Spatial Analysis -An Antarctic Example (for ArcGIS v. 10)

I. Goal
To learn to use ArcToolbox Spatial Analyst and 3D Analyst tools, as they apply to digital elevation models and rasters derived from them, to answer some simple questions and produce attractive maps.

II. Problem
What does Antarctica look like beneath the ice? A continent of mountain ranges, deep valleys, plains, inland seas, offshore islands and the like exists there, for the most part invisible but for a few features that protrude above the ice. Wouldn't it be nice to have a topographic map in shaded relief of Antarctica without the ice and with oceans filling areas that are below sea level? Wouldn't it be even nicer to have such a map that accounted for the isostatic rise of the land surface that would occur after the weight of the ice was removed? What would the continent look like if sea level rose by an amount equal to the volume of the water locked up in ice? How much ice is there? Digital data are available to make such maps and answers these questions, as is software to do so. Let's have a crack at it!

III. Data
Data for today's lab came from two web sources:
1. The Antarctic BEDMAP project
2. The Scientific Committee on Antarctic Research (SCAR) Antarctic Digital Database, version 3 (ADD v.3, 1:5,000,000 coverage).

BEDMAP provides rasters of Antarctic bedrock elevation and adjacent ocean floor bathymetry, of Antarctic ice thickness, and of Antarctic surface elevations. These rasters are provided in ESRI "Grid" format, ready for immediate use!

ADD v.3 is the source of 1:5,000,000 scale vector files that define the coastline of the continent and its ice shelves, areas of rock outcrop, glacial flow lines and point features with names. These data are stored in ESRI coverages, also ready for immediate use. Metadata describing how the data were created are available at the web sites and within metadata files viewable in ArcCatalog.

N.B. The SCAR data used in this lab is not the most current version. Downloads from the link above will provide such, but not at scale of 1:5,000,000. This lab is written to use the version 3 data sets, which are provided through a link below.

Data are stored in folders and sub-folders with the following formats and file names:

5 km x 5 km Raster Grid Files:

- ***bed_elev*** – a raster of orthometric elevations (see the metadata for a description of the vertical datum) for Antarctica bedrock and the surrounding ocean floor.
- ***ice_thick*** – a raster of ice thickness for Antarctic ice sheets and ice shelves.
- ***surf_elev*** – a raster of orthometric surface elevations of Antarctica.

Coverages (scale 1:5,000,000):

- ***coast05*** – a polygon coverage of Antarctica and the permanent ice shelves
- ***cont05*** – an arc coverage showing 500 meter contours of elevation
- ***gflow05*** – an arc coverage of flow lines for ice streams and glaciers
- ***rock05*** – a polygon coverage of rock outcroppings

Shapefile:

- ***SouthPole.shp*** – a point shapefile that contains the location of the South Pole.

Layer file:

- For your convenience, vector data have been grouped, symbolized, and stored as a layer file named ***ADD_v3_vector_layers.lyr***. Adding this layer file to your map saves having to individually load and create symbology for each of the vector layers.

The data sets for this exercise can be downloaded at **https://webspace.utexas.edu/wg3486/geo-webfolders/helper/www/Cutting_Edge**. Copy the entire "Antarctic_data" folder (zipped file, ~28 Mb) to your storage space and unzip it. If need be, use ArcCatalog to move or copy these coverages and grid files to other folders; do not use Windows Explorer.

A. Spatial Reference

A glance at the metadata shows that all data are stored in a Projected Coordinate System (PCS) with the following parameters:

PCS Type: Stereographic -South Pole
Units: meters
Latitude of Origin: -90.000000 (South Pole)
Central Meridian: 0.00000 (Prime Meridian)
Standard Parallel: -71.00000
False Easting: 0.00000
False Northing: 0.00000
Datum: WGS84

There is a predefined Projected Coordinate System (PCS) that matches this in ArcMap (i.e. "WGS 1984 Antarctic Polar Stereographic"); one could also be created by modifying an existing PCS. As practice, do this now:

1. Open a new map in ArcMap;
2. Right-click the "Layers" Data Frame heading in the Map's table of contents (TOC);
3. Select "Properties..." and then the "Coordinate System" tab;
4. From the area showing folder icons, select the coordinate system on the path: *predefined>Projected Coordinate Systems>Polar>South Pole Stereographic*

Note that the parameters of this PCS do not quite match those given above. With the South Pole Stereographic projection selected, modify this PCS by:

5. Clicking the Modify button;
6. Enter a new name (e.g. SCAR Antarctic Projection)
7. Select Stereographic_South_Pole from the drop-down menu of the Projection name;
8. Edit the Standard_Parallel_1 to read -71.000000.
9. Click OK and then the "Add to Favorites" button to make this PCS readily available for later use.

If you can't get this to work, simply loading any of the Antarctic data into ArcMap will also set the PCS, as the Data Frame will take on the coordinate system of the first file loaded and project everything else with a different PCS on-the-fly (in this case all data have the same PCS so on-the-fly projection is not needed). The PCS could also be imported from one of the data files using the "Import..." button in the Coordinate System tab of the Data Frame Properties.

IV. Procedure

The procedure we will follow involves the following general steps:

1. Create color, shaded relief maps of Antarctica and of Antarctic bedrock elevations. The bedrock elevation data we have includes offshore bathymetry that we would like to remove (or mask, i.e. hide), and both data sets need to be rendered with color ramps to show elevation.
2. Render Antarctic bedrock regions presently below sea level in blue. Use the raster calculator to construct a binary raster which can be symbolized as blue or transparent and overlain on the bedrock elevation map. We'll also create a zero elevation contour line from the bedrock elevation map to outline shorelines of the regions above sea level.
3. Calculate bedrock topography after it has rebounded from ice removal. Using the raster calculator, we will make a new bedrock elevation raster that accounts for isostatic rise. A new water raster will be constructed and rendered as above.
4. Calculate the volume of water locked up in Antarctic ice sheets and shelves. Use published sea level rises that result from melting of the ice to make a bedrock elevation map showing water in areas that would be below sea level.

We begin by first exploring the data.

A. Explore the Data

1. Open up ArcMap and add the layer file *vectors_Layers.lyr*, which is on the path *//SCARv3/scale1-5M*. Permanent ice shelves and ice tongues are in blue, land is outlined in black with no color, outcropping rock is shown in yellow and South Pole is a red dot, as shown below.

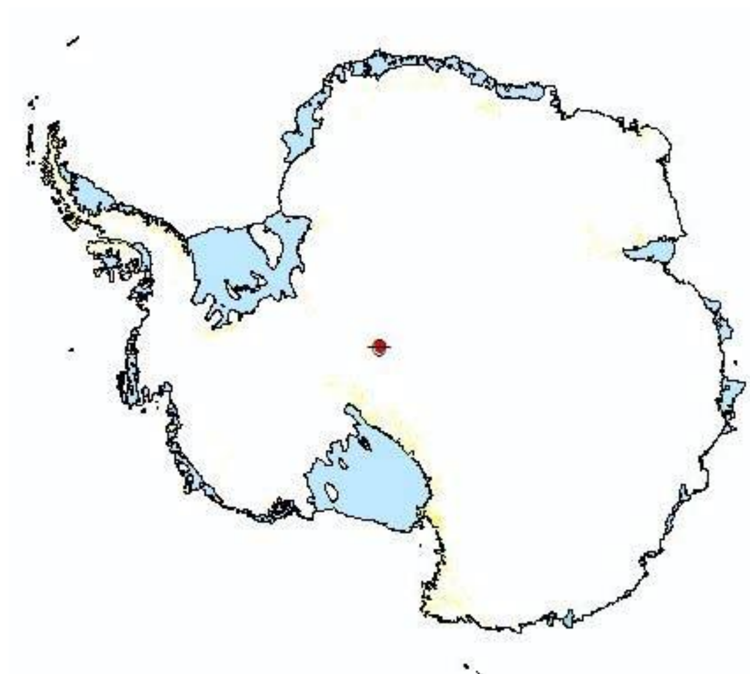


Figure 1. Antarctic vector layers.

2. Add the *surf_elev* grid. The default is a display that "stretches" the elevations along a continuous grayscale "Color Ramp", showing sea level (0 m) as black and the highest elevations as white, with the remaining 254 shades of gray representing intermediate elevations. The way in which the intermediate elevations are matched to one of the 254 shades of gray is given by the "Stretch Type" which can be changed through the Layer Properties Symbology tab. Experiment with the Stretch Type to get a feel for how the data can be displayed differently in grayscale.

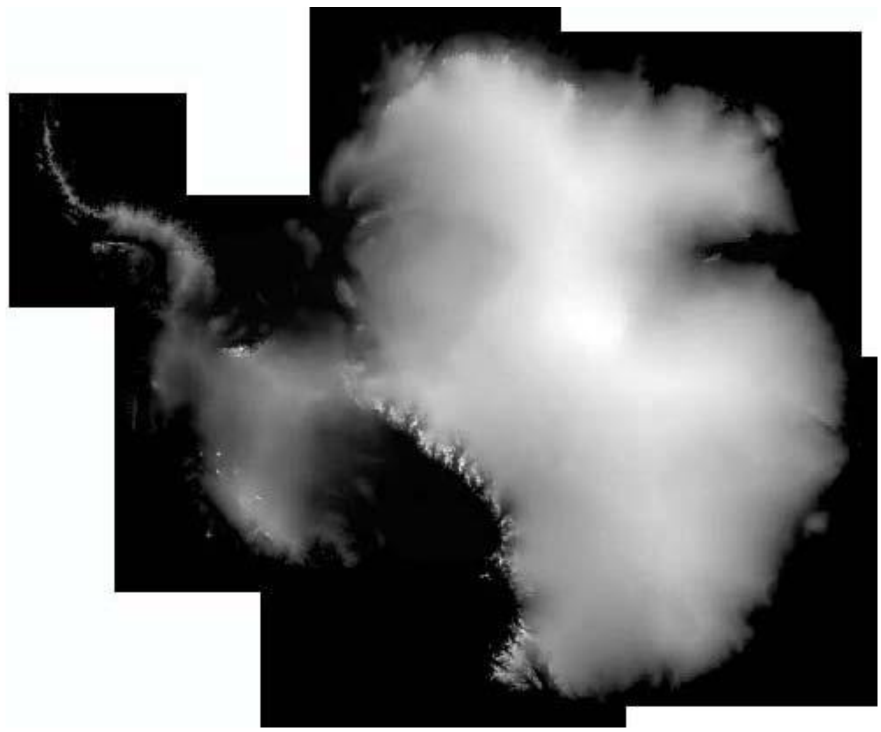


Figure 2. Antarctic surface elevation raster, displayed with default symbology.

Question 1: What is the resolution (in kilometers), data type (integer or floating point), data depth (in bits) and number of bands of this raster data sets? Answer this question by filling in the chart below:

Raster Layer	Resolution (km)	Data Type	Number of Bands	Data Depth (bits)

Question 2: What are the Mean, Maximum and Minimum elevations of the Antarctic continent?

Question 3: What is the Default Stretch Type when the *surf_elev* raster is first loaded?

3. Change the Symbology of the elevation raster to "Classified", click the "Classify..." button in in the Symbology tab, set the "Classification Method" to Defined Interval with an "Interval Size" of 200 (this will group elevations by 200m intervals), as in Figure 3 below. Click OK and select a "Color Ramp" from the Symbology tab (tip: Color Ramp names are accessible by right clicking on the color ramp and turning off the check mark next to the "Graphic View" option.) The Symbology tab should look like the one shown below.

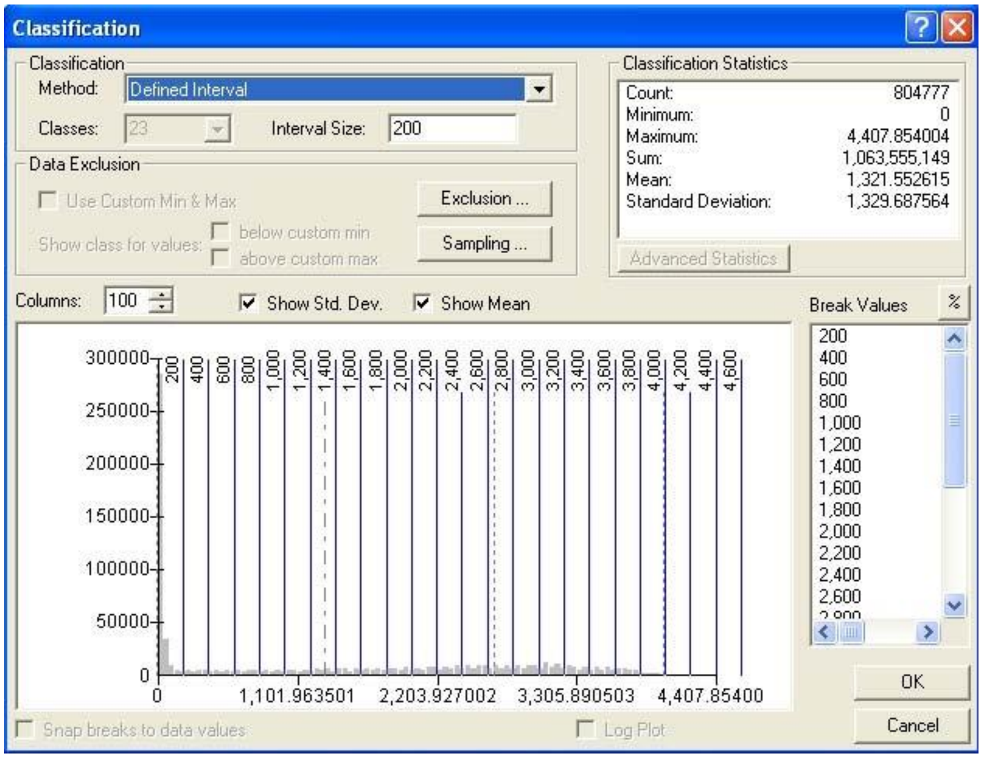


Figure 3. The classification of elevations by 23 equal intervals of 200 meters.

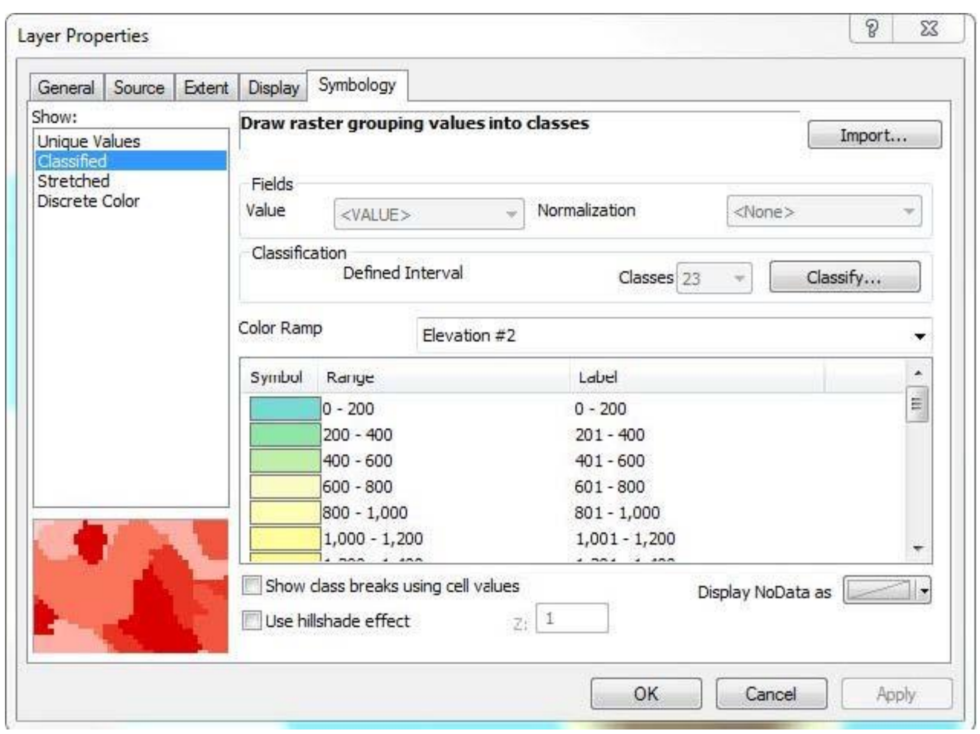


Figure 4. The symbology tab, with elevations classified at 200 m intervals and symbolized with the Elevation #2 color ramp. Clicking on "Label" will allow formatting of the labels to show no decimal places, as seen in the Label field above.

The resulting symbolized map should look like Figure 5 below.

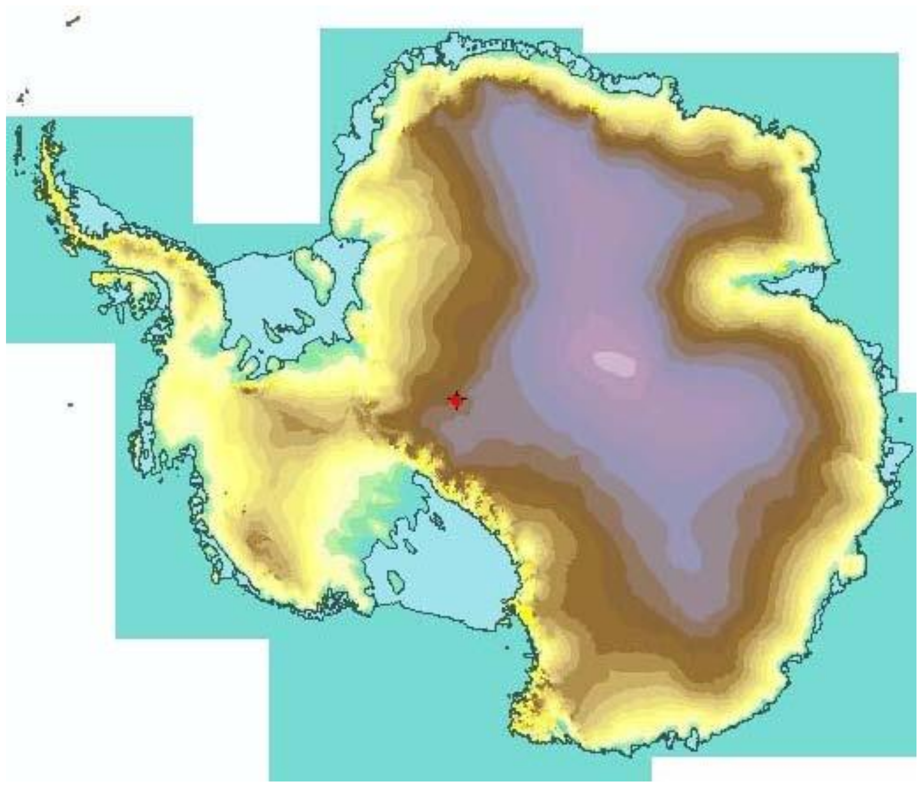


Figure 5. Antarctic elevations classified at 200 m intervals and symbolized with the Elevation #2 color ramp. Vector layers overlie the elevation raster.

This is just one of many ways to display the elevation raster. For appearance sake it would be nice to eliminate the irregular background that defines the boundary of the data region (the area displayed in teal color above, at zero elevation). We could selective symbolized, by classification, all areas of zero elevation with no color (e.g. using the Exclusion button in the Classification window and excluding 0), but there is a better, more permanent way!

B. Spatial Analysis -Environment Settings

1. From the menu bar at the top of at ArcMap, turn on the Spatial Analyst and 3D Analyst extensions ("Customize">"Extensions..."; check the boxes). This step is needed to have working Spatial and 3D Analysis tools in ArcToolbox. Even with our ArcInfo license, some of the tools used below will not work without this initial step.
2. Make a new folder in your Lab_7_data folder to store your new elevation grids. The folder name should be less than 13 characters long, with no spaces or special characters; e.g. use the name "*New_Grids*". Spatial analyses of raster data generally produce new raster datasets. It is very helpful to have a special folder to store them; they are otherwise easily corrupted and/or lost. Keep this important step in mind for future work. This folder will become your "working directory" for all spatial analysis in this lab.
3. Open ArcToolbox from within ArcMap and expand the Spatial Analyst Tools toolbox.

Our first analysis task, eliminating the irregular background region from our raster, will be done with an Extraction tool: "Extract by Mask". This will make a new raster with elevation values only within the area of our **Analysis Mask.** An Analysis Mask defines a region where an analysis will be performed -any raster cells outside of the mask are ignored during the analysis and, upon creation of the new raster, are given "no data" values. The "no data" cells can be rendered "invisible" by making them transparent. An Analysis Mask can be created from an existing raster (see Desktop Help, analysis mask), or a vector polygon layer can be used instead. We wish to restrict our analysis to the region within the coastline of Antarctica, so we'll use the *coast05 polygon* (a.k.a. *"5M coast polygon"*) coverage as our mask.

One last word on Analysis Masks**...** ***all spatial analyses using masks require that the mask have the same Spatial Reference of the raster being analyzed***. Such is the case in the procedure below, but this is a common stumbling block for novices. Keep it in mind for future work.

4. From within the Spatial Analyst Tools toolbox expand the "Extraction" toolbox and open the "Extract by Mask" tool.
5. Click the "Environments..." button at the bottom of the window. The "Environments..." button is available for every tool in ArcToolbox. The options here are numerous; those listed below are particularly useful for raster analyses:
    a. Expand the "**Workspace**" option and set it to your "*New_Grids*" folder (see Fig. 6 below). This ensures that results from your analysis will be sent to this folder.
    b. The "**Processing Extent**" defines the area of an analysis; when performing overlay analyses (involving more than one raster) it can be set so that results are restricted to the region where rasters overlap ("Intersection of inputs"; the default) or to the entire region of rasters ("Union of Inputs"). We will accept the default Extent ("Default"), which does not restrict the analysis to a particular region.
    c. The "**Cell Size**" option specifies the raster cell size (resolution) of any new raster created during analysis. It is hidden in the "Raster Analysis" option. With analyses using two or more rasters, it is always best to set this to "Maximum of Inputs" (the default) so that the new raster does not have cells smaller than any of the input rasters (this is the conservative approach; it does not require resampling of one or more of the input rasters). Leave this set at "Maximum of Inputs".
    d. A "**Mask**" setting is also available in the Raster Analysis options. In this case it is redundant because the "Extract by Mask" tool lets us explicitly set the Mask, doing the same thing as this option. Setting a Mask here before doing any other kind of analysis avoids having to first use the Extract by Mask tool and is thus a very useful option.
    e. Set the Environment settings to those shown in Figure 6 below and explore some of the others by expanding them and reading the Tool Help descriptions.

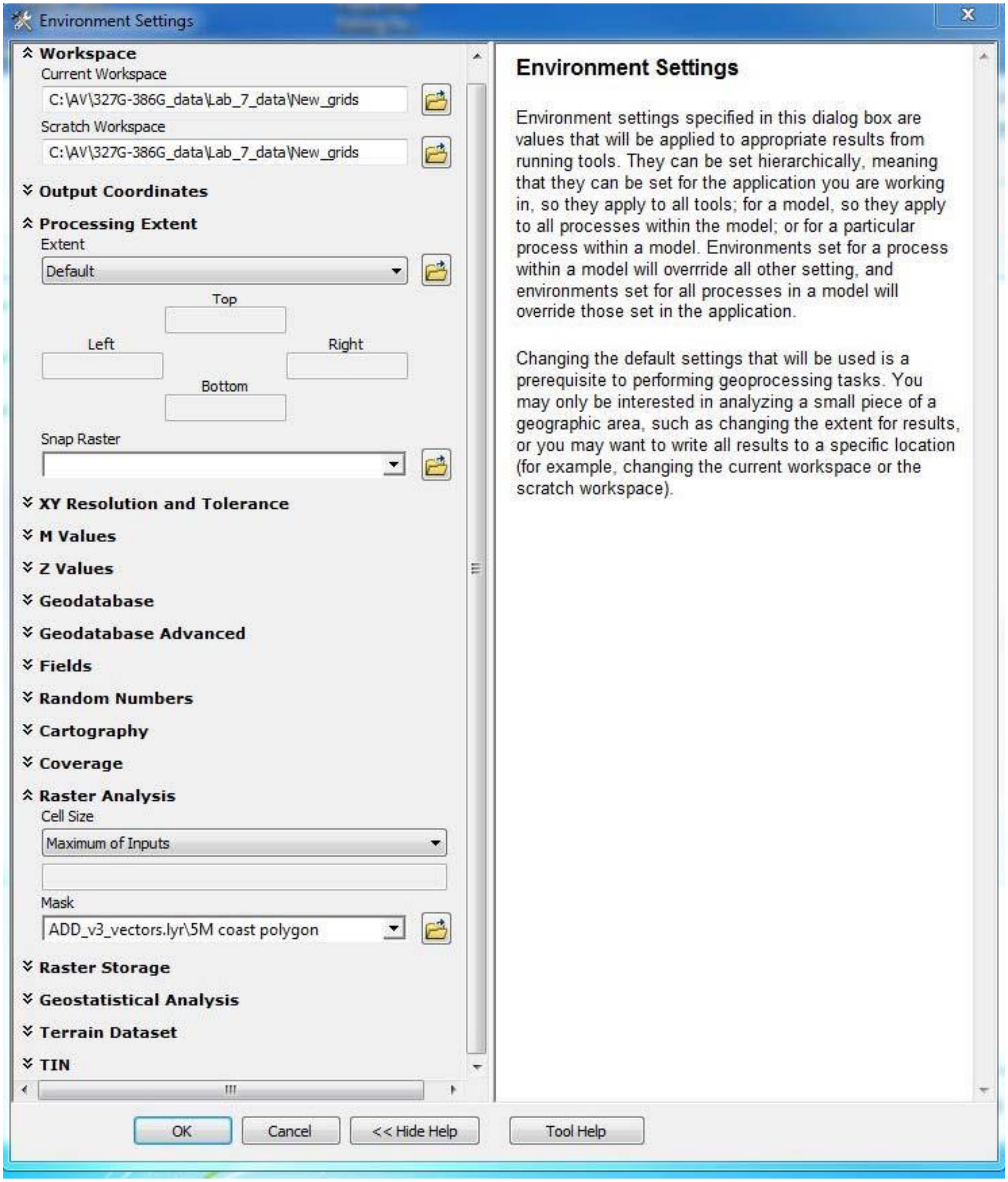


Figure 6. Environment Settings window showing "Workspace", Processing Extent" and "Cell Size" settings expanded and containing entries. Note the general description on the right about Environmental Settings.

C. Extracting by Mask -Clipping a Grid File

1. Within the still open "Extract by Mask" tool, set the input raster to *surf_elev*, set the mask to 5M coast polygon and specify a name for the Output raster that is 13 characters or less with no spaces or special characters (e.g. "*surf_elev_clp*") to be saved to your *New_Grids* folder. Click OK.

The result should resemble Figure 7.

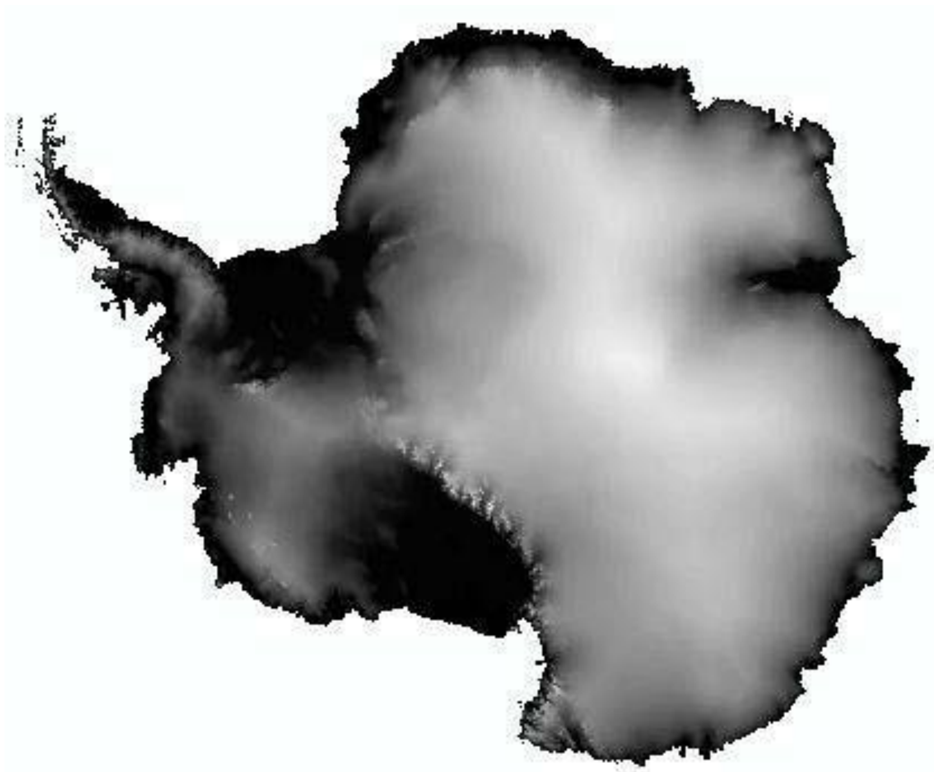


Figure 7. Result of "Extract by Mask" analysis. Compare with Figure 2.

2. Once the tool finishes, the new raster file is loaded into the table of contents. In comparison with Figure 2, note the absence of zero values beyond the coastline; cells are still there- rasters must always be rectangular or square, not irregular like Antarctica. These are now "no data" cells. To see them (they are presently transparent) go to the Symbology tab of this new layer, click the "Display NoData as" button and select a color.

The result, when displayed as 9 equal intervals of elevation, will look something like Figure 8.

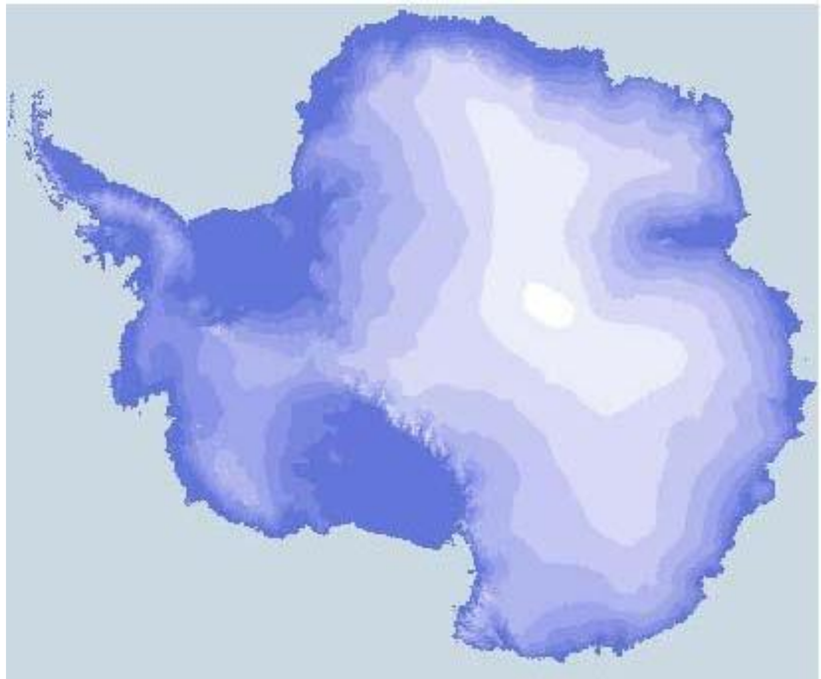


Figure 8. The new elevation raster, showing "no data" cells in gray and elevations classified in 9 equal intervals.

3. Undo what you just did (i.e. display no data as "No Color"), change the symbology to show a Stretched, Standard Deviations Color Ramp that is "Cyan-Light to Blue-Dark" and check the "Invert" box to set the lightest colors to the highest elevations. (The color ramp names - e.g. cyan-light to blue-dark - are visible by right-clicking on the color ramp in the symbology tab and selecting "display names".)

D. Spatial Analysis -Creating a Hillshade Raster

A "Hillshade" is a grayscale raster rendering that shows shadows and highlights to produce a "shaded relief" map. Placing a hillshade behind a grid that is partially transparent makes the grid look three dimensional. To create a hillshade:

1. In the Spatial Analyst Tools toolbox, expand the "Surface" toolbox and open the Hillshade tool. The Input raster will be your new *Surf_elev_clp* raster. The other parameters in this window can be left alone (most are self-explanatory, but see the Help file on Hillshade for details) except for the "Output raster" line. Before clicking OK, the new raster we are about to create needs a name and location - call it *hs_clip_elev* and browse to your *New_Grids* folder. Now click OK.
2. Move the new *hs_clip_elev* raster to the bottom of the Table of Contents, symbolize it with a Stretch Type of 2 (or less) Standard Deviations, turn it on, and make the *Surf_elev_clp* raster 40% transparent.

The resulting map should now look something like Figure 9.

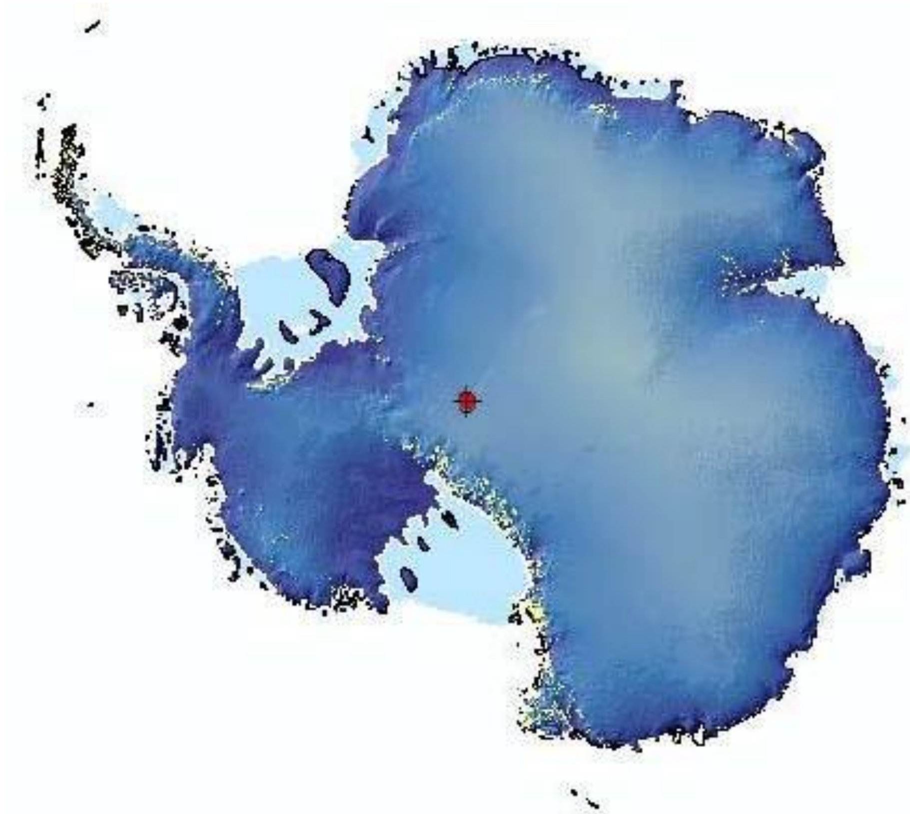


Figure 9. Antarctic topography, rendered with a blue color ramp that is 40% transparent with a grayscale hillshade beneath. The solid light blue areas are ice shelf/ice tongue vector polygons with white outlines that lie on top of the other layers. Yellow similarly shows rock outcroppings.

Question 4: The highest point in Antarctica is the Vinson Massif (a.k.a. Mount Vinson), in the Ellsworth Mountains.

a. Using the *surf_elev* raster, find the cell that contains the top of Mt. Vinson and give its latitude and longitude, *in decimal degrees*. Hint: The selection tools in the Selection menu do not work with raster data, nor is there an attribute table. Change the symbology to highlight cells over 4300 and 4400 meters. To get locations in decimal degrees, you can set the display units of the Data Frame in the Date Frame Properties window.
b. Find the height of Mount Vinson on the internet. What is it? Give a plausible reason why the known height doesn't match the height in our DEM.
c. What is the elevation of the cell that contains the South Pole?

E. Spatial Analysis -Antarctic Bedrock Elevations

1. Add the *bedrock_elev* raster. This raster shows topography beneath the ice and bathymetry of the sea floor to 60 degrees South latitude.
2. As above, "clip" this raster by "Extract by Mask" to the 5M coast polygon coverage. Save it with the name *clip_bed_elev* to your *New_Grids* folder.
3. Create a Hillshade for this new raster, as above, and save it as *hs_bed_elev* in the *New Grids* folder.
4. Symbolize the new raster with a color ramp; the "Precipitation" ramp, inverted, works well for bright colors. Set the display to 40% transparent to allow the bedrock elevation hillshade created in step 3 to show through.

Your result should resemble Figure 10.

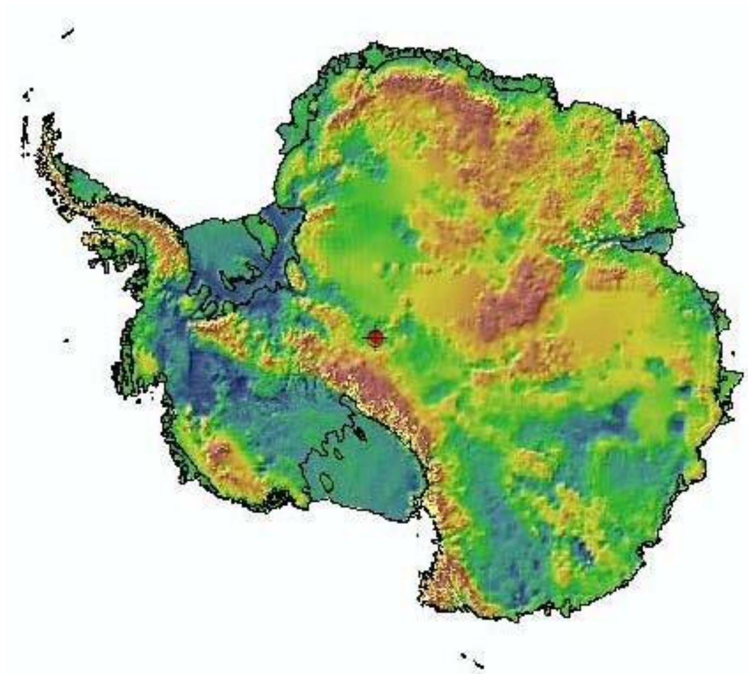


Figure 10. Antarctic sub-ice bedrock topography, including regions beneath the permanent ice shelves. Cooler colors are lower elevations, warmer higher. The solid black lines mark the shoreline of the continent and edges of ice shelves/tongues. Small bright yellow spots mark areas of outcropping rock.

Question 5: What are the mean, maximum and minimum elevations for the continent's bedrock? Hint: View the Symbology tab in the Layer Properties for the *clip_bed_elev* raster.

F. Spatial Analysis -Creating a Binary Raster

What parts of the above map are below sea level, what parts above? We can, of course, symbolize the raster to show this, but it can also be done another way. From the *clip_bed_elev* raster we'll compute a binary raster; cells with values of 1 will substitute for cells that are below sea level, those above sea level will be give a value of "nodata". We can then render the cells with values of 1 as blue (water) and nodata cells (land) will, by default, be transparent, making the underlying *clip_bed_elev* raster visible. To enhance the appearance of "shorelines", we can also produce and overlay a zero elevation contour.
To produce a binary raster, we will use a Conditional Statement in the "Raster Calculator", a very versatile tool in the Spatial Analysis Tools>Map Algebra toolbox. See ArcMap Help (search on "Conditional Statement") to understand the syntax and meaning of such statements. The statement we will use is **Con("grid"<=0,1)**, where "grid" is the *clip_bed_elev* raster.

1. Open the Raster Calculator and construct the expression Con("*clip_bed_elev*" <= 0,1) (see Fig. 11) by a combination of clicking on the calculator buttons and layer names. In the "Output raster" entry area, browse to your *New_Grids* folder and name the output raster *binary_water*. Click OK.
2. Render water areas blue, make the binary raster 50% transparent, and move it above the *clip_bed_elev* and *hs_bed_elev* rasters in the table of contents.

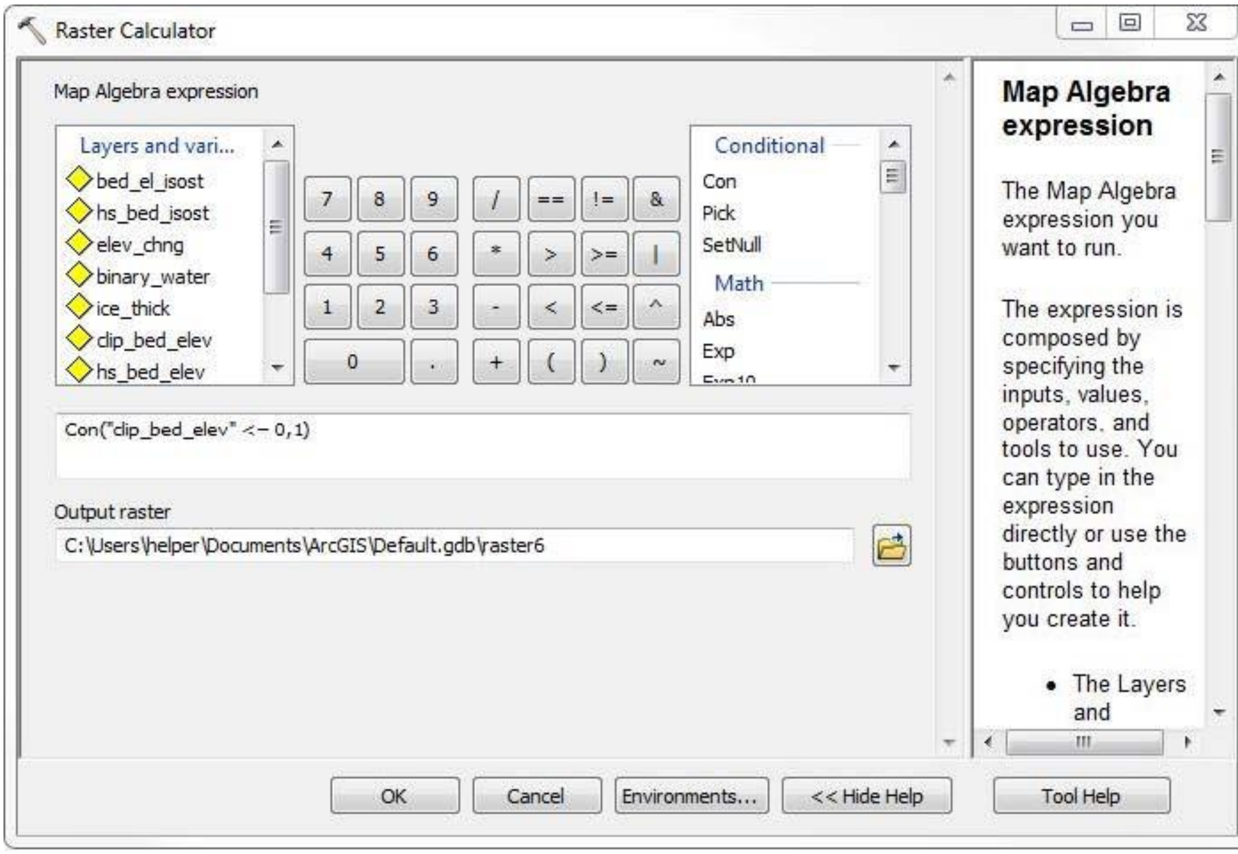


Figure 11. Raster Calculator with the conditional statement for creating the binary water raster from the clipped bedrock elevation raster.

Question 6: Explain, in words that include "if... then…" the meaning of the conditional statement used to generate the binary raster in step 1. Hint: Use ArcGIS desktop help and search "conditional statement" for explanations of similar examples.

G. Spatial Analysis -Creating a Contour Line

1. In ArcToolbox, find the Spatial Analysis Tools>Surface>Contour tool and open it. Set the "Input Raster" to *clip_bed_elev*, the "Output polyline features" to the name *bed_elev_zero_contour* (to be stored in your *Bedrock_elev* folder), "Contour interval" to 4400 (this will produce a single contour, because the highest elevation is 4364 m), the "Base contour" to 0, and "Z factor" (useful when x, y units are different from z units) to 1. Click OK.
2. Symbolize the new contour line in black or dark blue with a 0.5 point line width. Order the table of contents so the contour line is visible.

Your result should resemble Figure 12.

Figure 12. Antarctic sub-ice topography, showing regions below present sea level in blue and a "coastline" (zero-elevation) contour in black. A suggestion of water depth is provided by the selected color ramp and hillshade raster beneath. Looks like a terrific place to go fishing.

H. 3D Analysis -Calculating Ice Volume and Area

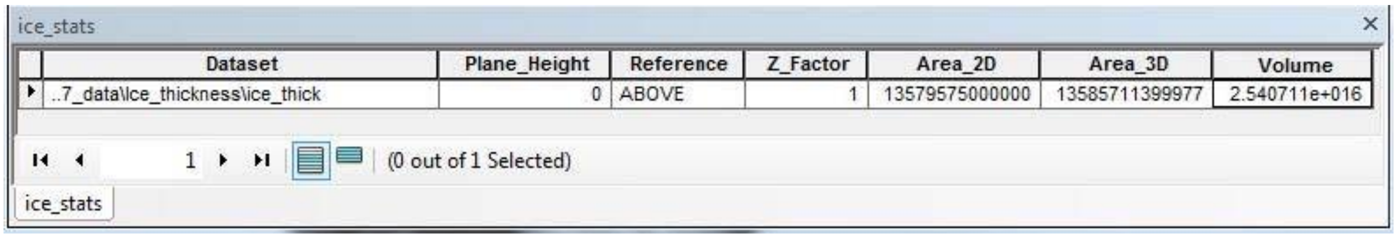
1. Add the *ice_thick* raster to the Table of Contents. This raster has 5x5 km cells that contain ice thickness values ranging from ~4500 to 0 meters. In some ways this raster resembles the bedrock elevation raster but these are not elevations, they are ice thicknesses!

Question 7: Although you were provided this ice thickness raster, you could have created one from the files you've so far worked with. How? Give your answer in a list of steps.

Question 8: How thick is the ice at South Pole? Where (in lat. /lon. decimal degrees) is the ice thickest?

2. If not already on, turn on the 3D Analyst extension (top of the ArcMap window; Customize>Extensions... check the 3D Analyst box) and display the 3D Analyst toolbar (Tools>Customize... check the 3D Analyst box). We will not use the 3D Analyst toolbar in this lab, though it presents several shortcuts to tools that are also available in ArcToolbox. Just thought you should see it and some of the tools available...
3. Open ArcToolbox, go to 3D Analyst Tools>Functional Surface, and find and open the "Surface Volume" tool.
4. In the Surface volume window, set the "Input Surface" to the *ice_thick* raster, the "Output Text File" to a location and name of your choosing (e.g. *ice_stats*), "Reference Plane" to ABOVE, and “Plane Height" to 0, and the "Z factor" to 1.
5. Click OK.
6. The tool creates a table and places it in the Table of Contents. Right-click on the table and "Open" to view the ice area and volume statistics.

The resulting statistics (Fig. 13) give the 2D area (plan view area), the surface area (area of the irregular surface defined by the top of the ice-thickness raster when the base of the ice is assumed to be level), and the ice volume (2D area x sum of all cell values). The units for the results are in the units of the spatial reference, in this case meters.



ice_stats

	Dataset	Plane_Height	Reference	Z_Factor	Area_2D	Area_3D	Volume
▸	..7_data\Ice_thickness\ice_thick	0	ABOVE	1	13579575000000	13585711399977	2.540711e+016

1 (0 out of 1 Selected)

ice_stats

Figure 13. Results of ice area and volume calculation.

Question 9: What is the volume of the Antarctic ice sheet and ice shelves/tongues, in *cubic kilometers*?
Question 10: What is the 3D surface area, in *square kilometers*, of Antarctic ice?

I. Spatial Analysis -Antarctic Topography After Ice Removal and Isostatic Rebound

Like a ship lightened of its load, melting of the south polar ice cap will result in the gradual rise ("rebound") of the underlying continent. The total rise (change in elevation) can be modeled as being directly proportional to the thickness of the ice and the ratio of the density of the underlying mantle to that of the ice. Specifically, for individual raster cells:

(Density of ice / Density of mantle) x (Ice thickness) = Elevation change

Taking:
Average density of ice = 0.98 g/cm^3
Average density of mantle = 3.34 g/cm^3

-the density ratio of ice to mantle is thus about 0.2825.

To obtain an elevation raster for the continent that includes this elevation difference, we will:

A. Multiply an ice thickness raster by 0.2825 to obtain elevation change;
B. Add the resulting raster to the bedrock elevation raster to obtain isostatically compensated elevations for the Antarctic continent.

Step A multiplies a integer raster (ice thickness) by a decimal value, resulting in a "floating point" raster (a raster that contains decimal values in the cells).

1. Open the raster calculator and enter the expression "*ice_thick*"*0.2825, specify a file name and storage location, and click OK.
2. Open the raster calculator again, load the newly calculated elevation change raster and add to it the *clip_bed_elev* raster; specify a file name (e.*g. bed_el_isost*) and storage location, and click OK.
3. Symbolize the new *bed_el_isost* raster, create and save a Hillshade, create a zero elevation contour, and make a map like Figure 14.

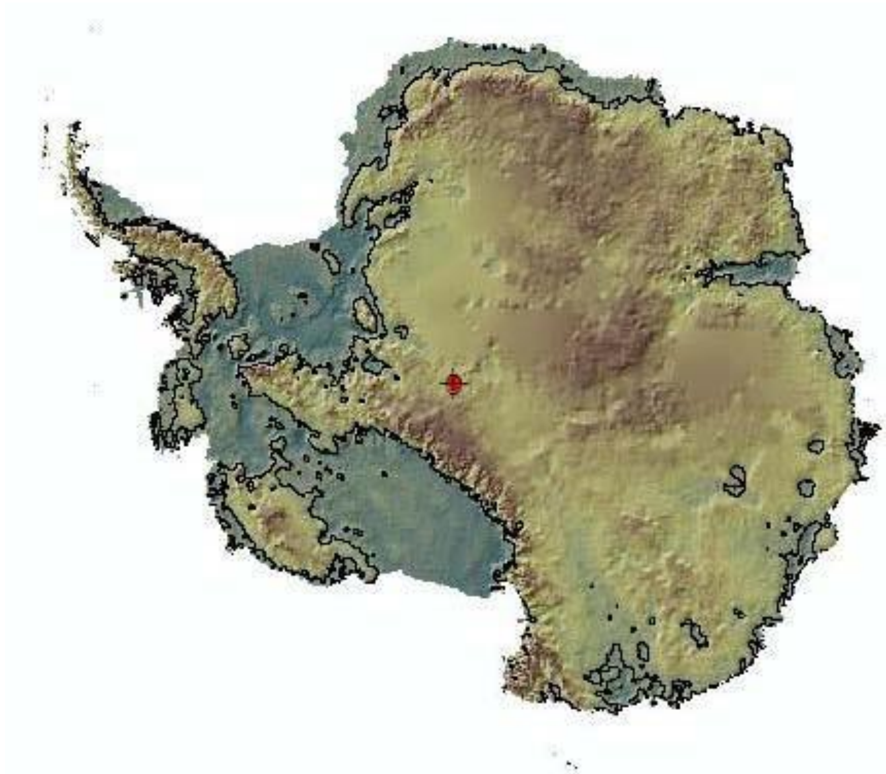


Figure 14. DEM of Antarctica without ice after isostatic rebound. Black line is present Sea Level contour.

Question 11: How do the mean, maximum and minimum elevations for the continent after isostatic rebound differ from those of the sub-ice topography before rebound (c.f. question 5)?

J. Spatial Analysis -A Map of "Greenhouse Antarctica" Showing the Effects of Isostatic Rebound and Sea Level Rise

Melting of the south polar ice cap, which contains for about 91.5% of the ice in the world, would raise sea level by about 73 meters; melting all of the ice on the planet would raise sea level by about 80.5 meters (see the literature in the *SL_Rise* folder in the *Antarctic_data* folder). To produce a map like **Figure 12** that shows higher sea level we must:

1. Subtract 80.5 meters from the cells of the *bed_el_isost* raster so that elevations are relative to this higher sea level (raster calculator can do this; c.f. section I)
2. Make a hillshade of this new raster.
3. Create a binary raster of regions above and below sea level (c.f. section D).
4. Create a shoreline (i.e. zero elevation) contour (c.f. section E)
5. Symbolize the results.

Your final product will resemble Figure 15.

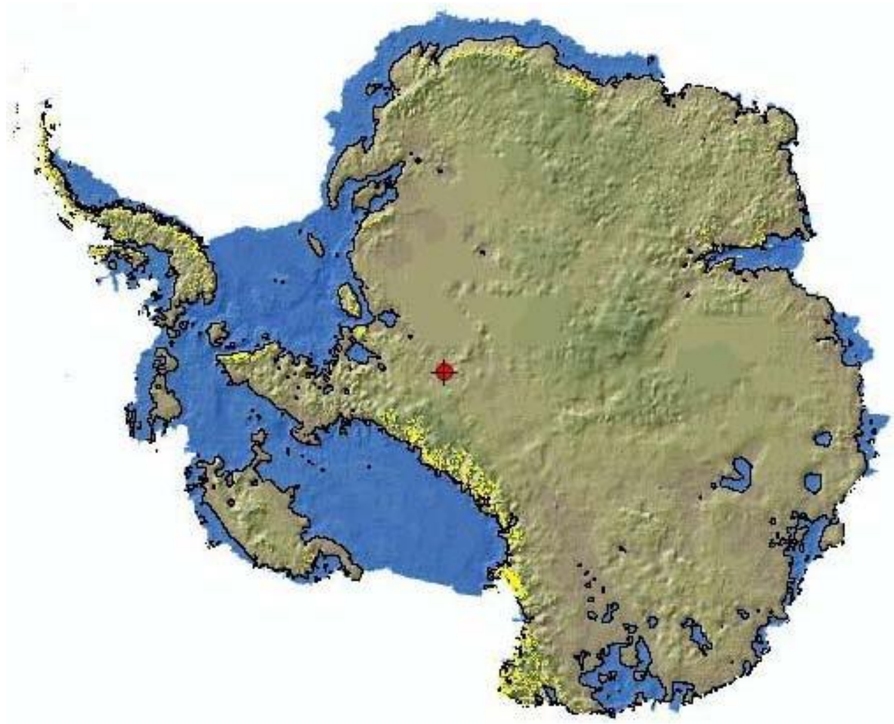


Figure 15. DEM of Antarctica after isostatic rebound and a sea level rise of 80.5 meters. Blue areas are below sea level. Black line is coastline/zero elevation contour relative to a mean sea level that is 80.5 meters above the present level. Bright yellow shows areas of present rock outcroppings; red dot is South Pole.

Question 12: The US Geological Survey has calculated volumes of ice for Antarctica (see the "Estimated_present.doc" file in the *SL_rise* folder) that are substantially larger than those you calculated. How much larger? Speculate on why your results are different.

Map to turn in: Construct a layout of your final raster. Using a color ramp of your choosing, symbolize the final raster with a defined interval of 500 meters. Your map should contain a label for South Pole and an explanation that includes a color ramp with corresponding elevations. The *Results_in_PowerPoint* folder contains a PowerPoint of several example layouts.

You're done!

M. Helper, Fall 2004; Updated Fall, 2013