Calculating the surface melt rate of Antarctic glaciers using satellite derived temperatures

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Extended Abstract

Understanding the surface melt rates of glaciers in relation to temperature is highly relevant given the predicted climate change scenarios and the fact that ice is a significant part of the physical geography of planet earth. At the global scale, ice melt from the major ice caps on earth are predicted to contribute significantly to sea level rise. At the habitat and ecosystem scale, ice melt could significantly change the availability of liquid water in alpine and polar regions. Given that liquid freshwater is a requirement for terrestrial biology and the scarcity of water limits biological activity, any change in the availability of liquid water will change habitats and ecosystems. This is particularly the case in Antarctica, which is considered the driest continent because of the sub-zero temperatures and the scarcity of liquid water limits biological activity (Fountain et al, 1999).

The surface melt rate of glaciers in relation to temperature is difficult to calculate because stream gauges need to be located near glaciers and monitored regularly. Also, for most temperate glaciers around the world, a high proportion of glacier melt seeps into the ground water and is not captured by stream gauges. For this reason, temperature index models of melt rate are calibrated specifically for particular catchments, usually using regression models that compensate for ground water flow.

The uniqueness of the McMurdo Dry Valleys in Antarctica provide an opportunity to calculate surface melt rates of glaciers because there are seven stream gauges that have been regularly maintained over the last decade, and ground water flow can be assumed to be insignificant because of permafrost (Chinn and Mason, 2015). The melting of glaciers is assumed to be restricted to the near surface because of the year-round subfreezing temperatures restrict hydraulic systems from developing (Dana, et al. 2002). This is not the case with temperate glaciers. The McMurdo Dry Valleys environment and flow gauge data provide a unique opportunity to develop a glacier surface melt rate model.

Models of ice surface melting have mostly been derived from energy balance or air temperature index calculations (Hook, 2003, 2005). An alternative to air temperature is the use of land surface thermal infra-red (IR) sensors aboard satellites. These provide spatial and temporal variation of land surface temperature (LST) at a variety of scales. For example, Landsat 8 captures thermal IR for most parts of earth at 60m pixels every 16 days, and MODIS captures thermal IR daily but at 1000m pixel size. LST measured by satellites, represent the balance of energy fluxes above and below the earth's surface. These LST measurements are distributed continuously across space and are "ready to use" measurements that do not require spatial extrapolation and modelling of point based weather station data. These measurements take into account elevation, aspect, sun angle and albedo, therefore additional modelling for these factors is not required. For this reason, satellite based LST are much simpler and more accurate than air temperature for modelling glacier surface melt.

The only prior comparable study that uses satellite land surface temperature to model glacier surface melt in the McMurdo Dry Valleys was completed by Dana et al. (2002). Their main focus of their study was the analysis of LST from six AVHRR images for a single day to determine if there was a relationship between LST of Taylor Valley glaciers and the corresponding stream discharge data. They concluded that satellite data had a strong relationship with diurnal stream flows. The core measurement that was derived from AVHRR images was the Temperature Area Index (TAI), which is defined as the number of pixels at or above a specified temperature. The TAI is a variation of the positive degree day measurement, and it is important that area (in this case pixel count) is included in the metric because glacier size has a significant influence on water discharge. In the Dana et al study, the best relationship (using ordinary least squared (OLS) regression) with stream flow was when the temperature threshold was minus 7°C. This threshold might seem unusual but the surface temperature of glaciers is rarely above zero. If they were, there would be considerable pooling of melt water and it would be the melt water that is above zero not the glacial ice. If the threshold is close to zero then many pixels that are producing melt water will be excluded. As the temperature threshold increases towards 0°C, the number of pixels at or above the given temperature threshold become increasingly zero, and many pixels that are producing melt water will be excluded. If the threshold is too low, pixels that are unlikely to produce water are included.

We build on the Dana et al research by developing an alternative degree-day metric that we call the Total Area Sum (TAS). Rather than counting the number of pixels above a threshold, the difference between the threshold and pixel temperature is calculated for each pixel and this is summed for the particular glacier. To build a robust model we used 77 cloud free Landsat images collected between 2013 and 2015 to produce a melt rate model based on daily land surface temperature changes. Alongside this, we develop a seasonal melt rate model based on 1660 MODIS images collected between 2002 and 2016. A major difference between Landsat and MODIS is the pixel size (60m versus 1000m respectively) and the frequency of the image capture. The larger cell size of MODIS makes it easier to work with but the disadvantage is the spatial accuracy. We used the Landsat 8 infra-red band to build a regression model showing the melt rate per hectare for a given land surface temperature (Daily Average Discharge L/sec/ha = 0.1 times surface temperature in Celsius + 0.7). While the MODIS LST data were used to build a seasonal average daily melt rate model, which is more conducive to the larger pixel size because of the number of images needed. A seasonal wide model can also include water flow data that has lag time because of the distance between glaciers and flow gauges. For the December-January melt period, the most suitable MODIS model is the mean TAS model using a temperature thresholds of -7°C, which has a r^2 of 0.791 and a coefficient of 3.4. Using this coefficient and scaling the MODIS pixel to one hectare (dividing by 100), the equation for seasonal mean daily discharge is (December-January):

> Seasonal Mean Daily Discharge (l/s) for a hectare of ice = 0.034 x (seasonal daily mean LST ^{0}C + 0.7) - for temperatures between -7^{0}C and 0 ^{0}C.

The utility of the seasonal MODIS model is demonstrated by calculating surface melt rates, water flows and wetness across the entire Ross Sea Region. The wetness index model developed by Stichbury et al (2011) was enhanced and applied to the whole of the Ross Sea region. The original wetness index model provided a relative wetness of different areas, which was calculated using the GIS terrain functions that calculate flow directions and flow accumulation. For calculating flow accumulation, each pixels was weighted by the number of days under snow. Areas under permanent snow were given equal weighting, so the accumulation results were only a relative index rather than actual water flows. The wetness index also includes slope, as water ponds in flat areas and therefore tend to be wetter. With the development of a spatial model of melt rate, the actual water flow accumulations can be calculated. The melt rates were used to weight each pixel so that the actual water flow accumulations were predicted. Since the resulting wetness model incorporates surface temperature, different climate change scenarios that effect surface temperature on wetness were modelled. The result is a spatial model of water availability across the whole of the Ross Sea Region that can be used to predict present hot spots of biology as well as future hot spots under different climate change scenarios. An unexpected large wet area to the southwest of the Ross Ice Shelf is estimated which requires further investigation and demonstrates the usefulness of a satellite LST derived surface melt rate model for monitoring large remote areas.

References

Chinn, T. and Mason, P. 2015 The first 25 years of the hydrology of the Onyx River, Wright Valley, Dry Valleys, Antarctica, Polar Record, doi:10.1017/S0032247415000212

Dana, G. L., Davis, R. E., Fountain, A. G., & Wharton, R. A. (2002). Satellite-derived indices of stream discharge in Taylor Valley, Antarctica. Hydrological Processes, 16(8), 1603-1616.

Fountain, A. G., Lyons, W. B., Burkins, M. B., Dana, G. L., Doran, P. T., Lewis, K. J., . . . Virginia, R. A. (1999). Physical Controls on the Taylor Valley Ecosystem, Antarctica. BioScience, 49(12), 961-971.

Hock, R. (2003). Temperature index melt modelling in mountain areas. Journal of Hydrology, 282(1–4), 104-115.

Hock, R. (2005). Glacier melt: a review of processes and their modelling. Progress in Physical Geography, 29(3), 362-391. doi:10.1191/0309133305pp453ra

Stichbury, G., Brabyn, L., Green, T. G. A., & Cary, C. (2011). Spatial modelling of wetness for the Antarctic Dry Valleys. Polar Research, 30(SUPPL.1).