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Brief communication: delivering a Digital-Twin-ready snow reanalysis

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Abstract.

We present DTE-SNOW, a Digital-Twin-ready framework for simulating the spatial and temporal dynamics of snow-water resources at 1 km resolution, based on satellite-derived precipitation, snow modeling, and the optional assimilation of Sentinel-1 snow-depth retrievals. Using test simulations over four European mountain basins (Ebro, Rhône, Po, and Inn), we show that DTE-SNOW achieves an average snow-depth bias of only a few centimeters (0.05 m when Sentinel-1 snow-depth assimilation is applied). The simulated spatial patterns successfully reproduce the topographic dependence of snow distribution, with correlations between mean annual Snow Water Equivalent (SWE) and elevation ranging from 0.63 to 0.77. Because DTE-SNOW is independent of in situ observations, it opens new opportunities toward a "SWE of everywhere" paradigm: a globally consistent estimation of snow-water resources within DestinE.

1 Introduction

The Destination Earth (DestinE) initiative, launched by the European Commission within the framework of the Green Deal and the Digital Strategy, aims to develop a highly accurate Digital Twin of the Earth system (DTE, see Alfieri et al., 2022). DTE leverages increased availability of data, including Earth Observation (EO), Artificial Intelligence, and massive computing resources needed for reproducing spatial scales and dynamics relevant for effective decision making. Ultimately, DTE supports the simulation, monitoring, and prediction of environmental changes, including extremes (Rigon et al., 2022; Brocca et al., 2024).

Building a Digital Twin capable of accurately representing Snow Water Equivalent (SWE) and in general snowpack dynamics is essential to reliably simulate future water availability, anticipate hydrological extremes, and support climate-resilient water management decisions (Alfieri et al., 2022; Avanzi et al., 2024; Girotto et al., 2024). Snow is a critical component of

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the global water cycle and a natural reservoir that stores freshwater during winter and releases it gradually through melting in spring and summer (Bales et al., 2006). In many mountain regions, snowmelt supplies rivers, groundwater, agriculture, hydropower, and drinking water for millions of people (Barnett et al., 2005). However, climate warming is reducing snowpack and shifting melt earlier in the year, disrupting the seasonal timing of streamflow and increasing risks of summer water scarcity and winter flooding (Simpkins, 2018).

In this paper, we discuss a robust framework developed throughout four DTE projects by the European Space Agency: DTE Hydrology, 4DMED-Hydrology, DTE Evolution and DTE Next. The goal is to deliver a DTE-ready reanalysis of snow water resources (DTE-SNOW). This framework relies on satellite-only precipitation inputs, spatially distributed snow modeling (Avanzi et al., 2022a), and the optional assimilation of Sentinel-1 snow depth retrievals. The reanalysis is evaluated using in-situ observations of snow depth across four study catchments in Europe: Ebro, Po, Rhone, and upper Inn. Results show mean biases that are close to zero at all elevations, making this algorithm a ready-to-deploy approach for real-world decision making in the DTE era.

2 Methods

DTE-SNOW relies on a combination of modeling and EO-based data (Figure 1). While the approach would work with any snow model, during our DTE projects we have consistently relied on Snow Multidata Mapping and Modeling (S3M), a spatially distributed, hydrology-oriented snow and glacier model providing snapshots of snow water resources by solving mass conservation and parametrizing melt through hybrid temperature-index and radiation-driven parametrization (Avanzi et al., 2022a). Additional physics include precipitation-phase partitioning, snow rheology, and snow hydraulics. Input data include total precipitation, air temperature, relative humidity, and incoming shortwave radiation. S3M is operationally used at various scales for water-resources forecasting (Avanzi et al., 2021, 2022b). In this application, we used S3M at daily resolution.

Input precipitation comes from HYPER-P_sat (Filippucci et al., 2025), a new high-resolution (0.0083°, daily) satellite-only precipitation product available from 2007 to 2024. The product is obtained by downscaling and merging precipitation estimates from SM2RAIN-ASCAT (Brocca et al., 2019) and IMERG-Late Run (Huffman et al., 2019). The downscaling procedure leverages high-resolution monthly precipitation information from CHELSA v2.1 (Karger et al., 2017). Once the data are downscaled, a triple collocation technique (Massari et al., 2017) is applied to the two datasets, with ERA5-Land (Muñoz-Sabater et al., 2021), downscaled using the same procedure, serving as the third member of the triplet. Two versions of the product are generated: HYPER-P (https://doi.org/10.5281/zenodo.15025514) and HYPER-P_sat (https://zenodo.org/records/15025462), which respectively include and exclude the information from ERA5-Land in the precipitation estimates. The latter was selected for this study to rely only on satellite products. The product is available online for the Europe-Mediterranean area but can be generated worldwide upon request.

Air temperature and relative humidity were derived from the Multi-Source Weather dataset (MSWXv1, Beck et al., 2022), which provides 3-hourly data at 0.1° spatial resolution. Air temperature was first aggregated to the daily temporal scale and subsequently downscaled to 1-km using monthly climatologies from CHELSA v2.1. The downscaling was performed using

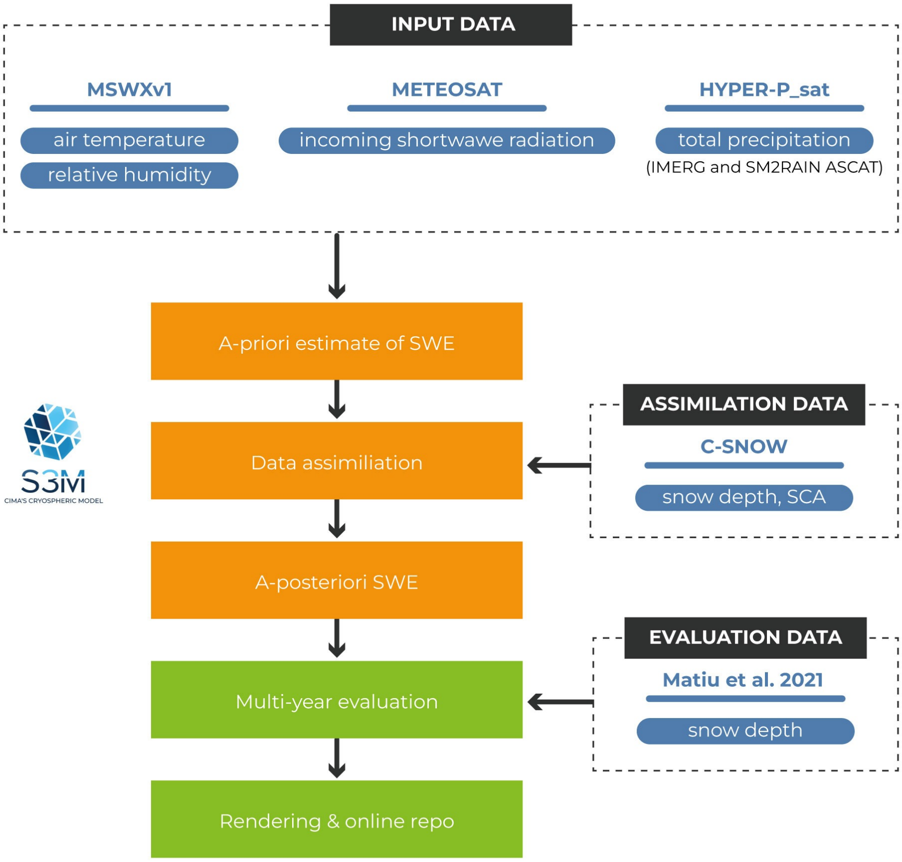

Figure 1. Schematic of the DTE-SNOW approach

monthly-additive correction factors, assuming MSWXv1 captures daily variability while CHELSAv2.1 accurately represents long-term fine-scale spatial patterns. Relative humidity was interpolated bilinearly from MSWXv1 resolution to 1-km. Incoming shortwave radiation was derived from Meteosat Second Generation (MSG) data at 3-km resolution (Trigo et al., 2011), aggregated from 30-minute to daily values following Rains et al. (2024), and subsequently interpolated bilinearly to 1 km.

The Sentinel-1 snow depth retrievals (C-SNOW) are based on a change detection method, conceptually translating the temporal changes in radar backscatter to changes in snow depth (Lievens et al., 2019, 2022). The underlying assumption is that the scattering contributions from the soil below a (dry) snowpack remain mostly constant during winter, while the accumulation of dry snow causes enhanced microwave signal depolarization, and thus increases the ratio of cross- over co-polarized backscatter (Jans et al., 2025). Wet snow conditions, which attenuate the microwave signal, are detected by the algorithm and masked. The dry snow depth retrievals used in this study cover the entire Mediterranean domain at 1 km spatial resolution and a temporal resolution according to the Sentinel-1 observation plan (with typically sub-weekly observations).

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Recent studies have shown that the assimilation of the Sentinel-1 snow depth retrievals improve simulations of river streamflow (Alfieri et al., 2022; Girotto et al., 2024; Brangers et al., 2024; De Lannoy et al., 2024).

To showcase the results of this approach, two model settings were considered. The first is an open loop simulation (September 2016 – August 2023) using HYPER-P_sat, MSWXv1, and MSG as input data. The second includes the assimilation of C-SNOW data (September 2016 – August 2021) using a simple Newtonian-relaxation approach that assigns equal weight to the model and the data (Avanzi et al., 2022a). We note that the choice of this simple assimilation scheme was made to align these results to those obtained by the operational applications of S3M (Avanzi et al., 2022c), but future applications may benefit from properly accounting for the respective uncertainties of data and models, as done in several EnKF studies (Dunmire et al., 2026). Also note that we employed the wet-snow masks in C-SNOW to filter data retrieved in such conditions.

We run simulations across four test basins: the Ebro catchment (Spain), the Rhone catchment (France), the Po catchment (Italy), and the upper Inn catchment (Austria). All these catchments have a significant snow contribution and available validation data. In particular, simulations were evaluated using a quality-checked dataset of in-situ observations of snow depth (Matiu et al., 2021), which comprises manual and automatic daily observations from a variety of national and regional weather monitoring agencies across the European Alps, and a collection of snow-depth-sensor data from the Ebro catchment provided by the Ebre Observatory. Contrary to SWE data, which are only sparsely collected across European mountains and often not publicly shared, snow depth provides an alternative proxy for snow mass with a dense spatial coverage of observations.

3 Results

The spatial distribution of open-loop simulations across the four basins shows a clear topographic signature, as expected (Figure 2). These signatures include lower SWE in lowland regions and inner-Alpine valleys, and higher SWE across mountain peaks. Note again that Figure 2 shows open loop results, which means that this topographic signature was obtained just using satellite-only precipitation and weather datasets, without the additional, beneficial assimilation of C-SNOW. Mean winter SWE between 2017 and 2023 shows a strong correlation with elevation: the Pearson's correlation coefficient was 0.67, 0.67, 0.77, and 0.66 for the Ebro, Po, Inn, and Rhone catchments, respectively (see again Figure 2).

The slight change in slope of mean SWE versus elevation above ∼3000 m in Figure 2 across the Po, Inn, and Rhone catchments is due to spurious, multi-year accumulation of residual snow at high elevations, where a number of processes not included in S3M take place and that would instead affect SWE: avalanche movement, sublimation, wind redistribution, and glacier mass balance. While these processes may be relevant at the local scale, their impact at the catchment scale (the reference scale of a DTE-hydrology project) is minor, given the small area of these regions.

The evaluation of the simulations with in-situ snow depth across all catchments shows good agreement for both open-loop and assimilation (DA_ C-SNOW), though DA_C-SNOW better captures high amounts of snow depth above 2.5-3m, which are absent in the open-loop configuration (Figure 3a). The average bias is 0.05m (16%) for DA_ C-SNOW and -0.03m (-9%) for open-loop, while the correlation is slightly better for DA_C-SNOW with 0.80 compared to 0.77 for open-loop. Overall

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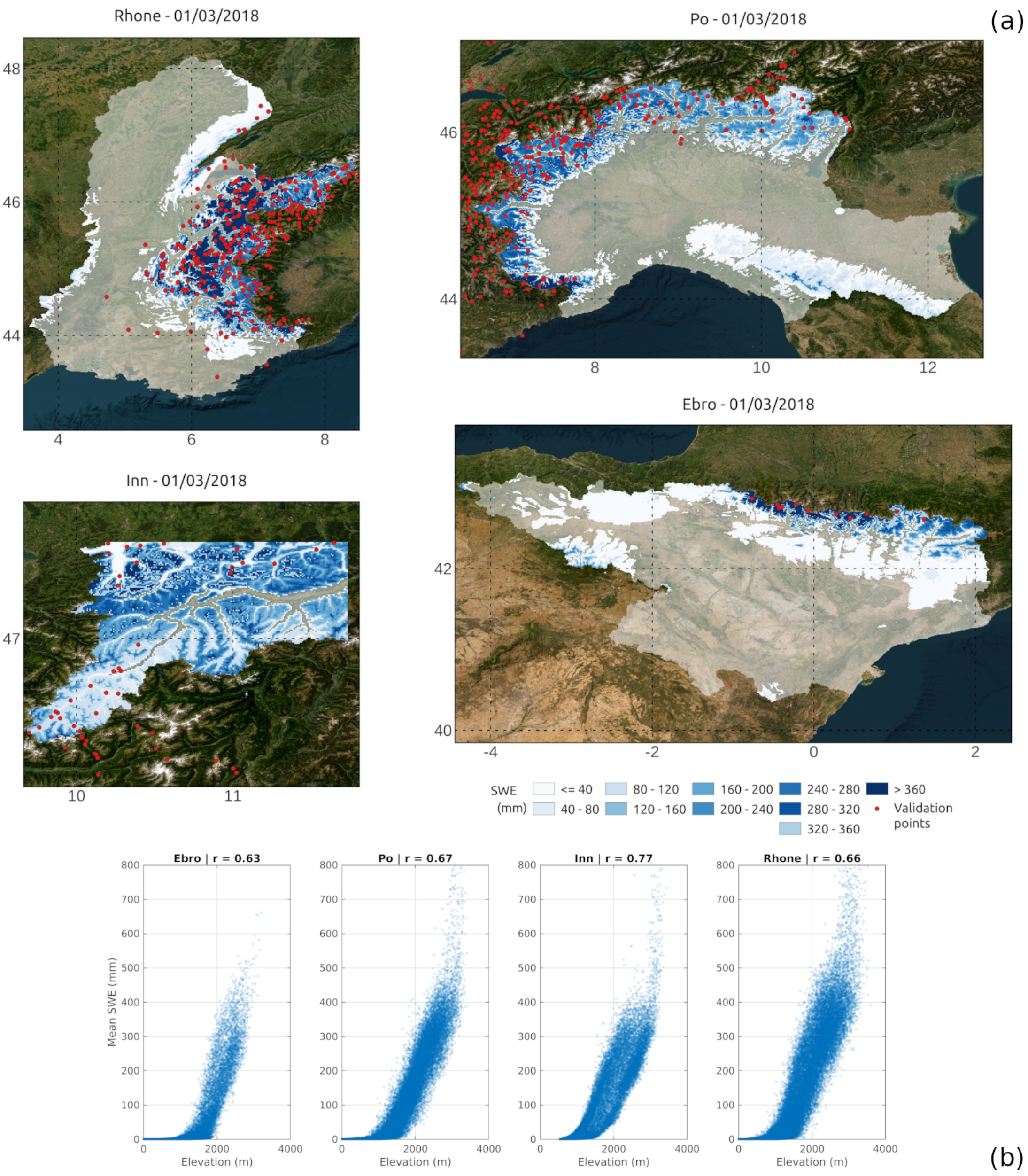

Figure 2. a) Snapshots of snow water equivalent for the four basins on the sample date March 1, 2018 (open loop simulation) and b) regression of mean snow water equivalent (December-June) vs. elevation. Background map from the Esri satellite theme | Powered by Esri.

C-SNOW helps to better mimic the overall distribution of snow depth with higher values, but it overestimates the snow depth where shallow snow is observed.

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Separating by month and elevation bands as a proxy of mean snow depth and seasonal/topographic characteristics of the snowpack, biases are negligible until 1500 m across all months (Figure 3b). For the band 1500-2000 m, where the average snow depth is generally deeper, biases are on average zero in the early season until January, while towards the end of the season biases become negative for open-loop and positive for DA_C-SNOW. This pattern of overestimation for C-SNOW and underestimation of open-loop becomes stronger at higher elevations (> 2000 m) and starts earlier than at lower elevations, already in November/December.

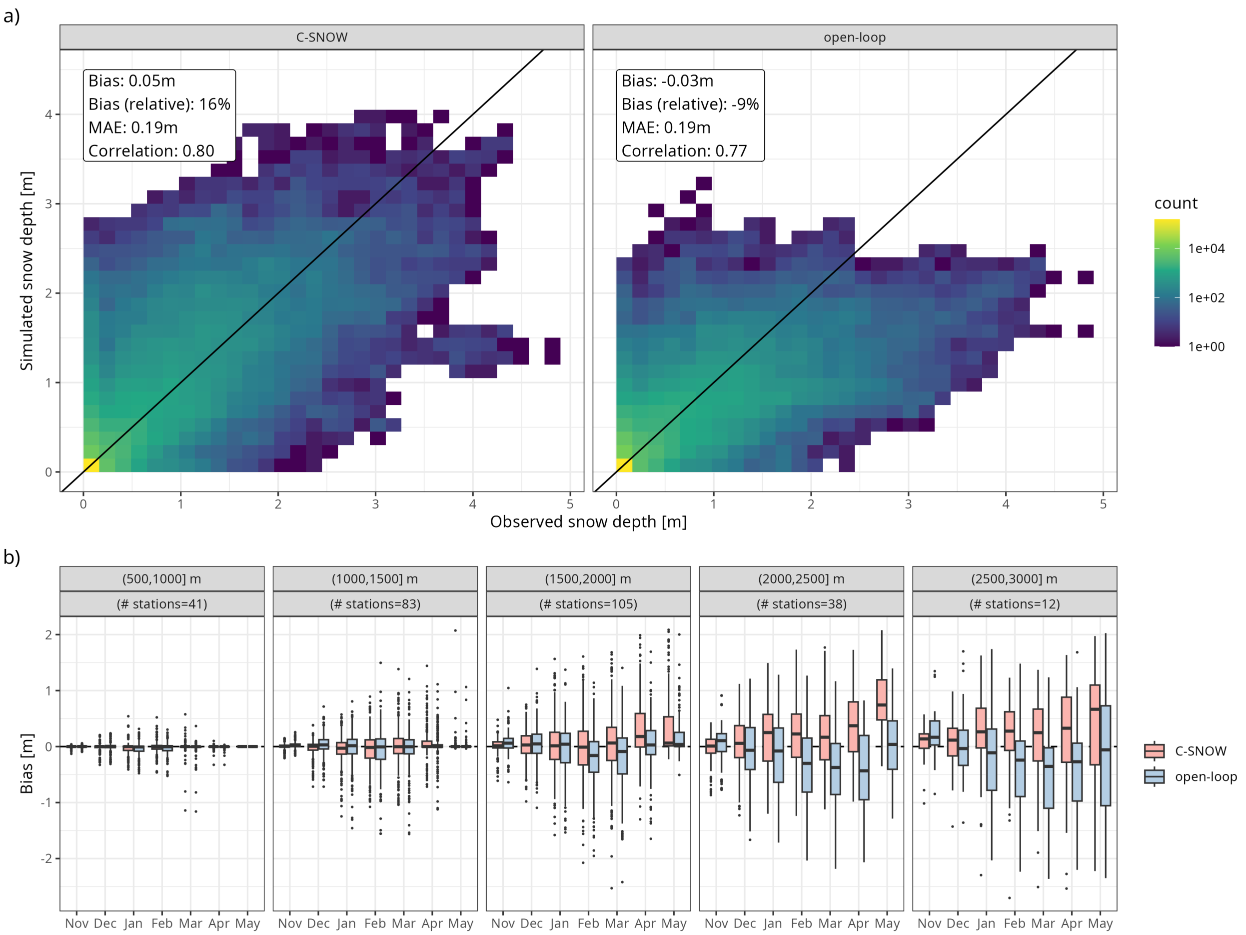

Figure 3. a) Scatter plot of observed vs. simulated snow depth (open loop and with assimilation) including all data points in space and time; b) Bias by elevation and month, boxplots show distribution of biases calculated per station, year, and month that had at least 25 values per group; number of stations per elevation class is the median over all years and months.

4 Discussion and Conclusions

Accurate estimation of snow water resources using only satellite-derived precipitation, snow modeling, and the optional assimilation of Sentinel-1 snow depth retrievals is not only feasible, but yields mean biases below 0.05 m and correlations exceeding 0.77 at 1-km resolution. The independence from in-situ observations is particularly advantageous within the DestinE framework, as it enables the scalable application of this approach from regional to global domains, effectively supporting a “SWE of everywhere” paradigm. This scalability is reinforced by the consistent performance observed across the four study catchments, which span a range of climatic conditions and snow regimes (Sturm and Liston, 2021). Furthermore, the 1-km spatial resolution substantially exceeds that of existing large-scale reanalyses based on Earth system models (e.g., ERA5 or ERA5-Land in Europe), and approaches that of operational national snow products, which typically rely heavily on in-situ observations (Olefs et al., 2020; Avanzi et al., 2022c).

The extension of this paradigm to larger spatial scales will particularly benefit from the robust performance of HYPER-P_sat as a precipitation forcing. Estimating precipitation in snow-dominated regions is inherently challenging due to both the sparse distribution of gauges and their reduced accuracy during snowfall events (Avanzi et al., 2021). Moreover, complex orographic effects, such as elevation gradients and cross-valley variability, limit the reliability of precipitation radar products (Germann et al., 2006). Our results show that HYPER-P_sat can provide precipitation estimates that translate into credible simulations of snow depth across mountain landscapes, at least up to 2 m (Figure 3). Although very high snow-depth values are not always reliable benchmarks for 1-km model outputs, since they may reflect highly localized conditions rather than representative landscape-scale signals (Grünewald and Lehning, 2015), their underestimation can be mitigated through the assimilation of C-SNOW. Overall, the joint use of satellite-derived precipitation and snow depth emerges as a viable strategy for producing landscape-scale snow reanalyses, particularly in data-scarce regions where in-situ observations are limited or unavailable.

The main operational question that DTE-SNOW addresses is deceptively simple: how much snow is accumulated across the landscape at a given time? Additionally, how much of this snow is melting, and how much is still accumulating? Answering these questions has major implications for real-world decision-making, particularly in temperate and Mediterranean regions, where snowmelt provides critical support to irrigation, hydropower, ecosystems, and freshwater supply during periods when demand increases but precipitation declines (Massari et al., 2022). Addressing these challenges requires high-resolution, high-frequency data with consistent performance across diverse catchments and topographic conditions (Pagano et al., 2014; Dozier et al., 2016). DTE-SNOW has demonstrated the capability to meet these requirements.

The emergence of DTE approaches based solely on remote datasets does not signal the end of in-situ observations. On the contrary, such datasets remain (and will continue to be) essential. For instance, the development of S3M relied extensively on in-situ snow depth and SWE measurements (Avanzi et al., 2022a), as was also the case for C-SNOW and HYPER-P_sat. In addition, in-situ records typically span much longer time periods than EO-based datasets, making them invaluable for climate-change studies (Marty et al., 2017), while their high temporal resolution and local representativeness support detailed process understanding.

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Given that the availability of in-situ observations varies globally due to budgetary and topographic constraints, future work within the DestinE framework should prioritize flexible data-assimilation approaches capable of leveraging heterogeneous data availability. Another key direction will be coupling DTE-SNOW with fully integrated hydrological models, enabling a seamless representation of the water budget across spatial and temporal scales.

Author contributions. FA, HL, SG, FD, LA, AL, LB, CM, and GDL designed the DTE-SNOW framework across various ESA projects. PF, LB, and CM developed and provided the HYPER-P_sat data. OBV and DGM processed the remaining input data. PQS and MM provided evaluation snow data and supported DTE-SNOW validation. FA wrote the manuscript with inputs from HL, PF, OBV, MM, CM, GDL, and LA. All authors revised the manuscript.

Competing interests. At least one of the (co-)authors is a member of the editorial board of The Cryosphere.

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Data availability. HYPER-P_sat data are available at https://zenodo.org/records/15025462. MSWXv1 data are available at https://www.gloh2o.org/mswx/. MSG radation data are available at https://lsa-saf.eumetsat.int/en/data/products/radiation/. C-SNOW data are available at https://ees.kuleuven.be/eng/apps/project-c-snow-data/. Snow depth data are available in Matiu et al. (2021) and at https://www.obsebre.es/ca/. S3M is an open-source model available via Avanzi et al. (2022a).

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