Royal Holloway Geography for Schools Lecture Series

Glacier mass balance activity

Author: Dr Bethan Davies

Case study: USGS Benchmark glaciers in the USA

A-Level Syllabus:

- AQA Glacial Systems and Landscapes, glaciers as natural systems, glacial budgets, recent and prospective impact of climate change.
- OCR Glaciated Landscapes: systems and glacier mass balance; influence of climate on glaciated landscape; specific skills in mass balance calculations.

Introduction

Globally, glaciers have been a significant driver of sea level rise over the last century, and especially since the 1940s (Frederikse et al., 2020). The almost universal retreat of glaciers over recent decades has been well documented (Zemp et al., 2019), making them an icon of global climate change.

The Alaskan region covers 86,723 km^2 in 27,109 glaciers (Kienholz et al., 2015). It contains 19.0 ± 4.9 x 10^3 km^3 of ice, one of the largest ice volumes outside of Greenland and Antarctica (Farinotti et al., 2019), equating to a sea-level equivalent of 43 ± 11.2 mm (this is the amount that global sea levels would rise, on average, if all the ice in Alaska melted).

This Alaskan region currently contributes more to sea level rise than any other region. From the years 1961 – 2016, the cumulative mass change of Alaskan glaciers was -3019 billion tonnes, resulting in 8.3 mm sea-level rise (Zemp et al., 2019).

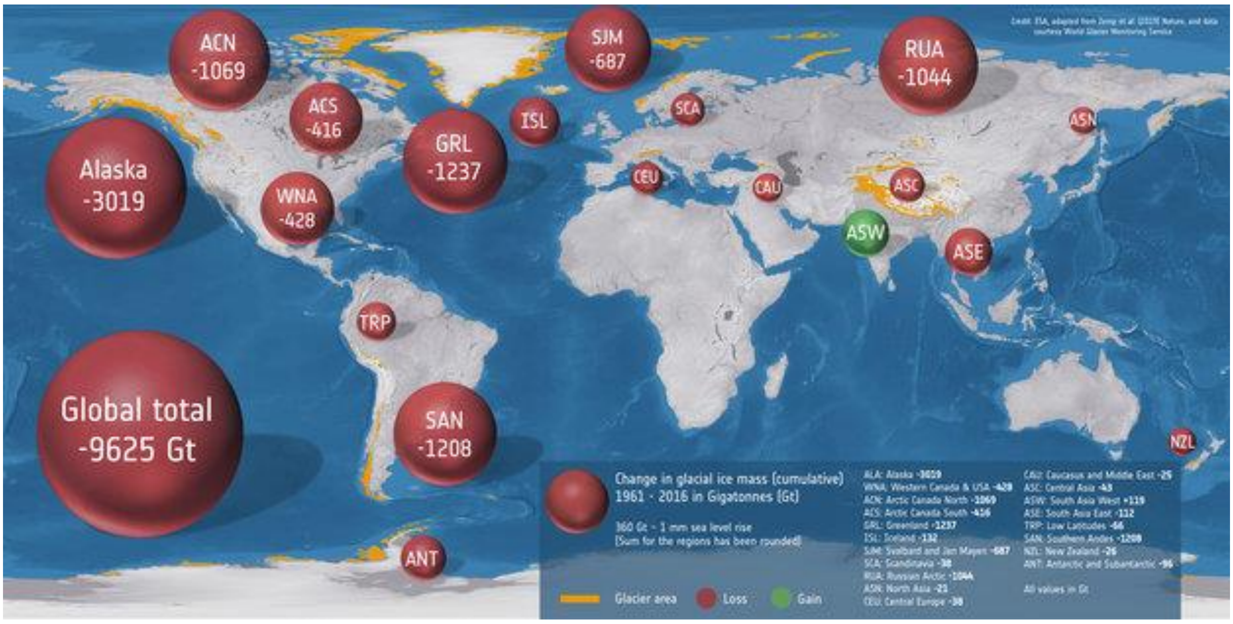

Figure 1. Global regional glacier budgets, from Zemp et al. 2019.

For more information about Geography at Royal Holloway visit: www.royalholloway.ac.uk/research-and-teaching/departments-and-schools/geography/

Follow us: @RHULGeography

USGS Benchmark Glaciers

The United States Geological Survey (USGS) has measured glacier mass balance on five 'benchmark glaciers', which span the maritime and continental climate regimes of the western United States. The USGS has maintained a long-term glacier mass-balance programme since the late 1950s on these glaciers.

Direct field measurements of point glaciological data are combined with weather and data on ice surface elevation change to estimate seasonal and annual glacier mass balance.

The five USGS Benchmark glaciers are Gulkana, Wolverine, Lemon Creek (Figure 2**), South Cascade and Sperry (**Figure 3**) (O'Neel et al., 2019). We are going to investigate the glacier mass balance for these glaciers from the late 1950s to 2019 AD.**

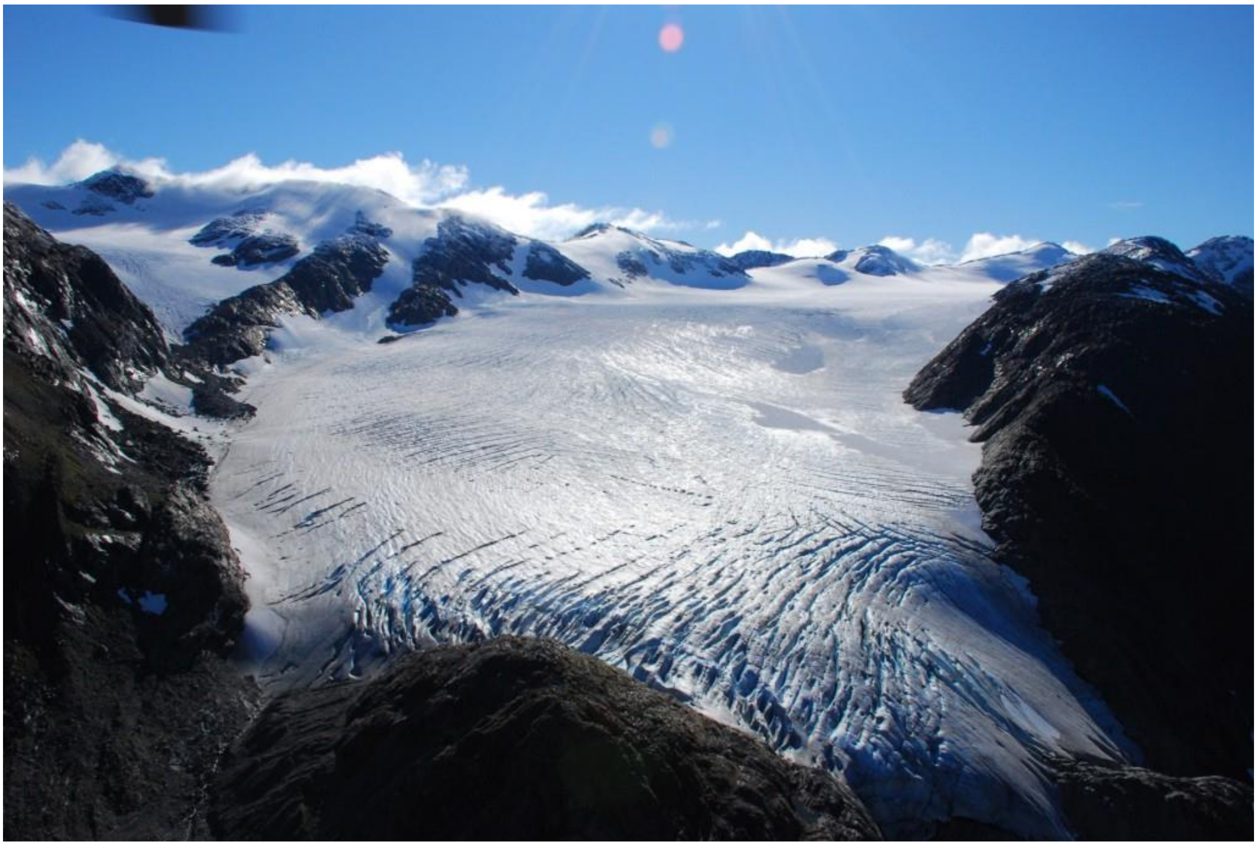

Figure 2. Lemon Creek Glacier, in August 2007 (L. Bernier) (WGMS, 2013)

Gulkana Glacier is in the high-latitude continental climate of Alaska's Delta Mountains (Figure 3**) (O'Neel et al., 2019). Wolverine Glacier is in the high-latitude marine climate regime of Alaska's Kenai Mountains, and has been monitored since 1966. Lemon Creek Glacier (**Figure 2**) is in a high-latitude marine climate regime, in the NE Coast Mountains, adjacent to Juneau Icefield. South Cascade Glacier in Washington State has been monitored since 1958, and has a mid-latitude maritime climate, characteristic of the North Cascade Mountains. Sperry Glacier is located within Glacier National Park, Montana, and has a mid-latitude continental climate. These five benchmark glaciers therefore span a range of regional climates and latitudes.**

You can learn more about glacier mass balance monitoring here, or in this video from Juneau Icefield.

You can learn more about these glaciers from the World Glacier Monitoring Service (WGMS):
https://wgms.ch/products_ref_glaciers/lemon-creek-glacier-pacific-coast-range/

For more information about Geography at Royal Holloway visit:
www.royalholloway.ac.uk/research-and-teaching/departments-and-schools/geography/

Follow us: @RHULGeography

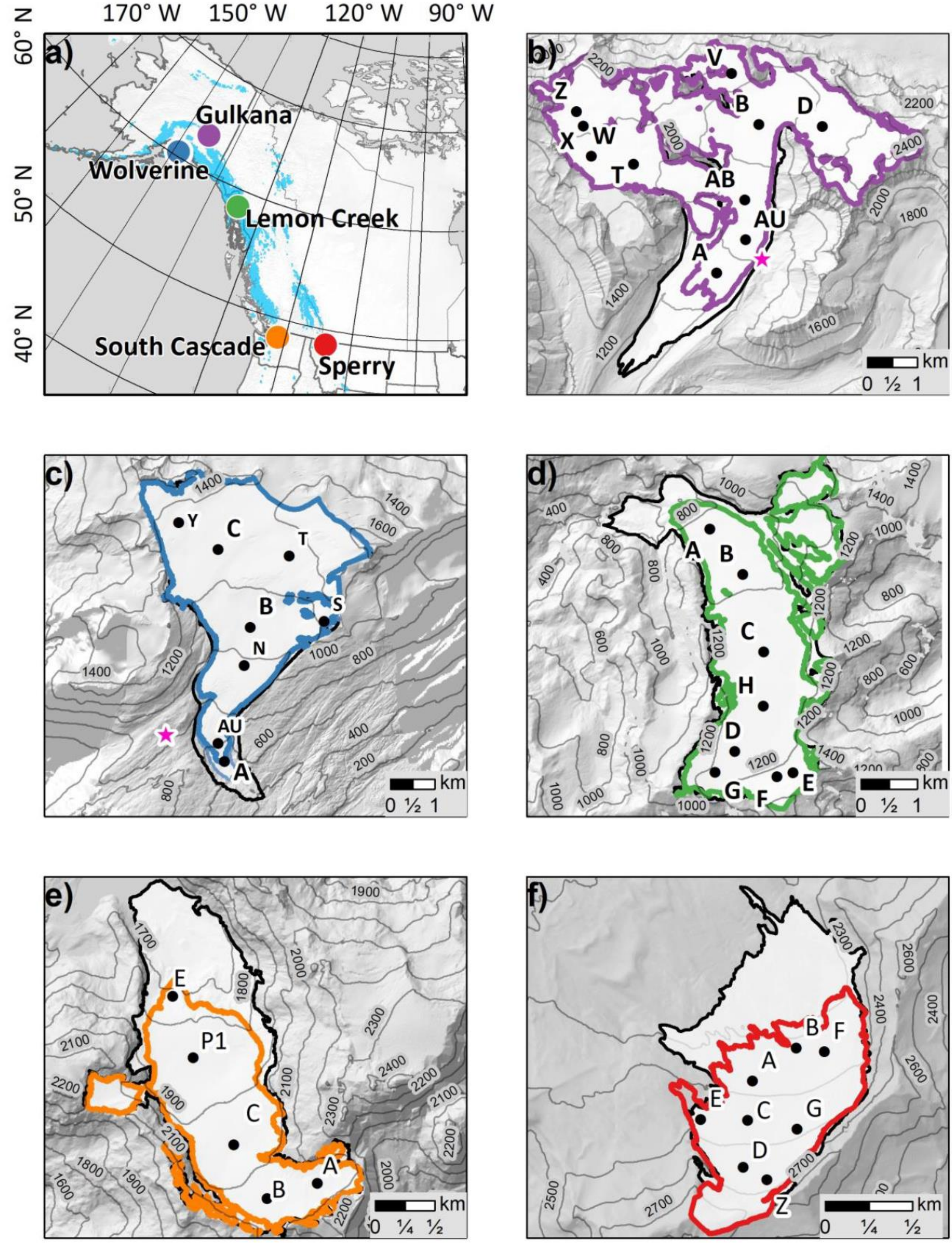

Figure 3. USGS benchmark glaciers. A) Present-day glacier extent (cyan), with the locations of the five benchmark glaciers. The individual panels show maps of Gulkana (b), Wolverine (c), Lemon Creek (d), South Cascade (e) and Sperry Glaciers (f). Glacier extent in mid-century (1948-1958) is shown in black, colours show glacier extent in 2018. From O'Neel et al. (O'Neel et al., 2019). *Letters on each map correspond to locations were mass balanced was measured each year.*

For more information about Geography at Royal Holloway visit:
www.royalholloway.ac.uk/research-and-teaching/departments-and-schools/geography/

Follow us: @RHULGeography YouTube

Calculating glacier mass balance

The purpose of this USGS research project was to quantitatively evaluate changes in mass balance over time at specified glaciers.

The USGS runs a computer program to calculate a glacier-wide mass balance from these point measurements (see locations of point measurements in Figure 3**. The output data represents surface glacier mass balance. Multiple field measurements are averaged, to account for surface variations.**

Mass balances are reported in metres water equivalent units per annum (w.e. a^{-1}), and represent the integration of multiple field units. The "m w.e." unit describes glacier mass in specific units as the thickness of an equal mass that had the density of water. The m w.e. is obtained by dividing a particular mass of snow or ice by the density of water: 1 m w.e. = 1000 kg $m^{-1}/\rho w$.

Each glacier exhibits cumulative mass loss since the mid-20th Century, with average rates of -0.58 to -0.30 water equivalent per annum (w.e. a^{-1}).

The "Equilibrium Line Altitude" is also calculated (Figure 4**). This "ELA" is the altitude on the glacier where net accumulation (net mass gained by the glacier) is equal to net ablation (net mass loss on the glacier). Above the ELA, snow remains throughout the summer, and the glacier has a net gain of mass. Below the ELA, snow melts through the summer, meaning that bare glacier ice is visible. There is a net mass loss below the ELA.**

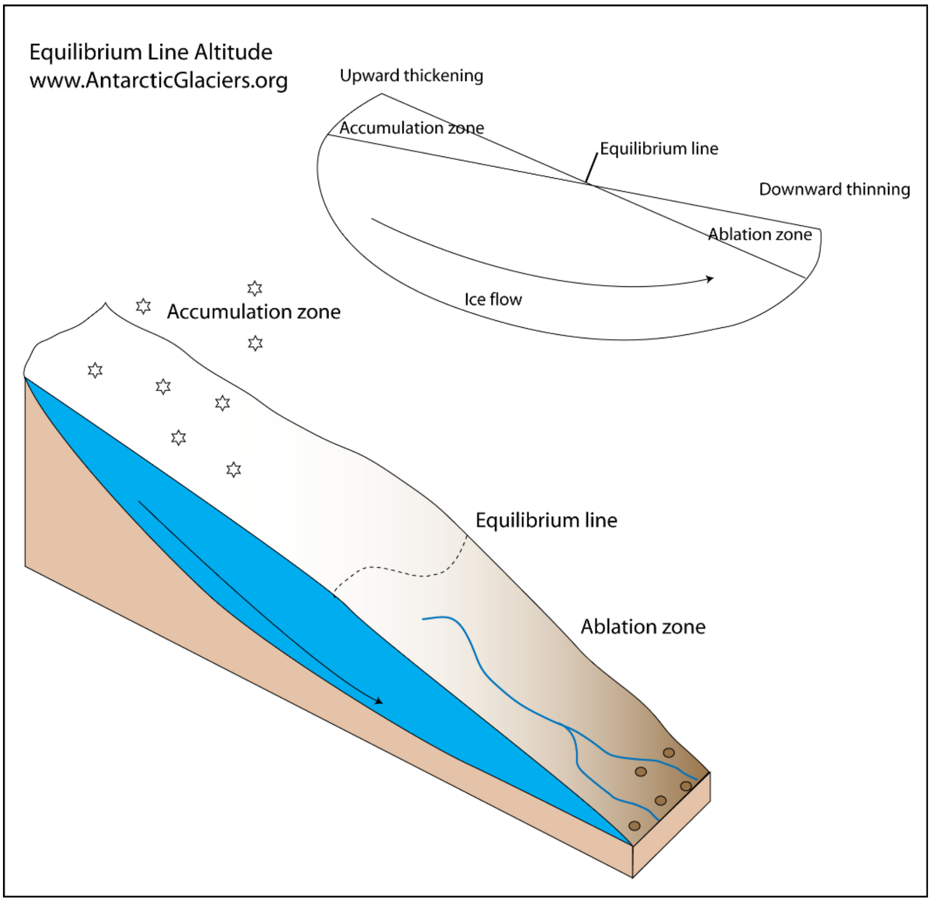

Figure 4. Glacier equilibrium line altitude (ELA), with the Accumulation Area above the ELA and the Ablation Area below the ELA (Bethan Davies, www.AntarcticGlaciers.org).

For more information about Geography at Royal Holloway visit: www.royalholloway.ac.uk/research-and-teaching/departments-and-schools/geography/

Follow us: @RHULGeography

Data access

The USGS dataset is publically available (McNeil et al., 2016). The data can be downloaded from the USGS data portal:
https://alaska.usgs.gov/products/data.php?dataid=79

Data citation:
McNeil, C. J., Sass, L. C., Florentine, C. E., Baker, E. H., Peitzsch, E. H., Whorton, E. N., Miller, Z. S., Fagre, D. B., Clark, A. M. and O'Neel, S. R., 2016, Glacier-wide mass balance and compiled data inputs: USGS benchmark glaciers (ver. 4.0, November 2019): U.S. Geological Survey data release, https://doi.org/10.5066/F7HD7SRF.

Save the dataset to your computer and unzip the data. You should see five folders, one for each glacier, and a PDF ReadMe file. Look through the ReadMe file to understand the dataset.

There are several spreadsheets for each glacier. We will look at the '*Output*' file for each glacier. This gives the calculated glacier-wide winter mass balance in m w.e. (Bw), summer mass balance in m w.e. (Bs) and annual mass balance (Ba) in m w.e. for each glacier (teachers may just want to provide the *output* files for their students).

There is also an annual calculation for the *Equilibrium Line Altitude (ELA).* There are calculations for each year available. The units for the ELA are metres above sea level.

Data Analysis

Investigate the 'Output' excel file dataset for each glacier. Look through the column headings and think about what the mean and what they show. You may want to work as a group to compare glaciers.

Analyse the Equilibrium Line Altitudes

1. In Excel, **calculate** the averages (means) for each of the five benchmark glaciers.

2. How does the ELA vary according to the different regional climate and latitudes of the five benchmark glaciers?

3. What differences do you observe? What might be driving these differences?

Analyse the Glacier Mass Balance

1. Using data for the *last 10 years* and the *first 10 years* of the dataset, **calculate** the average summer balance (Bs), winter balance (Bw) and annual glacier-wide mass balance (Ba). Is there a difference in the average glacier mass balance over these two different time periods? What about the average summer and winter mass balances?

2. Over these two time periods, is the average annual mass balance (Ba) positive or negative? What does this mean for the glacier? Will the glacier grow, or shrink?

1. We will now calculate the *Cumulative mass balance*. In a new column, calculate the cumulative mass balance by adding each year's mass balance to the previous year.

2. Plot line graphs for each glacier of the cumulative mass balance and the ELA for each year for each glacier. **Describe** the trends that you observe.

Critically assess the trends in glacier ELA and glacier mass balance

1. What trends do you observe?

For more information about Geography at Royal Holloway visit:
www.royalholloway.ac.uk/research-and-teaching/departments-and-schools/geography/

Follow us: @RHULGeography

2. Are the glaciers behaving differently in the different climatic regions or zones?

3. How does cumulative glacier mass balance vary over time?

Further reading

- Data access: https://alaska.usgs.gov/products/data.php?dataid=79
- O'Neel 2019 paper: https://www.cambridge.org/core/journals/journal-of-glaciology/article/reanalysis-of-the-us-geological-survey-benchmark-glaciers-longterm-insight-into-climate-forcing-of-glacier-mass-balance/8C7B11056F0A16E78113D59F50A680D8
- Glacier mass balance: http://www.antarcticglaciers.org/glacier-processes/mass-balance/ (personal blog of Dr Bethan Davies)
- World Glacier Monitoring Service: https://wgms.ch/products_ref_glaciers/lemon-creek-glacier-pacific-coast-range/
- Lemon Creek Glacier Retreat: https://glacierchange.wordpress.com/2010/07/26/lemon-creek-glacier-retreat-juneau-icefield-alaska/ (personal blog of Prof. Mauri Pelto).
- Lemon Creek glacier retreat in 2018: https://blogs.agu.org/fromaglaciersperspective/2019/03/06/lemon-creek-glacier-2018-ablation-and-glacier-runoff/ (personal blog of Prof. Mauri Pelto).

References

Farinotti, D., Huss, M., Fürst, J.J., Landmann, J., Machguth, H., Maussion, F., Pandit, A., 2019. A consensus estimate for the ice thickness distribution of all glaciers on Earth. Nat. Geosci. https://doi.org/10.1038/s41561-019-0300-3

Frederikse, T., Landerer, F., Caron, L., Adhikari, S., Parkes, D., Humphrey, V.W., Dangendorf, S., Hogarth, P., Zanna, L., Cheng, L., Wu, Y.-H., 2020. The causes of sea-level rise since 1900. Nature 584, 393–397. https://doi.org/10.1038/s41586-020-2591-3

Kienholz, C., Herreid, S., Rich, J.L., Arendt, A.A., Hock, R., Burgess, E.W., 2015. Derivation and analysis of a complete modern-date glacier inventory for Alaska and northwest Canada. J. Glaciol. 61, 403–420.

McNeil, C.J., Sass, L.C., Florentine, C.E., Baker, E.H., Peitzsch, E.H., Whorton, E.N., Miller, Z.S., Fagre, D.B., Clark, A.M., O'Neel, S., 2016. Glacier-Wide Mass Balance and Compiled Data Inputs: USGS Benchmark Glaciers: U.S. Geological Survey data release. https://doi.org/10.5066/F7HD7SRF

O'Neel, S., McNeil, C., Sass, L.C., Florentine, C., Baker, E.H., Peitzsch, E., McGrath, D., Fountain, A.G., Fagre, D., 2019. Reanalysis of the US Geological Survey Benchmark Glaciers: long-term insight into climate forcing of glacier mass balance. J. Glaciol. 65, 850–866. https://doi.org/DOI: 10.1017/jog.2019.66

Zemp, M., Huss, M., Thibert, E., Eckert, N., McNabb, R., Huber, J., Barandun, M., Machguth, H., Nussbaumer, S.U., Gärtner-Roer, I., 2019. Global glacier mass changes and their contributions to sea-level rise from 1961 to 2016. Nature 568, 382–386.

For more information about Geography at Royal Holloway visit:
www.royalholloway.ac.uk/research-and-teaching/departments-and-schools/geography/

Follow us: @RHULGeography YouTube