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NASA PRECIPITATION DATA IN VIRTUAL GLOBES: MOVING BEYOND 2D REPRESENTATIONS

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ABSTRACT— A prototype has been developed that enables Google Earth to access the ~13 terabyte precipitation archive of the Tropical Rainfall Measuring Mission (TRMM). While other organizations distribute TRMM satellite data for display in Google Earth, this prototype is the first application that allows Google Earth to examine single-orbit files at full resolution in 3D. This archive access tool is intended for researchers, but the paper also presents a separate Google Earth prototype intended for public outreach. The public outreach prototype provides detailed 3D visualization of a single precipitation event. The paper provides instructions for using the prototypes and explains the implementation issues. These prototypes demonstrate strengths and weaknesses of using Google Earth for archive access and scientific visualization. The Precipitation Processing System developed these prototypes as part of its support of the Global Precipitation Measurement (GPM) Mission.

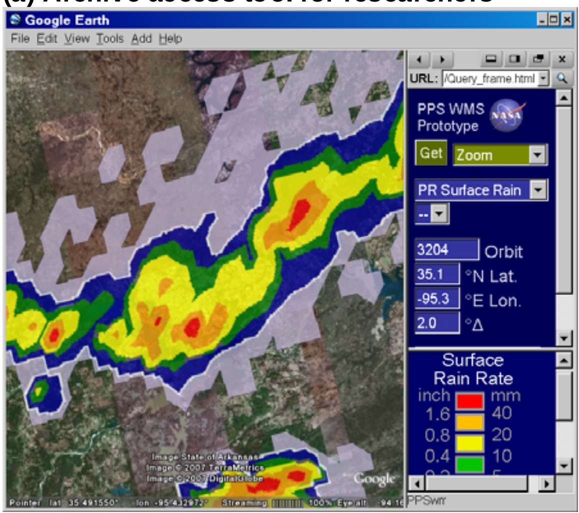
1. INTRODUCTION

Google Earth is a widely used "virtual globe" application, an application that displays geographic data in 3D. Google Earth access to NASA precipitation estimates is currently limited to time-averaged, two dimensional summaries of recent observations. These realtime observations are available on the NASA web site and the Japan Space Exploration Agency (JAXA) web site (See section 3.3).

The Google Earth prototypes described in this paper allow users to examine the original single-orbit data (not time-averaged summaries). Figure 1 shows screen captures of the two prototypes. The first prototype provides researchers with access to the satellite data archive of the Tropical Rainfall Measuring Mission (TRMM) which contains observations from 1998 to the present. The second prototype is a 3D visualization format intended for public outreach.

This paper describes how to use the prototypes and explains implementation details. This approach reveals strengths and weaknesses of the Google Earth interface as a scientific

(a) Archive access tool for researchers



(b) 3D file for public outreach

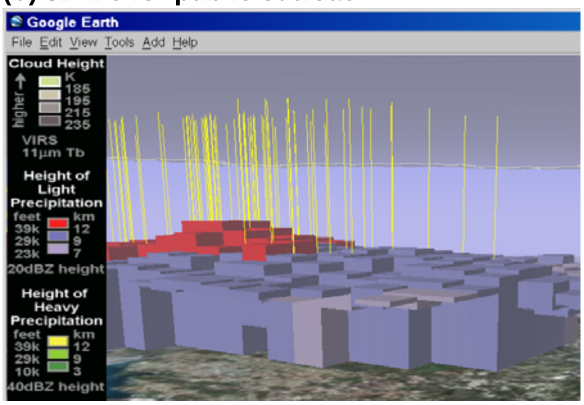


Figure 1. Screen captures of the two prototypes described in this paper. (a) See section 3.3 for details. (b) See section 3.6 for details.

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visualization tool. Both prototypes described in this paper were developed by the Precipitation Processing System (PPS) at NASA's Goddard Space Flight Center.

2. DATA AND FILE FORMATS

The TRMM satellite data set is useful for prototyping data distribution applications for the Global Precipitation Measurement (GPM) Mission scheduled for launch in 2013. GPM will calibrate a constellation of satellites with passive microwave radiometers using a core satellite with a dual-frequency precipitation radar and a passive microwave instrument (*Hou* 2006). The TRMM satellite carries a single frequency radar, passive microwave instrument, visible and infrared instrument, and a lightning sensor (*Kummerow et al.* 1998; *Kozu et al.* 2001; *Christian* 2000).

The file format of the TRMM archive is the Hierarchical Data Format (HDF). An advantage of the HDF format is that HDF files are self-describing, containing all necessary metadata for reading them. Libraries for reading HDF files are available for low-level programming languages, such as C and FORTRAN, and come pre-installed in some high-level programming languages, such as IDL and Matlab. In contrast, most Geographic Information Systems (GIS) and virtual globes have limited if any ability to read HDF files. Google Earth cannot read HDF, and the TRMM archive of single-orbit HDF files is too large (~13 terabytes when compressed) to be easily converted into a Google Earth format. Since 1998, the TRMM satellite has collected over 57,000 orbits of observations. For each orbit, there is 1.0 gigabyte of HDF standard products (0.23 gigabytes when compressed).

Virtual globes, such as Google Earth, display files written in the Keyhole Markup Language (KML) (http://code.google.com/apis/kml/documentation/). KML is an instance of the Extensible Markup Language (XML) which is a pure-text file format. A KML file can contain geometric objects (points, lines, and surfaces) and references to images. A KML file also provides instructions on how to display these geometric objects and images on a map of the Earth. There are several options for where to locate the images that a KML file refers to. One option is to use the "zip" utility to compress a collection of files including a KML file and the images that it refers to. The resulting zip file is given the KMZ file extension. Another option is for the KML file to use a URL to refer to images on the local computer or on the internet. The third option is to use a URL that includes CGI parameters so that the image can be dynamically generated by another system. The KML objects defined below will be mentioned throughout the paper.

- **GroundOverlay**. An image to be displayed horizontally relative to the Earth at a specified altitude.
- **ScreenOverlay**. An image containing non-geographic information to be displayed at a specified pixel location in the Earth view portion of the Google Earth window.
- **Point Placemark**. A clickable point on the surface of the Earth or in space that is marked with a pushpin or other icon. When the icon is clicked, a pop-up window appears with the description of the Placemark.
- **LineString Placemark**. A line specified by a series of points defined by latitude, longitude, and altitude.
- **Polygon Placemark**. An area specified by a series of points along its edge.

3. SOFTWARE

3.1. Google Earth

Google Earth is a client-server application that can also be thought of as a file viewer for KML and KMZ files. This paper uses the Windows XP release of Google Earth, version 4.2. The archive access prototype described in this paper will not run on the Mac OS X release of Google Earth because the Mac version lacks the file associations of Windows XP (See section 3.3). *Carlson* (2007) claims that 300 million computers now have Google Earth installed, which is comparable to the 400 million computers that *Hamm* (2006) claims have Microsoft Office installed.

Google Earth is just beginning to be used in scientific research and for the distribution of scientific data. Conference papers describe how KML GroundOverlays can be combined with Point Placemarks to assist with scientific research (*Scharfenberg* 2007; *Smith et al.* 2007; *Smith and Lakshmanan* 2006; *Ortega et al.* 2006). Starting in 2007, the free Google Earth client has a "NASA" layer in the lower left corner which contains some NASA outreach images (*Caverly* 2007; *NASA* 2007). Some NOAA data is distributed in formats that Google Earth can display (*Baldwin* 2007). NOAA's data offerings for Google Earth may expand in the future (*Roberts et al.* 2007).

The free Google Earth client can have three parts to its main window (Figure 2). On the left is the "sidebar," which allows the user to display or hide specific objects in KML files. In the center is the Earth view. On the right is the built-in web browser. By default, the web browser is along the bottom of the Google Earth window, but the archive access prototype looks best when one presses the side button ◨ to move the web browser to the right side of the Google Earth window. The built-in browser is the only place in the Google Earth client where user data can be collected via an HTML form and JavaScript.

3.2. Web Map Service (WMS)

A Web Map Service (WMS) is an image generation application that is run by a web server to fulfill a web client's CGI request (*de la Beaujardiere* 2006, p. v). The WMS specification was first published in 2000 by the Open Geospatial Consortium (*OGC* 2007; *de la Beaujardiere* 2006). The WMS specification defines the names and meaning of parameters in the CGI request.

A WMS server responds to two kinds of requests: a request for an image and a request for metadata that describe what images can be generated. These requests are called GetMap and GetCapability requests, respectively. In response to a GetCapability request, a WMS server responds with an XML file that defines the data available from the WMS server. In response to a GetMap request, the WMS server responds with a dynamically generated image. Since WMS responses are transmitted via HTTP, a WMS server must begin each response with two special lines. Those two lines are an HTTP Content header that states the mime-type of the file to be transmitted and a completely blank line (See Table 3 and *Apache* (2007)).

For this paper, a WMS server was developed to access single-orbit TRMM files in the compressed HDF archive. Pre-existing WMS servers appear unable to work easily with single-orbit files. A single-orbit file is somewhat more difficult to visualize than a grid file because each observation in an orbit swath is associated with an explicit latitude and longitude. In contrast, a grid only requires that the visualization software keep track of the grid boundary and resolution. The NASA Goddard DAAC, for example has developed a WMS server that works on time-averaged grid files (*DAAC* 2008). The British National Space Centre has also developed a WMS server that works on grid files (*ICEDS* 2006).

3.3. The PPS WMS Server

One of the two prototypes described in this paper is an archive access tool based on Google Earth. The user model for this tool is given in Table 1, which provides the outline for the next three sections of this paper.

The PPS WMS server sends images, KML files, and KMZ files to the Google Earth client. The web browser built into the Google Earth window displays an HTML form to collect user input for making the requests that are sent to the PPS WMS server. JavaScript processes the HTML form input to hide some of the complexity of the WMS request. By default, the WMS server's HTTP responses would be displayed in the built-in web browser. The exception is if the HTTP response has the KML or KMZ mime-type (Table 3). In that case, the built-in web browser redirects the HTTP response to the Earth view at the center

Table 1. The user-model for the Google Earth archive access tool that provides visualization and access to the TRMM HDF archive of single-orbit precipitation estimates.

Step	Description
1	The researcher examines low resolution browse images of individual orbits
2	The reseracher examines high resolution zoom images to choose a geograpic region of interest
3	The researcher downloads from the archive the HDF file that contains this orbit of data for further analysis

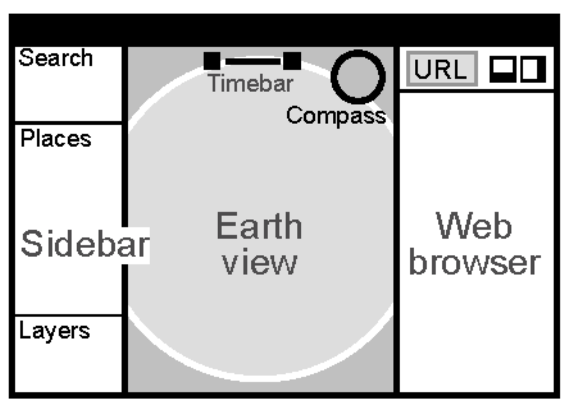


Figure 2. A schematic diagram of the main window of the free Google Earth client.

of the Google Earth window (Figure 2). Figure 7 summarizes the interaction between the built-in web browser, the WMS server, and the Earth view.

To begin using the PPS WMS server, a researcher downloads a small KML file from the PPS web site. Table 2 shows the file's contents.

This KML file is opened in Google Earth to gain access to both realtime and archive data. TRMM realtime data is generated between 3 and 8 hours after the time of observation (*Huffman et al.* 2007; *Kubota et al.* 2007). The existing Google Earth access to TRMM realtime data is limited to gridded multi-orbit composites, which is one reason why the prototype in this paper focuses on non-gridded single-orbit files. *Turk et al.* (2008) describe plans at the Naval Research Laboratory to enable Google Earth to display single-orbit tropical cyclone images from passive microwave instruments on the TRMM satellite and other satellites.

To access archive data, the researcher clicks on the Archive object in the KML file listed in Table 2. When the Archive object is clicked, the built-in web browser loads an HTML page that allows the user to generate WMS requests (Figures 1a and 2). As described in the next section, the HTML page permits the researcher to begin with only a broad idea of the time and location of interest.

3.4. Accessing Browse Images Using the PPS WMS Server

According to the user model in Table 1, the first step to using the prototype is to display one day's worth of browse images. Browse images can be displayed rapidly because they are pre-generated and each one covers the entire Tropics. The disadvantage of a browse image is that a storm appear somewhat grainy due to the image's low resolution. Figure 3 shows a pair of browse images as displayed in Google Earth.

The researcher specifies the day of interest in the HTML form. In response, the PPS WMS server generates a KML file containing GroundOverlays that point to browse images on the PPS web site. When Google Earth opens this KML file, a pair of browse images are displayed for the first orbit of the specified day. The wider swath is for the TRMM Microwave Imager (TMI) and the narrower swath is for the TRMM Precipitation Radar. Each swath shows the surface precipitation rate (millimeters of rain per hour) for one instrument. Each day, the TRMM satellite makes 15 or 16 orbits around the Earth.

To quickly scan through the day, the researcher can use the Google Earth timebar in two ways. A time range can be selected that shows the entire day as a composite image created on the fly from the individual orbit images. Alternatively, the day can be played like a movie loop, showing each orbit successively.

The browse images displayed in Google Earth have been modified by background processing from the standard PPS browse images. Standard browse images have features that enhance their use in traditional data ordering systems but that hamper their use in Google Earth.

The Google Earth version of a PPS browse image has a transparent background. One strength of Google Earth the ability to overlay multiple layers of geographic information, which is facilitated by having transparent backgrounds in each layer. The Google Earth version of a PPS browse image also crops the text labels and color key of a standard browse image because these items would be difficult to read when squeezed at the poles in Google Earth. Often these items

Table 2. Outline of the PPSwms.kml file that provides Google Earth access to the TRMM archive

Object name	Object description
PPSwms	Document object, the top-level object
Realtime	Folder
3 hour global precipitation	GroundOverlay with image located on the NASA TRMM web site. (http://trmm.gsfc.nasa.gov/affinity/download_kmz.html)
1 hour global precipitation	Placemark with a hyperlink to a sample KMZ file on the JAXA web site. (http://sharaku.eorc.jaxa.jp/GSMaP/index.htm)
Archive	Placemark with a hyperlink to the HTML page that generates requests for the PPS prototype WMS server. (http://www-tsdis.gsfc.nasa.gov)

would be outside the Google Earth field-of-view.

The orbit time does not need to be burnt into the Google Earth version of a browse image because orbit time is stored in the KML file that is transmitted to the Google Earth client by the PPS WMS server. The KML TimeSpan is used by the Google Earth timebar to allow the user to select a time of day. To provide color table information, JavaScript displays an appropriate color table in the lower right corner of the Google Earth window (Figure 3a).

The dynamically generated KML file also contains one ScreenOverlay for each orbit. The ScreenOverlay points to an image on the PPS web site that shows the orbit's number, date, and start time. Google Earth displays the ScreenOverlay in the lower left corner of the Earth view (Figure 3a).

As described so far, the archive access capabilities of Google Earth are only a small step forward from the capabilities of traditional data ordering systems. Google Earth, however, has built-in functionality that allows for a more dramatic advance in the way researchers access the TRMM archive. More specifically, the Google Earth "window" into the TRMM archive can include Placemarks that appear to be imbedded within the archive to highlight data of interest. As part of the prototype, the PPS WMS server generates these Placemarks from a list of events stored in a text file in the WMS server's configuration directory. Were this prototype to become operational, a more complete list of events could be used. For example, the event list could include severe precipitation events identified in the TRMM precipitation feature database of *Zipser et al.* (2006). The operational list could also assimilate the existing record of TRMM satellite maneuvers that explain the causes of occasional gaps in the observations.

At the center of Figure 3a is a KML Placemark imbedded in a day's browse images. The storm in Figure 3a was identified by *Zipser et al.* (2006) as one of the most intense in a decade of TRMM observations. In Google Earth, the KML Placemark takes the form a box around the storm and a clickable icon. When the user clicks on the icon, a pop-up window appears.

As shown in Figure 3b, this pop-up window states the location and time of the event and gives two links for exploring the event. Clicking on the first link will load that event's location and orbit number the Google Earth built-in web browser (Figure 1a). With this information loaded in the HTML form, the researcher is one click away from generating a dynamic zoom image of that event.

Such Placemarks are easy for PPS analysis to maintain. For each Placemark, analysts or automated scripts would need to add only one line of text to the list of events in the WMS server's configuration directory.

When the researcher clicks on the first link in the pop-up window (Figure 3b), what appears to occur is the location and orbit number of the Placemark are transferred into the fields of the HTML form in the built-in web browser. Unfortunately, there is no easy way to perform this action in the existing Google Earth client. The work-around used in this prototype is that clicking on the Placemark sends the PPS WMS server a location and orbit number. The PPS WMS server

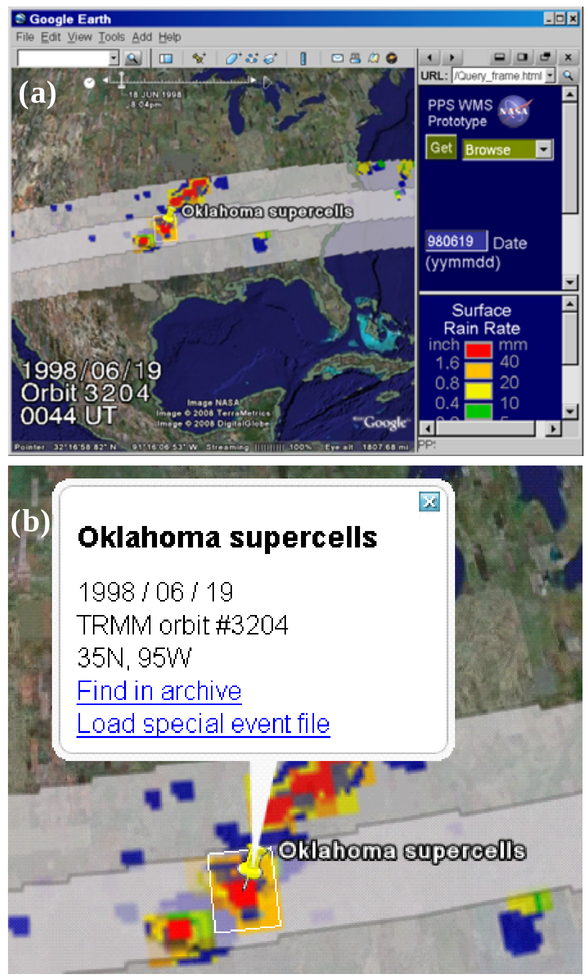


Figure 3. A screen capture of static PPS browse images as modified for display in Goolge Earth. (a) Browse images for TRMM orbit #3204. (b) The pop-up window that appears when one clicks on the Placemark over the Midwestern storm observed in TRMM orbit #3204.

responds by generating an HTML frame that contains that location and orbit number in its header. When the built-in web browser loads this HTML page, JavaScript reads the header and fills in the HTML form accordingly. The Globe Glider application uses an alternative approach to reading information from Google Earth (http://globeglider.net). Globe Glider uses a KML NetworkLink in a manner not documented in the KML specification. It is not clear if this alternative method can also read the current value of the Google Earth timebar. To generate a zoom image, it is necessary to know both location and time (or equivalently location and TRMM orbit number).

The sample Placemark in Figure 3b also has a second link. The second link downloads from the PPS web site a 3D KMZ file that provides detailed 3D visualization of the multiple TRMM instrument observations of that storm. This kind of manually constructed 3D file is described in section 3.6. Were the archive access prototype to become operational, there would be only a limited number of these manually created 3D files. Such files would be created only for events of historical importance. This kind of 3D file is primarily intended for public outreach. It requires only a small effort, however, to link a 3D file into the Google Earth archive access tool. The 3D files do not interfere with a scientist's browsing, and a detailed visualization of a major precipitation event might be helpful on occasion.

3.5. Generating Zoom Images Using the PPS WMS Server

So far the paper has described the first step in the user model (Table 1) which is to refine the location and time of interest using low resolution browse images. This section describes how to further evaluate which orbit is of interest using dynamically generated zoom images.

The PPS WMS server manages a staging area of temporary files that is used to speed up the generation of zoom images. When a researcher requests a zoom image of a specific variable, orbit number, and geographic location, the PPS WMS server first looks in the staging area for a small binary file containing the required TRMM data. If the binary file exists, then the PPS WMS server reads it and generates an image in under 2 seconds for most TRMM orbit variables. If the binary file does not exists, then the PPS WMS server checks the staging area for an uncompressed copy of the HDF file. If one exists, the PPS WMS server makes a binary file.

If an uncompressed copy of the HDF file does not exist in the staging area, then the PPS WMS server must create one. Uncompressing a TRMM 2A25 file takes approximately 30 seconds, which is longer than the HTTP timeout period for Google Earth. For this reason, the PPS WMS server starts a background job to uncompress the HDF file and then immediately sends a short HTML message to Google Earth before the uncompression operation finishes. This HTML message notifies the user that the data is being staged from the archive and that the user should resend the request in 30 seconds. The PPS WMS server monitors the staging area and deletes older files as necessary to prevent the staging area from becoming full.

When the researcher requests a single zoom image, the PPS WMS server generates the image and transmits it to the Google Earth client in a KMZ file that contains both the image and a KML file that explains how to display the image (Figure 4a).

If the researcher wishes to examine the vertical structure of a storm cell, the archive access prototype does has a limited ability to do so. When the researcher selects the "combination" WMS request, the result is shown in Figure 4b. The PPS WMS server generates a vertical stack of horizontal radar reflectivity cross sections. Stacked reflectivity cross sections are a technique that has been used for decades to visualize the 3D structure of a storm (*Cotton and Anthes* 1989, pp. 461–462).

As described in the user model (Table 1), the researcher examines browse and zoom images in order to choose an HDF file to download from the archive. The PPS WMS server gives the researcher two download options. One option is to request a single HDF file. The PPS WMS server responds with HTTP headers that redirect the browser portion of the Google Earth window to the PPS FTP server. This is done by specifying an HTTP Location header immediately after the HTTP Content header. The other download option is to request an FTP directory. The PPS WMS server responds in the same way as before except that the HTTP Location header specifies an FTP directory rather than an FTP file. An FTP directory contains all standard products for the given orbit and for all other orbits that occurred during the same day.

3.6. 3D File for a Severe Storm

So far the paper has discussed browse and zoom images, and the only 3D visualization has been the stacked contours shown in Figure 4b. This section describes a KMZ file that provides detailed 3D visualization. To develop IDL software to generate these prototype KMZ files, four severe storms were selected: a Midwestern U.S. supercell, a squall line over Florida, Hurricane Katrina (2005), and isolated convection over Africa.

A 3D KMZ file was generated for the severe convective storms that passed through eastern Oklahoma on 19 June 1998. During the summer, the central United States periodically has severe storms that can cause damage due to lightning strikes, large hail, tornadoes, flash floods, or fast surface winds. According to NOAA's Storm Event Database, Oklahoma felt many of these effects on 19 June 1998. One of these storms was among most intense observed by the TRMM satellite (*Zipser et al.* 2006).

Figure 5a shows variables that are displayed when the 3D KMZ file is first opened in Google Earth. There are too many objects in the 3D KMZ file to display them all at once. Instead, the user works with the Google Earth sidebar to display a few objects at a time.

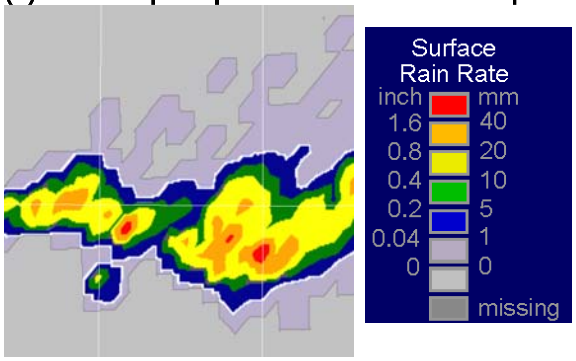
In Figure 5a, cloud top temperatures are displayed in grayscale and were observed by the TRMM Visible and Infrared Scanner (VIRS) 11 micron infrared channel. The colder the 11 micron brightness temperature (Tb) in degrees Kelvin (K), the taller the cloud top is likely to be. The KMZ file instructs Google Earth to display the clouds semi-transparently so that radar-observed precipitation is visible inside of the clouds. The precipitation is displayed by means of a 3D surface that contains all TRMM Precipitation Radar observations above a 20 dBZ radar reflectivity threshold. This threshold indicates the presence of light rainfall. The color coding of the reflectivity surface is based on the maximum altitude that the 20 dBZ signal reaches inside of each column of data. To a first approximation, the taller a storm cell, the more likely it contains strong updrafts, heavy precipitation, hail, and lightning (*Williams* 2001). The yellow dots are the geographic locations of lightning strikes observed by the TRMM Lightning Imaging Sensor (LIS). For the screen captures in Figure 5, the surface of the Earth was covered with a gray background to highlight the TRMM data being displayed.

Figure 5b shows a side view of the storm. On the left is the central updraft region of the storm and on the right is the storm's anvil. The lightning strikes that appeared to be yellow dots in the top view (Figure 5a) are seen to really be vertical lines in the side view (Figure 5b).

Table 3. The Mime-types associated with files used in the PPS WMS prototype.

Mime-type (all one line)	File type
text/html	HTML
image/png	A PNG image
application/vnd.google-earth.kml+xml	A KML file
application/vnd.google-earth.kmz	A KMZ file
application/x-gzip	An HDF file compressed by gzip
application/x-hdf	An HDF file

(a) Surface precipitation from a WMS request



(b) Radar reflectivity and surface precipitation from several WMS requests

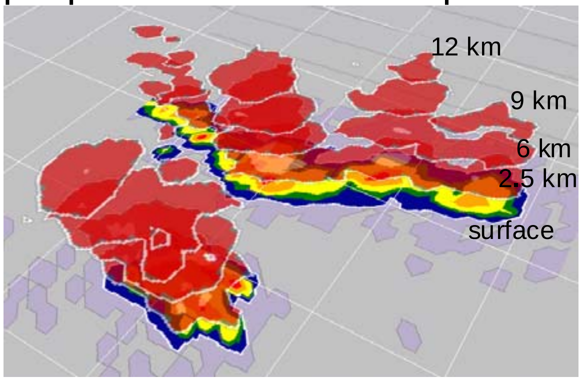


Figure 4. Screen captures of dynamically generated zoom images as displayed in Goolge Earth. (a) A single image of TRMM 2A25 surface precipitation rate. (b) A "combination" view of horizontal radar reflectivity contours that are stacked at altitudes from 2.5 km to 12 km. The dark and light red represent 30 and 50 dBZ reflectivity, respectively.

Figure 5c shows a vertical cross section of radar reflectivity through the middle of the storm. The 3D surface has been made mostly transparent using the Google Earth sidebar so that the vertical cross section can be seen within the 3D surface. The vertical cross section shows that there are two regions of strong radar reflectivity, suggesting two updraft regions. These two regions would be difficult to identify if the 3D KMZ file only provided a 3D surface, not the vertical cross section. The vertical cross section in Figure 5c has the desirable property of having crisp edges no matter how closely one zooms in on it because the vertical cross section is composed of KML polygons. In contrast, the horizontal cross sections in Figure 4b have imprecise edges because they are images, not a collection of polygons. Precise edges are a desirable quality in scientific visualization.

Figure 5d shows some ancillary data to help provide context for the TRMM Precipitation Radar observations. More specifically, the figure shows grid lines marking the climatological freezing height and tropopause height for this location and month. The tropopause height comes from *Hoinka* (1999), and the freezing height comes from the TRMM 2A25 algorithm. Storms that extend above the freezing height get an extra boost from the release of latent heat of fusion (*Zipser* 2003). When a storm overshoots the tropopause, it suggests that the storm may have vigorous updrafts (*Djuric* 1994).

To provide the societal context of the storm, the 3D KMZ file contains Placemarks with ground reports from the NOAA Storm Event Database (Figure 6a) (http://www.ncdc.noaa.gov/oa/climateresearch.html). Most ground reports occurred a few hours earlier (~2100 UT on 18 June) when the storms were approximately 50 km west compared to the storm locations during the TRMM satellite overflight (0130 UT on 19 June). Figure 6a also shows the estimate of surface precipitation rate from TRMM Precipitation Radar observations. The edge of the Precipitation Radar swath is indicated with blue lines. The TRMM VIRS cloud top temperatures are displayed semi-transparently in shades of gray.

To provide a meteorological context, the 3D KMZ file contains the synoptic scale winds at the time of the TRMM overflight (*Kalnay* 1996). From the 500 mbar winds (white arrows) in Figure 6b, it appears that the storms observed by the TRMM satellite were at the base of a trough in the mid-tropospheric winds, which is a favorable location for severe convection to occur (*Wallace and Hobbs* 2006). Vectors are drawn only for wind speeds above 10 m/s and the length of the vector is proportional to the wind speed (a 43 km length for each 10 m/s of wind speed).

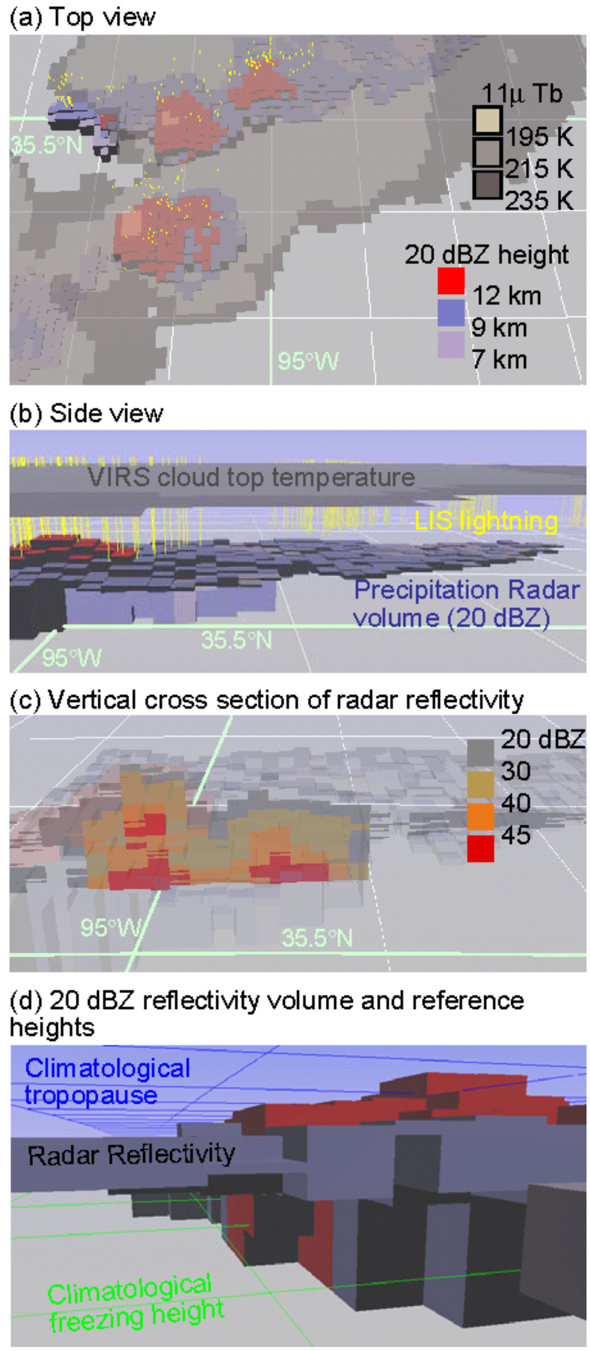


Figure 5. Various Google Earth screen captures from a 3D KML file for Oklahoma supercells observed by TRMM on 19 June 1998.

4. DISCUSSION

Creating an archive access tool would have been easier if the Google Earth interface included a mechanism for the user to manually enter a date and location of interest. Currently, the only way to edit WMS parameters in the Google Earth sidebar is to edit the actual URL of the WMS request. A future release of the free Google Earth client could include a built-in mechanism for altering WMS query parameters. Such a mechanism would likely require that the Google Earth client make a GetCapabilities request of the WMS server and interpret the metadata received in response. The work-around used in this paper is an HTML form in Google Earth's built-in web browser. This work-around has the disadvantage of working under only Windows XP, not MAC OS X.

The archive access tool could be made more convenient if the fields of the HTML form were automatically updated based on changes in the location and time of the Earth view portion of the Google Earth window. It would be exciting if JavaScript running in the built-in web browser could access properties of the Earth view portion of the Google Earth window. For example, it would be useful if JavaScript could access a parent.earth object with read-only properties of latitude, longitude, altitude, and time.

There are several disadvantages to the KML file format for 3D scientific visualization. Because KML is pure text, KML is less efficient than binary formats (such as HDF) for storing floating point values. The thousands of polygons needed for 3D rendering of severe storms can quickly make a KML file prohibitively large and slow to display in Google Earth. In the 3D KML file described in the previous section, 9,000 polygons were needed to store the 3D radar reflectivity surfaces at 20 and 40 dBZ and the horizontal and vertical cross sections of cloud height and radar reflectivity. For a modest personal computer, 9,000 polygons appears to be near the upper limit of how many polygons can be displayed at one time in Google Earth.

Another difficulty with generating 3D KML is an arcane detail about generating polygons. A KML polygon has the specified color only when it is viewed from one side, i.e., the side in which the vertices stored in the KML file are in counterclockwise order. It takes careful programming in the HDF-to-polygon conversion routine to make sure that the correct vertex order is written to the KML file. This issue is not mentioned in the KML specification, but it is discussed in the KML e-mail group (http://groups.google.com/group/kml-support).

It would assist scientific programmers if the KML specification were expanded to include two specialized objects for visualizing 3D scientific data. First, it would be helpful if one could store a 3D array of observations in a KML file, plus a threshold for defining a 3D surface. It would then

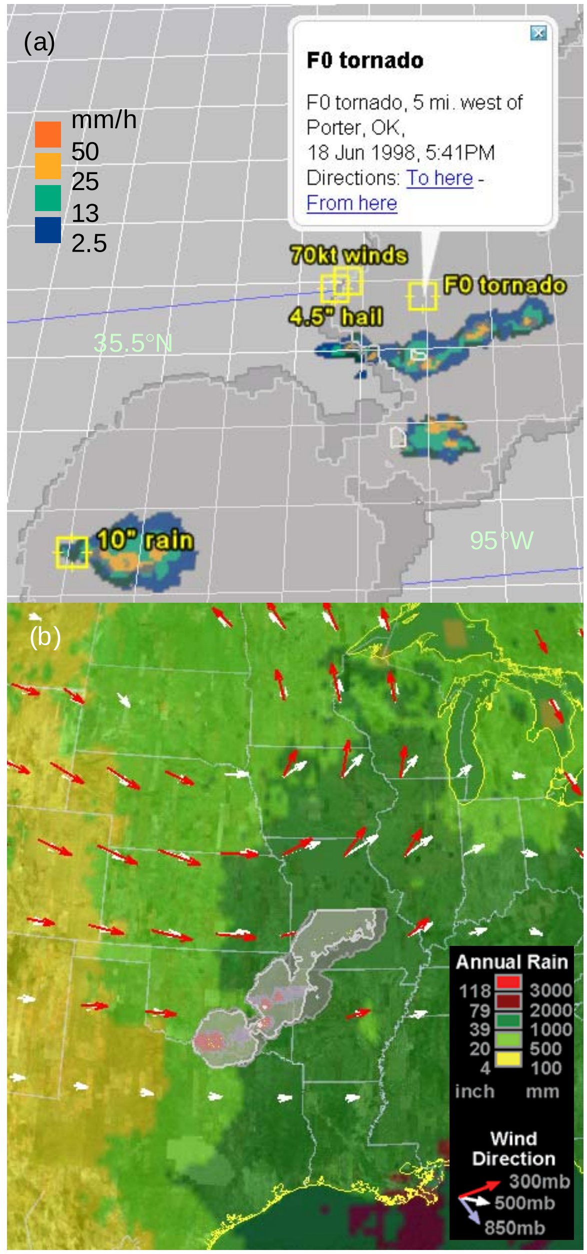


Figure 6. Ancilary data. (a) Storm effects, cloud cover, and surface precipitation rate. (b) NCEP 500 and 300 mbar wind vectors (white and red).

be up to the Google Earth client to calculate the polygons associated with that 3D surface when the KML file were read into Google Earth.

Second, it would be helpful if the KML specification included a VerticalOverlay object that was defined the same way as a GroundOverlay except that the VerticalOverlay would be oriented vertically. In the existing KML specification, there are three work-arounds for creating vertical cross sections, but none of them is ideal. The work-around chosen in this paper is to build up the vertical cross section by defining a small vertical polygon for each observation in the dataset. This solution is less than ideal because it can create a large number of polygons. An alternative solution is to create a single large vertical polygon and paint its area with an image that shows the cross section of the observations. This solution's drawback is that satellite data cross sections are so large that Earth's curvature has to be taken into account, which is difficult to do with a large polygon. The third solution would be to use an external model cited by the KML file (*Chen et al.* 2007). The drawback to this solution is that it uses an external data type, whereas the other solutions are purely KML solutions and therefore can be generated as text output.

A last consideration for displaying 3D data using KML polygons is that the results would sometimes benefit from adjusting the direction of the light source. Currently, the light-source direction is fixed in Google Earth.

5. CONCLUSIONS

Based on PPS prototyping, a virtual globe appears useful for accessing a scientific data archive and for 3D visualization. More specifically, Google Earth can be used to browse the archive of TRMM precipitation data. The archive access tool described in this paper displays low resolution static images and high resolution dynamically-created zoom images. The dynamically created images are requested using the Web Map Service (WMS) specification.

Prototyping has shown that one strength of the KML format is its ability to combine different kinds of data in 3D. Horizontal images can be stacked at specific altitudes to reveal the vertical structure of a storm or a vertical cross section can be constructed with polygons. A 3D surface can also be constructed from polygons for a specific threshold within a 3D volume of observations. The advantage of polygons over images in scientific visualization is that polygons always have precise boundaries even when examined close up.

The Google Earth interface and the KML file format also have weaknesses when trying to provide access to the TRMM precipitation archive or when visualizing scientific data in 3D. Google Earth cannot read the HDF format, which is the format of the TRMM precipitation archive. A WMS server can generate images for Google Earth from HDF files, but there is no mechanism in the Google Earth client for the user to edit the WMS parameters. Under Windows XP, Google Earth has a built-in web browser that can allow the user to edit WMS parameters, but it is somewhat difficult to pass information between the built-in web browser and the Earth view portion of the Google Earth window. It is computationally expensive to convert 3D observations into KML representations of 3D surfaces and cross sections. For this prototype, libraries were developed in the IDL language to perform these KML generation tasks.

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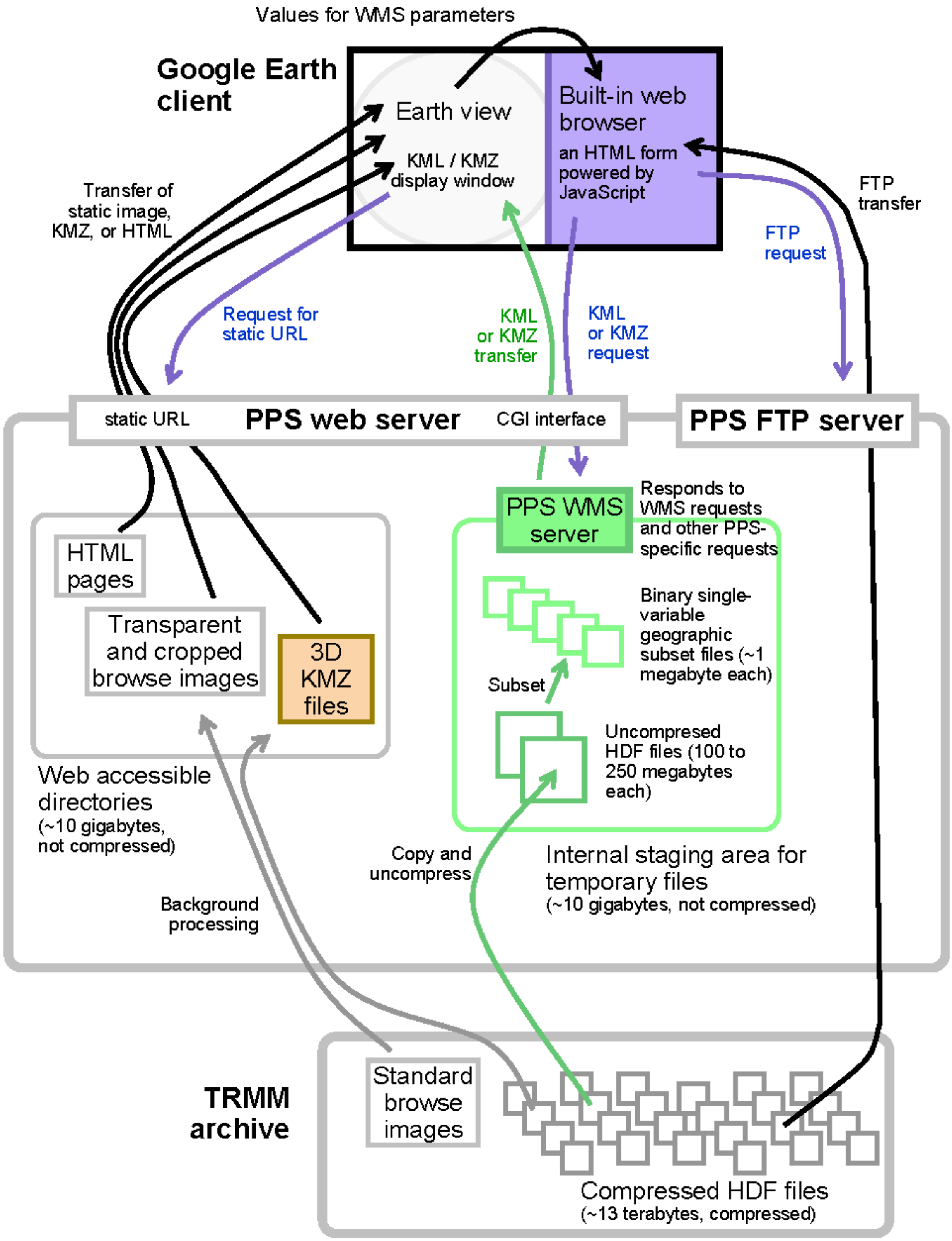

Figure 7. The client-server architecture of the archive access prototype described in sections 3.3 to 3.5.