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Towards continuous measurements of snow drift and sublimation in polar environments

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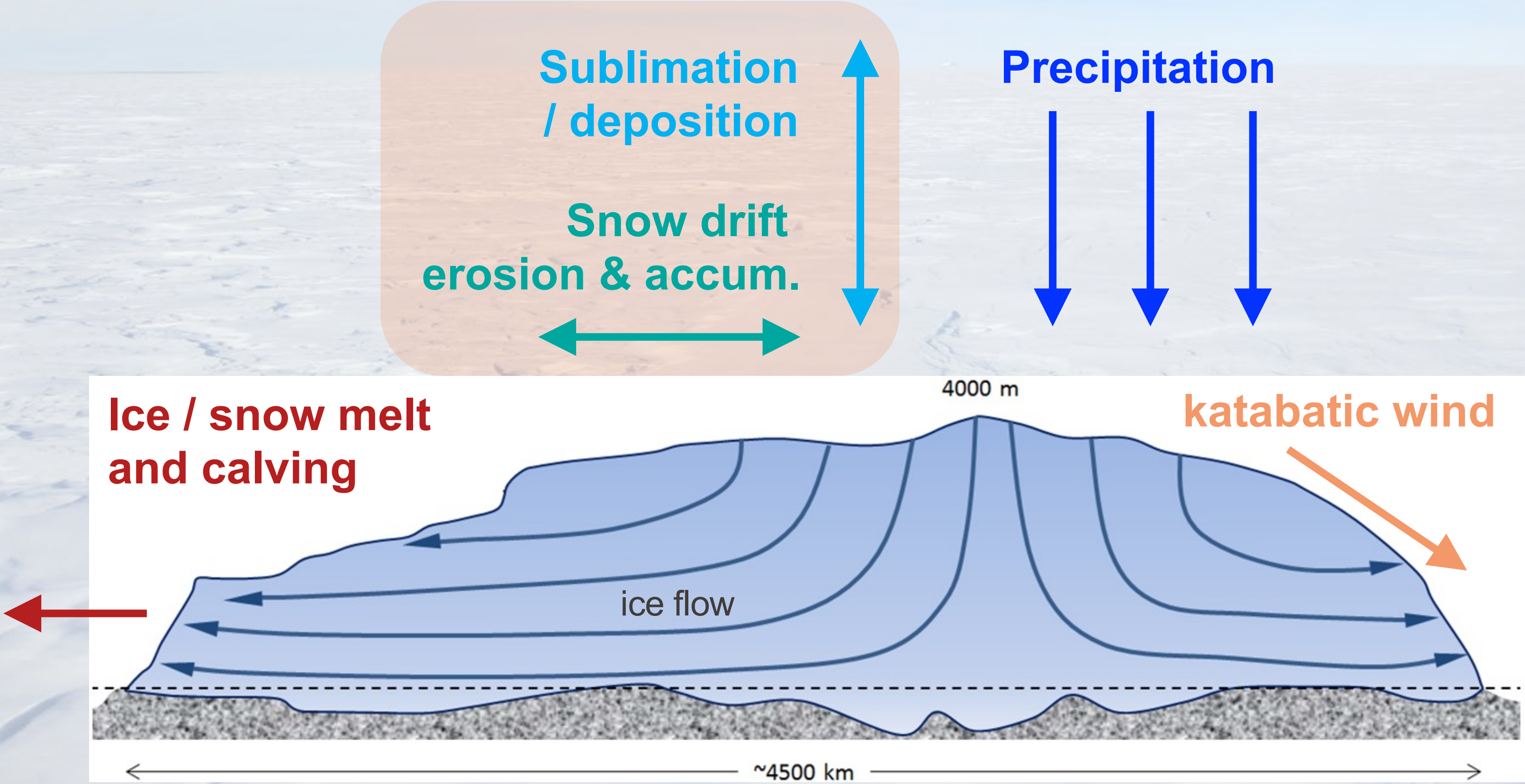
Ice sheet mass balance



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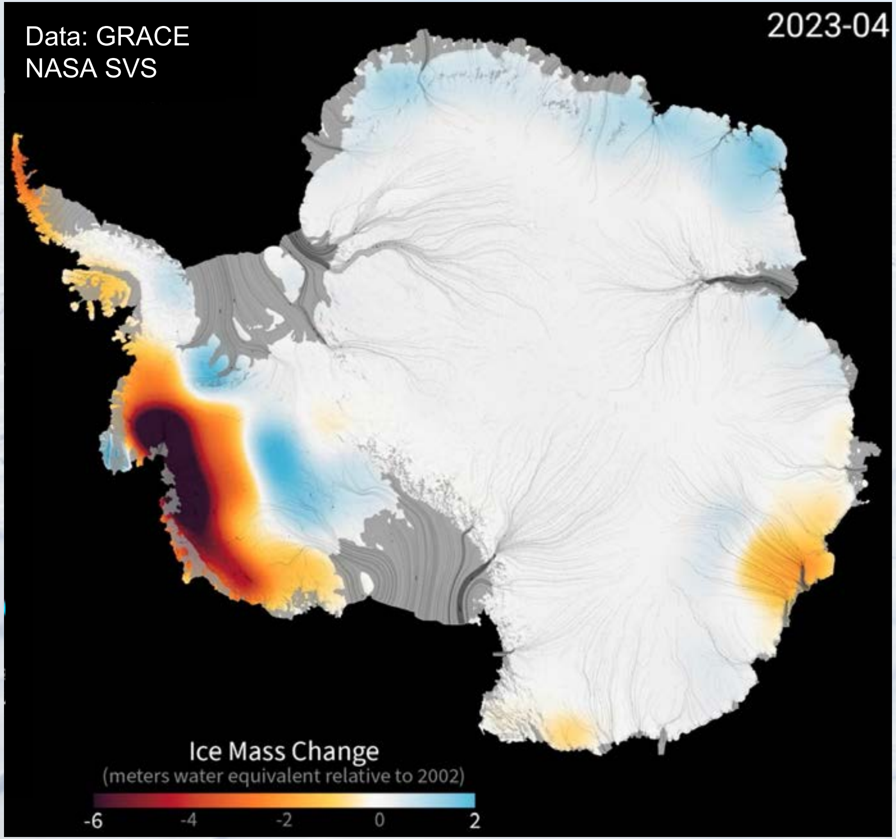
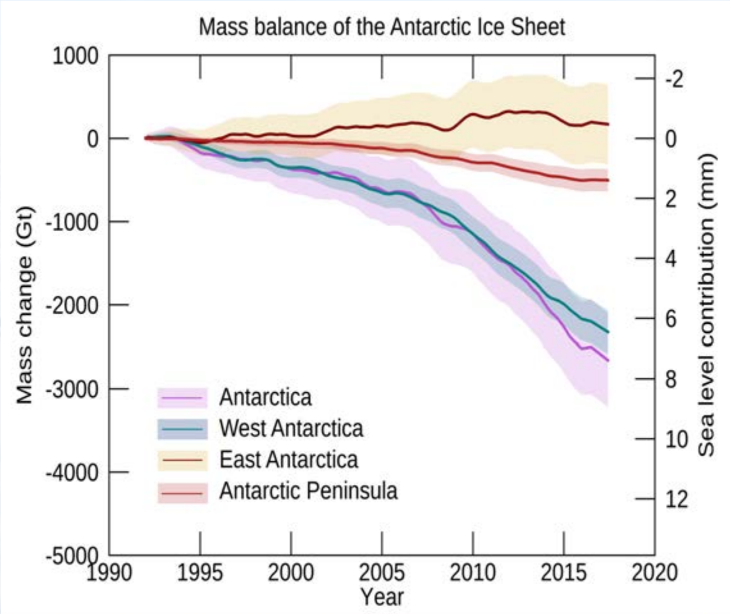
Antarctic land ice mass changes and sea level rise





Total cumulative Antarctic ice sheet mass.
Change relative to 1992.
Data source: IMBIE Shepherd et al., (2020)
Credit: IMBIE/ESA/NASA.

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Background and Objectives

- Continuous reliable quantitative observation of energy and mass balance components is challenging, in particular for snow drift and associated sublimation
- Recent and rapid progress in satellite remote sensing does not replace ground truth in-situ observations, in fact, the latter are necessary for validation and more
- Addressing the complex and coupled processes of snow drift and sublimation is essential for accurate EB and MB calculations
- Novel and innovative instrumentation for polar regions is necessary and may soon be available for operational use

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Princess Elizabeth Station, Antarctica

- Snow energy balance
- Snow mass balance
- Katabatic flow
- Snow transport / drift
- Sublimation

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Examples of snow transport: (1) snow saltation

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Examples of snow transport: (2) suspension / drift

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Examples of snow transport: (3) blowing snow

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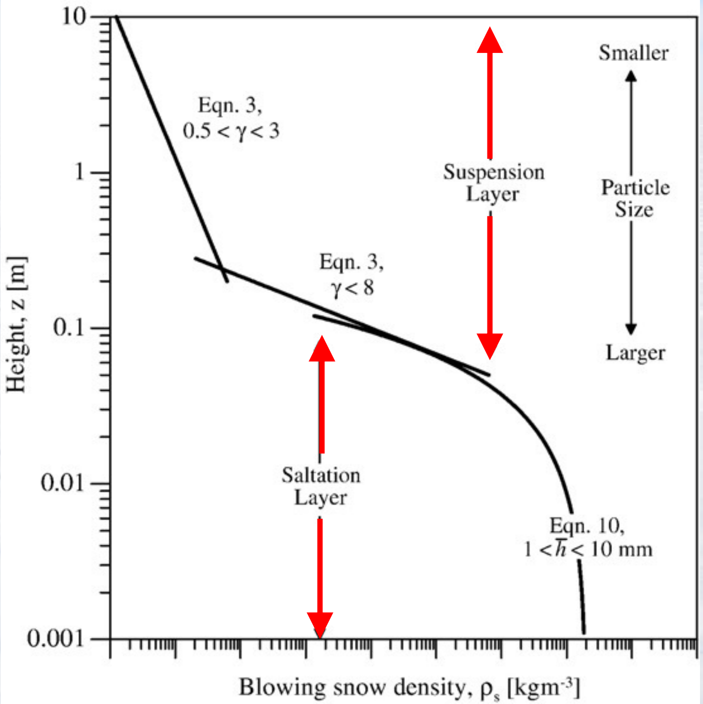
Theoretical and conceptual background



Schematic of the blowing snow density profile, from Gordon et al. (2009), CRST

Some pioneer work

- Bagnold, (1941):
  The Physics of Blown Sand and Desert Dunes
- Thorpe and Mason, (1966):
  The evaporation of ice spheres and ice crystals

Recent theoretical and modeling progress

Development of LES and CRYOWRF*
* = Model combination of SNOWPACK and WRF

- Sharma et al., (2018), TC → theoretical background
- Comola et al., (2019), GRL → adding particles
- Melo et al., (2022), JGR → adding particle cohesion
- Sharma et al., (2023), GMD → adding sublimation

Sublimation from static surface and dynamic layer

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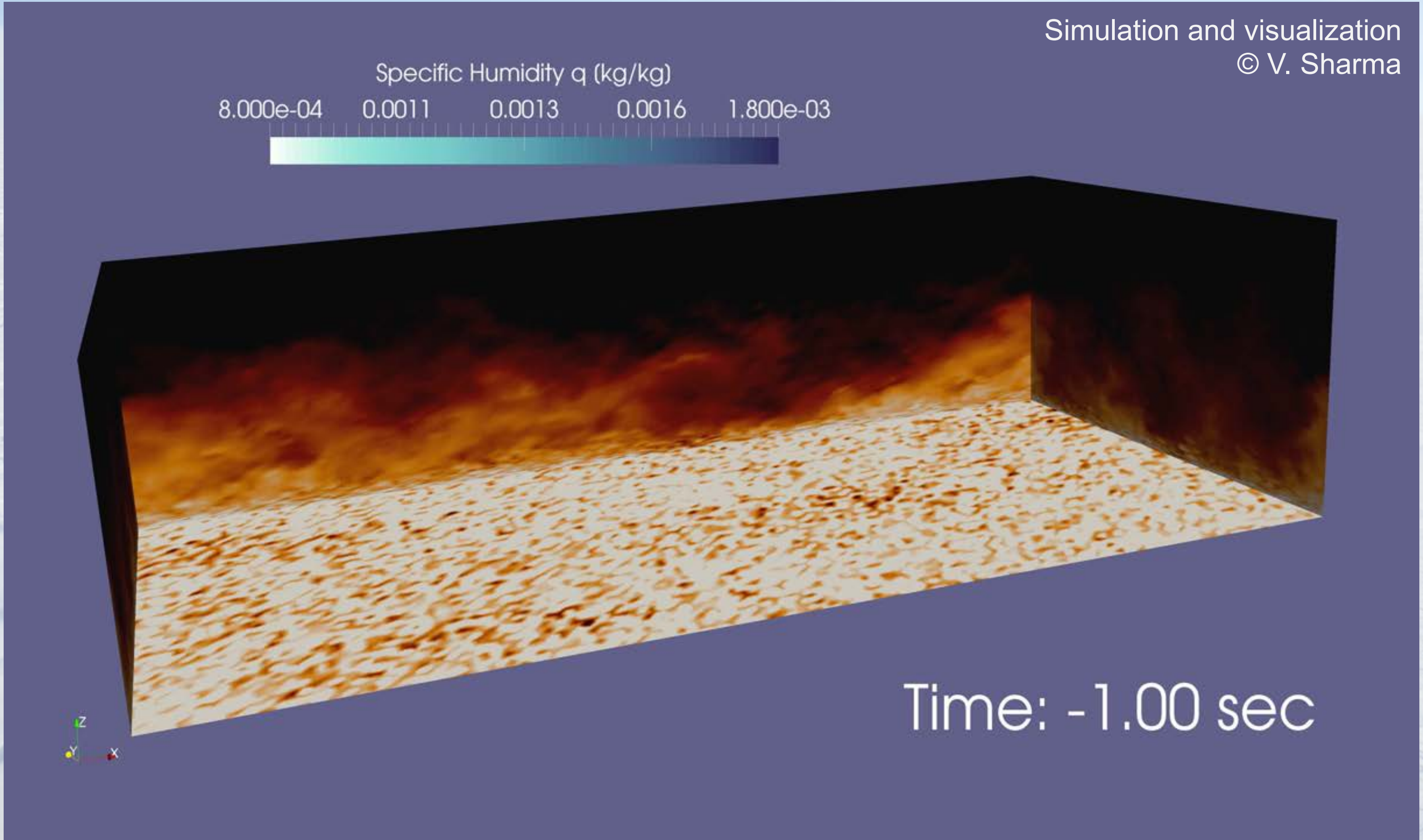
Modeling snow drift and particle sublimation: CRYOWRF



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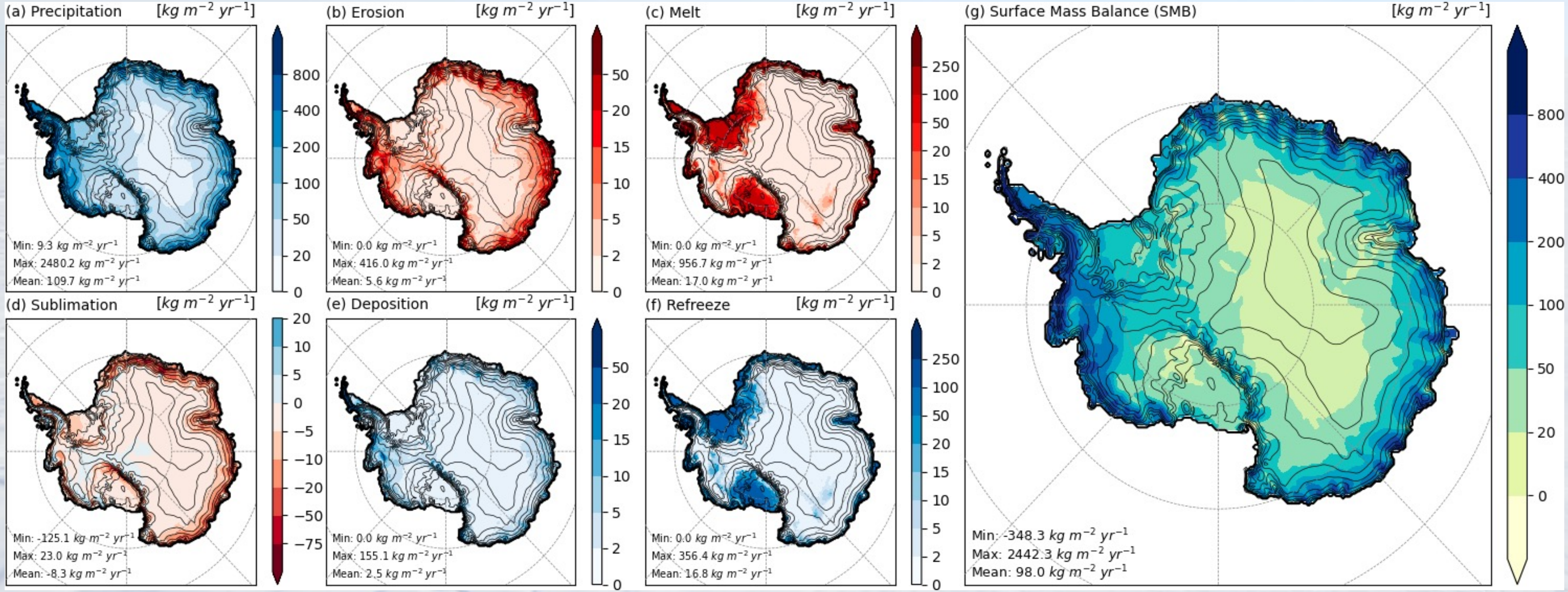
CRYOWRF large scale simulation

Precip. Erosion Melt SMB



Sublimation Deposition Refreeze

Components of the surface mass balance output from CRYOWRF.
Sharma et al., (2023), GMD

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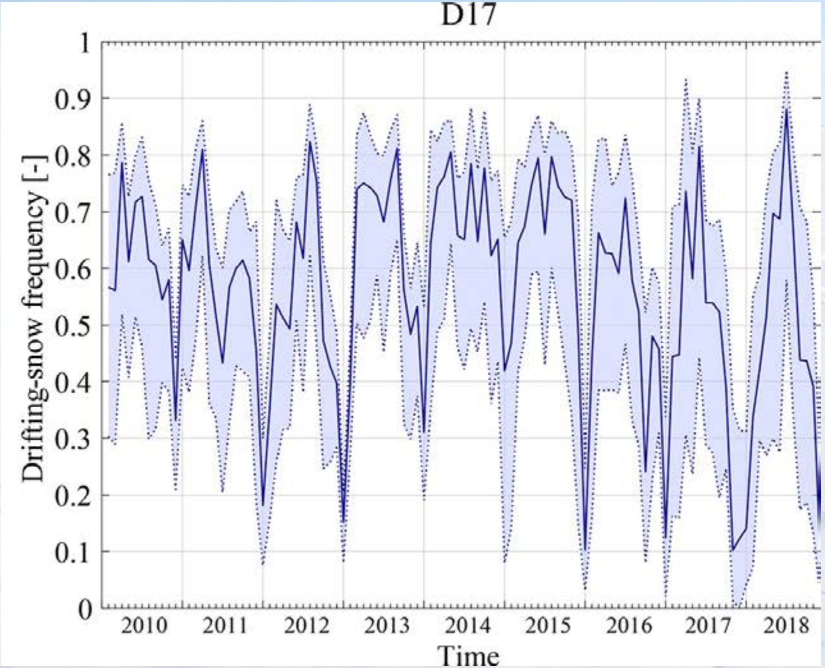
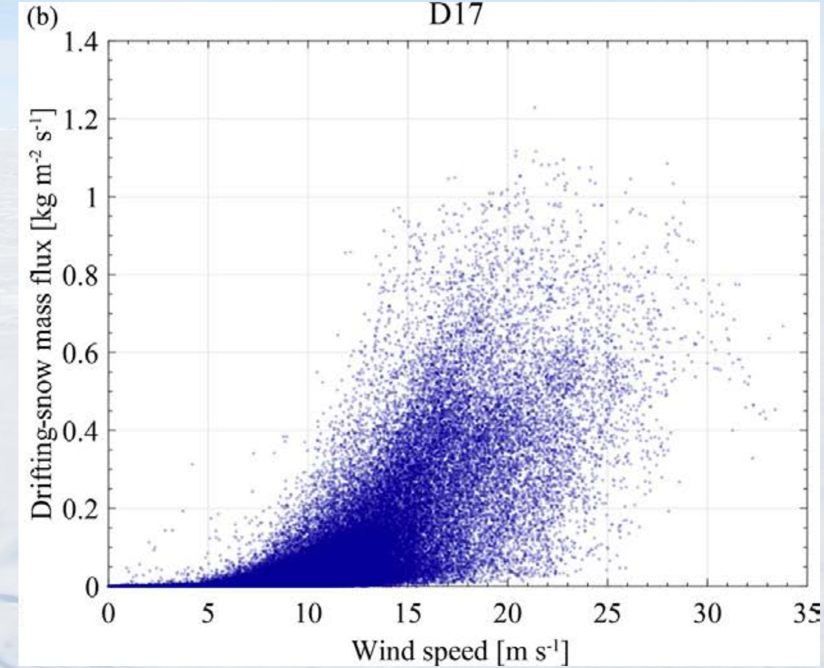
Milestone in measurements – FC4, Adélie Land, EA





Amory, (2020), TC: 2010 to 2020 and ongoing

FlowCapt (FC4) acoustic particle counters and mass fluxes

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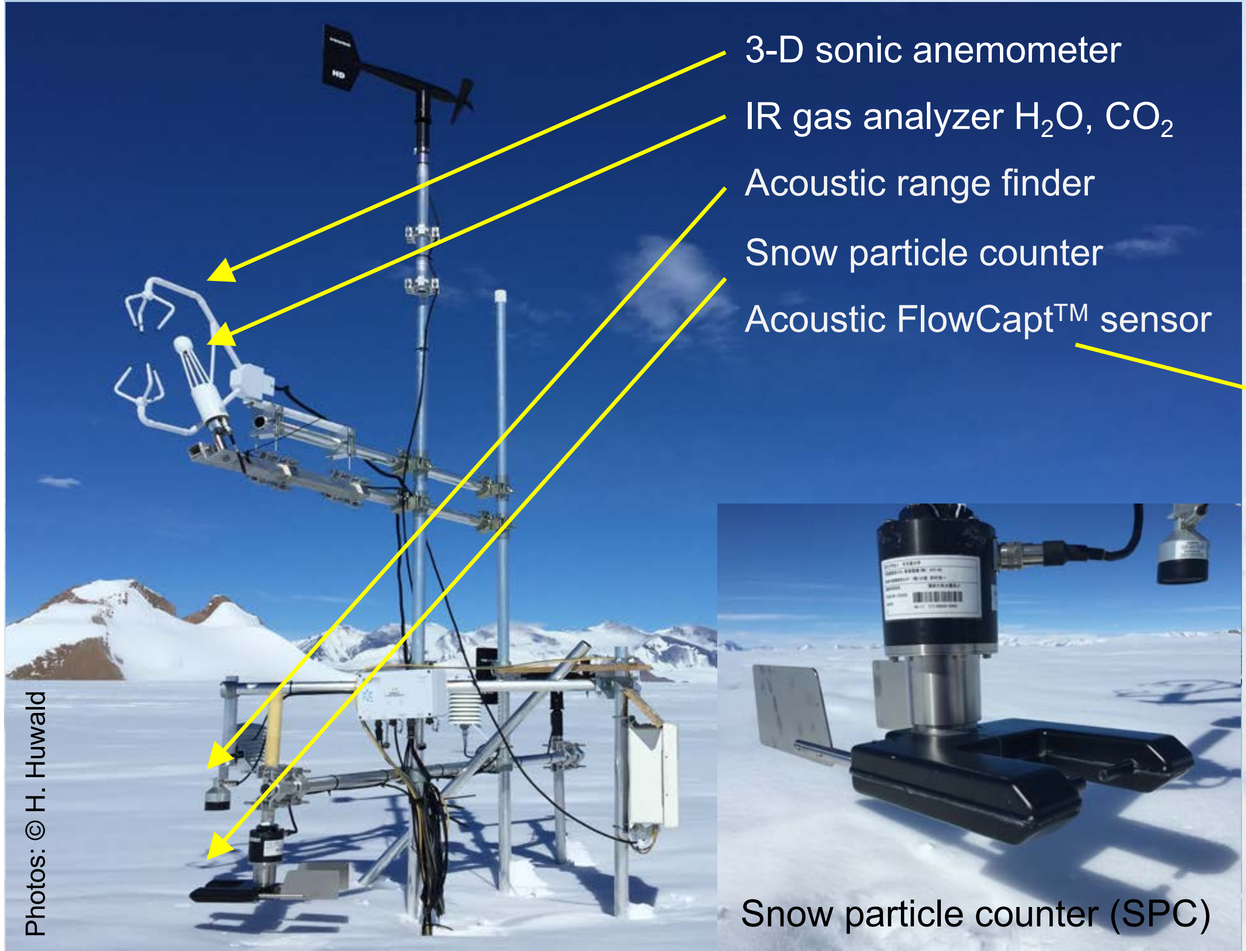
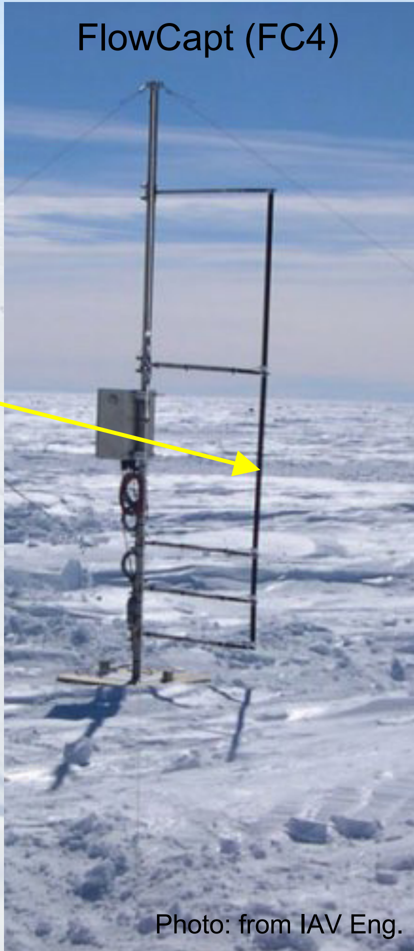
Mass balance station at PE station, Antarctica



Photos: © H. Huwald

Snow particle counter (SPC)



FlowCapt (FC4)

Photo: from IAV Eng.

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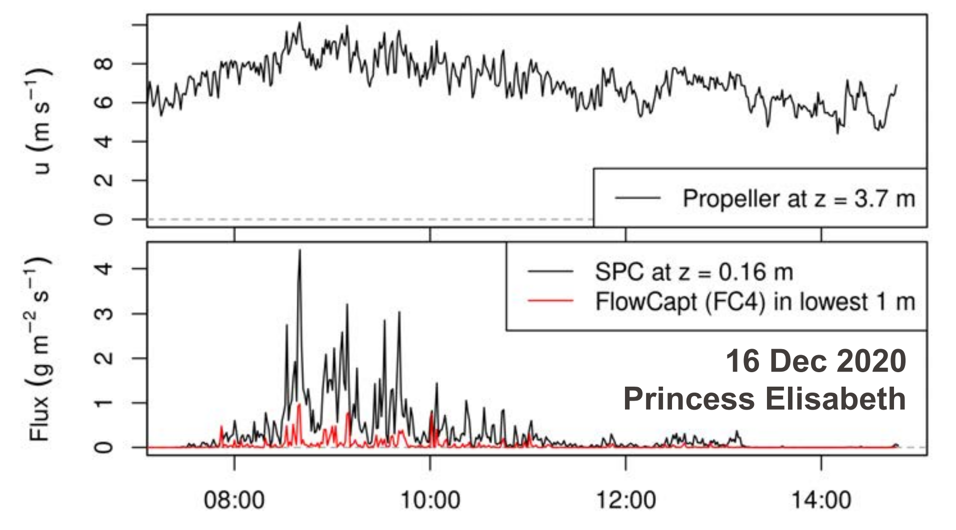
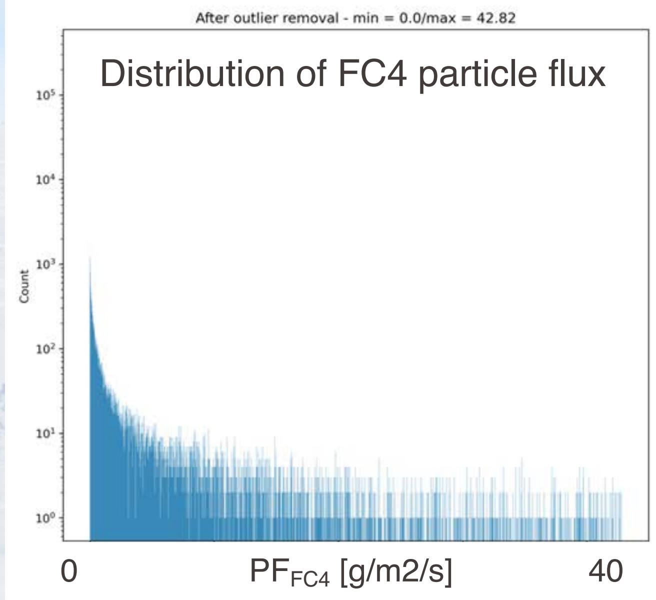
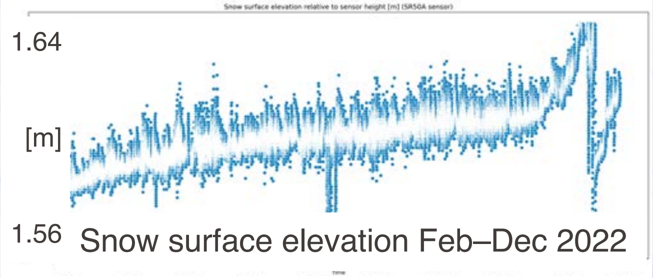
Acoustic (FC4) vs. optical (SPC) sensor snow particle flux







- Comparison of FC4 and SPC snow saltation mass fluxes at Princess Elisabeth Station, Antarctica.
- Snow surface evolution measurements imperative for SPC data interpretation.
- Related simulations frequently underestimate the transported snow mass in terms of number of events simulated but overestimate individual events.

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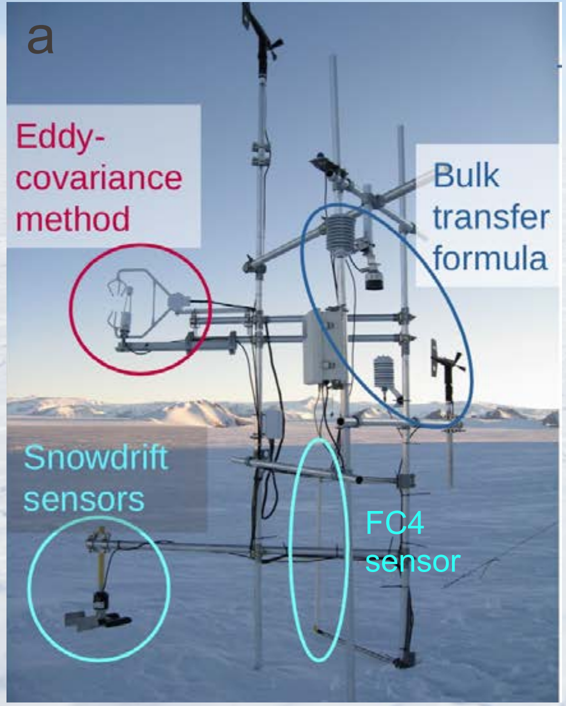
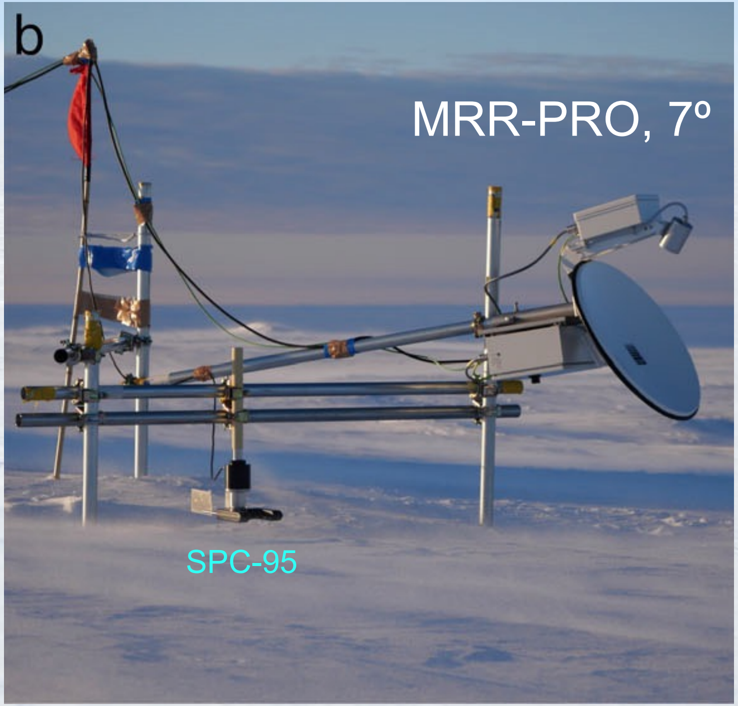
Estimating the depth of the blowing-snow layer with MRR





- Micrometeorological station with SPC and FC4 devices (a) and tilted MRR (b) for snow drift observation
  Sigmund et al., (2022), BLM
- Related study for Antarctic precipitation: 3 MRR-PROs in Sør Rondane Mountains, QML, EA
  Ferrone and Berne, (2023), ESSD

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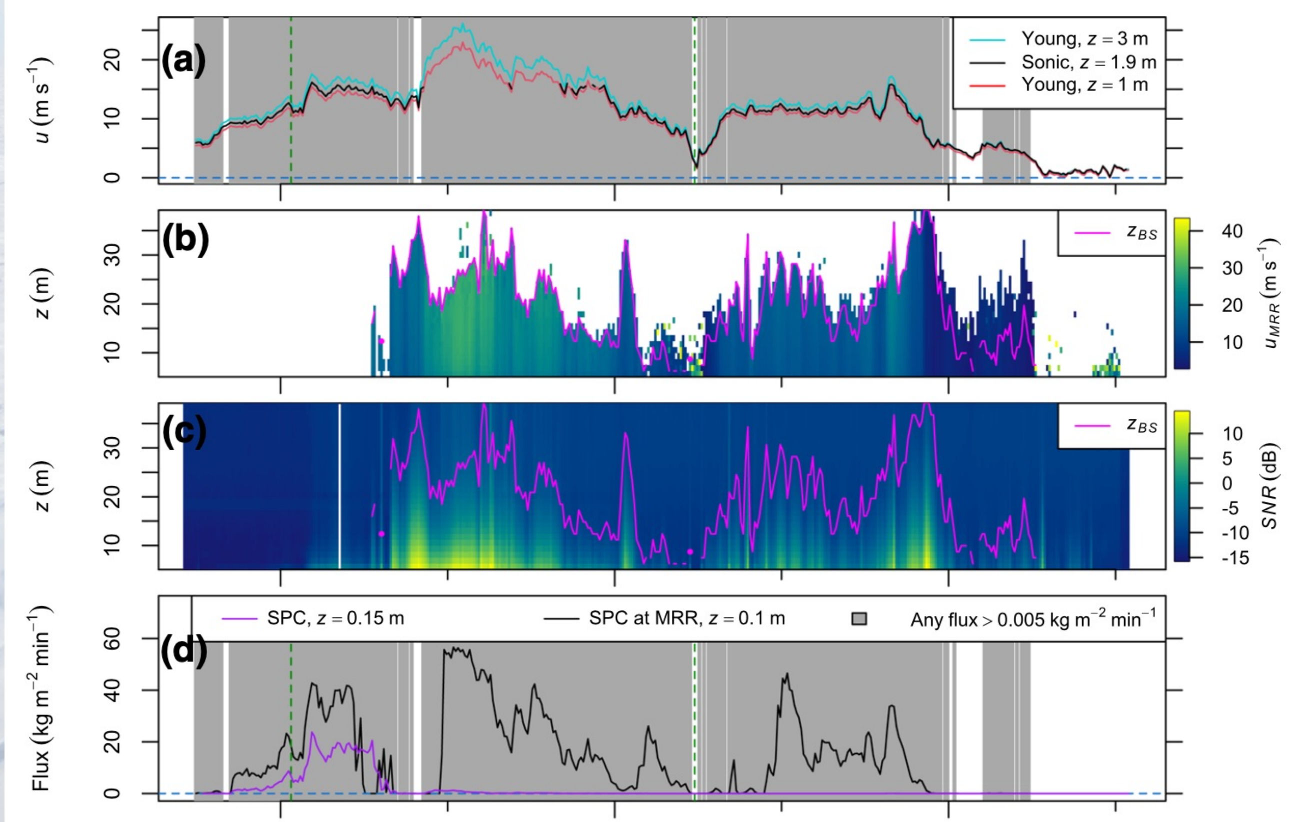
Estimating the depth of the blowing-snow layer with MRR

Example: Blowing snow event at Syowa S17 (10-13 Jan 2019).



Sigmund et al., (2022), BLM

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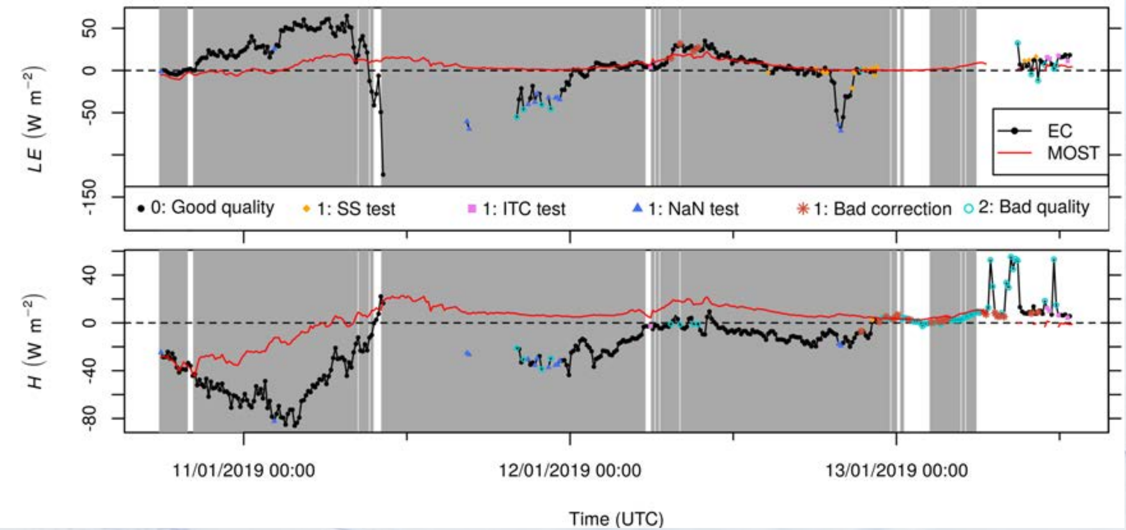
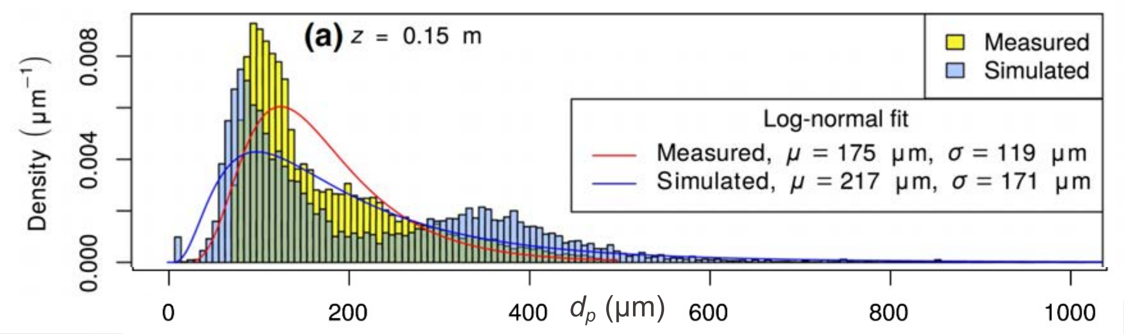
Measuring surface-atmosphere exchange in Antarctica



Discrepancy between eddy-covariance (EC) and bulk transfer (MOST) methods points towards significant errors and uncertainties in conditions of drifting and blowing snow



Particle size distribution (pdf) measured with SPC and simulated at S17, Syowa, Antarctica

Sigmund et al., (2022), BLM

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Radar measurements of blowing snow off a mountain ridge

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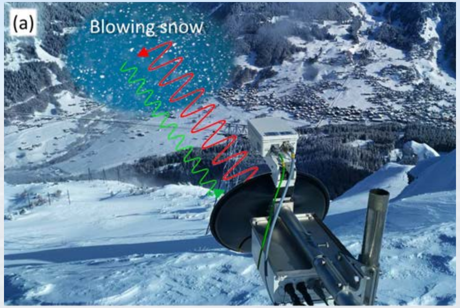
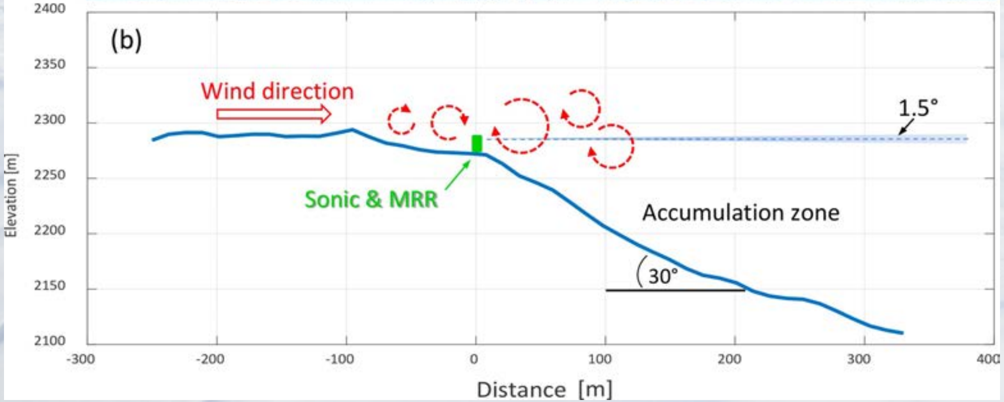
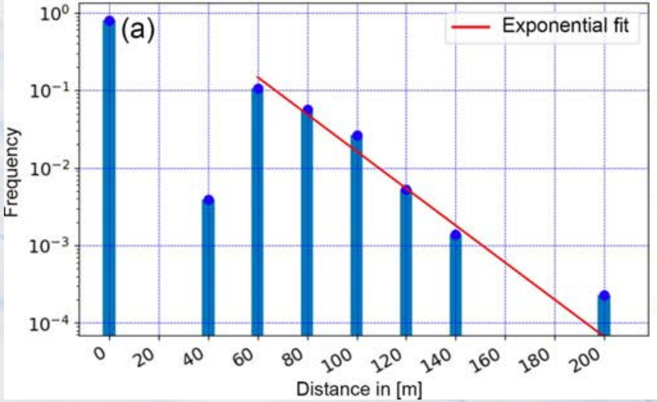
MRR in horizontal configuration
Walter et al., (2020), TC



- Measurement of blowing snow velocities
- Validation with 3D ultra-sonic anemometer
- Travel distance of particles as function of wind speed
- Particle entrainment increases with wind speed and turbulence intensity
- Deposition pattern and distribution investigated with drone-based photogrammetry





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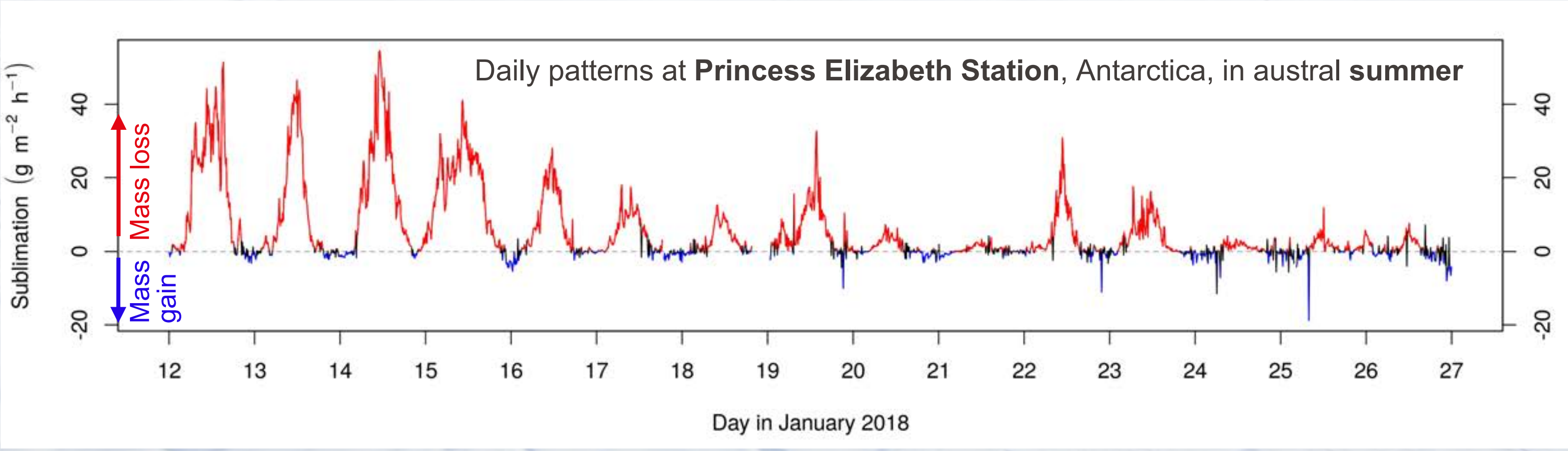
How much snow is removed by sublimation?

Favored by
- Dry air
- Solar heating
- Strong winds
- Blowing snow



Bulk parametrizations strongly underestimate turbulent fluxes during drifting and blowing snow events (Sigmund et al., 2022, BLM). Overall exchange over snow surfaces seems more intense than many current models suggest.

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Alternative sensors for EC over snow and ice surfaces?

- Well established theory
- Reliable commercial EC systems
- High accuracy reference station
- Considerable power consumption

- New theory and methodology
- Low-cost sensors and components
- Spatially distributed sensors in network
- Low power consumption for remote sites

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Low-cost fast-response humidity sensors

- Fast: response time, 1-5 Hz
- Temp. range: -25ºC to 40ºC
- RH range: 0 – 100%
- Error in RH: < 1%
- High capacitive sensitivity
- Low SNR
- Robust& small
- Inexpensive: < €100

- Capacitive humidity sensors with sufficient response time potentially suitable for EC applications have become available
- Tested a candidate sensor in controlled environment in an experimental chamber
- Imposed reproducible step variations in humidity in temperature-controlled environments: 23ºC and -13ºC
- Measured rate of change of each sensor from a series of tests conducted (τ_{63})
- Experimental setup had some limitations, including uncertainties in calibration process

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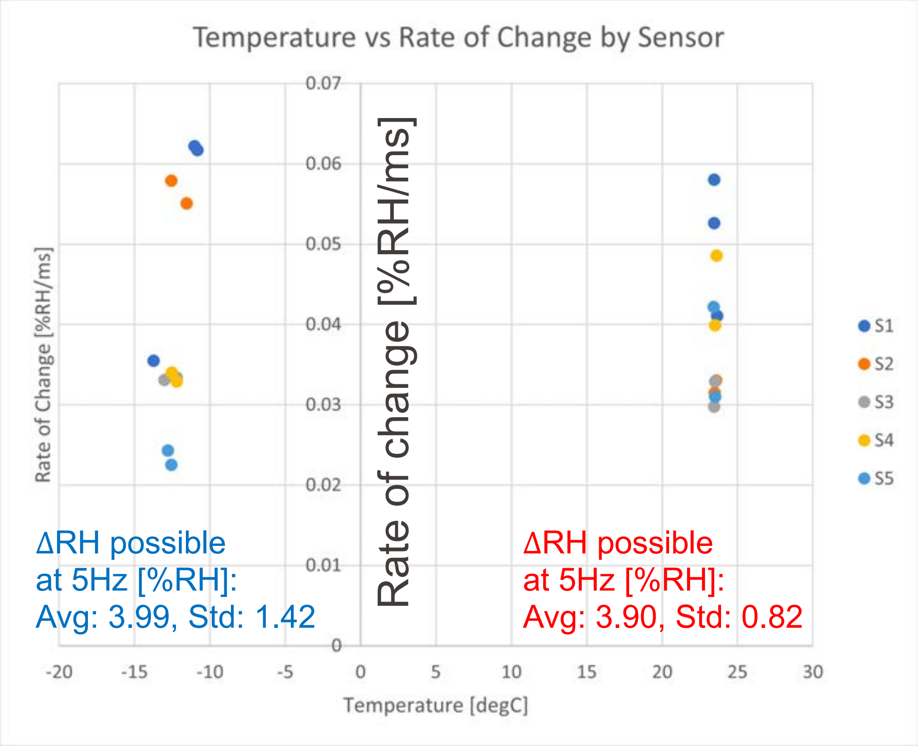
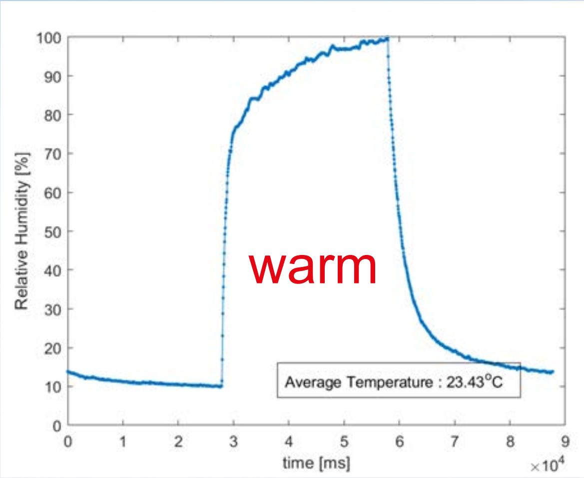
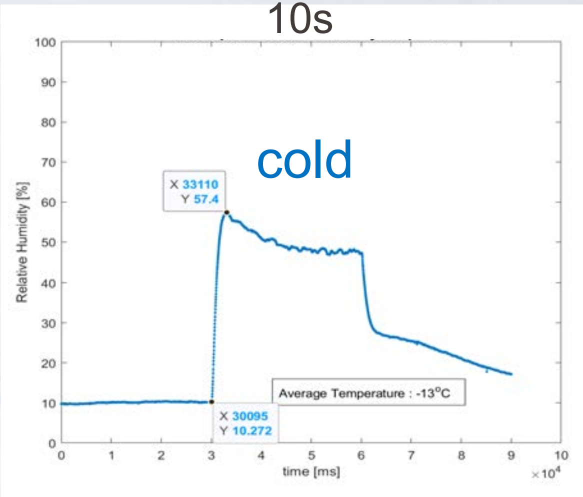
Preliminary sensor test results





10s



Measured rate of change of each sensor from a series of tests. While values show a spread, they are consistent w.r.t. each sensor (good reproducibility).

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Technical and logistical issues and problems

- Some of the difficulties come from the extreme and harsh environment:
  - Freezing of SPC bearings
  - Riming of Laser windows
  - Variable snow height (sensor burried)
  - FC4 partially burried
- These problems require engineering solutions (e.g., height of SPC)
- Most instruments need service and maintenance for good quality data and are subject to power limitations in remote locations
- Sensors are often (too) expensive for spatially distributed deployment
- Innovation in robust low-cost, good quality sensing systems is required

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Conclusion and outlook

- Continuous reliable quantification of snow drift and sublimation is challenging
- Separate quantification of sublimation from surface or drifting particles is difficult
- Bulk approaches strongly underestimate heat and moisture fluxes during snow drift
- Innovation in sensing technology is required to complement existing systems
- The use of low-cost fast-response capacitive humidity sensors may be a viable option for humidity fluctuations in EC and thus for sublimation measurements
- Gathered evidence motivates continued testing and exploration of this approach

– Thanks for you attention –

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