Understanding Our Changing Climate Unit 3: Global Sea-Level Response to Ice Mass Loss

Susan Kaspari (Central Washington University) and Bruce Douglas (University of Indiana)

In this unit students will use GRACE ice mass loss time series from Greenland and Antarctica to calculate sea-level rise due to the addition of freshwater inputs from melting ice sheets. The students will calculate how much the ice loss contributes to sea-level rise and examine InSAR data to investigate which regions of the ice sheets are losing the greatest mass. Lastly, students will extrapolate how much sea-level rise will occur by 2100 based on recent observed rates of sea-level rise, and compare these values to sea-level rise projections from the Intergovernmental Panel on Climate Change.

Two types of data will be used in this unit:

1. Gravity Recovery and Climate Experiment (GRACE) satellites have produced maps of global time-variable gravity, which can be used to monitor mass changes in land ice and the oceans.
2. Interferometric Synthetic Aperture Radar (InSAR) can be used to monitor the velocity of glaciers.

The following requires students to create graphs of data sets. Ensure that the axes on all graphs are labeled and include correct units. For the questions requiring quantification, please identify the methodology you used to obtain your answer, including the equations used.

Part 1: Greenland and Antarctica Mass Loss

1. **Reflection**: Mass loss of the Antarctic and Greenland ice sheets is occurring due to climate change. Which ice sheet do you think has lost greater mass during the past 15 years and why? The purpose of this question is not to answer it correctly, but rather to reflect on potential differences between the ice sheets and how differences in their geographic locations may affect the rate at which they are changing. Answer this question prior to working with the GRACE data, and please do not change your answer after getting further into this unit (3 pts).

2. Access the spreadsheet. From the tab GRACEdata create a graph that includes changes in mass for Greenland and Antarctica from 2002 to 2017, and include a copy of the graph here (3 pts).

3. Based on the data plotted in Question 2, which ice sheet is losing greater mass (1 pt)?

4. Superimposed on the long-term trend of ice mass loss is a seasonal “sawtooth” pattern. What do you think is driving the seasonal signal in the GRACE data? (3 pts).

5. Below are InSAR images that show the ice velocity for Antarctica and Greenland (both are expressed in meter/year). For Antarctica, note that many of the places with fastest velocities are actually ice shelves (places where the ice sheet has moved out into the ocean and is
floating; the ice is no longer grounded). Additionally view the animation ice flow based on InSAR data for Greenland: https://www.youtube.com/watch?v=GDXq8Oa5d5Q and Antarctica: https://www.jpl.nasa.gov/video/details.php?id=1015

Based on these images and the animation, answer the following:

a. What do these images and the animation show regarding the spatial variability in ice flow for ice sheets? How homogeneous or heterogeneous are ice flow velocities across the ice sheets? (3 pts)

b. What are factors that may be contributing to the observed pattern in ice flow velocities? (3 pts)

6. Reflection: Was your projection in Question 1 regarding if Greenland or Antarctica is losing greater mass consistent with the observed GRACE data that you plotted in Question 2? If not, think further. What may be factors in causing one ice sheet to lose greater mass? (3 pts)
Part II Ice Sheet Mass Loss and Equivalent Sea Level Rise

The ice sheet mass loss trends recorded by GRACE for Antarctica and Greenland indicate that land-based ice has melted, and this mass is being added to the oceans. To convert a mass of ice into the global sea-level equivalent (SLE) rise requires knowing the following:

i. The area covered by oceans on Earth = 3.618 x 10^8 km^2

ii. A 1 mm increase in global sea level requires 10^3 m^3 (10^-12 km^3) of water for each square meter of the ocean surface, or 10^-12 Gt of water.

iii. The volume of water required to raise global sea levels by 1 mm is calculated by:

\[ \text{Volume} = \text{area} \times \text{height} \]
\[ \text{Area} = 3.618 \times 10^8 \text{ km}^2 \]
\[ \text{Height} = 10^{-6} \text{ km (1 mm)} \]

\[ \text{Volume (km}^3) = (3.618 \times 10^8 \text{ km}^2) \times (10^{-6} \text{ km}) = 3.618 \times 10^2 \text{ km}^3 = 361.8 \text{ km}^3 \text{ water}. \]

iv. To convert km^3 of water to Gt of water; 1 km^3 water = 1 Gt water and 1 Gt of ice = 1 km^3 water. So, 361.8 Gt of ice will raise global sea levels by 1 mm. Thus the sea-level equivalent (SLE) equation required for your calculations is:

\[ \text{Equation 1: SLE (mm) = mass of ice (Gt) x (1 mm) / 361.8 (Gt)} \]

7. Sea Level
   a. Using the SLE Equation 1, return to the GRACE data tab in your spreadsheet, and calculate the change in sea-level equivalent (SLE) due to the ice mass change for Antarctica and Greenland (columns E and F are prelabeled in the spreadsheet). You should be calculating the SLE for each data cell to create a time series spanning 2002–2017. Note, you will need to consider whether your values should be positive or negative and correct accordingly (i.e., should a reduction in Greenland land-based ice result in an increase or decrease in sea level?)
   b. For column G “Sea-Level Equivalent (mm) due to Antarctica + Greenland mass loss” sum the Antarctica and Greenland SLE equivalent for each row (e.g., B2+C2; B3+C3) to create a time series spanning 2002–2017.
   c. Create a graph of SLE equivalent spanning 2002–2017 that includes the following three datasets (3 points):
      i. Sea-Level Equivalent (mm of sea-level height) due to Antarctica mass loss
      ii. Sea-Level Equivalent (mm of sea-level height) due to Greenland mass loss
      iii. Sea-Level Equivalent (mm of sea-level height) due to Antarctica + Greenland mass loss

8. Based on the graph that you created above, is Antarctica or Greenland a larger contributor to observed sea-level rise since 2002? (1 pt)

9. When you get to this point of the lab, obtain a paper graph from your instructor that includes the Antarctica and Greenland ice mass loss sea-level equivalent data in addition to observed sea-level rise from satellite radar altimetry (these data are used in Unit 2: Global Sea-Level Response to Temperature Changes). Does ice sheet mass loss account for observed sea level? What additional sources of sea-level rise need to be accounted for that are not plotted on this graph? (3 pts).

10. For this question, you will examine Figure 3.15 from http://www.ametsoc.net/sotc2016/Ch03_GlobalOceans.pdf (it will be given to you as a separate handout), which includes global mean sea level, monthly averaged global ocean
mass from GRACE, and monthly averaged global mean steric (density related) sea-level rise. Steric sea-level changes are affected by both changes in the ocean temperature and salinity, with ocean warming dominating steric sea-level rise. Based on this graph, and the text in same document in Section f. Sea-Level Variability and Change (p. S79-S81), answer the following:

a. Which contributes greater to sea-level rise: inputs of mean ocean mass or steric sea-level rise? (1 pt)
b. What are the sources that contribute to ocean mass sea-level rise? (3 pts)
c. Examine panels b and c of the same graph, which show linear sea-level trends from altimetry data. Based on these plots, how homogeneous/heterogeneous is sea-level rise globally? (3 pts)
d. Why is sea-level rise occurring more rapidly in some regions relative to other regions (3 pts)?

Part III. Synthesis: Global Mean Sea-Level Budget Summarized

11. In this section the observed contributions to global mean sea-level rise from thermal expansion, ice sheets, glaciers, and land water storage are evaluated to rank the sources of sea-level rise. In the Excel spreadsheet, access the tab SourcesSeaLevelRise. Create a bar graph of the observed contributions to global mean sea-level rise from the various sources. Include a copy of the graph here (3 pts).

12. a) How much of observed sea-level rise came from ice sheets?

b) Based on this graph and part a, fill out the following table, and rank the sources of sea-level rise between 1993 and 2010 from 1 (largest contribution) to 3 (smallest contribution). Note: some addition is required here as sum of the categories from the graph you just created are combined (3 pts).

<table>
<thead>
<tr>
<th>Source</th>
<th>mm/yr sea-level rise</th>
<th>Ranking</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thermal Expansion</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total melting ice</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Land Water Storage</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
13. Reflection: Are the rankings of the contributions to sea level rise as you expected or are they a surprise? What have you learned about the sources of sea level rise that you previously were not aware of? (3 pts)

Part IV. Projecting Sea-Level Rise by the Year 2100

14. Here you will estimate how much further sea level will rise by the year 2100.
   a. In the same spreadsheet, go to the “Sealevelrise” tab and plot the data spanning 1993–2017. Include a linear trend line and the linear equation on the graph, and paste a copy of the graph here. (3 pts)
   b. Apply the linear equation to calculate how much further sea level will rise between 2010 and 2100 based on observed rates between 1993 and 2017. Be sure to include your formula and show the details of your calculation, and convert your answer from mm to m (3 pts)
   c. Notice that since ~2010 the rate of sea-level rise has increased. Based on the rate of increase since 2010 (again applying a linear trend since 2010) calculate how much sea level will rise based on the rate of increase observed between 2010 and 2017. A simple way to do this is to plot the sea-level rise data from 2010 to 2017 to obtain the appropriate linear equation. Be sure to include your formula and show the details of your calculation, and convert your answer from mm to m (3 pts).
   d. Based on the two methods that you used to calculate sea-level rise, how much sea-level rise is projected based on recent sea-level rise rates of change (summarize the results from parts a and b from this question) (1 pt):

15. Below is a graph of projected sea-level rise that will occur by 2100 from the 2014 Intergovernmental Panel on Climate Change report. RCP on the graph stands for representative concentration pathways, with low numbers associated with less climate warming and higher numbers associated with greater climate warming. For more information on the RCP scenarios, refer to [https://en.wikipedia.org/wiki/Representative_Concentration_Pathways](https://en.wikipedia.org/wiki/Representative_Concentration_Pathways) or [http://sedac.ipcc-data.org/ddc/ar5_scenario_process/RCPs.html](http://sedac.ipcc-data.org/ddc/ar5_scenario_process/RCPs.html)
How do the values that you calculated above compare to the values shown on this graph? For which scenarios do your numbers match? For which scenarios don’t they match? (3 pts)
16. For the scenarios that do not match, why? What do you think are factors that would lead to higher sea-level rise than those that you calculated? (3 pts)

References