Mapping high elevation spatial snow depths using tri-stereo optical satellite imagery

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1. Motivation

Within the semi-arid Andes of Central Chile (33 - 36°S), the mountain snowpack represents a significant socio-economic importance and a sharp contrast to the limited, seasonally-dependent precipitation occurring at low elevations (Falvey and Garreaud, 2007; Meza et al., 2012). Recent 'mega-drought' years have heightened the importance of water storage in the Central Andes (Garreaud et al., 2017), though there remains much uncertainty as to the quantity and spatial distribution of the high altitude snowpack. Despite a sound knowledge of snow processes, highly complex terrain and data scarcity generate difficulties for numerical modelling attempts which may rely upon simple assumptions. These assumptions regularly fail to capture the heteorgeneity of spatial snow depths which can be dictated by interaction of topographical and meteorological factors, which then translates into uncertainty of the simualted seasonal hydrograph response (Freudiger et al., 2017).

Measurement strategies for deriving spatial snow depth are numerous but can be limited by accessibility (Probe measurements), cost, range (airborne Light Detection and Ranging (LiDAR)), ground control (Airborne Structure from Motion), topographic shadowing (terrestrial LiDAR) or spatial resolution (gridded satellite products). Accordingly, we explore a recently developed methodology for deriving spatial snow depth from optical stereo image triplets of the French (CNES) Pléiades 1A and 1B satellites, following the approach of Marti et al. (2016).

2. Study Site and Data

The glacierised catchment of Rio del Yeso is used to test the 136km^2 Pléiades acquisitions for a snow-covered (4th September, 2017) and snow-free (6th January, 2018) scene. Digital Elevation Models (DEMs) are generated for each scene using NASA's Ames Stereo Pipeline (Shean et al., 2016), and the resultant DEMs are differenced to obtain a snow depth map (Figure 1). The snow depth map is sampled at a resolution of 4 m and compared to a terrestrial LiDAR scan (Reigl VZ-6000) for a similar time period.

3. Pléiades and LiDAR

DEM differencing for snow free terrain reveals an mean and standard deviation of 0.21 and 0.15 m respectively for the raw Pléiades product.
- Negative snow depths for ~12% of the catchment.
- 17% of missing data as a result of image saturation over snow.

The raw snow-free Pléiades DEM is co-registered against the snow-free DEM of the LiDAR acquisition and the snow depths of the two sources are compared (Figure 2).

Evaluation at the sub-basin scale reveals a general under-estimation of Pléiades (median error = -0.22 m with a normal distribution) and bias of greater under-(over-)estimation on south (north) slopes.
Correction of the raw data based upon the median difference and a relation of northness angle (aspect relative to north) is generated. Areas visibly without snow in the Pléiades orthoimages are set to zero.

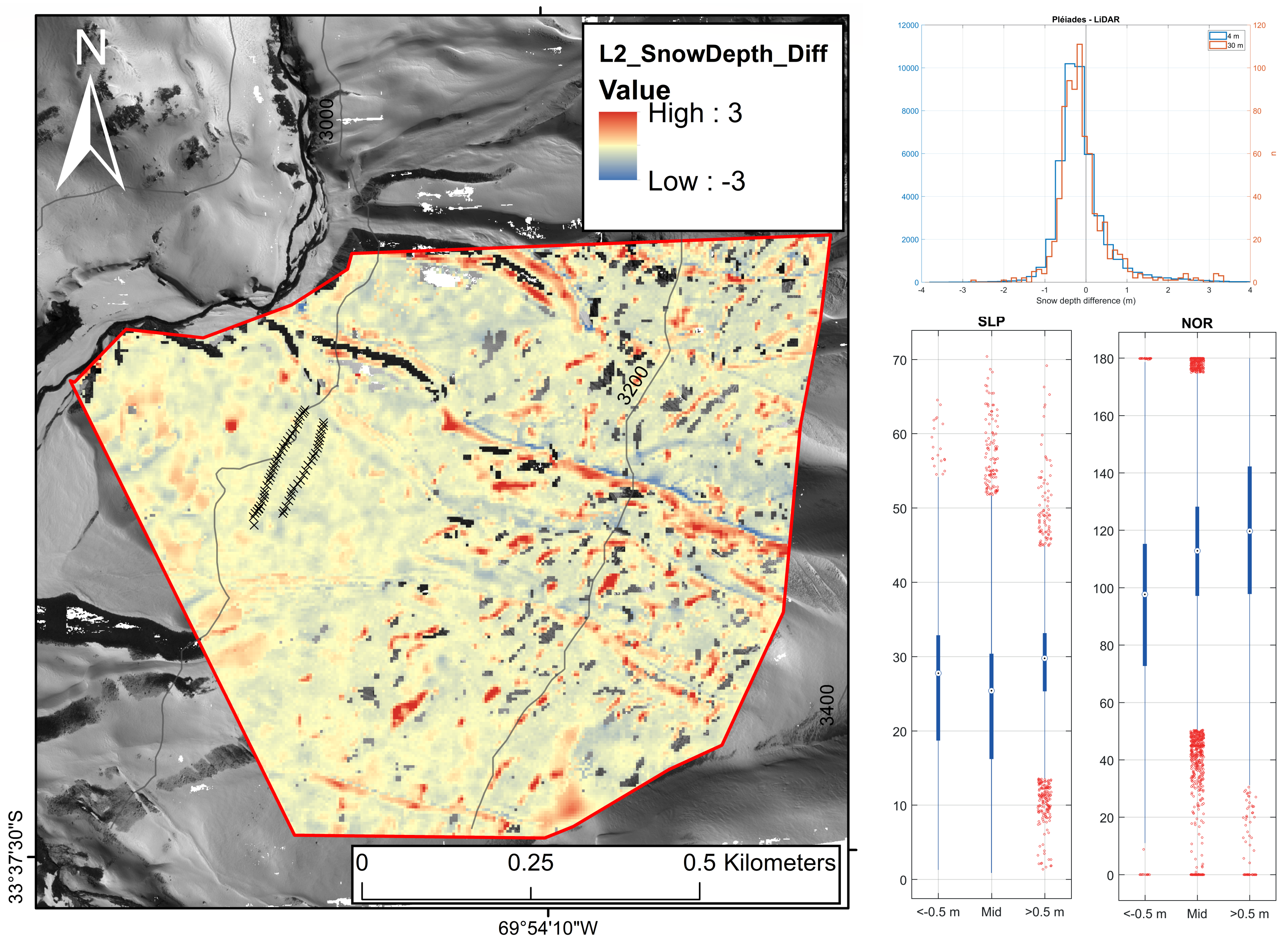

Figure 2: (left) a map of the distributed difference in snow depth (Pléiades - LiDAR, m) where blue denotes under-estimation of Pléiades. (right upper) the histogram of the differences at different spatial resolutions and (right lower) the grouping of error brackets aganst slope (SLP) and northness (NOR).

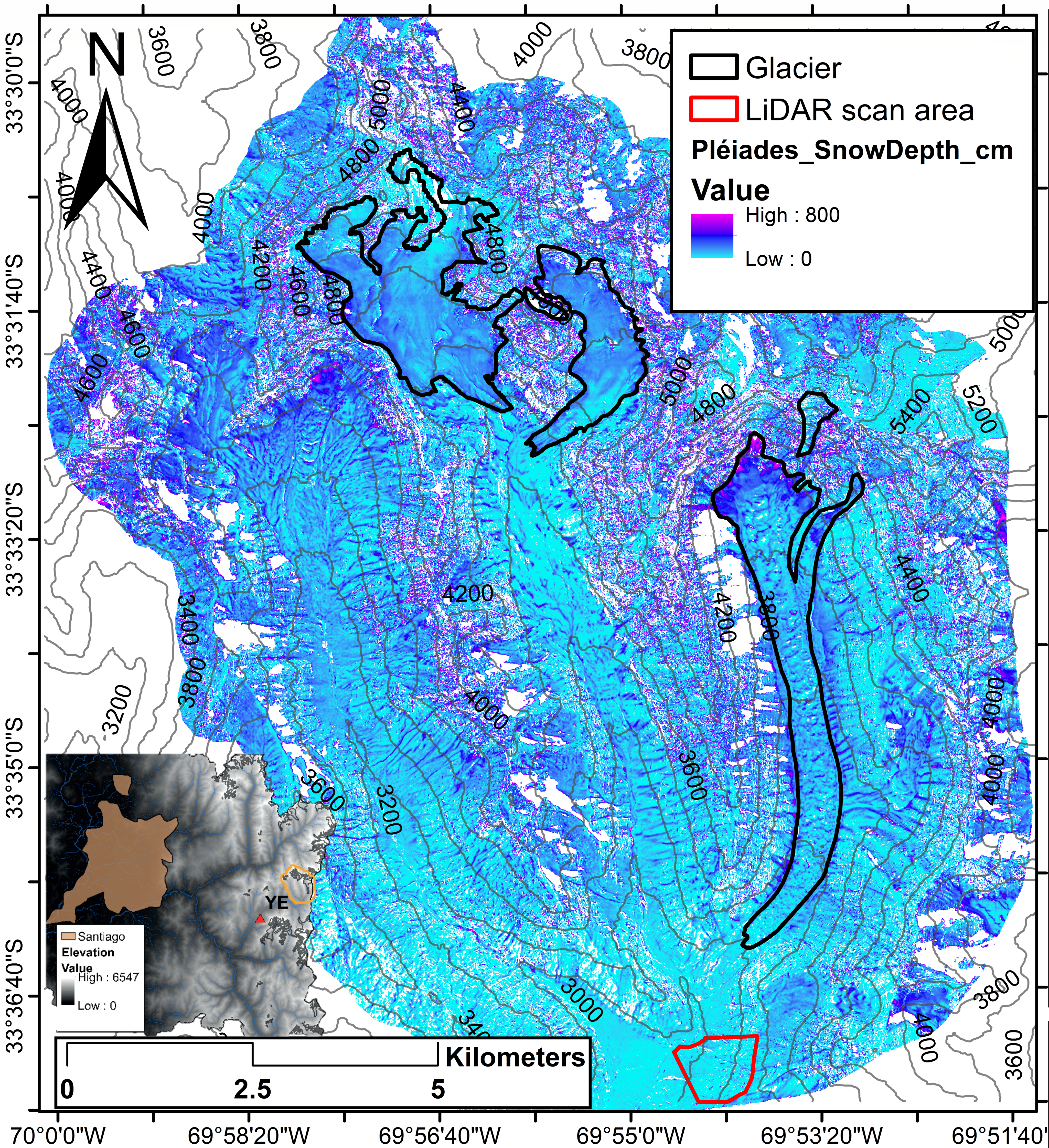

Figure 1: A map of the spatial snow depth of the Rio del Yeso catchment, Central Chile, and its loction within the Metropolitan region (inset). The red box denotes the location of the terrestrial LiDAR scan for comparison.

7. Take home messages

- Pléiades optical stereo triplets are able to derive high spatial and temporal resolution DEMs which are compared to generate snow depth maps.

- The information can be scaled up at reasonable cost and provides distinct information to carefully considered approaches currently employed.

- Corrections are necessary and spatially distributed ground validation/evaluation is ideally required to provide a range of offset values.

8. References

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4. Comparison with other methods

- The correction of the raw Pléiades product is important and has a large impact on the elevation-snow depth relationship (Figure 3).

- The corrected mean Pléiades snow depth reveals a maximum ~4500 m a.s.l. followed by a fall in mean snow depth for the highest elevations (following findings of previous works).

- Estimation of snow depth based upon topographic parameters of the basin and published coefficients from other study sites (following Grünewald et al., 2013) yields a high dependence upon elevation such that over-estimation for the highest, exposed slopes is common and that snow depth is under-estimated across the other predictors ('TOPO'- red lines in Figure 3).

- A physically-based estimation of end-of-winter snow depth is derived from the distributed blowing snow model (DBSM - ESSERY et al., 1999) using local weather station information, multi-method calibration of air temperature and precipitation gradients and regional wind fields from ERA Interim (Dee et al., 2011). The simulation without snow transportation ('EXTP') nevertheless strongly under-predicts the amount of snow determined by the Pléiades DEM differencing, only vaguely matching patterns related to solar exposure ("Northness") which is one of the most highly influential variables in predicting the snowpack in Central Chile.

- Accounting for wind transport effects ('WIND') has minimal additional influence and removal of snow is mostly at the ridges and summits of the basin. The appropriateness of this model for high elevation, complex terrain, however, could be questioned.

These approaches represent just some of the alternative approaches for estimation of spatial snow depth, but all reveal large differences from our obtained dataset.

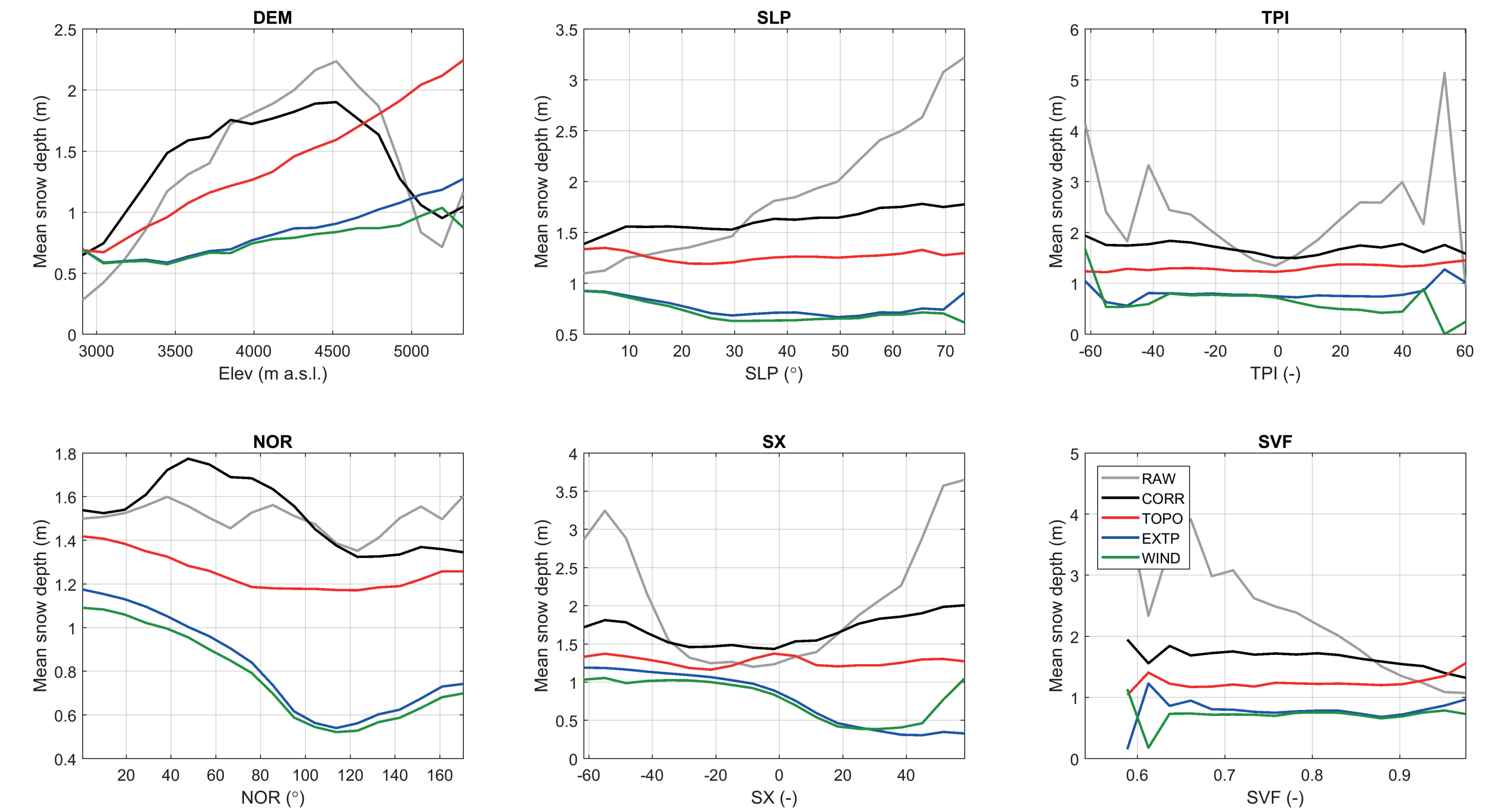

Figure 3: Mean snow depths (m) for ranges of topographical predictors from an independent ASTER GDEM, where: "DEM" = elevation (m a.s.l.), "SLP" = slope (°), "TPI" = Topographic Position Index (-), "NOR" = Northness (° from South), "SX" = Winstal et al. (2002) parameter (-) and "SVF" = Sky View Fraction (-). Pléiades snow depths are shown before (grey) and after (black) correction.

5. Advantages of Pléiades in Central Chilean Andes

+ Very high spatial and temporal resolution (0.5 m with a daily revisit)

+ Aided by frequent clear sky conditions during later winter/early spring season

+ Detailed information not available from statsitical/physically-based models.

+ Able to identify heterogeneous patterns associated with wind distribution and avalanching

+ Relatively cheap platform

6. Disadvantages of Pléiades in Central Chilean Andes

- Error associated with image saturation

- Uncertainty and noise for steep terrain (> 40°) and difficulty deriving shallow snow depths

- Requires validation and correction based upon ground-based observations for similar time scales and ID of no-snow areas to correct negative snow depths

- Requires careful timing for glacierised basins (to exclude Z-differencing of glacier ice)