Snow Depth Variability of Wind Loaded Slopes
BIG SKY - MONTANA

Snow Dynamics & Accumulation - Spring 2022

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INTRODUCTION:

Understanding snow depth variability in complex mountain terrain at the slope scale is an integral part of explaining both our water resources and avalanche hazards. This is especially critical in areas where large amounts of snow are transported and deposited by wind. Leeward slopes can accumulate three to five times more snow than nearby wind-protected valleys (McClung and Schaerer 2006). Above treeline, this is often induced by orographic lifting, complex terrain/pressure relationships, and carried out through preferential deposition (Lehning et al. 2008), saltation, and suspension. The wind is an often poorly quantified variable, and topographic features with a change in slope as little as 10 degrees can significantly change drift development (McClung and Schaerer 2006). Prevailing winds and daily wind direction and speed in complex mountain terrain have consequential effects on blowing snow deposition and depth (Dadic et al. 2010). Many models have been tested to try and incorporate wind deposition through storm and atmospheric models as it translates to spatial variability of depths (Winstral, Marks, and Gurney 2013). But nothing has been officially implemented to rectify this shortcoming in official models, and the majority of forecasting for wind slabs still relies on manual observation and local knowledge of the terrain (McClung and Schaerer 2006). In addition, this field day (March 30, 2022) nearly coincided with the date traditionally used to calculate the annual water availability of the summer's snowpack (Pagano et al. 2009) which is useful for forecasting the seasonal water supply.

For this project, snow depth was measured in two sites highly prone to wind deposition, in an attempt to quantify variation in the height of snow at the slope scale, and by aspect, with respect to the local prevailing wind direction. In addition, this project was conducted at the same study plot locations as Nata De Leeuw's master's thesis sites in the hope that she could incorporate this data into her project to understand the spatial variability of depths on the slope.

LOCATION:

The study sites consisted of two separate plots at the Yellowstone Club in Big Sky, MT. The first field site, "Spirit," is located directly underneath and just downhill from the top of the American Spirt Lift at 45.23986, -111.44252, and 2674 meters. The second field site, "Eglise," is in a gully 200 meters E of the top of Great Bear Lift.. is at 45.20717, -111.42558, and 2833 meters. Both field sites are shown in the Map below in ***Figure 1.*** Spirit is located on an East facing slope, and Eglise is within a gully that sees a broader range of aspects (SE-NW). Both are topographically located in areas of high wind deposition and blowing snow activity.

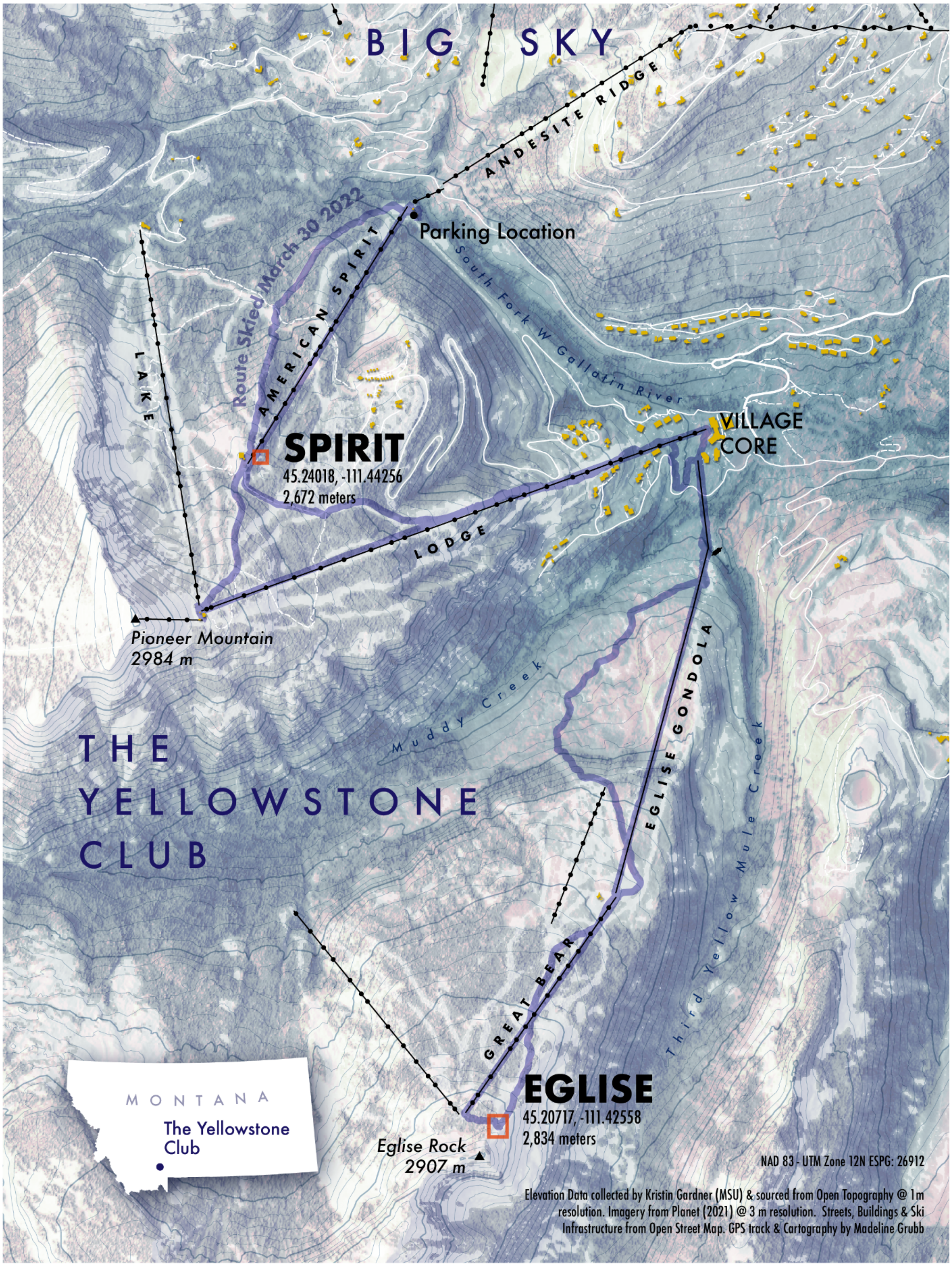

Figure 1: Overview Map Depicting Site Locations and Route Skied on March 30, 2022

FIELD METHODS:

Gridded GPS Data for the height of snow was collected on March 30, 2022, at two field sites. A rough grid plan for probing was laid out at each site based on the desired coverage area and the time allotted for data collection. At the Spirit site, the grid was triangular, with a probe strike in each row located as precisely as possible, between the two strikes above it, and at the same distance away. At the Eglise site, the grid was rectangular, with each strike taken at roughly the same horizontal and vertical location in each row. At the Spirit site, each probe strike was on average 1.23 meters apart from the other strikes, and at the Eglise site, 2.82 meters. A probe strike was taken at every point along the grid and measured on an android tablet at each specific GPS location. An Emlid RS2 Reach GPS receiver was used to collect coordinate information down to about 0.25-meter accuracy. 90 data points were taken at the Spirit site in an irregular grid, and 100 at Eglise, in a roughly 10x10 grid (one row contained only 9 points and another 11). GPS Accuracy and Sample count for each data point can be seen in ***Table 1*** below. Route skied between each site can be seen above in ***Figure 1.*** Nata De Leeuw and Maddie Beck assisted in field data collection. They also dug a pit at each site on the day of the study for Nata's fieldwork.

Table 1: GPS Accuracy information from the Reach RS2.

Count	Samples	PDOP	Easting RMS	Northing RMS	Elevation RMS	Lateral RMS
190	21	1.11	0.25	0.22	0.50	0.34

GIS METHODS:

The raw data was exported off the GPS unit as a .csv file and uploaded to ArcGIS pro. An interpolated surface was derived for each site using Empirical Bayesian Kriging. EBK differs from other Kriging models by using an intrinsic random function at the core of the model. Instead of attempting to follow an overall mean, the model allows for deviations in data that stray from the mean of the dataset, such as we would expect to see with the variability of snow depth. EBK repeats this estimation process for a large number of semivariograms, which are then combined into one interpolation surface, and a separate surface that shows the average standard error of all the combined semivariograms. This interpolated snow depth raster was resampled to 1-meter in scale, and points were derived from each pixel cell for comparisons of our collected data and our interpolated data. These were analyzed with respect to a 1-meter DEM provided by Kristin Gardner in 2005 ("OpenTopography - Big Sky, MT: Patterns of Nitrogen Export & Land Use Change" n.d.). The aspect of the slope, as derived from the DEM was binned into categories, and statistically summarized with respect to the interpolated data points.

RESULTS:

Snow depth was measured across both sites as being consistently variable, and this was translated into our interpolated models with varying levels of accuracy. At Spirit, where 90 measurements were taken with a mean snow depth of 210 cm, we saw a range of values from 95 to 270 cm and a standard deviation of 39 cm ***(Table 2)***. This translated fairly well to our 224-point interpolated model. For most of our sites, we saw less than 10 cm of standard error between our GPS locations, which translates to higher accuracy of interpolation across the grid of measurements, as seen in ***Figure 3***. At Eglise, where 100 data points were collected, at a grid around twice as dense (1.23 m compared to 2.8 m), we saw a mean snow depth of 125 cm. There was far more variability, with a minimum of 14 cm, a maximum of 318 cm, and a standard deviation of 72 cm. This translated into an 1112-point interpolated model with a mean snow depth of 129 cm. The standard deviation for the model was 72 cm, and the minimum and the maximum became more tightly clustered at 17 cm and 289 cm ***(Table 3).*** The spread of the real versus interpolated data can be seen in the box plot below in ***Figure 2.***

Table 2: Statistical Summary of both Real & Interpolated Data Collected at Spirit

Spirit Data	Count	Mean Snow Depth (cm)	Min. Snow Depth (cm)	Max. Snow Depth (cm)	STD Snow Depth (cm)	Med. Snow Depth (cm)
Real Data Points (Probing)	90	210	95	270	39	223
Interpolated Points (Kriging)	224	210	93	256	34	220

Table 3: Statistical Summary of Both Real & Interpolated Data Collected at Eglise

Eglise Data	Count	Mean Snow Depth (cm)	Min. Snow Depth (cm)	Max. Snow Depth (cm)	STD Snow Depth (cm)	Med. Snow Depth (cm)
Real Data Points (Probing)	100	125	14	318	72	120
Interpolated Points (Kriging)	1112	129	17	289	68	132

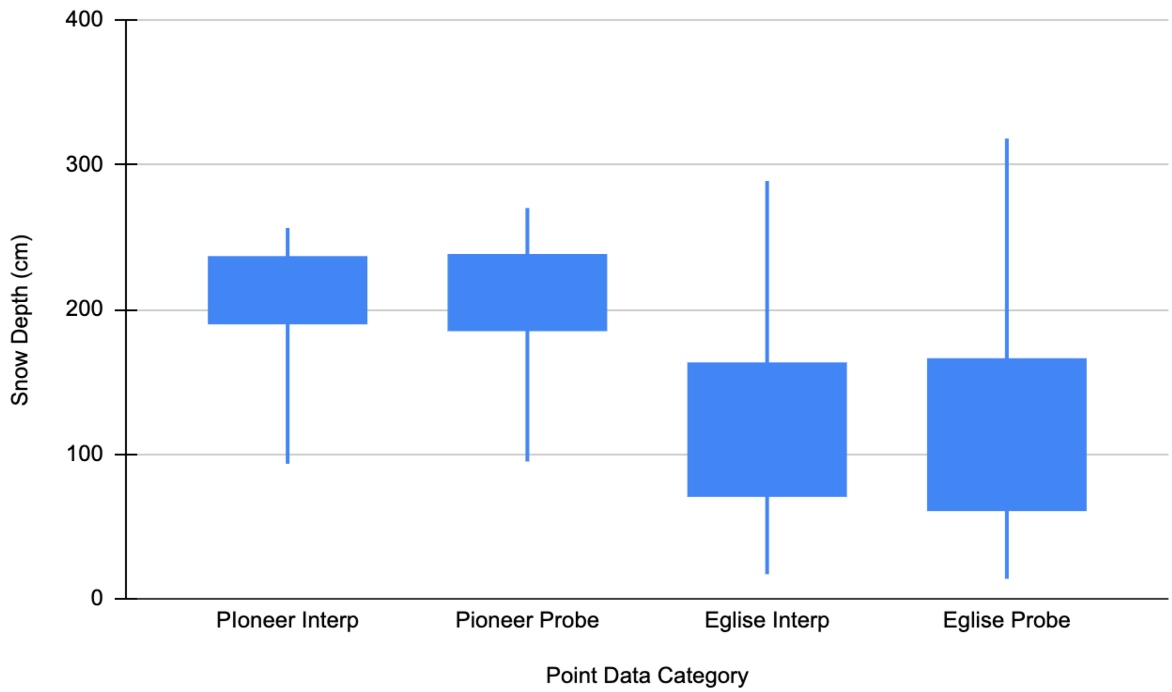

Figure 2: Boxplot showing the relative distribution of Real vs Interpolated Point Data

A correlation could also be drawn between snow depth and aspect. This was especially apparent at the Eglise site, where we observed a wide variety of aspect values. East-facing slopes saw the areas of highest accumulation, with a mean depth of 155.1 cm. And Northwest slopes saw the lowest snow depth values of 50.7 cm.

Aspect	Interpolated Pts.	Mean Snow Depth (cm)	Min. Snow Depth (cm)	Max. Snow Depth (cm)	Std. Dev. Snow Depth (cm)
East	169	215.9	125.4	256.2	28.0
North	541	101.3	17.7	284.1	57.9
Northeast	276	187.8	125.2	288.7	46.3
East	144	155.1	89.7	279.2	49.0
Southeast	1	159.1	159.1	159.1	0.0
Northwest	47	50.7	28.9	107.7	15.1

The first map created ***(Figure 3)***, shows the measured probe sites as well as the standard error of the predicted value from the Kriging model. The second map ***(Figure 4)***, depicts interpolated snow depth across each site, with select estimated values called out for reference.

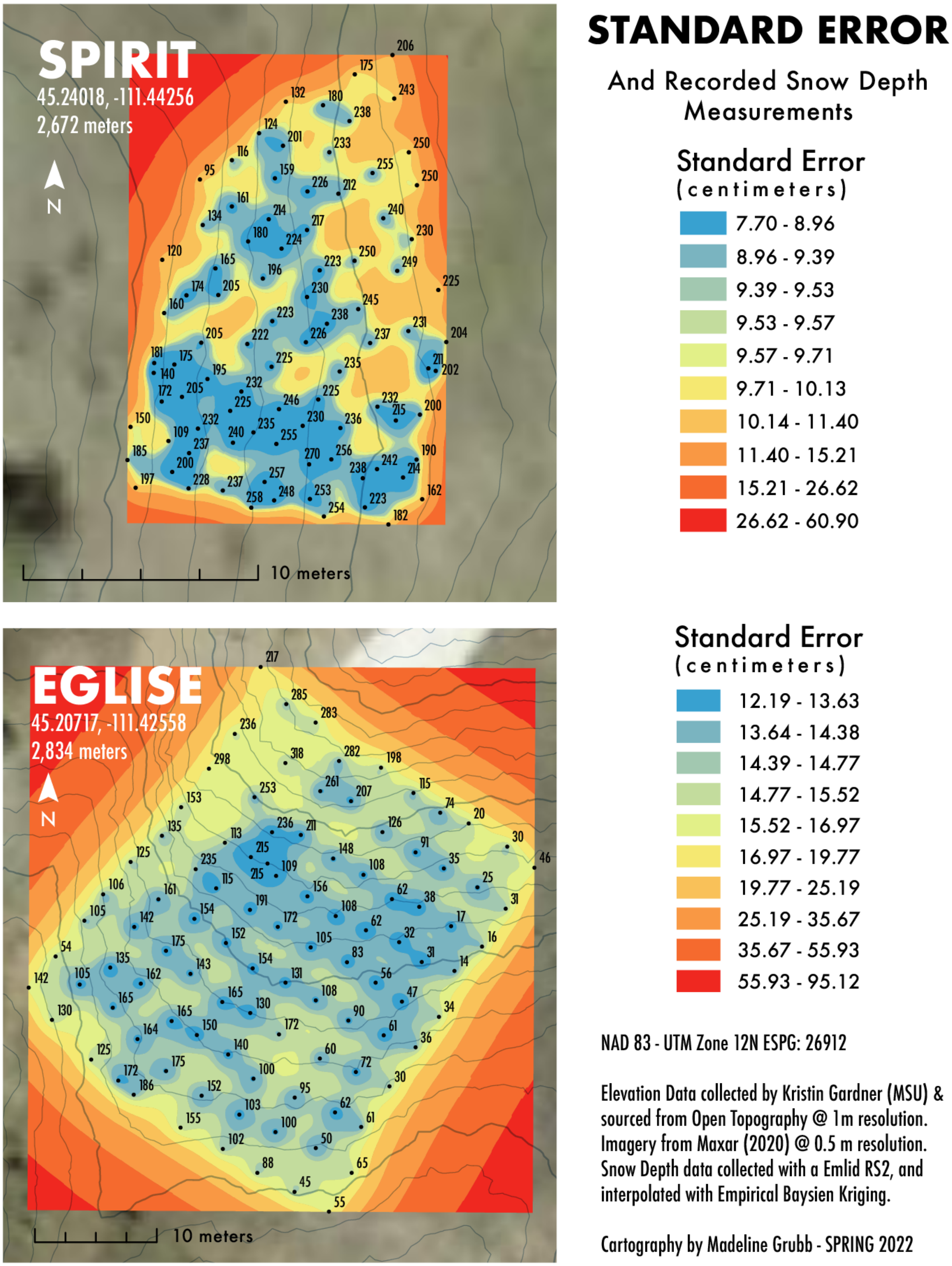

Figure 3: Map Depicting SE of the Interpolated Surface, and Snow Depth Probe Measurements

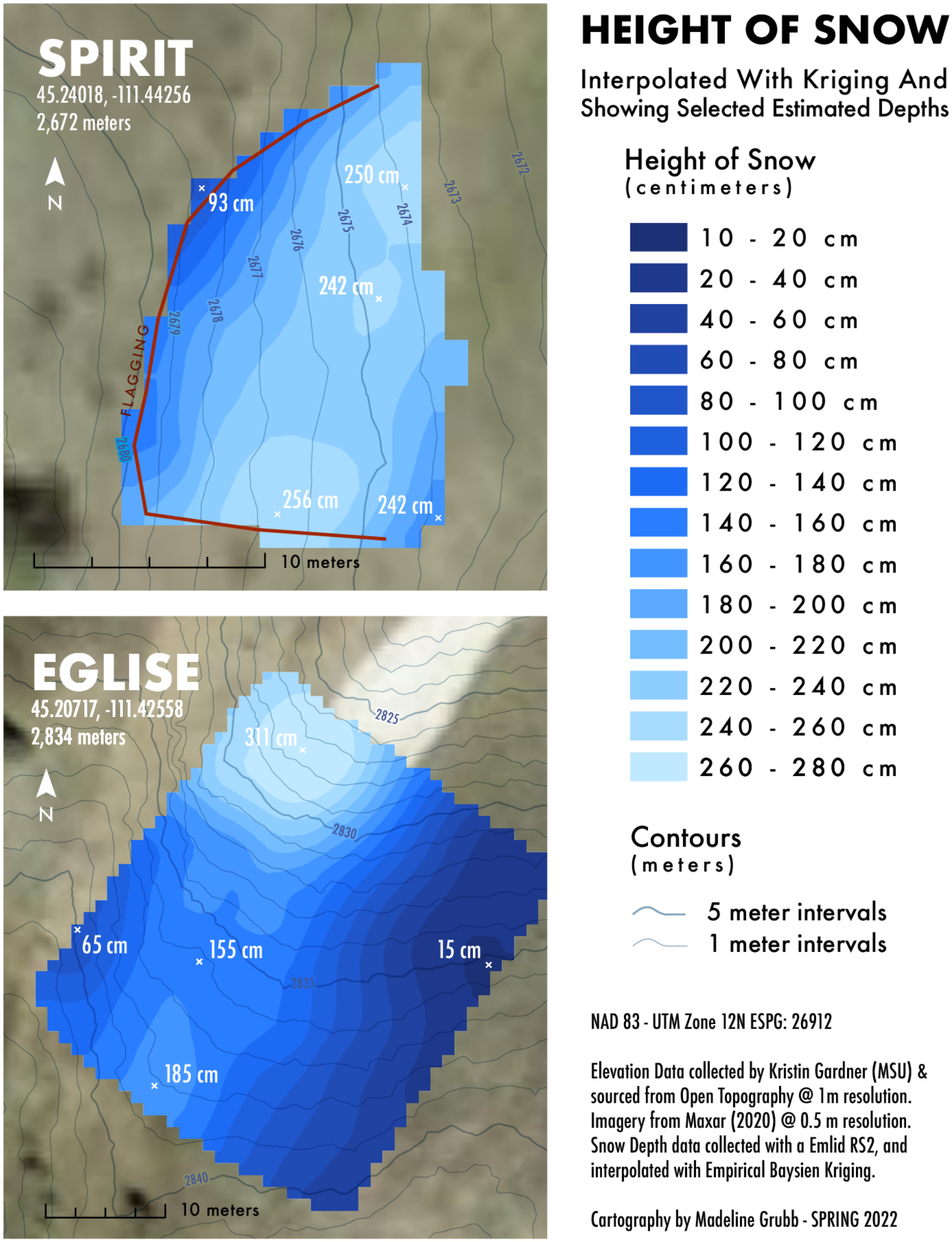

Figure 4: Map Depicting Interpolated Snow Depth Surface at Both Sites, based on an Empirical Bayesian Kriging Model. Select Snow Depth Estimates Included for Reference. 1 Meter Contours.

DISCUSSION:

Snow depth, as expected presented great slope-scale variability at each site. This variability was exasperated by what aspect a measured depth was on, and the topographic features that controlled wind deposition. The gully at Elgise, for instance, saw a much larger range of values, likely due to its topography, and the nature of wind-driven ablation and deposition occurring on some slopes and not on others. This makes sense at Eglise with the S-SW prevailing winds, stripping the Northwest slopes while depositing snow in the center of the gully on East-facing slopes. Spirit sees primarily SW winds, which would translate to loading on the gently sloping east-facing ridge.

Our interpolated model was more accurate at Spirit than it was at Eglise, and this can be seen on the Standard Error map in ***Figure 3***. Part of this could be due to the scale of the slope being measured. Spirit was 223 m^2 while Eglise was 1118 m^2. But it could also be attributed to the nature of the triangular versus rectangular grids. Spirit has a lower overall standard error, but where high levels of error do occur, they appear more clustered when compared to Eglise, which has a relatively consistent (albeit slightly higher standard error). The third reason this inconsistency of error may be expressed at Spirit but not at Eglise is due to the fact the methods were being tested for the first time at Spirit, and there may be a higher level of introduced human error, both in measurements, and grid spacing. Both of which would have an effect on interpolated accuracy.

A major limitation of this project is the fact that it was only conducted once and on a seasonal scale. While some preliminary conclusions can be drawn with respect to aspect and prevailing seasonal wind direction, it would be beneficial for future studies to look at both height of snow, and wind slab depth, several times as the season progresses. This could be done in conjunction with major storms and specific wind events, for a better understanding of the data.

CONCLUSION:

What the data does show, is that snow depth is incredibly variable at these two sites that we know experience high wind activity. Snow depth estimation can be used in combination with Snow density, to estimate Snow Water Equivalent, and because April 1 has historically been used as a proxy for the average date of maximum SWE (Pagano et al. 2009), it should be fairly representative of available SWE coming out of these study plots. Our main finding is the development of a workflow that can interpolate and asses both snowpack heights and their potential errors to a relatively high degree of accuracy. If this workflow could be implemented to calibrate other data and wind/atmospheric modeling techniques, it could be potentially beneficial in better understanding wind loading at the slope scale, and higher accuracy forecasting down the line with respect to small scale topographic features. This could be used in conjunction with work done by (Dadic et al. 2010) to validate output data created by forecast models. Field data collection could also be used in combination with a GIS-based approach to build on the work done by (Winstral, Marks, and Gurney 2013) in order to create better spatial-based slope scale models.

References:

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