Impact of Seasonal Snow Cover on InSAR Deformation Measurement of Global Volcanoes

Tianyuan Zhu[1], Juliet Biggs[1], Alison Rust[1], Maria Loreto Córdova[2]

[1]Dept. of Earth Sciences, University of Bristol, Wills Memorial Building, Queens Road, Bristol, UK, BS8 1RJ

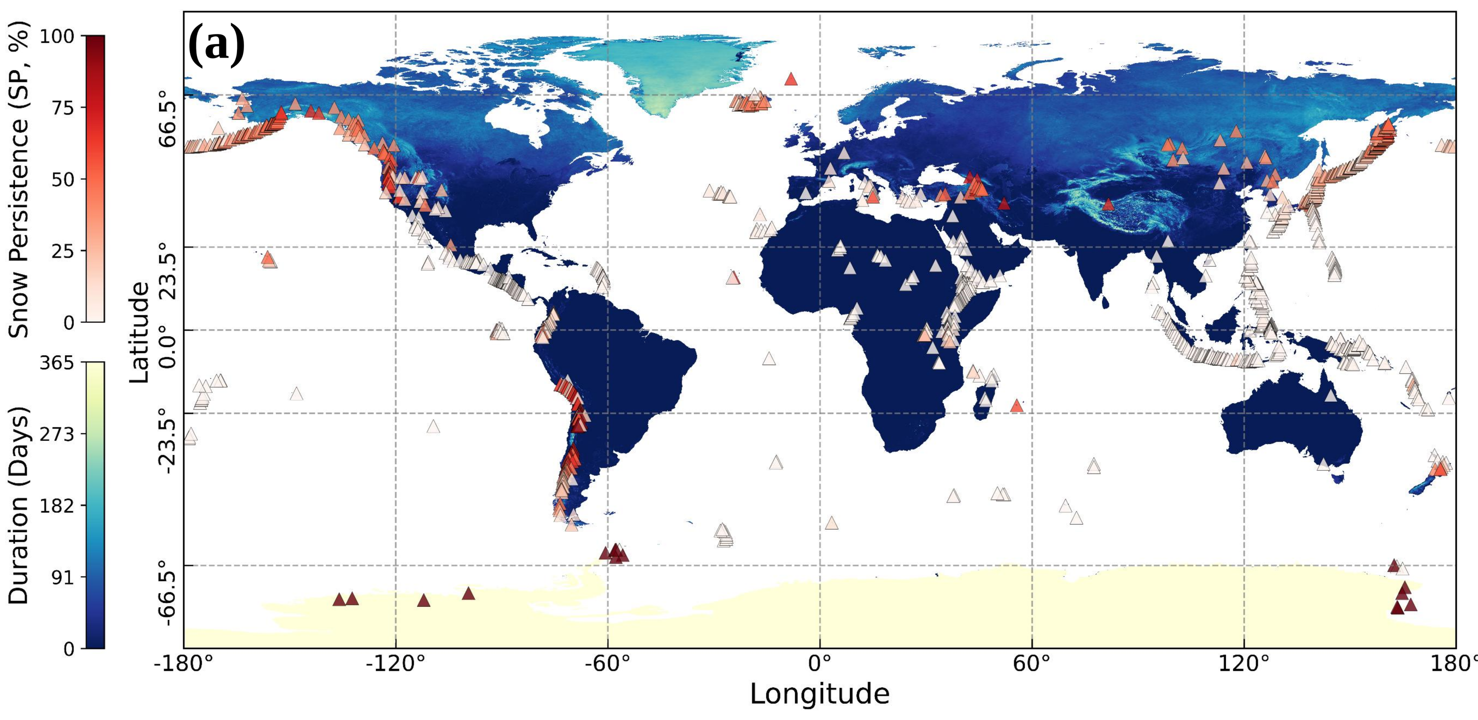
[2]Servicio Nacional de Geología y Minería (SERNAGEOMIN), Santiago, Chile

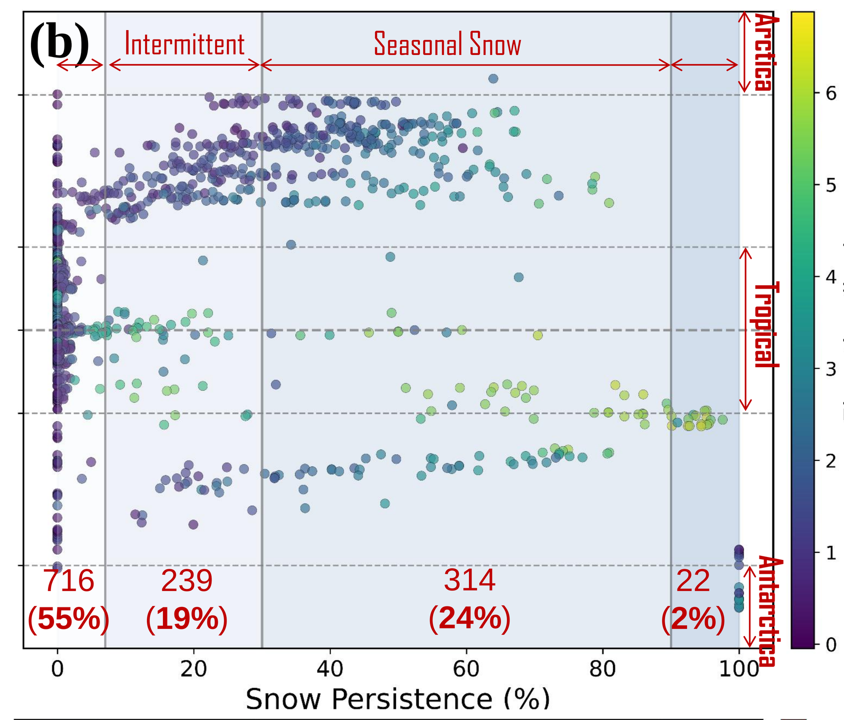
Corresponding author: Tianyuan Zhu ✉ tianyuan.zhu@bristol.ac.uk 𝕏 @TianyuanZhu

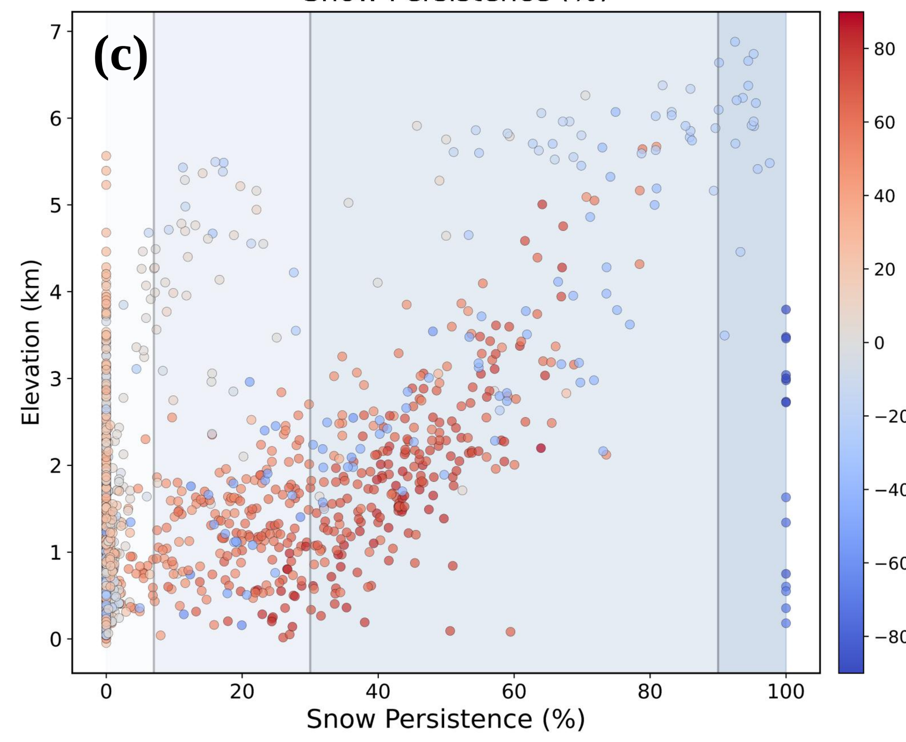
University of Bristol

1. Snow Persistence on InSAR Monitored Volcanoes

- InSAR has been increasingly applied to monitoring volcanic deformation over last 30 years because of its high spatial and temporal coverage.
- Seasonal snow cover is challenging for InSAR measurements due to loss of **coherence** and **unwrapping errors**.







Snow Persistence (SP): a fraction showing the presence of ground snow in a typical year[Hammond, 2018].

$$SP = \frac{SD}{365 - ND}$$

- **SD**: number of days with snow cover.
- **ND**: number of days with no data (night, cloud and fill);
- Four snow zones[Hammond, 2018]:
  - Little/no snow (0-7%);
  - Intermittent snow (7-30%)
  - Seasonal snow (30-90%)
  - Permanent snow (90-100%)

- Volcanoes with higher snow persistence are common at high latitudes and high altitudes (Fig. 1).
- Nearly half (**47%**) of the InSAR-monitored volcanoes have **intermittent/seasonal snow cover (7-90%)**, which will reduce the coherence of interferograms.
- Many volcanoes with high SP are active and experiencing significant deformation.

Fig.1 (a) Global snow cover duration in a typical year (2017) based on MODIS (MOD10C1) dataset and SP of InSAR-monitored volcanoes[GVP, 2023]; (b) & (c) Distribution of global volcanic SP vs. Elevation and Latitude.

2. Laguna del Maule

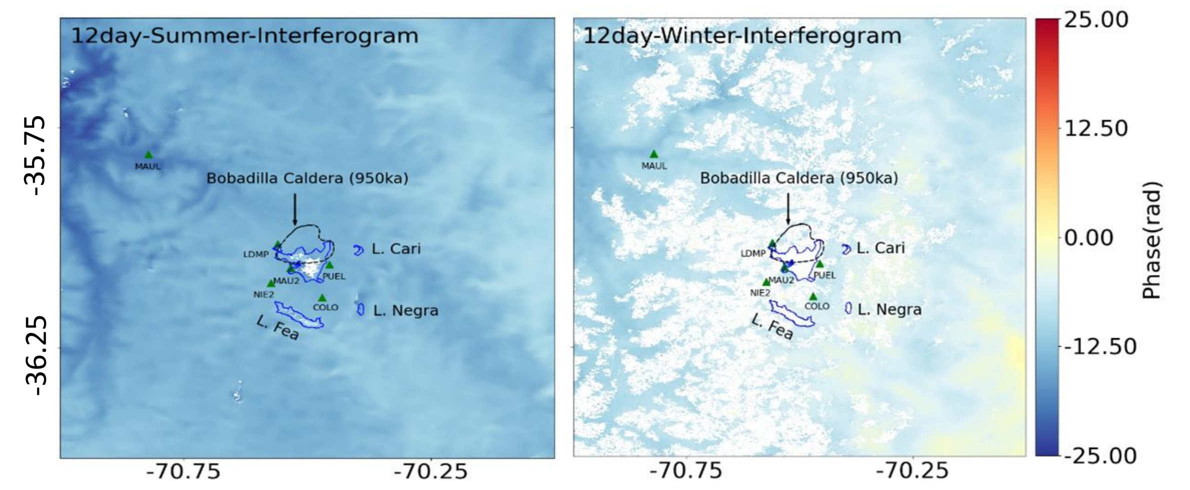


Fig. 2 12-day Unwrapped Interferograms at Laguna del Maule area.

- **Case Study: Laguna del Maule (LdM)** is a large, deforming caldera in the Andes South Volcanic Zone (SVZ), Chile, with strong seasonal (7 months/yr) snow cover and steep-sided lava flows; **Snow Persistence = 73%.**
- The strong seasonal snow cover of the Andes leads to poor coherence of interferograms;
- The auto-processing **underestimates** deformation and deformation rates at LdM compared to GPS measurements.
- By incorporating long time-span, summer-to-summer interferograms (blue) and re-unwrapping (green), the corrected deformation agrees better with GPS observation (red).

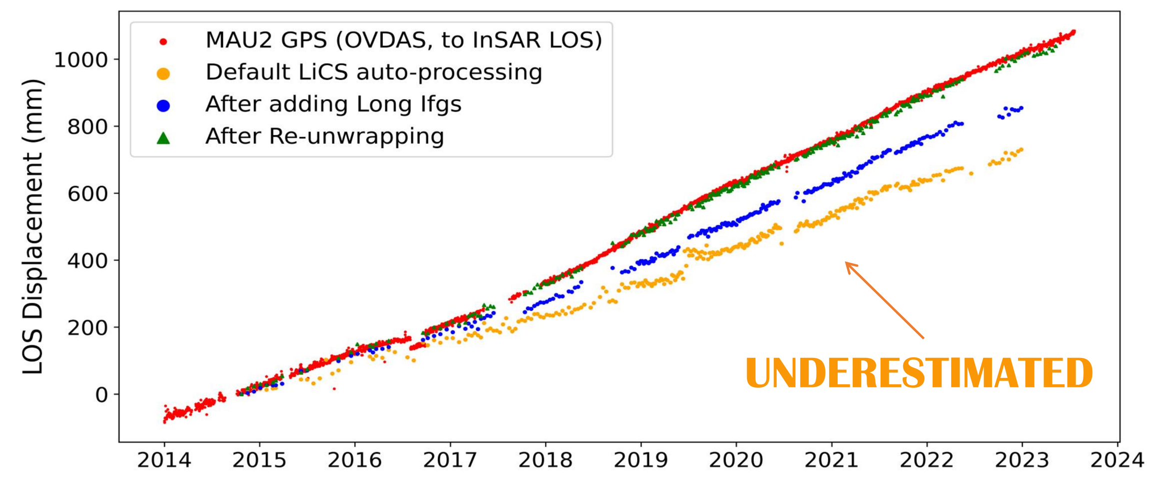
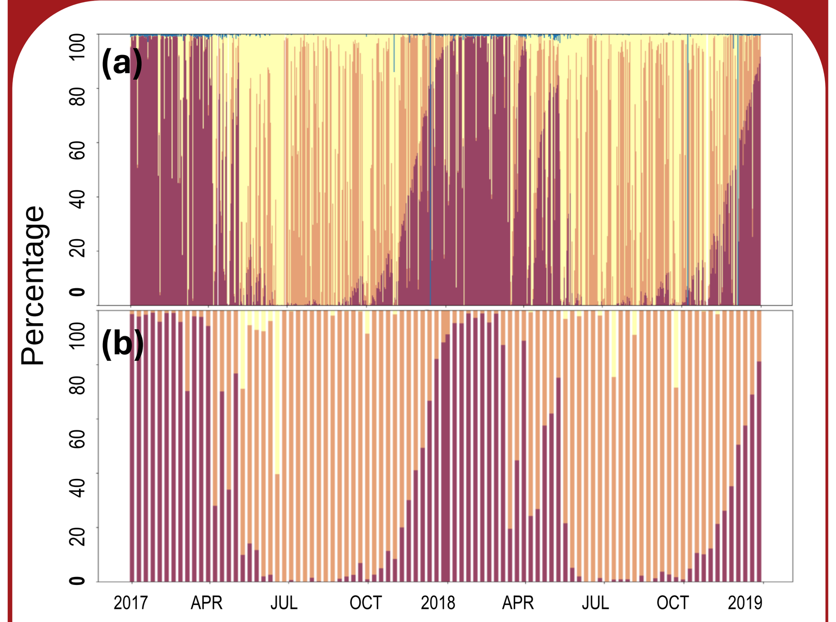


Fig. 3 The comparison of LdM time series displacement on LOS at MAU2 (Oct 2014 – Jun 2023).

3. MODIS Snow Cover vs InSAR Coherence at Laguna del Maule



- MODIS **Daily** Snow Cover Products at LdM show a seasonal trend, with cloud (yellow) during winter;
- MODIS **8-Day** Snow Cover Products maximise the snow cover and minimise the cloud cover.

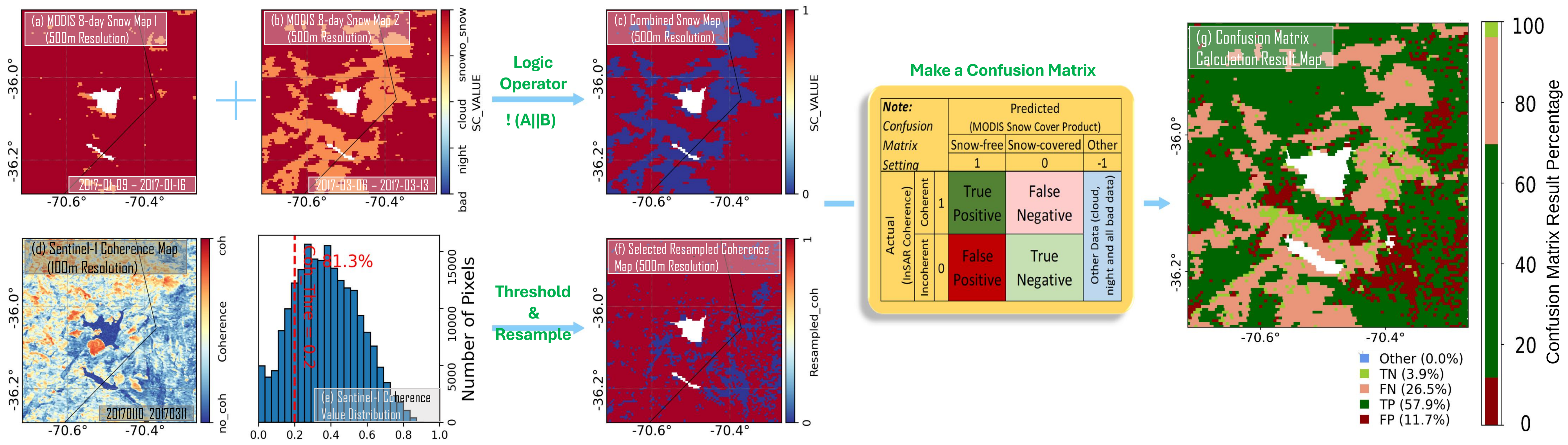
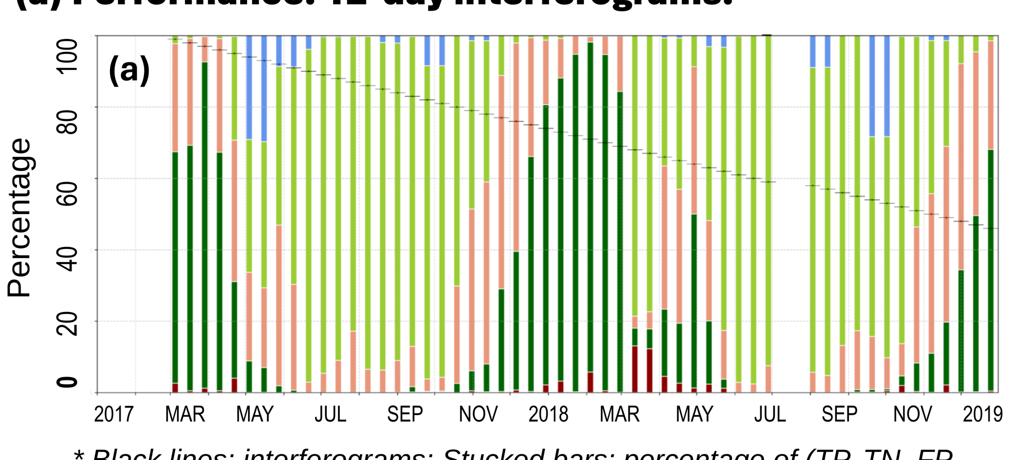


Fig. 4 [left] Data flags of MODIS Daily (a) and 8-day Snow Cover products. Fig. 5 [right] An example of the comparison process between MODIS 8-day snow map and Sentinel-1 InSAR coherence.

Fig. 6 [bottom] Temporal evolution of confusion matrix statistics (percentage of TP, FP, FN, TN) with different interferograms in 2017-2018. Black lines: the length of interferograms.

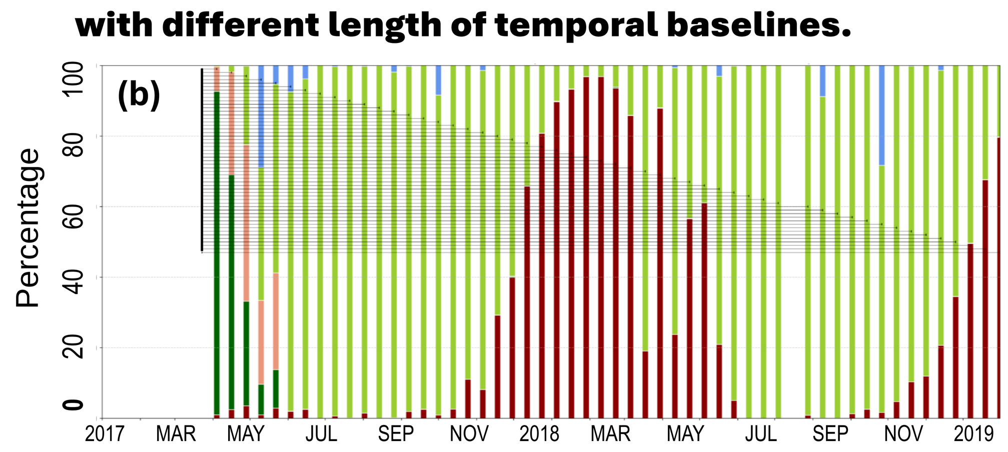
(a) Performance: 12-day interferograms.



** Black lines: interferograms; Stucked bars: percentage of (TP, TN, FP, FN and Bad data).*

- **Overall Accuracy = 76%**
- **Peak Accuracy = 99%**
- **False Negatives (FN):**
  - Frequently occur in interferograms with short temporal baselines, more common in spring and fall.
  - Caused by snow detected on other days within the MODIS 8-day snow product period.

(b) Samples: interferograms starting from the same date (2017-03-23) with different length of temporal baselines.



- **Overall True Negative (%) = 67%**
- **True Positive (%) decrease with time-span.**
- **False Positives (FP):**
  - Often occur in interferograms with long temporal baselines.
  - Caused by decorrelation due to factors other than snow, such as **vegetation.**

4. Optimized Network Design

Time-span Requirement: **12-480** days

Total Connections: **17033** pairs

Step 1: Filter S1 epochs using MODIS

if MODIS Snow Coverage <= 80%:
epoch selected;
else: skip;

Connection Remain: **6222** pairs, *Fig 7 (a)*.

Step 2: : Filter S1 interferograms using MODIS

if predicted coherence >=80%:
interferometric pair selected
else: skip;

Connection Remain: **2104** pairs, *Fig 7 (b)*.

Step 3: Optimise Connections [Smittarello 2021] :

***k:** max number of connections flowing in and out of a Sentinel-1 acquisition (k=3);*

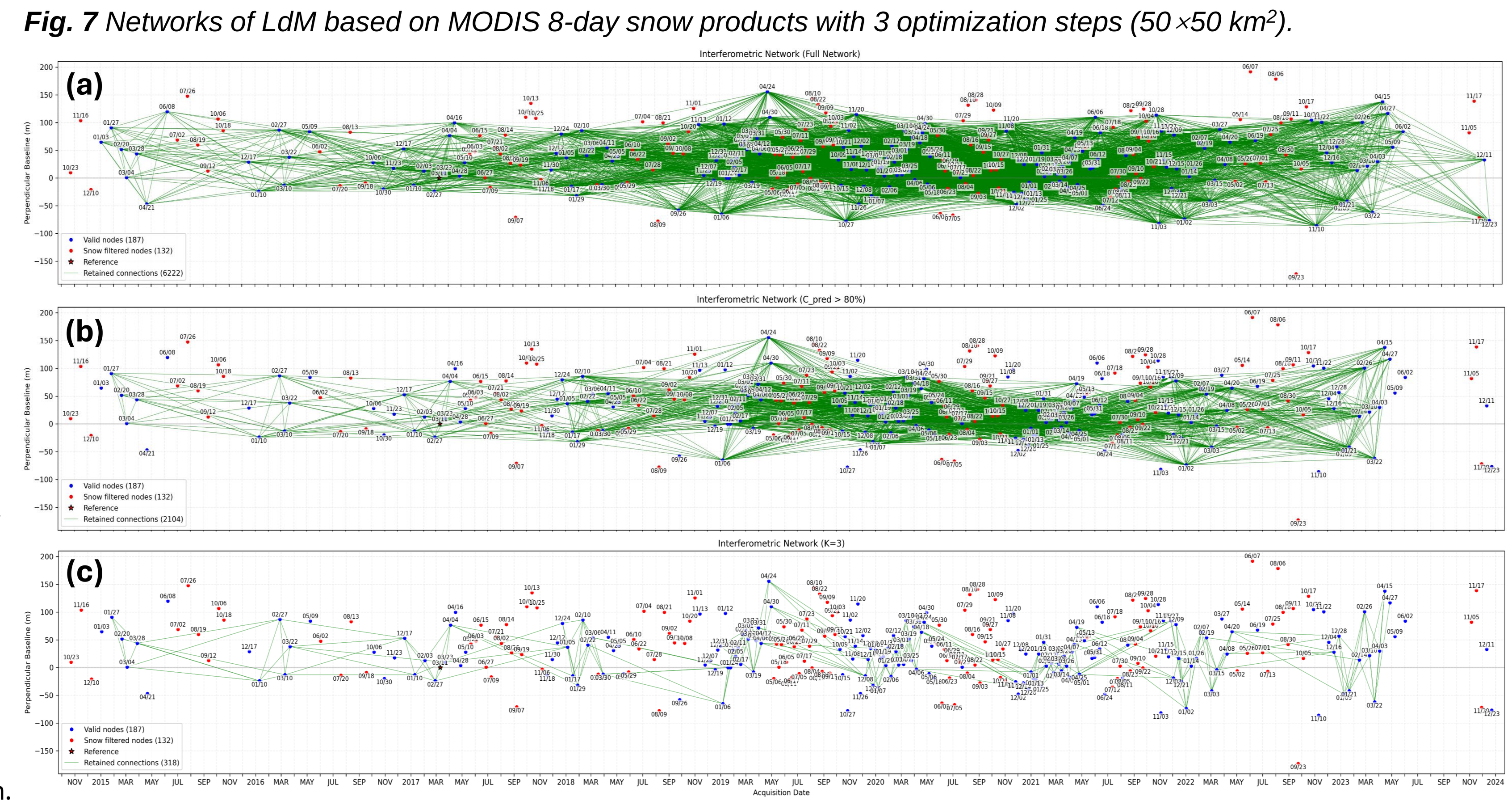
***o:** number of pairs flow out of an acquisition;*

***v:** number of pairs flow into an acquisition.*

if o<=k:
all pairs flow out will be kept;
else:
if v<=k: all out-arcs will be kept;
else: remove arc with min predicted coh.
renew all v and o and loop again.

Connection Remain: **318** pairs, *Fig 7 (c)*.

Fig. 7 Networks of LdM based on MODIS 8-day snow products with 3 optimization steps (50 ×50 km²).



5. Conclusion

- Seasonal snow cover affects nearly 50% of global volcanoes, specifically in **high latitude and altitude** regions, posing significant challenges to InSAR time series analysis (Section 1).
- Comparison with OVDAS GPS observations shows that InSAR has the ability to provide reliable deformation at LdM, but the auto-processing system underestimated it (Section 2, Fig. 3).
- MODIS snow maps show a strong correlation with Sentinel-1 coherence maps and can be used for predicting coherence of interferograms (Section 3).
- The optimized network is well connected and reduces the required interferograms from **17033** to **318,** significantly improving computational efficiency and saving storage (Section 4, Fig 7).

References

[1] Global Volcanism Program (2024). Volcanoes of the World. https://doi.org/10.5479/si.GVP.VOTW5-2023.5.1. [Database].

[2] Hall, D. K. and Riggs, G. A. (2021a). MODIS/Terra Snow Cover Daily L3 Global 500m SIN Grid,Version 61. [Day CMG Snow Cover]. Accessed: [Dec 2023].

[3] Hall, D. K. and Riggs, G. A. (2021b). MODIS/Terra Snow Cover 8-Day L3 Global 500m SIN Grid,Version 61. [Maximum Snow Extent]. Accessed: [Jul 2024].

[4] Hammond, J. C., Saavedra, F. A., and Kampf, S. K. (2018). Global snow zone maps and trends in snow persistence 2001–2016. International Journal of Climatology, 38(12):4369–4383.

[5] Lazeck` y, M., Spaans, K., Gonz´alez, P. J., Maghsoudi, Y., Morishita, Y., Albino, F., Elliott, J.,Greenall, N., Hatton, E., Hooper, A., et al. (2020). Licsar: An automatic insar tool for measuringand monitoring tectonic and volcanic activity. Remote Sensing, 12(15):2430.

[6] Morishita, Y., Lazecky, M., Wright, T. J., Weiss, J. R., Elliott, J. R., and Hooper, A. (2020). Licsbas:An open-source insar time series analysis package integrated with the licsar automated sentinel-1insar processor. Remote Sensing, 12(3):424.

[7] Smittarello, et al., (2022). Pair selection optimization for InSAR time series processing. Journal of Geophysical Research: Solid Earth,127(3):e2021JB022825.