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PROTOTYPE DEVELOPMENT OF MACHINE-TO-MACHINE OPERATIONAL NEPHANALYSIS
by
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March 2006
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Weather is essentially geo-spatial data that can be integrated with Geographic Information Systems (GIS). In this research a small prototype is designed and developed in order to demonstrate the basic capabilities of GIS-enabled operational meteorology. As the Air Force moves to net-centric operations, enabling weather information across an enterprise GIS is essential. Providing images is a fast and efficient means of enabling weather in a GIS. Providing the information in raw format is a better way to distribute GIS enabled weather. Since operators and users may still require an image format, both information and images should be provided. In order to provide the best possible support, Air Force Weather needs to rethink how it provides weather information, especially in a net-centric force. Air Force Weather has been slow to adopt this approach for various reasons such as a lack of bandwidth. The lack of resolution and accuracy of the numerical models was also a key consideration. While the models are still imperfect, their spatial resolution is now good enough to be used realistically in a GIS environment. The prototype developed for this research shows real-time delivery of weather information in GIS is possible and practical.

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PROTOTYPE DEVELOPMENT OF MACHINE-TO-MACHINE OPERATIONAL NEPHANALYSIS

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Weather is essentially geo-spatial data that can be integrated with Geographic Information Systems (GIS). In this research a small prototype is designed and developed in order to demonstrate the basic capabilities of GIS-enabled operational meteorology. As the Air Force moves to net-centric operations, enabling weather information across an enterprise GIS is essential.

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Sitting in class doesn't make someone a scientist any more than sleeping in a garage makes someone an automobile. I owe much to the faculty and staff of the Department of Meteorology; through the many hours of their gifted lectures and engaging labs, I have grown into a more scientific thinker.

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I. INTRODUCTION

A. OVERVIEW

Weather at its essence is geo-spatial data. Weather observations and forecasts are typically for a specific point in time and space. Geographic Information Systems (GIS) are a robust and mature technology used to manipulate and deliver geo-spatial data. Many of the Command and Control (C2) systems used by the United States Air Force (AF) operate with a GIS infrastructure. Air Force Weather (AFW) does not fully integrate with this capability and typically operates on separate and isolated systems. A draft of AF doctrine for AFW conveys the need to better integrate with the war fighter.

> Machine-to-machine dissemination improves the chances that critical weather information and its impact on operations will reach decision-makers in time to capitalize on time-sensitive opportunities and other operations (AFDD 2-9.1, 2006).

Currently much of the weather information transfer between systems is done manually; this is an inaccurate, error prone and time consuming process. Operational weather products should flow to the war fighter through an integrated C2 infrastructure. This thesis will explore techniques within the current state of the science to better integrate operational weather products with C2 functions.

B. PROBLEM

The Department of Defense (DoD) is moving to net-centric operations (Stenbit, 2003). This increases the need to integrate all information into the C2 infrastructure. Integrating weather information across many different platforms is a challenge. For example the National Oceanic & Atmospheric Administration (NOAA) through the National Weather Service (NWS) is beginning to offer weather products in a GIS enabled format (National Weather Service, 2006). Currently, NOAA only offers the data in downloadable shapefiles (National Weather Service, 2006). Their products are limited in both coverage and depth. The NWS is focused on the continental United States (CONUS) while Air Force interests are global. Additionally, current NWS products do not provide the broad array of parameters needed by an operational Air Force forecaster.

C. SCOPE

This research demonstrates the feasibility of creating a GIS distribution system for weather data using limited resources. The focus was to create a proof of concept, demonstrating portability and scalability. Initially, the intent was to provide realistic cloud pictures via GIS. However, the ability to provide weather information generically across a network was realizable. Clouds became the parameter providing the proof of concept of the delivery of numerical weather model data in a GIS format.

D. APPROACH

Defense budgets are decreasing, so the ability to provide a low cost solution to the problem is not only appealing but necessary. The Air Force Weather Agency (AFWA) and the Naval Postgraduate School (NPS) already have licensing agreements with ESRI. However, this is a complex proprietary solution. A review of the current state of the art in the Open Source community showed there were already pieces of software available that are comparable to ESRI's products. The approach taken here was to build a scalable and portable system from free and open Off-the-Shelf (OTS) software. "Free" in this case is defined as low to no cost and "open" is defined as having source code available for inspection and modification if required.

E. ORGANIZATION OF THESIS

Chapter II gives a basic overview of GIS today, including participants, current methodology and the industries' move to integrate weather data into GIS systems. It also discusses the current capabilities of the Air Force and the services' vision for the future. Chapter III discusses the implementation details of the prototype and Chapter IV reviews the results. Chapter V provides a summary and recommendations for integration of GIS into current AFW operations. Ideas for future research are also discussed.

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II. BACKGROUND

A. MAJOR PARTICIPANTS

The GIS community is mature and the associated tools are relatively easy to use and feature rich. One of the largest commercial providers of GIS software at this time is ESRI Inc., founded in 1969 as Environmental Systems Research Institute (ESRI. 2006). ESRI's products are widely used to manipulate and provide GIS data. ESRI has only recently begun to natively exploit weather data in their tools. The National Oceanographic and Atmospheric Administration (NOAA) has started to provide some of its daily weather data in GIS formats. Data Transmission Network (DTN) is a private company based out of Omaha, Nebraska and its subsidiary Meteorologix advertises their ability to provide their customers with weather information in a GIS format (DTN, 2006).

1. Governmental

The number of products provided by the National Weather Service (NWS) is growing on a regular basis to meet the directive given in the National Weather Service Strategic Plan for 2005 - 2010 (National Weather Service, 2005). Currently, Next Generation Radar (NEXRAD) imagery is provided in a GIS enabled format. Observations and forecasts are now provided as an XML feed with latitude and longitude embedded in the data. Other products are offered and more are planned for the immediate future. This incremental approach could serve as a model for future AFW implementation of GIS services.

2. Commercial

DTN provides streaming weather data for many industries across the United States (US), including agriculture and petroleum. DTN has a subsidiary, Meteorologix, which provides systems specifically for weather data. One of Meteorlogix systems, MxInsight natively displays weather information in a GIS format (Meteorlogix, 2006a). Some of Meteorlogix's clients include municipal police and fire departments. The Bellevue, Washington police department uses the localized, tailored forecasts to plan manning requirements (Meteorlogix, 2006a). Meteorlogix represents a small example of what is possible with GIS enabled weather information.

ESRI has established many de facto standards; for example, the shapefile is the standard file format for storing and distributing GIS data. Their systems are designed for the small business to the largest enterprise operations. However, ESRI has only recently entered the arena of enabling and/or providing weather data in a GIS environment. They do have active committees studying and discussing the implementation of weather in GIS. One of their flagship products, ArcView, in its current iteration does not include the ability to interact with raw weather data. This is planned for the next release, where ArcView 9.2 will support NetCDF formats (ESRI. 2006).

B. CURRENT METHODOLOGY

1. Governmental

The NWS has some information in a GIS format and provides it in the form of shapefiles and text based XML formats at this time. Over the past year the number of products in a GIS format has consistently grown. Given the mandate in the NWS Strategic Plan which states:

> We will work with the weather, water, and climate enterprise to investigate, develop, and expand the use of new technologies in data management and information systems, such as new internet-based standards and Geographic Information Systems (GIS), to accelerate development and implementation of appropriate NWS and NOAA products and services and to integrate these services in ways that are meaningful to our customers (National Weather Service, 2005).

the number of products provided will continue to grow.

2. Commercial

Meteorologix supports over 20,000 users, including various police and fire departments. They also provide weather information for Europe and Asia as demonstrated by a web site advertising their capabilities (Meteorlogix, 2006b). ESRI has designed their tools to interoperate and provide data across the broad range of tools and options they offer. This is well documented in an ESRI document System Design Strategies available on ESRI's web site (Peters, 2005).

C. GIS: STANDARDS AND INTEROPERABILITY

1. Standards

On their web site, the Open Geospatial Consortium, Inc. (OGC) define themselves as

> a non-profit, international, voluntary consensus standards organization that is leading the development of standards for geospatial and location based services. Through our member-driven consensus programs, OGC works with government, private industry, and academia to create open and extensible software application programming interfaces for geographic information systems (GIS) and other mainstream technologies (OGC, 2006).

This group has defined basic standards for the interoperability of GIS. The most widely used of these standards is the Web Mapping Service (WMS) and the Web Features Service (WFS). Even ESRI implements these standards in their GIS server ArcIMS and allows for the use of these standards in their client applications (ESRI. 2006).

WMS and WFS are two open standards for dissemination of information across a GIS. Both are well documented on the OGC web site. Most open source software implements at least one of these standards.

ArcSDE is the ESRI front-end to geo-enable a database backend. ArcIMS provides web services and can implement both WMS and WFS. With a large section of the GIS industry using ESRI products they successfully advocate the use of their proprietary methods to provide more capabilities than WMS and/or WFS.

2. Interoperability

Data and software standards are necessary across the DoD because they allow interoperability. In May of 2003 the Chief Information Officer (CIO) of the Department of Defense John Stenbit issued the DoD Net-centric Data Strategy. The key attributes of the (Data) Strategy include:

- Ensuring data are visible, available, and usable when needed and where needed to accelerate decision-making
- "Tagging" of all data (intelligence, non-intelligence, raw and processed) with metadata to enable discovery of data by users
- Posting of all data to shared spaces to provide access to all users expect when limited by security, policy or regulations
- Advancing the Department from defining interoperability through point-to-point interfaces to enabling the "many-to-many" exchanges typical of a net-centric data environment

The data goals are enumerated in Table 1.

Table 1. Net-centric Data Strategy Guide - Data Goals (From: Stenbit, 2003)

Goal	Description
Goals to increase Enterprise and community data over private user and system data	
Visible	Users and applications can discover the existence of data assets through catalogs, registries, and other search services. All data assets (intelligence, non-intelligence, raw, and processed) are advertised or "made visible" by providing metadata, which describes the asset.
Accessible	Users and applications post data to a "shared space." Posting data implies that (1) descriptive information about the asset (metadata) has been provided to a catalog that is visible to the Enterprise and (2) the data is stored such that users and applications in the Enterprise can access it. Data assets are made available to any user or application except when limited by policy, regulation, or security.
Institutionalize	Data approaches are incorporated into Department processes and practices. The benefits of Enterprise and community data are recognized throughout the Department.
Goals to increase use of Enterprise and community data	
Understandable	Users and applications can comprehend the data, both structurally and semantically, and readily determine how the data may be used for their specific needs.
Trusted	Users and applications can determine and assess the authority of the source because the pedigree, security level, and access control level of each data asset is known and available.
Interoperable	Many-to-many exchanges of data occur between systems, through interfaces that are sometimes predefined or sometimes unanticipated. Metadata is available to allow mediation or translation of data between interfaces, as needed.
Responsive to User Needs	Perspectives of users, whether data consumers or data producers, are incorporated into data approaches via continual feedback to ensure satisfaction.

The desired end-state of this strategy is interoperability among all DoD agencies and services.

D. AIR FORCE WEATHER AND GIS

1. Developing Expertise

The Air Force has already seen the need to train its personnel in the use of GIS. In “GIS in the Defense and Intelligence Communities Vol. 2” Mr. Danny Portillo, HQ USAFA/DFEG writes

> GIS Software is used to support core courses that all cadet must take during their tenure at the academy. Beginning with the class of 2009, all cadet-issued laptops will contain the basic ESRI ArcGIS software toolsets to support a variety of core courses. Using GIS at USAFA will eventually become as common as using Microsoft Office products.

A basic understanding of what GIS is and what it provides to the war fighter will allow these new officers to more quickly integrate into current operations. AFW does not yet have any training program for GIS. Given its continuous interaction with the war fighter at all levels from operational planning at a Combined Air Operations Center (CAOC) to the Apache pilot requesting a flight planning brief, AFW could provide better service to the war fighters by developing widespread ability to understand and use GIS. This is reflected in the AFW Strategic Vision which states:

> GI&S are powerful capabilities for mapping features in a geo-locatable format. This means that weather information can be “layered” over infrastructure information such as the power grid, water distribution system, population demographics, and other important databases. The applications of GI&S range from homeland security to the AOC planning cell where the Master Air Attack Plan is built (Zettlemoyer, 2005).

2. Current Capabilities

Currently, AFW has several capabilities that will ease the transition to providing GIS products to the war fighter. At AFWA a team of programmers is developing expertise in GIS. AFWA is already a center for the dissemination of weather products. The infrastructure is already in place for the dissemination of weather information in a GIS format.

A team of programmers at AFWA is developing a working methodology for distributing forecast data in a GIS enabled format. A short visit to AFWA in October of 2005 showed active implementation of a plan. The team Non-commissioned Officer in Charge (NCOIC) provided a schematic, Figure 1, of the infrastructure plan being implemented. The team at AFWA is already broken down into specialists. One airman is responsible for extracting data from GRIB (GRIdded Binary) data sets. Another is responsible for user interfaces and how data is handled once it is in the server.

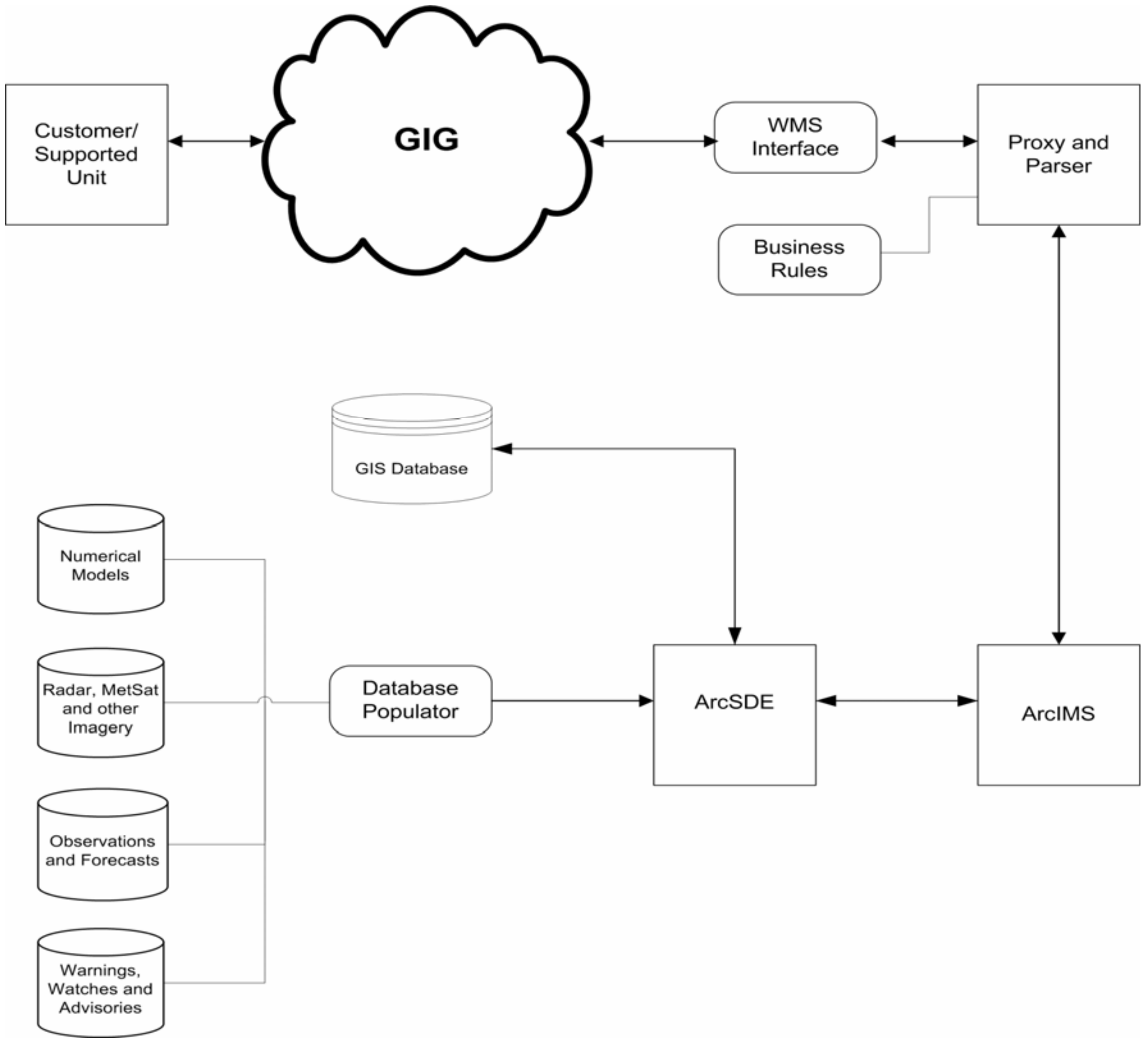

Figure 1. AFWA GIS Plan

This plan and associated team structure is in line with case studies and suggestions provided in "The Design and Implementation of Geographic Information Systems" (Harmon and Anderson, 2003). A specific case study discusses a state government that started implementation years before and had still not achieved success. Given the challenge to the AFWA GIS team, involving the leadership is one of the biggest problems they face. After budget constraints, lack of leadership involvement and personnel changes are two of the biggest reasons given for implementation failures (Harmon and Anderson, 2003). Another problem common to all implementations of GIS in an enterprise is storage requirements and database design.

(1) AFWA: Current and Forecast Data. AFWA is a centralized storage facility for current and forecast weather information. This is an important piece of developing an enterprise GIS. Additionally, forecasters both deployed and in garrison already use AFWA as a main data source. AFWA also extends its full capabilities on to SIPRNET and has built-in capabilities to handle sensitive and classified geo-spatial data.

(2) AFCCC: Historical Data. Climate data is archived at AFCCC. Currently, they provide limited access to this data via a web based GIS interface (AFCCC, 2006). Once the data is made available across the enterprise in a GIS format the capabilities created will prove invaluable to both AFW and the Air Force.

AFW remains committed to providing accurate and timely weather information to the war fighter. This is a broad mission that is resource intensive. AFWA is a centralized storage facility for current and forecast weather information. This means providing GIS enabled formats to the war fighter can be done from a centralized point already known to the war fighter and meteorologist. Climate data is stored in a centralized facility and could be provided the same way as from AFWA. Once one piece is implemented and the process understood the same process can be implemented rather rapidly at the other centralized facility. However, AFW will need to see incremental changes as true enterprise GIS is implemented in order to accept and appreciate the benefits for both meteorologists and war fighters (Harmon and Anderson, 2003).

E. SOFTWARE

Software is the heart of a modern GIS system. However, software is the largest variable of the pieces required for an enterprise GIS system. Rather than list software used, general issues about software will be discussed.

1. Currently Used by Air Force

Currently the Air Force uses a variety of different software for mission planning and operations. Northrop-Grumman provides at least two of the pieces: Command and Control for the Personal Computer (C2PC) and the Joint Mission

Planning System (JMPS). Both are essentially mapping software and on Northrop-Grumman's web site C2PC is heralded as "Combat-proven Interoperability for Windows" (Northrop Grumman, 2006b). C2PC can operate at both the mission planning level and the tactical level (i.e. tracking aircraft and troop movements). Northrop Grumman is also aware of the need for interoperability and has established a lab for the purpose of testing systems. According to the Northrop Grumman site:

> The cornerstone of the Geospatial Interoperability Program is the Open Compliance Configuration and Management (OCCAM) Lab. The lab is designed for research, development and interoperability evaluation of geospatial technologies. Prototyping work includes implementing components of geospatial enterprise architectures and enterprise web services management. Additionally, the OCCAM Lab hosts web-based standards compliance testing tools currently in use by the Open Geospatial Consortium, Inc. (OGC) (Northrop Grumman, 2006a).

2. Commercial and Off-the-Shelf (OTS)

Commercial Off the Shelf (COTS) or Government Off the Shelf (GOTS) software is usually robust and reliable. COTS and GOTS software is usually also supported by either contractors in place or via some type of technical support. A change to COTS or GOTS software is relatively difficult and depends on the contract and/or complexity of the software as well as the availability of the source code.

3. Open Source

Open Source software has the benefit of having the source code freely available for evaluation or modification. In "Free Software, Free Society: Selected Essays of Richard M. Stallman" Stallman states

> …a program is free software, for you, a particular user, if:
>
> - You have the freedom to run the program, for any purpose.
> - You have the freedom to modify the program to suite your needs.
> - You have the freedom to distribute modified versions of the program, so that the community can benefit from your improvements. (Stallman and Lessig, 2002)

However, unless an open source project is mature and well supported the software is not usually as well documented and easy to use as commercial counter parts. This is because

> products often begin as open source projects directed by a “lead” user, because the culture of open science is quite strong in the developers and participants. Nevertheless, they are eventually forced into the private sector as the market grows and non-developer users demand support, documentation, and enhancements to the ease of use. (Gambardella and Hall, 2005)

The number of open source products available for GIS is numerous and growing.

III. GIS SYSTEM DESIGN AND IMPLEMENTATION

A. TOOLS

1. Open Source

The tools available for the development of a prototype for this study included both the suite of ESRI products and the broad array of Open Source projects. Open source software allows the use of the program for any purpose and modification of the source code is necessary (Stallman and Lessig, 2002). Open Source provided a more usable solution as a proof of concept was the final goal not a production implementation. If a piece of open source was found unusable it could be modified or a different program could be chosen. The necessity of a separate administrator for each component was also avoided as full control over the machines used could be retained. Some pieces of open source are as robust and usable as commercial counter parts and in some cases more so. Some are not but the features they provide proved adequate for the prototype in this project. Some programs such as the database engines required better hardware than the modest hardware stipulated in the parameters of the prototype, especially for larger data sets.

2. Standards Compliant

Conformance to standards was a primary consideration as interoperability with the tools the war fighter uses was the goal. Interoperability is achieved through the use and enforcement of standards. While open source does not usually have the documentation and ease of use of its commercial counter parts (Gambardella and Hall, 2005), open source was a better pick for the prototype. Full functionality was not required to demonstrate the capabilities of integrating weather information across an enterprise but full compliance with standards was and open source software could be chosen based on its compliance with standards.

3. Tools Used

The modular design specified in the design parameters allowed flexibility in tool choices. A broad array of tools were used and most were specialized tools designed for one task. The process breaks nicely into three key tasks: Automation, Image Generation and Product Delivery. These key tools used are discussed in this section. Other tools such as database engines are discussed later as they are not required for the prototype but do increase its effectiveness and generality.

a. Image Generation

Existing code that would expedite the image creation process was needed. Additionally, libraries of existing code to manipulate database sources and text files were also needed. All of these libraries as well as many more were available in Sun Microsystems's programming language Java. Java also has the virtue of being able to run on multiple platforms regardless of where it was compiled. While native compiled code is quicker, Java was fast enough with average image generation taking 30 seconds. Many open source tools exist for the development of Java programs.

b. Delivery

Delivery of the images in a GIS format required two different pieces of software. First is a web server to handle the overhead and provide a common protocol for communication across a network. Apache, an open source web server, is also the most used web server on the internet (Netcraft, 2006). MapServer is an open source Common Gateway Interface (CGI) program that provides the images in a geo-rectified manner over the network via a web server. MapServer provides both Web Mapping Service (WMS) and Web Feature Service. For the prototype only WMS was used. Figure 2 shows the process, from the numerical model through text file generation and image creation to delivery via a web server and requests through a WMS.

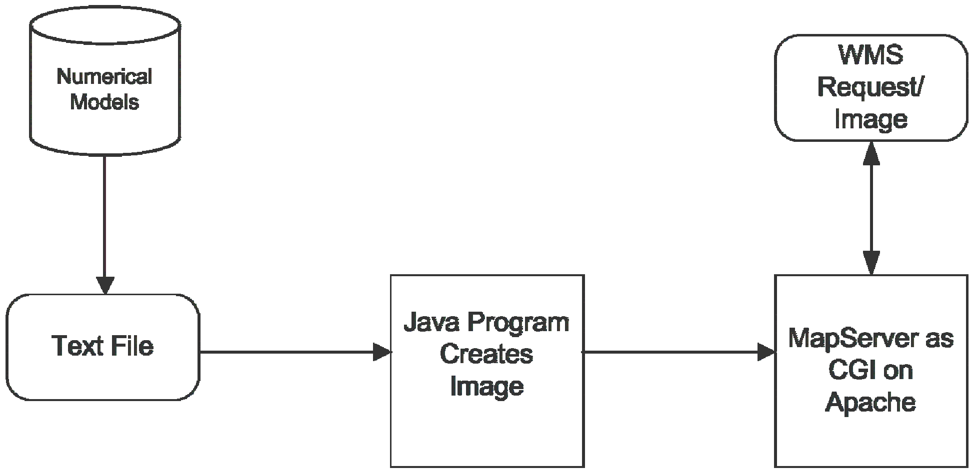

Figure 2. Process flow for Delivery

c. *Automation*

Acquiring the data was done using a widely used open source language Perl and ftp. Once the data was available locally, the process of generating a text file and then the image from the text file was done using several differing programs. Extracting the data from a GRIB file was done using wgrib which “is known to work on machines ranging from 486s to Cray supercomputers” (wgrib. 2005). Java was then used to generate the image. This process was tied together using a shell script. The script also placed the generated images in the proper directories. Common Unix/Linux tools were made available in a Microsoft Windows environment by a system of software called Cygwin. Cygwin is a Linux-like environment for Windows (Cygwin. 2006). This design choice increased portability of all parts of the prototype.

B. ACQUIRING THE DATA

1. Background Data

Free Landsat images of the entire globe are available as a WMS from the NASA Jet Propulsion Laboratories (JPL). The JPL provides these images in several formats, including smoothed 500 meter resolution data and one kilometer data which depicts snow coverage for each month. This method of acquiring the background data is more in line with the Net-centric Operations and Warfare vision of accessible and interoperable data sets that are responsive to users needs (Stenbit, 2003).

2. Numerical Weather Model Data

Four different numerical models were used to provide the meteorological data. The first two were operational cloud models. The World Wide Merged Cloud Analysis (WWMCA) is an analysis provided every three hours that integrates observational data from several different sources. The Stochastic Cloud Forecast Model (SCFM) was used to generate the cloud forecast. Both of these models were available from the Air Force Weather Agency (AFWA). Delivery of these models' output was automated. Wind forecasts were generated from the Global Forecast System available from the NWS via either ftp or http. The final model used was an experimental cloud model, similar to the SCFM, generated as part of ongoing research at the Naval Postgraduate School (Leach, 2006).

C. PROCESSING THE DATA

1. Extracting the Data

A common program for extracting data from Grib files is wgrib (wgrib. 2005). It is a straight forward program written in an extremely portable manner in C. The publicly available version lacks geo-rectification capabilities. This was corrected by Professor Pfeiffer. The corrected code extracts the requested parameter into a three column text file. Table 2 shows the beginning of extracted total cloud cover from the World Wide Merged Cloud Model (WWMCA).

Table 2. wgrib geo-rectified output

# geo: 1024 1024		
# geo: (lat, lon, value)		
-20.9300	145.0000	66
-20.8256	144.8881	0
-20.8778	144.9441	0
…		

All parameters are output in a very similar manner. Winds are output in two separate files, one for u vectors and the other for v vectors. The direction and speed are then calculated as the resultant from these two vectors.

Another program available is Degrib (Degrib: NDFD GRIB2 Decoder. 2004). Available from the NWS, this tool provides both GUI and command line interfaces. Degrib has the ability to parse GRIB 1 and GRIB 2 formats. Degrib can output geo-rectified comma separate text files and shapefiles.

2. Using a Database

The optimal way to handle the data is to put it into a database. All GIS have common functions. Rigaux, et al. (2001) list these as:

- Data input and verification
- Data storage and management
- Data output and presentation
- Data transformation
- Interaction with end users

Given these basic functions he concludes “the kernel of a GIS is therefore a database management (DBMS).”

Having the data in a database allows aggregated data to be filtered. It allows the data to be readily available to any program that can access a database. Most modern languages have the capability to access databases, either natively or in a library. Java, for example uses the Java Database Connector (JDBC) (White, 1999). There are two methods for handling spatial data in a database. Either it can be entered as spatial data into a spatially aware database or it can be entered as a tuple (latitude, longitude, value) into any database.

a. Spatially Aware Database

PostgresSQL is an open source database engine that can be made into a spatially aware database with an extension, PostGIS (PostGIS. 2006). The extensions provided by PostGIS include operators for calculating values such as closest-point, distance and intersections (Douglas and Douglas, 2003). MapServer knows how to interact with PostGIS and can server layers directly from the database. Tools also exist to port shapefiles into the PostgresSQL (Mitchell, 2005). GIS client software such as ESRI's ArcView and the open source client OpenJUMP can also interact with PostGIS databases. Spatially aware databases provide the ability for spatial analysis. Spatial analysis does not only allow simple calculations such as closest points and distance but also allows the war fighter to find the closest available aircraft for a mission based on numerous criteria such as aircraft speed, flight level winds, visibility and ceilings, etc.

b. Generic SQL Database

Not all database engines have spatial capabilities. Additionally, if the database is not conformant to standards developing an interface for it would be necessary before it can interact with other tools such as ArcView or MapServer. Designing a simple database using latitude and longitude for each data point and relating those to the value would allow more flexibility in choosing a database engine. A non-spatial design would also allow it to interact with it. The ability to spatially analysis data from the database would require more external coding with this format, increasing complexity, development time and costs. The data would have to be processed for each layer then the spatial analysis would have to be calculated on the client machine.

3. Image Creation

For the prototype, the data, whether it is from a text file or is retrieved from a database, is programmatically placed into a two dimensional array. The array represents a grid of latitude and longitude. For a simple latitude-longitude grid the process is straight forward. For a different projection such as polar stereographic the process is more complex. For example at the pole the single point must be expanded into 360 points. At points near the poles where several points of actual data may exist a nearest neighbor algorithm was used to fill the 360 points needed. The GFS is typically published on a latitude-longitude grid and was the easiest to map to a two dimensional array. Both the WWMCA and SCFM use a polar stereographic projection and more complex computations are required and the image creation time is consequently longer.

D. DISTRIBUTING THE DATA

1. Image Format

Several different methods can be used to disseminate the weather images. One of the easiest methods for dissemination is to place the files and associated world files in a directory available via an ftp service. Automated delivery of the images via e-mail is another relatively easy method of delivery. Both methods are efficient and common. Older systems with low bandwidth could easily implement either method. This is not the ideal solution and does not meet the vision laid out by the Chief Information Officer of the DoD.

2. World File

Distributing the data in a geo-rectified image is the most effective given time and resource constraints. This involves an image and a world file. A world file is simply a text file with information about the image, what latitude and longitude the upper left corner is at and the size of each pixel. The size of each pixel is a calculated value. The width is calculated by dividing the longitude width of the image by the number of pixels the image is wide. For example, if the image is 1440 pixels across and extends from -180 to 180 then the width value for each pixel is $\frac{180-(-180)}{1440}=\frac{360}{1440}=0.25$ or in more general terms pixel width w_p can be defined as

$$w_p = \frac{eastern\_longitude - western\_longitude}{number\_of\_pixels\_wide}.$$

The same is true of the height of a pixel just along the other axis. In general terms pixel height h_p can be defined as

$$h_p = -\left(\frac{northern\_longitude - southern\_longitude}{number\_of\_pixels\_high}\right).$$

The height is negative because by latitude if you start at the northern corner of the image you are moving in a negative latitude direction as you move down the image. Figure 3 shows the top left corner of an image with the data points associated with a world file shown. Figure 3 is followed by Table 3 which shows a complete world file.

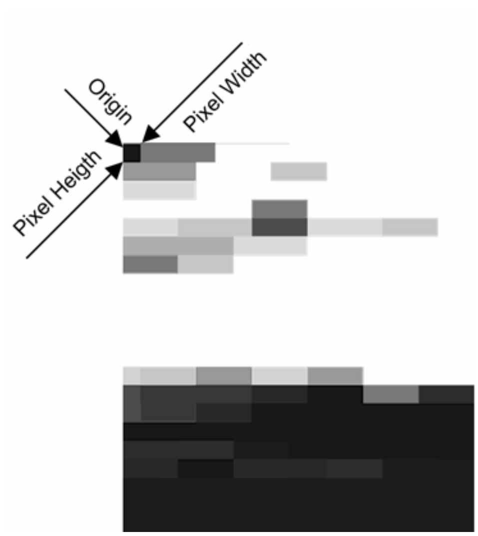

Figure 3. Location of data points for a World file

Table 3. Sample world file

0.25
0.0000
0.0000
-0.25
-180.0000
90.0000

Line one and four are the pixel size calculated from the formulas above. Lines two and three are rotation/shear values and from the documentation should normally be zero (Warmerdam, 2006). The last two lines are the upper left corner of the image in map units. For this example the map units were latitude and longitude, other types could and are used. It can be concluded the world file could easily be created automatically and in a production environment this may be ideal. For the prototype all the create images had similar dimensions and the world file was created manually and reused as often as possible.

3. Delivery of WMS and WFS

MapServer, depending on compilation options, supports using jpeg, png, tif and gif images with WMS. All can be made geo-rectified by MapServer by the inclusion of a world file in text format usually with an extension of *wld* or *tfw*. The last piece that remains in order for the information to be provided to the users via the internet is a map file. A full discussion of the map file and its functions is provided in “Beginning MapServer: Open Source GIS Development” (Kropla, 2005). However, Table 4 is an example of an entry needed in a map file to enable WMS.

Table 4. Map file entry to enable WMS

```
WEB
   …
   METADATA
                    "wms_title" "Cloud Analysis Server"
                    "wms_abstract" "Cloud Services"
                    "wms_extent" "-180 -90 180 90"
                    "wms_accessconstraints" "none"
                    "wms_contactperson" "The Contact Person"
                    "wms_contactorganization" "Naval Postgraduate School"
                    "wms_contactposition" "Server Administrator"
                    "wms_fees" "none"
                    "wms_onlineresource""http://localhost/cgi-
                    bin/mapserv.cgi?map=/home/mapdir/server_clouds.map&
                    amp;"
   END
END
```

The information in the map file needed to enable Web Mapping Services is in a section labeled “web”. The first line of the sample above is the start of the web section and the last line closes the section with an end statement. In a map file all sections and subsections are closed with an end statement. The metadata section is simply data describing the data the server is capable of delivering. Lines 4 through 7 describe:

- the title of the service
- a short description or abstract of the service and data
- the geographic extent of the data provided in map coordinates
- any limitations
- who to contact about the service and/or data
- what organization is providing the service
- what position the contact person is in
- any applicable fees for using the service

The map file used by MapServer is not case sensitive. However, all of the documentation and examples provided by the University of Minnesota (UMN Mapserver. 2006) and Kropla (Kropla, 2005) capitalize all keywords.

The content of the metadata section is provided by MapServer in XML format to clients making a GetCapabilities request. A GetCapabilities request is one of the standard communication protocols defined by the OGC to enable WMS and WFS. The associated data provided is specified elsewhere in the map file. The type of service specified above is WMS. WFS specification is done in a similar manner, and does provide more functionality. MapServer does not provide the capabilities of editing the underline data provided by WFS. The impact this has on functionality depends on the way MapServer is used.

E. DISPLAYING THE DATA

The final implementation design is shown in Figure 4. This concept is similar to the working plan used by the AFWA GIS team.

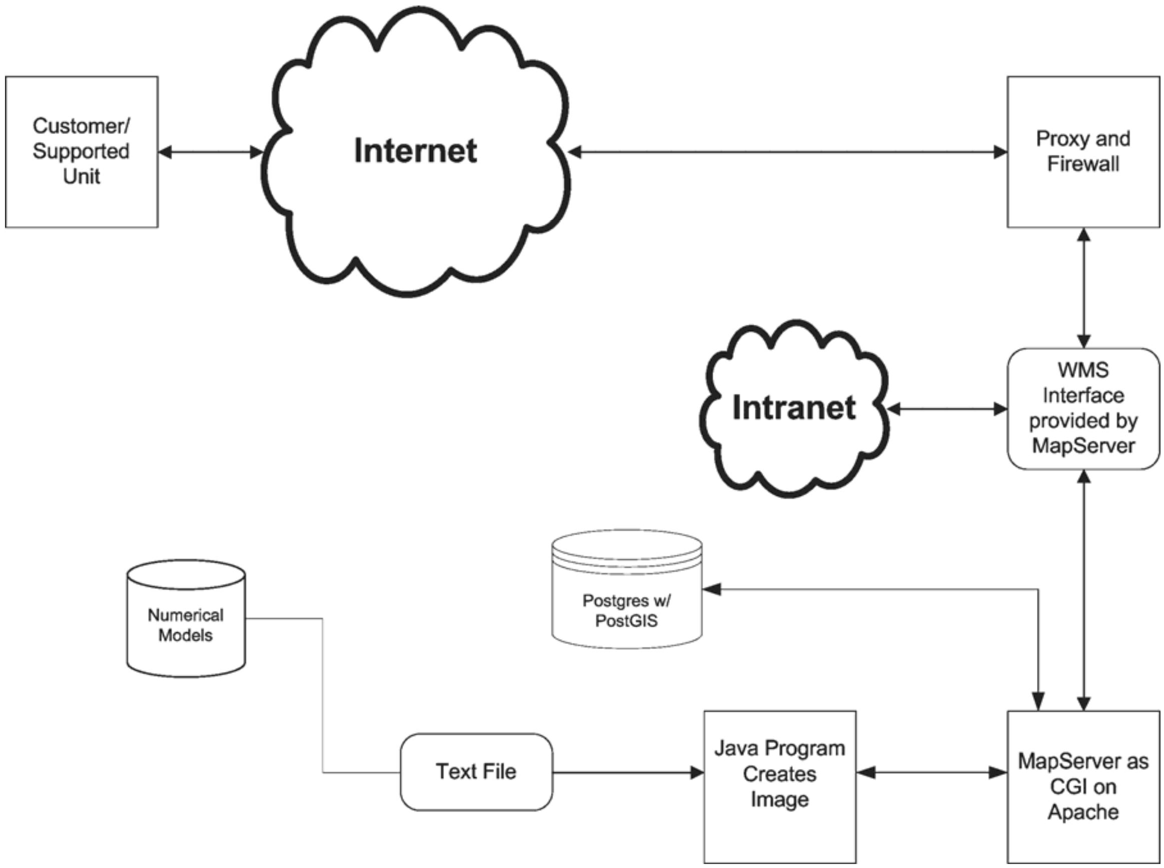

Figure 4. Implementation schematic of the prototype

This proof of concept does not include external or internet access to GIS weather data.

With MapServer providing data via an Apache web server, the next step is to show that the data can be displayed and used. This is done via two different interfaces. The first is a web interface and the second is a GIS client application. Both are used to show the potential and flexibility of weather information delivered in this format. Using a web browser as an interface provides a very flexible way to use the information. The interface must first be programmed using a mixture of hypertext markup language (html) and MapServer with its associated map files.

Using a GIS application such as ArcView or OpenJUMP is even simpler than the web interface from a programmatic view point. The user accesses the data with an OGC compliant WMS. Given a link to get a server's capabilities the user is able to view the data in a format they are trained and familiar with.

Air Force Weather will most likely employ both methods. A web interface provides a relatively simple way to provide GIS weather information to the war fighter in a highly portable manner. This method would deliver weather information to all users regardless of their ability to interact with an enterprise GIS. While it is an effective and efficient mode of dissemination a web interface does not provide the full capabilities stipulated in the Net-centric Data Strategy Guide (Stenbit, 2003). Providing data as a WMS or WFS is in line with the goals of the Net-centric Data Strategy Guide and would allow AFW to integrate seamlessly with all levels of operations creating the most benefits for the war fighter and the meteorologist.

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IV. IMPLEMENTATION RESULTS

Once all the pieces are assembled and tested a limited demonstration of the capabilities of GIS enabled weather information was accomplished. First, raw imagery from various cloud models is shown and discussed. Then, results from image generation of wind fields is shown and discussed. This is followed by the results gathered using a web interface. Finally, the data is demonstrated in a GIS client. Both the web interface and GIS client use the WMS capabilities of the prototype.

A. ANALYSIS AND FORECAST OF CLOUD COVERAGE

Figure 5 shows the output from the Worldwide Merge Cloud Analysis (WWMCA). Some obvious artifacts of the model are present, for example in the bottom half of the image towards the middle a sharp line is present. This is the edge of a satellite pass. When zooming in and panning around the image other artificial features of the WWMCA become easily apparent. This is caused by the data set used rather than of the methods of display.

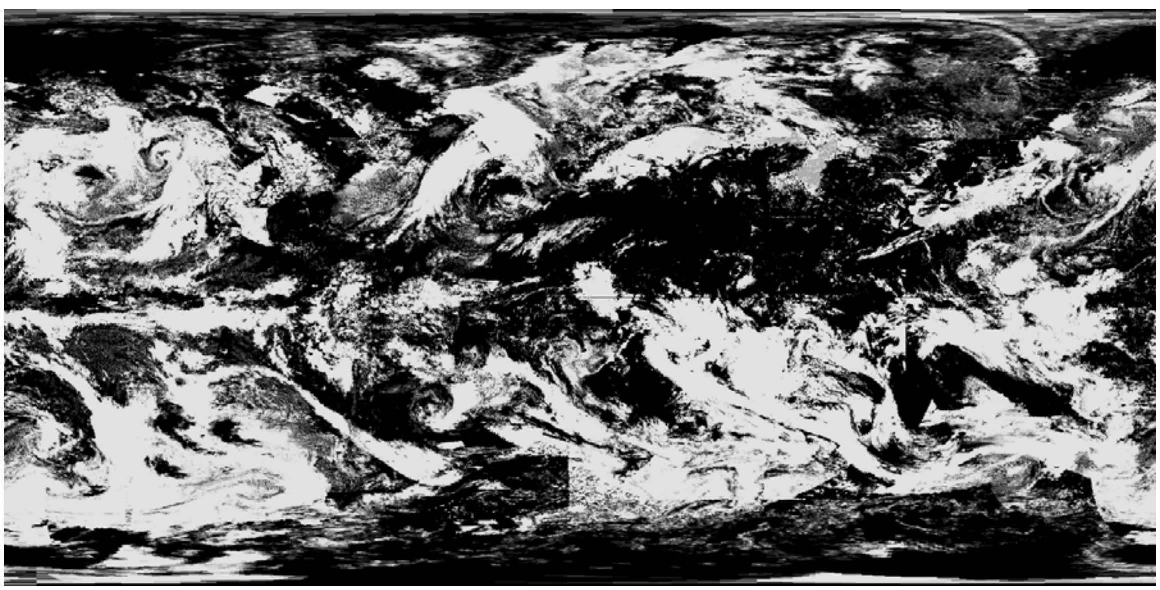

Figure 5. Raw Geo-rectified Cloud Analysis from WWMCA

Figure 6 was generated from the Stochastic Cloud Forecast Model (SCFM) and the color scheme was inverted from that used in Figure 5. This was done to demonstrate that the method developed and employed was flexible enough to easily allow for changes based on requests from the war fighter or any other supported agency. Additionally, the image is smoother than the previous image of the WWMCA. This is the difference between the data sets though the image makes the difference more apparent. While not immediately apparent in the SCFM image a smoother gradient from white to black is also noticeable, especially in a zoomed view.

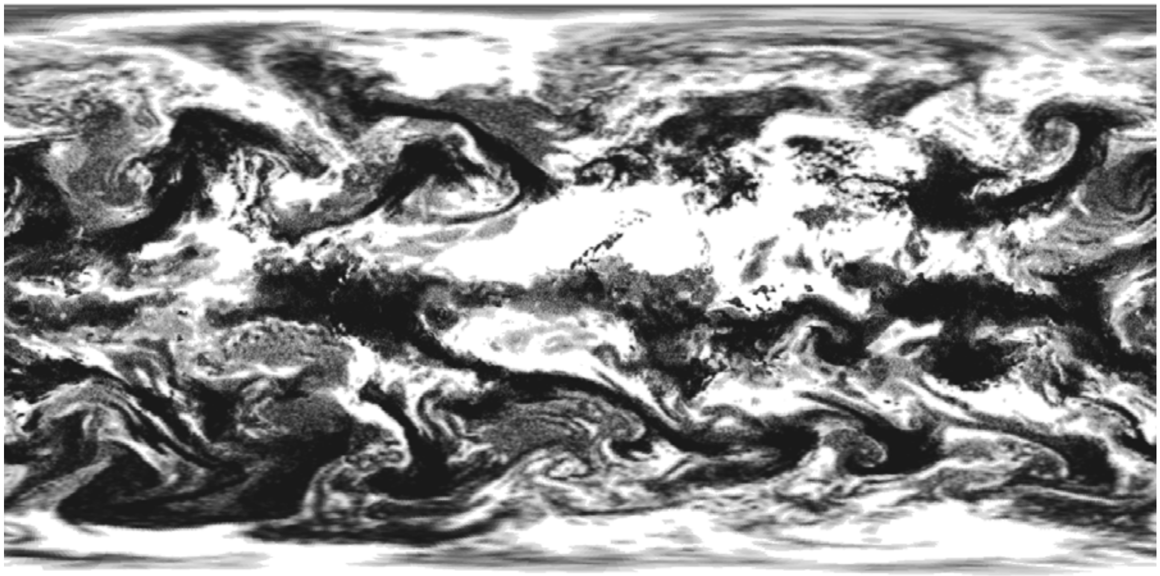

Figure 6. Raw Geo-rectified Cloud Forecast from operational model with grey scale inverted

A zoomed portion of the cloud analysis image is shown in Figure 7 and shows both realistic details similar to a meteorological satellite image and the very tight gradient from black to white. The beginnings of pixilation are seen in this image. When the images are viewed in a GIS environment either web based or stand alone client this pixilation is more pronounced. Immediately following the zoomed analysis image is Figure 8, a zoomed forecast image. This shows the differences in the data sets better than the original images. While the forecast image still shows structure similar to an inverted meteorological satellite image the gradient is much smoother than the gradient in the analysis. Once again this is simply the difference in the data sets. The actual data is not recalculated or manipulated by the associated algorithm to create the image; it is simply converted from numbers to a gray scale.

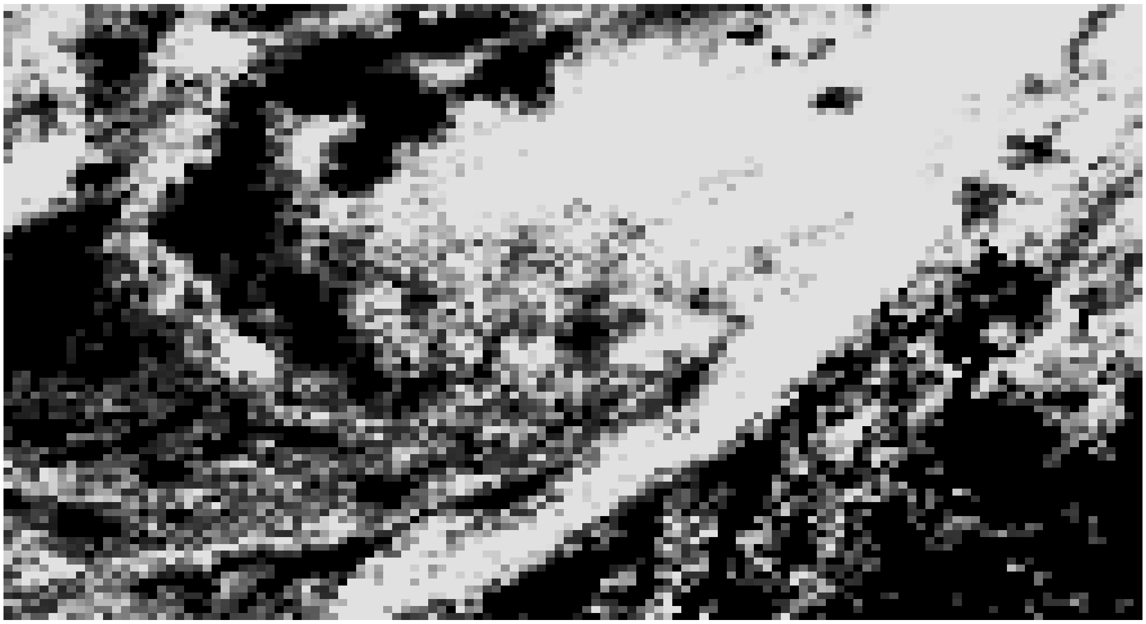

Figure 7. Zoomed Geo-rectified Cloud Analysis

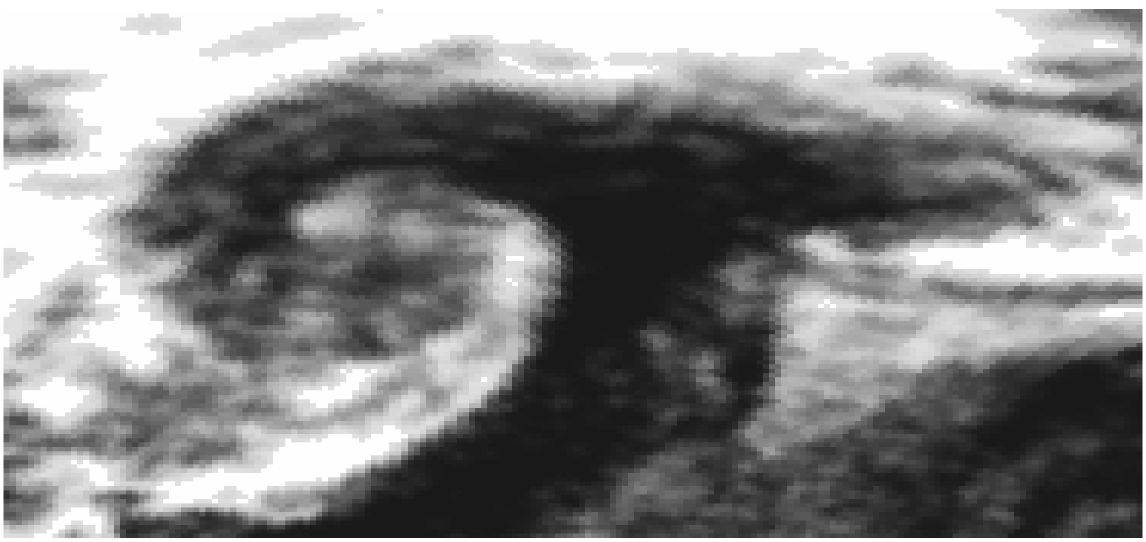

Figure 8. Zoomed Geo-rectified Cloud Analysis

Data from an experimental cloud model was provided by Leach, 2006. This allowed the creation of further images from completely different data sets (Figure 9).

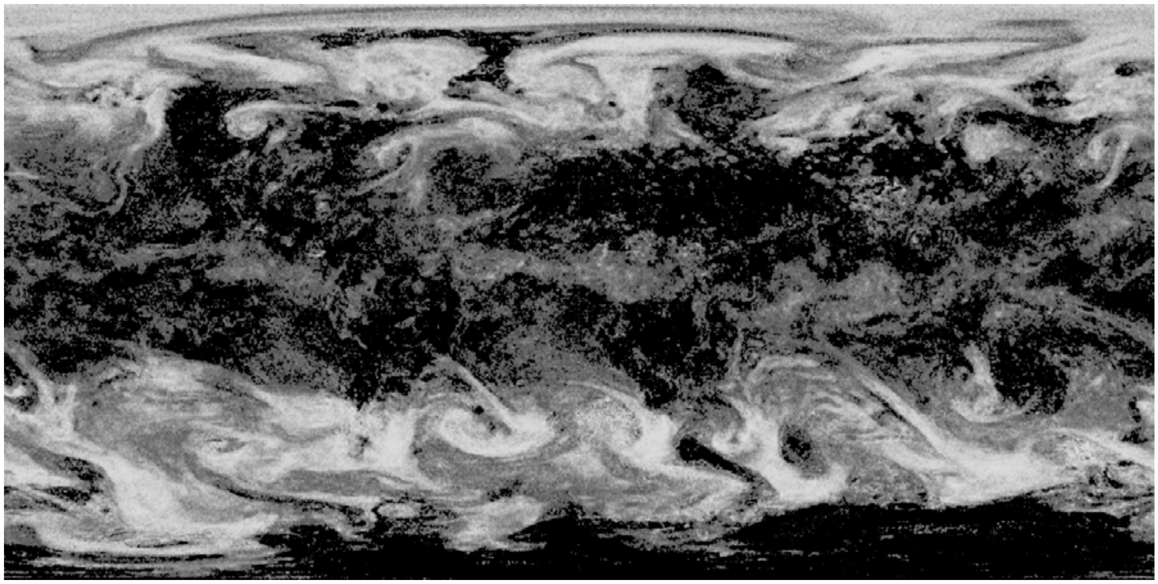

Figure 9. Raw Geo-rectified Simulated Cloud Image from Experimental Model

Creating this image demonstrated two things. First, this prototype could be used regardless of the model or data set used. Second, different model sets have different strengths and weaknesses and generating a second image from them easily shows these differences. Putting these different model data sets in a geo-rectified image also allows the modeler to compare how their model faired over different terrain. In addition to terrain, different models could be overlaid to show exactly how the models differed.

Creating images from model data sets is perfect for dissemination via WMS. MapServer proved very capable of delivery of WMS over a Local Area Network (LAN). Additionally, other software such as ESRI's ArcIMS could quickly be integrated into the infrastructure and provide the WMS service. If the war fighter did not have WMS capabilities the geo-rectified images could be deployed via a web interface or simply sent as an attachment to an e-mail.

B. SUCCESSES AND LIMITATIONS OF FORECAST WIND FIELDS

Generating wind field images was more challenging than creating cloud images. Figure 10 shows a wind image overlaid on a simple map of southwest Asia. The wind barbs are barely recognizable, and if one increases the area the image covers the wind barbs are no longer discernable. The full raw image when viewed as a full image is a gray shaded image with no discernable information.

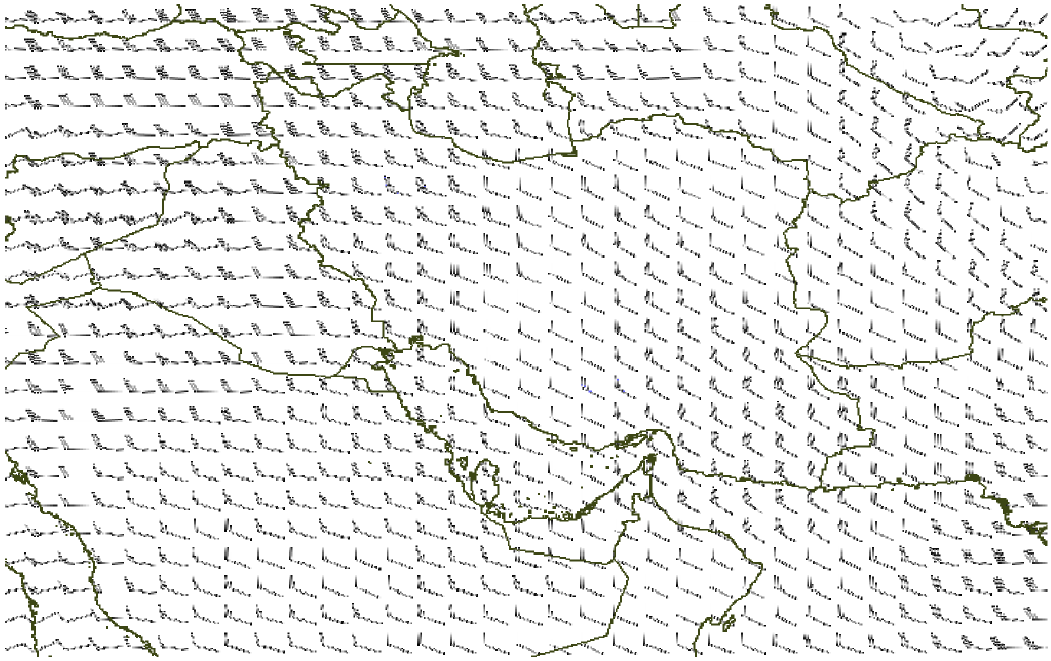

Figure 10. Raw wind image

This is an inherent problem with the image format. If known to the operator it might be acceptable. When the image is zoomed to an area the size of Iraq or Colorado, the wind barbs are nicely proportioned as shown in Figure 11. The addition of the background looks nice but also demonstrates another weakness of the image format; the color of the wind barbs is fixed and if displayed against a similar colored background would be rendered unusable. The last image in this series shows the wind barbs over Kuwait and shows the problems with zooming. While still not a significant problem for this scale, if zoomed to Kuwait City the wind barbs would be too large to be useful. Generating wind images demonstrated the necessity of providing the raw data to the war fighter and allowing the war fighter to render it according to their needs.

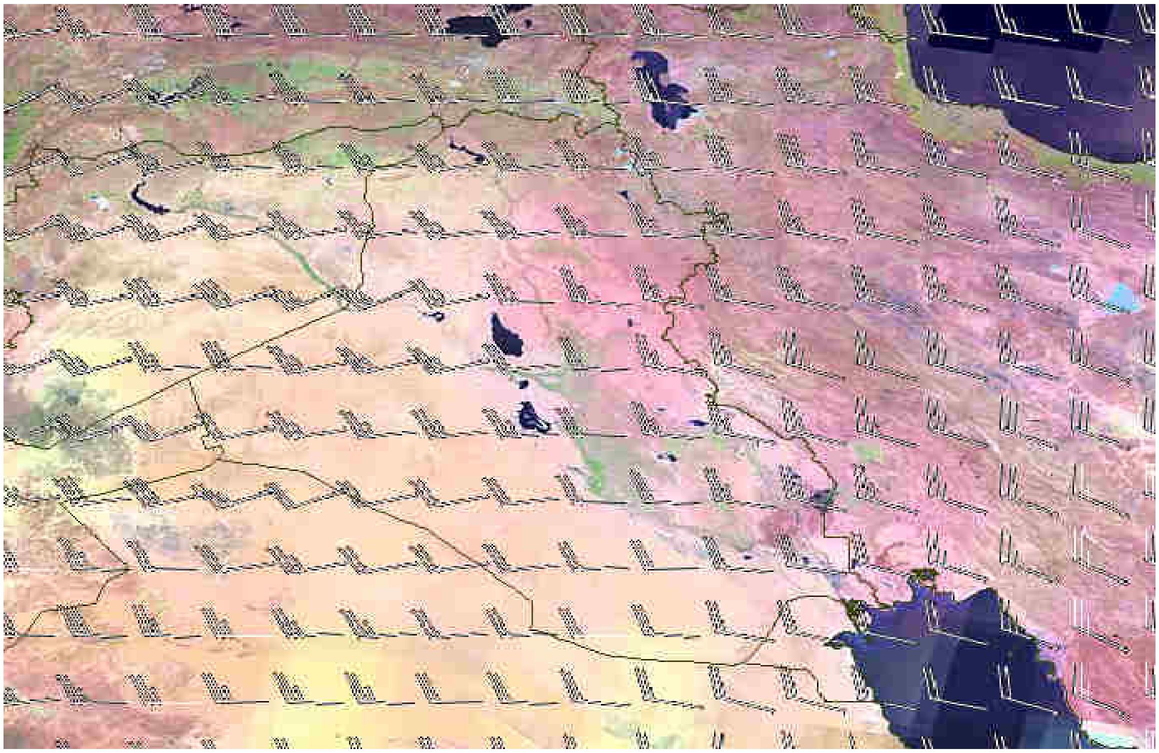

Figure 11. Winds Displayed over Iraq

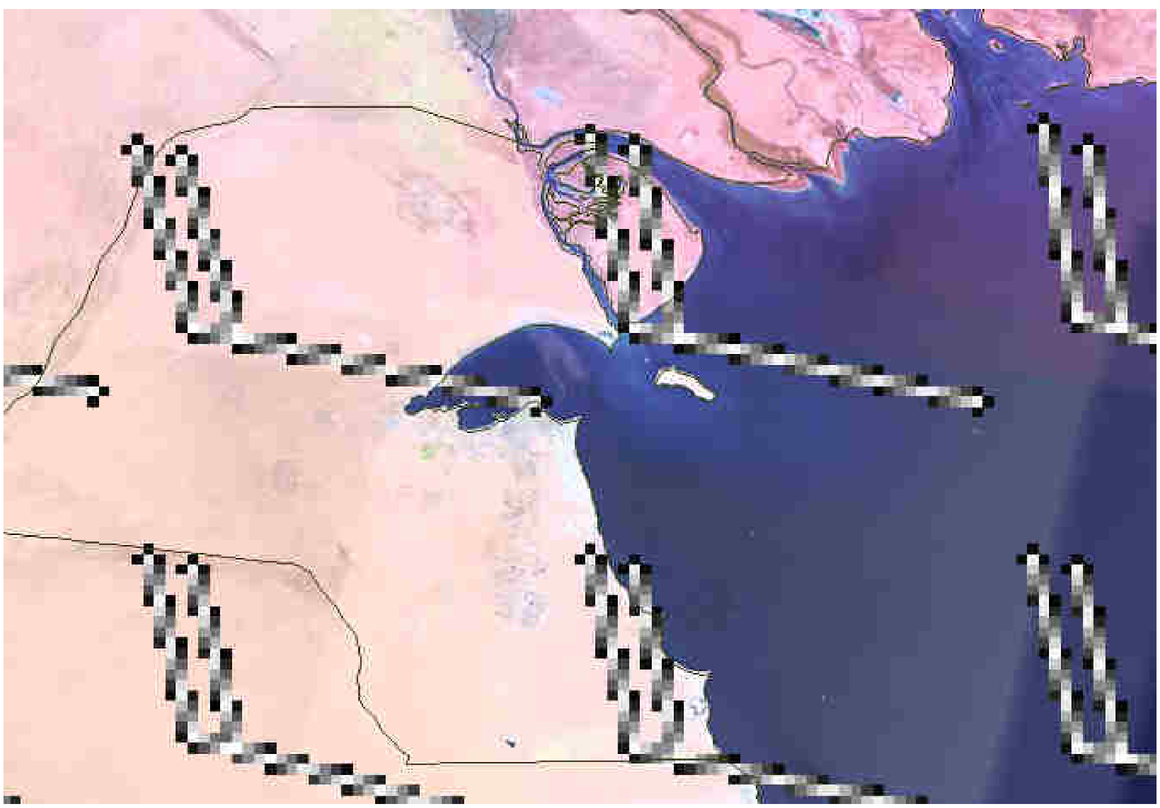

Figure 12. Winds Displayed over Kuwait

C. DISTRIBUTION OF FIELDS AND DATA

The ideal method for the delivery of the images across an enterprise is WMS. Once the images were created and served, the ability to exploit them was achieved. WMS provides images not data. This is a very important distinction and not readily apparent in a web browser. Once the images are used in a GIS client the difference is more apparent. Below is a global image of an experimental cloud model with a simple background image of terrain.

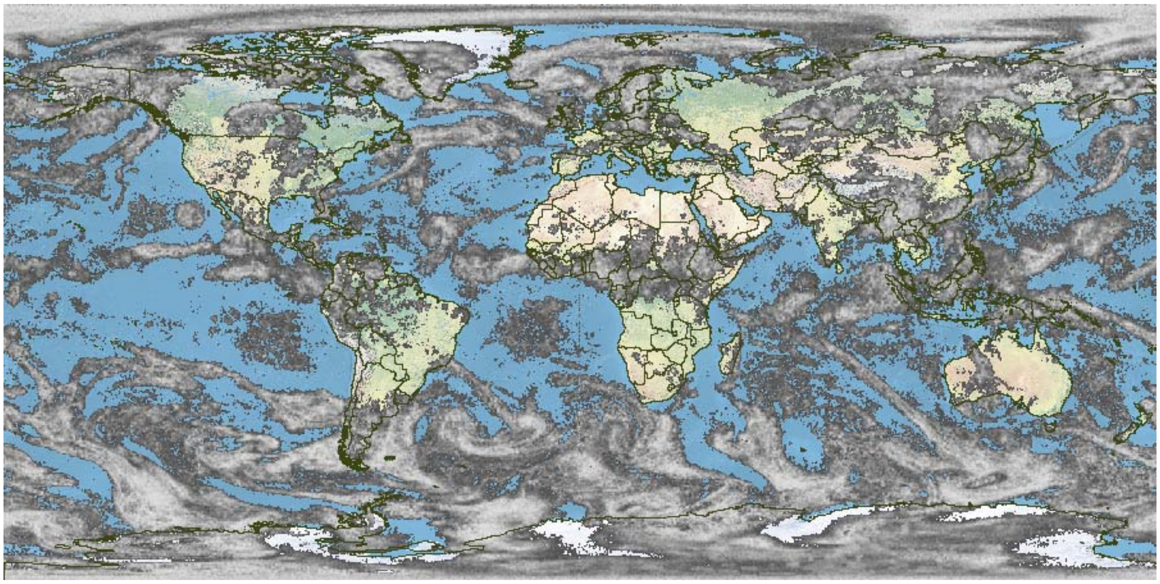

Figure 13. Cloud forecast with background for nice visual affect

The biggest drawback of images is they are not easily manipulated. While they are easily zoomed and panned and other information can be over or under laid, the image remains unchanged. This is good for providing simple information to the war fighter. For more complex tasks image limitations are unacceptable.

D. PROOF OF CONCEPT RESULTS

Next, we describe a working demonstration. A working demonstration of the prototype showed what works and how it works. First, a web interface and its possibilities is shown. Then a GIS client application and a small set of its capabilities are demonstrated.

1. Web Browser Interface

Providing the images in a web browser is a quick and reliable way to get the images to the users. In the expanding technology of today all but the oldest of computers are capable of running a web browser and accessing a network. Even, PDAs and cellular phones now have the capabilities to access web sites and these technologies, too, are readily available to the war fighter. This format is very appealing in that it can provide the information to a variety of users from the Headquarters level down to the marine in a humvee. The weakness in this method is the provider of the data specifies what the user can and can not display and/or overlay. The provider also specifies the format the information is in. Figure 14 and Figure 15 demonstrate the capabilities of a simple web interface.

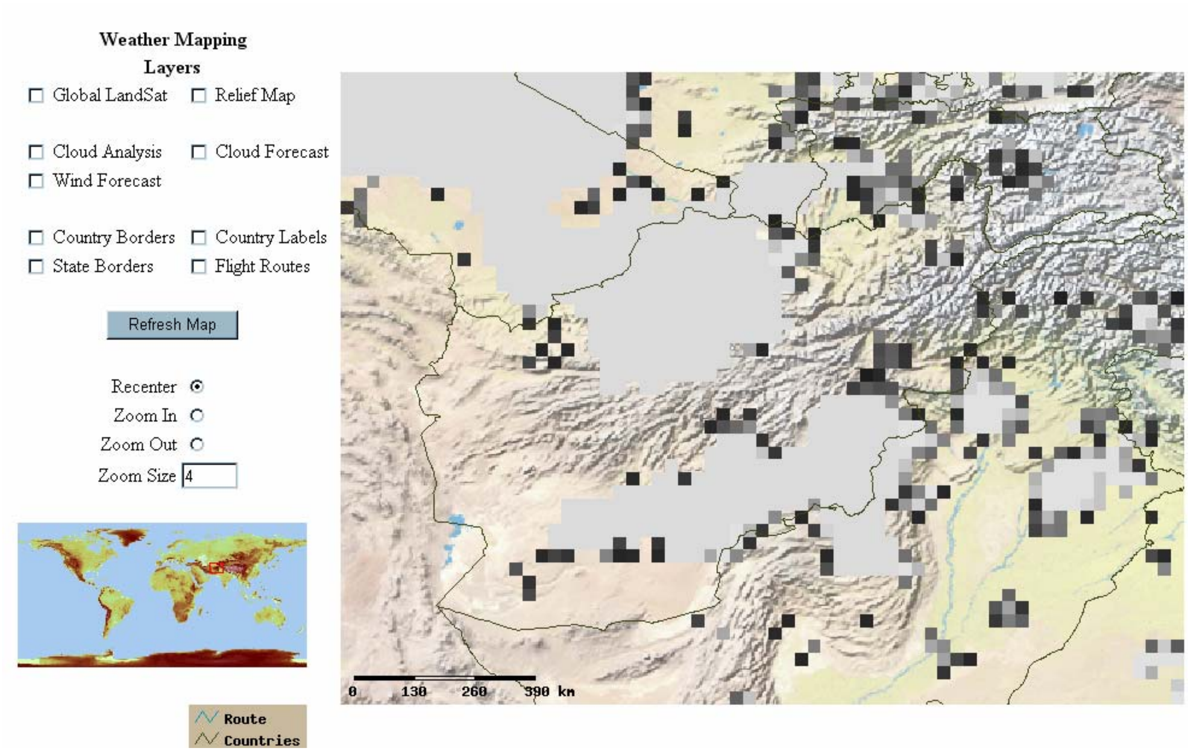

Figure 14. Web Page Providing Data, Overlays and the abilities to Pan and Zoom

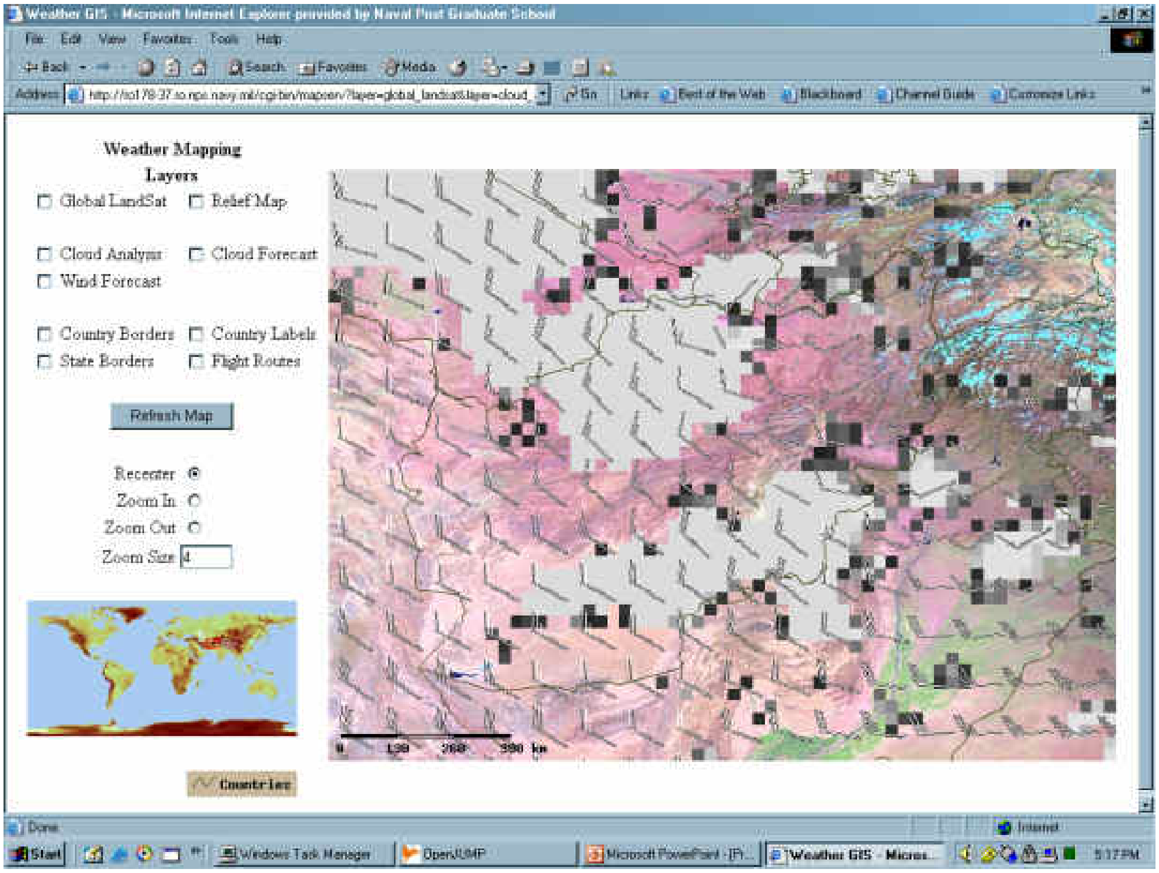

Figure 15. Internet Explorer showing display with winds overlaid.

Simple displays as shown above are relatively easy to program and a knowledgeable user can program similar ones in one to two hours. More complex displays are possible including the ability to dynamically change the map display size and layers used. A small example of an extension to MapServer called MapLab (MapLab. 2006) is shown in Figure 16. Figure 17 demonstrates MapLab's ability to add different data sets from different servers.

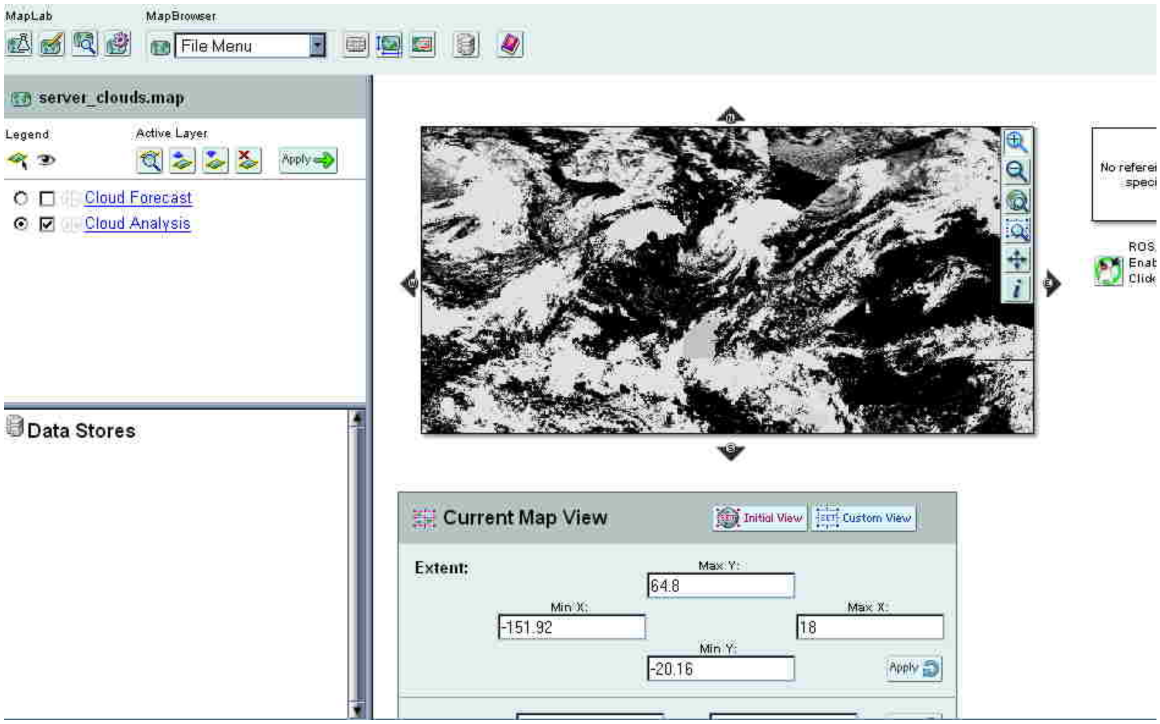

Figure 16. Web Interface for MapServer called MapLab

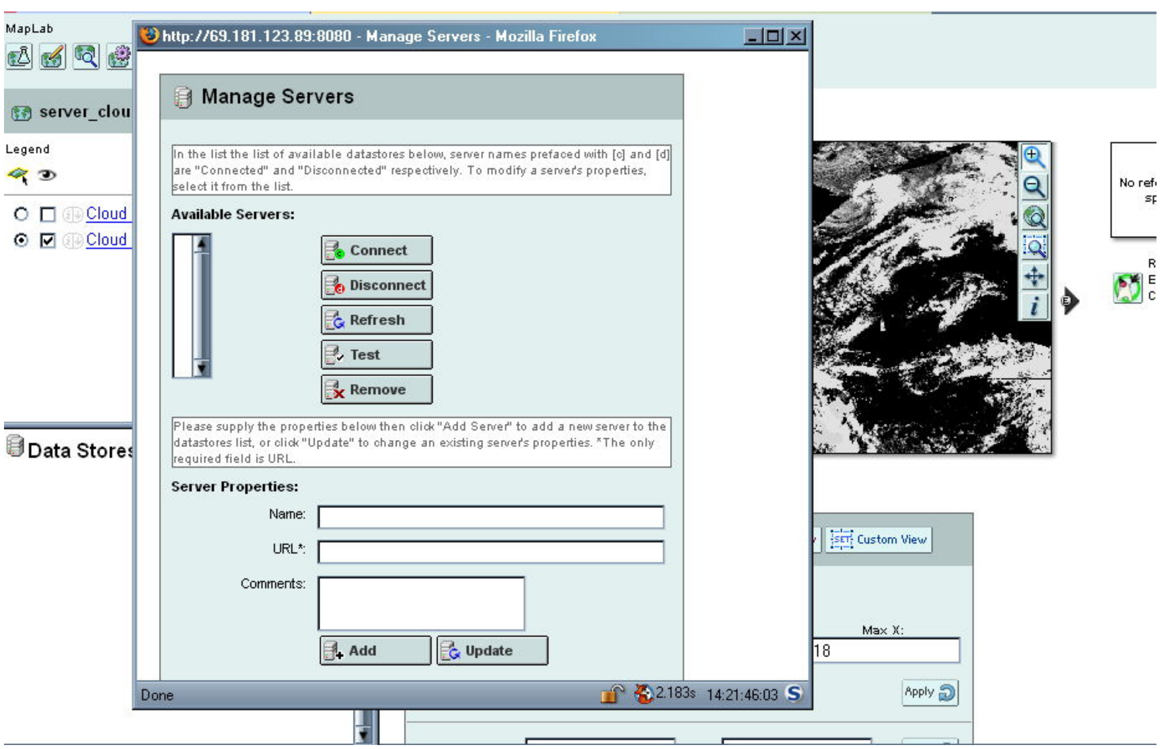

Figure 17. MapLab window, showing ability to add different data sources

MapLab extends MapServer in a modular way and makes the development of very complex web based applications possible. Other extensions for MapServer are also available and provide similar capabilities.

2. GIS Client Interface

Stand alone GIS clients provide an even more robust and flexible solution. Figure 18 shows an open source client called OpenJUMP (OpenJUMP. 2006). OpenJUMP is displaying several layers, including cities, urban areas, roads, and state lines. Under these layers is the cloud analysis with inverted colors, black is one hundred percent covered. The background is below all the other layers is Landsat imagery provided from JPL's WMS server.

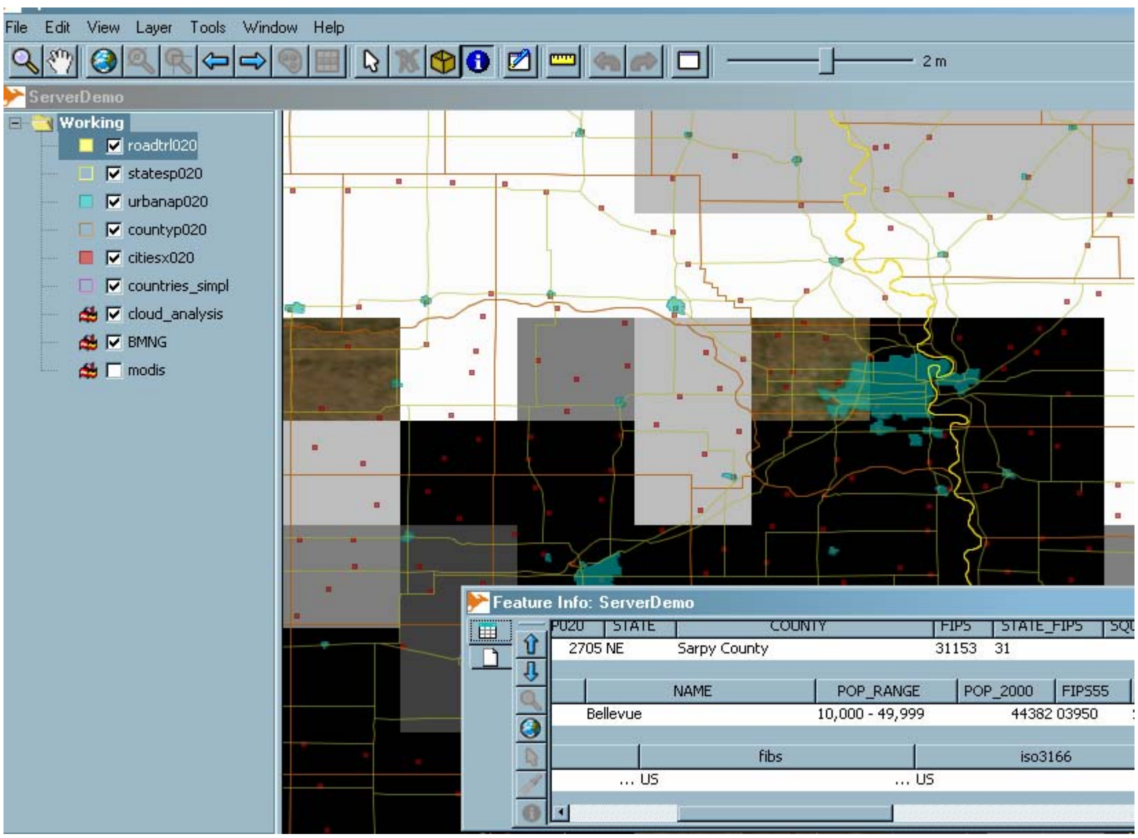

Figure 18. Cloud Analysis displayed in a GIS application from WMS

The pop up window in Figure 18 shows the statistics associated with one of the features in the urban areas layer. Similar data can be displayed from all of the layers provided as data. The left panel of the program also lists all the layers available for display. With the click a mouse button a layer can be turned on or off. The order of the layers can be changed by dragging one layer above or below another layer. The properties of each layer such as color, size and font are easily changed from this panel. The power of layers in a GIS client becomes apparent with use. The ability to see a metropolitan area such as in Figure 18 on top of a layer clouds allows both the operator and meteorologist to see that more clouds cover is forecasted over the eastern parts of Omaha than the western. Overlaying wind speeds in the deserts of Iraq over a layer of the location and types of sand would allow forecasters to more easily pin point significant areas of blowing sand. The flexibility of a GIS client application over a web interface is easily seen. Other GIS clients, free or commercial, provide similar functionality.

Figure 19 shows southwest Asia with forecast winds and clouds overlaid. The clouds are slightly transparent, another capability of the GIS client. More importantly, a layer has been added from a spatial enabled database. Figure 19 shows two different flight routes. The first is a straight line from Kuwait City airport to Baghdad airport. The longer line to the east was added from OpenJUMP. The line was drawn and several way points were added. Once this was done visually the data was added to the database. This is a very powerful feature as forecasters could edit data provided by a database, adjusting it for terrain or any other parameter, and then update the database. The war fighter could then view the adjusted forecast from the same database.

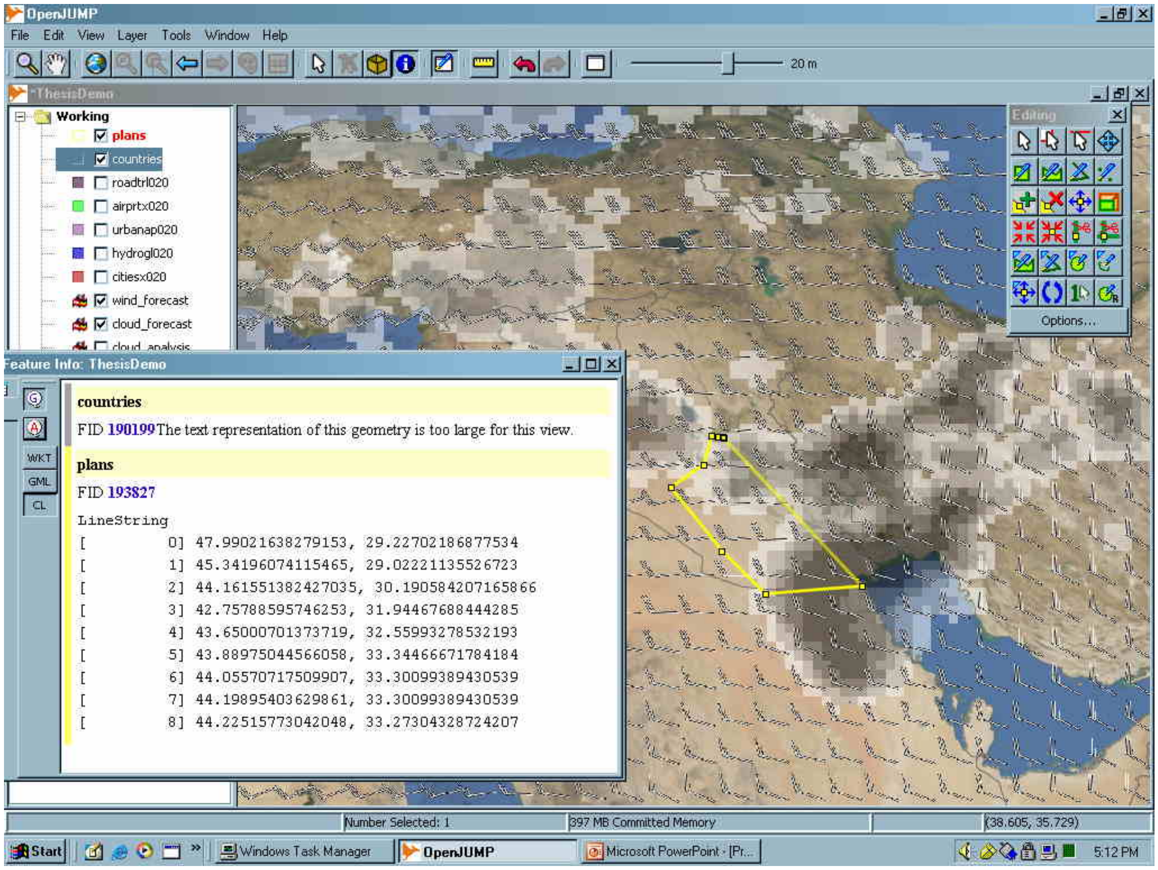

Figure 19. Cloud and Wind forecast displayed in a GIS application from WMS

3. Application

For planning, weather information in a GIS format is extremely useful. It allows the war fighter to visualize in the common operating picture the weather parameters that most effect their operations. In the tactical environment the ability to overlay real time weather data is imperative. This is both for the operator and the meteorologist. Within the weather community the ability to spatially analyze weather parameters will yield benefits from both a scientific and operational perspective.

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V. SUMMARY AND CONCLUSIONS

A. SUMMARY OF PROCEDURES AND RESULTS

The infrastructure built within this research for the dissemination of forecast data in a GIS enabled format is relatively robust and easily extendable. Other parameters can be easily added. Parameters, such as geo-potential height, where isopleths are desired a different approach would be needed. However, the algorithm would be only need to be altered not redefined.

Vector depiction of weather phenomena such as wind was not very successful. This is a problem inherent with the image format. Additionally, the limited code done with this parameter was long and tedious and required a separate section of code for each range of values. This is not an ideal way to solve the problem. Rather than relying on Java's 2D image library for creation of the image in a standard format, i.e. JPEG or PNG, use of Java's extensive XML capabilities to create a SVG graphic should have been used. However, initial use of SVG with MapServer proved to be cumbersome and awkward. The images created and displayed were bulky and at the time didn't show promise. Later work showed a further look into this area would have been justified.

Time limited exploration into data enabled formats such as WFS and direct access to a data base. Initially direct access to PostGIS was used to create images with MapServer via the network. However, given the modest hardware used and a lack of tuning of the database the display time was well over 200 seconds or close to three and a half minutes for the cloud analysis data sets. This was for initial and subsequent displays so improvement was not seen when zooming in or panning. This was unacceptable as most, if not all, users would not use the system for lack of responsiveness. Thus direct image creation from a database was dropped in favor of creating a static image and distribution via WMS.

B. CONCLUSIONS

1. Weather and GIS

As weather is essentially geo-spatial data its integration with GIS was extremely successful. This small prototype demonstrated just a few capabilities of such a system. Enabling weather data and information across an enterprise GIS such as what is stipulated by Net-centric Operations and Warfare would further exploit capabilities. These capabilities are required of Air Force Weather as the war fighter moves into a seamless net-centric force.

2. Images or Data

Providing images is a fast and efficient means of enabling weather in a GIS format across an enterprise. This is not necessarily the most effective method, providing the data or information in raw format via WFS or database access is a far more robust and flexible way to achieve the goals stipulated by the DoD Chief Information Officer. The operators and other users may at times require the graphical representation provided by WMS. Ultimately, Air Force Weather should deliver both formats whenever feasible.

C. RECOMMENDATIONS

1. Training

In order to provide the war fighter with the best possible support, Air Force Weather needs to rethink how it provides its weather data. The war fighter has moved to using GIS environments. This move started as early as the mid to late nineties. Air Force Weather has been slow to adopt this approach. This is for various reasons, first and foremost the lack of bandwidth and the lack of resolution and accuracy of the numerical models used. While the models still remain imperfect they are now high resolution enough to be used realistically in a GIS environment, especially windowed models such as the MM5. As technology has improved and the military has moved to a more net-centric model, the delivery of weather data and information in a GIS enabled format is now realistic. This implies an immediate need to retrain meteorology personnel to use GIS tools.

In addition to immediately retraining all qualified meteorology personnel in GIS technologies, AFW needs to consider training airmen from the beginning to think about and to use GIS. Once this initial training is in place advance training in spatial analysis for the experienced forecasters could provide explosive growth in our ability not only to provide the war fighter with more accurate and timely meteorological information but also better analyses and a deeper understanding of weather impacts to operations.

2. Retool

Rethinking and retraining will require new tools. The prototype demonstrated the ability to use generic GIS tools to display and modify weather data. Therefore, AFW instead of using weather specific tools would use the same tools the war fighters, but with meteorological extensions. This reduces the cost for retooling AFW and more closely connects AFW technology improvements to war fighter technology improvements. This would create a synergistic tie between AFW and the war fighter enabling more open communications about capabilities and processes.

D. FUTURE WORK

1. WFS

The most obvious continuation of this work is to focus on providing data. The prototype in this research only provided images. The ultimate goal that will yield the highest benefits to operators and meteorologists is to provide the data in a GIS enabled format. The most effective way to do this is through WFS. While MapServer does provide WFS it does not currently provide transactional WFS or the ability to alter the data being served (UMN Mapserver. 2006). This is useful for delivery of weather data and information to the war fighter but does not harness the full potential of GIS, especially for the meteorologist. So, ultimately, another product such as ESRI’s ArcIMS and ArcSDE would likely have to be used. Initially the ability to provide WFS with unalterable data would prove useful for limited applications. To provide a proof of concept demonstrating WFS using the infrastructure built for the prototype in this research would prove beneficial.

2. Three Dimensional (3D)

In a personal communication, Dr. Don Brutzman, one of the leaders in Distributed 3D Environments, stated 3D is not a replacement for but an augmentation of 2D. 2D visualizations will continue to be used. However, in addition to being essentially geo-spatial, weather data and information is also 3D. War fighters operate in 3D space and the ability to provide them 3D representations of current and forecast weather conditions is a service they eagerly anticipate. ESRI already has 3D plug-ins and capabilities for their desktop products and analytical toolsets. With the prototype in this research the only 3D capabilities are very limited. While marginally usable in prototype it is not even a good simulation of 3D and does not show the associated parameters continuously through the defined values. This is one area where future work could deliver significant results.

3. Time

Another area that is problematic for the display of weather in GIS is time. Weather happens continuously or at the very least in a time sequence, GIS currently is unable to depict a time sequence. The NWS does not even attempt to tackle this problem with their distribution of geo-referenced images, they simply distributes single images (RIDGE for GIS Users. 2006). A serious look at this problem is necessary for true incorporation of weather into GIS.

4. Complex Parameters

Weather analysis and prognosis requires the calculation of many parameters not explicitly calculated in the numerical models. Whether it would be better to provide the raw data and let the end user, either meteorologist or war fighter, calculate these values or provide them either as images or data is an area prime for future research. There are many pros and cons of each and additional research is needed.

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