Modeling the spatial distribution of moulins near Jakobshavn, Greenland

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ABSTRACT

Recent observations suggest that moulins can pressurize the subglacial system and enhance basal slide for short periods near Swiss Camp, Greenland (*Zwally et al.*, 2002). Contemporary moulin distribution must be understood to predict future moulin distribution. Moulin density was calculated from the known locations of 318 moulin in a study area surrounding Swiss Camp, Greenland. Moulin density reaches a maximum of 0.89 km^{-2}, which corresponds to a minimum moulin catchment area of 1.13 km^2. A multivariate spatial regression model was successful in reproducing half the variance in observed moulin density. The significant predictor variables in this model are (in order of importance): annual melt rate, ice thickness, mean shear strain rate, surface slope, driving stress and longitudinal coupling. Moulins appear to cluster together, producing relatively local high moulin densities. This model suggests that ice and bedrock geometry, ice dynamics and surface mass balance are not responsible for this clustering. We therefore speculate that moulin density at a given location may be due to the advection of upstream effects or positive thermodynamic feedbacks between moulins.

BACKGROUND

Glaciohydrology may have been a key contributor to the eventual demise of the Scandinavian Ice Sheet (*Arnold and Sharp*, 2002). The influence of meltwater on the ice dynamics of the Greenland Ice Sheet is of interest due to sea level rise implications. The velocity at which a glacier flows is the product of three distinct physical mechanisms: (i) internal deformation, (ii) basal slide and (iii) basal sediment deformation. Of these mechanisms, only basal slide is expected to respond to climatic change on relatively short time-scales (*Marshall and others*, 2005; *Bartholomaus and others*, 2007). Basal sliding speed, which is proportional to subglacial water pressure and/or storage, has been observed to vary on synoptic time-scales in both Alaskan alpine glaciers and marginal portions of the Greenland Ice Sheet near Jakobshavn Isbrae / Swiss Camp (*Zwally and others*, 2002; *Anderson and others*, 2004; Figures 1 and 2).

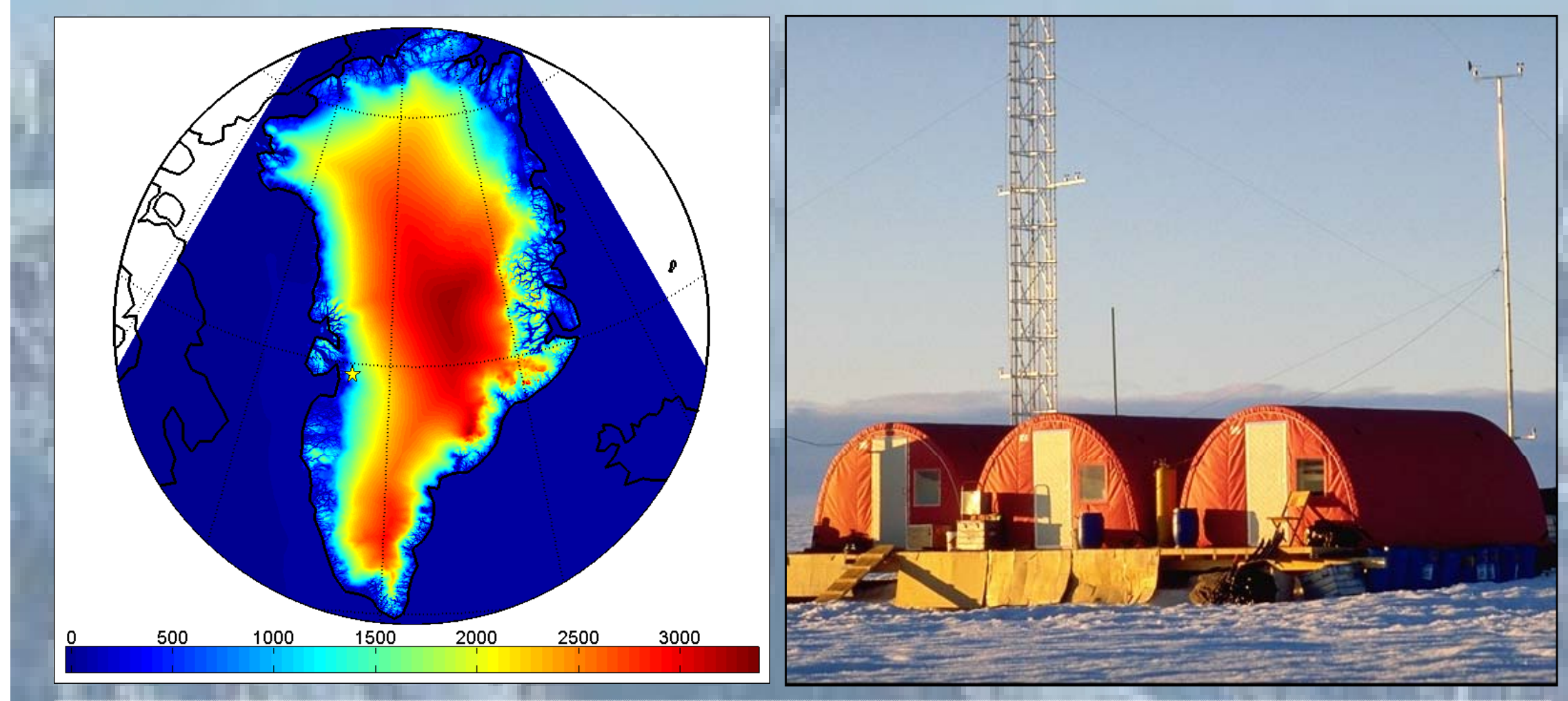

Figure 1 – Left: *A 625 m digital elevation model of the Greenland Ice Sheet (*Scambos and Haran*, 2002) with the location of Swiss Camp, near Jakobshavn Isbrae, shown with a yellow star.* **Right:** *Swiss Camp, Greenland (photo: K. Steffen).*

Moulins are vertical conduits which transport water from the surface of a glacier to its subglacial system. Moulins have a tendency to collect surface meltwater from a large surface area and discharge this water into the englacial (and subsequently subglacial) system at a single point (Figure 3). Therefore, the entry of water into the englacial system is highly spatially heterogeneous. Before the spatial variations in subglacial water pressure and storage beneath the Greenland Ice Sheet can be parameterized, the spatial distribution of moulins must be parameterized (Figure 2).

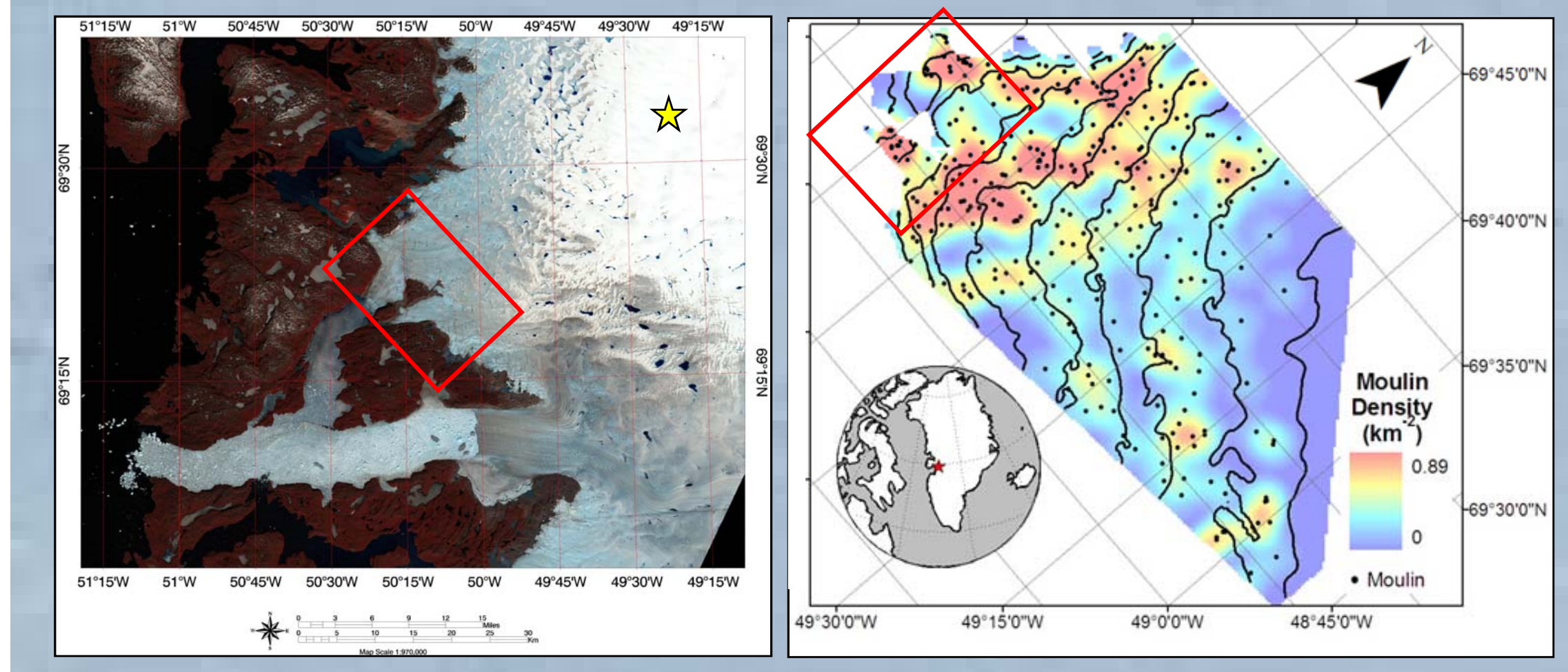

Figure 2 – Left: *A 1993 Landsat image of the margin of the Greenland Ice Sheet near Swiss Camp illustrates the abundance of surface meltwater (K. Steffen). The calving fronts of Jakobshavn Isbrae (bottom of the image) and Dead Glacier (center of the image) are visible. The location of Swiss Camp is shown with a yellow star.* **Right:** *Observed moulin density in the study area. The red boxes represent the same area which approximates the map sample in Figure 4.*

Although the present-day moulin distribution in the study area is closely related to latitude, longitude and altitude, using these variables to explain moulin density implicitly ties any model to contemporary atmospheric temperature patterns and lapse rates. A useful model of moulin distribution must explain moulin density at the typical scale of ice dynamic model resolution (> 500 m) and be allowed to evolve through time using only atmospheric temperature and ice and bedrock geometry. This investigation uses multivariate regression of an observed moulin distribution in the Jakobshavn region to create a model of moulin density which can be incorporated into a larger ice sheet model.

Figure 3 – *Moulins near Swiss Camp, Greenland, collect surface meltwater from large areas and discharge this water into the englacial system at a single point (photos: D. McGrath / K. Steffen).*

METHODS

The Danish Meteorological Office (DMO) has produced a topographic map, based on 1985 aerial photography, for a 40 by 20 km portion of the Greenland Ice Sheet just north of Jakobshavn Isbrae (*Thomsen et al.,* 1988; Figure 4). The point locations of 318 moulins identified by the map were digitized. These point locations were converted to a 500 m gridded density dataset of the area using a kernel density function (Figure 2). This observed moulin density dataset was then modeled using a stepwise multivariate regression. The types of independent predictor variables used in this regression included: (1) ice and bedrock geometry, (2) ice dynamics, and (3) surface mass balance.

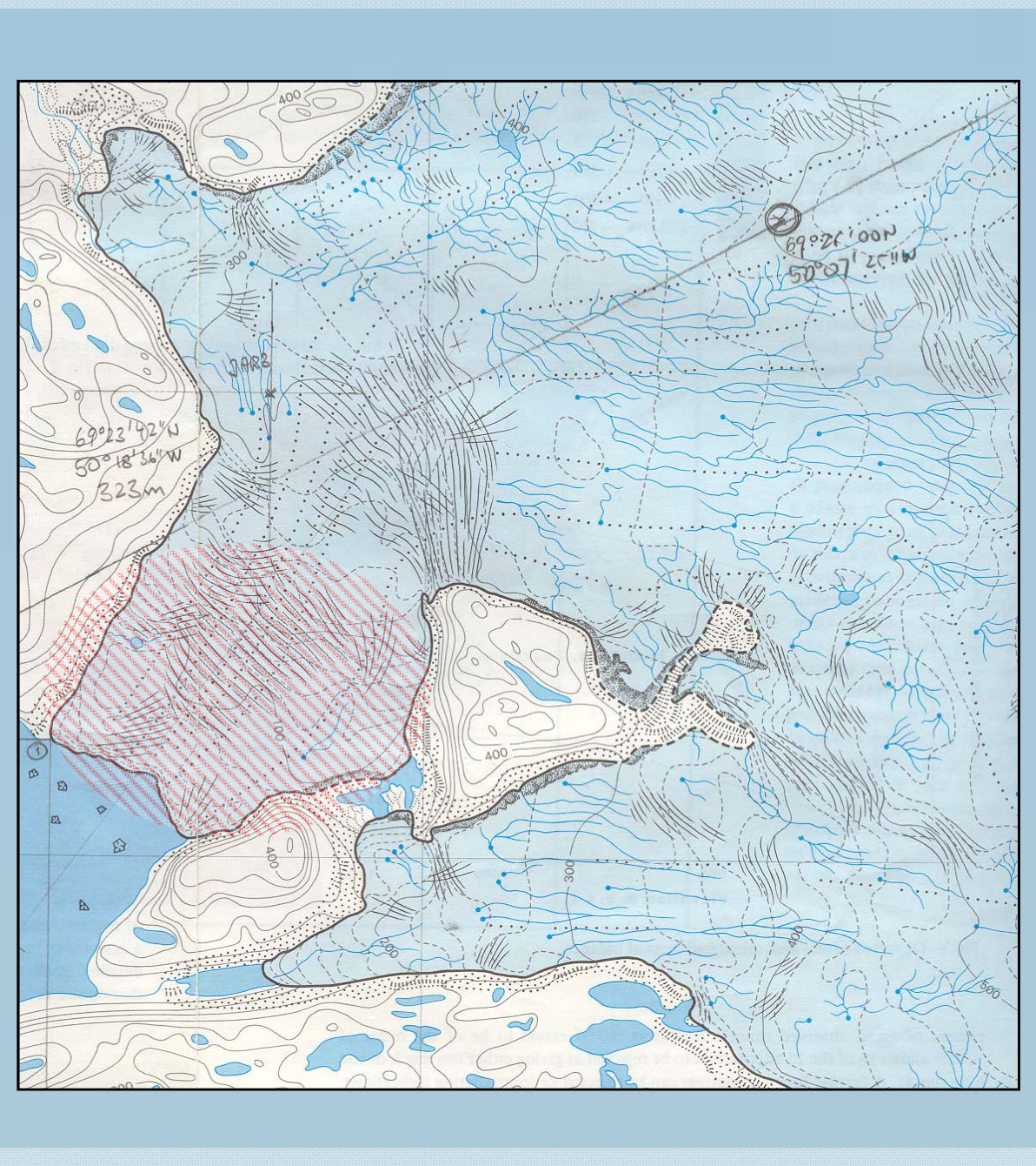

Figure 4 – *A portion of the DMO topographic map derived from 1985 air photos (*Thomsen et al., *1988). Moulins are the blue dots at the end of converging supraglacial streams. The terminus portion of Dead Glacier was excluded from the multivariate regression due to an extreme bedrock over-deepening (red hashing). This map area generally corresponds to the red boxes in Figure 2.*

Ice and bedrock geometry were derived from a number of datasets. The contour lines of *Thomsen et al.* (1988) were digitized and then kriged into a digital elevation model (DEM). This model was combined a 625 m DEM derived by satellite imagery (*Scambos and Haran*, 2002). As air photo-derived DEMs are known to be more accurate near exposed bedrock while satellite-derived DEMs are more accurate over flat interior regions of an ice sheet, a hybrid surface elevation DEM was created which used the *Thomsen et al.* (1988) DEM below 700 m and *Scambos and Haran* (2002) DEM above 900 m. A high-resolution ice thickness dataset was interpolated to 500 m resolution and subtracted from the hybrid surface elevation DEM in order to determine the bedrock topography within the region (*Plummer et al.*, 2008).

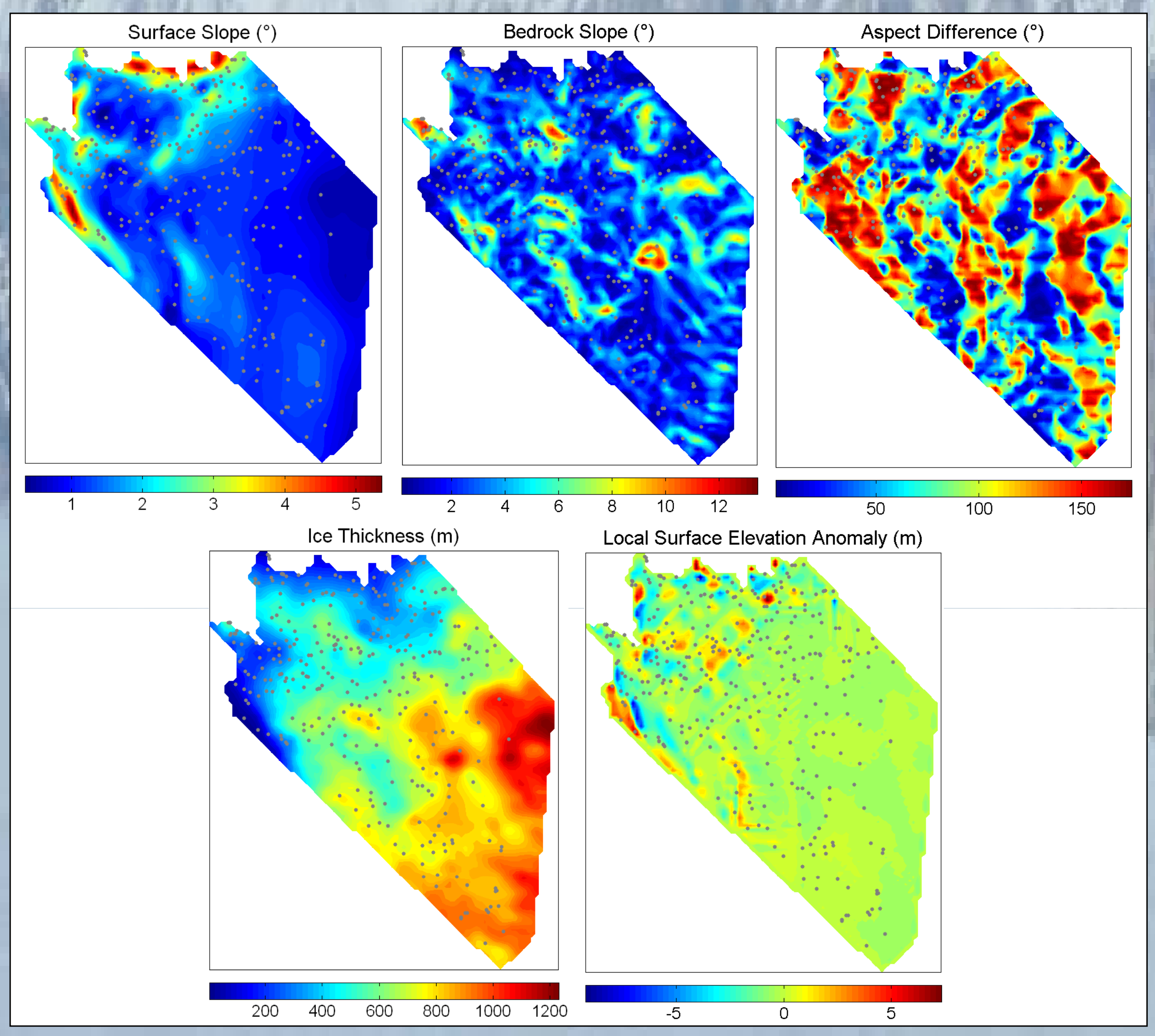

Figure 5 – *The ice and bedrock independent variable: surface slope, bedrock slope, the aspect difference between the ice and bed surfaces, ice thickness and local surface elevation anomalies (*Thomsen et al., *1988;* Scambos and Haran, *2002;* Plummer et al.*, 2008). Grey dots indicate observed moulin locations.*

The ice thickness and hybrid surface DEMs were used to calculate the ice and bedrock geometry independent variables of: (i) surface slope, (ii) bedrock slope, (iii) the difference between the bedrock and ice surface aspects, (iv) local surface elevation anomalies and (v) ice thickness (Figure 5). Local surface elevation anomalies were calculated as the elevation difference between the elevation of a given grid cell and the mean elevation of the neighboring eight grid cells.

The DEMs were also used to calculate the ice dynamic independent variables of: (vi) driving stress, (vii) longitudinal coupling stress, and (iix) mean shear strain rate (Figure 6). Longitudinal coupling stress was calculated according to *van der Veen* (1987), and driving stress was calculated as the sum of the shallow ice approximation and the longitudinal coupling at each grid cell. Mean shear strain rate was approximated as velocity divided by ice thickness (*Burgess et al.*, 2005).

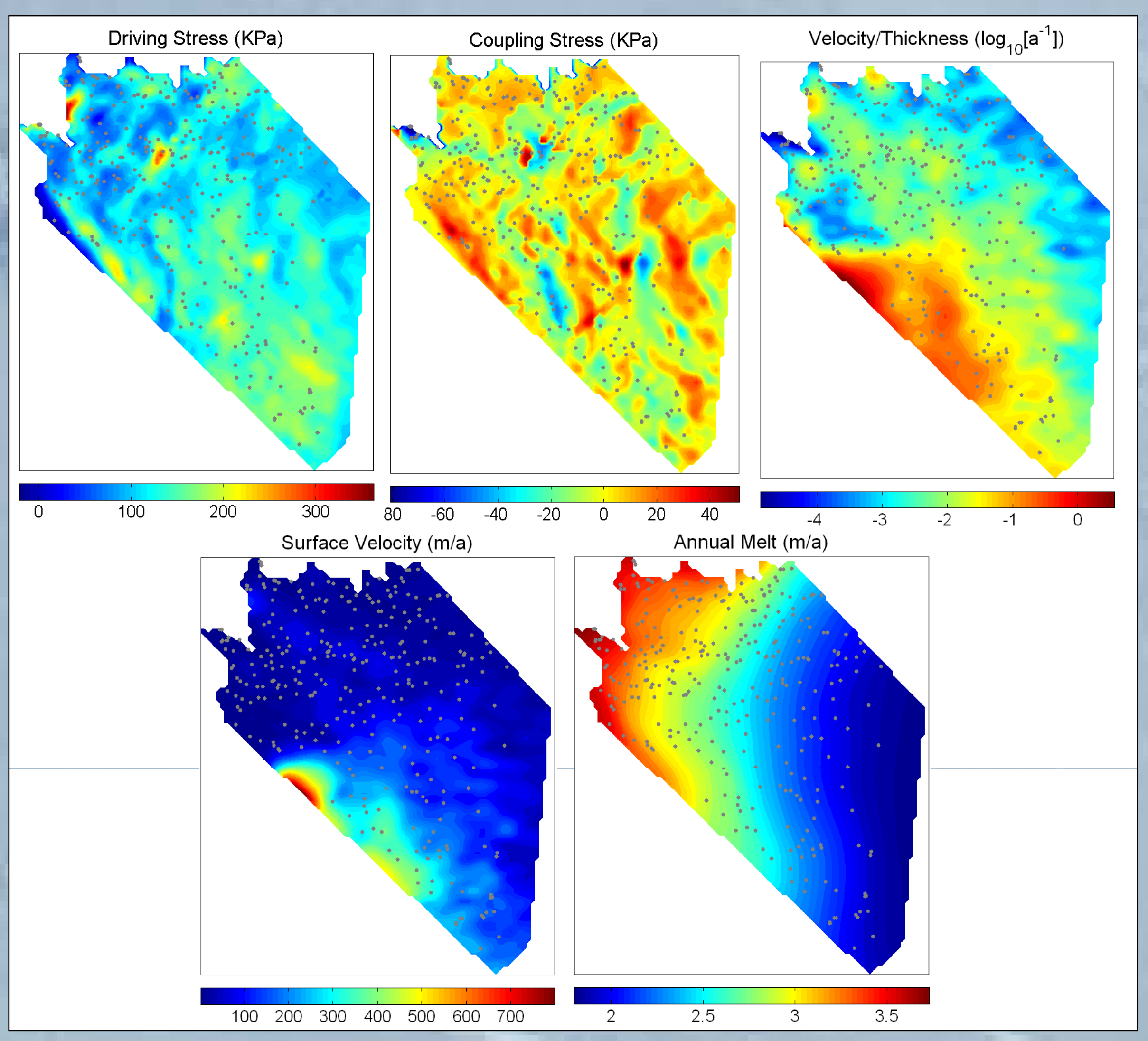

Figure 6 – *The ice dynamic independent variable: driving stress, longitudinal coupling stress, mean shear strain rate (expressed as surface velocity divided by ice thickness) and ice surface velocity (*Rignot and Kanagaratnam, *2006). Surface mass balance is parameterized by annual melt rate, which is calculated according to a previously developed positive degree day model (*Thomas et al., *2003). Grey dots indicate observed moulin locations.*

Ice surface velocity (ix) was not calculated, as that would require *a priori* assumptions about ice temperature, but rather interpolated from a high resolution dataset (*Rignot and Kanagaratnam*, 2006; Figure 6). Surface mass balance, parameterized as annual melt rate (x), was calculated based on a positive degree day (PDD) model. This PDD model has been previously validated with Greenland Climate Network (GC-Net) data and applied to the Jakobshavn region (*Thomas et al.*, 2003; Figure 6). Positive degree days were calculated using previously published lapse rates and latitudinal gradients and the 25 year mean monthly temperature record from nearby Ilulissat, Greenland (*Hanna et al*., 2005).

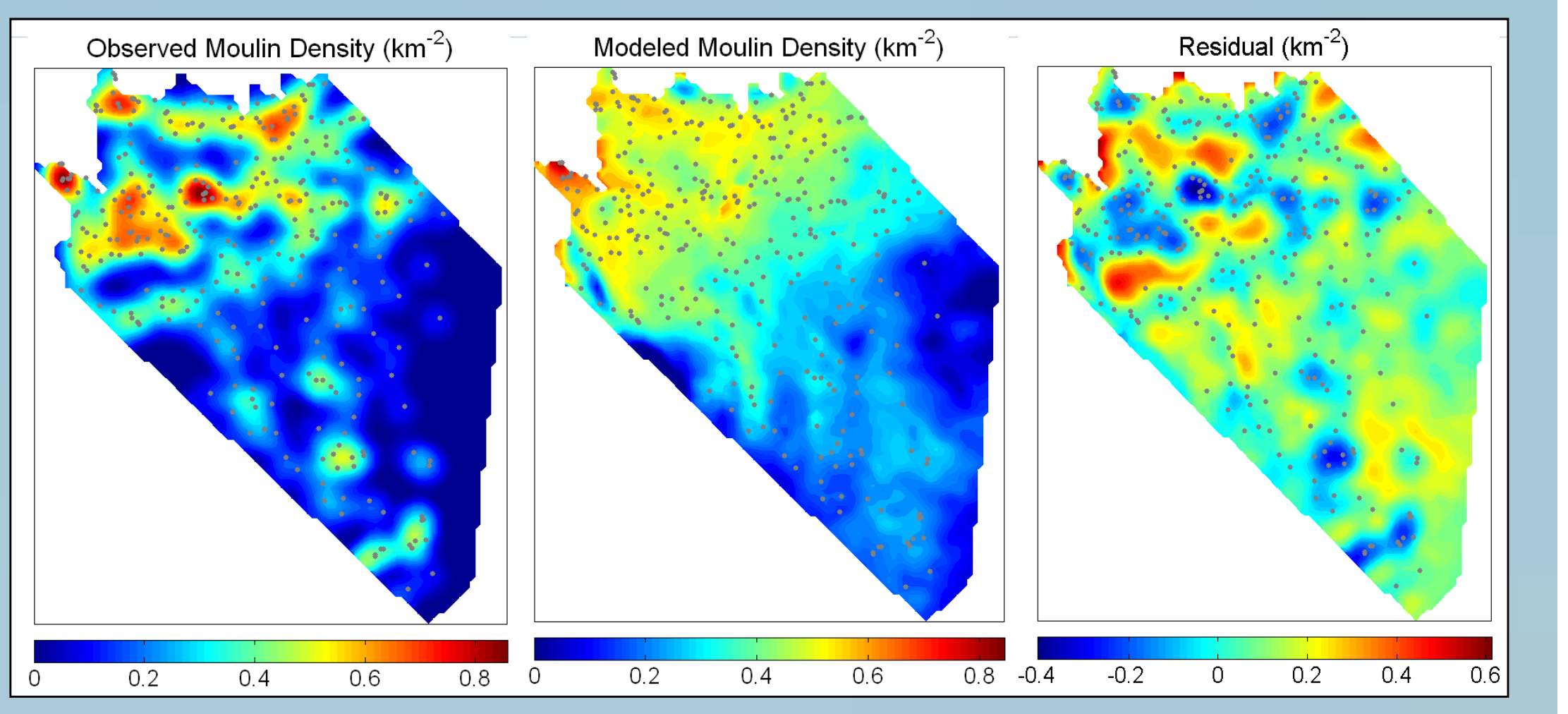

Figure 7 – *Observed moulin density (*Thomsen et al., *1988), modeled moulin density (Equation 1) and model residual (modeled minus observed). Grey dots indicate observed moulin locations.*

RESULTS AND DISCUSSION

Observed moulin density (D_{obs}) generally increases toward the margin of the Greenland Ice Sheet, with values ranging from 0 to 0.89 km^{-2} (Figure 7). This corresponds to a minimum moulin catchment area of 1.13 km^2 ($1/D_{obs}$). The stepwise multivariate regression model describes approximately 50 % of the variance in observed moulin density ($r^2 = 0.52$) with a standard error, or absolute residual value, of 0.12 km^{-2}. Annual melt rate (M; in m/a), ice thickness (H; in m), driving stress (τ_d; in Pa), longitudinal coupling stress (τ_c; in Pa), surface slope (α; in °), and mean shear strain rate (ε; in a^{-1}) are significant predictor variables in the regression model ($p < 0.001$), while surface velocity, bedrock slope, the difference between the bedrock and ice surface aspects, and local surface elevation anomalies are not significant predictor variables ($p > 0.05$). The modeled moulin density (D_{mod}) at a given location within the study area can be described by:

$$D_{mod} = c_1 \cdot M + c_2 \cdot H + c_3 \cdot \tau_d + c_4 \cdot \tau_c + c_5 \cdot \alpha + c_6 \cdot \varepsilon + 0.43 \qquad \text{Equation 1}$$

where c_1 through c_6 are the regression coefficients (Table 1). These coefficients suggest that moulin density increases with increasing melt rate and driving stress, while moulin density decreases with increasing longitudinal coupling stress (more compression), ice thickness, surface slope and mean shear strain rate.

Coefficient	Value	Units
c_1	0.127	$km^{-2}/m/a^{-1}$
c_2	$-6.78 \cdot 10^{-4}$	km^{-2}/m
c_3	$2.31 \cdot 10^{-6}$	km^{-2}/Pa
c_4	$-3.62 \cdot 10^{-6}$	km^{-2}/Pa
c_5	-0.142	$km^{-2}/°$
c_6	-0.473	km^{-2}/a^{-1}

Table 1 – Coefficient values for Equation 1.

The observed moulin density appears to have clusters or hotspots of relatively high local moulin density. As seen by model residual, the model does not capture this local variability in moulin density. Intuitively, clusters of moulins can be attributed to local depressions in the surface topography. This study, however, finds that anomalous surface depressions, resolved down to the 500m scale, are not correlated with observed moulin density (Figure 5). Surface topography anomalies smaller than the resolution of the DEM used in this study (i.e. narrow channels) may be responsible for the establishment of moulin hotspots.

Alternatively, a physical process unrelated to (i) ice and bedrock geometry, (ii) ice dynamics and (iii) surface mass balance, such as thermodynamic positive feedbacks between moulins, may be responsible for the presence of moulin hotspots. Additionally, the simple multivariate regression model used in this study assumes that the moulin density of a given grid cell is a function of the parameters of that grid cell. This approach does not account for the possibility that observed moulin density is a function of events upstream (i.e. crevassing) which are advected downstream by ice flow.

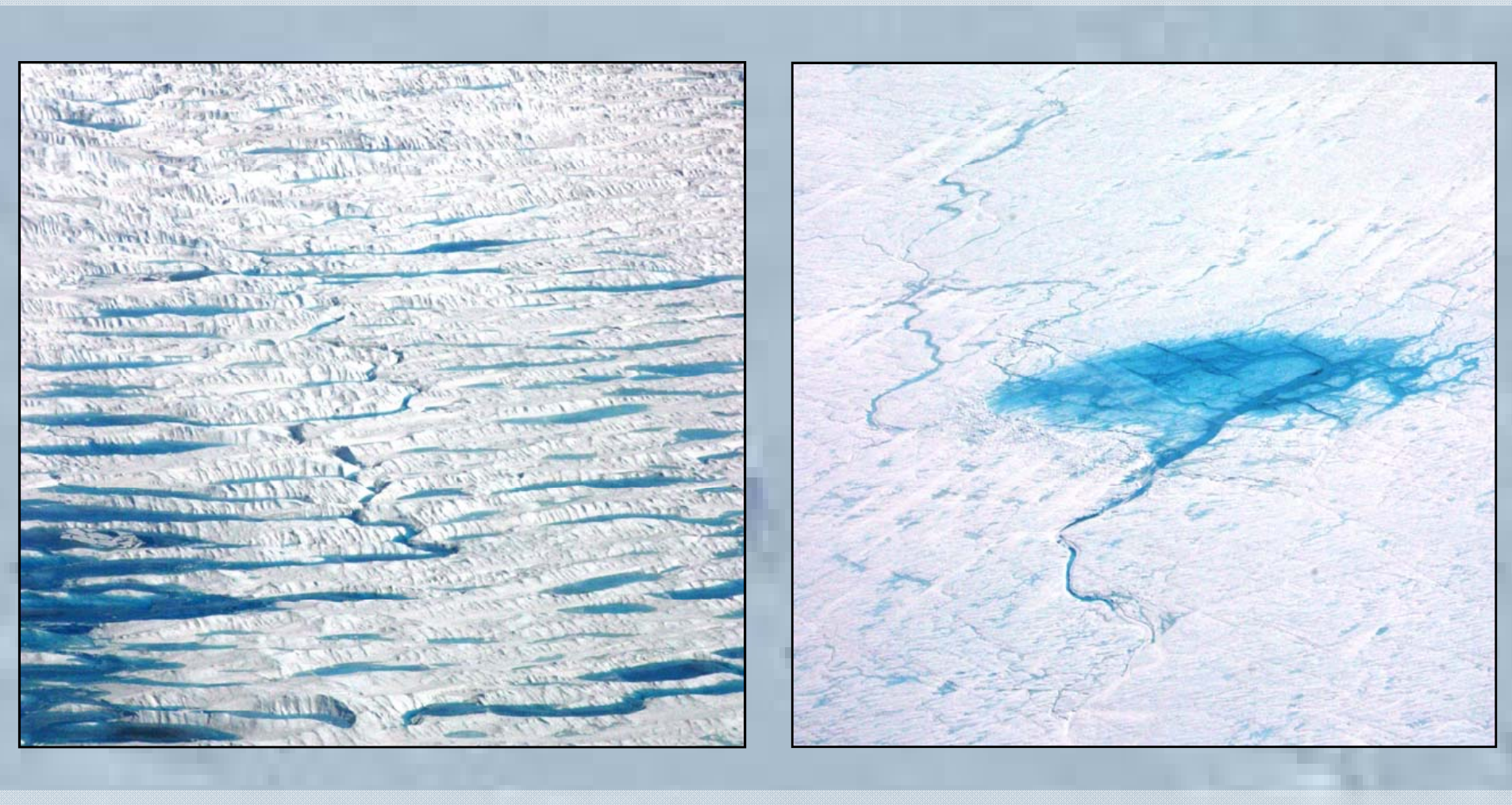

*Figure 8 – Supraglacial streams drain water-filled crevasses (***Left***) and a supraglacial lake (***Right***) near Swiss Camp, Greenland (photo: W. Colgan).*

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