that outlines the threat area. These products are issued by local NWS forecast offices and typically have duration of 30 minutes to a few hours, depending on the warning type. Convective outlooks and convective watches, issued by the Storm Prediction Center, are similar products that cover a larger area at a longer forecast time scale: several hours for a Tornado or Severe Thunderstorm Watch, and one to three days for a Convective Outlook. Local storm reports are point observations of severe weather, usually collected by a storm spotter or from the general public in near-real-time.

(n) Storm feature tracking

Storm cell features are identified and tracked using a geospatial image processing technique (Lakshmanan *et al*. 2009; Lakshmanan *et al*. 2003). The algorithm tracks reflectivity features, but also generates statistics based on other input fields so that the trends of those various storm intensity parameters may be displayed. For instance, one may observe how the lightning intensity has changed with a storm cell over time (Fig. 8). Forecasters follow trends of storm parameters to assess whether or not a storm will become severe, or, if it is already severe, to estimate when it will decrease in severity.

## 3. Techniques for visualization

The WDSS-II maintains data internally in netcdf and XML formats, but has data conversion routines that are capable of ingesting and writing out data in many different formats. For the purpose of mapping in virtual globes using KML, we focus on only those image formats that are supported by both WDSS-II and KML. The KML NetworkLink tag is used extensively to update the images in real-time. Color scales for the data are available as KML ImageOverlays. All KML GroundOverlay images are time-stamped, and therefore may be animated.

(a) Two-dimensional data fields

Two-dimensional data fields are converted into images with supporting KML files using one of three strategies. Image creation relies on the open-source Geospatial Data Abstraction Library[6] (GDAL) or on the open-source Portable Network Graphics[7] (PNG) library. Two types of image creation simply involve a pixel-to-pixel mapping of a single netcdf file to single GeoTIFF[8] or PNG files, as WDSS-II also uses a cylindrical (WGS84) coordinate system internally. For each GeoTiff or PNG image, a KML file is generated with a GroundOverlay tag and TimeStamp or

[6] GDAL - Geospatial Data Abstraction Library
http://www.gdal.org
[7] Portable Network Graphics (PNG) Specification (Second Edition)
http://www.w3.org/TR/PNG/
[8] GeoTIFF
http://trac.osgeo.org/geotiff/

TimeSpan. GeoTIFF images may be viewed in other Geographic Information System (GIS) software packages that do not support KML, so it may be desirable to generate geoTIFF images in some instances. PNG files have the added benefit of typically being half the size of geoTIFF files, in our implementation, which impacts the bandwidth required to distribute the images.

Because many of the images generated by WDSS-II may be as large as 20 million pixels in size, a better strategy for generating and distributing them employs the use of the KML Region tags. In this strategy, multiple PNG files (or "tiles") and supporting KML files are created by WDSS-II and are loaded into the virtual globe based on the level of detail required to match the view. Thus, when viewing from a high elevation in the virtual globe, the full resolution of data is not required because the human eye cannot differentiate that level of detail from a great distance. This greatly increases the processing and bandwidth efficiency of the process, because only the tiles for a specific region and level-of-detail required by the user's current view are loaded.[9] In this case, the tiles are created as 256x256 pixel PNG files, and match the Google Maps tile overlay specification.[10]

(b) Polygons

National Weather Service watches, warning, and outlooks are created with the KML LineString and Polygon tags, and the accompanying text describing the threat is contained in a Placemark tag. Thus, users can see both the area affected and read a detailed description of the weather

[9] Working with KML Regions
http://code.google.com/apis/kml/documentation/regions.html
[10] Google Maps API documentation
http://code.google.com/apis/maps/documentation/overlays.html

event, overlaid on any of the two-dimensional weather data images and geographic information.

(c) Point observations

ASOS observations, storm reports, and storm centroid locations are all displayed via KML Placemark tags. With Google Earth 5 KML extensions, it is possible to embed HTML and Javascript inside a Placemark description, which enables the ability to generate data-driven graphs inside a pop-up balloon (Fig. 8). Our implementation uses the jQuery[11] and flot[12] Javascript libraries.

## 4. Severe weather analysis applications of virtual globes

Since we started producing and disseminating KML format imagery in 2005, the virtual globe interface to these products has been used extensively to improve the collection of meteorological observations, help validate NWS severe weather warnings, and to monitor severe storms in real-time. Integrating these experimental meteorological data sets with the virtual globe interface via KML and the ability to overlay other geographic data sets such as address and phone number information allows many applications for the data that were not previously possible.

For example, during the Severe Hazards Analysis and Verification Experiment (SHAVE; Smith *et al*. 2006) real-time 3D CONUS radar data was employed in tandem with geographic

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[11] jQuery
http://jquery.com/
[12] flot
http://code.google.com/p/flot/

information to create a targeted, high-resolution verification dataset for severe weather. The high temporal and spatial resolution verification data that were collected describes the distribution of hail sizes, wind damage and flash flooding produced by severe thunderstorms. Prior to the initial SHAVE operations in spring 2006, most severe weather reports were collected from storm spotters in the field. The temporal and spatial resolution of these reports was on the scale 30 to 60 minutes and over 1000 km$^2$ – about the duration and size of a typical NWS Severe Thunderstorm or Tornado Warning. To facilitate research that allows more specific and accurate warnings in the future, a much higher resolution of data is needed – on the order of 10 km$^2$ and 1 to 5 minutes. Such high-resolution storm damage data sets do not generally exist, except for a few small samples of data collected as part of expensive field projects.

The SHAVE dataset was collected by scientists who examined MESH, Rotation Track, and flash flood guidance products in a virtual globe, overlaid the data with geo-referenced phone numbers from businesses and residences and used this information to make targeted phone calls. After a storm passed a location, several phone calls were made to these numbers to verify if any severe weather occurred with the storm. This type of data collection has been very effective in creating a much higher temporal and spatial resolution data set of storm reports. Figure 6 shows a comparison of the reports collected by SHAVE and the NWS for a typical event.

A second way that WDSS-II KML products have been used extensively since 2005 is for guidance in post-event damage surveys. Following a tornado event, damage surveys teams use the Rotation Tracks product to estimate the possible extent of tornado damage and to help plan a route to take to look for tornado damage. In addition to driving routes for NWS, NSSL, and local emergency management survey teams, the Rotation Tracks KML is used to assist the Federal Emergency Management Agency plan routes for aerial surveys of tornado damage, and is used to provide guidance for the International Charter on Space and Major Disasters. Following the completion of an investigation, photographs of damage taken during survey are geo-referenced and may be compared to the high-resolution satellite imagery of Earth's surface contained in virtual globes of what the area of interest looked like before it was damaged. Because of frequent requests for the Rotation Track KML that had expired off of the real-time data stream by survey crews and NWS offices, an automated system was implemented to help fulfill these archived data requests (Manross *et al*. 2008).

Although these KML severe weather products have not yet become part of the official data streams supported by the NWS for use in forecast offices, many NWS offices do use the data in a virtual globe as part of a situational awareness display during severe weather warning operations (Foster *et al.* 2009). Situational awareness displays, as used by NWS forecasters, are intended to put small-scale thunderstorms into a large-scale perspective, and to provide geographic context for where storms may impact life and property.

## 5. Conclusion

Virtual globes are a powerful tool to help users visually integrate meteorological data sets with geographic information to assess impacts of weather events at specific locations. The wide acceptance of the KML standard allows data sets that were previously limited to a purely research-oriented audience to be distributed widely, opening up many new possibilities for the use of these products.

Stellman *et al*. (2009) describe the use of virtual globes, georeferenced severe weather algorithm products and targeted phone calls to improve the verification efficiency of NWS warnings. They attribute a 10% increase in the rate of Tornado and Severe Thunderstorm Warnings from 2007 to 2008 by simply making telephone calls to businesses that they identified as being in the center of the storm's path in Google Earth. Foster *et al*. (2009) describe many ways that virtual globes are used in NWS operations to increase situational awareness during storm events, for impact analysis of events, and severe weather event verification. Our website that serves out georeferenced severe weather products to virtual globe clients was visited by over 10 000 unique visitors in May 2009 alone; over 7 million products were downloaded from the site in just that month.

The general availability of standard virtual globe clients and the specification of standard data formats and protocols have enabled the democratization of georeferenced data. However, such general purpose tools and software come with the limitation that unique characteristics of weather data sometimes can cause problems. For example, several of the more advanced weather analysis functions in the original WDSS-II GUI, such as the ability to query data, are not yet available in commercially available virtual globes. Instead, images must be interpreted through the use of a color scale to determine approximate data values. There are other shortcomings as well. Because the atmosphere is three-dimensional and rapidly changing in time, future improvements to virtual globes include the need to robustly handle real-time data streams that may have some latency associated. For instance, a satellite image that updates every 15 to 30 minutes does not synchronize well in Google Earth with radar data that updates every 2 minutes.

These limitations can be addressed by building a custom virtual globe client for weather data, but this sacrifices the advantages of a freely available, standardized tool. In practice, therefore, we use a custom virtual globe client (the WDSS-II GUI) for some purposes and the standard virtual globe client (Google Earth and NASA WorldWind) for others. Currently, we are building the WDSS-II GUI functionality on top of the NASA WorldWind Java API so as to derive the benefits of both a standard toolkit and custom functionality.

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| Product | Approx. temporal resolution of output | Approx. spatial resolution of output |
|---|---|---|
| Radar reflectivity-based products: | 5 min | 1 $km^2$ |
| Reflectivity | | |
| Echo Tops | | |
| Relative Echo Height | | |
| Max Expected Size of Hail | | |
| Vertically Integrated Liquid | | |
| Radar velocity-based products: | 2 min | 0.25 $km^2$ |
| Azimuthal Shear | | |
| Rotation Tracks | | |
| Geostationary Weather Satellite: | 7-25 min | |
| Infrared | | 16 $km^2$ |
| Visible | | 1 $km^2$ |
| Water Vapor | | 16 $km^2$ |
| Lightning: | 1 min | 1 $km^2$ |
| Density | | |
| Probability | | |
| Surface Observations | 15-60 min | Varies |
| NWS Warnings | 1 min | Varies |
| NWS Storm Reports | 1 min | Varies |

Table 1: Temporal and spatial resolution of KML products generated by the WDSS-II system in real-time.

**Figure Captions**

Figure 1: An early version (2000) of the WDSS-II GUI virtual globe with full 3D pan, zoom, tilt, and data interrogation controls and multi-radar data from Arizona.

Figure 2: State of the art circa 2002: In order to utilize multi-radar severe weather algorithms in real-time, a NWS forecast office had to ingest radar data from proximate radars and set up a WDSS-II algorithm server to compute and serve out products on their local area network. These products could then be visualized by a custom-built virtual globe display that provided a georeferenced coordinate system to visualize multiple weather datasets.

Figure 3: In 2005, the availability of a well-supported virtual globe client that could obtain data in standard formats over HTTP using a documented transport protocol enabled us to disseminate highly accurate data that covered the entire coterminous United States (CONUS) over the web. Users of the data required nothing more than a KML browser.

Figure 4: Reflectivity Composite image of Hurricane Wilma (2005) visualized using the Google Earth client and standard data formats and transport protocols.

Figure 5: 18 dBZ echo tops for thunderstorms in Oklahoma visualized using a modified WorldWind client and standard data formats and transport protocols. The ability to overlay geographic data such as roads, cities and schools from other sources is a key advantage of standard virtual globe toolkits. Detailed analysis of data requires the ability to query the raw data values (inset).

Figure 6: 2-hour Hail Swath product overlaid with reports from the Severe Hazards Analysis and Verification Experiment and NWS local storm reports as seen in Google Earth.

Figure 7: 0-2 km Rotation Tracks for the May 3, 1999 tornado outbreak in Central Oklahoma, shown with actual tornado paths from post-event damage surveys (white lines) from the National Oceanic and Atmospheric Administration. The visualization here is using a custom virtual globe built at the National Severe Storms Laboratory.

Figure 8: Reflectivity cluster identification (blue hexagons) with trends of reflectivity (yellow/black) and Lightning Flashes (blue/black). The orange and red polygons are NWS Severe Thunderstorm Warnings and Tornado Warnings, respectively. The visualization here is on Google Earth.

Figure 1
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Figure 2
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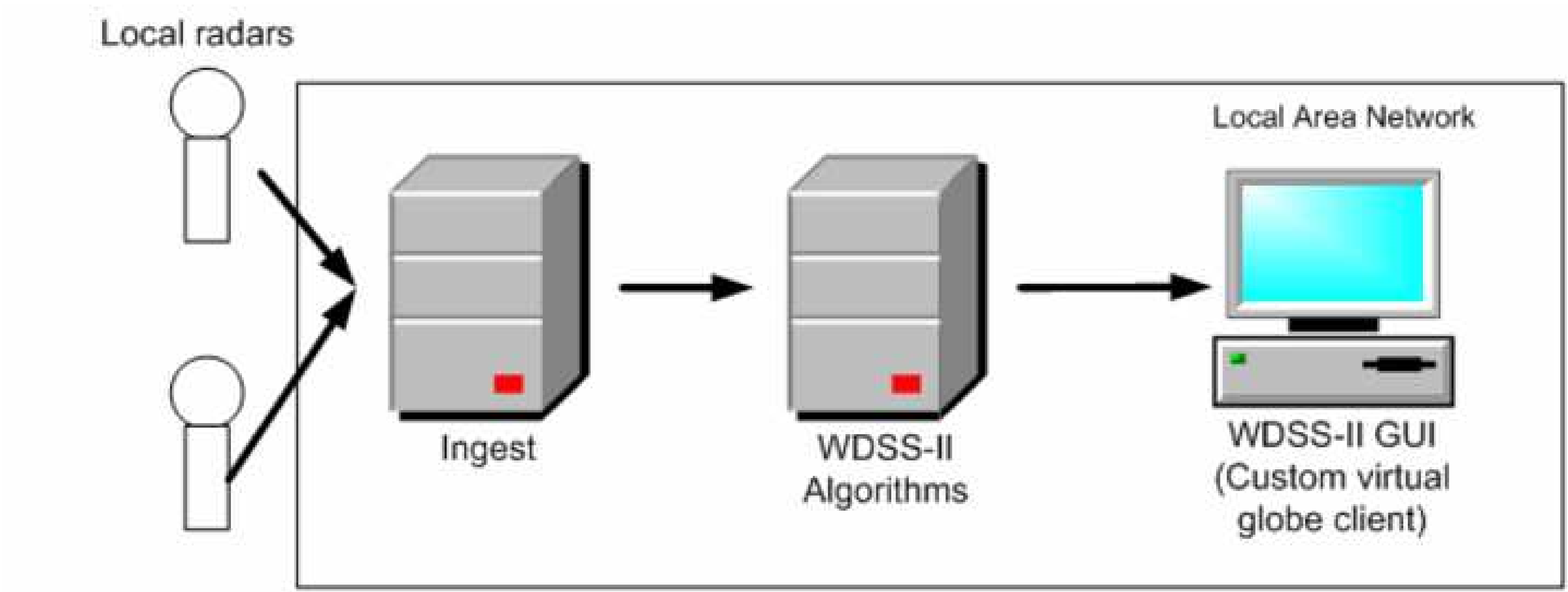

Figure 3
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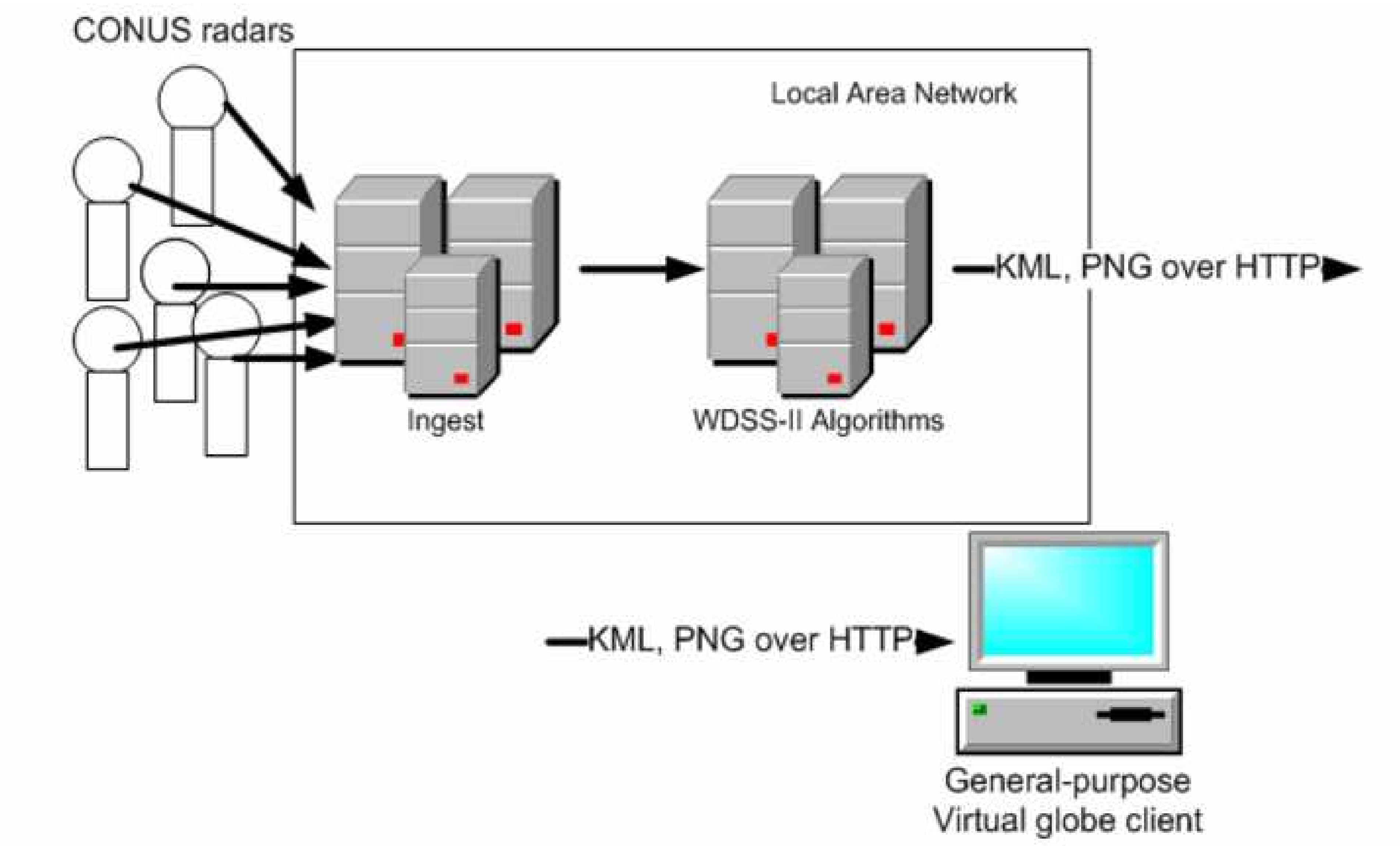

Figure 4
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Figure 5

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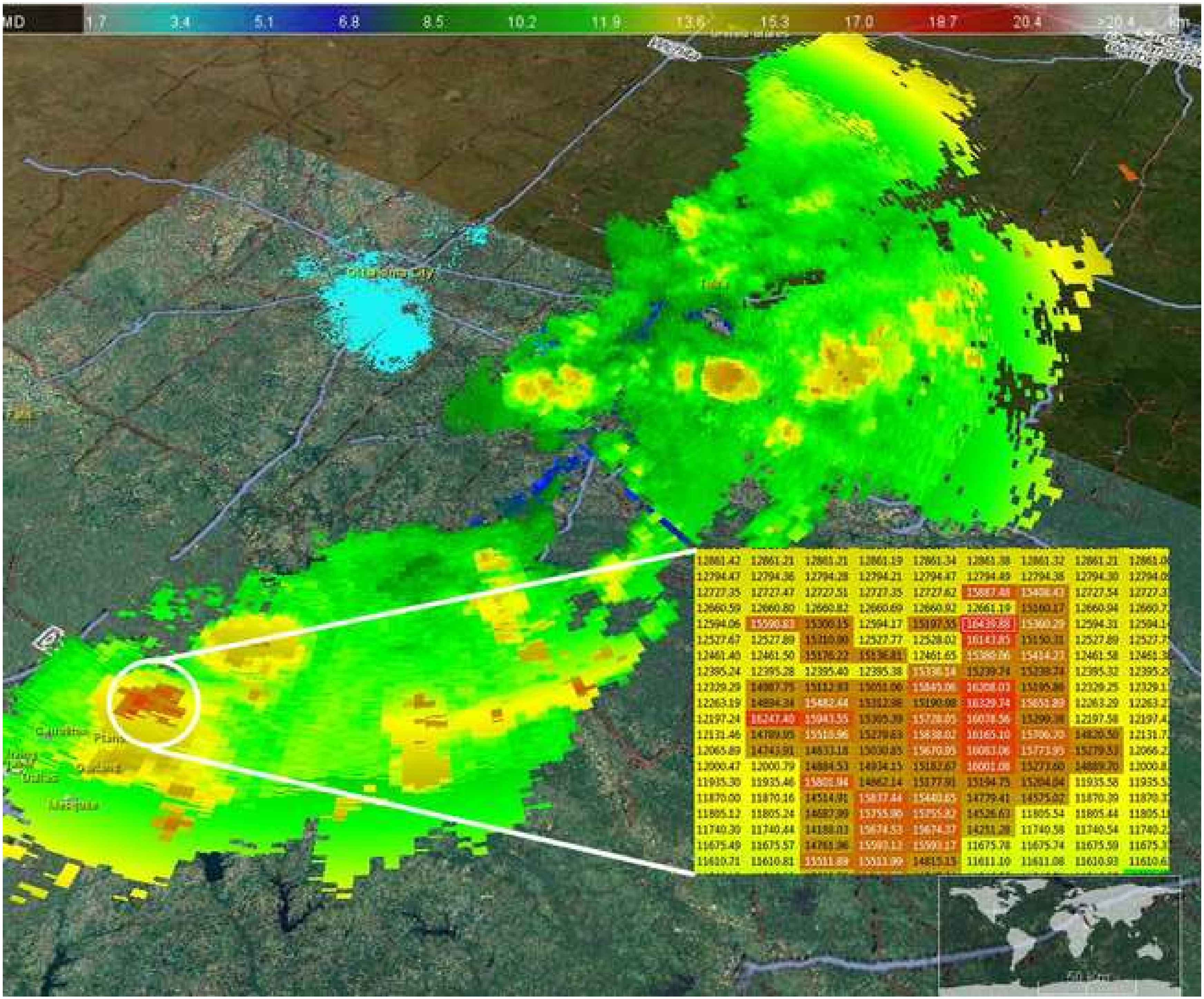

Figure 6
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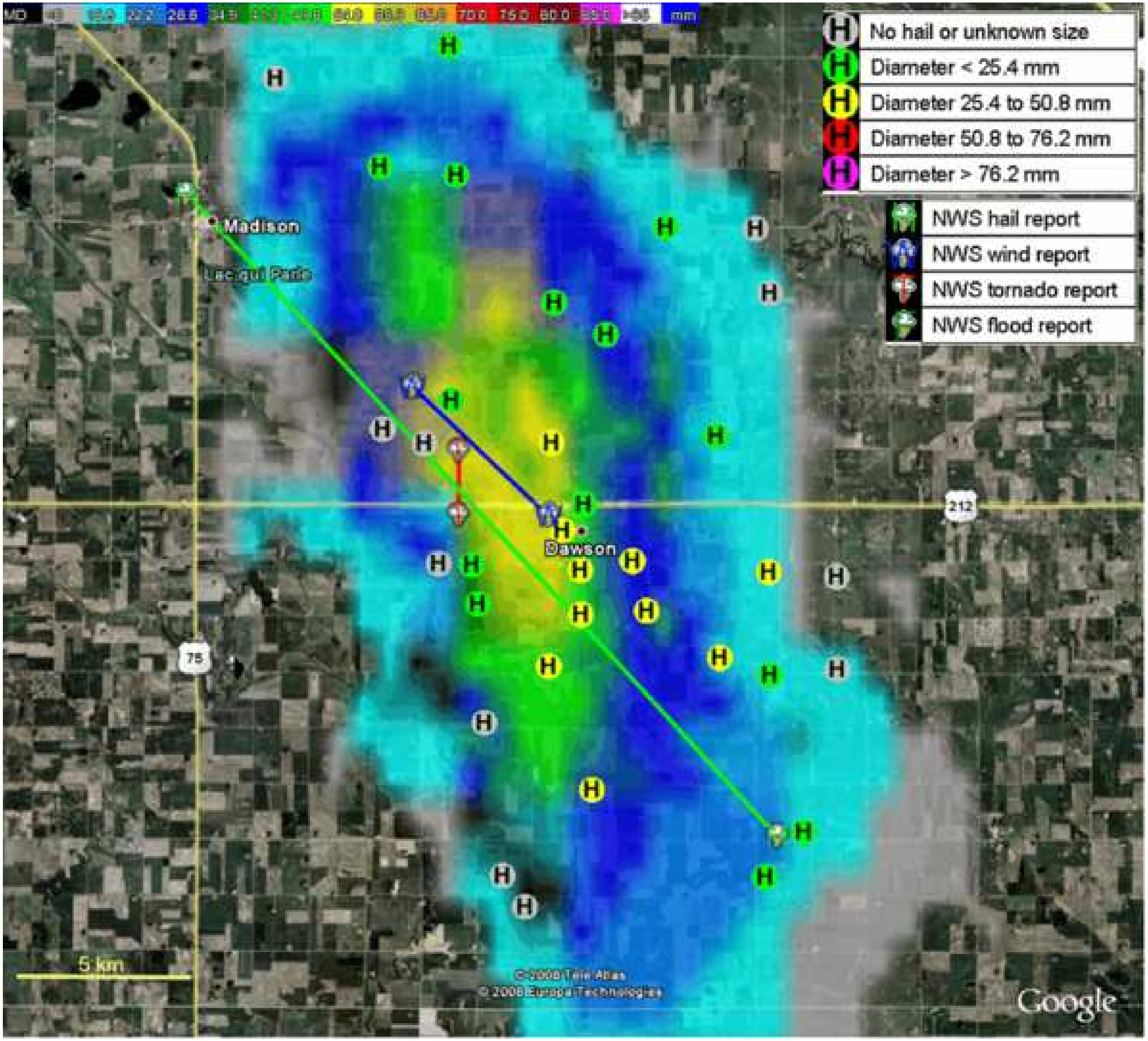

Figure 7
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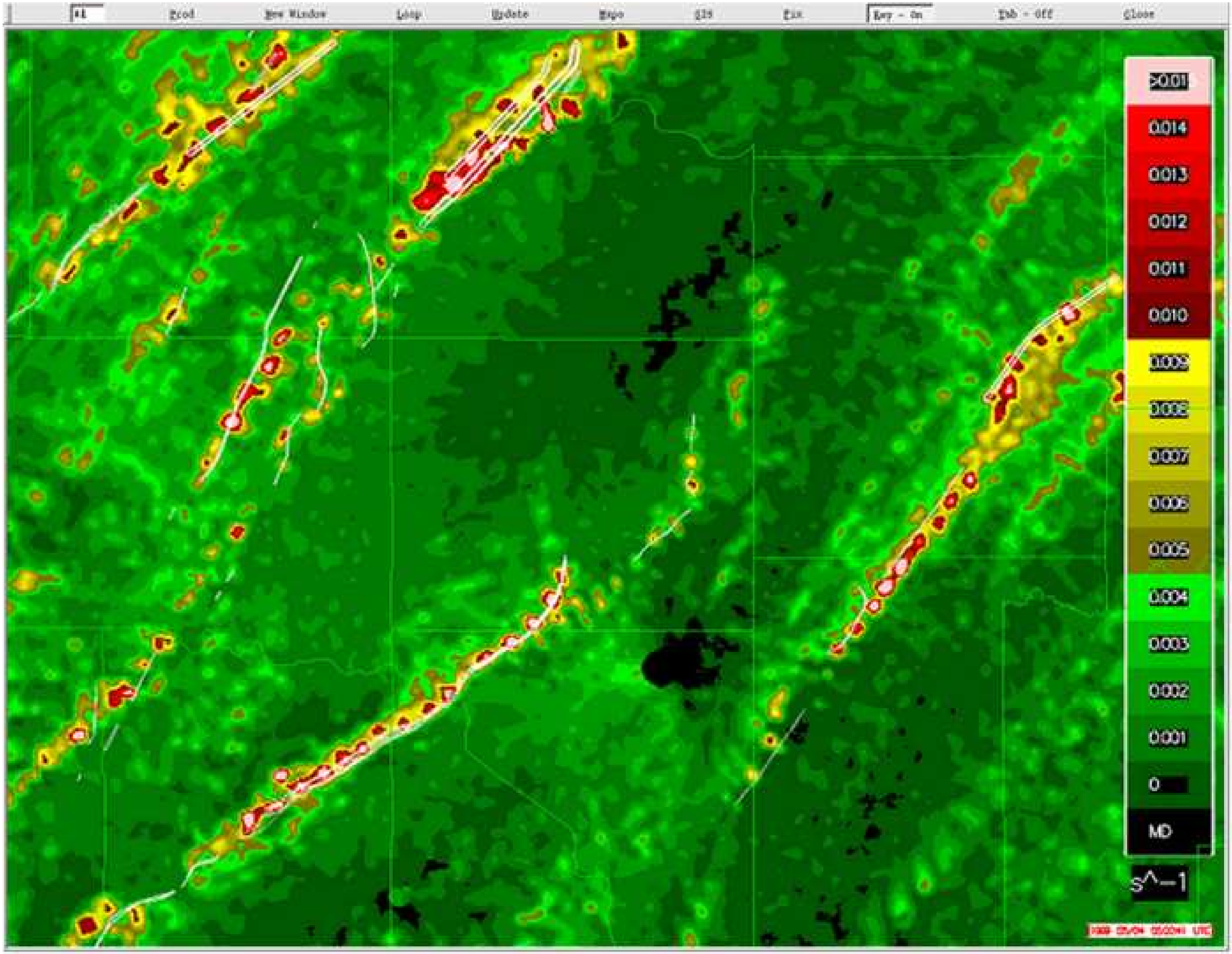

Figure 8

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