The Big Thaw: gauging the past, present and future of our mountain water resources

Using novel lake-based snowfall measurements in the Rockies, Alps, and Himalayas to assess and optimise the representation of snowfall in the MetUM regional atmospheric model at kilometre grid-scales

Sid Gumber, Andrew Orr (anmcr@bas.ac.uk), Paul Field, Hamish Pritchard, Federico Covi, Pranab Deb, Marc Girona-Mata, Emily Potter, and Martin Widmann

British Antarctic Survey
NATURAL ENVIRONMENT RESEARCH COUNCIL

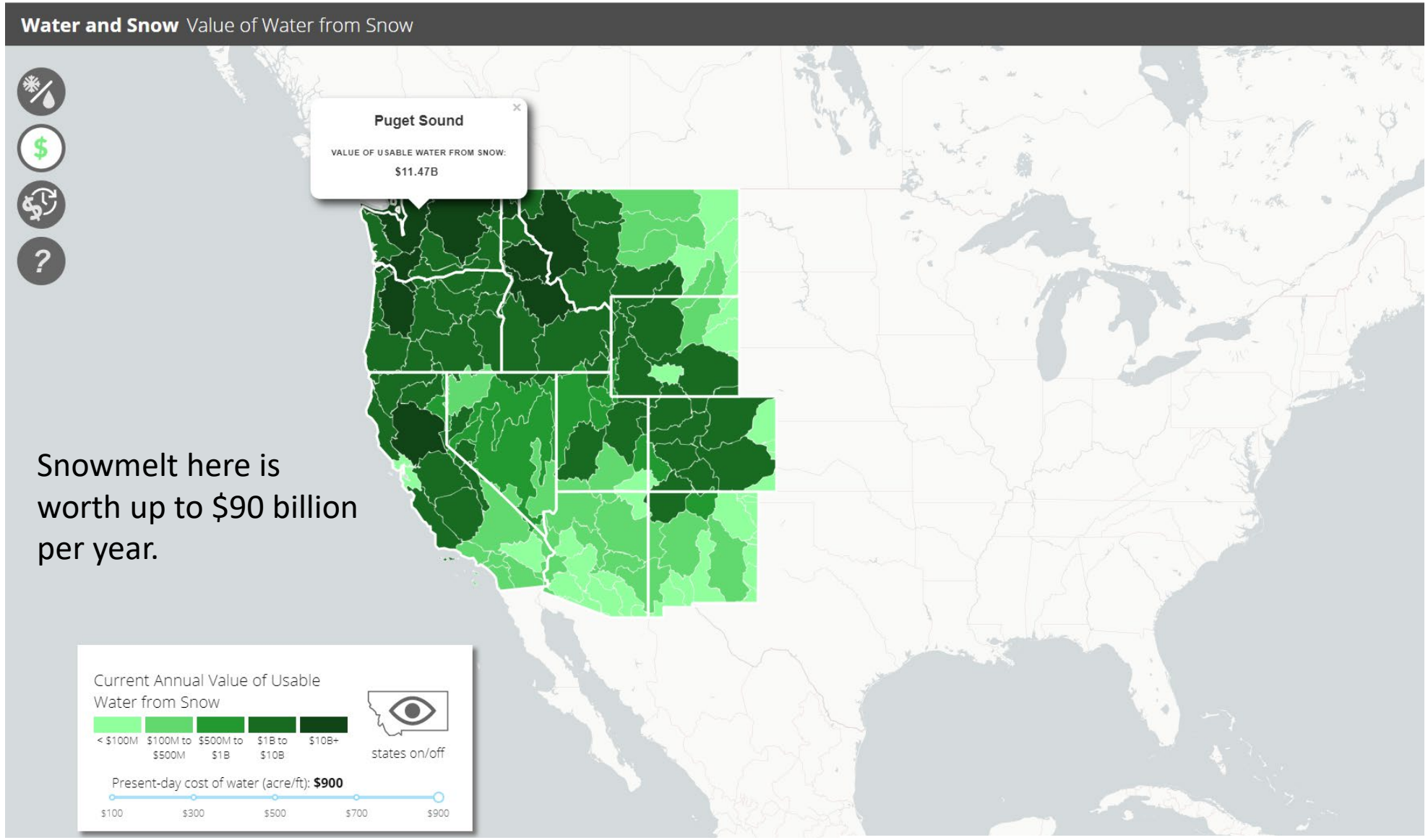
UNIVERSITY OF BIRMINGHAM

Met Office

Indian Institute of Technology, Kharagpur

University of Sheffield

Snow is valuable



Sturm et al. (2017) Water and life from snow: A trillion-dollar science question.

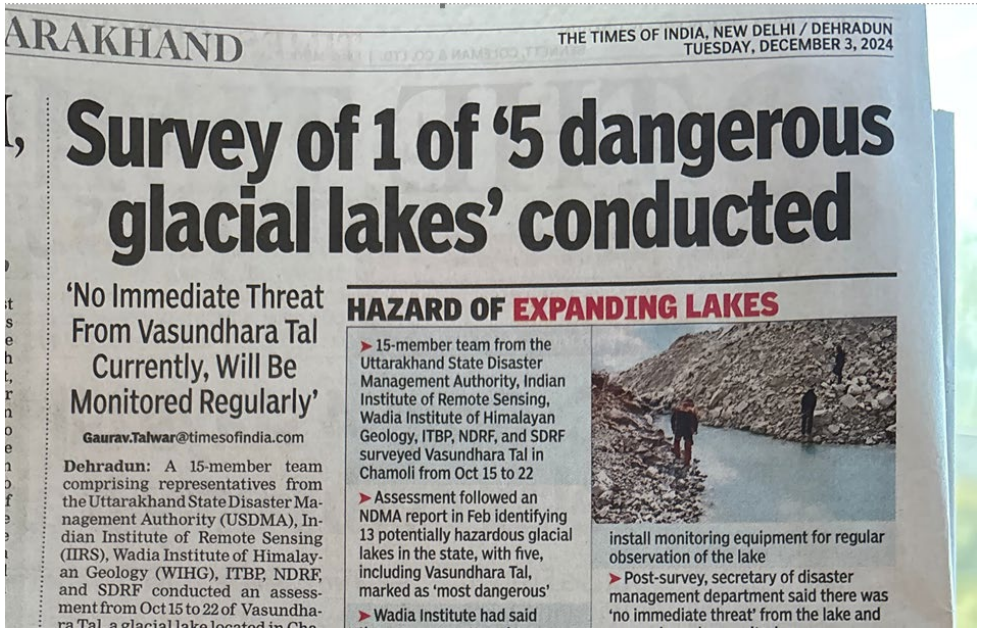
Snow is valuable

Pritchard (2019). “Asia’s glaciers protect large populations from drought stress" ***Nature*** 369.

Snow is hazardous

Rescuers carry workers after an avalanche near Mana village in Chamoli district of India's Uttarakhand state on February 28, 2025 [Hanout/State Disaster Response Force via AFP]

Imja Lake—the long, silty lake in this 2010 photo—has grown in front of Imja and Lhotse Shar glaciers (top right) in the Himalayas. In 2016, engineers lowered Imja Lake by 3.5 meters to reduce the chances of a large glacial lake outburst flood. Credit: Jeffrey S. Kargel, Planetary Science Institute,



ARAKHAND

THE TIMES OF INDIA, NEW DELHI / DEHRADUN
TUESDAY, DECEMBER 3, 2024

Survey of 1 of '5 dangerous glacial lakes' conducted

'No Immediate Threat From Vasundhara Tal Currently, Will Be Monitored Regularly'

Gaurav.Talwar@timesofindia.com

Dehradun: A 15-member team comprising representatives from the Uttarakhand State Disaster Management Authority (USDMA), Indian Institute of Remote Sensing (IIRS), Wadia Institute of Himalayan Geology (WIHG), ITBP, NDRF, and SDRF conducted an assessment from Oct 15 to 22 of Vasundhara Tal, a glacial lake located in Cho

HAZARD OF EXPANDING LAKES

- 15-member team from the Uttarakhand State Disaster Management Authority, Indian Institute of Remote Sensing, Wadia Institute of Himalayan Geology, ITBP, NDRF, and SDRF surveyed Vasundhara Tal in Chamoli from Oct 15 to 22
- Assessment followed an NDMA report in Feb identifying 13 potentially hazardous glacial lakes in the state, with five, including Vasundhara Tal, marked as 'most dangerous'
- Wadia Institute had said

install monitoring equipment for regular observation of the lake

- Post-survey, secretary of disaster management department said there was 'no immediate threat' from the lake and

Left: Aljazeera. Top right: EOS.
Bottom Right: Times of India

Snowfall data gap

Science question: How can we constrain snowfall amount over major mountain ranges?

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- In-situ measurements also too sparse and too poorly distributed to adequately constrain snow in weather and climate models.

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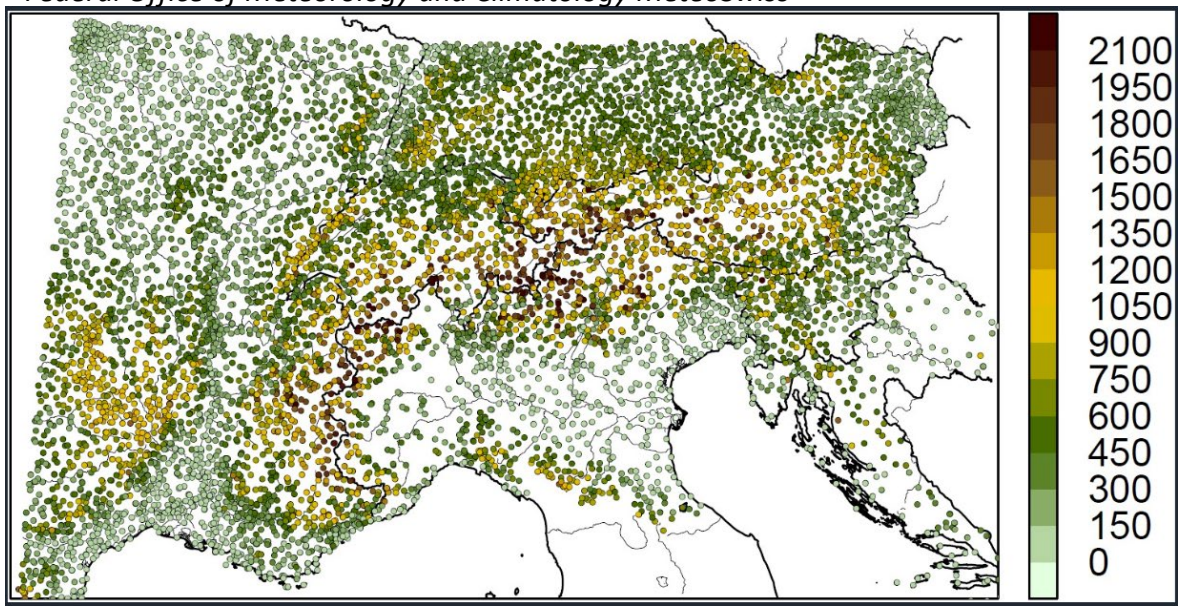
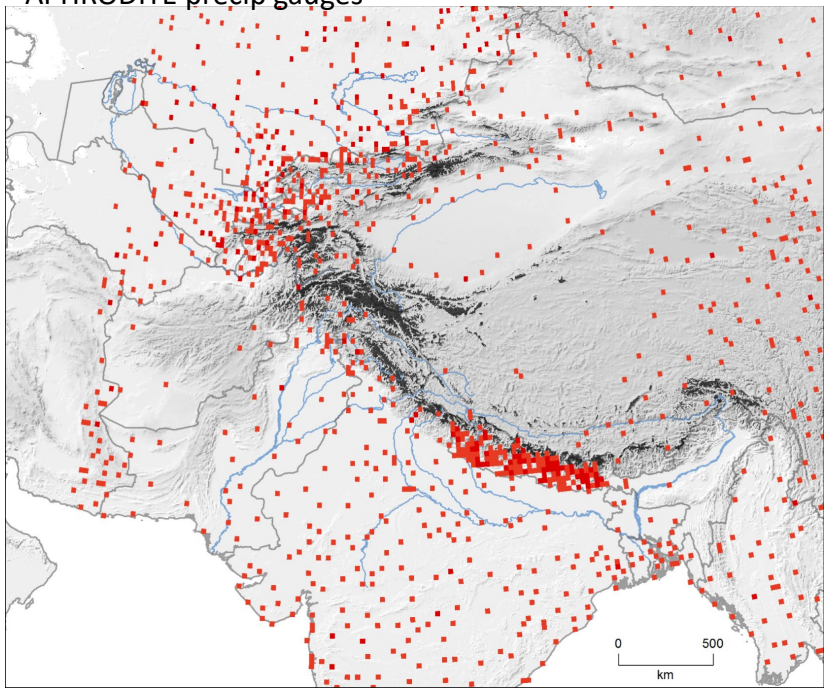
Federal Office of Meteorology and Climatology MeteoSwiss



APHRODITE precip gauges



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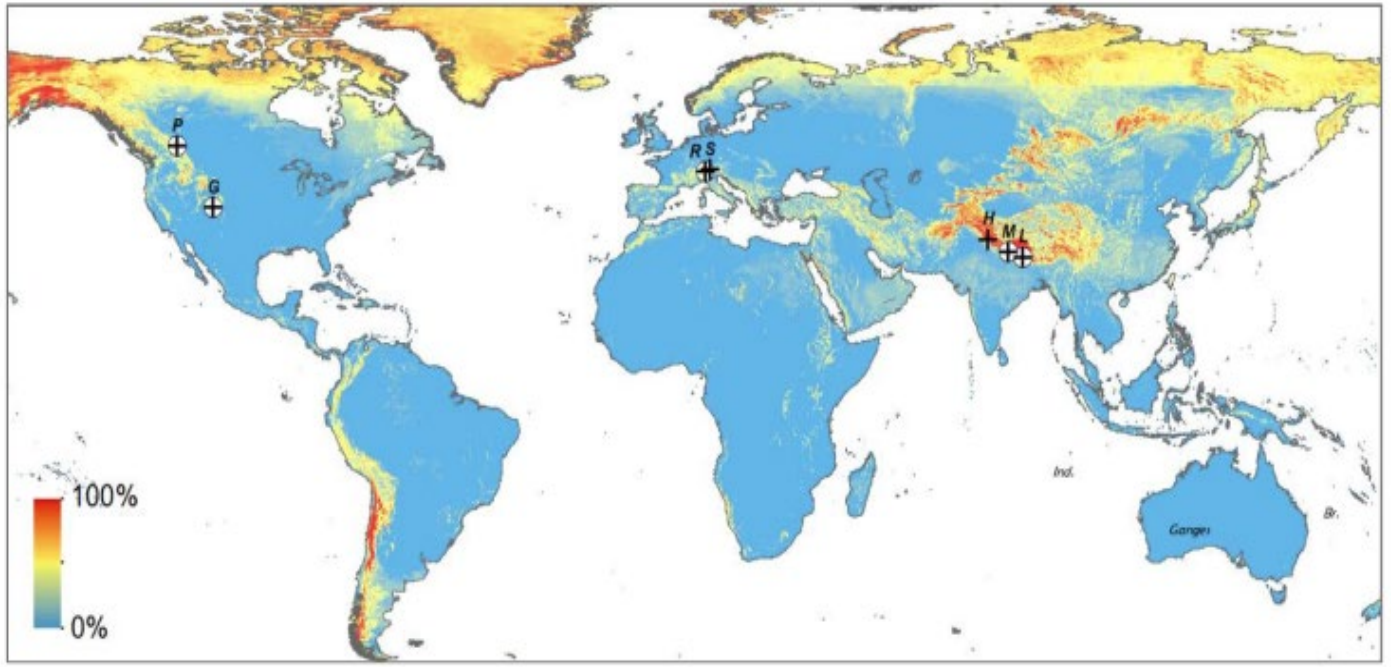
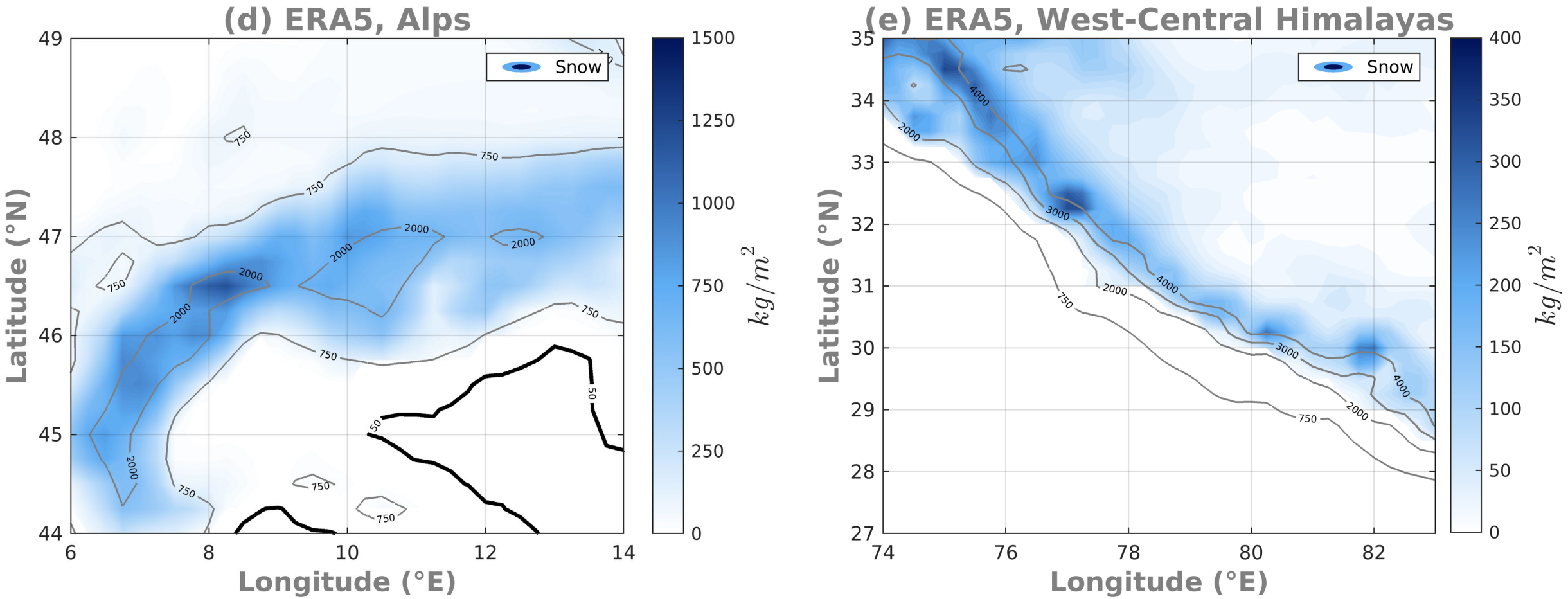


Precipitation correction-factors that must be applied to the observation-based "WorldClim v2" annual climatological precipitation product in order to agree with observations and models of catchment hydrology (Pritchard et al., 2021).

Current Gold Standard/ Maps of Alps and Himalayas



Accumulated total snowfall (kg/m^2) from ERA5 over the Alps (left) and west-central Himalayas (right) for the winter period of 2023-2024. Also shown are the model topographic heights.

ERA5 is the fifth generation of reanalysis data from the European Centre for Medium-Range Weather Forecasts (ECMWF), providing a comprehensive dataset of atmospheric, land surface, and ocean wave parameters. It's a global dataset that covers the period from 1940 to the present, with hourly data available. ERA5 offers a high spatial resolution of approximately 31 km and detailed vertical resolution, making it a valuable resource for climate research and monitoring

Lake-based snowfall measurements

- Measuring snowfall based on time-series of (frozen) lake water pressure (Pritchard *et al.*, 2020)
- Lake surface area millions of times larger than pluviometer coverage

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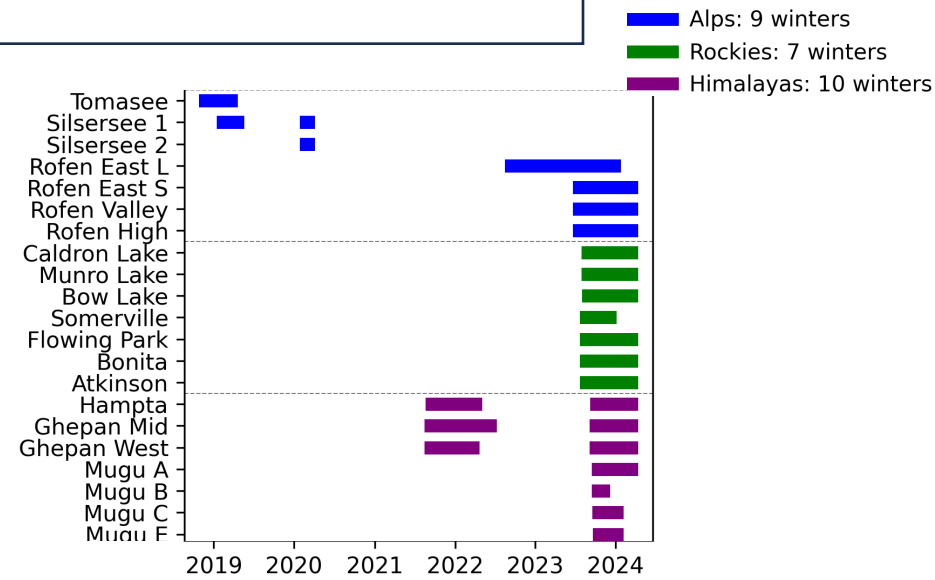

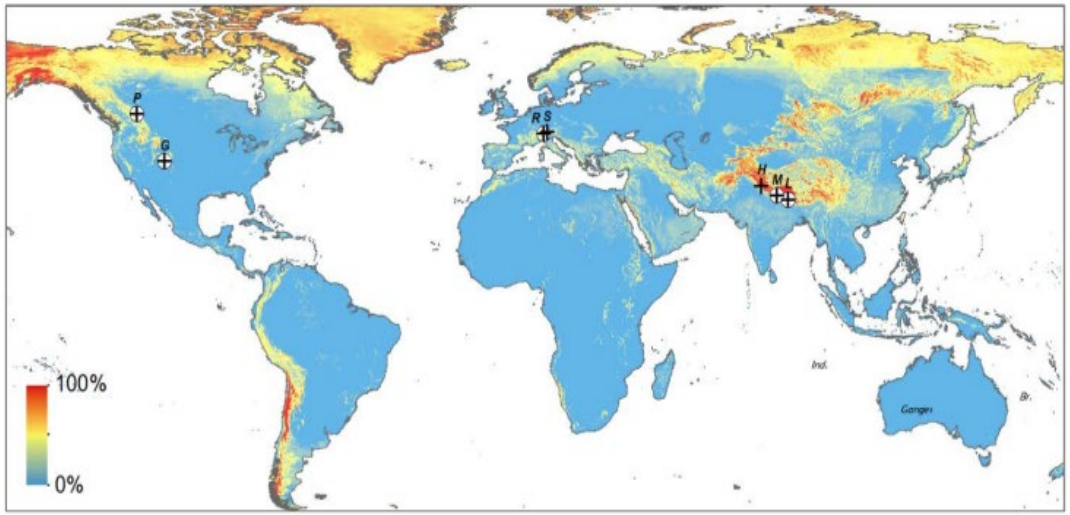

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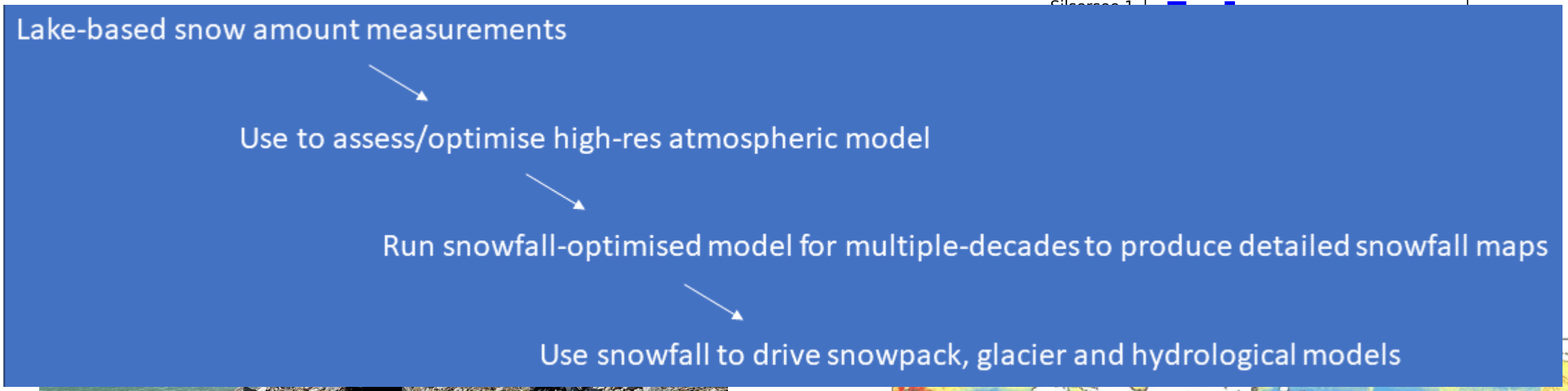
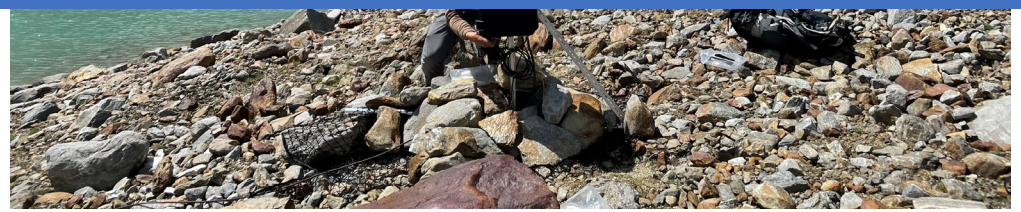
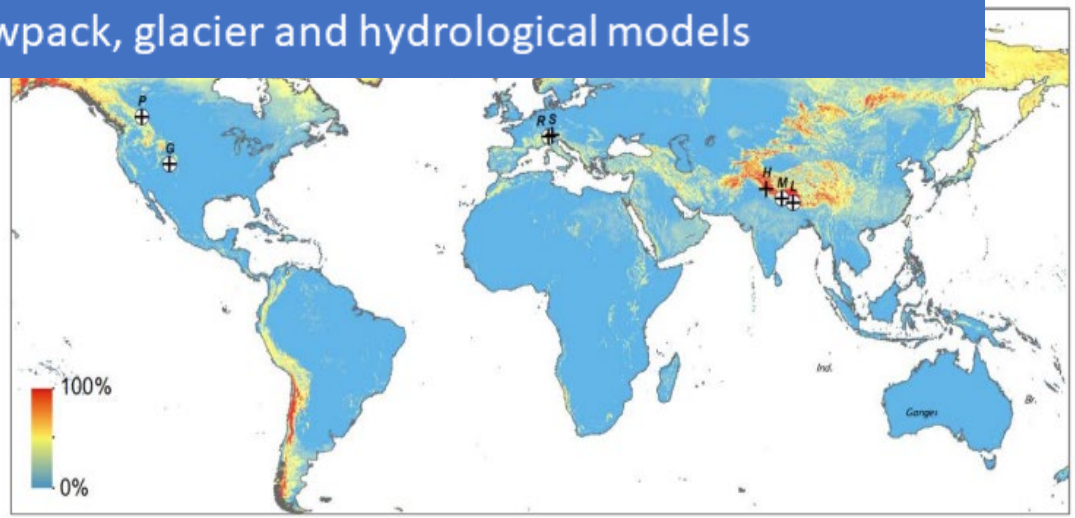
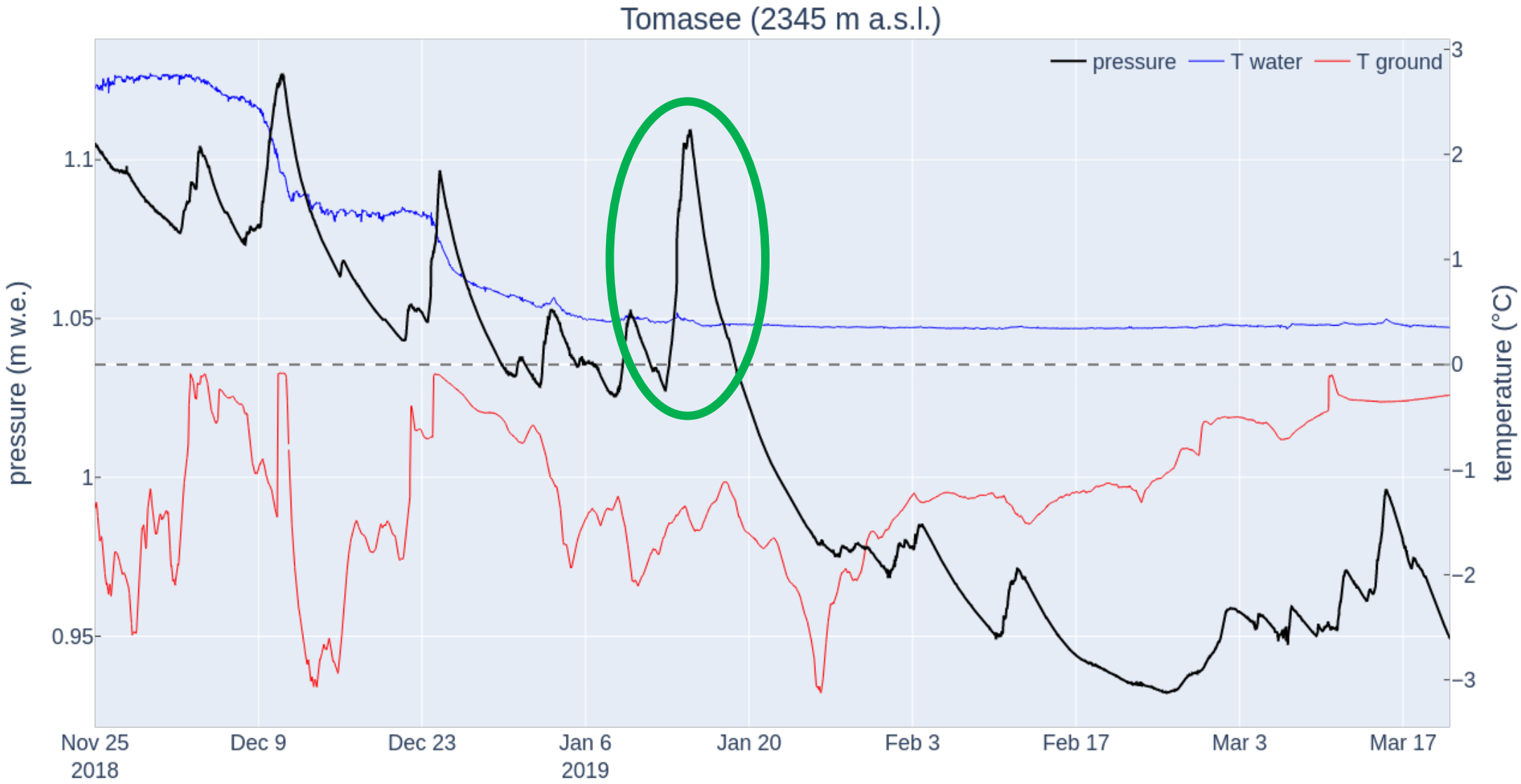




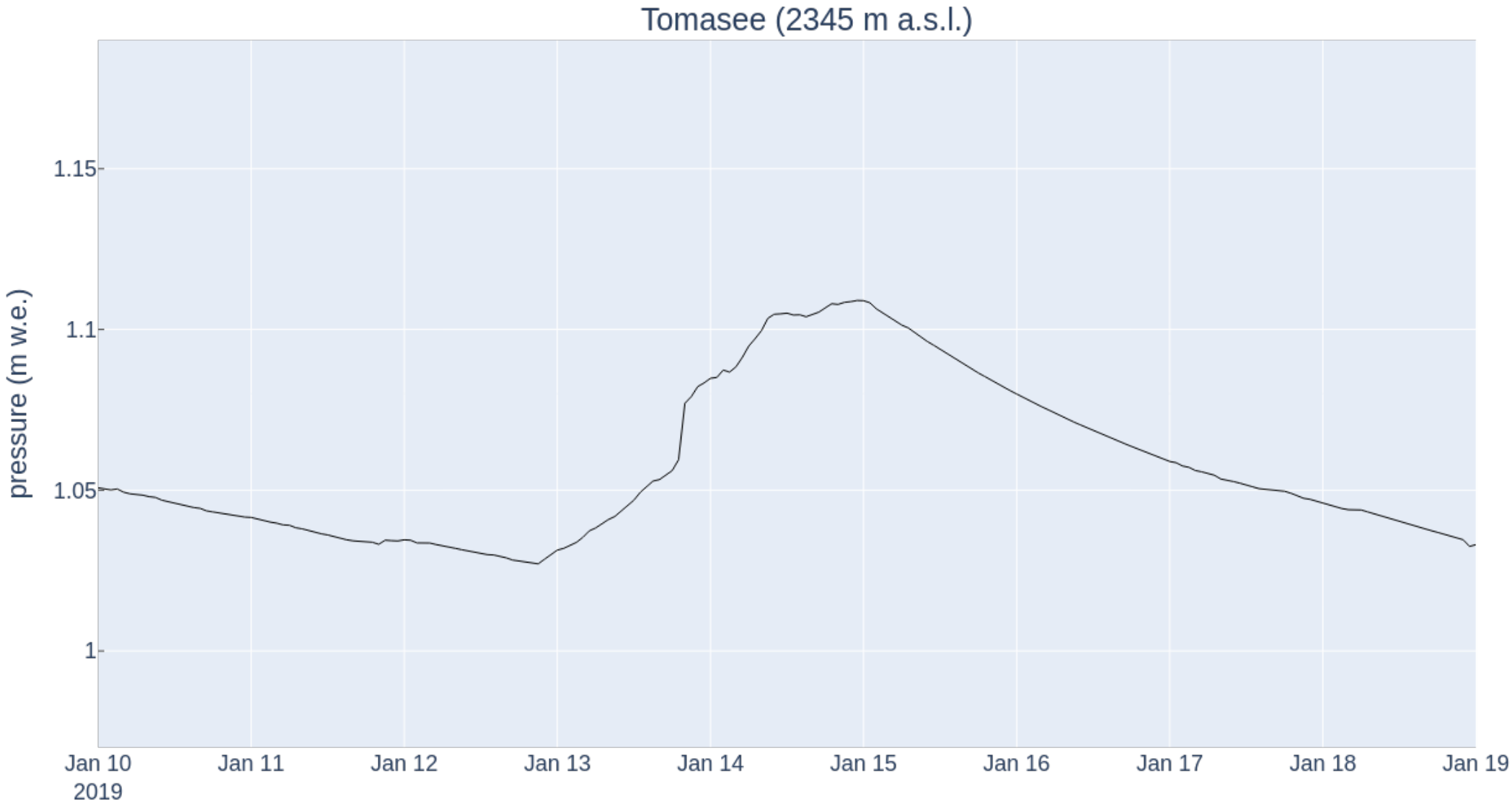


Processing lake-based snowfall data



Time-series of pressure from lake-based sensor for Tomasee for the winter season from 2023-24

Processing lake-based snowfall data



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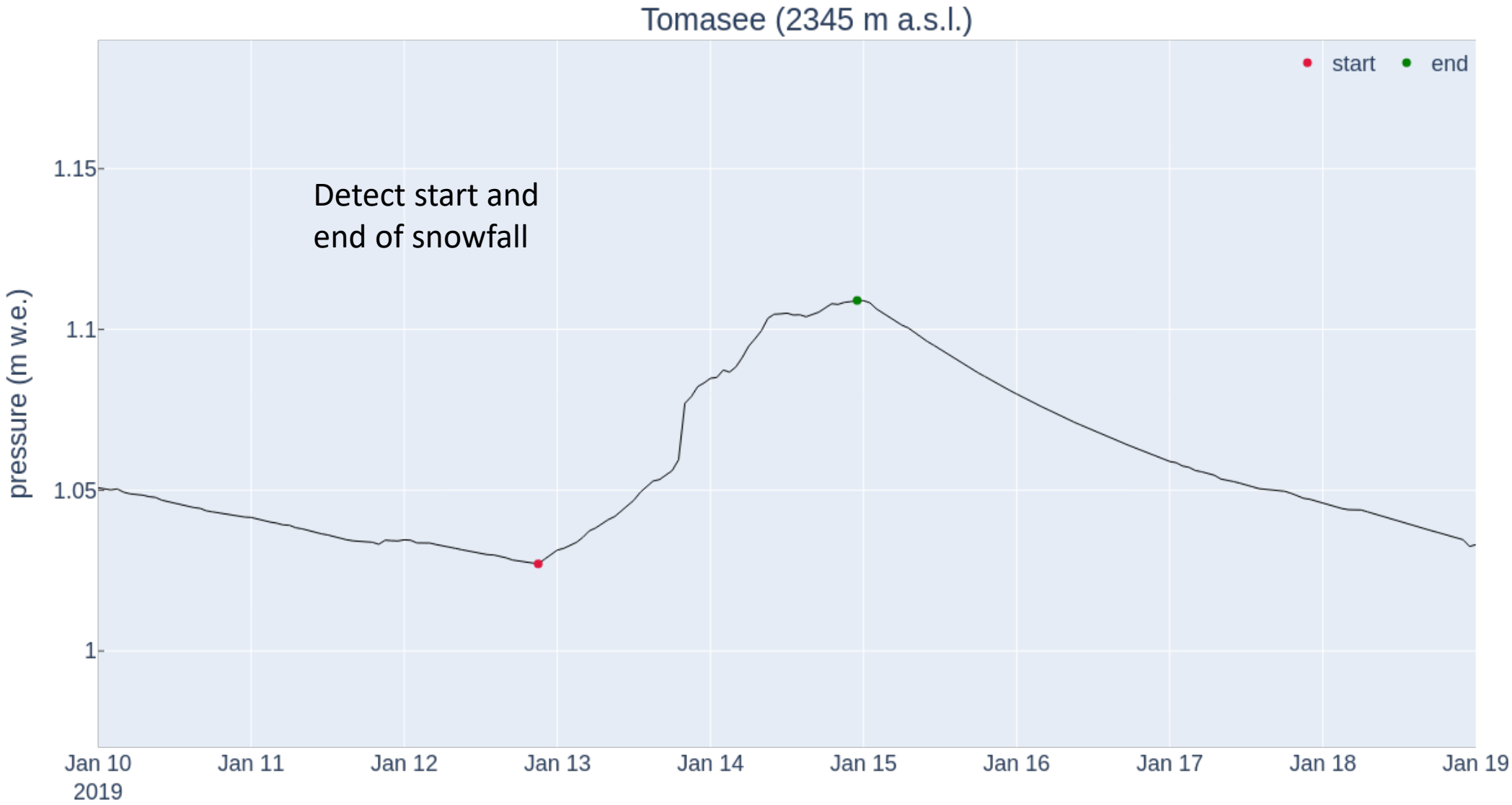

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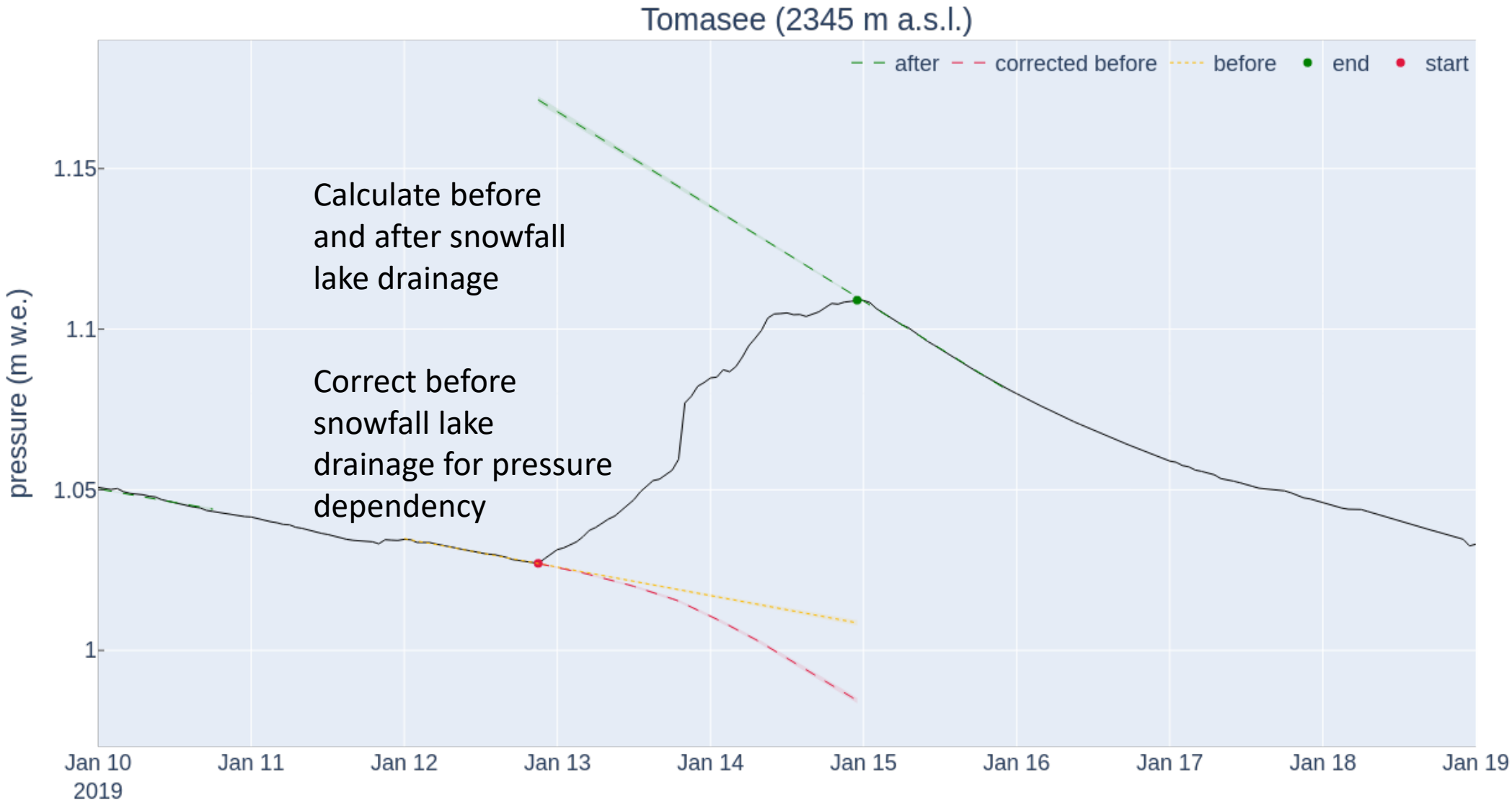

Time-series of pressure from lake-based sensor for Tomasee

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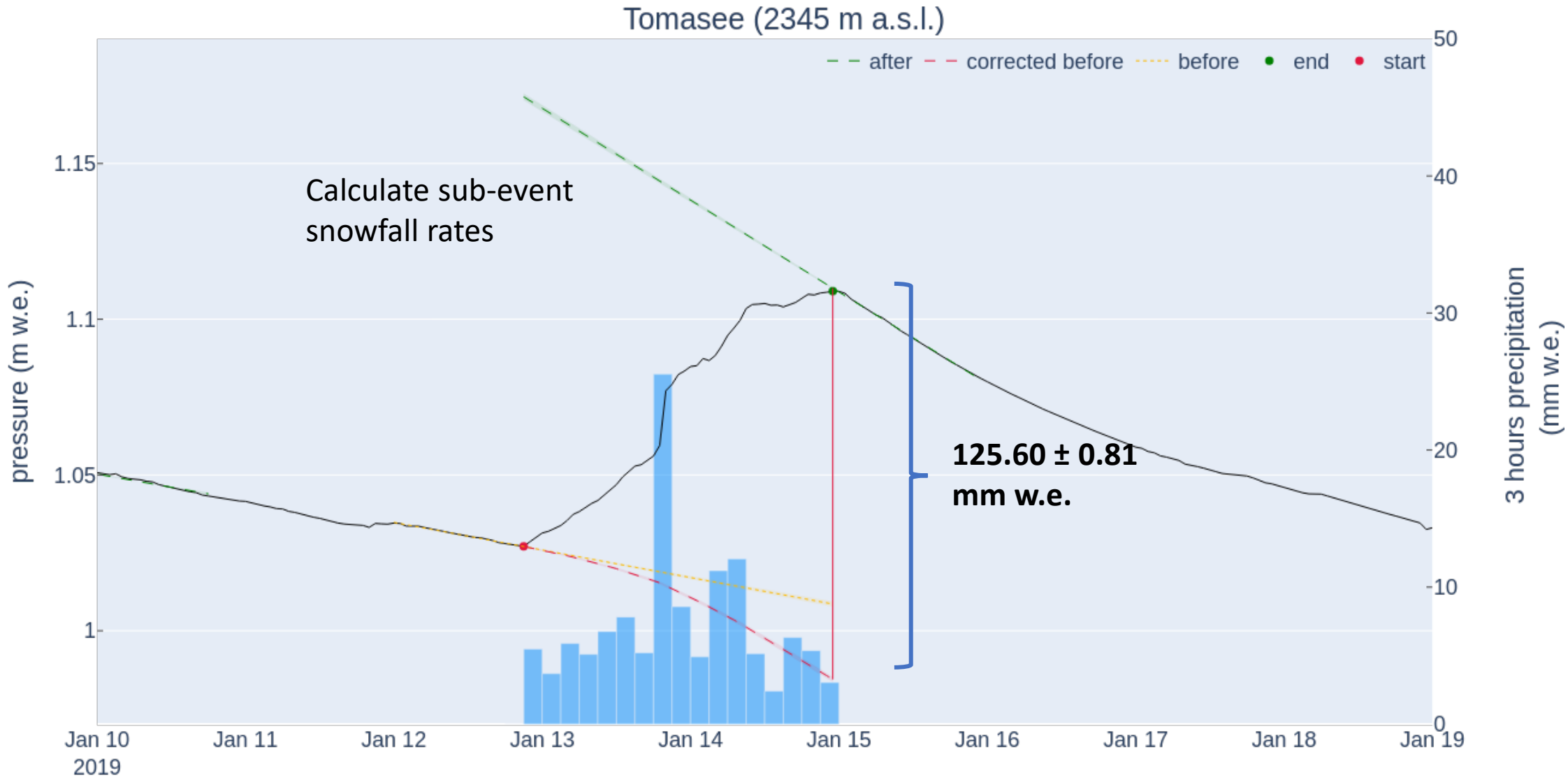
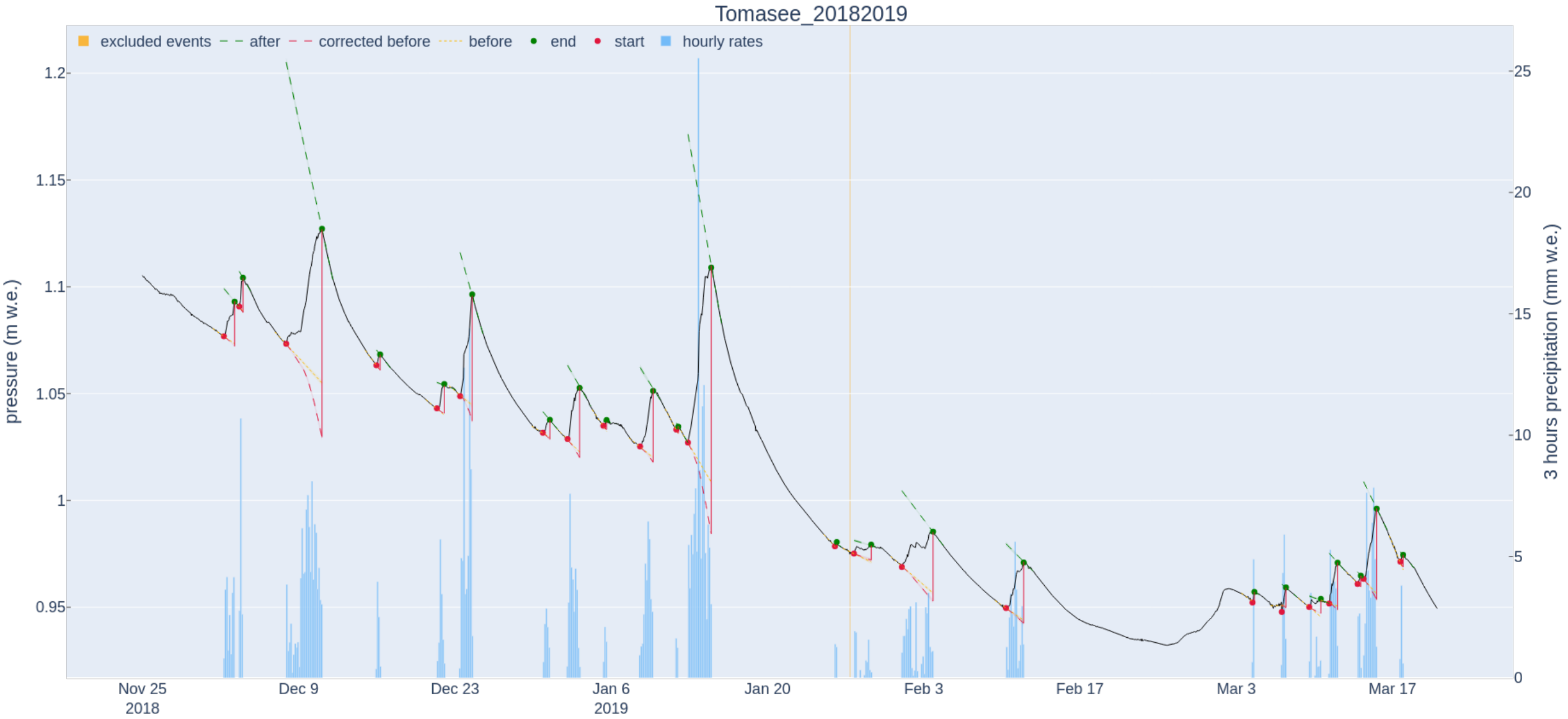


Time-series of pressure from lake-based sensor and associated snowfall for Tomasee

Processing lake-based snowfall data

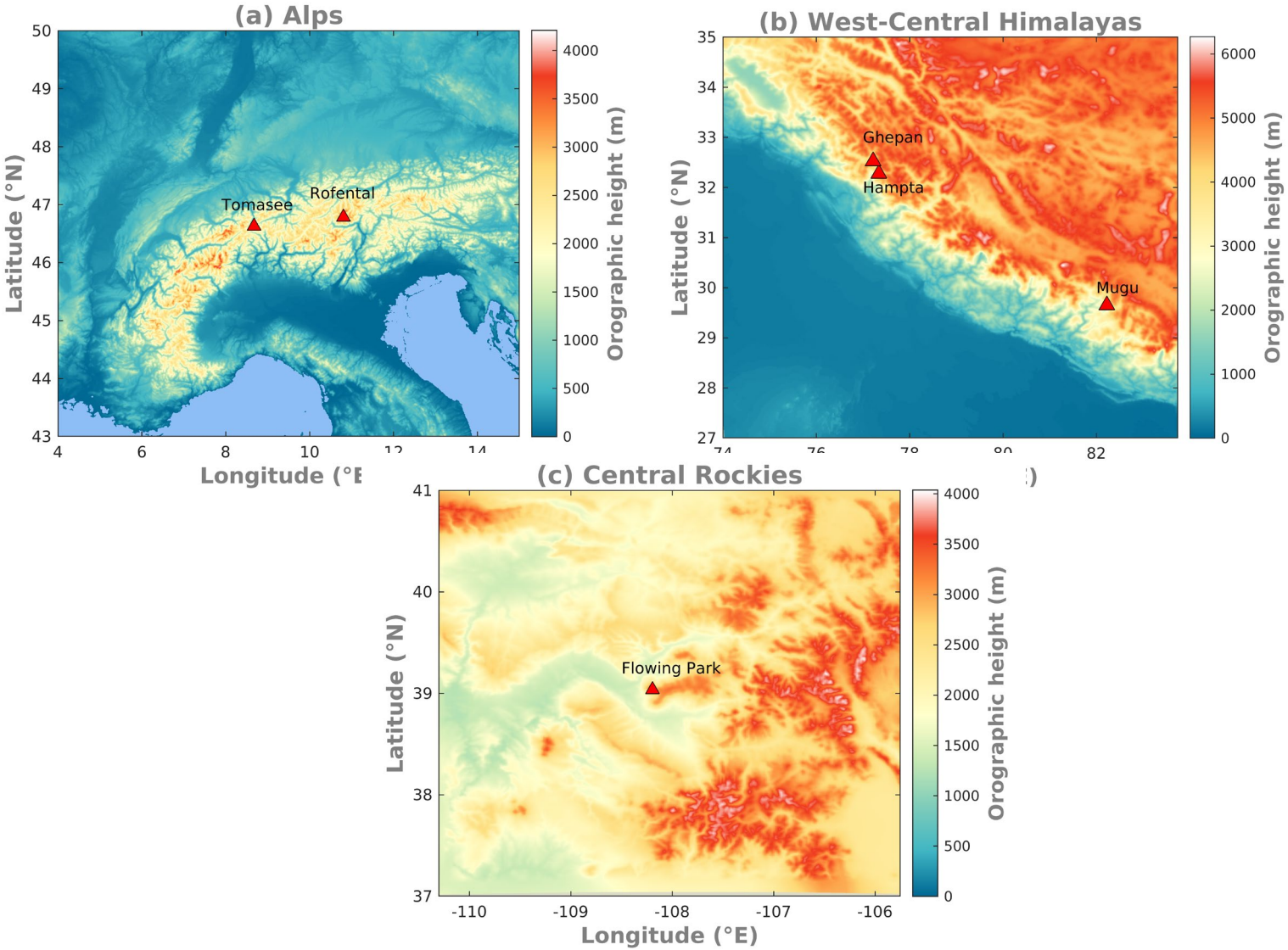


Time-series of pressure from lake-based sensor and associated snowfall for Tomasee

Modelling snowfall using a regional atmospheric model

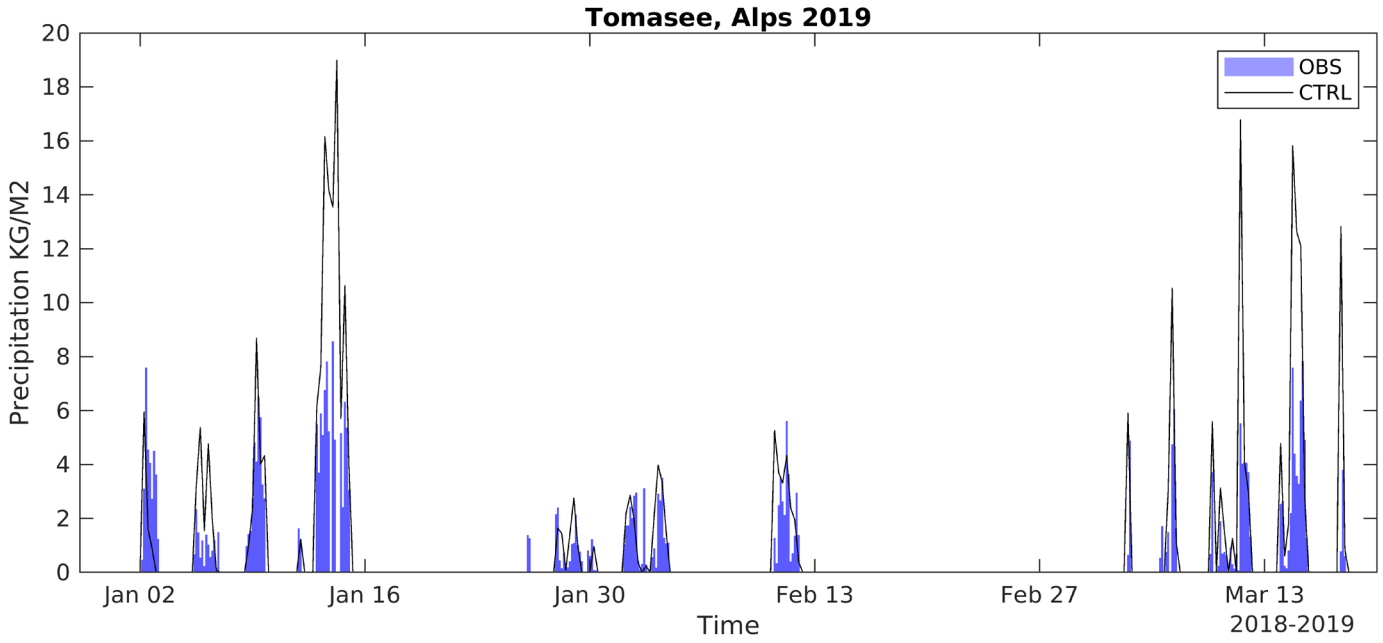
Model setup

- UK Met Office Unified Model (MetUM)
- Microphysics: CASIM Double Moment
- ERA5 forcing data
- Daily reinitialization approach
- Horizontal resolution: 1.5 km
- Vertical resolution: 70 levels / 40 km
- Three domains:
  - Alps (650x650 points)
  - Himalayas (650x650 points)
  - Central Rockies (USA)



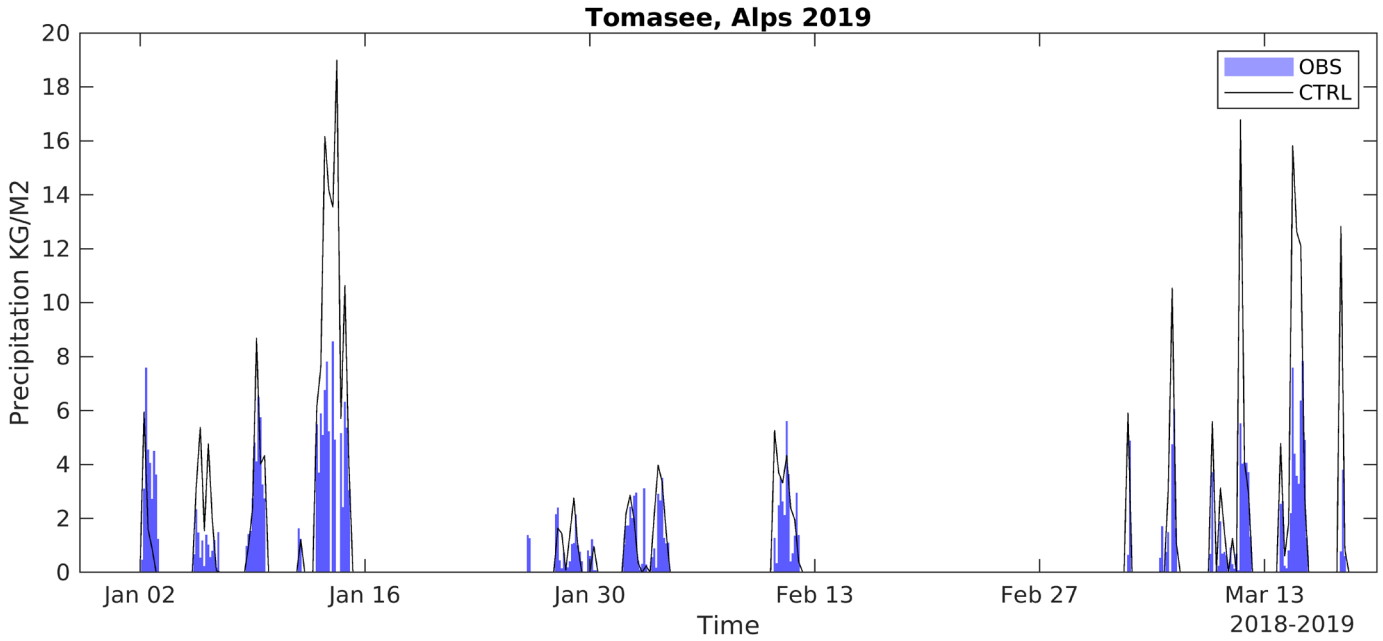
Maps showing model domains and orography (m) at 1.5 km grid spacing for the (a) European Alps, (b) west-central Himalayas, and (c) central Rockies, with the positions of the lake-based snowfall measurement sites indicated by red triangles. Note that the panels have different scales.

Modelling snowfall / Alps example



Time series of three-hourly snowfall of observed and modelled snowfall at Tomasee (kg m^{-2}) for the period 01 Jan 2019 to 31 Mar 2019.

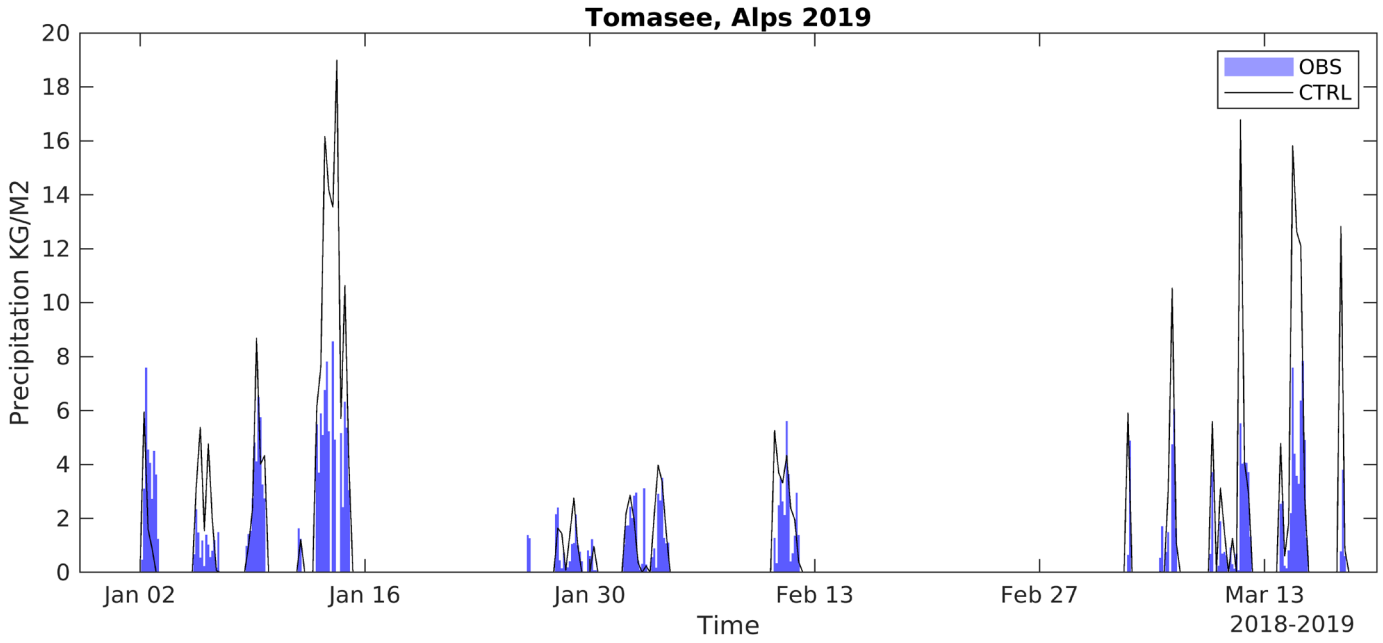
Modelling snowfall / Alps example



Control (CTRL) simulation

- Captures snowfall occurrence relatively well
- Onset/end of events well captured
- Consistent over prediction of snowfall amounts

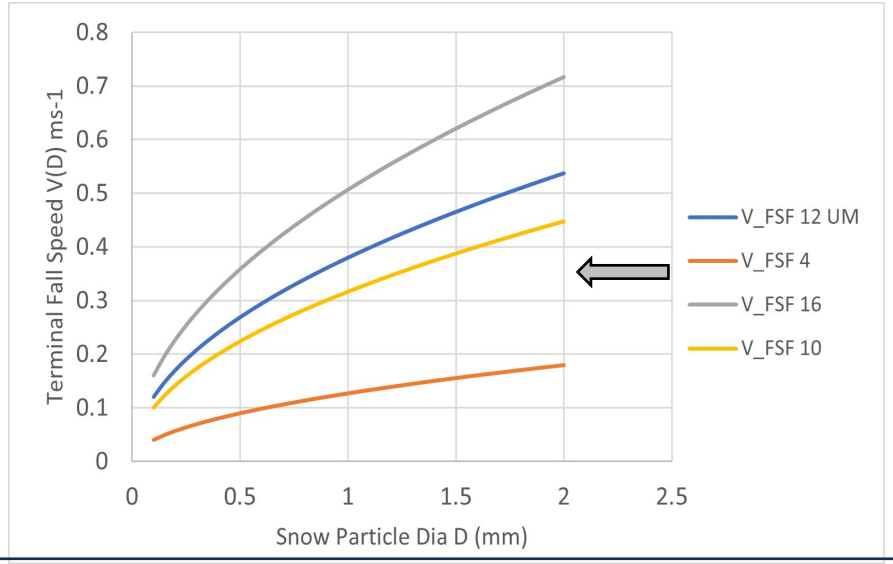
Modelling snowfall / Alps example



Sensitivity experiment (EXP): Reducing hydrometeor fall-speed

$$V_x(D) = \boldsymbol{a_x} D^{b_x} e^{f_x D} \left(\frac{\rho_0}{\rho}\right)^{g_x}$$

Where a_x, b_x, f_x and g_x represent the parameters for fall speed relationships



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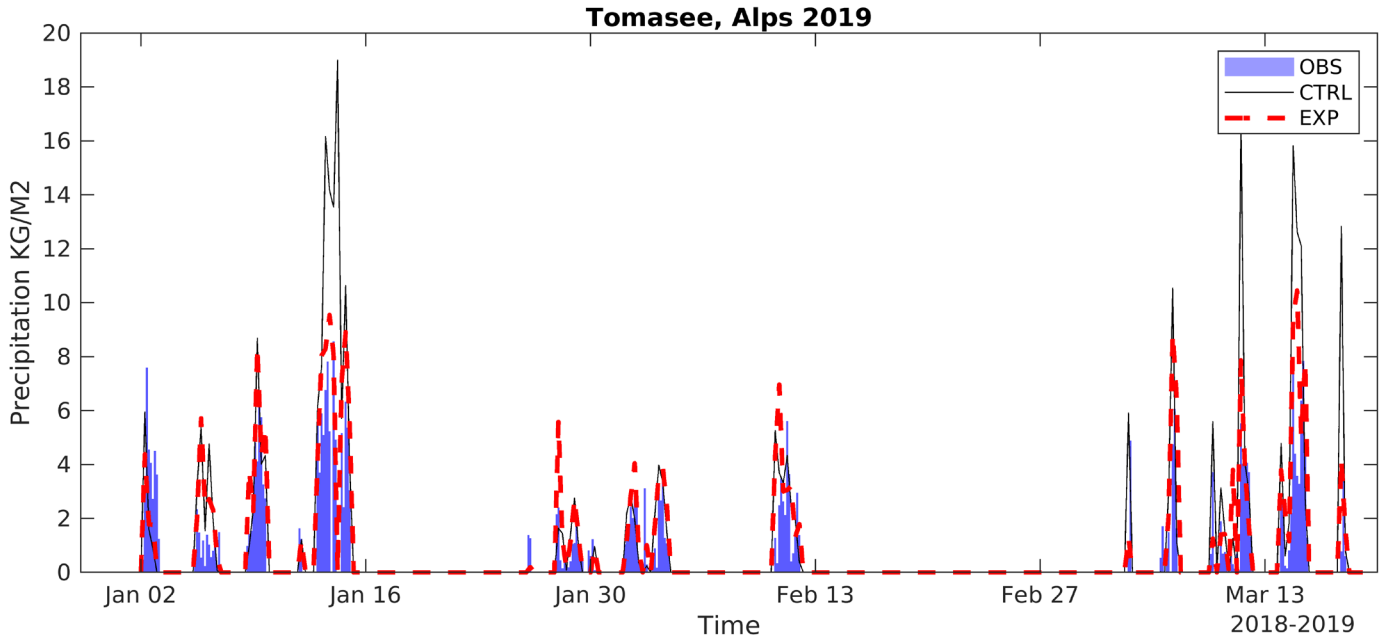
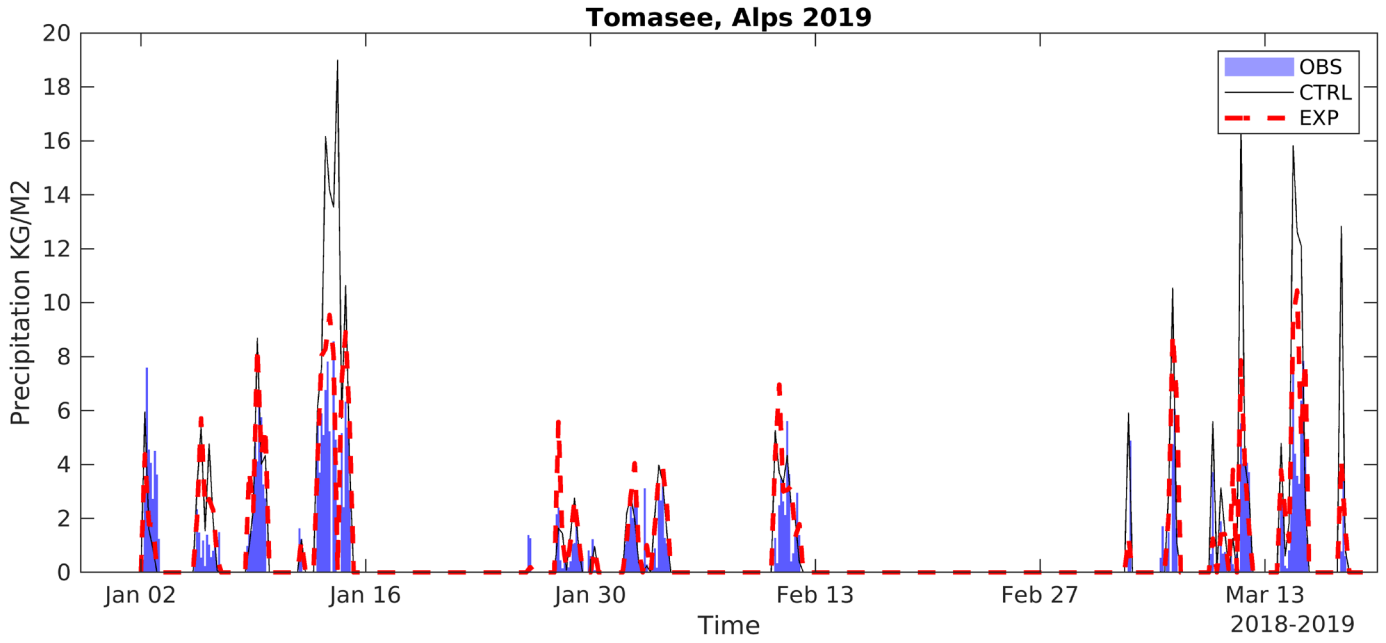
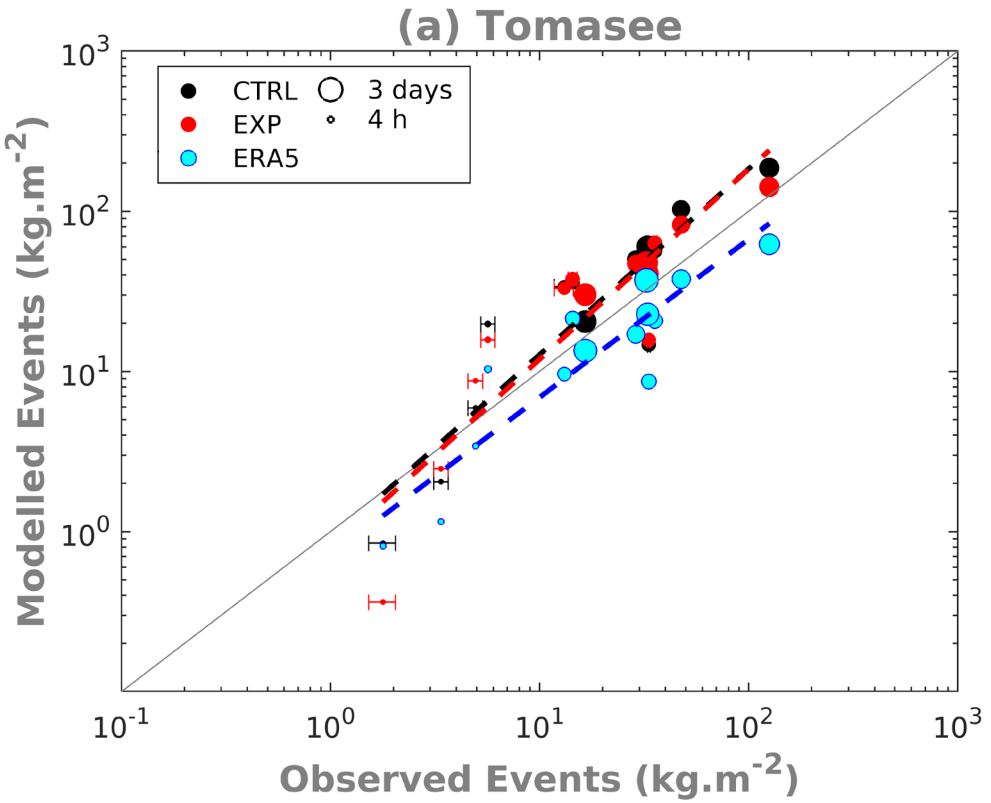


Sensitivity (EXP) simulation

- Reduces over-prediction / better agreement with amounts
- Onset/end of events well captured
- Precipitation sensitive to hydrometer fall-speeds

Modelling snowfall / Alps example





<u>Sensitivity (EXP) simulation</u>

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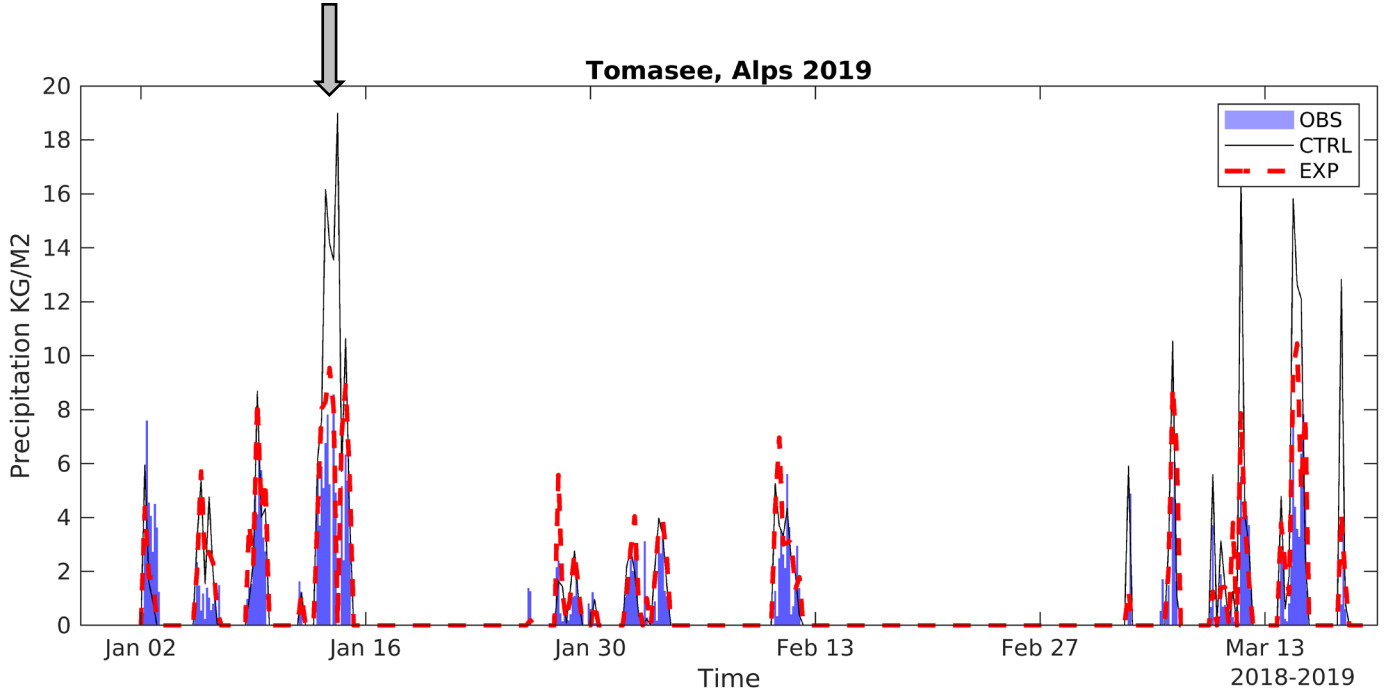
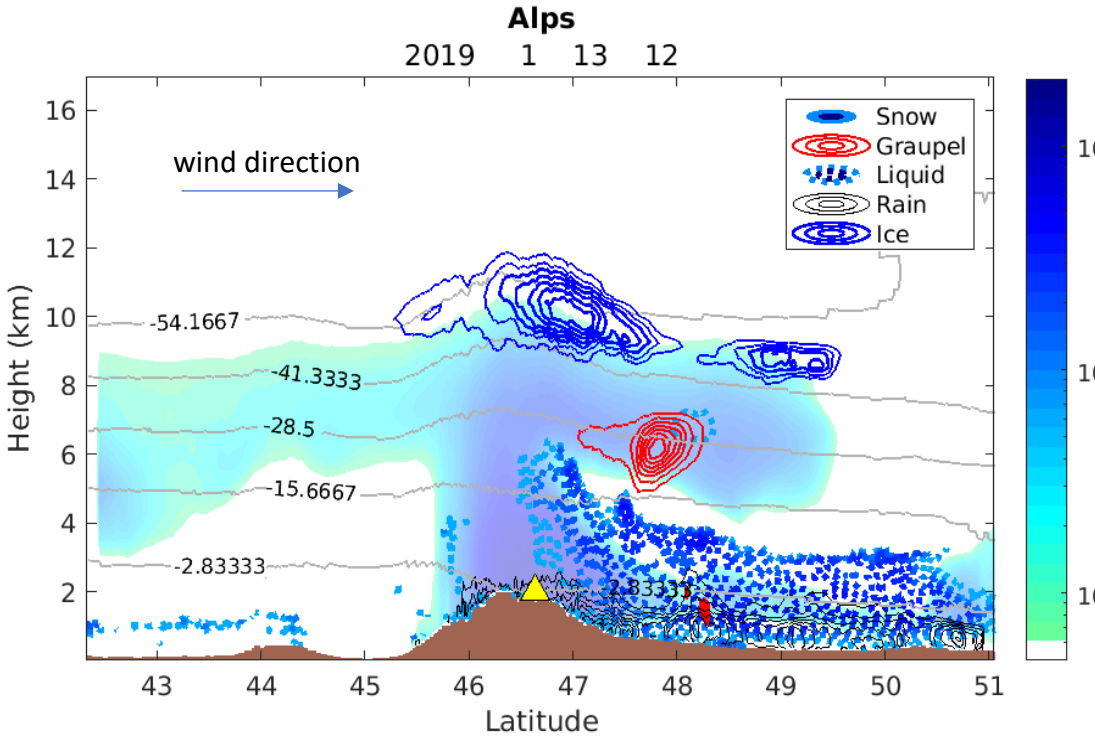
Scatterplots of observed versus modelled snowfall totals (kg m⁻²) for all events at Tomasee. The modelled outputs are from the CTRL (black) and EXP (red) simulations. Additionally, snowfall totals from ERA5 are shown in cyan.

Modelling snowfall / Alps example

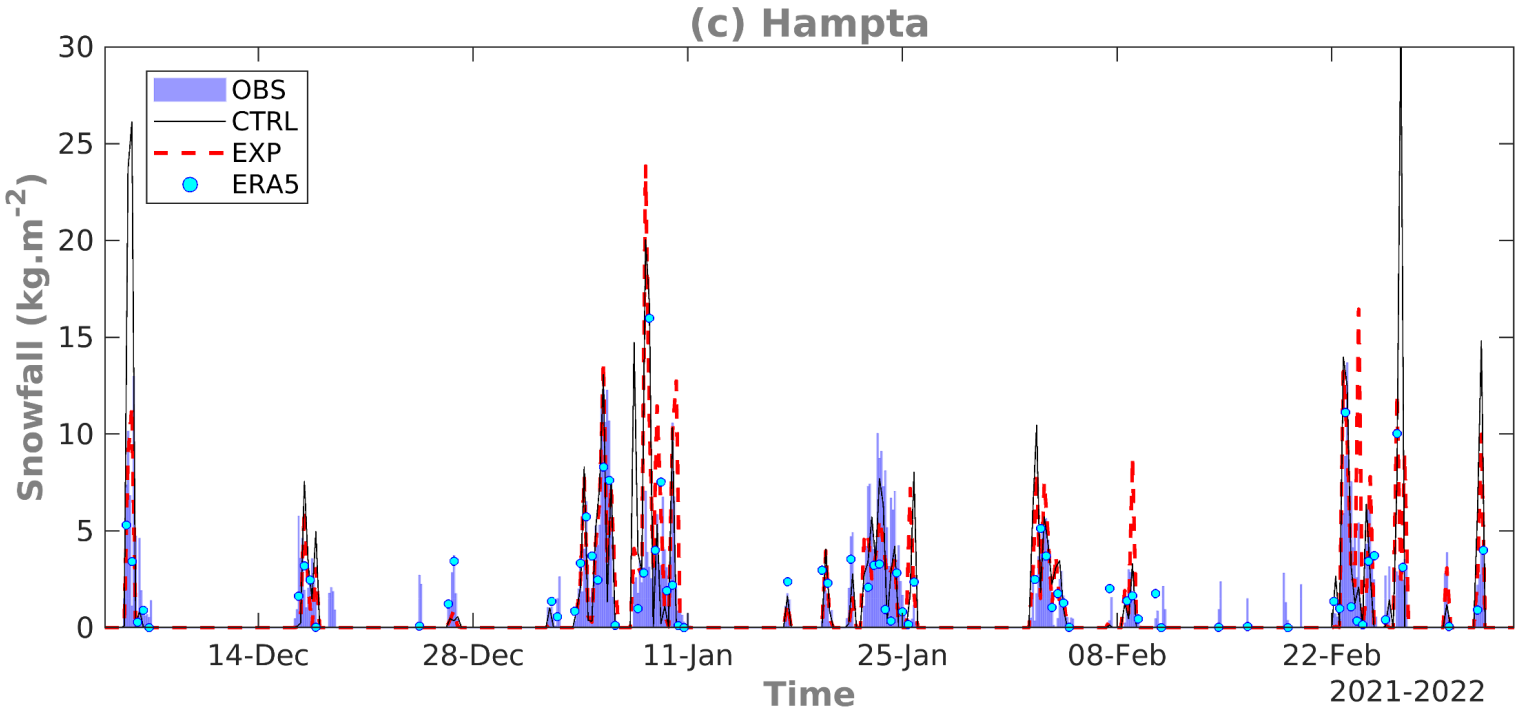


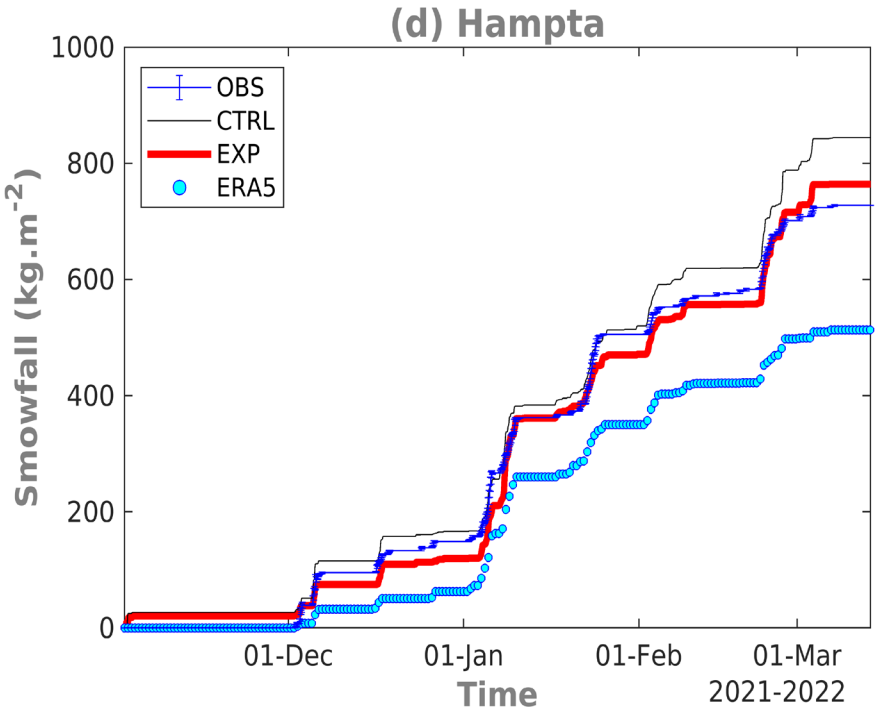


Latitude-height transects of the hydrometeors over the Alps from the MetUM for January 13, 2019.

- Enhanced vapor deposition forming ice crystals
- Formation of graupel (in red) – large ice crystals falling through supercooled cloud droplets (riming)
- Ice crystals freeze onto small snow spheres (aggregation)

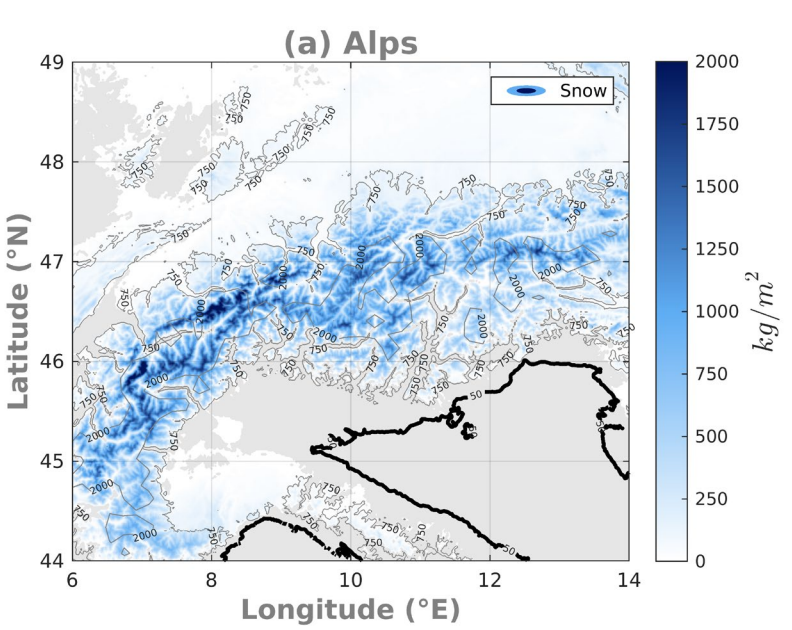
Modelling snowfall / Himalayas example

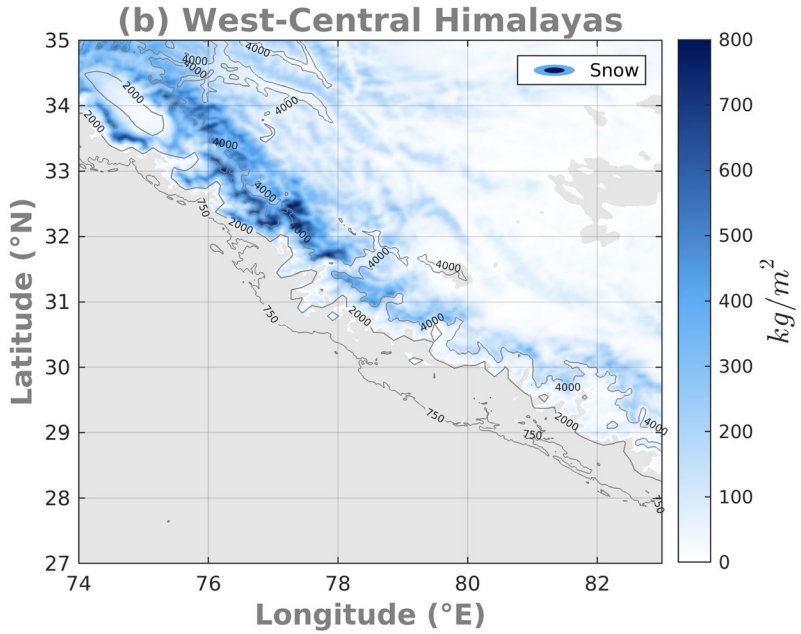


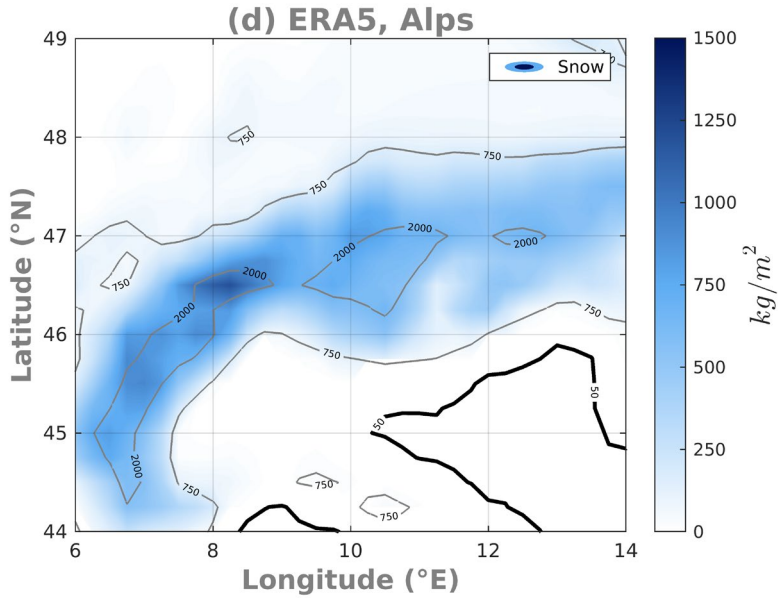


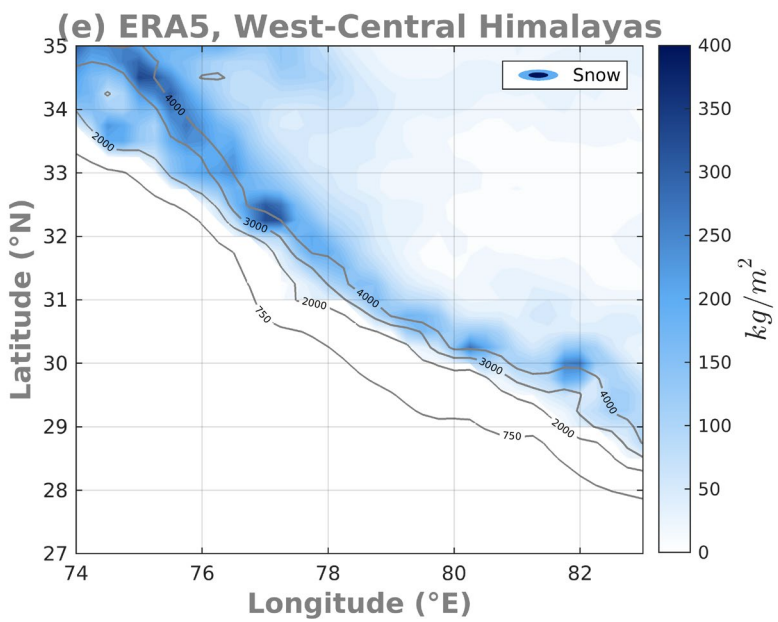
Time series of three-hourly (left) and seasonal cumulative snowfall (kg m^{-2}) (right) of observed and modelled snowfall at Hampta in the west-central Himalayas for 01 Nov 2021 to 31 Mar 2022. Additionally, snowfall totals from ERA5 are shown in cyan.

Modelling snowfall / detailed maps of Alps and Himalayas



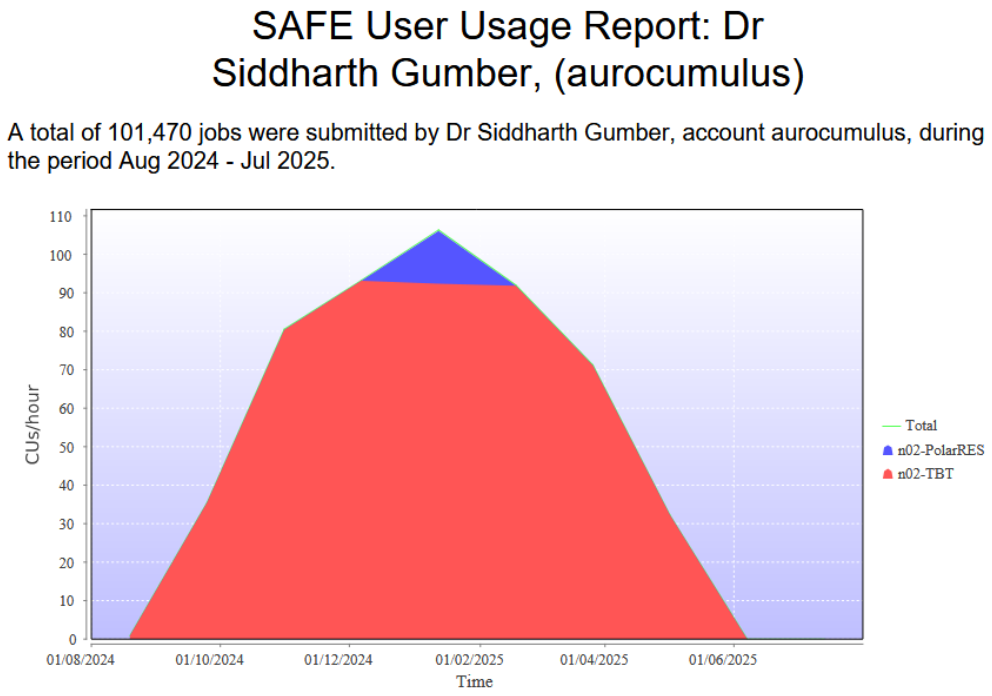


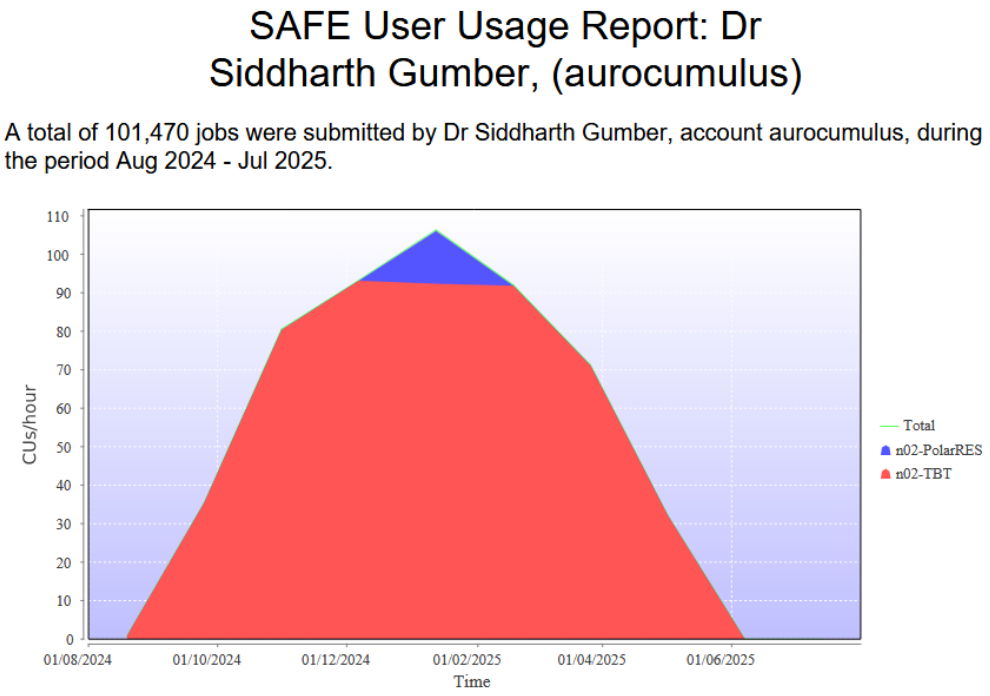




Accumulated total Snowfall ($\mathbf{kg/m^2}$) from the MetUM (top) and ERA5 (bottom) for the winter period of 2023-2024. Also shown are the model topographic heights.

Employing Archer2 for high-resolution state-of-the-art snowfall modelling





Resource	Budget	Users	Charged Usage / CUs
Archer2	n02-TBT	User 1	436,368
Archer2	n02-TBT	User 2	

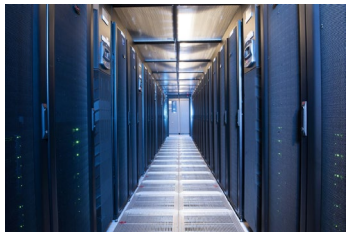
Fact: Assuming that we used all 5860 compute nodes or 750,080 cores (5860 X 2 X 64 core) continuously, that would equate to a little over **0.5815 h** of continuous full Archer2 use per user

Or using **1 full node (128 cores)** continuously for about **142 days**.

Cylc Workflow – Automatic Transfers from Archer to Jasmin

More than 20 years of snowfall simulations 1999-present day

- Alps
- Himalayas
- Pindus



JASMIN data facility

- SOF Disk 30TB
- Elastic Tape 300TB

command-format=rsync -aLv %(sources)s username@**hpxfer4**.jasmin.ac.uk:%(target)s

20210122T1200Z	submitted
archive_files_Alps	waiting
archive_files_Himalayas	waiting
HOUSEKEEP	waiting
glm	submitted
Alps_km1p5_RAL3	submitted
Him_km1p5_RAL3	submitted
HPC_SERIAL	waiting
20210123T1200Z	running
glm	submitted
Alps_km1p5_RAL3	running
Him_km1p5_RAL3	submitted
20210124T1200Z	running
glm	running
Alps_km1p5_RAL3	waiting
Him_km1p5_RAL3	waiting

Limitations:

- Shifting data from Disk to TAPE using ET commands and JDMA – sometimes unreliably slow – directory locking issues
- Can keep track of requests through the ET-monitor – but opens through a Jasmin machine / NoMachine client – stopped working after the new Windows upgrade
- Rogue batches from other users disturb the whole system
- Lacks proper user interface

Thank you

Hampta Pass Lake
Indian Himalayas