



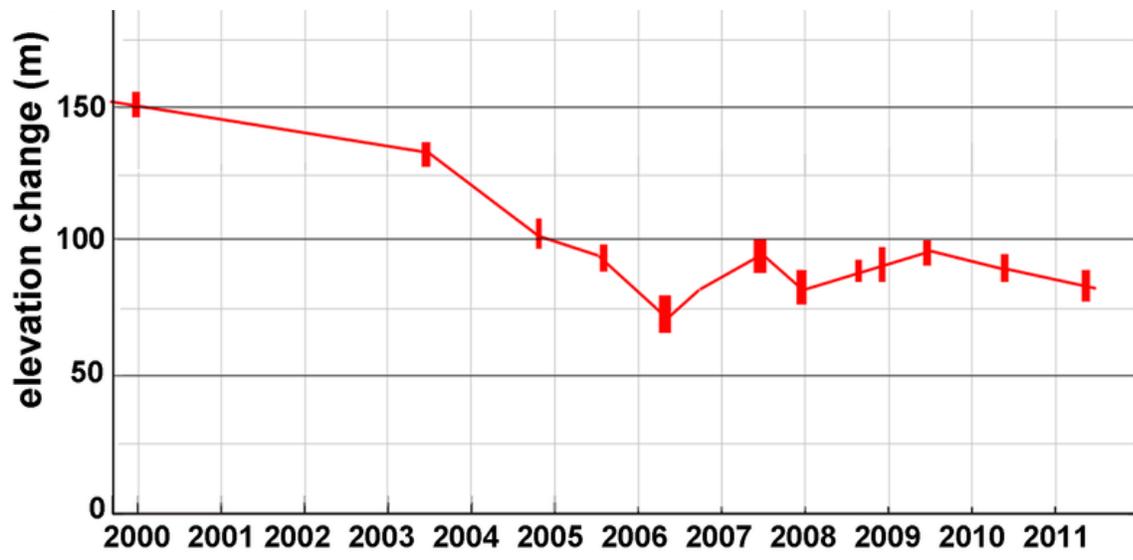
## Ice Mass & Sea Level Change Unit 4: An Uplifting Story - Student Exercise

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*In this exercise, you will use bedrock GPS data and ice elevation data from Helheim Glacier in SE Greenland to think about how changes in ice mass can lead to changes in sea level.*

### Part 1: Ice elevation data

Measuring the elevation of an ice sheet's surface over time can provide information about how the ice sheet is changing. Scientists measure how the surface elevation of the Greenland Ice Sheet changes using techniques called repeat satellite altimetry and airborne altimetry. The data below (from Csatho et al., 2014) show the elevation change of the surface of Helheim Glacier in SE Greenland using a satellite altimeter called ICESat (Ice, Cloud, and land Elevation Satellite) and airborne altimetry from NASA's Operation IceBridge.



**Figure 1:** Ice elevation time series for Helheim Glacier from ICESat and airborne altimetry (Csatho et al., 2014).

(1) First, consider the 2000–2003 data. Calculate the total change in ice elevation in meters from 2000–2003. Then, calculate the average rate (speed) of ice elevation change in meters per year that occurred from 2000–2003.

Starting elevation of the surface of Helheim Glacier (2000): \_\_\_\_\_ m

Ending elevation of the surface of Helheim Glacier (2003): \_\_\_\_\_ m

Total change in ice elevation from 2000–2003: \_\_\_\_\_ m

From 2000–2003, the ice sheet’s elevation changed by an average of \_\_\_\_\_ m/year.

Do the data indicate that the Helheim got thicker *or* thinner from 2000–2003?

(2) Next, consider the 2003–2006 data. Calculate the total change in ice elevation in meters from 2003–2006. Then, calculate the average rate (speed) of ice elevation change in meters per year that occurred from 2000–2006.

Starting elevation of the surface of Helheim Glacier (2003): \_\_\_\_\_ m

Ending elevation of the surface of Helheim Glacier (2006): \_\_\_\_\_ m

Total change in ice elevation from 2003–2006: \_\_\_\_\_ m

From 2003–2006, the ice sheet’s elevation changed by an average of \_\_\_\_\_ m/year.

Do the data indicate that the Helheim got thicker *or* thinner from 2003–2006?

(3) Finally, consider the 2006–2011 data. Calculate the total change in ice elevation in meters from 2006–2011. Then, calculate the average rate (speed) of ice elevation change in meters per year that occurred from 2006–2011.

Starting elevation of the surface of Helheim Glacier (2006): \_\_\_\_\_ m

Ending elevation of the surface of Helheim Glacier (2011): \_\_\_\_\_ m

Total change in ice elevation from 2006–2011: \_\_\_\_\_ m

From 2006–2011, the ice sheet’s elevation changed by an average of \_\_\_\_\_ m/year.

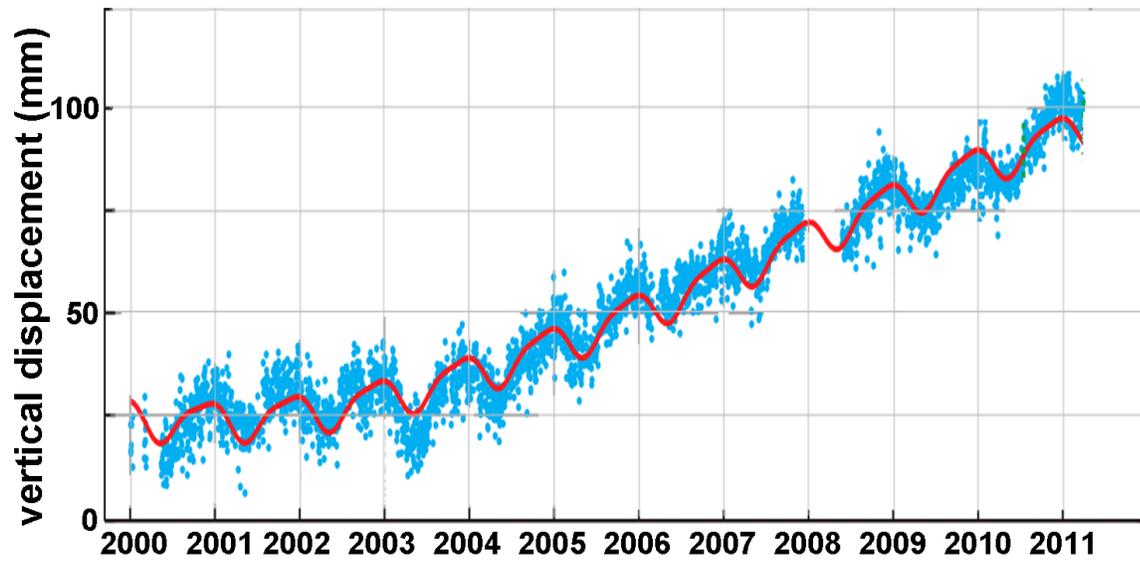
Do the data indicate that Helheim got thicker *or* thinner from 2006–2011?

(4) Discuss how changes in Helheim’s ice elevation could have an impact on the amount of water being discharged into the ocean and the subsequent potential impacts on sea level.

## Part 2: GPS data

The Greenland GPS Network (GNET) is made up of more than 50 global positioning system (GPS) stations that can measure millimeter-scale changes in bedrock elevation. As illustrated in the animation that you watched, the majority of these GPS stations are located along the coast of Greenland and are used to record both seasonal and longer-term changes in bedrock elevation caused by ice mass changes.

The figure below (after Bevis et al., 2012) shows a GPS time series for Kulusuk, a field site located approximately 60 km (~37 miles) from Helheim Glacier in SE Greenland.



**Figure 2:** Time series of GPS vertical displacement near Helheim Glacier (Bevis et al., 2012).

(1) Based on what you observed in the animation, which Earth process(es) cause(s) the bedrock elevation to increase (rise)? Which Earth process(es) cause(s) the bedrock elevation to decrease (lower)?

(2) Approximately how much did the elevation of the bedrock surface fluctuate from the beginning of 2001 to the beginning of 2002?

(3) Compare the bedrock elevation at the beginning of 2001 to the bedrock elevation at the beginning of 2002. What was the difference in bedrock elevation between these two times?

(4) Take a look at the data from 2000–2011. Does the overall trend indicate an increase *or* decrease in bedrock elevation? Propose a hypothesis for why this trend is observed.

(5) Do you see any changes in the overall trend? If so, in which year did the change begin? In general, how did the data begin to change?

(6) Next, consider the 2000–2003 data. Calculate the total change in bedrock elevation in millimeters from 2000–2003. Then, calculate the average rate (speed) of change in bedrock elevation in millimeters per year that occurred from 2000–2003.

Starting bedrock elevation (2000): \_\_\_\_\_ mm

Ending bedrock elevation (2003): \_\_\_\_\_ mm

Total change in bedrock elevation from 2000–2003: \_\_\_\_\_ mm

From 2000–2003, the average rate of change in bedrock elevation was \_\_\_\_ mm/year.

(7) Consider the 2003–2011 data. Calculate the total change in bedrock elevation in millimeters from 2003–2011. Then, calculate the average rate (speed) of change in bedrock elevation in millimeters per year that occurred from 2003–2011.

Starting bedrock elevation (2003): \_\_\_\_\_ mm

Ending bedrock elevation (2011): \_\_\_\_\_ mm

Total change in bedrock elevation from 2003–2011: \_\_\_\_\_ mm

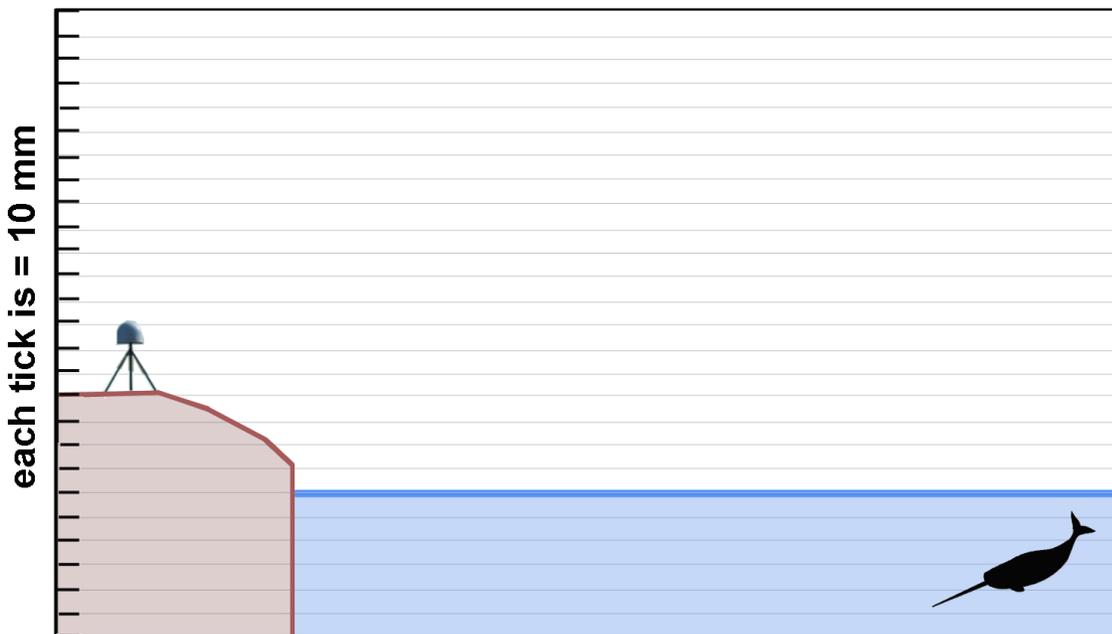
From 2003–2011, the average rate of change in bedrock elevation was \_\_\_\_ mm/year.

(8) Think back to your ice elevation calculations for Helheim Glacier that you did in Part 1. In the table below, summarize your calculations and interpretations for ice elevation and bedrock elevation for the two time periods. Does there appear to be a relationship between ice elevation and bedrock elevation? If so, briefly explain this relationship. Are there any inconsistencies in the relationship between ice elevation and bedrock elevation?

time period	average rate of ice elevation change (m/year)	thinning or thickening of ice?	average rate of bedrock elevation change (mm/year)	raising or lowering of bedrock surface?
2000–2003				
2003–2011				

**Part 3: What is happening to sea level in SE Greenland?**

The schematic diagram below shows the bedrock surface in pink (with a GPS station installed on the bedrock surface), sea level in blue, and change in elevation on the Y-axis of the diagram. Notice that each tick on the Y-axis represents 10 millimeters of elevation change.



Now that you have done some thinking about ice elevation and bedrock elevation changes in SE Greenland, it is time to think about how these changes have the potential to influence sea level in the study area.

- (1) Consider the ice elevation data for Helheim Glacier from 2003–2011.
  - (a) Do the changes observed in ice elevation add water to the ocean *or* take water from the ocean?
  - (b) Will this cause sea level to rise *or* fall?
  - (c) Would you expect this to be a worldwide sea level change *or* a sea level change only in SE Greenland? Briefly explain your answer.
  
- (2) Helheim Glacier is estimated to contribute to  $\sim 0.01$  mm/year to sea level change. Considering that global sea level is changing by approximately 3 mm/ year, what is the total change in sea level from 2003–2011?
  
- (3) Change the location of the blue line (sea level) on the diagram to reflect the total amount of sea level change from 2003–2011.
  
- (4) Consider the bedrock GPS data for Kulusuk (near Helheim Glacier) from 2003–2011.
  - (a) Do the changes observed in bedrock elevation result in a sea level rise *or* fall?
  
  - (b) Would you expect this to be a worldwide sea level change *or* a sea level change only in SE Greenland? Briefly explain your answer.
  
- (5) Change the location of the pink line (bedrock elevation) on the diagram to reflect the total amount of bedrock elevation change from 2003–2011.
  
- (6) Take a look at the new bedrock elevation and water level for SE Greenland that you sketched on your diagram. Based on the new locations of the bedrock elevation surface compared to the surface of the ocean, has sea level risen *or* fallen in SE Greenland?
  
- (7) Which Earth process is contributing more to observed sea levels in SE Greenland: changes in the amount of water in the ocean *or* changes in the bedrock elevation surface?
  
- (8) How would your answers to questions 6 and 7 be different in an area that is not covered with ice?

## References

- Bevis, Michael, John Wahr, Shfaqat A. Khan, Finn Bo Madsen, Abel Brown, Michael Willis, Eric Kendrick, Per Knudsen, Jason E. Box, Tonie van Dam, Dana J. Caccamise II, Bjorn Johns, Thomas Nylén, Robin Abbott, Seth White, Jeremy Miner, Rene Forsberg, Hao Zhou, Jian Wang, Terry Wilson, David Bromwich, and Olivier Francis. 2012. Bedrock displacements in Greenland manifest ice mass variations, climate cycles and climate change. PNAS 2012 109 (30) 11944-11948, 2012, doi:10.1073/pnas.1204664109
- Csatho, Beata M., Anton F. Schenk, Cornelis J. van der Veen, Gregory Babonis, Kyle Duncan, Soroush Rezvanbehbahani, Michiel R. van den Broeke, Sebastian B. Simonsen, Sudhagar Nagarajan, and Jan H. van Angelen. 2014. Laser altimetry reveals complex pattern of Greenland Ice Sheet dynamics. PNAS 2014 111 (52) 18478-18483, doi:10.1073/pnas.1411680112

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