**Rubric and Key for Permafrost Module (25 pts)**

Suggestions:

You can have the students type the answers directly into the Jupyter Notebooks and have them turn them in for grading; however, we suggest having them write the answers in a lab notebook that can be turned in. For smaller classes, grading may be done during class. For keys to figures, please see the Jupyter Notebook key. While we provide answers and a rubric for all questions, the instructor may choose to grade only a few selected questions to make the grading easier, based on the most important learning outcomes for the course.

Part 1. Examining Permafrost data

4. The complete reference is: Roth, K., & Boike, J. (2001). Quantifying the thermal dynamics of a permafrost site near Ny‐Ålesund, Svalbard. Water Resources Research, 37(12), 2901–2914. [http://doi.org/10.1029/2000WR000163](http://doi.org/10.1029/2000WR000163" \t "_blank). (1 pt)

Pause for analysis: Permafrost temperature with depth and time.

4. They should have a chart in their notebook that looks something like the following. The temperatures will vary; accept any reasonable result. (1 pts)

Day 563, 1999, July

|  |  |  |
| --- | --- | --- |
| Depth | Color | Temperature |
| 0 m | orange | 12 C |
| 0.5 m | yellow | 7 C |
| 1 m | green | 2 C |

Discussion questions. Answers will vary slightly.

1. Coldest surface temperatures: -15 C. Warmest surface temperatures: 12C. (1 pt)
2. Coldest months: Feb-Apr. Warmest months: July-Aug. (1 pt)
3. The temperature appears to change more over the year at the surface. (1 pt)
4. Deeper underground it takes longer to warm and cool because it isn’t exposed to the air. They may also note that temperature increases with depth in the winter and decreases with depth in the summer, showing the lag in cooling and warming with the seasons. (Accept any reasonable answer) (1 pt)

Pause for analysis: Comparing ways of displaying temperature with depth.

1. The green profile looks like it corresponds to Nov 1998 because it is about -3 C at the surface to about 0 C at 1 m. October and May/June look similar. (1 pt)

2. The green curve is colder than the orange curve except at the deepest depths, where they are about the same. The orange curve also changes a lot more. In November, heat will diffuse from deeper underground, where it’s warmer, to the surface, where it’s colder. In July heat diffuses from the warmer surface down to the cooler depths. This occurs because the air is cooling the surface in November, which is why it is warmer deeper underground, while the ground is warming in July, so the surface is warmer than the deeper depths, so heat diffuses down. (1 pt)

3. The purple temperature profile was measured March 2000 around the 800th day. This is the coldest day both at the surface and at 1 km. (1 pt)

Pause for analysis: calculating the derivative

df/dx = 2x. This should make sense because it is linear, like the graph. (1 pts)

Try your skill: vertical heat flux

1. jh = -Kh\*np.diff(T\_July\_1998)/np.diff(z) (1 pt)
2. jh = -Kh\*np.diff(T\_Nov\_1998)/np.diff(z) (1 pt)

Pause for analysis: heat flow

1. Students will need to recall from the introduction that a positive value of jh means heat is moving down. In July, the heat flux is generally positive, so heat is flowing down from the surface. In November, heat flux varies a lot with depth. It is positive at the surface, so that heat is flowing down. But it quickly transitions to negative, so the surface heat will not penetrate far. From 0.25 m to 1.2 m it is negative, such that heat is flowing up. Below 1.2 m it is strongly positive, indicating that heat is flowing down again. (This variation makes sense because November is a transition season; the deeper layers have had time to warm up, but now air temperatures are cooling). (1 pt)
2. Heat flux is the greatest at the deepest depth (~1.23 m) for both cases. (1 pt)
3. Which profile (July 1998 or November 1998) has the greater heat flux? Overall July, because it is always fairly strongly positive. (1 pt)
4. In July, temperature decreases fairly linearly, and strongly, going down, so the heat flux is mainly up. In November, the temperature profile varied a lot near the surface and then was fairly constant underground. (1 pt)

Pause for Analysis: Permafrost data from Nome, Alaska

1. The Nome data goes much deeper than the data for Svalbard but is only given for summer (July/August). The depth range at Svalbard (surface to 1.2 m depth) is not included for most of the Svalbard profiles. (1 pt)

2. Inter-annual variability in surface temperatures. (They may note that near-surface temperature is increasing and attribute it to climate change, but detecting trends in climate requires a decade of data or more, rather than just 4 years.) (1 pt)

3. The heat fluxes will be generally negative below 10 m (heat flowing up) because it is warmer deeper underground. From the surface to 6 m below ground the opposite will be true. (1 pt)

Pause for Analysis: examining Nome heat fluxes

2. The heat fluxes are all about the same below 20 m and differ near the surface. 2011 stands out as the only profile with positive heat flux down to 12 km, and 2007 stands out as having very strong near-surface heat flux (but this data is absent for the other profiles). (1 pt)

3. Accept any reasonable answer (1 pt)

4. In 2011 the permafrost was warmer with a positive heat flux down to deeper depths. This indicates that heat would diffuse down deeper into the permafrost, with implications for permafrost thawing. (1 pt)

Post-activity reflection

1. The measurement technique for the deeper measurements was coarser. (0 pts)

2. Permafrost is permanently frozen ground. We care about it because warming due to climate change is causing permafrost to that. This has important implications, from releasing methane, which as a potent greenhouse gas will lead to further warming, to making buildings in the Arctic unstable. (1 pt)

3. Students might suggest a longer time record of measurements than what is shown here to understand better how climate change is affecting permafrost, more measurements in more places to get better coverage, or finer vertical resolution. Accept any reasonable answer. (1 pt)

4. jh = -Kh dT/dz. From the introduction, “Kh is the thermal conductivity, and it quantifies how well permafrost is able to transfer heat.” dT/dz is the derivative of the temperature with depth, or the change in temperature with a small change in depth at some depth position. (1 pt)