D3D: using 3D visualization and other Vis5D tools in an operational forecast office

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1. Introduction

The NOAA Forecast Systems Laboratory (FSL) is tasked with evaluating and transferring potentially useful applications that may be present within the research community into operations. Visualization of numerical model output in three-dimensions is one such application that has been used by researchers to examine output from research models for some time, but is currently not available as part of the weather display system known as the Advanced Weather Information Processing System (AWIPS) that is part of the National Weather Service (NWS) modernization.

There are a number of software programs that are available for 3D visualization, and one that has been used frequently for years by research meteorologists is Vis5D, developed by the University of Wisconsin-Madison beginning in the early 1980s (*Hibbard*, 1986). In our presentation during the Eighth ECMWF Workshop on Meteorological Operational Systems we discussed FSL's efforts to explore putting Vis5D into the operational environment, including software design issues as well as methods of evaluation and experimental deployment. Here we review these issues, as well as give an overview of the capabilities of the software. In addition, some of the important issues that were discussed during breakout sessions at the conference will be examined.

2. Visualization history at FSL

2.1 *Early visualization development*

Currently the visualization effort at FSL is a relatively small one involving two programmers and one meteorologist working part-time with a project leader. At this time 3D visualization is not in the plans for implementation within AWIPS, although this could change if operational meteorologists within the NWS find the application to be of use in real-time forecasting. The current software designed to display observations and model output in AWIPS is known as D2D for Display 2-Dimensional (*Wakefield*, 1998), developed at FSL over the last 20 years and now a part of every NWS Weather Forecast Office (WFO). In keeping with this theme the new visualization software is known as D3D (Display 3-Dimensional).

Exploratory work with visualization at FSL began around 1990 with the need to examine output from a local-scale model for various external projects, and a commercial software package known as Application Visualization System (AVS5) was used extensively. AVS5 was used to display analyses from our locally developed Local Analysis and Prediction System (LAPS, *McGinley et al.* 1991) that were included in real-time on the LAPS homepage located at http://laps.fsl.noaa.gov. After several years of exploration with AVS, a decision was made to switch to Vis5D because of its superior animation capabilities, long history in the meteorological community, its non-restrictive availability (it is offered freely to users by the University of Wisconsin-Madison), and enthusiastic support from its developer, Bill Hibbard. In addition, some operational meteorologists within the NWS were familiar with Vis5D 3D displays through the informal use of Vis5D to display output from operational models at some WFOs (a capability aided by the University of Wisconsin's Meteorology Department). Also, Vis5D displays of output from a cloud-scale numerical model simulating convective storms were part of a training module distributed to all WFOs by COMET (the Cooperative Program for Operational Meteorology, Education and Training, operated out of UCAR in Boulder, Colorado; the module was titled Anticipating Convective Storm Structure and Evolution, released in 1996, see http://www.comet.ucar.edu).

2.2 *Initial D3D development and evaluation*

Our philosophy in developing potential 3D-visualization for operations is to mimic as much as possible the structure of D2D, so as to minimize the learning curve for using the application. This involved considerable changes (some examples will be shown) to some of the interfaces within Vis5D. Other important changes to Vis5D were necessary to allow the software to work in an operational setting. These are discussed in *McCaslin et al.* (1999, 2000), and include how the program interacts with the database to allow it to use the same files that D2D uses, as well as the need to be able to switch to different models without having to restart the application.

One of the major changes first made for D3D was to replace the main Vis5D interface (Fig. 1a) for selecting and modifying products with an interface that mimicked the D2D product selector known as the "Volume Browser" (Fig. 1b shows the D3D version).

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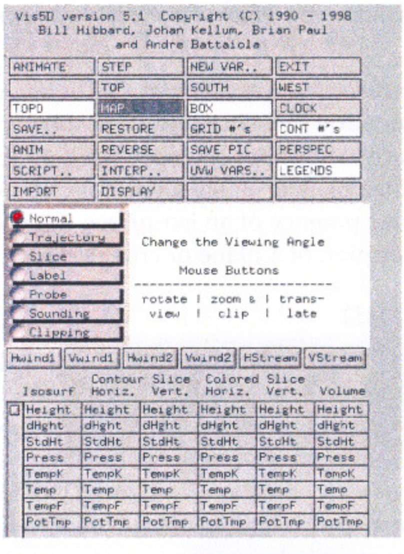

Fig. 1a. Vis5D product selection matrix.

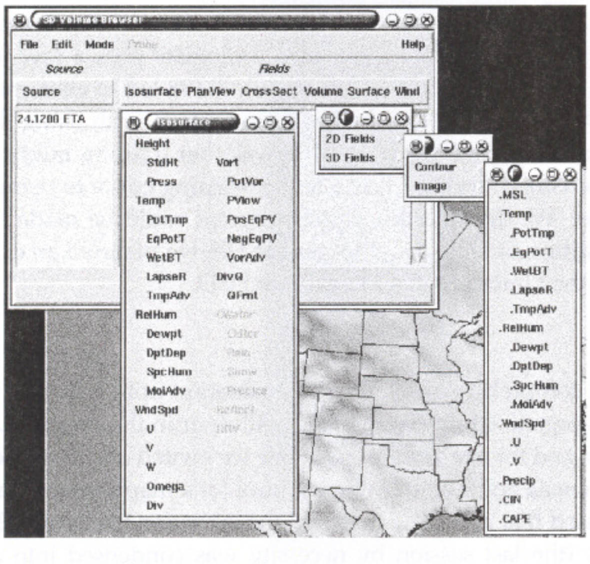

Fig. 1b. D3D Volume Browser, shown with some submenus open.

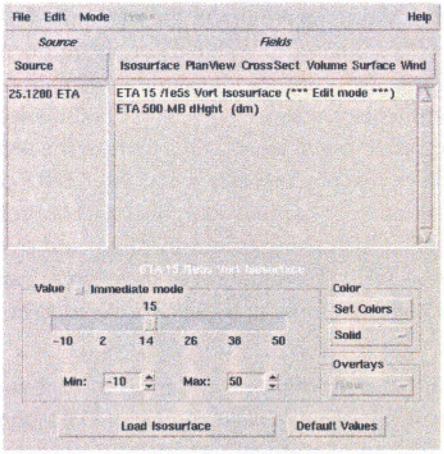

Fig. 2. D3D Volume Browser in "edit mode" for editing an isosurface of vorticity.

Although functionally the Vis5D matrix-like interface was effective, this step made D3D physically appear much like D2D.

Some requirements for displaying and editing the fields in D3D were different from D2D, necessitating some deviation for the behavior of the Volume Browser. An example is shown in Fig. 2, where necessary editing functions for a field displayed as an isosurface in D3D, for example, are handled by clicking on the field in the Volume Browser, which then opens up a GUI that enables one to change a number of product attributes, some of which are not even options in D2D (such as transparency of an isosurface, for example). The slider bar can also be used to control different attributes, such as location of a plane or cross section.

2.3 *Early meteorological testing of D3D*

Once a number of changes were made to D3D to allow it to access the real-time database as well as to make most of the GUIs appear more like they do in D2D, meteorological testing began. Initially D3D was introduced to FSL meteorologists through the FSL Daily Weather Briefing (DWB), a relatively informal 30-min weather discussion that has been occurring daily at FSL since the early 1980s. In the DWB, interested meteorologists from FSL and other Labs lead a weather briefing once or twice a month. Using D3D for at least part of the DWB was encouraged (one purpose of the DWB is to test and informally evaluate new techniques), and interested presenters were trained in the basics. This informal evaluation led to some suggestions for further improvements to D3D, but after several months of this effort, we decided that a somewhat more formal evaluation would be useful.

An evaluation method used for years at FSL to develop D2D was the forecast exercise, using either real-time or case ("displaced real-time" or DRT) data. In the summer of 1998 such an exercise, called RT98, was run to test D3D using real-time data and enlisting the efforts of FSL meteorologists plus a few forecasters from the local WFO (which at the time was located in Denver, about 50 km away). RT98 led to even more suggestions about improvements that could be made to D3D as well as difficulties encountered with using the software or making sense of 3D visualization. One issue that was apparent after RT98 was that training might be a critical part of using D3D, even though we had taken great care in trying to reduce the learning curve to using the software by making many of the interfaces more D2D-like. We decided that more progress could be made through a more formal exercise than RT98, and again in the tradition of D2D development at FSL we planned an exercise in 1999 and invited operational forecasters from across the United States to evaluate D3D.

2.4 *RT99*

RT99 was a major effort to get a comprehensive and broad evaluation from a diverse group of operational meteorologists. The United States NWS is organized into six regions, with four in the continental U.S. For RT99 we invited one WFO forecaster from each region, and for a broader perspective we invited one from each of the National Centers within the NWS. (See http://www.wrh.noaa.gov/wrhq/nwspage.html for a map showing the WFO locations and a list of the National Centers.) We were pleased that almost all accepted the invitation to attend a 2-week evaluation of D3D, which required three separate sessions (the last session by necessity was condensed into a single week) from October to December of 1999.

The 2-week format allowed for a much more structured and detailed amount of training than in RT98, which was much of the first week in the form of hands-on training, generally in the morning, followed by exercises using both DRT and real-time data. The exercises involved examining various details of a weather situation and often comparing how one went about finding the information using D3D to finding the same information using D2D. Ample time was available for the forecasters to record free-form comments through an electronic notebook setup, while other comments were gathered through more formal questionnaires filled out at least daily. During the second week of the exercise the forecasters were tasked with attempting some specific weather forecasts using three DRT cases, choosing forecasts that they might not know the answer even if they were marginally familiar with the cases (a problem that can arise with DRT cases). As another twist we had the participants lead a DWB using primarily D3D (and of course real-time weather). Finally, a full afternoon was devoted to a comprehensive written evaluation of the exercise, and the last morning session consisted of an informal debriefing and discussion. Of course some of these efforts had to be condensed or eliminated for the tighter one-week session.

As expected, RT99 yielded an enormous amount of input, and indeed some suggestions are still in the potential queue for future development, while a number of others have become part of D3D (some of these will be noted when the D3D tools are discussed in Section 3). There was an overwhelming positive response to D3D by the forecasters, and indeed many wanted to take a version of the software back to their home office (this was not possible for several reasons, one being that the AWIPS workstations used at the time were not powerful enough to run both D3D and D2D). Although some participants found isosurfaces, the basic 3D tool, sometimes confusing, most felt they were a great way to visualize the atmosphere, and together with the other D3D tools provided a very quick way to peruse and better understand lots of model output. Many of the participants quickly learned ways to better quantify the output they were seeing by combining isosurfaces with other D3D tools such as cross sections or plan views, and/or by coloring the isosurface by another variable like height or pressure. D3D is very interactive (even more so than D2D), and forecasters enjoyed the ability to move cross sections around and get instant feedback, or to peruse the data with the very interactive sounding tool.

Not every response was positive, of course. For instance, the very interactive nature of D3D made it imperative that it be run on a responsive enough machine, and indeed, when participants spent time on somewhat slower machines they were easily frustrated. Isosurfaces were intriguing to use and most felt were very revealing in what they showed, yet there was still a feeling of uncertainty as to how one might best use them in operational forecasting. In addition, there was an almost universal issue of georeferencing with isosurfaces. A fairly common response was that training would be needed not only in how to operate D3D (the "buttonology") but also in how to apply D3D meteorologically. This feeling was not universal, however, and we purposely did not make strong suggestions for the exercise in order to learn more about how the meteorologists used the various D3D tools. However, it is a training concern that we are still considering. Other issues raised included the desire to see overlays of real data (observations, for example), using D3D to display radar data, and the ability to display multiple models at the same time. Some of the changes that have been made to D3D as a result of all of the evaluations within the context of looking at the various D3D tools are discussed next.

3. The D3D tools

3.1 *Isosurfaces*

As noted earlier, isosurfaces are the main 3D-visualization tool in D3D, and it is not available to operational meteorologists within the NWS. Examples are shown in Fig. 3, contrasting a simple monocolor isosurface with how it appears when colored by another variable, in this case height, which adds quite a bit of information to the isosurface. One also has the option of displaying multiple isosurfaces of the same variable at different values, and using different values of transparency to display them together. It is also possible to display a number of isosurfaces from different variables together. A change we made to the Vis5D isosurface display based on RT99 input was to add the ability to overlay another field onto an isosurface. This is especially useful for isentropic applications, where one could overlay winds on a theta isosurface, for example.

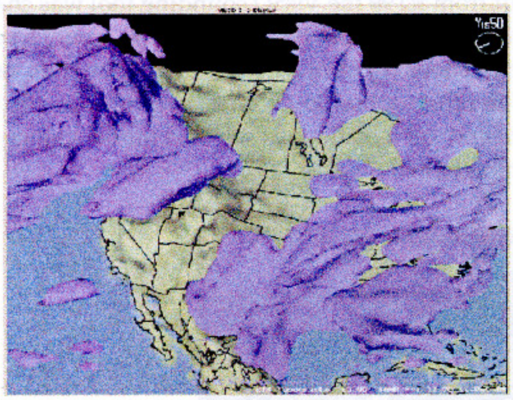

Fig. 3a. Single color isosurface enclosing values of 90% and higher relative humidity from the Eta model.

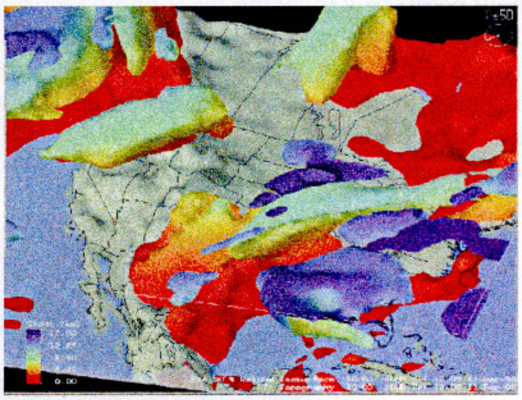

Fig. 3b. The same isosurface colored by height.

3.2 *Plan views and cross-sections*

An example of plan views and cross sections is given in Fig. 4, showing them combined with an isosurface. Both plan views and cross sections are highly interactive; they can be manuevered through the volume of data by either grabbing at the edge of the plan view or the "handle" on the cross section (both of these are standard Vis5D features), or by using a slider bar that is part of the Volume Browser, much like the one illustrated in Fig. 1. The advantage of the slider bar method is that one can be zoomed in or tilted at any angle and still manuever the planes. Although plan views and cross sections are 2D tools, the highly interactive nature of these features in D3D makes them extremely powerful for rapid perusal of a great deal of information.

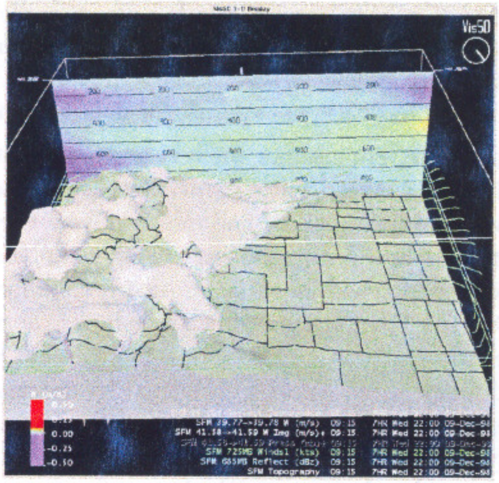

Fig. 4. A combined D3D view from the FSL local model showing an isosurface of reflectivity, a plan view of 725 mb winds, and a cross section with an image of vertical velocity and contours of pressure.

3.3 *Sounding tool and probe*

Another D3D tool that is a 2D depiction but available in a much more interactive mode than in D2D is the sounding tool. This tool is not only a standard thermodynamic sounding, but also has a hodograph display and a separate display where one can plot up to three variables as a function of height. An example is shown in Fig. 5. In its form in Vis5D and its use during RT99 only the sounding and vertical plot options were available, but this was still an extremely popular tool, especially with the forecaster from the Storm Prediction Center, who enjoyed the instant sounding depiction when roaming the cursor through the volume.

The cursor used for this application (see Fig. 5) has a vertical extension to the surface, making it ideal for georeferencing, and in fact some suggested having this type of cursor available to use with isosurfaces for such a purpose (without necessarily invoking the sounding tool). Based on input from RT99 the Vis5D sounding tool was changed to allow for a hodograph plot as well as a plot of convective parameters that can be read from the model's surface based grid and shown as values (see Fig. 5). One has the option of choosing from a number of parameters, as well as the option of displaying all or any of the three displays. The other option known as the probe, as the name implies, allows the user to move a cross-hairs cursor in 3D space and get a readout of selected model values interpolated to that point, with the user determining the specific parameters to display.

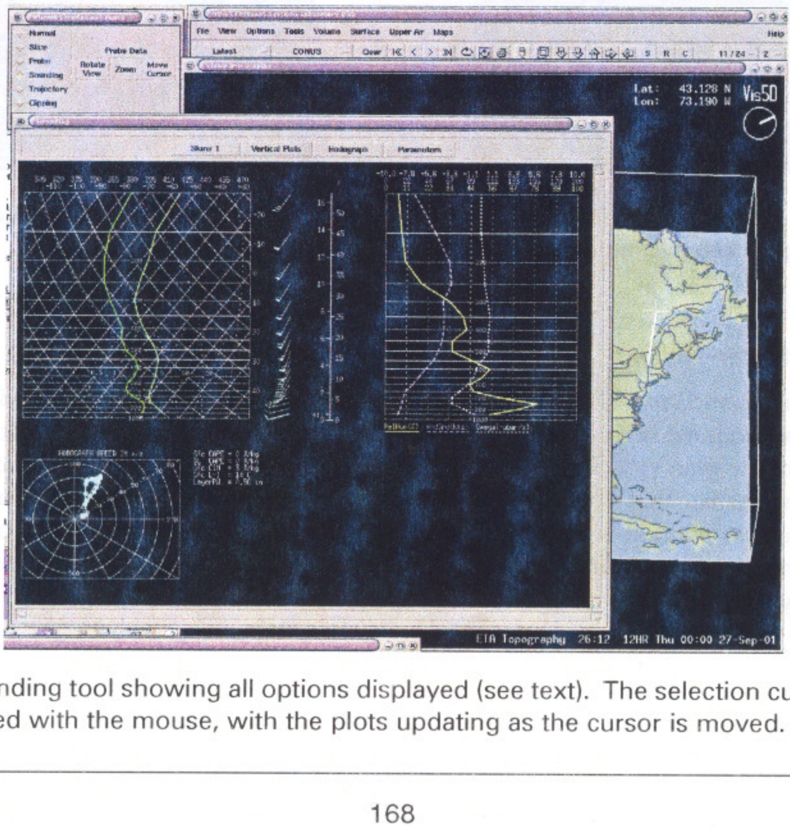

Fig. 5. The D3D sounding tool showing all options displayed (see text). The selection cursor, shown at the far right, is moved with the mouse, with the plots updating as the cursor is moved.

Through an added GUI one can position the cursor at a location relative to the ground as well as at a vertical level, and if desired can lock the probe to a specific level (either a pressure level or height AGL). This GUI makes the probe a potentially more useful tool, though its overall use has been somewhat limited, especially when compared with the sounding tool.

3.4 *Trajectories*

Trajectories are usually discussed at some point in the education of a meteorologist, but operationally in the NWS there has been no way to generate trajectories with model output. AWIPS has a limited set of pregenerated trajectories from a single model that can be displayed, but to our knowledge, these are not often used in operations. Vis5D makes it easy to generate either backward or forward trajectories beginning at any point in the model output, and our modifications have been to create a GUI that retains this ease of use but also allows for a quick generation of some potentially useful options. An example of four of the options is shown in Fig. 6, along with the GUI. The simple trajectory calculation plots a trajectory from a single point, which essentially looks like the probe, and can be located in 3D space using the probe GUI. The trajectory can be displayed as a thin line or a thicker ribbon (both are shown as the white and yellow single trajectories in Fig. 6), and can be colored by another variable if desired. The calculation of the trajectory uses a method, developed by Bill Hibbard at the University of Wisconsin, that uses a simple yet effective way of interpolating between available model output times (in research applications one would normally have many more model output times available to directly use for a trajectory calculation) that may be 6 h apart, and our experience has shown that the trajectories look very reasonable. Other options shown in Fig. 6 include "column," a script that launches a vertical column of trajectories at 50 mb intervals at a single point (shown by the group of blue trajectories), "row," another script that launches trajectories in an east-west row at a user-selected spacing, and "series," which is similar but in the north-south direction. A paper discussing potential operational trajectory applications was presented by forecasters at the Boulder (Colorado) WFO during the Interactive Symposium on AWIPS (*Barjenbruch et al.*, 2002). Given that operational forecasters have not had much experience with trajectories, it will likely take some time before their potential use is fully explored.

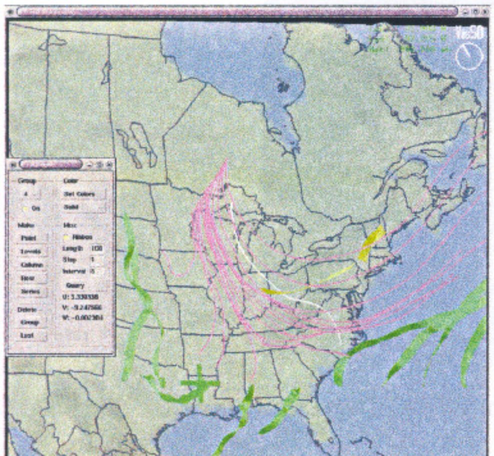

Fig. 6. D3D trajectories showing four options (see text).

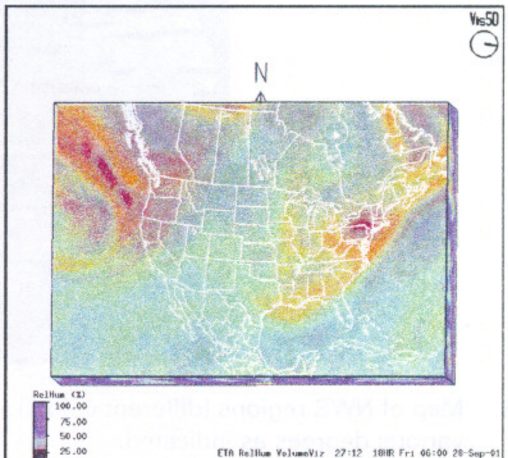

Fig. 7. Example of a model field of relative humidity rendered using volume visualization.

3.5 *Volume visualization*

The final D3D tool is one that has not been evaluated much at this point because it can be fairly computer intensive and, under the current D3D implementation of software rendering of graphics, slow for many of the computers using D3D. However, volume visualization, like isosurfaces, is a true 3D depiction, as shown by the example in Fig. 7, but instead of rendering a surface of a variable at a given value, as in the isosurface, the entire volume of data for that variable is rendered as a kind of "visual fog." The colors can be edited to enhance specific ranges of the data, as was done with the example for the relative humidity display in Fig. 7 to make it appear somewhat like a satellite water vapor image. Our limited experience with volume visualization during RT99 suggested that it was most effective when used in combination with an isosurface display.

4. D3D deployment, issues, and plans

As noted earlier, D3D is currently not in the official future plans of AWIPS, the operational workstation for the NWS. As discussed at the conference, this creates its own set of potential operational problems, since forecasters would like to use an integrated workstation. A view noted during the conference was that for one of the countries that has attempted to introduce 3D to forecasters the effort failed because the application was not integrated into the existing workstation. It is too early in our effort to determine if this factor will be a significant hindrance to operational D3D use in a testing phase. Our experience with other applications both support and contradict this idea; that is we have found forecasters willing to use separate displays (for examining other model data on the web, for example), but at the same time our local model was not extensively used until it was integrated into AWIPS.

Given our unofficial status at this time, we have proceded with D3D in several ways: by spreading the word about the application through various conferences that forecasters might attend, making these presentations available on our homepage, and readily making the software available to any interested forecaster (it is fully contained, with some case study data, on a single CD, and upgrades can be downloaded from our homepage). One very important change that has occurred since RT99 has been the availability of high performance but inexpenive computers that can replace the current AWIPS workstations. This is made possible by the ability to use common off-the-shelf new machines running Linux, which enables them to run the Unix AWIPS and D3D software. Recently the NWS has begun replacing two of the older workstations at each WFO with the newer Linux boxes, but prior to this individual WFOs often (and still do) purchased machines on their own to run special applications in their office. It is on these machines that most of the offices that have chosen to accept a test version of the software have installed D3D, with the key issue for NWS Headquarters that access to the real-time database feeding the AWIPS workstations is not compromised by any such outside application. Our testing shows that D3D has minimal if any impact on the operational AWIPS when installed in such a manner.

Fig. 8. Map of NWS regions (different colors) with locations of WFOs. Ovals show the sites that have D3D, to various degrees as indicated.

The current deployment of D3D at NWS (Fig. 8) follows a recent surge of potential users who were given CD copies during the AMS Annual Meeting last January. This meeting represented somewhat of a milestone for D3D exposure, as there was a separate session devoted mainly to D3D with contributions from several WFOs as part of the Interactive Symposium on AWIPS held during the Annual Meeting. Our near-term plan is to try and take a more active role in acquiring feedback from the various sites that now have D3D. We hope to do this through our homepage, by making available an electronic questionnaire and other feedback mechanisms. One of the original WFOs to get D3D (the Portland, Maine office, which had a participant in RT99) has developed its own questionnaire that was used to survey their forecasters for their paper during the AWIPS Symposium (*Cannon et al.*, 2002), and this may be incorporated into what we develop. There are still improvements to D3D that could be made, some based on RT99 input, including multiple model context, displaying actual data, and continued development of a 3D radar display. Because D3D is in experimental status, funding is limited, but other agencies have expressed interest in the software, and recent work through a U.S. Space Agency funded project on a potential 3D lightning display could result in data displays in D3D without much further effort. An interesting new Vis5D application of flow visualization was demonstrated at the conference by a Swiss Laboratory, and we hope to pursue this feature at some point.

While we are encouraged by the number of sites (Fig. 8) that have expressed an interest in D3D, we are somewhat concerned about the actual level of use at many of the sites. During a breakout session at the conference there was considerable discussion about the potential usefulness of 3D in operational forecasting. Some of the interesting issues discussed included the observation that while meteorologists generally find the 3D displays intriguing, they often resort back to the more familiar 2D depictions when developing their forecasts (see Johnson, 2002). We have observed a similar behavior in general, and while the atmosphere is clearly 3D, most forecasters have been educated in the 2D meteorological world. This suggests, as noted earlier, that training in how to use 3D products will probably be necessary. An interesting suggestion we received at the AWIPS Symposium was to try putting a "Case of the Month" feature on our homepage, which might have contributions from various WFOs, and could demonstrate how D3D might be used. The longer term solution might be the use of 3D visualization in meteorological education at the college level, which would likely yield future forecasters expecting to see such visualization as part of an operational workstation.

5. Acknowledgements

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