Classroom Exercises in GIS Meteorology

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1. INTRODUCTION

A comprehensive set of exercises has been developed for the Geography curriculum at George Mason University by the author, and offered as GEOG 309 – Introduction to Climate and Meteorology. This novel approach to the traditional undergraduate Weather and Climate course is made possible by new computerized classrooms at GMU's "Innovation Hall", where each student has a Windows XP workstation with ESRI ArcGIS Desktop and access to the Internet. Students are introduced to meteorology using real weather data and phenomena, and learn how to use ArcGIS in the process. The set of twelve exercises closely follows the Ahrens © 2005 text, but branches out to include technical topics and methods that are easily introduced using GIS techniques. The exercises are: 1) surface charts, 2) upper air, 3) radiation, Sun & Galaxy, 4) satellites, 5) clouds & skew-T logP charts, 6) radar & precipitation, 7) numerical models, 8-10) severe storms, 11) climate change & ice ages, and 12) air pollution & air parcel trajectories. This approach to Weather and Climate

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tests Prof. Shipley's claim that the public of the future will be able to analyze complex information for themselves and draw their own conclusions, provided that they have access to that information. Such access is not assured, and is threatened by precautions imposed for national security, or cost barriers associated with commercialization and privatization. This set of GIS exercises gives students some of the tools they will need to prove that Global Warming is just a "bunch of hot air".

Note – This extended abstract was originally prepared for the ESRI 2005 International User Conference, but was not presented in that forum. The text is repeated here with occasional notes to document changes.

2. So *What* was I Thinking?

I first started teaching GEOG 309, Climate & Meteorology, to students at George Mason University in the Spring semester of 1991. Several textbooks and ancillaries are available for undergraduate level meteorology, with new titles appearing every year. Out of the numerous introductory-level textbooks and workbooks available for undergraduate study in meteorology and climatology, I mostly use the Ahrens (2003, 2005) texts offered by Thomson – Brooks/Cole. This series has the added benefit of an excellent

Figure 1 – The GEOG 309 Class of 2005, Spring Semester, at George Mason University. The two images span the classroom (left to right) from the Professor's "podium". Innovation Hall room 320 is equipped with 27 XP workstations, preloaded with ESRI and other GIS software, each connected to a local network and the Internet. The AV Control Panel supports a 28th XP workstation, the Professor's laptop, VHS, DVD, and a document projection system. Innovation Hall opened in the Fall of 2003. The "Great Book" is Pielou (1991).

compendium by Roland Stull (2000), **Meteorology for Scientists and Engineers**, which provides most of the formulae needed to implement meteorology and climate functions in a GIS. The Stull Companion has become a staple reference on my bookshelf. Over the years I've been able to migrate from slides on an overhead projector to a full computerized GIS-enabled classroom with video projection (Figure 1). Despite all this technology, however, field trips remain the most important feature of this class, since "*One hour in the field is worth an entire semester of harangue in the classroom*" (my quote). Since the advent of ArcView 1 circa 1993, the slides started to incorporate displays derived using GIS techniques. Students began to have email accounts. Then students began to appear with GIS experience in secondary school, but were told that the GIS lab was open only for graduate study. I credit my GEOG 309 students with the concept of using GIS to examine all hydromet data and perform most hydromet analysis and display functions. A brief discussion of my current perspective on this topic is published under the title "*GIS Applications in Meteorology, or Adventures in a Parallel Universe*" (Shipley, 2005). The GEOG 309 class syllabus is maintained online at http://geog.gmu.edu/classes/geog309/g309.htm.

Addendum 11/05 – I have selected a new text companion for the GIS Exercises starting in Spring 2006, namely Understanding Weather & Climate by Aguado and Burt (2004).

3. What Worked, and What Didn't

Meteorologists are so used to doing their job the "traditional way" that they may not see advantages for using GIS in their weather enterprise, and they may think the "Emperor has no clothes" – see note 1. In fact, there is a GIS learning barrier of sorts for meteorologists since the terminology is different, the point and click functions may not be familiar, and why use new tools when those you already have are sufficient? People who already use GIS actually have access to a sophisticated weather processing system, but it is currently somewhat difficult to acquire and apply weather information in a GIS. Non-meteorologists have the additional hazard of misapplying weather data. So if you're not a black belt, paper bag-wearing meteorologist, you may need to pay more attention to the limitations and idiosyncrasies of weather data and information. Most GEOG 309 students start out as non-meteorologists who are also not GIS users.

The greatest pitfall in the computerized classroom is time spent with Information Technology (IT) staff and malfunctions, or our inadvertent misuse of IT. The Innovation Hall infrastructure is shared with numerous classes, and we found dwindling capacity for storage of the large **geodatabases** employed by our GIS applications. Resource sharing became such an issue that we stopped using the shared drives entirely, and either downloaded the exercises from the GEOG 309 website, or passed around zipped directories on multiple copies of CDROMs. In every case, relative addressing has become mandatory (in ArcMap, Map Properties/ Data Source Options). Additional time was wasted this year on workstation software that was not maintained to current patches and updates.

My original goal was to train each student on the principles and procedures of GIS, using hydromet data to grow every application from scratch. Due to the general lack of student GIS training at this time, it is better to first provide full working GIS documents, and then ease students into specific GIS capabilities one step at a time. I found that once students learned to navigate GIS and became comfortable with the user interface, many quickly applied the tools to new datasets. On the other hand, there were a select few who are still wondering how to turn the system ON (if you're reading this, you know who you are :). Now at the end of my second semester at Innovation Hall, my thinking on the best way to introduce GIS to this group and in this environment is:

Goal #1 – Turn the system ON and navigate the operating environment (apparently the hardest part!)

Goal #2 – Get familiar with GIS User Interface and basic GIS functions

Goal #3 – Use GIS and Operating System tools to study (examine) weather data

Goal #4 – Use GIS to analyze and manipulate weather data

Goal #5 – *Advanced*: Import raw (not *GIS-Ready*) weather data into GIS

There is tremendous potential here. GIS provides a new way to look at, examine, and analyze weather and climate data, weather conditions and phenomena, and numerical weather predictions and forecasts. A few students complained that I was wasting their time since they did not see themselves using GIS in the future. Perhaps so, but perhaps not. A few of the exercises are detailed below. Not all of the exercises are complete, and can be considered work in progress. On the other hand, several of the topics are subject to change due to rapid developments in research and technology. It is challenging to stay current in this field of climate and meteorology.

4. GIS Meteorology Exercises
4.1 Exercise #1 – The Weather Map

Consider the amount of weather information that everyone is now receiving daily through the media – on television, radio, in print, and on the Internet. Students begin my class already familiar with complex weather symbolization and
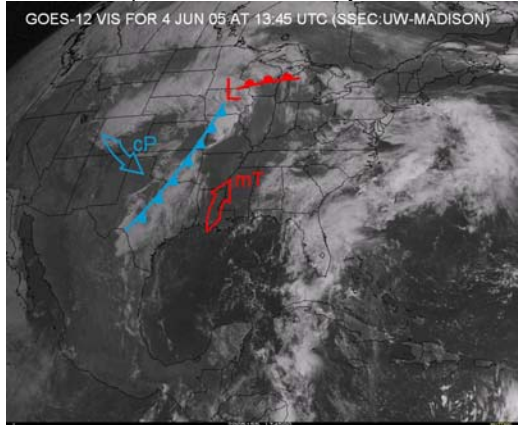

Figure 2a – Visible satellite image on 4 Jun 05, introduces students to satellite cloud images and their relationship to surface weather patterns. Adapted from SSEC, University of Wisconsin.
http://www.ssec.wisc.edu/data/geo.html.

GIS can significantly enhance familiarity with the information, standards, and techniques employed to develop surface maps. Our first attempt was to create surface maps in GIS from scratch, requiring the students to retrieve data, convert them to formats compatible with GIS, then manipulate the symbology to get the desired result. *This approach was a complete disaster.* Those few students with GIS experience were done in five minutes or less, but most students were strewn out across the detailed step-by-step instructions, and a

Figure 3 – ArcMap presentation of surface data over an InfraRed GOES satellite image. The Fronts are hand drawn. Surface station data are included as point features. Symbology shows temperature classification in Fahrenheit and wind direction. Students use Spatial Analyst to contour ("analyze") surface parameters.

terminology, sometimes with surprising misconceptions. They have been exposed to satellite images similar to Figure 2a (below left), but it's usually their first exposure to the companion surface map shown in Figure 2b (below right). These figures can be used to discuss air masses, fronts, circulation, convection, surface observations, "weather", and much more.
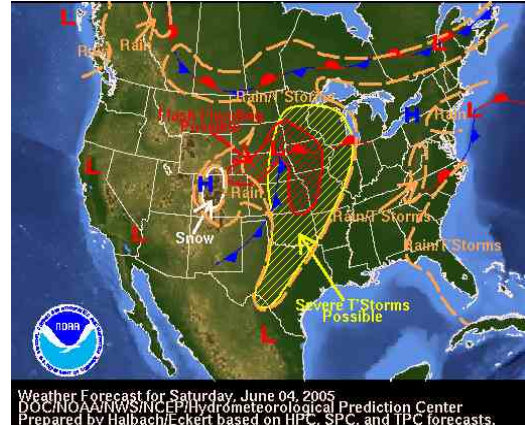

Figure 2b – Surface weather map forecast for 4 Jun 05, courtesy of NOAA's National Weather Service (NWS). All texts use coupled maps and imagery to discuss weather patterns and terminology, see note 2.
http://www.nws.noaa.gov/outlook_tab.php.

few were still looking for the "start" button. The most effective approach in the first lesson is to provide an ArcMap document complete with data and symbology, as shown in Figure 3. The details on how to create such a map can come later, but it is more effective in a first lesson to review basic operations (pan, zoom, info at point, etc.), examine the data, and review the principles of map projections. Given Spatial Analyst, students can derive their own "isobars" (*isohectoPascal?*), isotherms, isohumes and what have you. The

Figure 4 – Surface observations become real during a field trip to the NWS Test Facility in Sterling, VA. Joe Fiore (SAIC) is shown describing the function of the Automated Surface Observing System (ASOS) to the GEOG 309 class of 2005.

lesson is complete with a field trip to your local ASOS Test Facility, a unique opportunity in the Washington, DC area (Figure 4).

The primary objectives of this first lesson are 1) to introduce students to real weather data (primarily surface observations and satellite images), and 2) to make sure all students know how to navigate the IT infrastructure and operate the basic functions of ArcMap. The contouring functions provided with Spatial Analyst provide an excellent opportunity to introduce some basic weather "analysis" concepts.

4.2 Exercise #2 – Upper Air

One of the exciting new developments in meteorology is the GPS sonde, newly acquired by NOAA under the Radiosonde Replacement Program (http://www.nws.noaa.gov/rrs/index.htm). Smaller, lighter and capable of higher spatial and temporal resolution than the radio- or rawin-sonde currently in operation, the GPS sonde will significantly improve *in situ* temperature and humidity soundings. After plotting an operational sounding by hand, GEOG 309 students participated in a GPS sonde test launch at Sterling, VA. A partial sample of GPS sonde data is given in Table 1. Images from the test launch are shown in Figures 5 and 6.

It is relatively easy for most of us (GIS types) to "decode" Table 1 and load the individual rows as point event data. The data table is not quite *GIS-Ready*, but nearly so. Tracking the sonde using {Lon, Lat} is obvious. What may not be as obvious is using {T, z} to create a conventional Stüve Diagram, which plots Temperature {T} along the abscissa, and height {z} along the ordinate, as shown in Figure 7.

Table 1 – GPS sonde test data, for an unidentified sonde released at 10:35 edt on 28 Apr 05.

Balloon Release Time: 15:35.6
Balloon Release Lat : 38.97667
Balloon Release Long: -77.47694
Balloon Release Elev: 85 m
*********** Baseline Data ***********
Pressure Temperature Humidity
Station 1005.02
Radiosonde 1005.42 22.18 24.7
*********** Surface Observation Data **********
Surface Pressure : 1005.43 hPa (derived)
Temperature Dry Bulb : 13.7 Celsius
Temperature Dewpoint : 1.2 Celsius
Relative Humidity : 42 %
Pressure Correction : 0.41 hPa
Temperature 12hrs ago: 25 Celsius
Wind Speed : 9 knots
Wind Direction : 264 Degrees
Clouds Weather : 009000202

ET_min	P	T	RH	GPH	GMH	u	v	Lat	Lon	WS_kn	WS_ms	WD
0	1005.43	13.7	42	85	85	4.6	0.5	38.97667	-77.47694	9	4.6	264
0.017	1004.86	13.42	27.1	90	136	4.5	0.7	38.97675	-77.4758085	8.9	4.6	261
0.033	1004.27	13.47	27.5	95	139	4.6	0.8	38.9767503	-77.4757581	9.1	4.7	260
0.05	1003.49	13.39	27.9	101	142	4.8	0.8	38.9767603	-77.4756988	9.5	4.9	261
0.067	1002.95	13.29	28.2	106	145	4.9	0.8	38.9767703	-77.4756581	9.7	5	261
0.083	1002.3	13.22	28.5	111	148	5.1	0.8	38.9767803	-77.4755981	10	5.2	261
0.1	1001.39	13.12	28.9	119	151	5.3	0.9	38.97679	-77.4755381	10.5	5.4	260
0.117	1001.15	13.05	29.3	121	154	5.5	0.9	38.97679	-77.4754778	10.8	5.6	261
0.133	1000.1	13	29.81	30	158	5.6	0.9	38.97679	-77.4754088	11	5.7	261
0.15	999.71	12.95	30.2	133	161	5.8	0.9	38.97679	-77.4753678	11.4	5.9	261
0.167	998.78	12.93	30.5	141	164	6	1	38.97679	-77.4752975	11.8	6.1	261
0.183	998.54	12.9	30.7	143	168	6.2	1	38.9767903	-77.4752181	12.2	6.3	261
0.2	997.91	12.88	30.9	148	172	6.4	0.9	38.9768	-77.4751578	12.6	6.5	262
0.217	997.26	12.85	31.2	154	176	6.5	0.9	38.9768	-77.4750878	12.8	6.6	262
0.233	996.49	12.76	31.3	160	180	6.7	0.9	38.9768003	-77.4750178	13.2	6.8	262
0.25	995.95	12.71	31.6	165	184	6.9	0.8	38.97681	-77.4749478	13.5	6.9	263
0.267	995.49	12.63	31.7	168	188	7	0.7	38.97681	-77.4748775	13.7	7	264
0.283	994.85	12.6	32.1	174	193	7.1	0.6	38.97681	-77.4747978	13.9	7.1	265
0.3	994.32	12.53	32.4	178	198	7.2	0.5	38.97681	-77.4747275	14	7.2	266
0.317	993.86	12.45	32.5	182	202	7.3	0.4	38.97681	-77.4746478	14.2	7.3	267
0.333	993.22	12.36	32.6	188	207	7.4	0.3	38.9768097	-77.4745775	14.4	7.4	268
0.35	992.57	12.28	32.9	193	212	7.4	0.2	38.9768	-77.4744975	14.4	7.4	268
0.367	992.23	12.21	33	196	217	7.5	0.1	38.9768	-77.4744175	14.6	7.5	269
0.383	991.6	12.15	33.2	201	222	7.5	0	38.9768003	-77.4743381	14.6	7.5	270
0.4	990.71	12.1	33.4	209	228	7.5	-0.1	38.9768097	-77.4742778	14.6	7.5	271

. . . (101 minutes total)

Figure 5 – GEOG 309 students help launch a scheduled test of new GPS sondes at the NWS Test Facility in Sterling, VA.

Figure 6 – Nick Schmid (QSS) of the radiosonde test group explains the features and operation of a new GPS sonde.
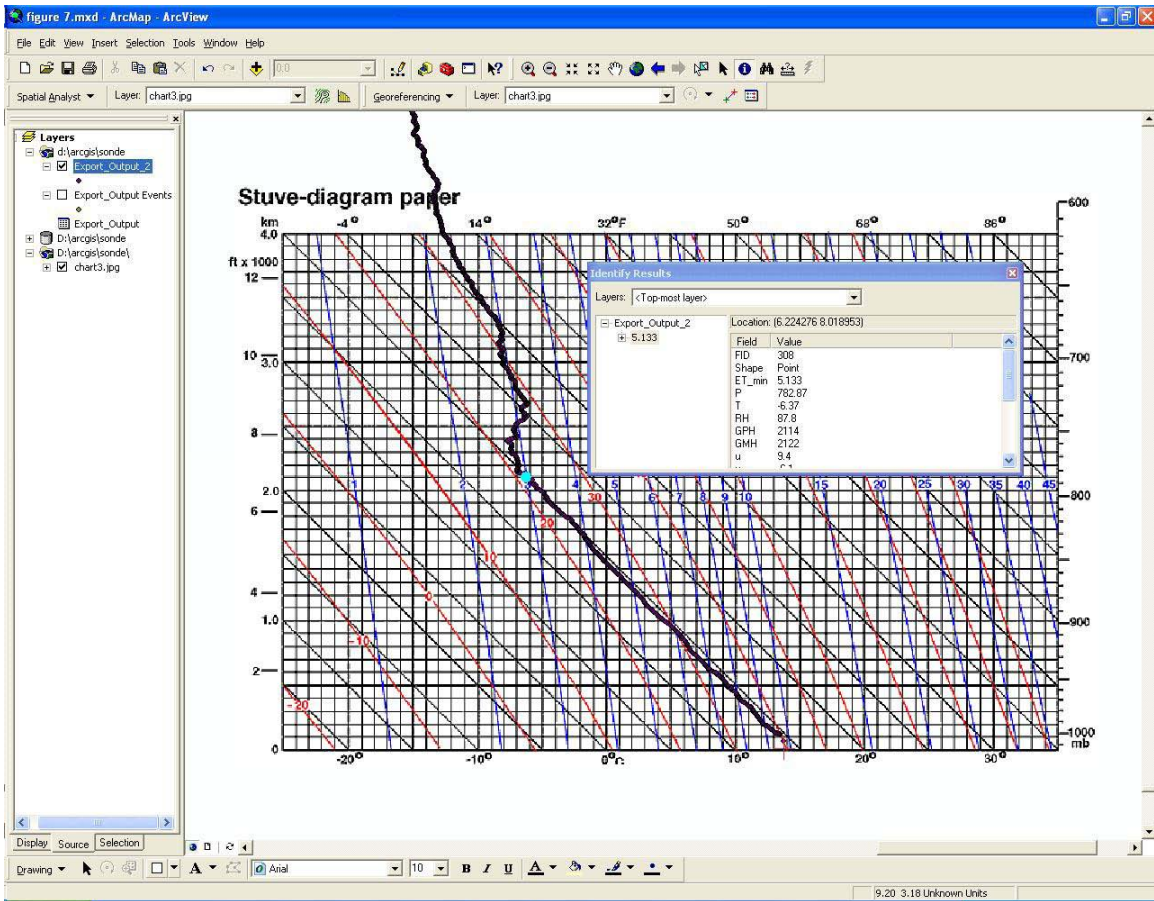

Figure 7 – GPS sonde test launch (sample data from Table 1) plotted on a conventional Stüve Diagram, lower atmosphere only. The point observations are superimposed on a Stüve Diagram jpg image, which is provided online for Glider Pilots, http://www.yorksoaring.com/weather/stuvedia.html. Projection parameters are set for {x, y} units in [C] and [km], and each sounding point has a full set of attributes providing interactive access and queries to the observations. The point at the base of the boundary layer inversion (2122 GMH) is selected, which marks the top of a Cumulus Humulis (Cu) cloud layer at ~ 5 kft. GMH = GeoMetric Height in meters (as determined by the GPS). GPH = GeoPotential Height as determined via the Hypsometric Equation (cf. Stull Eq. 1.18).

4.3 Exercise #3 – Radiation, Sun & Galaxy

Star catalogs and astronomical photographs provide a stunning view of the galaxy from the vicinity of Sol (our star) in Spatial Analyst. Sol orbits the Galaxy's central Black Hole about every 250 MY (million years), and has been around the loop about 16 times since stellar formation, give or take a loop or three. It's as though we're on the minute hand of a grand Galactic Clock, in about the 16th hour. Theories abound linking ice ages and mass extinctions to Solar passage through the Galactic spiral arms (which move about half the speed that Sol does), and/or plate tectonics (Pielou, 1991), or near-stellar collisions with a star named "Nemesis". Cosmic rays are modulated by the Solar magnetic field, affecting Be10 and C14 abundances in tree rings. Sol also appears to have "quiet time" on a regular basis, correlated with periods of cooler temperatures. The impact of all this on Global Climate is in play, with many climate modelers assuming the impacts of extra-terrestrial forcing to be small or even zero. So instead of a figure showing a static map of the Galaxy or our Solar System, what if we could fly through both in space and time? What if we do that in Spatial Analyst? The Chandra X-ray observatory suggests that a supermassive black hole lurks *only* 26,000 light years (LY) away at the center of our Galaxy, which spans about 100,000 LY from edge to edge. 26 kLY = 7,975 kparsec = 2.46 x 1017 km is just another projection.

4.4 Exercise #4 – Satellites

The class now transitions from the orbital mechanics of natural satellites to artificial satellites, especially polar-orbiting satellites with orbital altitudes in the 700 to 800 km range. Satellite position and pointing angles are mapped as points on the Earth Geoid, which are also known in my class as the satellite ephemeris. The concept is shown in Figure 8a (left) for EOS Terra on the Orthographic "World from Space" projection for one day, or approximately 14 orbits. Areas viewed remotely on a surface are modeled as polygons or "granules" – a relatively easy spatial object to create and manipulate in GIS. Profiling sensors, on the other hand, sweep through the atmospheric column providing data for atmospheric volumes which are not rectangular in the z-direction – and are not so easily modeled by GIS at this time. A "match-up" of MODIS granules with *in situ* and numerical model data is depicted in Figure 8b (right), which enables the spatial association of satellite data with independent observations. Going one step further, satellite imagery is mapped onto the granule polygons, as shown for a conjunction of MODIS/AQUA and Windsat over Antarctica in Figure 9. There are usually multiple overlapping images at different wavelengths or "bands" in each granule. The Raster Calculator is introduced at this point and used to difference or compare one band to another. Simple algorithms to extract derived parameters (now known as Environmental Data Records or EDRs) can also be attempted.
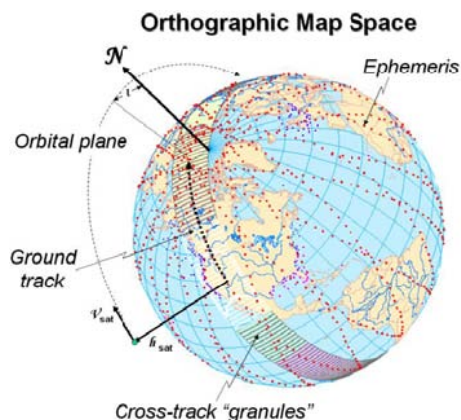

Figure 8a - One full day of satellite tracks for EOS Terra (NASA) as point features (red), from Reed et al. (2004). MODIS granules (30 seconds each) are shown as polygons for an ascending orbit over North America. The inclination angle ι is shown with respect to the Earth Axis of Rotation (North), measured from the northern-most position of the satellite.
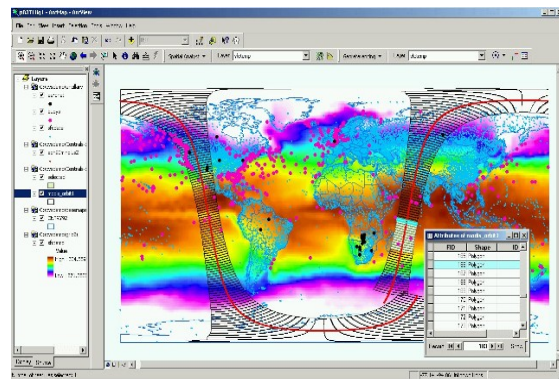

Figure 8b – MODIS granules as polygons for a single EOS Terra orbit on the Geographic projection, from Shipley (2003). The granule polygons allow GIS spatial queries to associate satellite images with in situ (e.g. buoys) and numerical model predictions or analysis (e.g. SST).
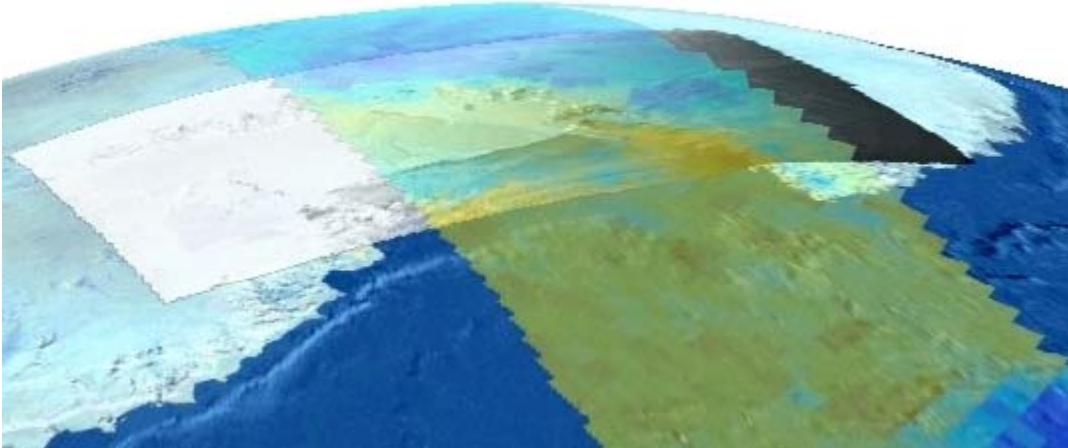
Figure 9 – Windsat (with permission of Peter Gaiser/ NRL) and EOS MODIS/AQUA granules crossing the Transantarctic Mountains, on 12 Nov 03 ~ 1500 ut, draped on ice surface elevation in ArcGlobe. The Windsat 10 GHz temperature in the vertical polarization channel is sensitive to surface ice properties. MODIS Band 31 (~ 11 µm) shows the exact location of the Ross Ice Shelf boundary. Instead of a few "stills" of locations or significant weather/climate events here and there, GIS can be used to tour the World, provided you have enough disk space.

4.5 Exercise #5 – Clouds & skew-T logP Charts

This is a work in progress. My own four kids taught me the value of doing things by hand. The problem with computers in the classroom is that you can click a button and most of the real work is done for you. If you don't actually do it, you'll probably forget it. I call this ***The Calculator Effect***. So I make the class draw at least one sounding by hand, or labor with Excel to achieve the same end. They universally loathe this exercise. After that, we can let the computers do the dirty work and maybe we'll appreciate it.

So consider the skew-T logP chart in Figure 10. What if we reverted to T-logP, and set up a thermodynamic projection in ArcMap? Plotting a sounding in ArcMap would be easy and similar to Figure 7. The pressure and temperature grid would be pre-defined polylines.   The remaining lines shown on the chart are dry and wet adiabats, and lines of constant saturation mixing ratio (g H2O per kg of dry air). Formulae for these are provided by Stull (2002). The same applies to Figure 7. These figures are great for solving the problem I call "The Cloud Goes over the Mountain" (Ex. 5,6 in the GEOG 309 syllabus).

4.6 Exercise #6 – Radar & Precipitation

This is one of my recent areas of interest – using GIS to support siting of National Weather Service NEXRAD and other radars, see Shipley (2005a). Procedures and open source for weather
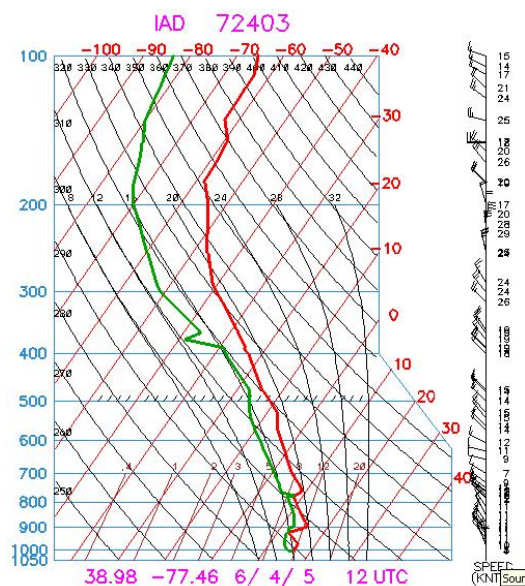

Figure 10 – Skew T – logP sounding for IAD (Sterling, VA) on 12 ut, 4 Jun 05. This is about the same time as the image in Figure 2a, and was released from the same location shown in Figure 5. http://www.arl.noaa.gov/ready.html.

radar data decoding are provided through the GMU Dept Geography at http://geog.gmu.edu/projects/wxproject/. This activity is documented in the literature. An exercise which estimates radar coverage blockage due to terrain occultation is easily accomplished, as shown in Figure 11.
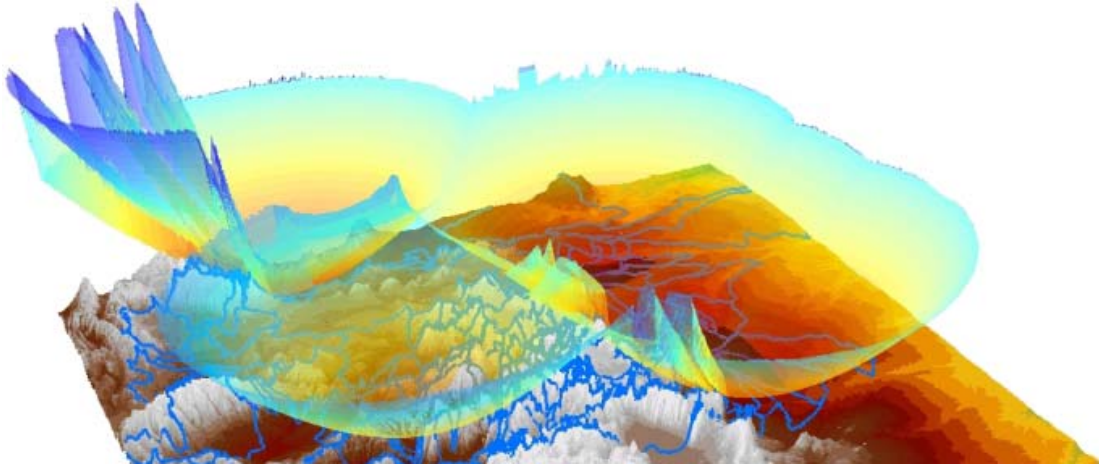
Figure 11 – Lowest sample volume possible for NEXRAD mosaic over Northern Colorado. Radars clockwise from upper left are KRIW (Riverton, WY), KCYS (Cheyenne, WY), KFTG (Denver/Boulder/CO), KPUX (Pueblo, CO), and KGJX (Grand Junction, CO). The NEXRAD radar scans at an elevation of 0.5 degrees above the local horizon, then steps up to the next elevation ~ 1.5 degrees, etc. Areas where local terrain blocks the beam are at risk for flash floods without warning. Such risk is usually mitigated by the placement of real-time rain and stream gages. Shipley (2005a).

4.7 Exercise #7 – Numerical Models

This activity is at once the easiest and the hardest to accomplish. Once numerical model grids are converted to rasters or GRIDs, they are *GIS-Ready* and are easily classified, analyzed (contouring), compared, combined, draped, etc. The biggest problem, however, is getting these data into a *GIS-Ready* form in the first place. There are several data formats for model grids, and the conversion to GIS usually requires Spatial Analyst. Early experiments with AV3 are shown in Figure 12a, where the Map (now Raster) Calculator is

used to produce derived parameters. Such parameters derived by GIS are identical to the same fields provided with the original GRIB file, to within 5 significant digits. Spatial analyst is particularly useful when addressing pressure gradients, flow of air around High and Low pressure centers, and other facets of constant height or constant pressure surfaces. As shown in Figure 12b, a low pressure center in the Southern Pacific actually appears as a "depression" in the 850 hPa surface, with air circling into this hole (much like a drain) in a clockwise direction as expected in the Southern Hemisphere.
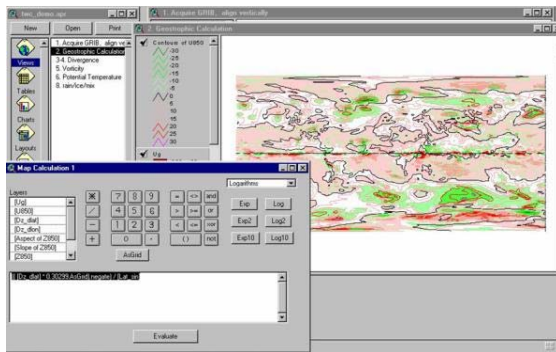

Figure 12a – The Raster Calculator proves useful again for extracting derived parameters from the five basic model state variables {p, T, q, u, v}. Shown here is the derivation of Geostrophic Wind Speed (east-west or "u" component) in ArcView 3, using the Geostrophic Wind equation from Stull (2002). Additional formula were tested for Divergence, Vorticity, Potential Temperature and a decision tree for rain/ice.
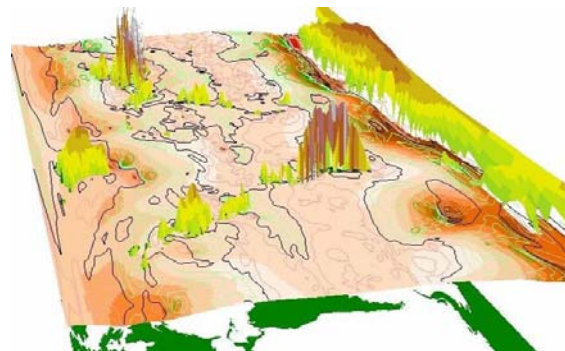

Figure 12b – East-West component of geostrophic wind on 850 hPa [mb] height surface from the MRF global model (1-degree lon/lat resolution). 3D Analyst is used to show topography of the 850 mb surface. A global terrain model is included to show where the 850 hPa surface is below the surface, but we all know that "air does not flow through rocks" (easily). Reprinted from Shipley et al. (2000).

4.8 Exercises #8 through #10 – Severe Storms

There are fantastic resources available for GIS examination of severe storms including Thunderstorms, Lightning, Tornadoes, and Tropical Cyclones (*aka* Hurricanes in the U.S.). Besides the usual GIS actuarial enumeration of frequency and statistics of severe weather incidents and injury/loss by State, Country, etc., more detailed databases are available for a more scientific look at these phenomena. Two web-enabled ArcIMS sites have recently emerged courtesy of NOAA's National Weather Service, namely the Tornadic Information Mapping Service (TIMS), http://nwshqgis.nws.noaa.gov/website/tornadopath/viewer.htm, and the Emergency Manager Hurricane Site, (EMHURR, Experimental)

http://nwshqgis.nws.noaa.gov/website/emhurr/viewer.htm. A superb operational site for Tropical Cyclones is supported by the US Navy at http://www.npmoc.navy.mil/jtwc.html. GIS can combine Weather Service Bulletins (Watches and Warnings) as polygons, with satellite imagery, radar, lightning, surface observations networks/mesonets and other devices of opportunity to provide a unique view of nature "as observed", to be distinguished with "as modeled". Nature is always surprising us, and modelers will always be trying to catch up (my opinion). An Atmospheric Data Model case study using ArcGlobe is shown in Figure 13.
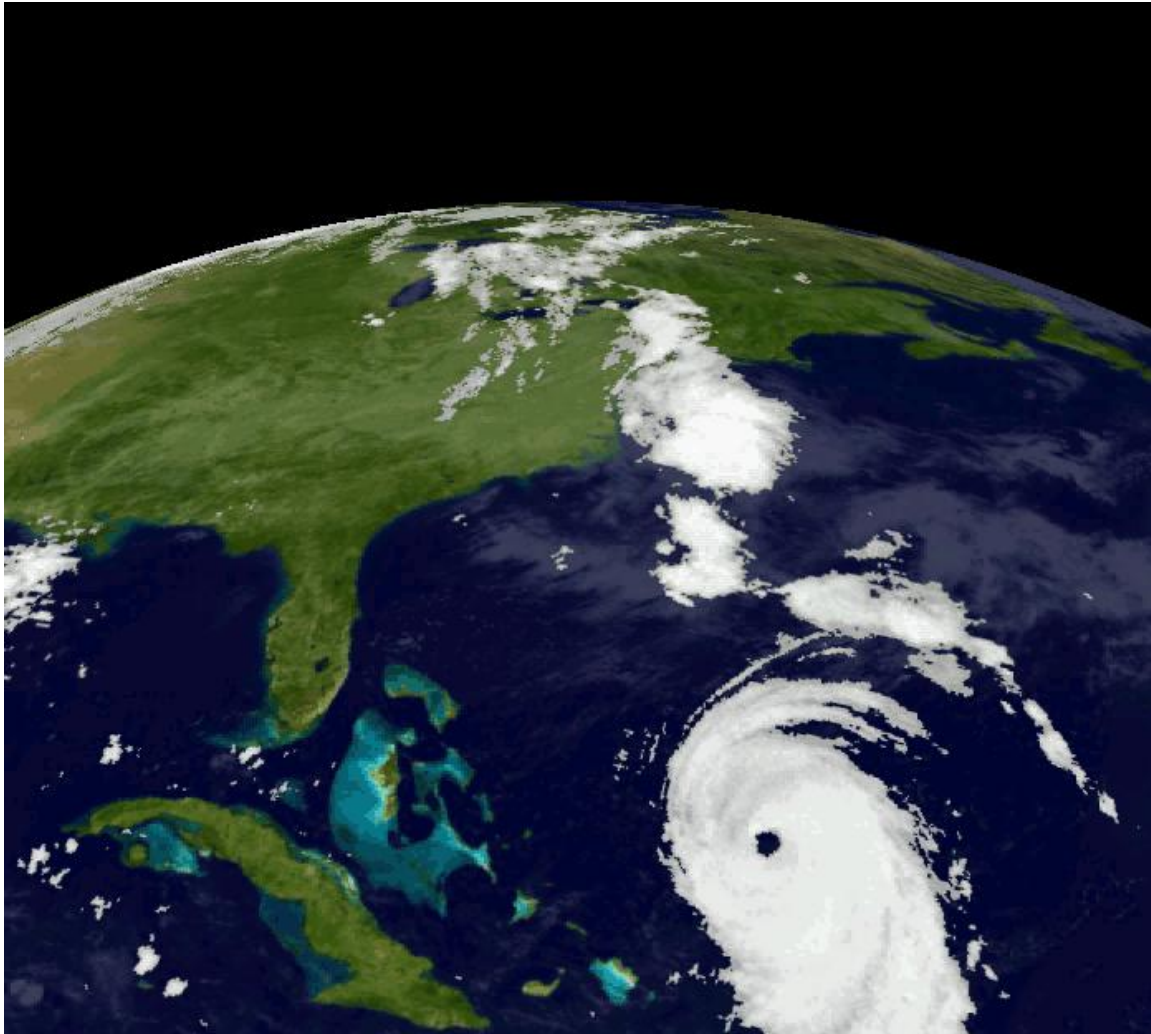

Figure 13 – ESRI Hurricane Isabel ArcGlobe Case Study, Atmospheric Data Model, based on meteorological data provided by NOAA's National Weather Service. AVI, ArcMap/ArcGlobe documents, and data are available at
http://support.esri.com/index.cfm?fa=downloads.dataModels.gateway.

4.11 Exercise #11 – Climate Change & Ice Ages

Ice melting, oceans rising over 100 meters in the last 20 kY, with rapid inundations at 14.2 ka (CRE-1, about 12,000 BC), 11.5 ka (CRE-2, about 9,500 BC), and 7.6 ka (CRE-3, about 5,600 BC), see note 3. Atlantis supposedly disappears, and the Black Sea Floods. So what's going to happen *The Day After Tomorrow*? Students can use GIS to trace ancient shorelines (neglecting isostatic recovery, so more reliable in non-glaciated areas) over the last 20 kY. They can also estimate sea level rise assuming ALL Antarctic ice melts, then determine where that new shoreline might be, and start saving to purchase property (a joke).

But what's causing all this warming? Is it really manmade CO2? If so, then Mankind truly controls his/her destiny. Is it a Solar cycle? If so, then our future is predestined and there's not much we can do about it. Where in the atmosphere does this warming occur? The so-called temperature record is really a measurement taken near the surface, mostly over land and in the Northern Hemisphere, and mostly near centers of population. If the GW models are correct, we should see warming in the middle troposphere (3 to 7 kft above ground level). But the satellite and radiosonde measurements don't appear to show any warming in the middle troposphere (yet, meaning some people question these observations). Since nearly all of the Introductory Texts listed below argue for the Greenhouse effect, I feel compelled to strike a balance with my students. An alternative explanation has been put forward by several, including R. Pielke Sr., et al. (2002), arguing that the recent temperature rise is related to change in land use/land cover. This concept fits well with my observations of the lower atmosphere taken with lasers from the ground but mostly from airplanes. As shown in Figure 14, a laser (lidar) depiction of aerosol tracers reveals the mixed layer – that air layer which is adjacent to and in thermal/momentum contact with the ground. Land surface changes are lowering the albedo of areas near urban centers, and "heat islands" with higher mixed layers as a result have grown to influence the long-term temperature record at surface stations located nearby. More recently, changes in the microclimate of the surface station environment have demonstrated (yet again) impacts to long-term trends for that station, Pielke and Davey (2005). This was understood long ago, and was explained to me by my professors using data from pre-WWII Germany. It takes a GIS to incorporate detailed surface land use changes, and station location site changes, and couple these with the convective properties and regional transport of heat (latent and sensible) in the urban/suburban atmosphere. Time will tell, but as far as I'm concerned, who needs CO2 to explain the temperature record?
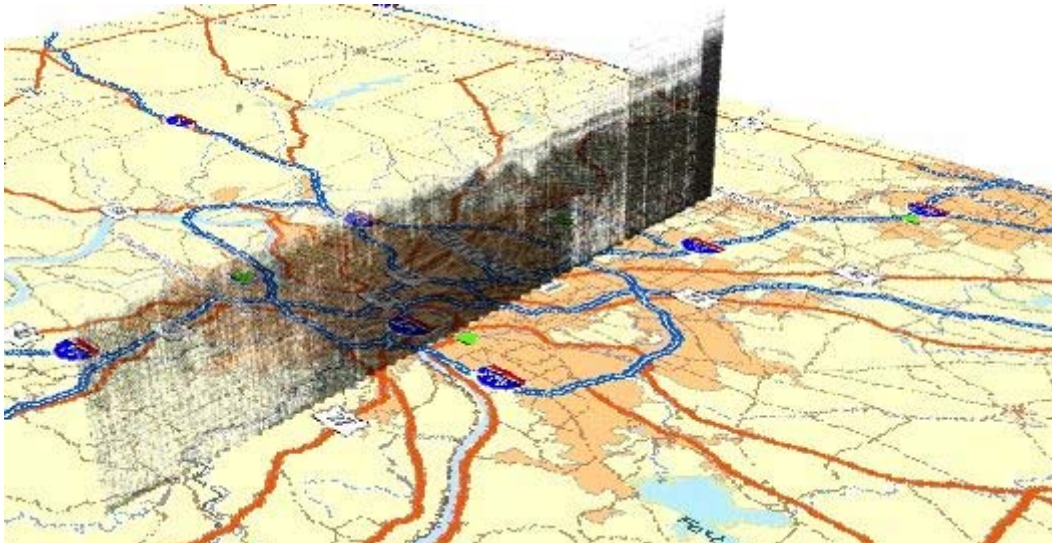

Figure 14 – A "smoking gun". Airborne lidar cross section of the Cincinatti, Ohio urban heat island, on a clear day about 1230 edt on 18 Jul 1980, extracted digitally from Browell et al. (1985). The ambient lower tropospheric wind was Northerly (from the North) at this time. The top of the aerosol layer (black indicates higher aerosol cross section) is capped at about 1500 meters AGL (Above Ground Level), and shows urban material being injected above and transported over a lower rural mixed layer height ~ 800 to 1000 meters AGL. These data are rendered as points (lidar backscatter = f{lon, lat, z}) in ArcScene over a current StreetMap, suggesting significant urban sprawl since 1980. The surface observation locations (green triangles) have probably been enveloped by this urban heat island in the last 25 years. Urban area size appears to matter.

4.12 Exercise #12 – Air Pollution & Air Parcel Trajectories

Finally, the hard-working students of GEOG 309 got a lesson in atmospheric trajectory analysis, but this time we let the computers provide the trajectories. NOAA's Air Resources Laboratory (ARL) provides a unique trajectory analysis capability on-line, which has been in use by Government Labs and Universities in this country and others. This site provides an essential service to the community in the form of Hysplit data, providing estimates and forecasts for the motion path of air parcels, also known as "air parcel trajectory analysis". Trajectories can be used to estimate transport of pollutants from region to region, or forecast the likely path of a volcanic eruption plume. Sample Hysplit data (current format) is shown in Table 2. It is not quite yet *GIS-Ready*, but nearly so. An earlier experiment with Hysplit data using GIS with the 3D-Analyst extension is shown in Figure 15.

Table 2 – Hysplit trajectories format and first set of 15 points, downloaded 25 Apr 05. Use column header "id", "lev", "yr", "mo", "dy", "hr", "t1", "t2", "t3", "lat", "lon", "z", "p".
Height in meters, and pressure in hPa.

```
 1PRESSURE
 1    1    5    4   25   11    0    1    0.0  39.710 -77.730   10.0    965.0
 2    1    5    4   25   11    0    1    0.0  39.710 -79.010   10.0    926.0
 3    1    5    4   25   11    0    1    0.0  39.170 -76.680   10.0    991.4
 4    1    5    4   25   11    0    1    0.0  38.350 -76.450   10.0   1000.1
 5    1    5    4   25   11    0    1    0.0  38.310 -75.120   10.0   1001.5
 6    1    5    4   25   11    0    1    0.0  38.850 -77.030   10.0    992.7
 7    1    5    4   25   11    0    1    0.0  38.550 -78.450   10.0    958.6
 8    1    5    4   25   11    0    1    0.0  37.520 -77.320   10.0    998.5
 9    1    5    4   25   11    0    1    0.0  37.320 -79.970   10.0    946.5
10    1    5    4   25   11    0    1    0.0  36.900 -76.190   10.0   1005.1
11    1    5    4   25   11    0    1    0.0  39.670 -75.600   10.0    993.3
12    1    5    4   25   11    0    1    0.0  39.130 -75.470   10.0    999.2
13    1    5    4   25   11    0    1    0.0  40.190 -76.760   10.0    976.7
14    1    5    4   25   11    0    1    0.0  39.870 -75.230   10.0    993.8
15    1    5    4   25   11    0    1    0.0  36.480 -82.400   10.0    939.8
 1    1    5    4   25   12    0    0    1.0  39.790 -77.486   11.2    960.2
 2    1    5    4   25   12    0    0    1.0  39.748 -78.661    3.2    941.1
```
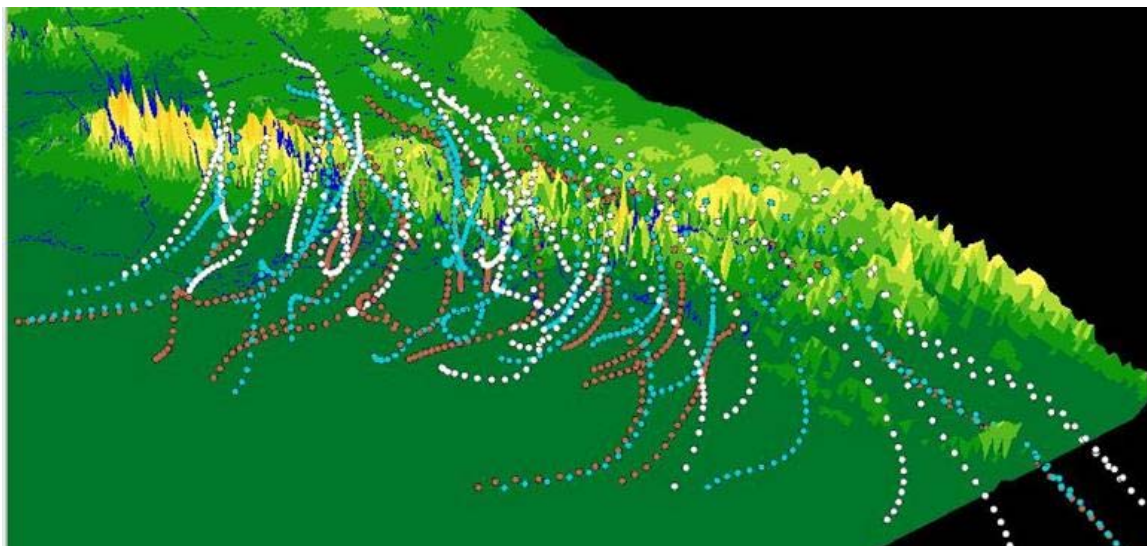

Figure 15 – 24 hour isentropic trajectories from Numerical Model Forecasts, using ARL Hysplit positions for air parcels starting at 500 m AGL (red), 1000 m AGL (blue), and 1500 m AGL (white), starting from locations in the Ohio River Valley on 5 Jan 1999 at 1200 ut. These trajectories indicate the paths that atmospheric trace materials could be expected to take on their way in 24 hours from the Ohio Valley to the Eastern Seaboard. http://www.arl.noaa.gov/ready.html

5. Conclusion

There is much work left to do, especially in visioning how weather and climate data become *GIS-Ready* in the first place. The debut of NetCDF in the next release of ArcGIS is a great leap forward (note 4).

That the Raster Calculator can duplicate calculations for derived parameters found in numerical model grids (GRIB format) and satellite xDRs (netCDF or HDF formats) is a surprise. We usually think that analysis of numerical models and/or satellite observations require high-power workstations and special-purpose software. The greatest challenge is to know what you're doing with these data. This applies to everyone, of course, from those of you who are new to meteorology as well as those of us who should know better. My best advice – keep an open mind and try to keep your facts straight.

If you are interested in helping build the GIS Atmospheric Data Model, visit the following locations:

NCAR Atmospheric SIG Group –
http://www.gis.ucar.edu/sig/index.html
ESRI Data Models –
http://support.esri.com/index.cfm?fa=downloads.dataModels.gateway
Atmospheric Data Model (ADM) –
http://support.esri.com/index.cfm?fa=downloads.dataModels.filteredGateway&dmid=36

This idea that GIS is a useful tool in Climate and Meteorology has been consuming me. I only teach one course a year, and promoting GIS through the vehicle of GEOG 309 has become a passion. My biggest conclusion remains the same: ***An hour spent on a field trip is worth more than 10 hours in the classroom.*** Here's a pic of the GEOG class of 2005 visiting Bob Ryan and Veronica Johnson at NBC Studios (WRC-TV) in Washington, DC. Do more field trips!
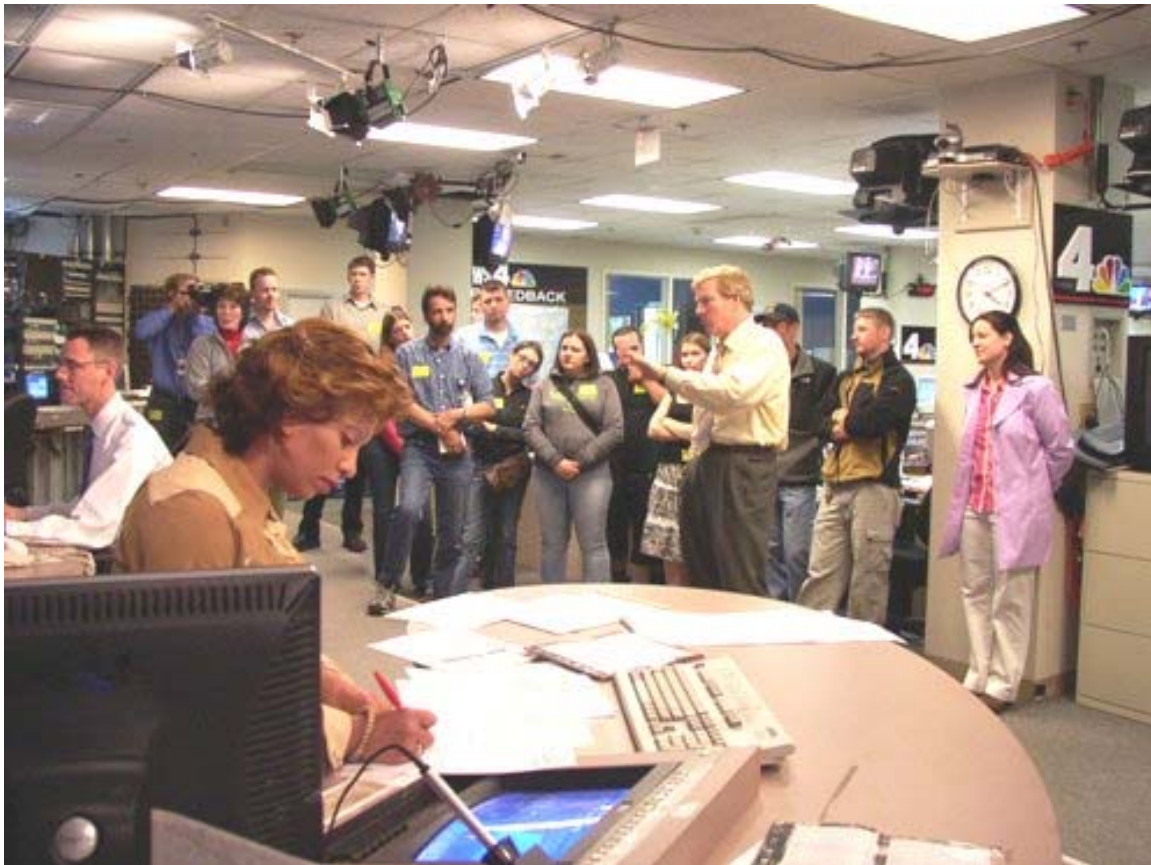

Figure 16 – The GEOG 309 Class of 2005 Visits Bob Ryan and Veronica Johnson at WRC-TV (NBC Affiliate) studios in Washington, DC. A favorite.

6. Disclaimer

Opinions expressed in this paper are the personal and professional opinions of Dr. Scott T. Shipley, and should not be construed as the opinions of George Mason University, the GMU Department of Geography, or Environmental Resources Technologies (ERT).

7. Acknowledgements

I want to give special recognition to the students of GEOG 309 at GMU, the IT staff of Innovation Hall, and the Dept of Geography, especially Sergei Andronikov and Na Liu, ESRI early promoter David Beddoe (now with IBM), Raytheon and ERT for recognizing the value of community service in teaching. Thank you.

I also acknowledge the contributions of the following individuals who helped or inspired this effort: Roger Shriver, Ira Graffman, and Joe Facundo, NWS. Joe Fiore and Paul Oosterhout – ASOS. Nick Schmid, Paul Rockwood and Jim Fitgibbons – GPS sondes. Bob Saffle and Steve Ansari – Radar. Bob Ryan & Veronica Johnson, WRC-TV4 (NBC Affiliate), Washington DC. Steve Zubrick, Science Operations Officer (SOO), KLWX WFO, Sterling, VA.

For Global Warming, special thanks to Fred Singer, winner of the "prestigious" Flat Earth award (http://www.flatearthaward.org/), who took the time to address the class of GEOG 309 in 2005, and patiently argue his position with Donna (2005 class member).

8. End Notes

Note 1 – "The Emperor's New Clothes", by Hans Christian Andersen (1805-1875), in **Eventyr, Fortalte for Børn** (Tales, Told for Children, vol 3, 1837). Opportunistic tailors (developers, entrepreneurs, …) convince a gullible emperor (administrator, CEO, …) to commission a new set of clothes (software system, process, standard, …) made of imaginary fabric. The emperor and subjects are unwilling to admit their error, and parade the new clothes until a child declares the obvious. I often use fairy tales and citations to literature and film to convey points and concepts, but many students appear to be unaware of these stories. "Kids – what's the matter with kids today?" (note 5)

Note 2 – Introductory meteorology texts without calculus, customary for a descriptive review of the field, terminology, and each professor's favorite opinions on current issues. All texts are similar in structure and content, since they are driven by the subject matter. Figures 2a and 2b usually appear in the first chapters:

Figure 2a (left) Figure 2b (right)

Aguado & Burt (2004), 2nd Ed., Pearson/Prentice Hall 1-3 1-13
Ahrens (2005), 4th Ed., Thomson Brooks/Cole 1.10 1.11
Ahrens (2003), 7th Ed., Thomson Brooks/Cole 1.12 1.13
Danielson, Levin & Abrams (2003), 2nd Ed, McGraw Hill 1.17(a) 1.18
Lutgens & Tarbuck (2004), 9th Ed., Pearson/Prentice Hall 9-20/22(a) 9-20/22(b)
Moran, Morgan & Pauley (1997), 5th Ed., Prentice Hall 1.7 1.3

Note 3 – CRE is a "Catastrophic Rise Event", during which Pleistocene and Holocene sea levels are postulated to rise 5 to 15 m in about 100 yr. Such high rise rates are controversial. For a discussion and references see
http://sofia.usgs.gov/publications/papers/geomorph_keys/paleo.html.

Note 4 – At the time this paper was submitted, support for netCDF is planned for release with ArcGIS 9.2.

Note 5 – Bye Bye Birdie (1960).

Addendum 11/05 – I highly doubt that these exercises are "comprehensive". They are indeed challenging. The author highly objects to the increasing limitations attached to images, text and data in the name of an "ownership society". This practice limits access to knowledge by those who can afford it. Therefore, the author's images, data and techniques are hereby released to public domain. The GNU license is herein invoked to protect this material from resale.

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