Title:	Using GRACE to evaluate change in Greenland's ice sheet
	Part I: Download, import and map GRACE data
	Part II: View and animate seasonal ice sheet mass changes
	Part III: Calculate and visualize annual ice sheet mass changes
	Part IV: Calculate annual mass loss rate
Product Type:	Curriculum
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Target audience:	Undergraduate/Graduate
Format:	Tutorial (pdf document)
Software requirements[*]:	ArcMap 9 or higher (ArcGIS Desktop) (Parts I, II, III, IV),
	ArcGIS Spatial Analyst (Parts III, IV)
Data:	All data required are obtained within the exercise.
Estimated time to complete:	All parts: 5.5 hrs
	Part I: 2 hrs.
	Part II: 0.5 hrs.
	Part III: 1.5 hrs. - 2 hrs.
	Part IV: 1 hr.
Alternative Implementations:	• Part I provides a standalone exercise producing a map of ice sheet mass
	• Parts I and II together provide a standalone exercise producing an animation of seasonal change in ice sheet volume
	• Parts I, II and III together provide a standalone exercise to produce animations of seasonal and annual ice sheet volume changes
	• Completing all parts (I through IV) include calculations of the total decadal mass change and corresponding sea level rise
Learning objectives:	Part I:
	• Understand the GRACE satellites and how they measure gravity
	• Understand the application of GRACE to measure ice sheet volume
	• Download, import and map GRACE data
	Part II:
	• View GRACE data in ArcGIS
	• Create an animation of seasonal ice sheet changes
	Part III:
	• Create an animation of annual ice sheet volume
	• Generate images to show annual changes in ice sheet mass
	• Calculate change in ice sheet mass over past decade
	Part IV:
	• Compute annual and decadal ice sheet mass change
	• Compute sea level rise

[*]Tutorials may work with earlier versions of software but have not been tested on them
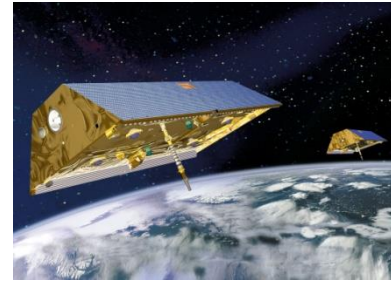
Using GRACE to evaluate change in Greenland's ice sheet
Part IV: Calculate annual mass loss rate

Objectives:

- Compute annual and decadal ice sheet mass change
- Compute sea level rise

In this exercise you will compute the annual mass change of the Greenland ice sheet using spatial analysis and compare your result with published data from NASA JPL.

1. Zonal statistics

We would like to confine our analysis to the landmass of Greenland and not the surrounding ocean because we are only interested in the mass change (melting of the ice sheet) over Greenland. (Did you know that the melting of continental ice sheets causes sea level rise, whereas the melting of sea ice does not.) To do this you will calculate the zonal statistics of the difference image that you generated in Pt III within the Greenland shapefile (from Pt III) using the Spatial Analyst tools, which can be found in ArcMap's toolbox.
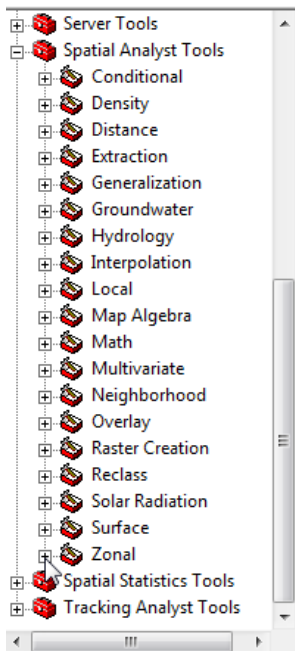
Spatial Analyst -> Zonal -> Zonal Statistics as Table, with Greenland as the feature.

You should get results like:

Rowid	COUNTRY	ZONE-CODE	COUNT	AREA	MIN	MAX	RANGE	MEAN	STD	SUM
1	Greenland	1	659	659	-116.7697	5.967561	122.73726	-45.583443	32.762466	-30039.488

You may have a positive rather than negative sign for the values. Please look at which image you subtracted from which (2011 from 2004 or 2004 from 2011) and make sure you understand whether a mass gain or a mass loss is occurring.

From the zonal statistics above we see that the mean change in the image pixel values is -45.583 cm water (equivalent height). (Your value may differ from this slightly.)

Write a sentence explaining what this means. If you don't commonly use cm, make sure you understand how many inches this is.

2. Area calculation

Right click on the Greenland polygon and Open Attribute Table. Depending on where you obtained your data you may find a column which contains the polygon area. If there is one present you can move on to the next section.

Inside the attribute table, select Options and Add Field. Give it a name (area), and make it a float format (so it can store fractional numbers). In the attribute table your new column should appear. Right click on the new (empty) column and select Calculate Geometry. Use the equal area projection and change the units to sq km. Press OK.
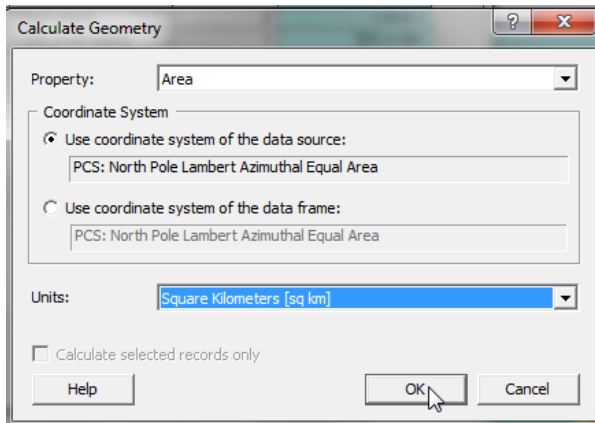
The areas in the attribute table should now be populated.

3. Mass change calculation

To find the total area, right click on the area column in the Attribute Table and choose Statistics. Find the Sum. It should be about 2,168,821 sq km. (Your value could be slightly different.)

The change in water equivalent volume is the average mass loss per pixel times the area. Be careful with the units:

$$45.583\text{e-}2*2116821\text{e}6 \text{ m}^3 = 965 \text{ km}^3.$$

Do your own calculation and verify your result against this. Did you get the same or a similar result? If not, what was your result?

This is the equivalent volume of water generated by the loss in ice between 2004 and 2011.

4. Annual mass loss

We will now calculate the mass loss over a single year from Aug 2009 to Aug 2010.

Generate a difference image for 2009 to 2010. (Do you remember how to do this from Pt III?)

Use Zonal Statistics to find the equivalent water column change over a single year.

Multiply by the area of Greenland to find the total mass loss. What are the units of this? (Be sure to specifiy.)

If this rate continues for a decade, what would be the total volume of ice mass loss?

Compare your results in 3 and 4 to the published data shown below.
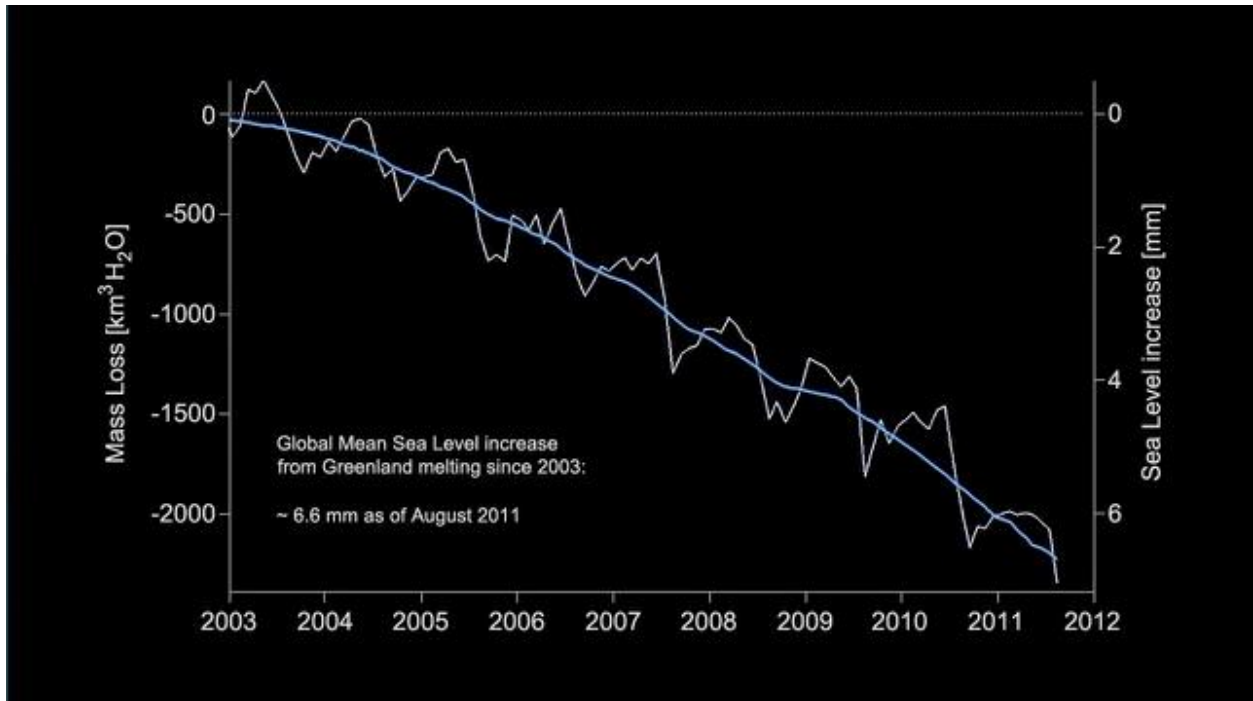
The graph above shows seasonal and annual mass loss from Greenland between 2002 and 2012. The mass loss from 2004 to 2011 is about 2000 km^3, which is larger than our results.

Our results do not take into account corrections which should be applied, but they are a reasonable estimate for a simple analysis. See Jacob et al (Nature 2012) including the online supplement, for a thorough discussion.

5. Sea level rise

What other data do you need to estimate the global sea level rise that this melting causes? See if you can find that data online.

Estimate the sea level rise that the decadal ice mass loss you calculated in 4 would cause.

How does this compare to the value shown in the figure above?