Merging ERA5 and ICESat-2 for snow depth distribution retrieval

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CNRM cnrs METEO FRANCE

Snow in the world

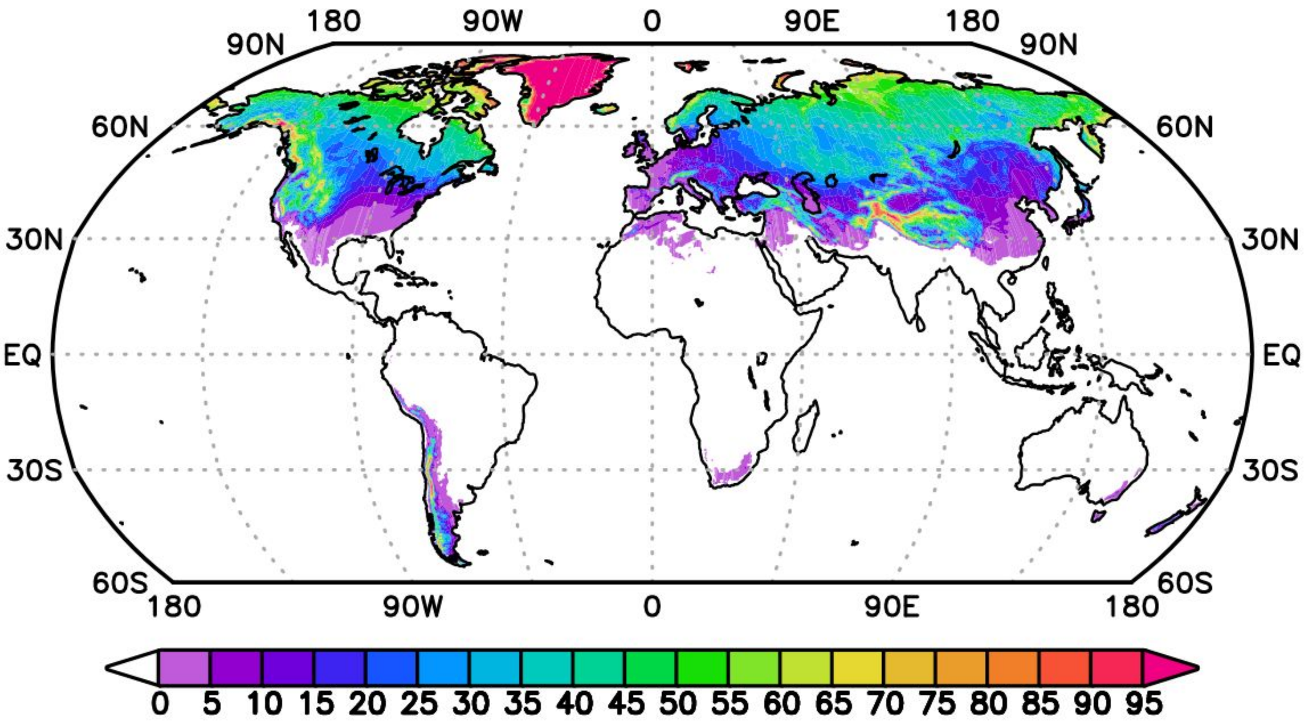


FIG. 3. Percentage of annual water-equivalent precipitation that falls as snow. Antarctica is mostly Ice and therefore not shown. These data were generated by creating annual averages of 39 years of monthly ERA5-Land water-equivalent snowfall and total precipitation data (see section 2b), calculating the ratio of the two variables, and multiplying by 100.

Sturm and Liston (2021)

Snow distribution pattern

Figure 3. Springtime over the Nulato Hills in southwest Alaska. The shallow snow has melted, making it easy to observe the areas where deep snow lay during the winter.

Sturm and Wagner (2010)

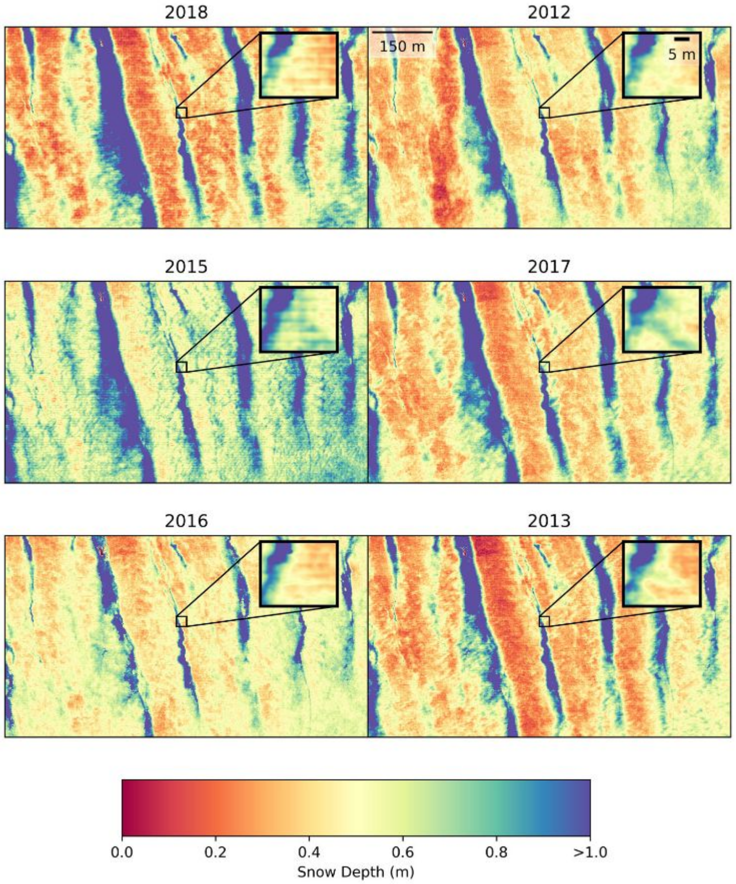


Figure 13. The drifts in the study area showed remarkable fidelity. Here all snow depth maps for the same area as in Figure 8 are shown. Not only is the overall pattern of drift and scour remarkably similar each year for these water track drifts but also in some cases even fine drift details (order 1 m, see inset maps) are repeated faithfully.

Parr et al (2020)

Snow distribution pattern

Figure 3. Springtime over the Nulato Hills in southwest Alaska. The shallow snow has melted, making it easy to observe the areas where deep snow lay during the winter.

Sturm and Wagner (2010)

Photo at Finse, Norway

Why do we care?

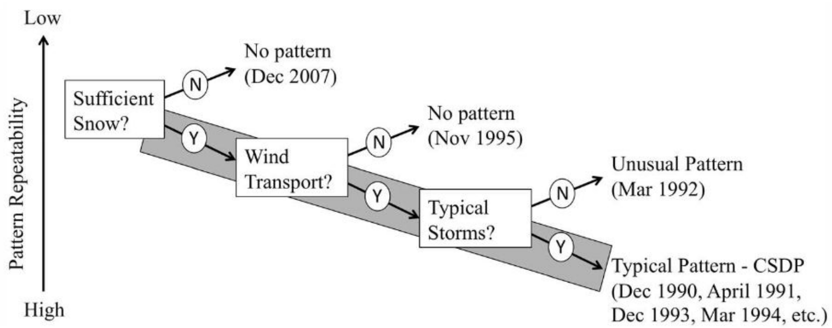
Snow distribution matters for:
- Hydrology
- Ecological processes
- Climate
- Society (power, tourism, transport)

In tundra snowpack it is ~40% of SWE locked in drifts (Parr et al. 2020)

In Norway:
- 95% power production from hydropower
    - 131 TWh in 2019
    - French nuclear: 362 TWh (2024)
    - French hydro: 75 TWh (2024)

Photo at Finse, Norway

How to measure and predict snow depth distribution?



Sturm and Wagner (2010)

> Measuring snow distribution at high resolution

- **Catchment scale:** probe transect, drone photogrammetry/lidar, GPR, dGPS
- **Regional scale:** airborne lidar, satellite photogrammetry, radar
- **Global:** yet to be solved

> Modelling snow distribution

- Approach 1: resolve as many redistribution physical processes (*e.g.* Vionnet et al. 2014)
- Approach 2: terrain based parameterization (*e.g.* Tabler's drift profile, Winstral Sx index)

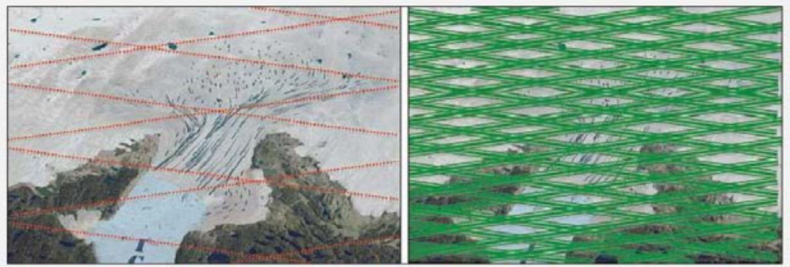
> Data assimilation (merging model and observation)

- > Nicola's presentation :)

> Downscaling

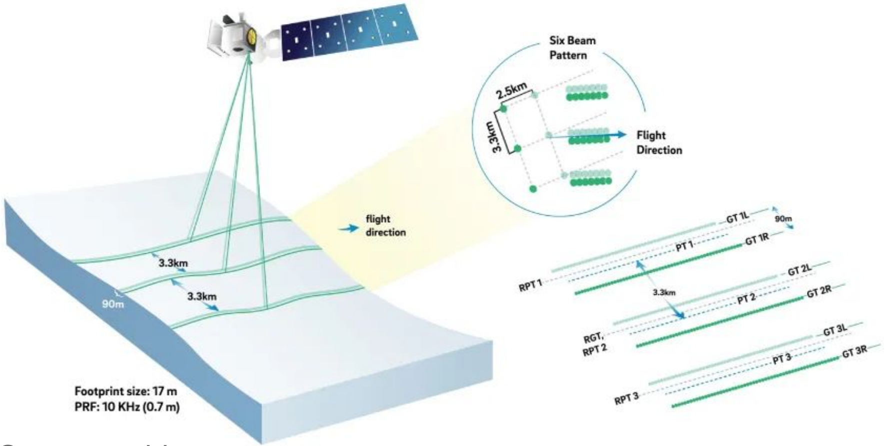
ICESat-2

- Launched in 2018
- Laser altimeter - 6 laser beams (10 kHz)
- 500 km in space, with accuracy of 4 mm
- Footprint ~15m
- 92 revisiting period



The original ICESat had a single laser beam, collecting data in a grid shown to the left. With ICESat-2's six laser beams, the satellite will be able to take measurements in a much denser grid, as seen on the right. (NASA)

Source: nasa.gov



Source: nsidc.org

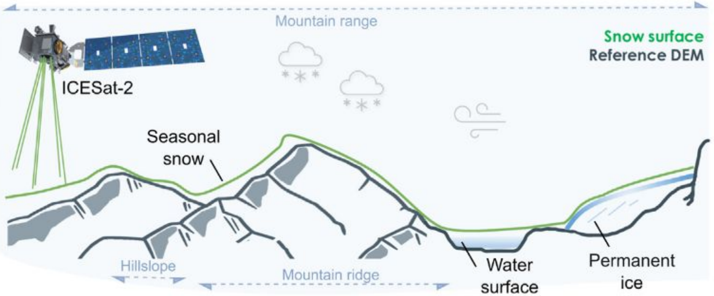
Previous work on retrieving snow depth at catchment scale:

- Deschamp-Berger et al (2023) (ATL06): a precision of ~ 1 m and a bias of ~ 0.2 m
- Enderlin et al. (2022) (ATL03): mean absolute deviation 0.2 m
- Besso et al. 2024 (ATL08): MAD of 0.2 m

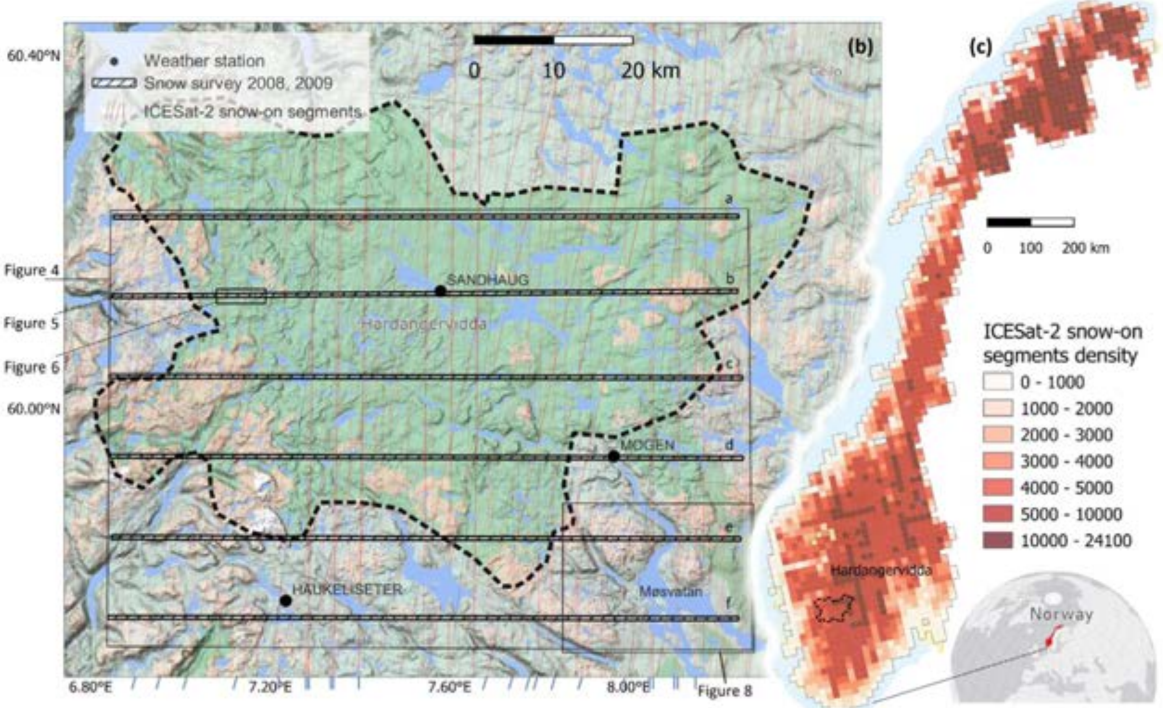
=> promising but need more work (e.g. correct for slope, etc.)

ICESat-2

200 km



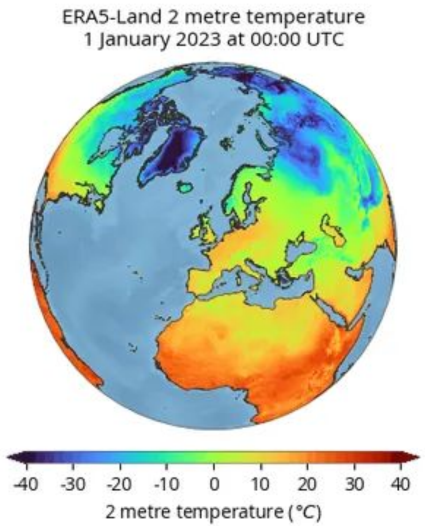
Mountain range
Snow surface
Reference DEM
ICESat-2
Seasonal snow
Hillslope
Mountain ridge
Water surface
Permanent ice



Weather station
Snow survey 2008, 2009
ICESat-2 snow-on segments
0
10
20 km
(b)
(c)
60.40°N
60.00°N
Figure 4
Figure 5
Figure 6
Figure 8
SANDHAUG
Hardangervidda
MØGEN
HAUKELISETER
Møsvatan
a
b
c
d
e
f
6.80°E
7.20°E
7.60°E
8.00°E
0
100
200 km
ICESat-2 snow-on segments density
0 - 1000
1000 - 2000
2000 - 3000
3000 - 4000
4000 - 5000
5000 - 10000
10000 - 24100
Norway

ECMWF ERA5 Land

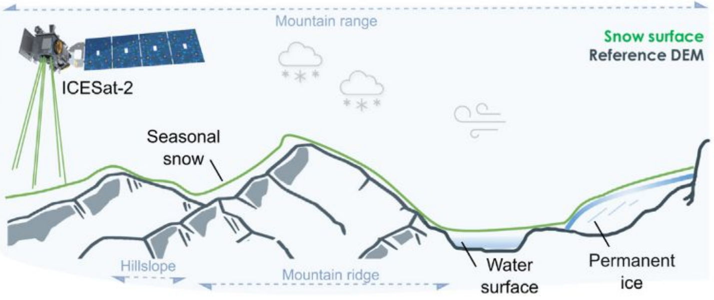
- 1950 to present reanalysis
- ~9 km spatial resolution
- Hourly atmospheric variables and land surface (*i.e.* snow depth)
- Global product



Source: cds.climate.copernicus.eu

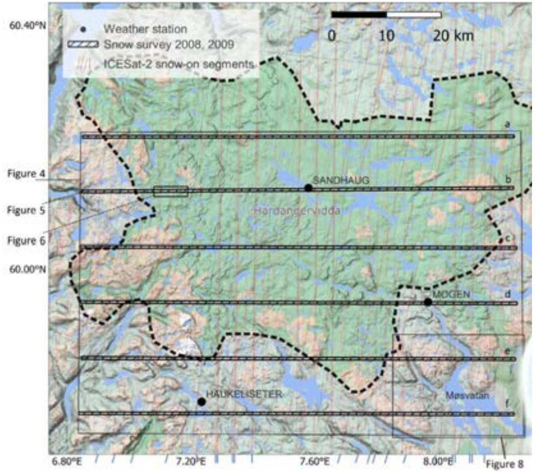
Input DEMs

- National DTM 1 m - lidar (Kartverket)
- National DTM 10 m - lidar
- Copernicus GLO-30 (DSM)
- FABDEM (DTM from GLO-30)



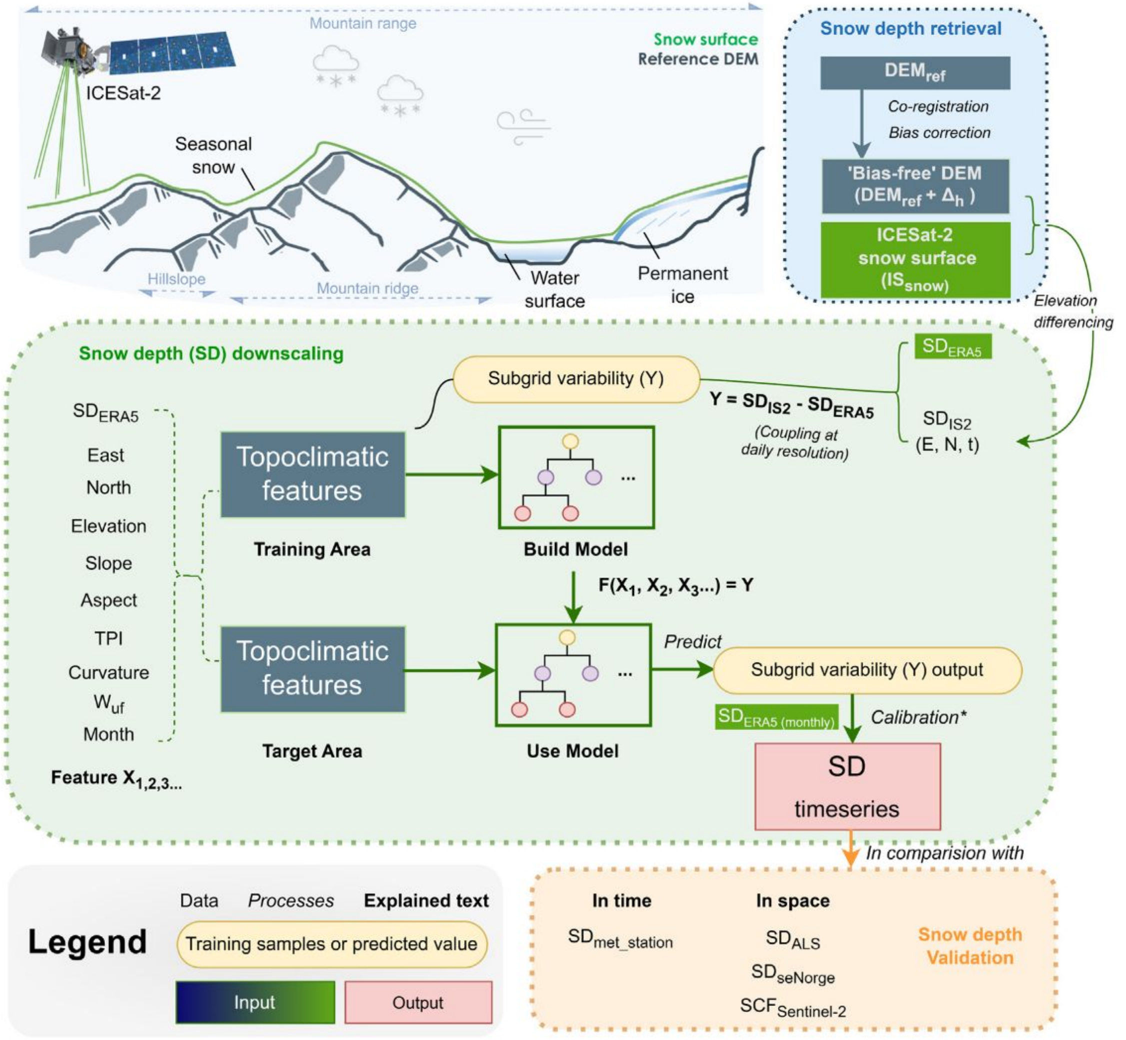
Validation data

- Airborne lidar data (Melvold and Skaugen (2013)
  - 2 m gridded snow depth
  - April 2008 and 2009
- SeNorge data
  - 1*1km snow depth interpolation from weather station network

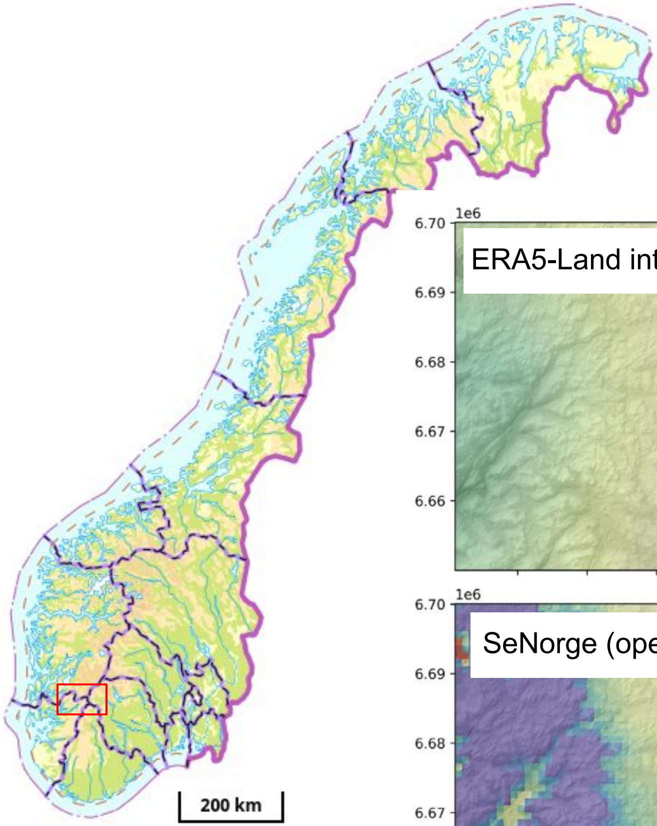


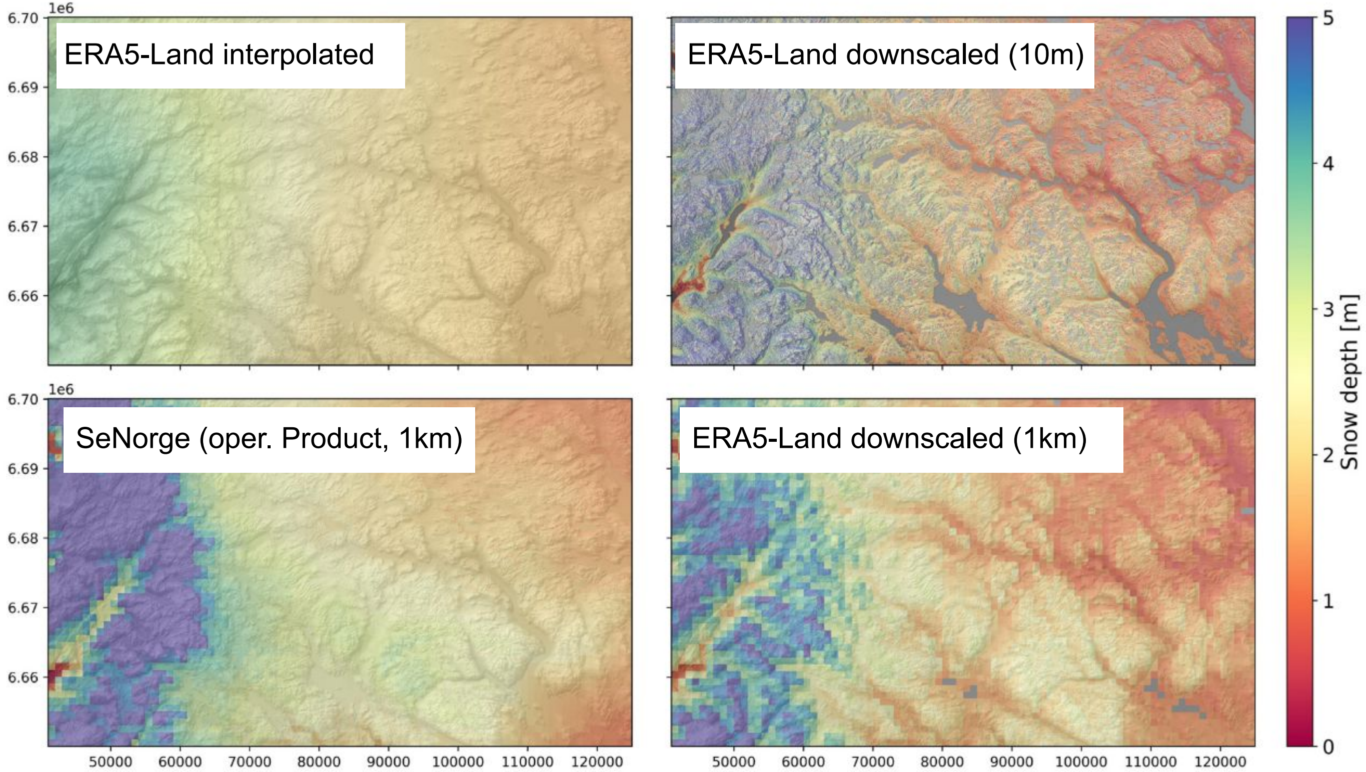
Source: www.senorge.no

Downscaling Scheme



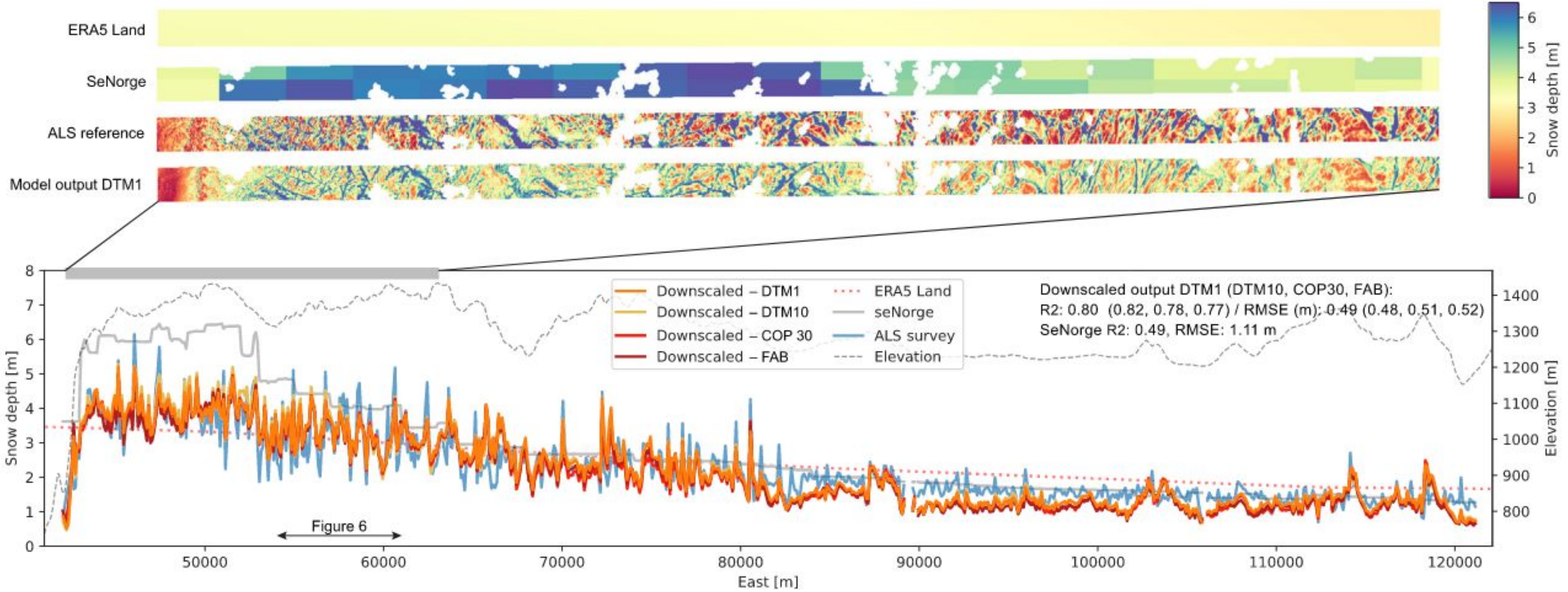
Results


200 km

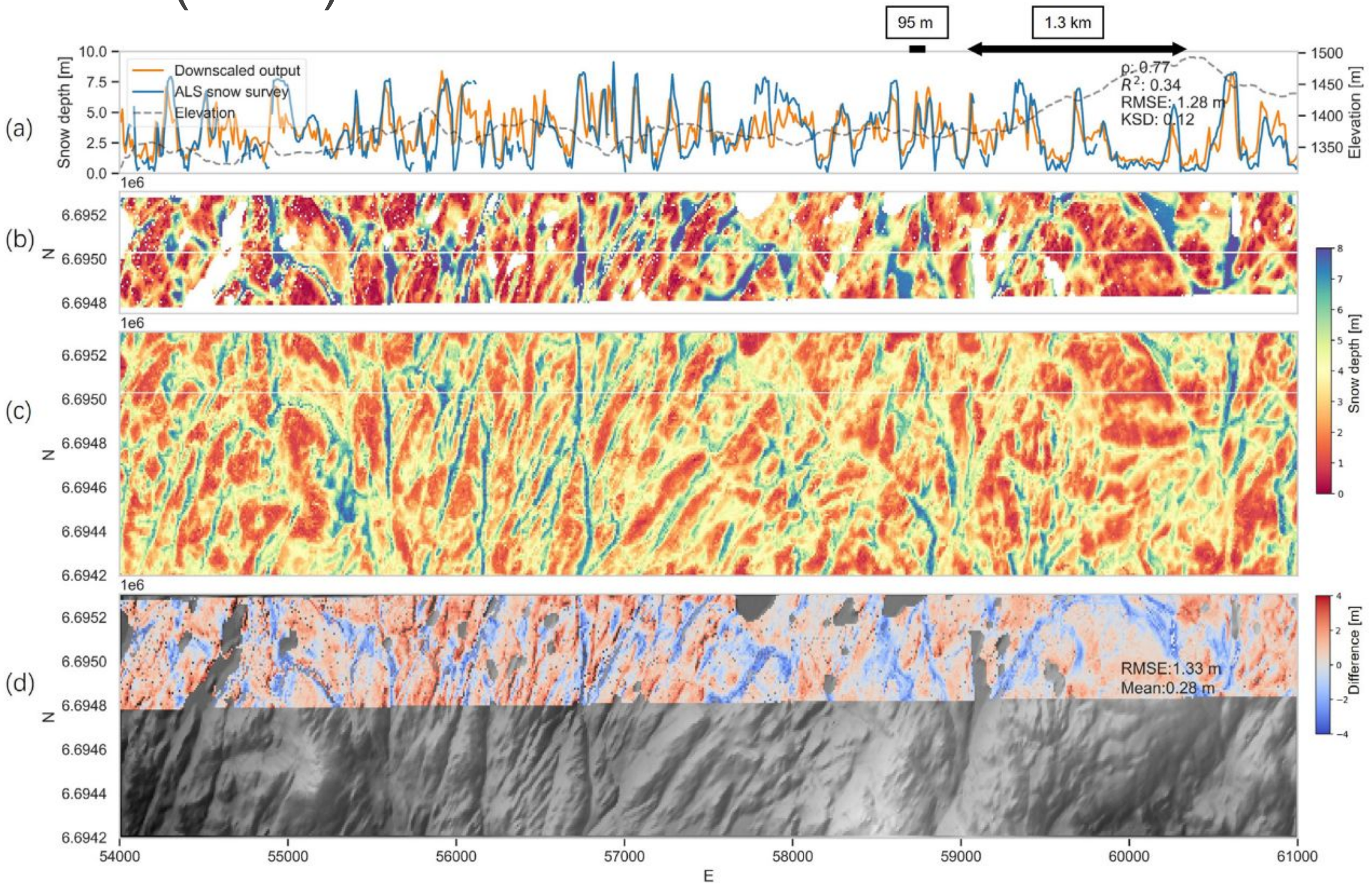

ERA5-Land interpolated
ERA5-Land downscaled (10m)
SeNorge (oper. Product, 1km)
ERA5-Land downscaled (1km)
1e6
6.70
6.69
6.68
6.67
6.66
50000
60000
70000
80000
90000
100000
110000
120000
Snow depth [m]
0
1
2
3
4
5

Results - mesoscale (100 m):

$$R2 = 1 - \frac{SS_{res}}{SS_{total}}$$



Results - microscale (10 m):



Conclusion

- A new method to retrieve peak snow depth variability, trained on ICESat-2 data, and applied to ERA5-Land
- R^2 of ~0.8 at mesoscale (100m)
- New relevant index: the cumulative wind factor
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Retrieving snow depth distribution by downscaling ERA5 Reanalysis with ICESat-2 laser altimetry

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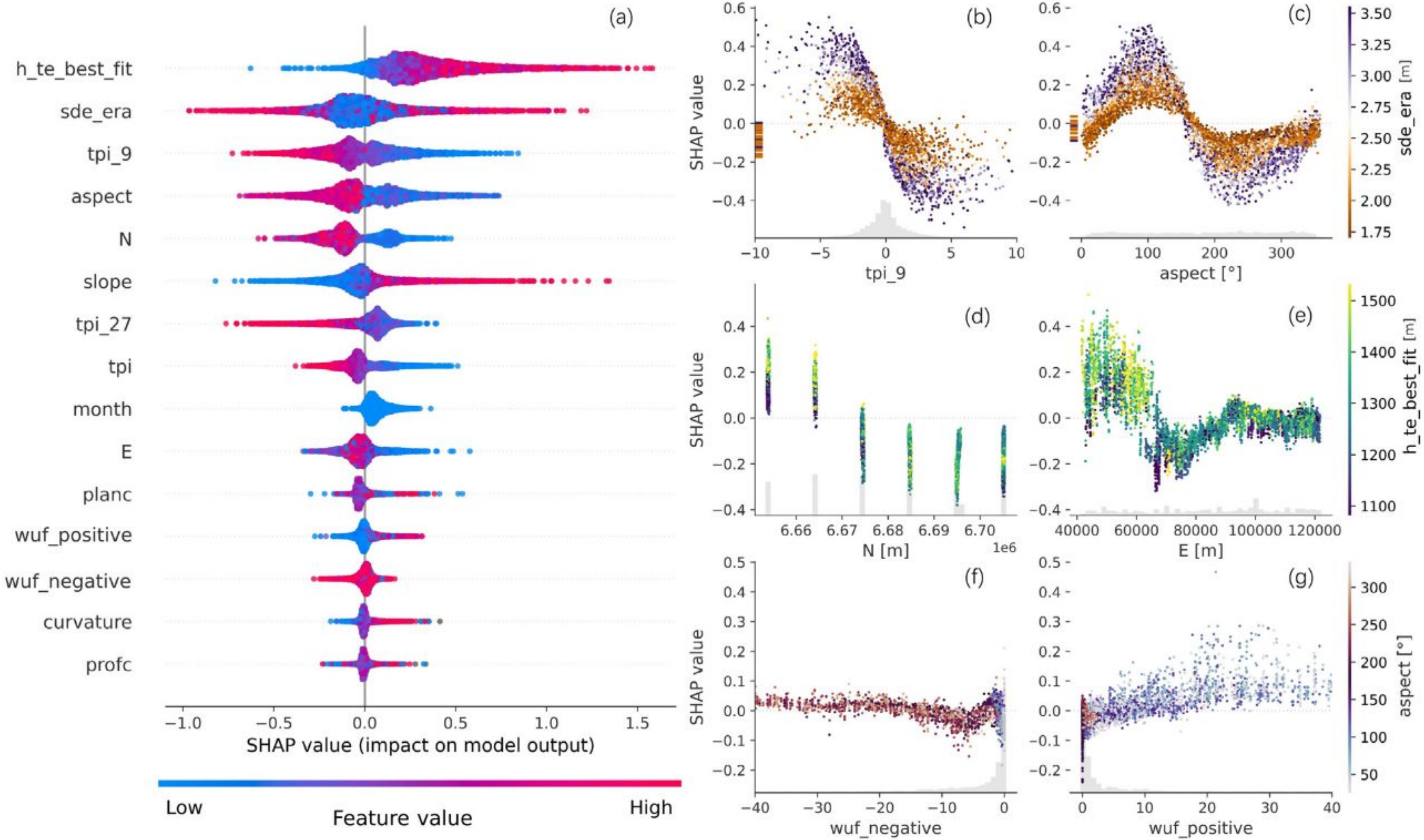
Merci

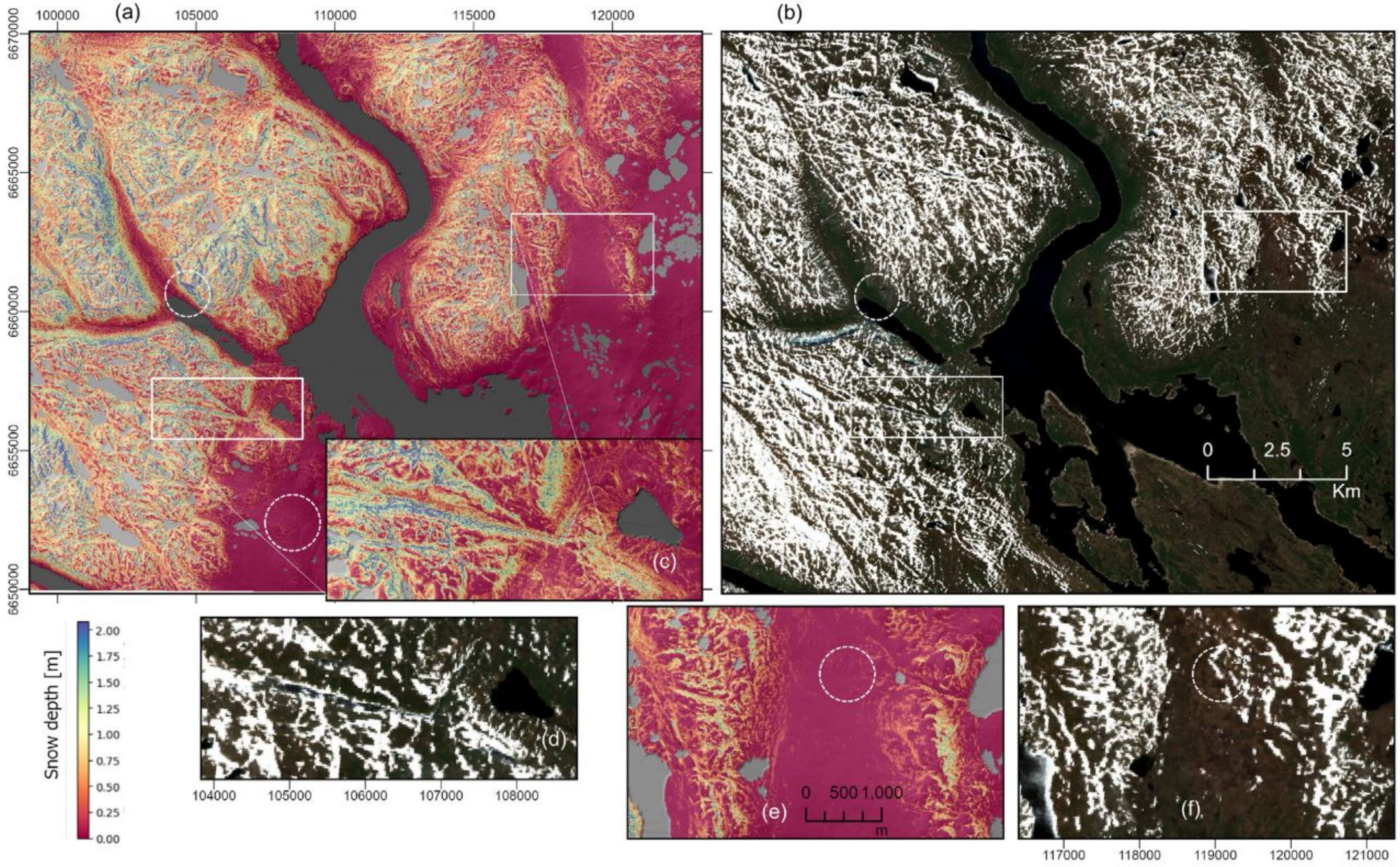


(a)
h_te_best_fit
sde_era
tpi_9
aspect
N
slope
tpi_27
tpi
month
E
planc
wuf_positive
wuf_negative
curvature
profc
SHAP value (impact on model output)
Low
Feature value
High
(b)
(c)
(d)
(e)
(f)
(g)
SHAP value
tpi_9
aspect [°]
sde_era [m]
N [m]
1e6
E [m]
h_te_best_fit [m]
wuf_negative
wuf_positive
aspect [°]

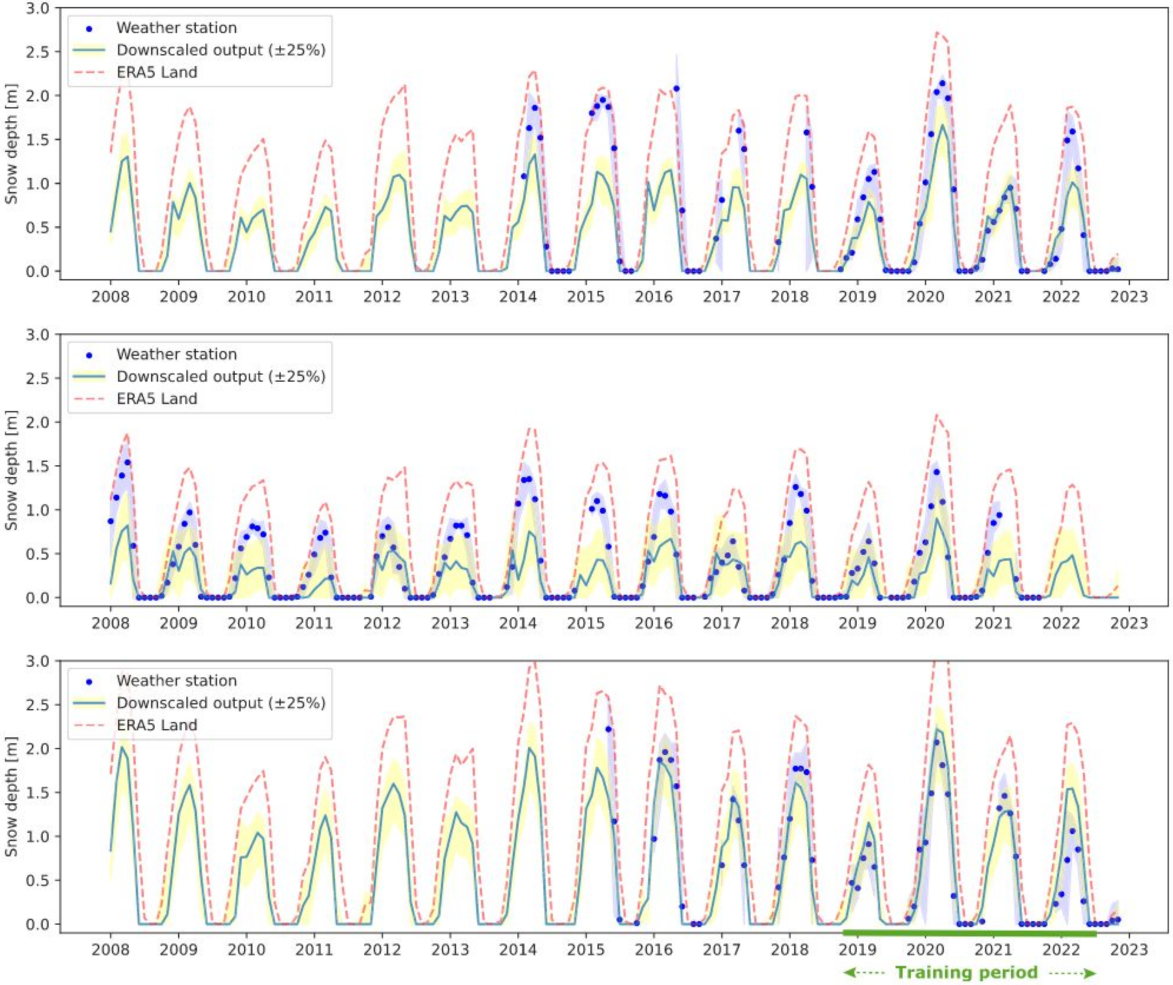
Mesoscale statistics

Table 1
Statistical comparison of snow depth estimates from different methods (downscaled output with snow retrievals based on different DEMs, seNorge, and ERA5 Land) against ALS snow survey data for all six flight lines (a–f) combined, for the years 2008 and 2009, respectively. $R2$, KSD and Spearmans' ρ are unit-less, RMSE is in m.

Dataset	April 2008				April 2009			
	$R2$	KSD	ρ	RMSE	$R2$	KSD	ρ	RMSE
DTM1	0.81	0.09	0.88	0.53	0.78	0.07	0.87	0.50
DTM10	0.82	0.12	0.88	0.56	0.79	0.08	0.88	0.513
COP30	0.80	0.10	0.88	0.57	0.75	0.07	0.84	0.554
FAB	0.81	0.11	0.89	0.56	0.77	0.07	0.86	0.54
SeNorge	0.49	0.21	0.84	1.12	0.65	0.13	0.86	0.60
ERA5 Land	−0.79	0.27	0.71	0.82	−0.34	0.24	0.72	0.68



(a)
(b)
100000
105000
110000
115000
120000
6670000
6665000
6660000
6655000
6650000
(c)
0
2.5
5
Km
Snow depth [m]
2.00
1.75
1.50
1.25
1.00
0.75
0.50
0.25
0.00
(d)
104000
105000
106000
107000
108000
0
500
1,000
m
(e)
(f)
117000
118000
119000
120000
121000



Weather station
Downscaled output (±25%)
ERA5 Land
Snow depth [m]
3.0
2.5
2.0
1.5
1.0
0.5
0.0
2008
2009
2010
2011
2012
2013
2014
2015
2016
2017
2018
2019
2020
2021
2022
2023
Training period

Cumulative wind factor

$$W_f = -cos(aspect - dir_{wind})$$

Bennett et al (2022)

$$W_{uf_{positive}} = \sum W_{f_{positive}} u_{wind}^3$$

Leeward - deposition

$$W_{uf_{negative}} = \sum W_{f_{negative}} u_{wind}^3$$

Windward - erosion