**Final Report by Joshua Holbrook on Center for Global Change research project “Determining anisotropic thermal conductivity of snow with needle probe measurements” funded in 2010**

I began to develop a new method for measuring thermal conductivity, adapted from the method of measuring isotropic thermal conductivity in snow with needle probes as used by Sturm, Johnson and others, in order to enable the determination of anisotropic thermal conductivities. [*Sturm et al.(2002)Sturm, Perovich, and Holmgren, Sturm and Johnson(1992)*] This method uses a needle generating a constant heat flux along its length to approximate an infinite line source, and transient temperature measurements of the center of the probe are used to calculate the thermal conductivity of the surrounding medium. Such needle probe measurements have particular relevance to measuring thermal conductivity of natural snowpacks where conductivity can be strongly anisotropic due to structures that develop from vapor transport-induced metamorphism, self-compaction and other mechanisms.

In general, the reasoning behind measuring and quantifying the thermal conductivity of snow is to allow researchers to build accurate climate models of arctic and sub-arctic regions. This is because of snow’s effects in the constant heat exchange occurring between the atmosphere and the ground. Because snow forms a layer above the soil, any heat conducting from the air into the ground (or vice versa) must also conduct through snow, as shown in Figure 1. Additionally, snowpack itself may store and release heat.

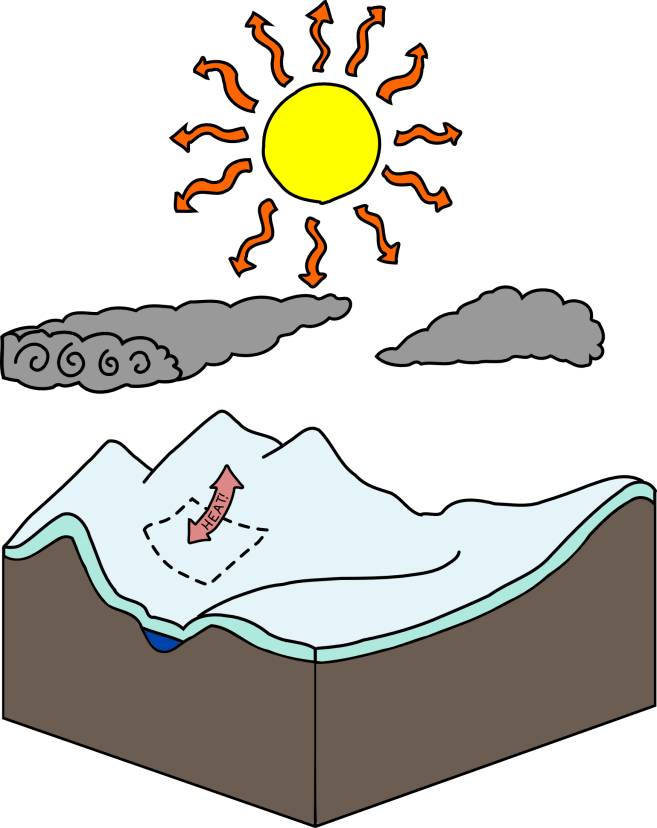
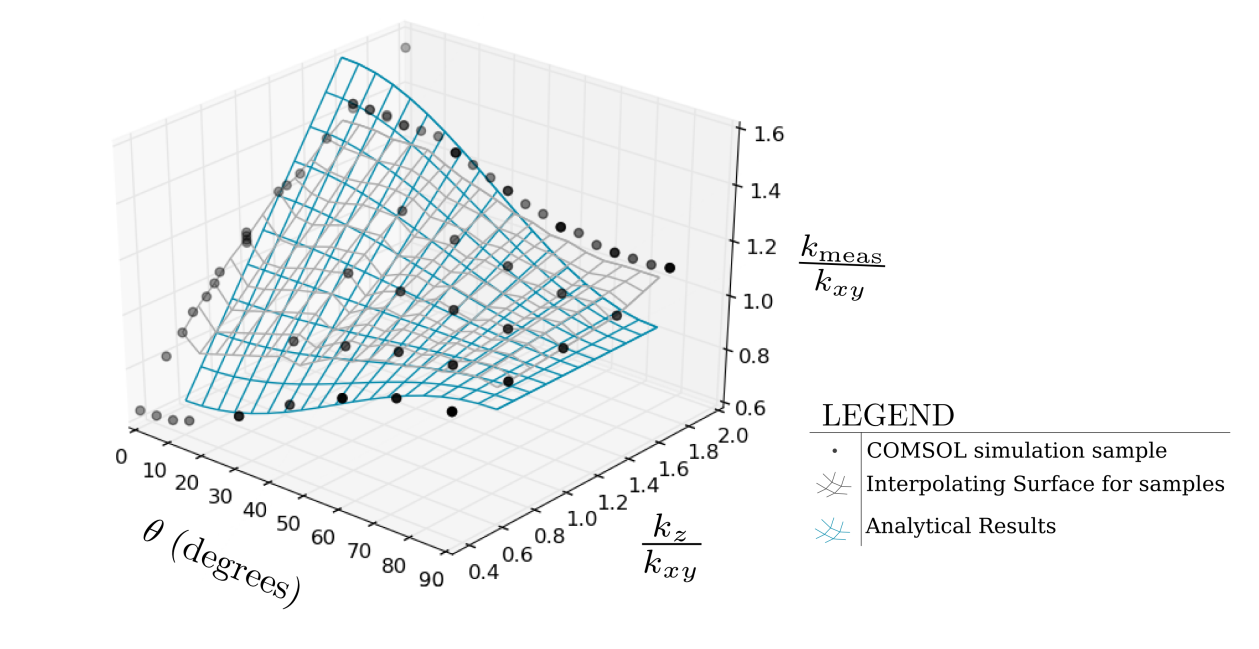


Figure 1: Arctic and Sub-Arctic climate is affected largely by heat transfer between the atmosphere and the ground. Snowpack adds thermal resistance transfer, affecting this heat transfer.

The development of this method in particular is motivated primarily by consistent discrepancies between density-conductivity relations empirically derived from guarded hot plate and needle probe methods. Generally, conductivity measurements by guarded hot plate methods (which induce a steady-state one-dimensional thermal gradient across a sample) tend to indicate higher conductivities than needle probe measurements for the same snow densities. One theory that could explain this is that the guarded hot-plate measurements are entirely a function of vertical snow thermal conductivity, while needle probe measurements tend to be a function of both vertical and horizontal snow thermal conductivities. However, in order to test this theory, a method for measuring anisotropic thermal conductivities must be devised.

Figure 2: A comparison of the numerical results and the analytical theory shows general agreement. Grey dots represent numerical simulation results, the grey surface represents an interpolating surface of the dots, and the blue surface represents the analytical model. Disagreement between the two may be due to edge effects and/or numerical model convergence issues.



I used both analytically-based solutions and finite element numerical solutions to the anisotropic case to calculate the expected effective thermal conductivity as a function of anisotropic thermal conductivity and needle orientation. The analytically-based solutions originate from modifications of the isotropic approach as detailed by Carslaw and Jeager, and do not account for the finite length of the real needle. [*Carslaw and Jaeger (1959)*] The finite element solutions are based on a 3D geometry that models edge effects; however, the mesh used for the finite element solutions is relatively coarse.

The results of both models show similar trends but have significant disagreements. The analytical approach correctly predicts isotropic thermal conductivities, while the numerical model predicts a higher thermal conductivity (on the order of 10%) than expected. This is believed to be due to the coarseness of the model mesh, based on the results of a small convergence study with the analytical model, where it was seen that a refined mesh resulted in smaller predictions for thermal conductivities on the order of magnitude required to explain this discrepancy. On the other hand, the analytically-derived model predicts the effective thermal conductivity to be a much stronger function of needle orientation than the numerical model for a given anisotropy. This is believed to be due to the modeling of edge effects in the finite element model. The differences in trends between the models may be seen in Figure 2.

Additionally, preliminary measurements of both anisotropic salt/sugar layered samples and of snow were taken. The anisotropic salt/sugar samples were layered in roughly one inch thick layers at varying orientations relative to the needle, while the snow measurements were taken with the needle at varying orientations relative to the snowpack's horizontal plane.

Unfortunately, real-world needle probe measurements are vulnerable to a relatively high level of variability in measurement as compared to the expected trends that would be seen in measurements as a function of needle orientation (for either model). This, combined with a disappointingly low number of successful measurements, meant that the null hypothesis could not be rejected in either set of measurements. However, the initial results of the snow measurements appeared to be promising.

Both models and measurements suggest that detecting anisotropy in such materials is possible, though made difficult by variability between measurements and the requirement of multiple measurements at various angles. Further measurements will be required in order to develop a statistically sound sample set, and further modeling will be required in order to establish a sufficiently accurate model.

These studies do suggest that anisotropy in snow may be able to explain in part the discrepancies between guarded hot plate and needle probe measurements in certain cases. In the case of alternating layers of snow, vertical conductivity is always greater than horizontal conductivity due to the geometry of the composite material, which would be expected to cause the opposite trend from what is seen in the guarded hot plate/needle probe discrepancies. [*Lunardini (1981)*] However, structural anisotropy, which may be caused by vapor transport, could be sufficient explain the differences.

**References:**

[*Carslaw and Jaeger (1959)*] Carslaw, H., and J. Jaeger (1959), *Conduction of Heat in Solids*, 2nd ed., Oxford University Press.

[*Lunardini (1981)*] Lunardini, V. J. (1981), *Heat Transfer in Cold Climates*, Van Nostrand Reinhold Company.

[*Sturm and Johnson(1992)*] Sturm, M., and J. B. Johnson (1992), *Thermal Conductivity Measurements of Depth Hoar*, Journal of Geophysical Research, 97 (B2), 2129–2139.

[*Sturm et al.(2002)Sturm, Perovich, and Holmgren*] Sturm, M., D. K. Perovich, and J. Holmgren (2002), *Thermal Conductivity and Heat Transfer Through the Snow on the Ice of the Beaufort Sea*, Journal of Geophysical Research, 107 (C21).

**Resulting Products and Presentations:**

[*Holbrook (2010)*] Holbrook, J. (2010), *Determination of Anisotropic Thermal Conductivity with Thermal Needle Probe Measurements*, in AGU Fall 2010 Posters.

[*Holbrook (2011)*] Holbrook, J. (2011), *The Measurement of Anisotropic Thermal Conductivity in Snow with Needle Probes*, Master’s thesis, University of Alaska Fairbanks

**The Role of the CGC Grant in My Graduate Experience:**

First of all, the CGC grant was the second grant I had ever applied for (the first being for the Undergraduate Research Competition), and the first I ever had to write a complete proposal for. This alone was a learning experience.

But then, of course, I was awarded a grant, and this research project became my thesis.

To me, “thesis” sounds like an understatement. I would hardly be exaggerating if I said that this research project took over a year of my life. I became an expert in a very particular field, and I worked more intensely and more passionately on this project, and for a longer period, than probably anything I’ve ever tackled previously. I pushed the boundaries not just of our collective knowledge of needle probe conductivity measurement techniques, but also my own abilities, patience and tenacity. I learned just how far I can push myself before losing my mind. I have experienced something few others have: Conducting professional-level academic research and writing a master’s thesis.

I am obscenely proud of what I’ve accomplished, and am grateful not only to my advisor and all the mentors I’ve found at this university, but also to CIFAR for enabling it all to happen. I am a different---and better---person than I was a year ago.

Thank you.

**Brief Financial Report:**

About $4,500 was spent on student wages during the month of August. An additional $1,300 was spent on travel and travel expenses for attending the AGU Fall 2010 conference, where I presented a poster. $200 dollars was spent on attendance fees for the same conference. Another $200 was spent on basic equipment, as I was able to borrow needle probe equipment from the U.S. Army Cold Regions Research and Engineering Laboratory. Remaining funds were spent on purchasing a needle probe of our own for future research.