Evaluating precipitation in a regional climate model using ground-based remote sensing measurements at Princess Elisabeth station, Dronning Maud Land

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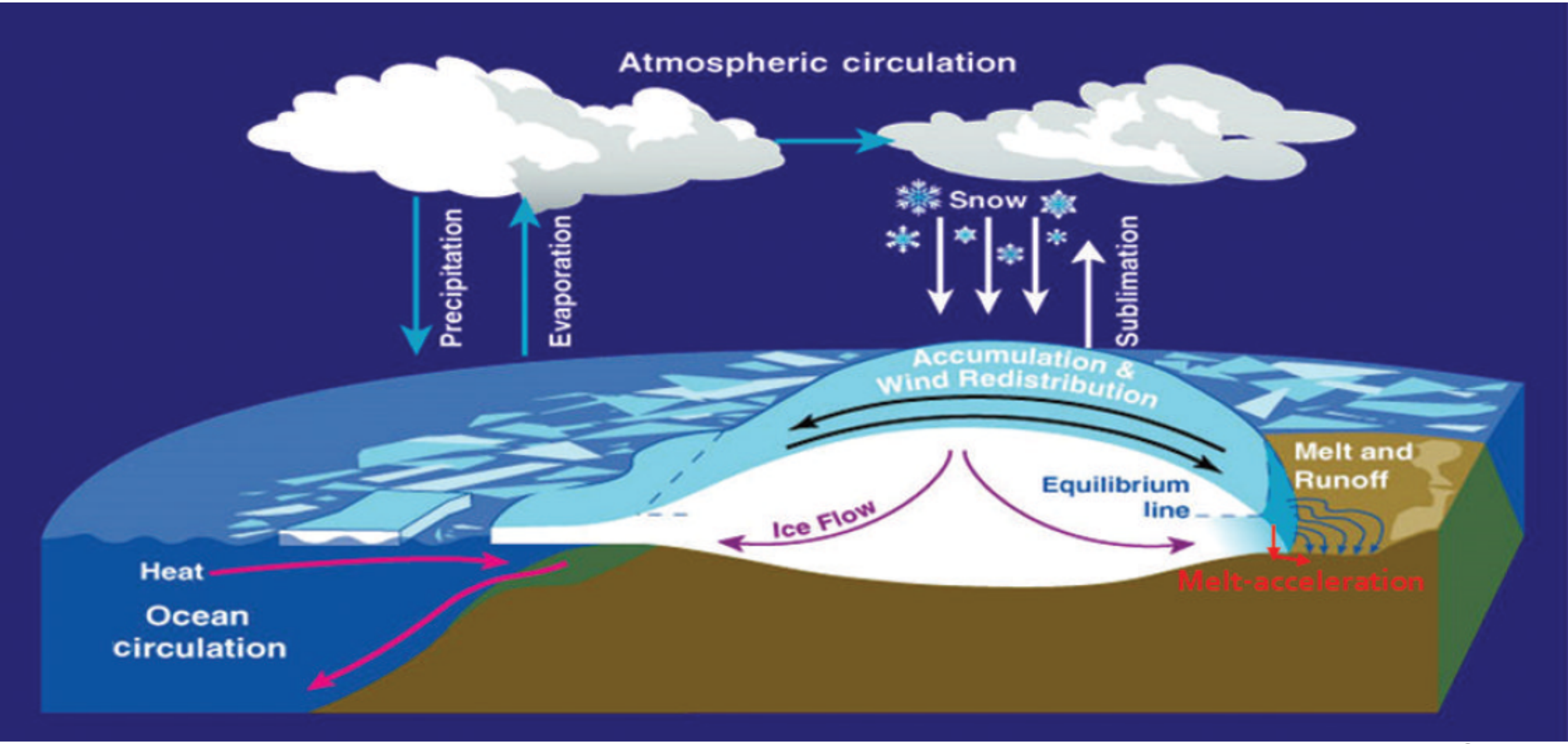
Antarctic surface mass balance:

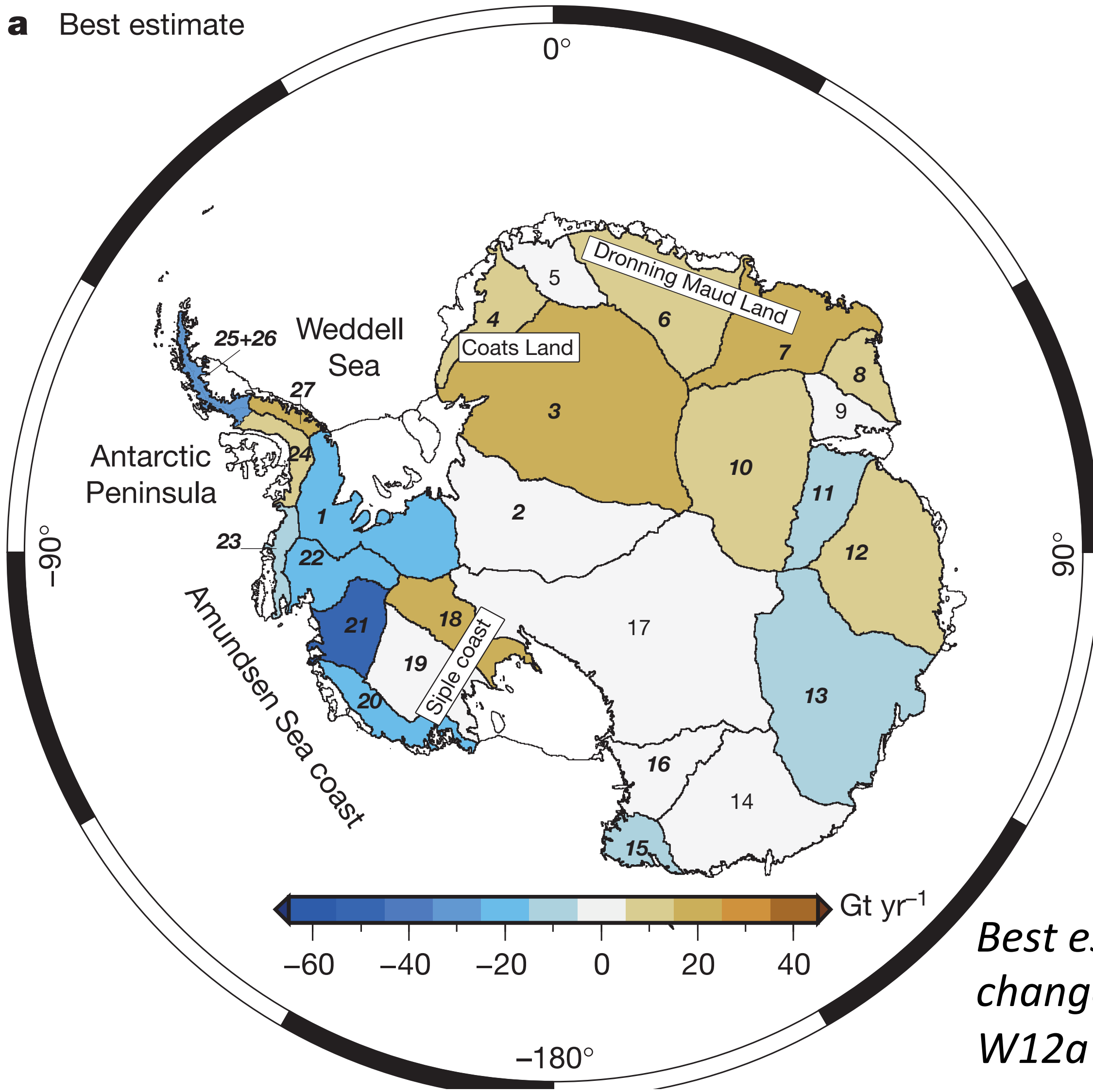
$$SMB = S \pm SUs - SUds \pm TR - MR$$

S = snowfall (+)
SUs = surface sublimation/deposition (+/-)
SUds = drifting snow sublimation (-)
TR = erosion or deposition of snow due to the wind-driven transport (+/-)
MR = melt and runoff (coastal areas) (-)



Major components of the Antarctic mass balance (credit: NASA)

Mass change rates by drainage basin
Aug 2002 – Dec 2010

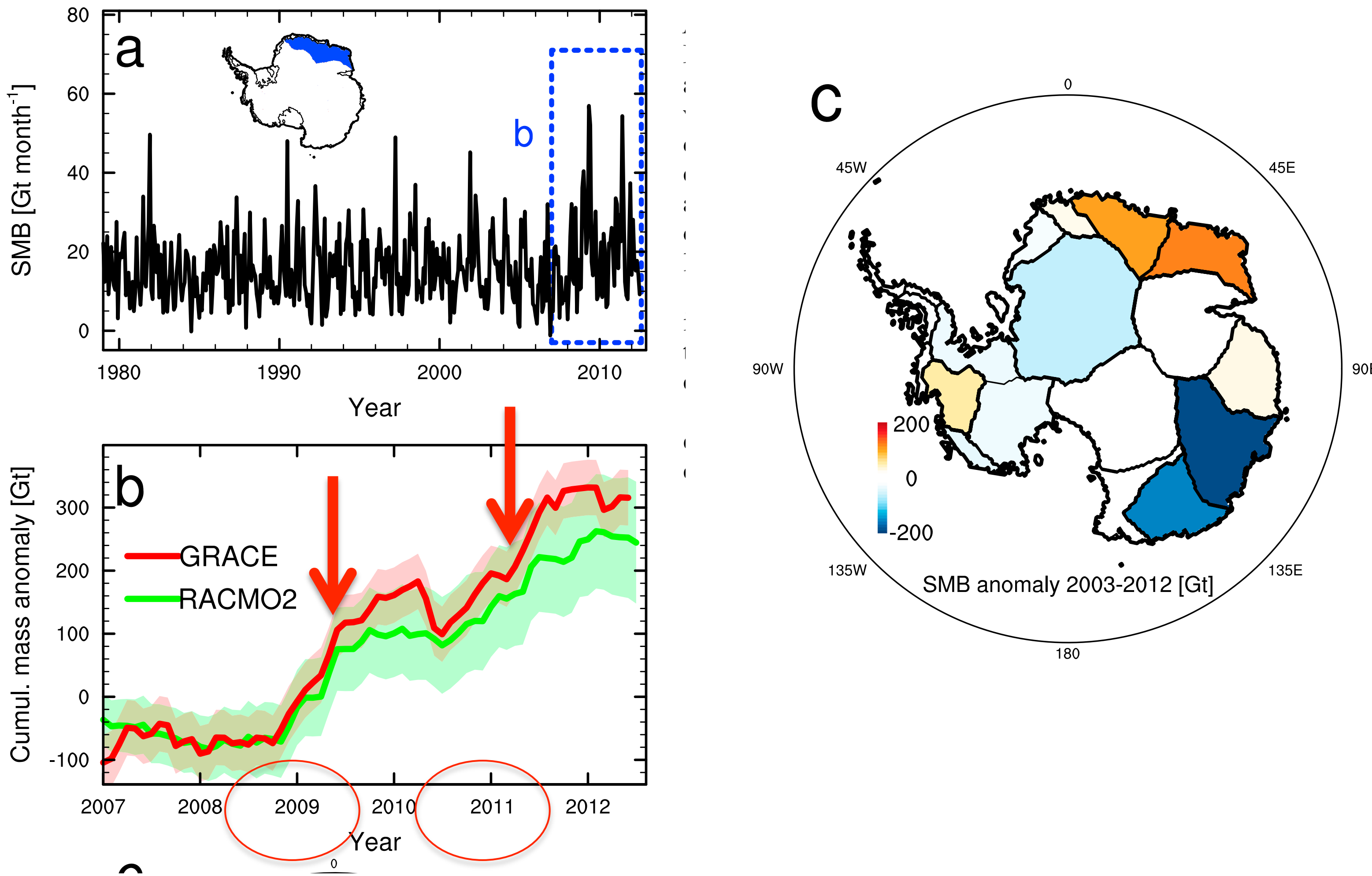


- Continental ice mass change: -69 Gt / year
- Mass **loss**: mostly in Amundsen sea basins
- East Antarctica: **gaining** substantial mass

Best estimate of ice mass change using the modified W12a GIA model

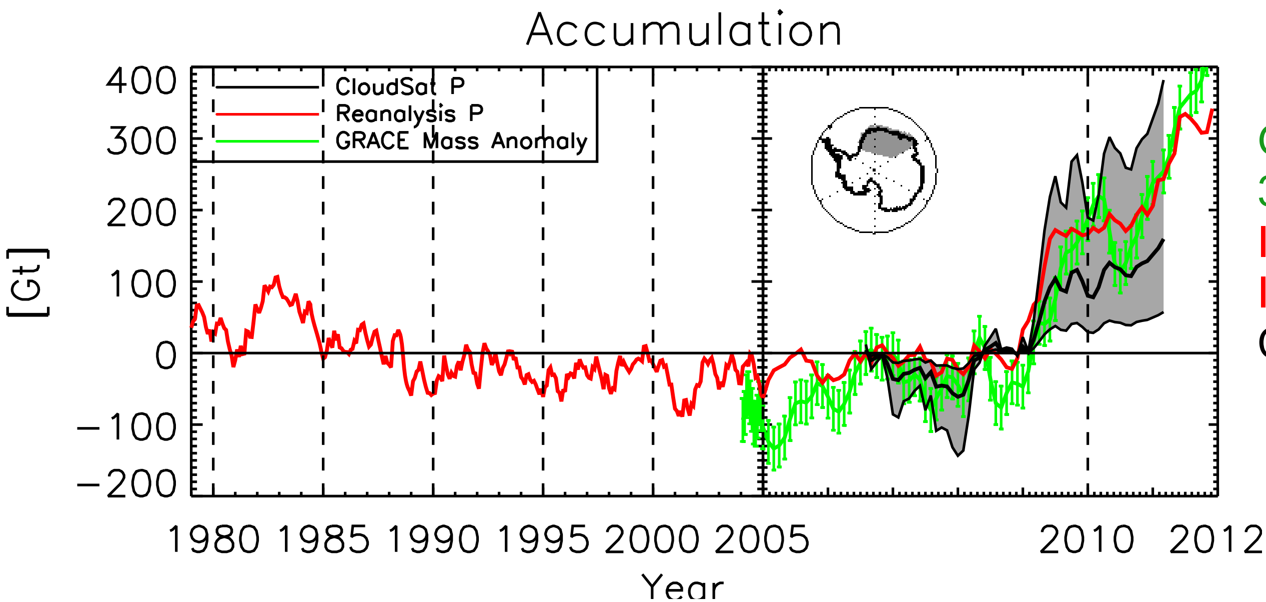
King et al. 2012, Nature

2009 snowfall amount was unprecedented since 1979 and resulting surface mass balance anomaly was measured the first time for at least 60 years.



Lenaerts et al. (2013)

A few strong snowfall events over Dronning Maud Land (DML) in 2009 and 2011 have been responsible for an anomalously high mass load over the East Antarctica counterbalancing the negative total mass trend over the Antarctic ice sheet (Boening et al. 2012, King et al. 2012).



Boening et al. 2012

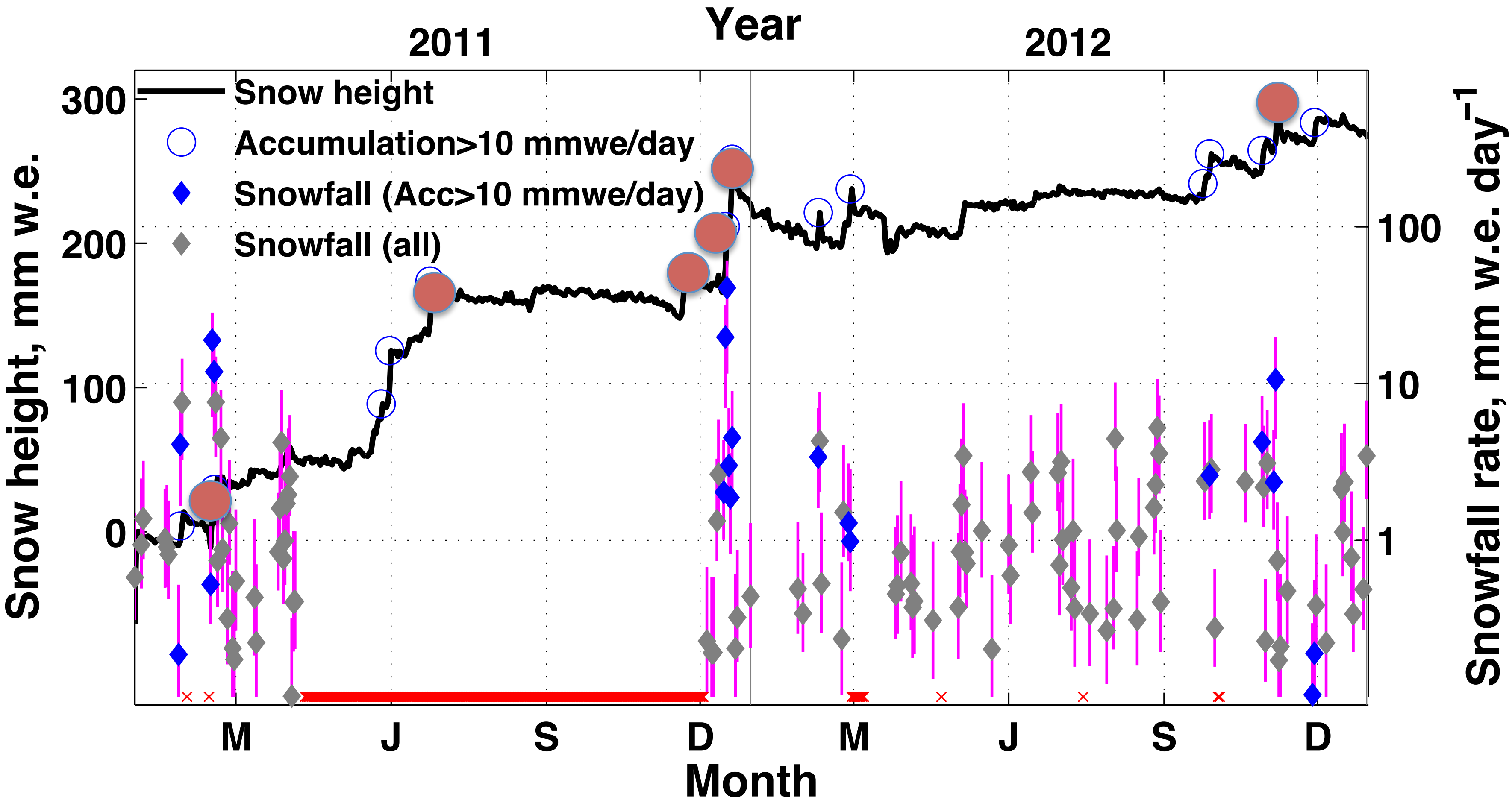
GRACE mass average over 30W-60E, 65S-80S

Integrated net precipitation (ERA-Interim)

CloudSat accumulated snowfall

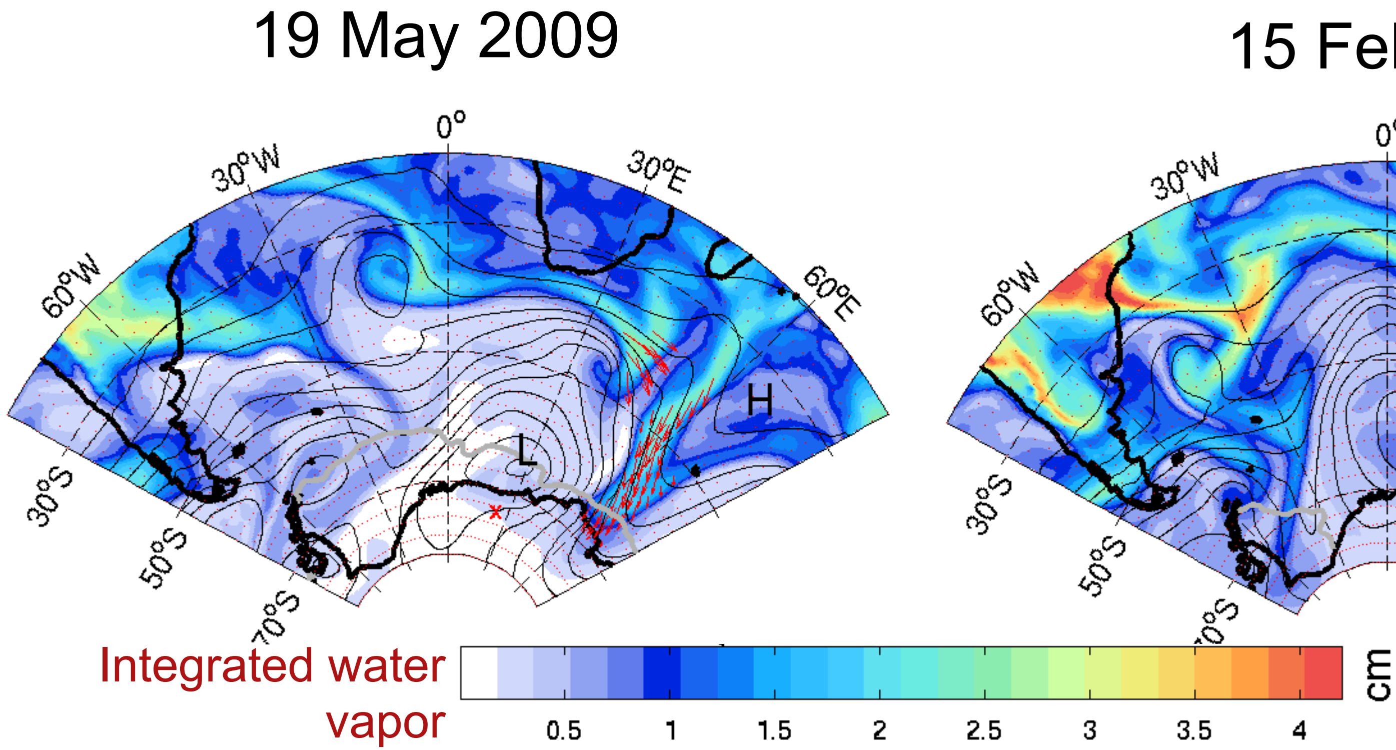
Daily snowfall and snow height:

atmospheric rivers => intense precipitation => anomalous snow accumulation



- ➢ *Gorodetskaya et al "Cloud and precipitation properties from ground-based remote sensing instruments in East Antarctica", Cryosphere 2015*
- ➢ *Gorodetskaya et al "The role of atmospheric rivers in anomalous snow accumulation in East Antarctica, GRL (2014)*

Atmospheric rivers = narrow, elongated, corridors of enhanced water vapor transport usually observed in the pre-cold frontal zone of cyclones warm sector and associated with long-distance moisture transport



Colors = integrated (900-300hPa) water vapour
Red arrows = total integrated moisture transport within ARs
black contours = 500 hPa geopotential height

➢ *Gorodetskaya et al "The role of atmospheric rivers in anomalous snow accumulation in East Antarctica, GRL (2014)*

Precipitation in observations and models:

- Importance of **high-resolution and continuous** (long-term) precipitation measurements – especially in order to capture such occasional extreme events

- Simultaneous **cloud observations** to understand precipitation formation processes

- Understanding **moisture transport and atmospheric dynamics** responsible for precipitation (especially extreme events)

- **Blowing snow observations** to separate precipitation from snow deposition/erosion by the wind

- **Snow height measurements** collocated with precipitation

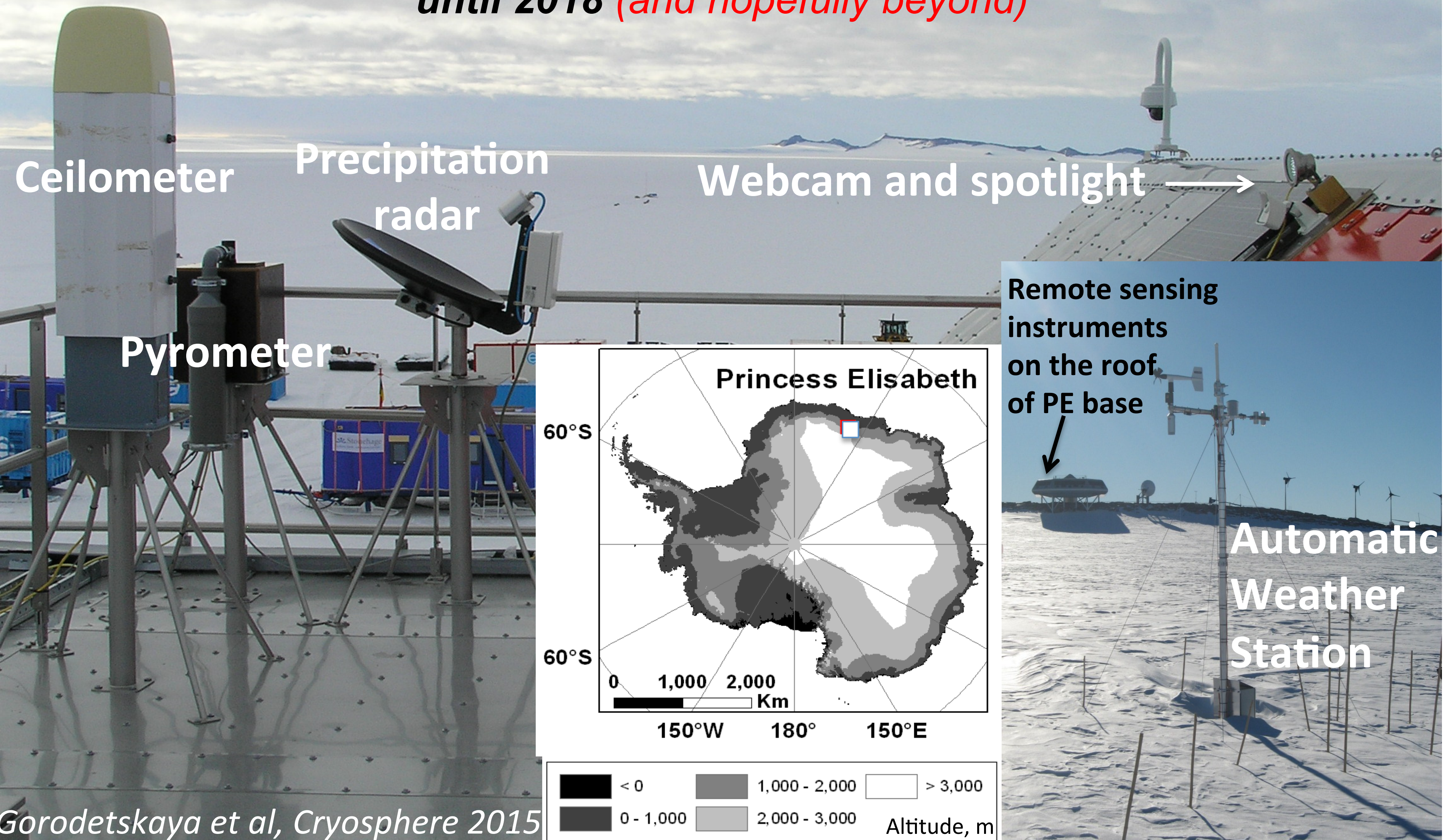
- => Evaluating precipitation in regional climate models...

Meteorology-cloud-precipitation observatory at Princess Elisabeth base in Dronning Maud Land, East Antarctica

*installed within the Belspo HYDRANT project **in 2009-2010***

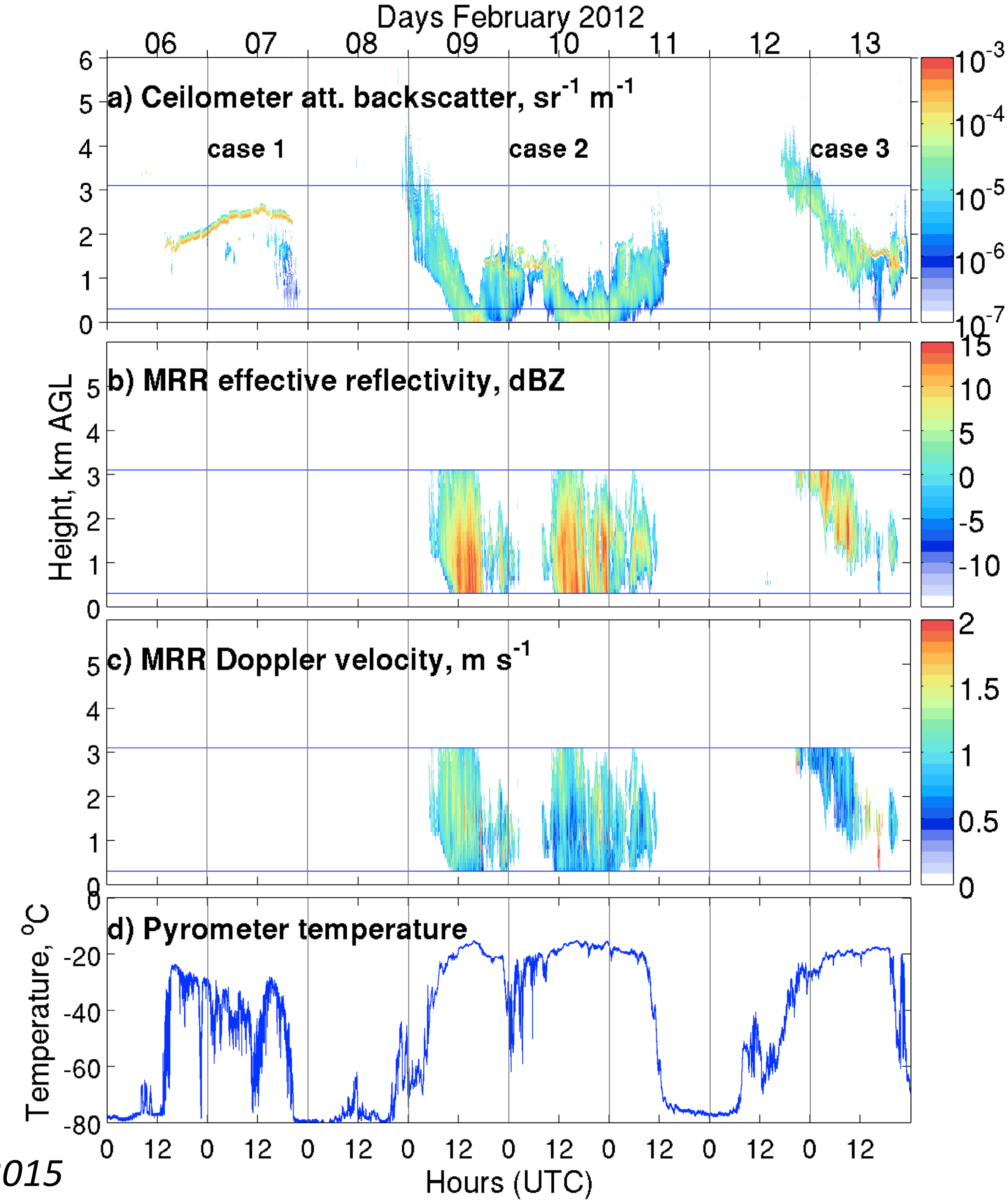
*expected **operational period** (under the Belspo AEROCLOUD project)**:***

until 2018 *(and hopefully beyond)*



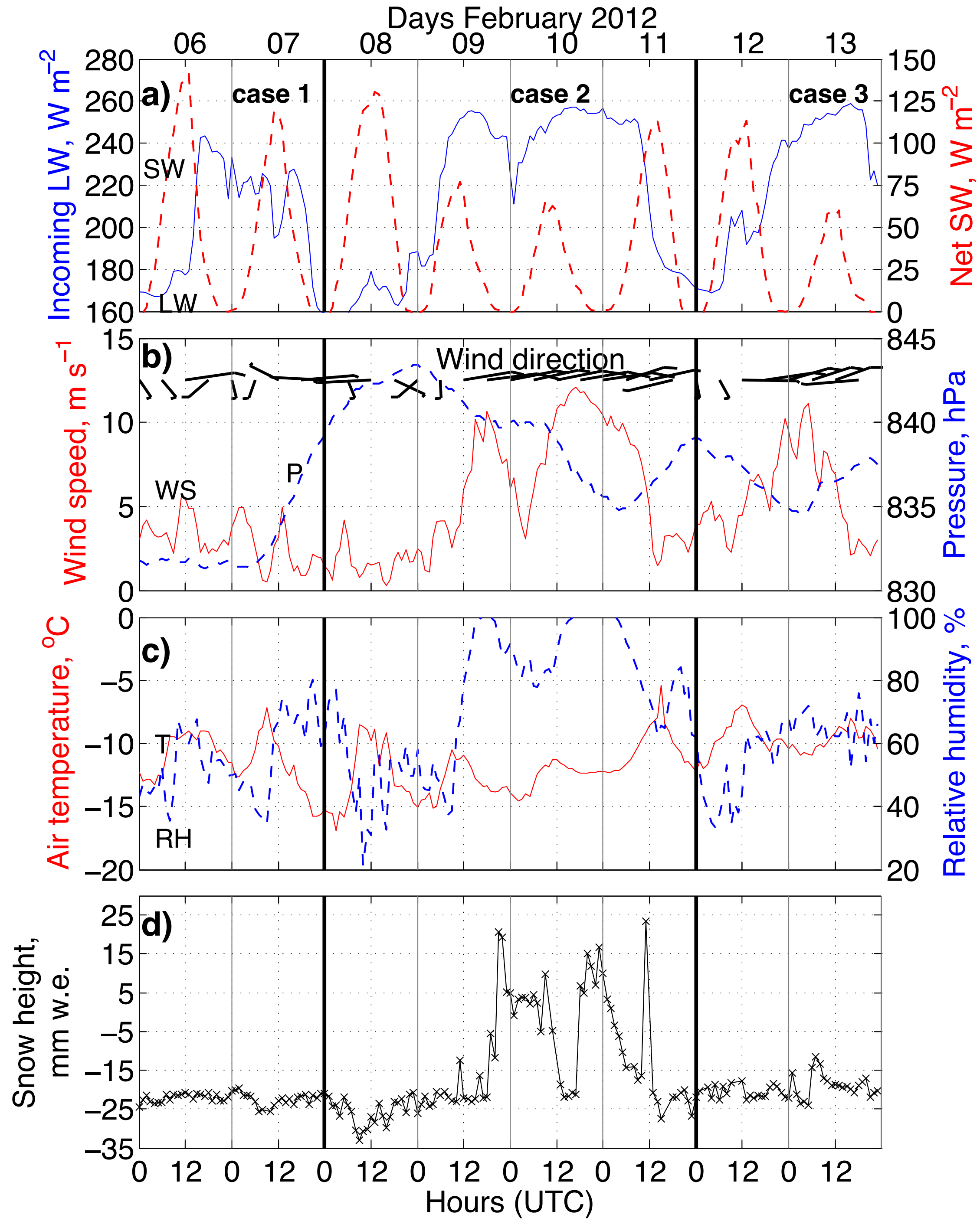
Gorodetskaya et al, Cryosphere 2015

Cloud and precipitation vertical profiles from ceilometer and radar



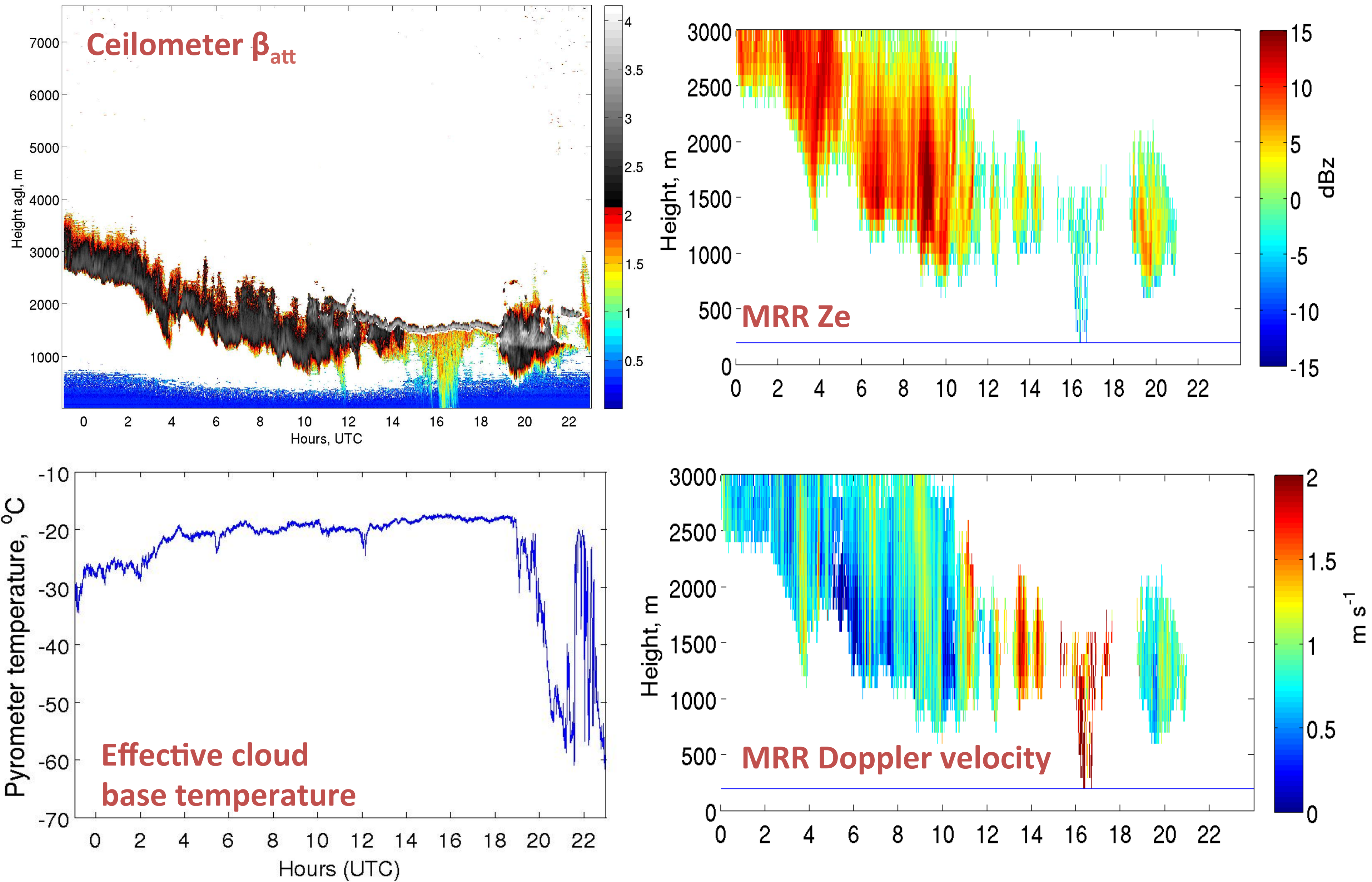
Gorodetskaya et al, Cryosphere 2015

Meteorological parameters measured/derived from Automatic Weather Station measurements



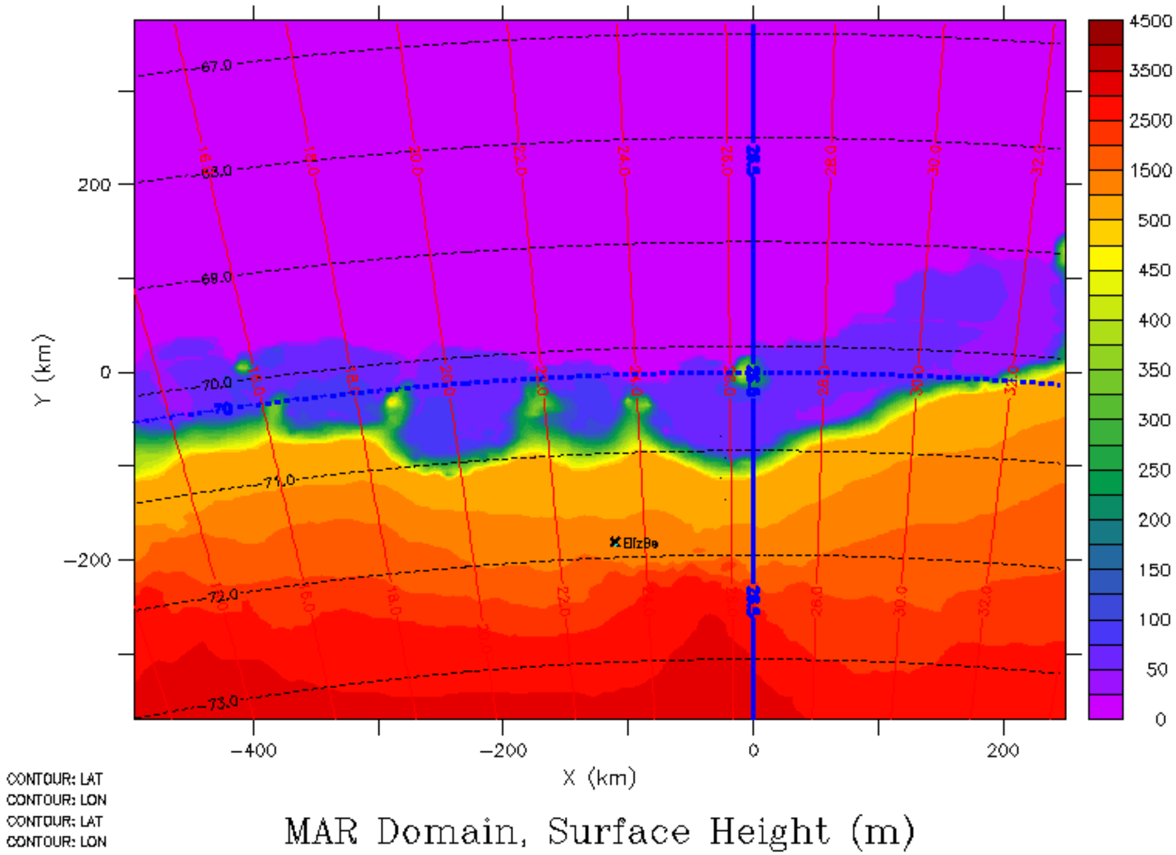
Gorodetskaya et al, Cryosphere 2015

13 February 2012 case:
ice cloud, virga, mixed phase cloud, snowfall



Modèle Atmosphéric Régional (MAR)

- Simulation over Dronning Maud Land centered over Derwael Ice rise, 5 km horiz rez



- ➢ 2-moment cloud scheme for ice clouds (ice nucleation parameterization following Meyers et al 1992; Prenni et al. 2007)
- ➢ 1-moment cloud scheme for other hydrometeors (cloud droplets, rain drops and snow particles)

Observations-to-model approach

- Calculate physical parameters using ground-based remote sensing to compare to the modeled cloud and precipitation properties. Physical parameters calculated using PE observations:

- snowfall rate
- cloud base height
- cloud base temperature
- cloud liquid occurrence
- radiative fluxes
- cloud radiative forcing

Process-based evaluation is possible!

Observations-to-model approach:

Snowfall rate

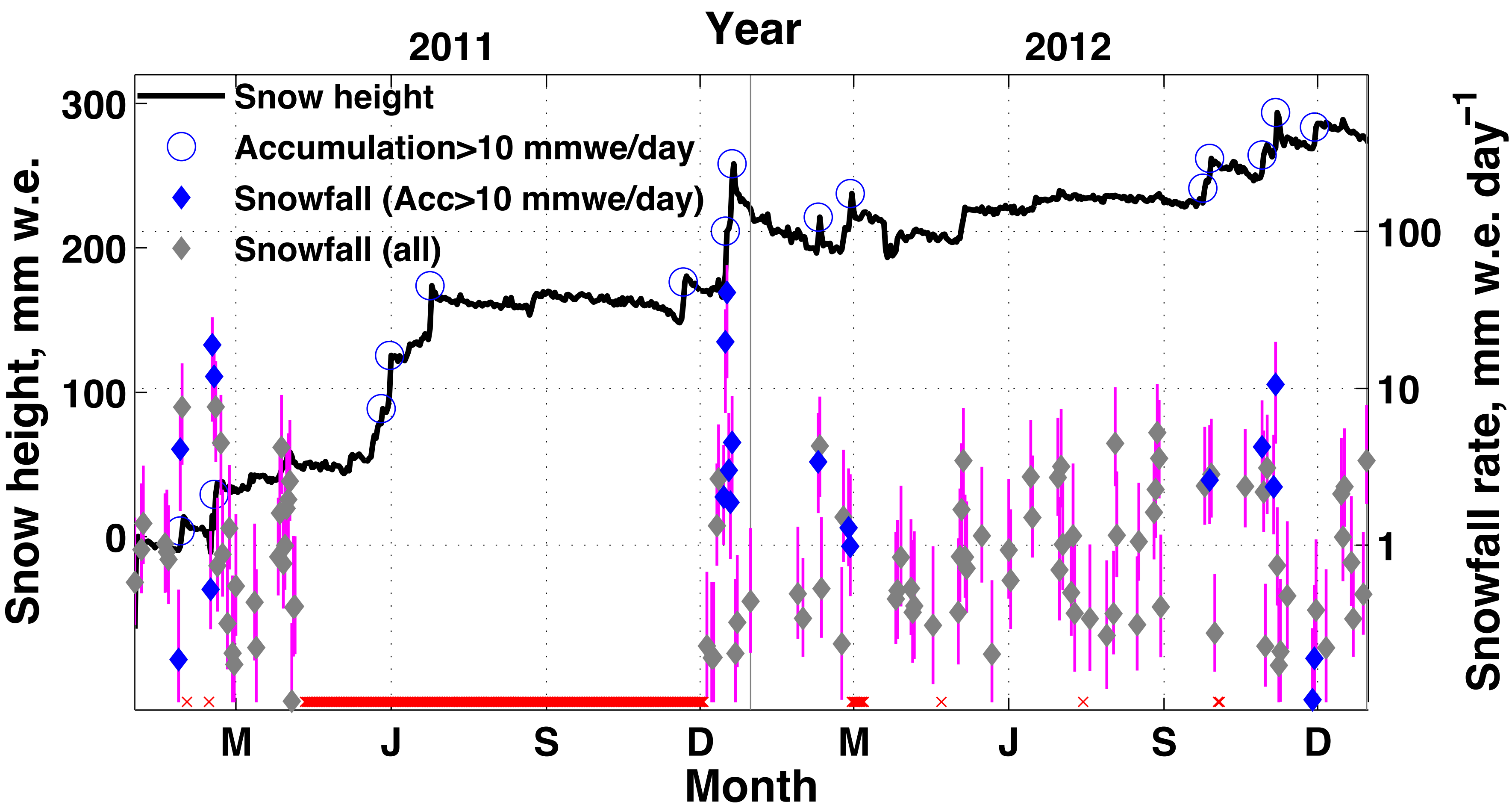
1) 1-minute radar effective reflectivity factor is derived using Maahn and Kollias (2009) processing the raw data
2) Take Ze at 400 m agl (10-min duration condition)
3) Nine Ze-S relationships for dry snow are used to convert Ze to snowfall rate (S) (Matrosov 2007, Kulie and Bennartz 2009) as in Gorodetskaya et al (2015)

Table: Ze –S relationships (Ze in $mm^6\ m^{-3}$, S in mm w.e. h^{-1}) for dry (unrimed) snow for various snowfall particle shapes and parameters.

Ice habit or parameters	Ze–S relationships
Three-bullet rosettes *	$Ze = 24.04*S^{1.51}$
Aggregates *	$Ze = 313.29*S^{1.85}$
Low-density spheres *	$Ze = 19.66*S^{1.74}$
Aggregate spheroids **	$Ze = 56*S^{1.2}$
- increasing r**	$Ze = 34*S^{1.1}$
- increasing (decreasing) m**	$Ze = 66*S^{1.2}$ ($Ze = 48*S^{1.2}$)
- increasing (decreasing) V **	$Ze = 46*S^{1.2}$ ($Ze = 67*S^{1.2}$)

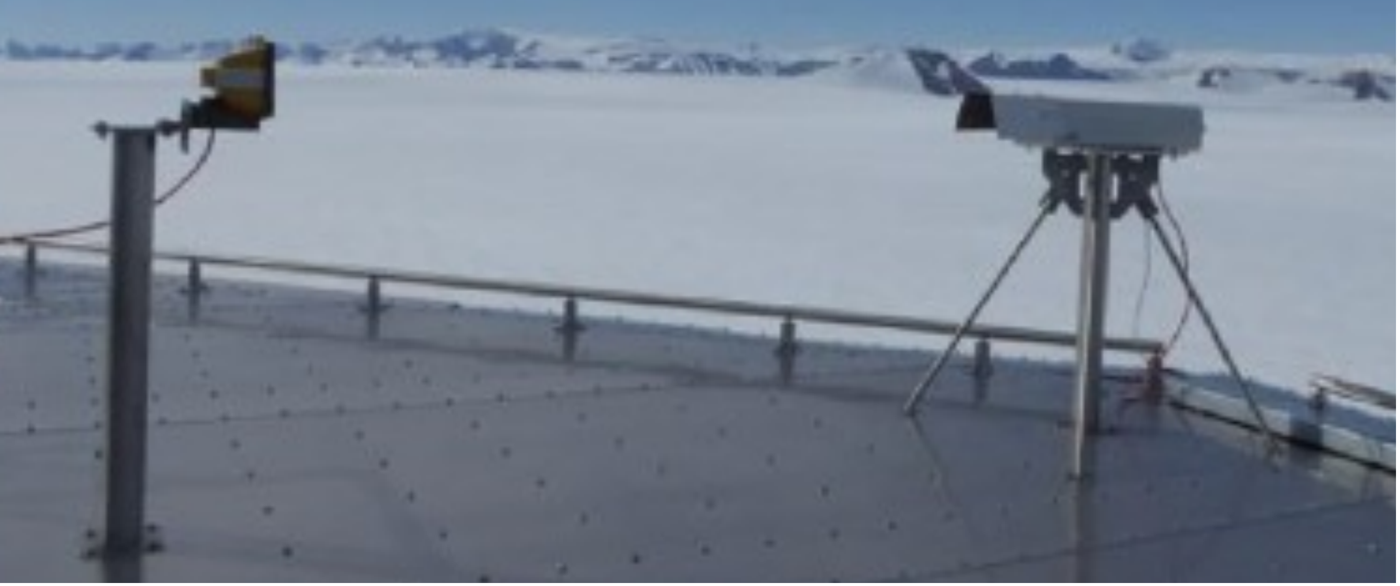
* Relationships derived by Kulie and Bennartz (2009) using different ice habit models and their backscattering characteristics at 35 GHz; ** Relationships derived by Matrosov (2007) for aggregated snowflakes approximated as spheroids using various assumptions on particle radius (r), mass (m)–size relations, and fall velocity (Vt)–size relations at 34.6 GHz.

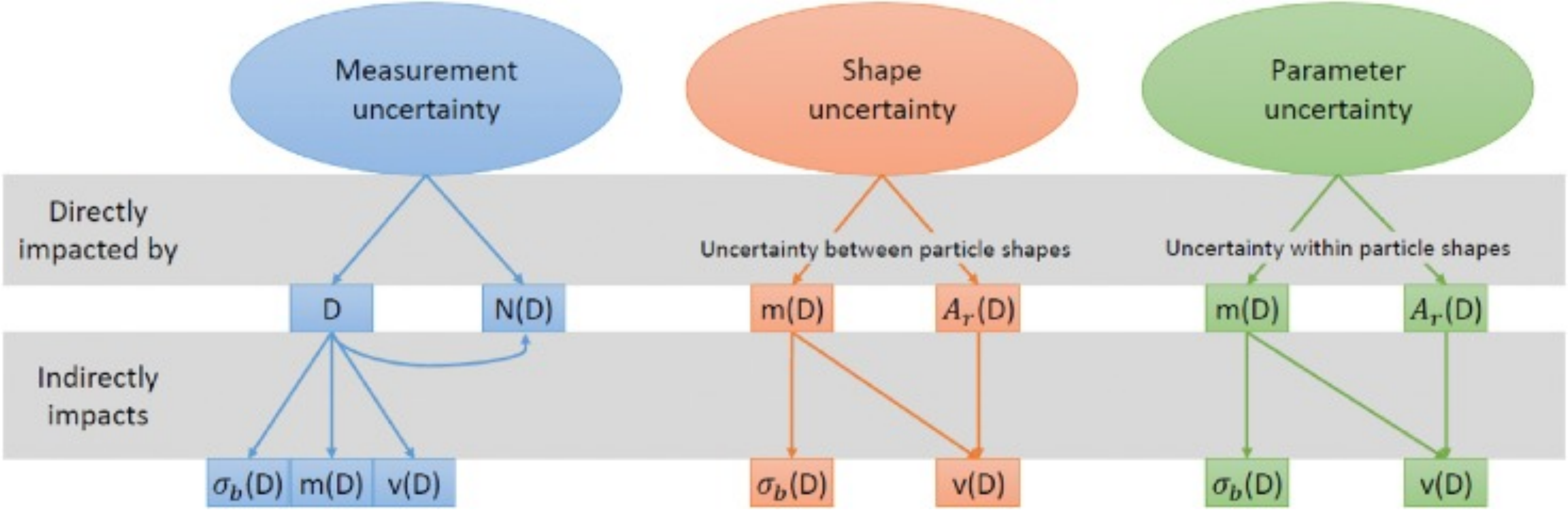
Snowfall rate derived from micro-rain radar and snow height changes from sonic height measurements



SVI/PIP: Snow video imager/Precipitation Imaging Package (NASA)

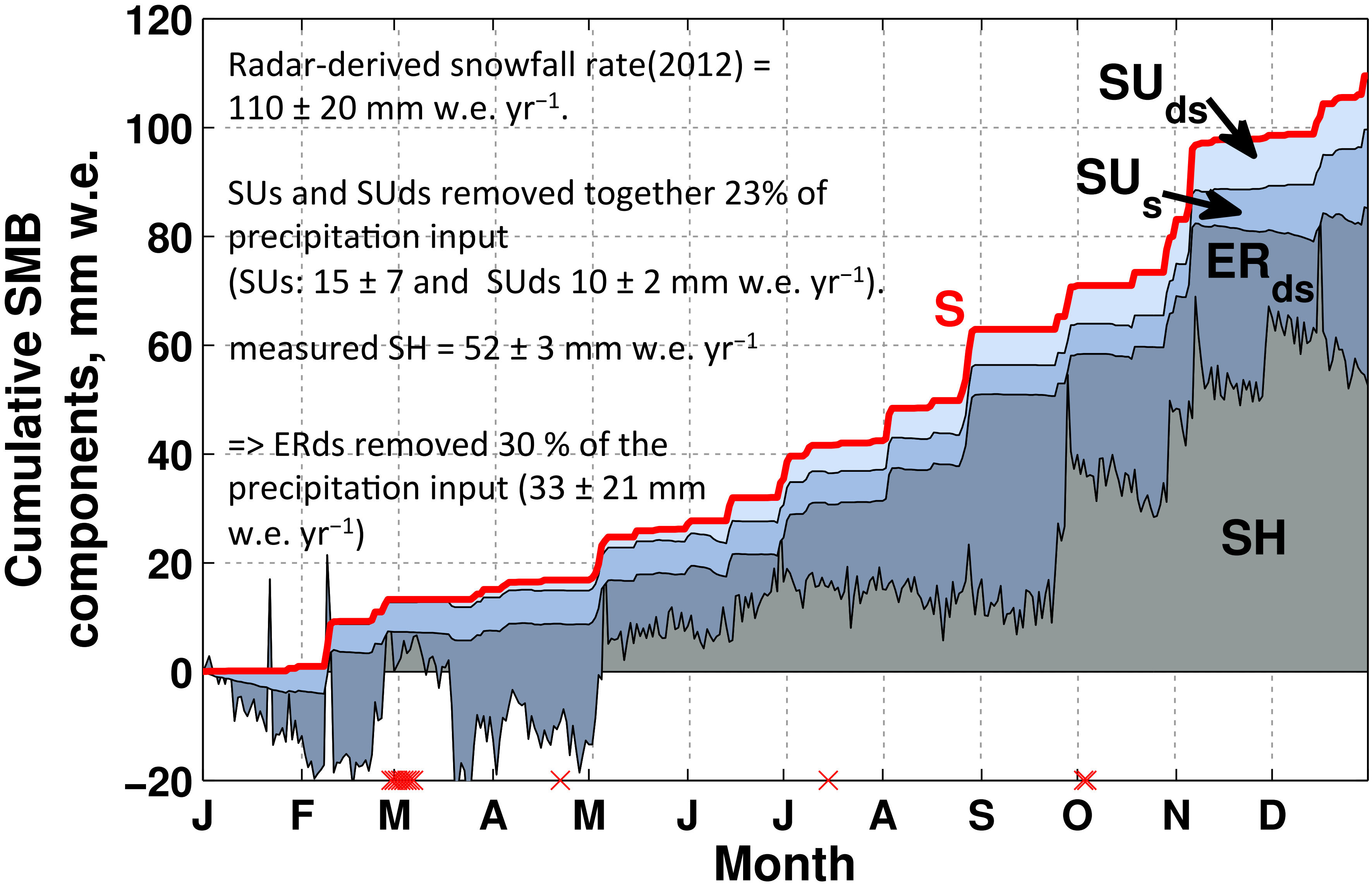
Souverijns et al 2017, Atm Research





Souverijns et al 2017, "**Estimating radar reflectivity - Snowfall rate relationships and their uncertainties over Antarctica by combining disdrometer and radar observations",** Atm Res, V. 196, 211–223

Surface mass balance

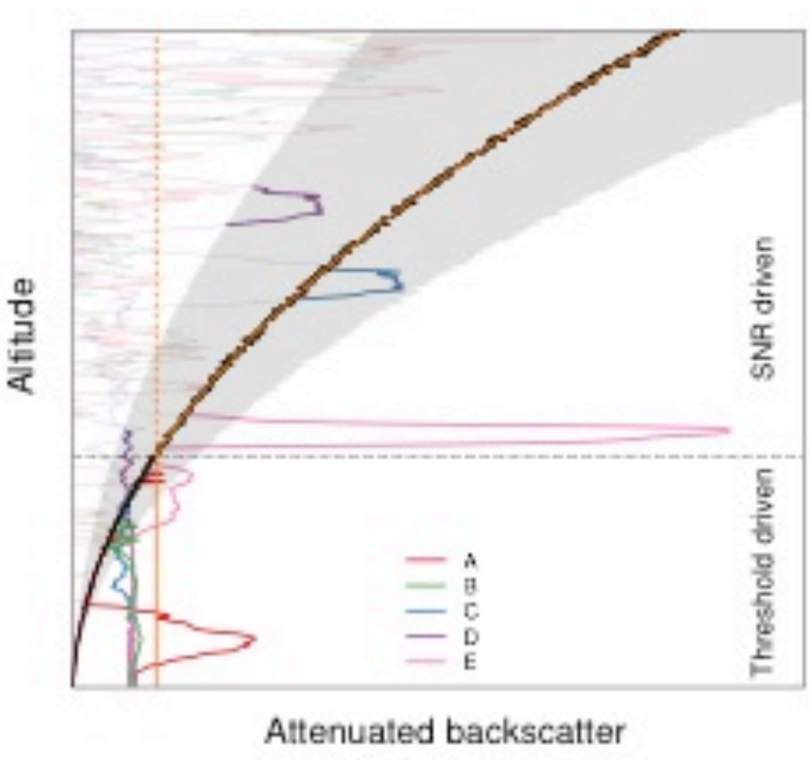


- *Gorodetskaya et al "Cloud and precipitation properties from ground-based remote sensing instruments in East Antarctica", Cryosphere 2015*
- *Thiery et al " Surface and snowdrift sublimation at Princess Elisabeth station, East Antarctica, Cryosphere (2012)*

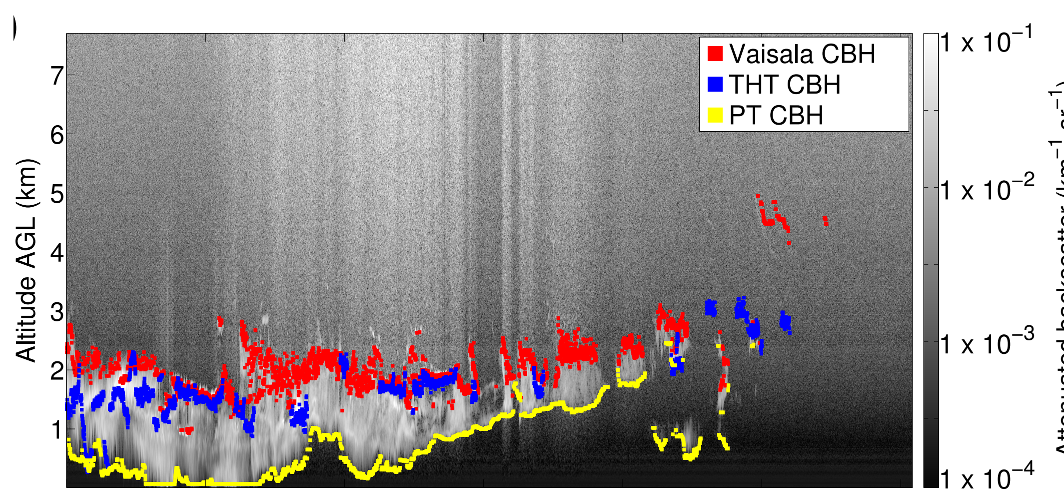
Observations-to-model approach:

Cloud base height

1) Ceilometer raw data = attenuated backscatter profile (beta)
2) Noise reduction
3) Polar Threshold algorithm (Van Tricht, K., Gorodetskaya, I. V., Lhermitte, S., Turner, D. D., Schween, J. H., and Van Lipzig, N. P. M.: An improved algorithm for polar cloud-base detection by ceilometer over the ice sheets, Atmos. Meas. Tech., 7, 1153-1167, doi:10.5194/amt-7-1153-2014, 2014.)



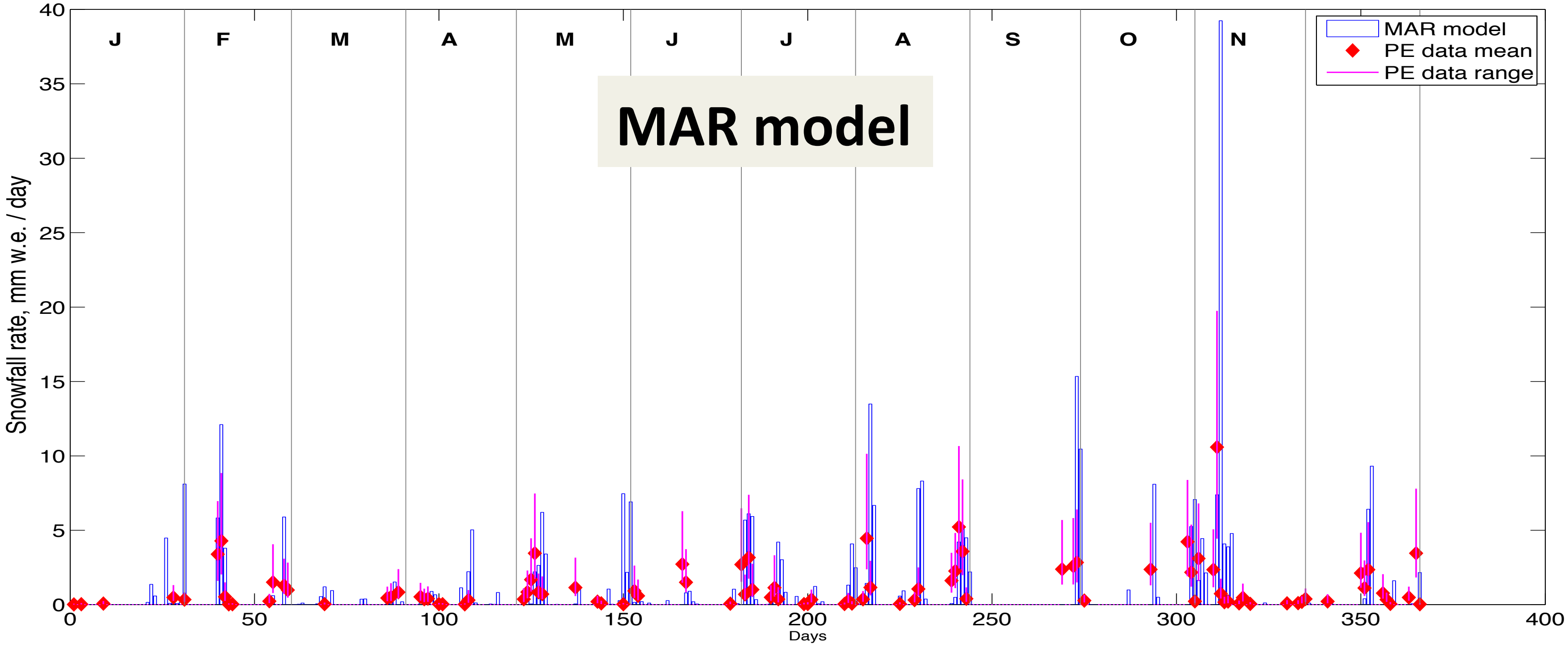
Theoretical working of the Polar Threshold algorithm for detecting cloud base height

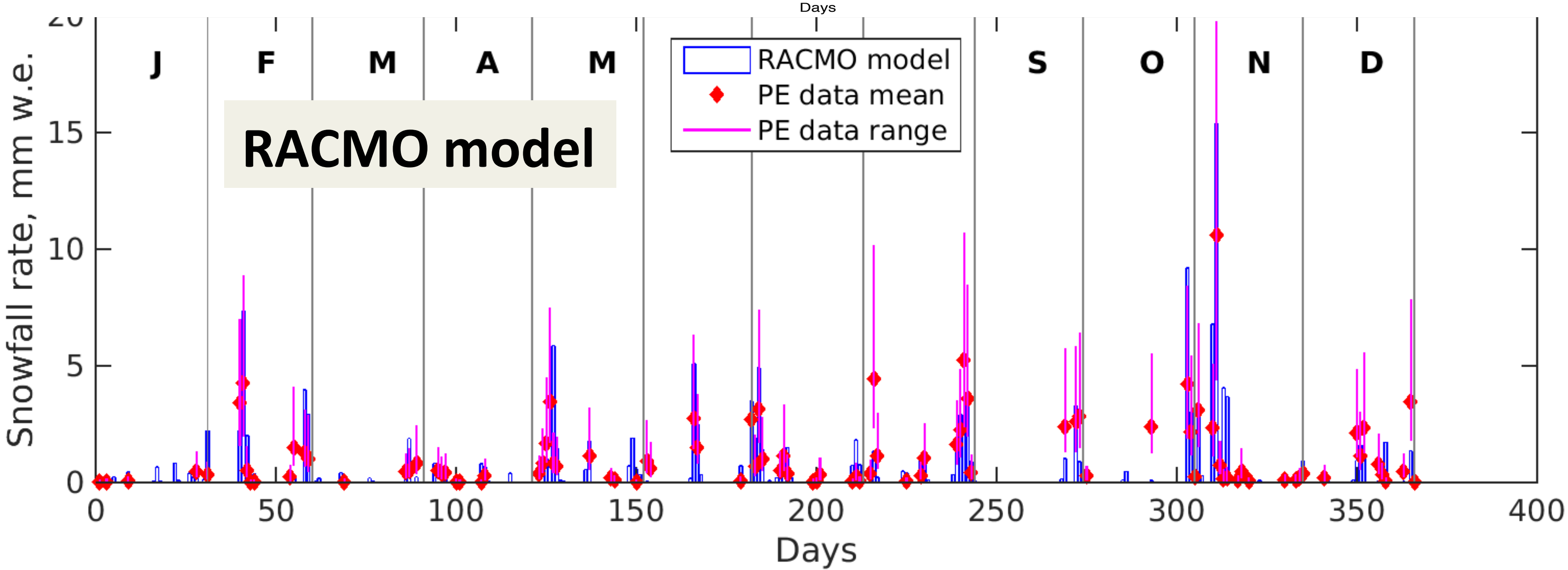


Comparison of cloud base height detection from different algorithms (Vaisala, THT and PT)

Van Tricht et al 2014, AMT

Daily snowfall rate during 2012 from PE obs and models





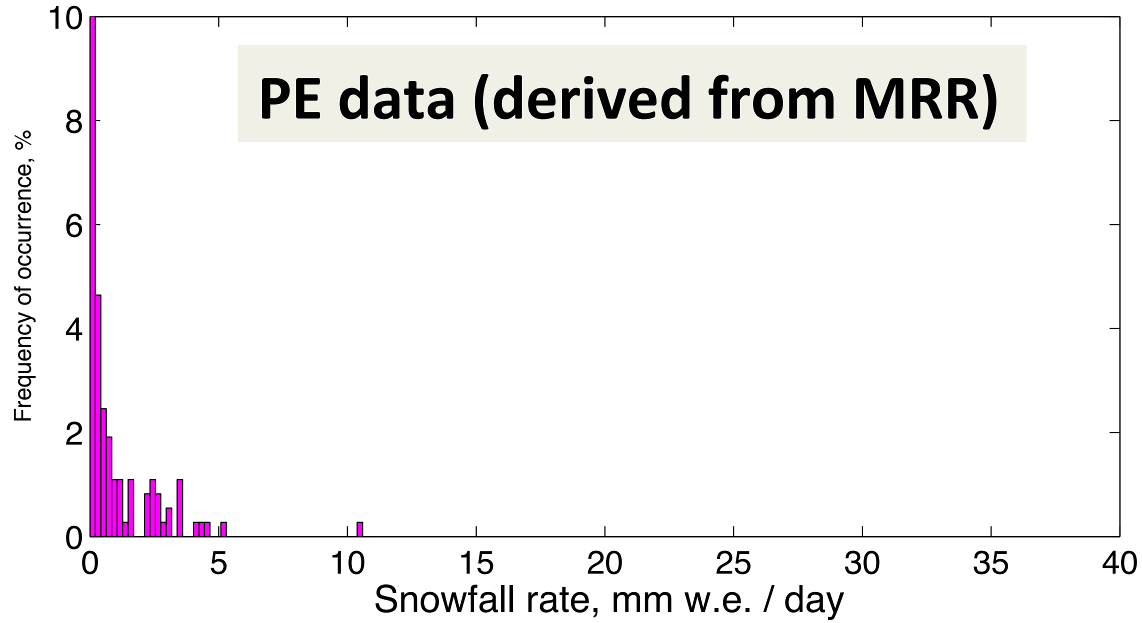
Precipitation statistics

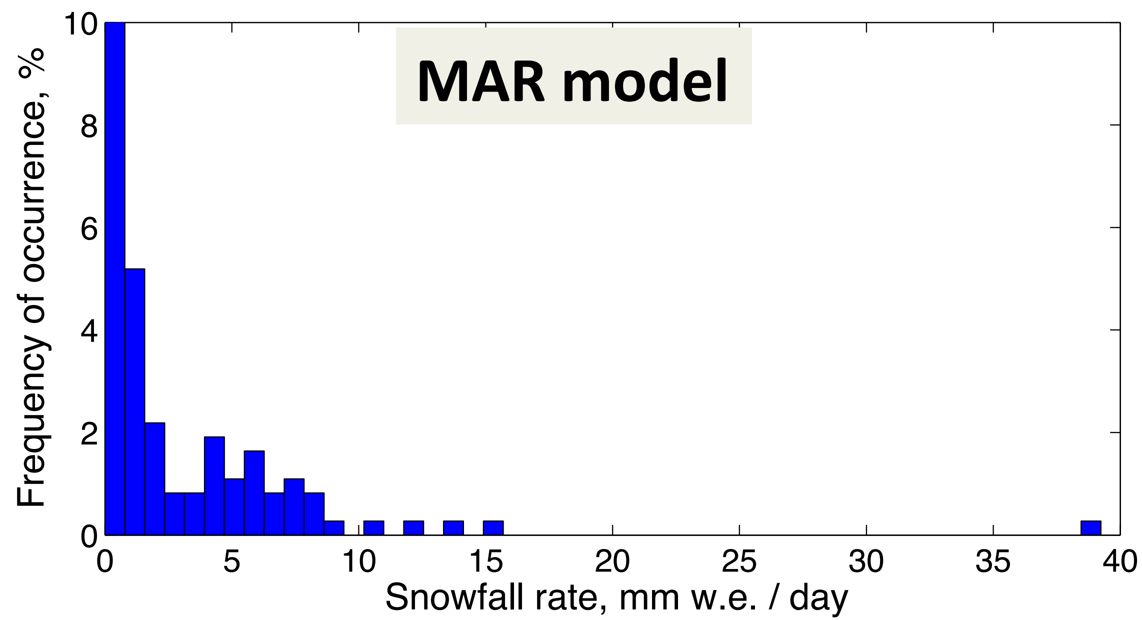
Daily SR distributions

- Extreme values are generated by different processes => the statistics of (and underlying PDFs corresponding to) the different physical processes may be different

- Antarctic escarpment zone: desert.. any precipitation amount is "extreme value" and correspond to **synoptic regime**, while most extreme values standing out = **atmospheric rivers**

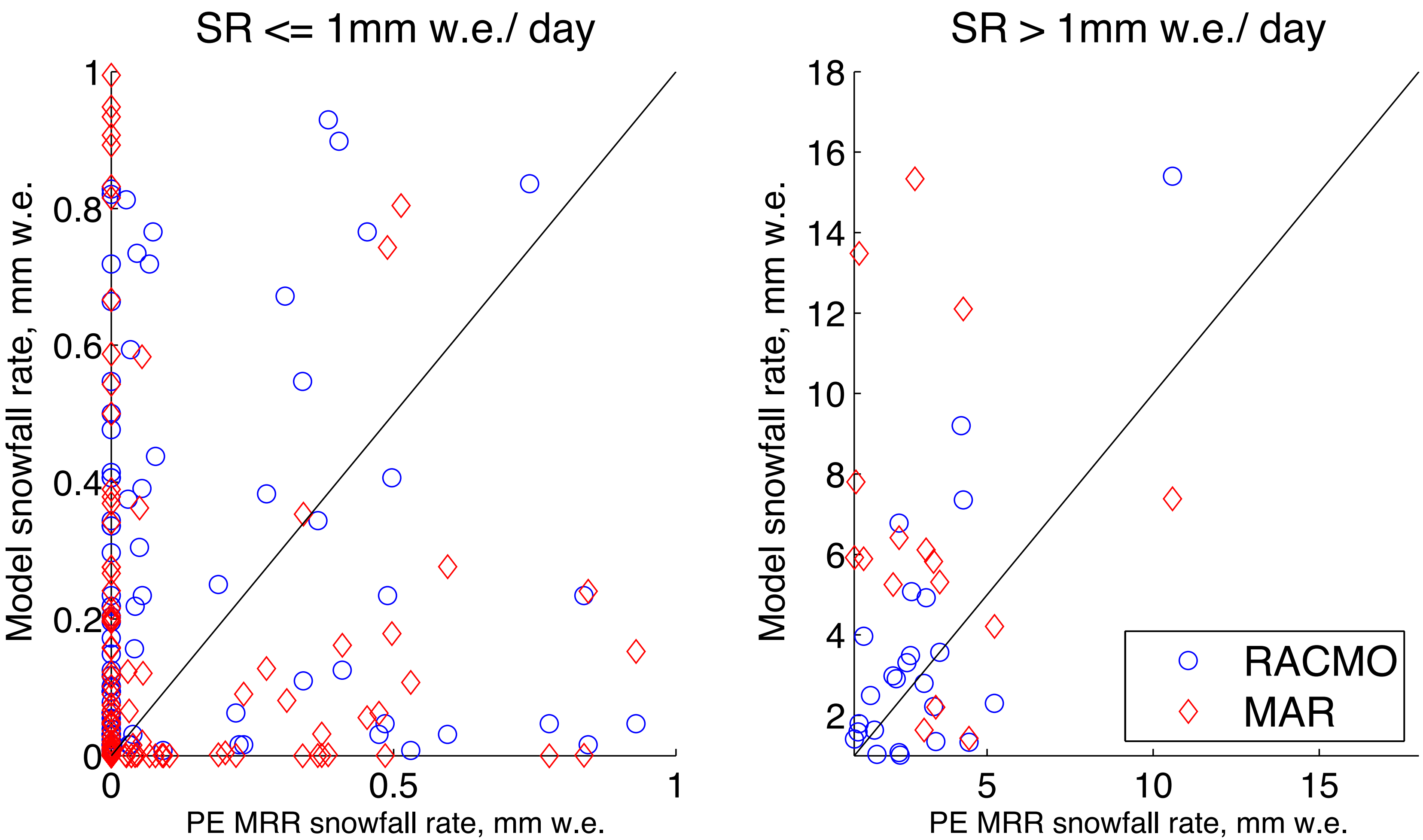
- Compare distributions using GEV distribution – Weibull (as for gamma distribution for strong positive skewness use shape parameter $\alpha < 1$)





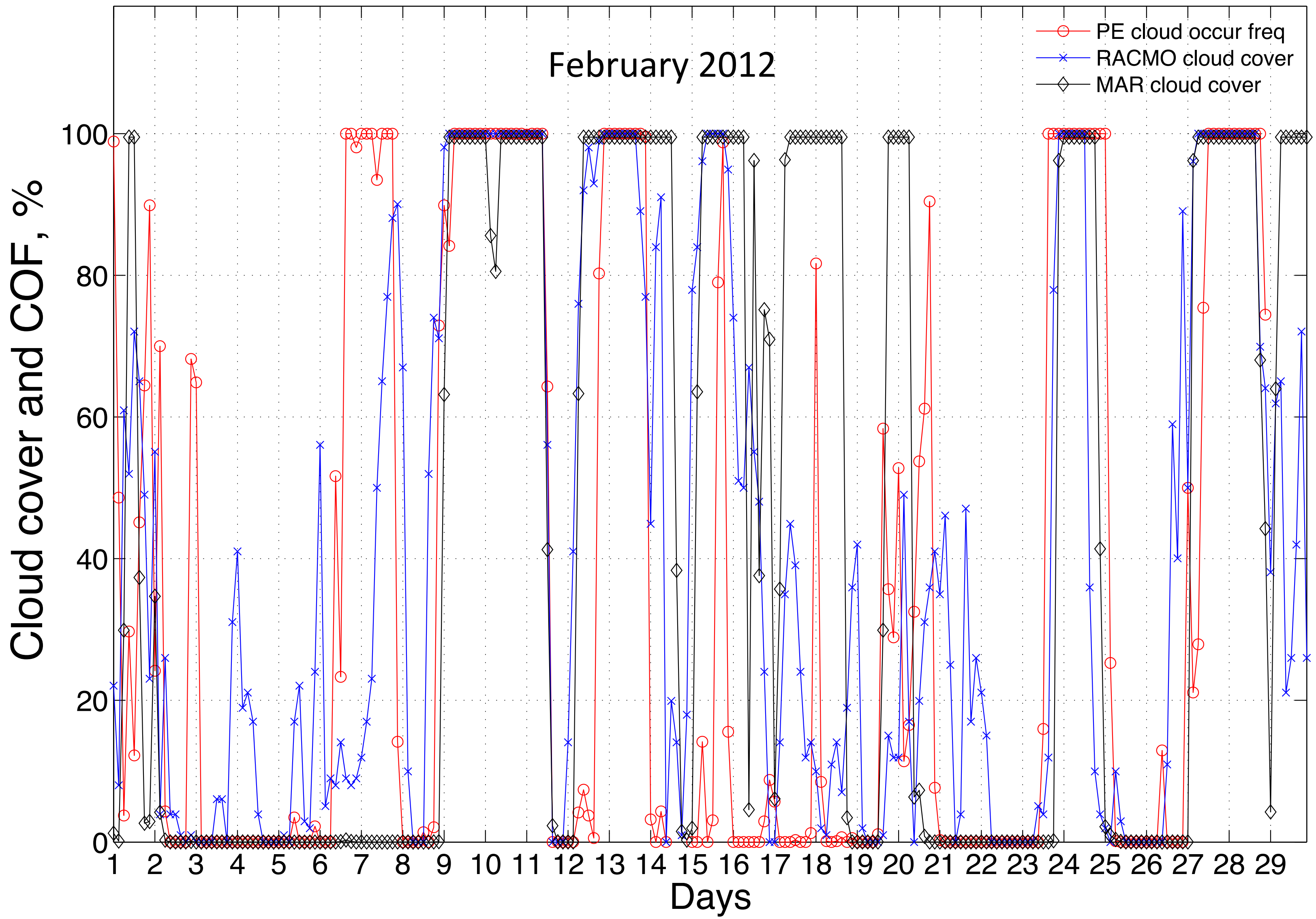
Precipitation statistics

Scatter plots of daily snowfall rate: models vs PE obs for small daily SR (<=1 mmwe / day) and large daily SR (> 1 mmwe/day)



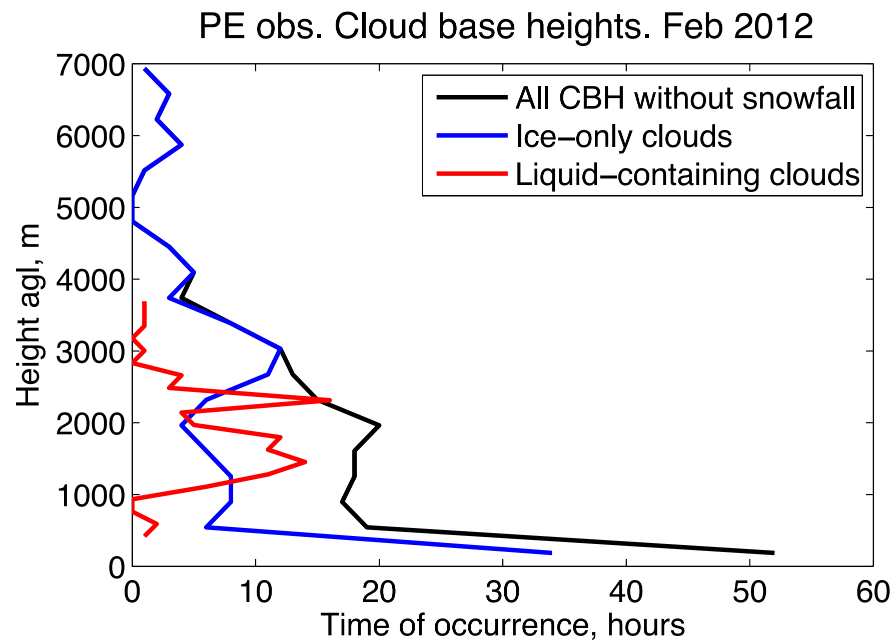
Cloud properties statistics

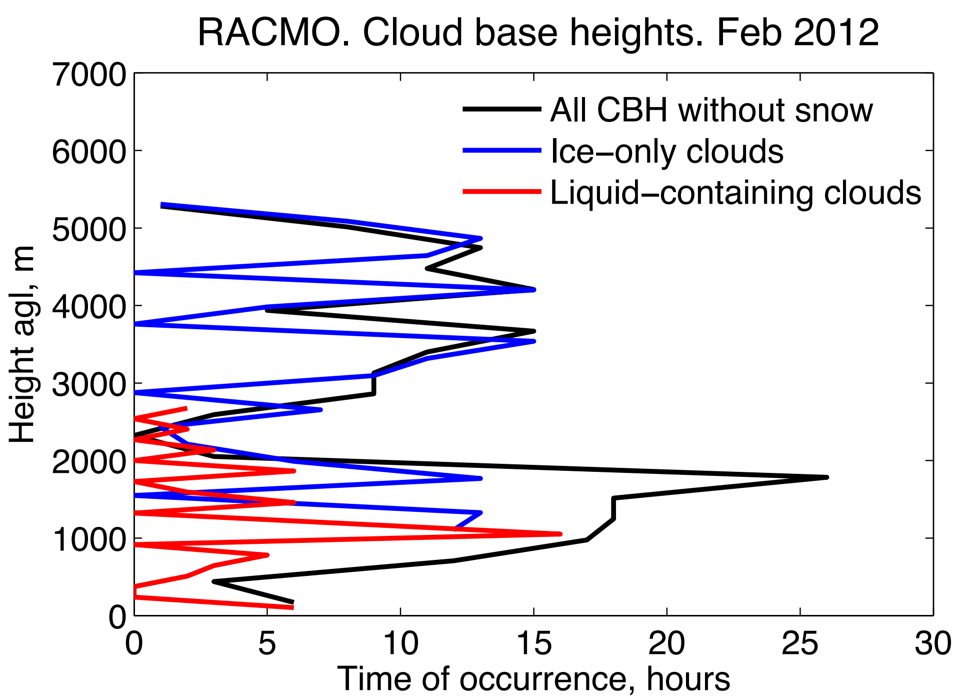
PE cloud occurrence frequency and RACMO/MAR cloud cover % (daily during Feb 2012)

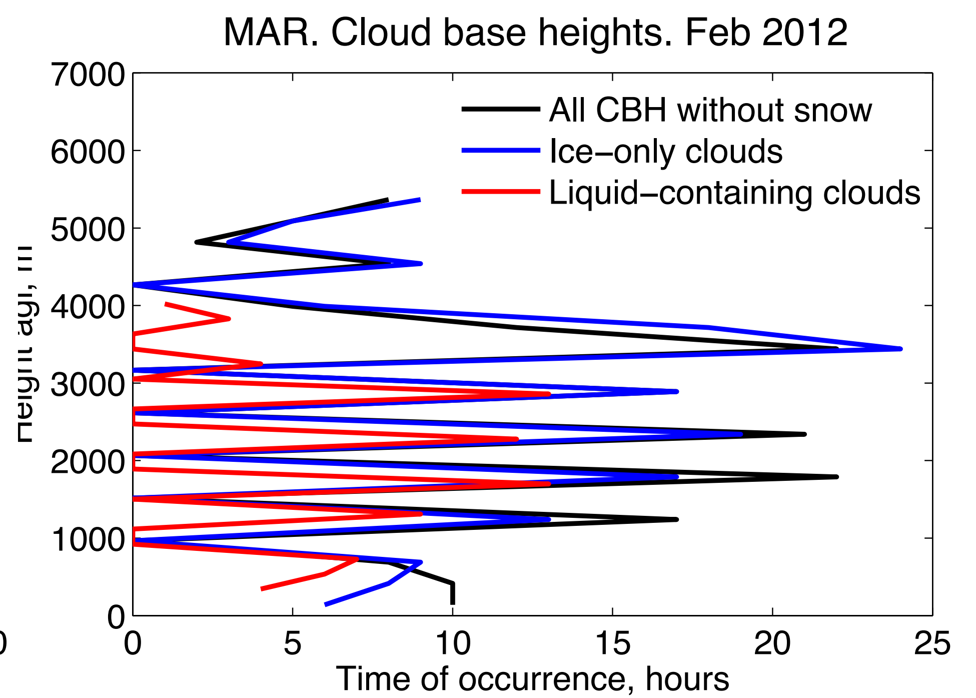


Cloud properties statistics

Cloud base heights occurrence frequency for PE obs, MAR and RACMO for all, ice-only, and liquid-containing clouds during February 2012

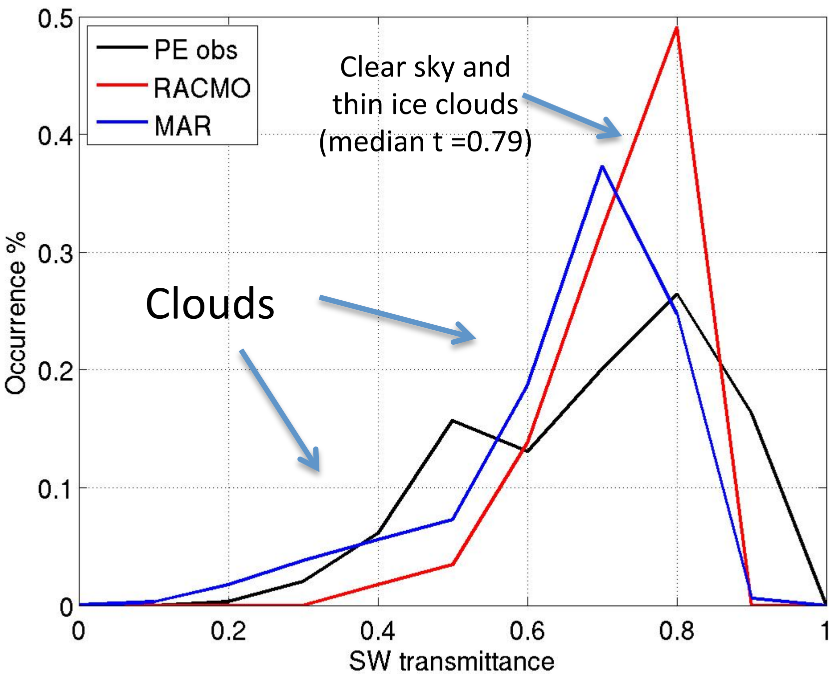






SW transmittance for all atmospheric states – cloudy or clear from PE obs (AWS radiometers), RACMO and MAR models during February 2012

$$t = \frac{SW_{in}}{SW_{in\_TOA}}$$



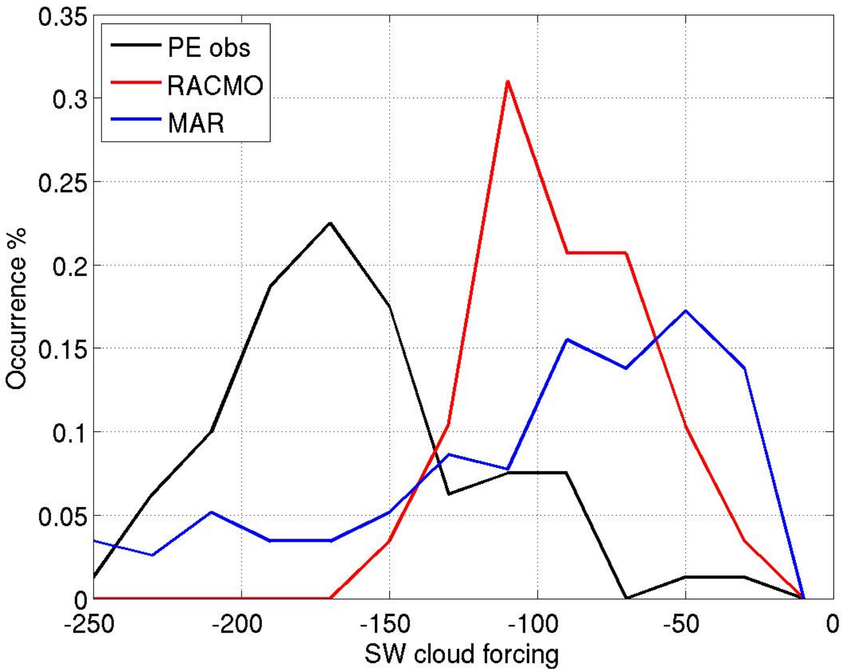
- Clear sky SW transmittance: too high in both MAR and RACMO model (lack of water vapour!)
- Cloudy SW transmittance for t>0.6 : too high in both models (optically thin ice clouds are too thin)
- Cloudy SW for t<0.5 (liquid-containing clouds): MAR better compares to observations, while RACMO underestimate liquid-containing clouds (relatively low transmittance)

SW cloud forcing for PE obs (AWS radiometers), RACMO and MAR models during February 2012

$$SW_{in}(clearsky) = t_0(clearsky) * SW_{in\_TOA}$$

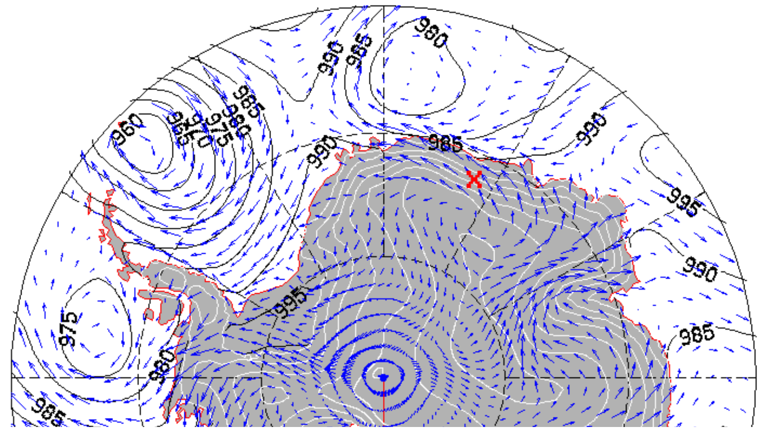
$$CF_{SW} = SW_{in} - SW_{in}(clearsky)$$

- PE obs: high frequency clouds with SWCF=-200..-150 W m-2 (liquid containing!)
- RACMO misses these clouds completely
- MAR has less frequent but optically thicker clouds compared to PE obs
- Both models skew towards optically thin (ice) clouds



Case/process studies

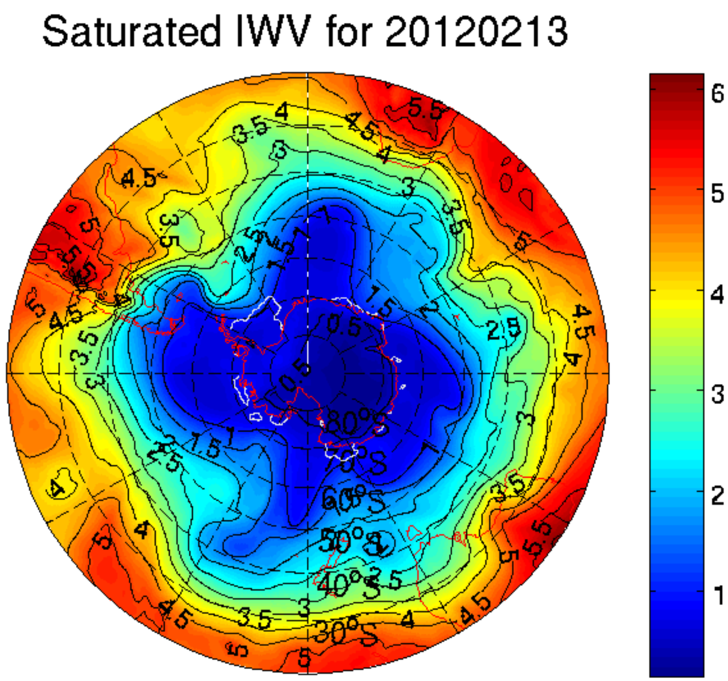
- **Case 1: 13 Feb 2012: ice and mixed phase clouds with virga and snowfall**



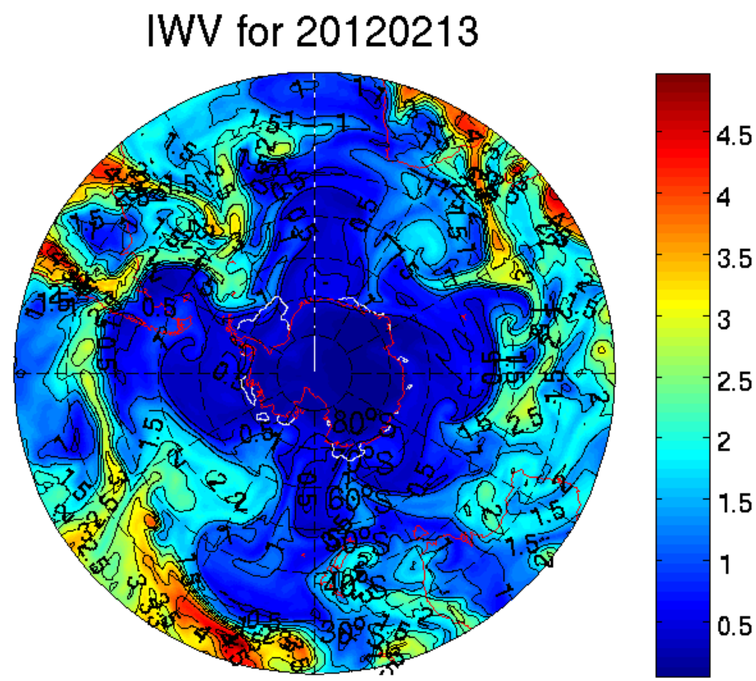
Warm synoptic regime day at PE
(regime definition by Gorodetskaya et al. JGR2013)

Case/process studies

- **Case 1: 13 Feb 2012: ice and mixed phase clouds with virga and snowfall**

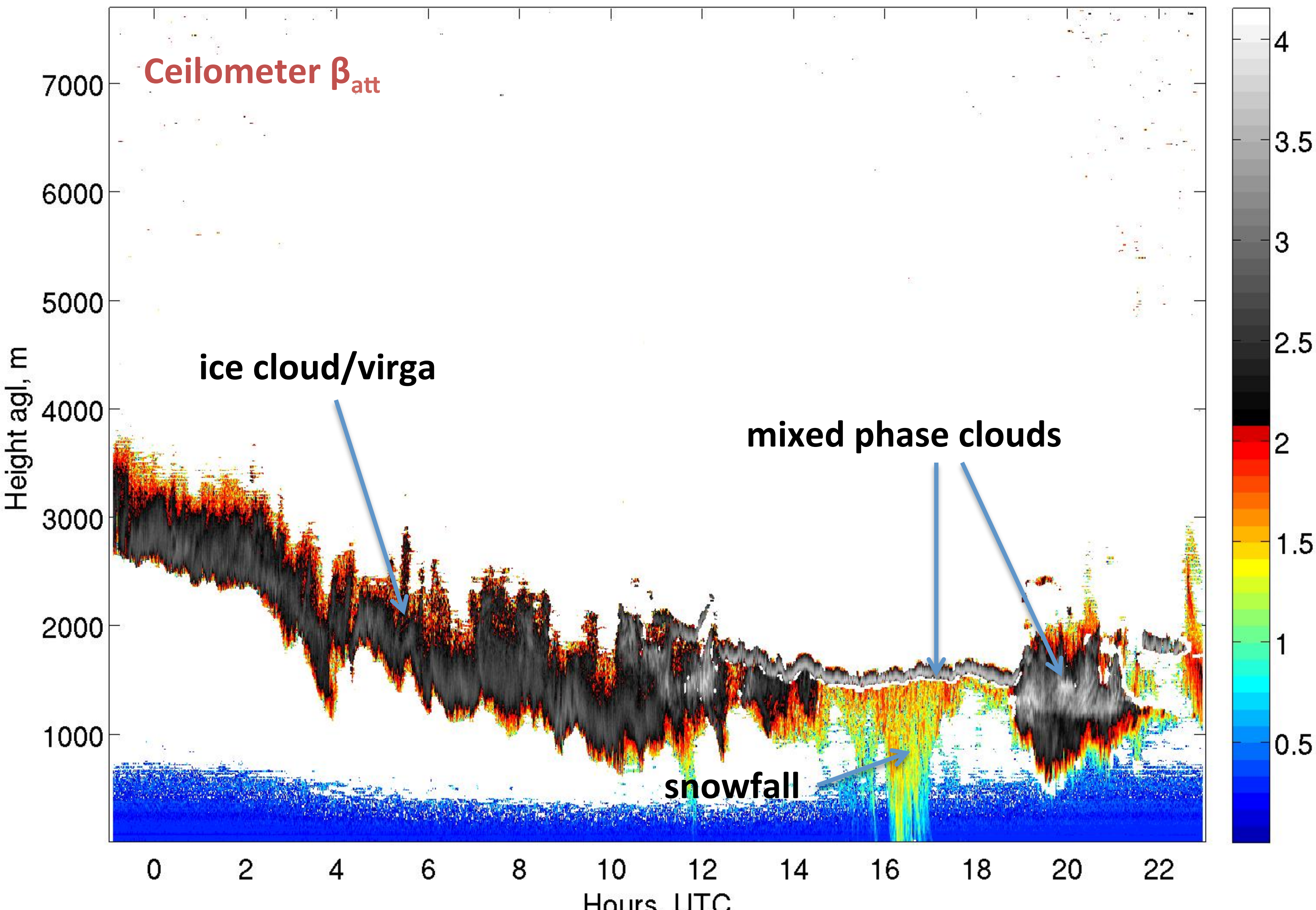


Heat advection



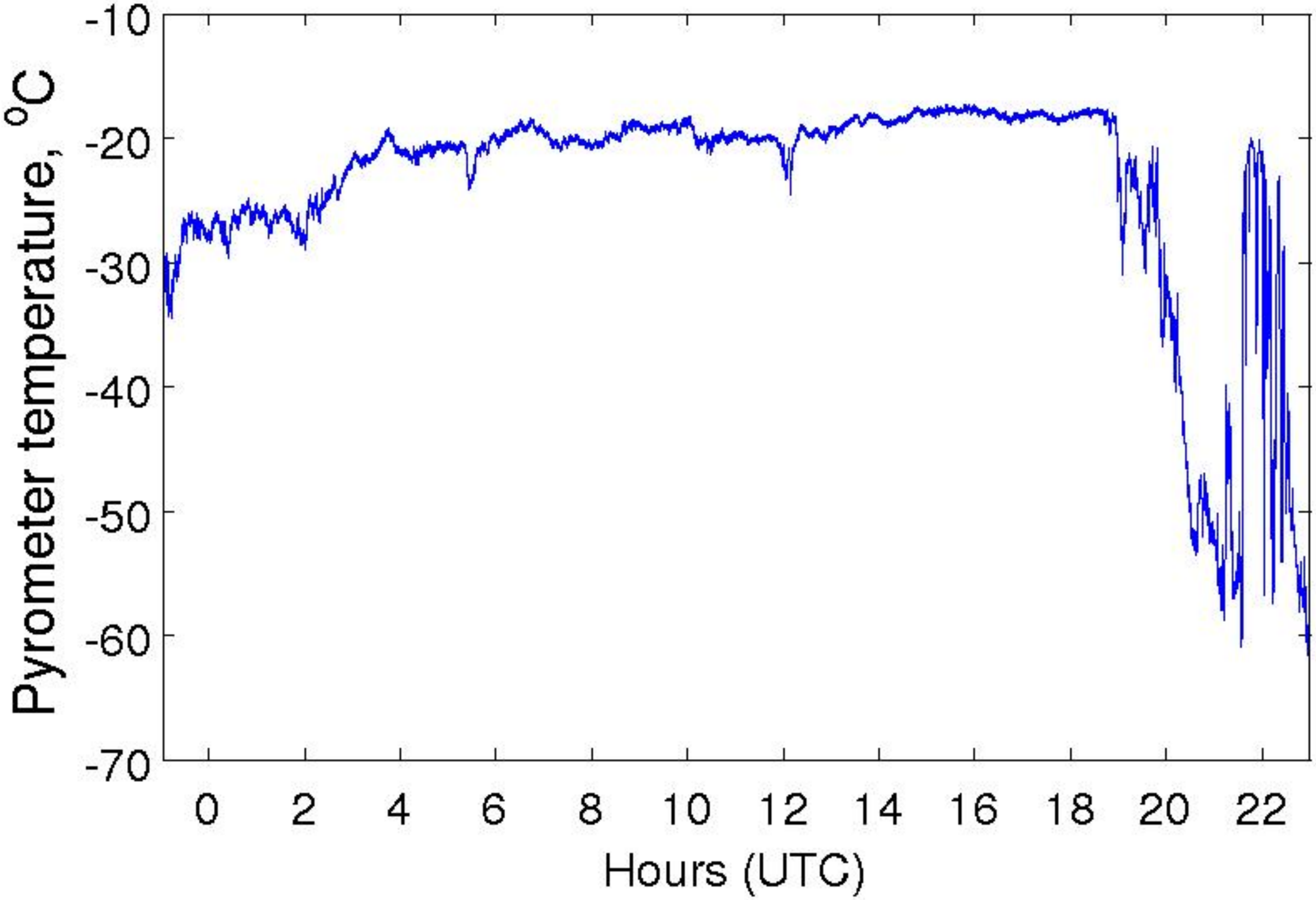
Integrated water vapour

Cloud vertical structure from ceilometer
(13 Feb 2012)

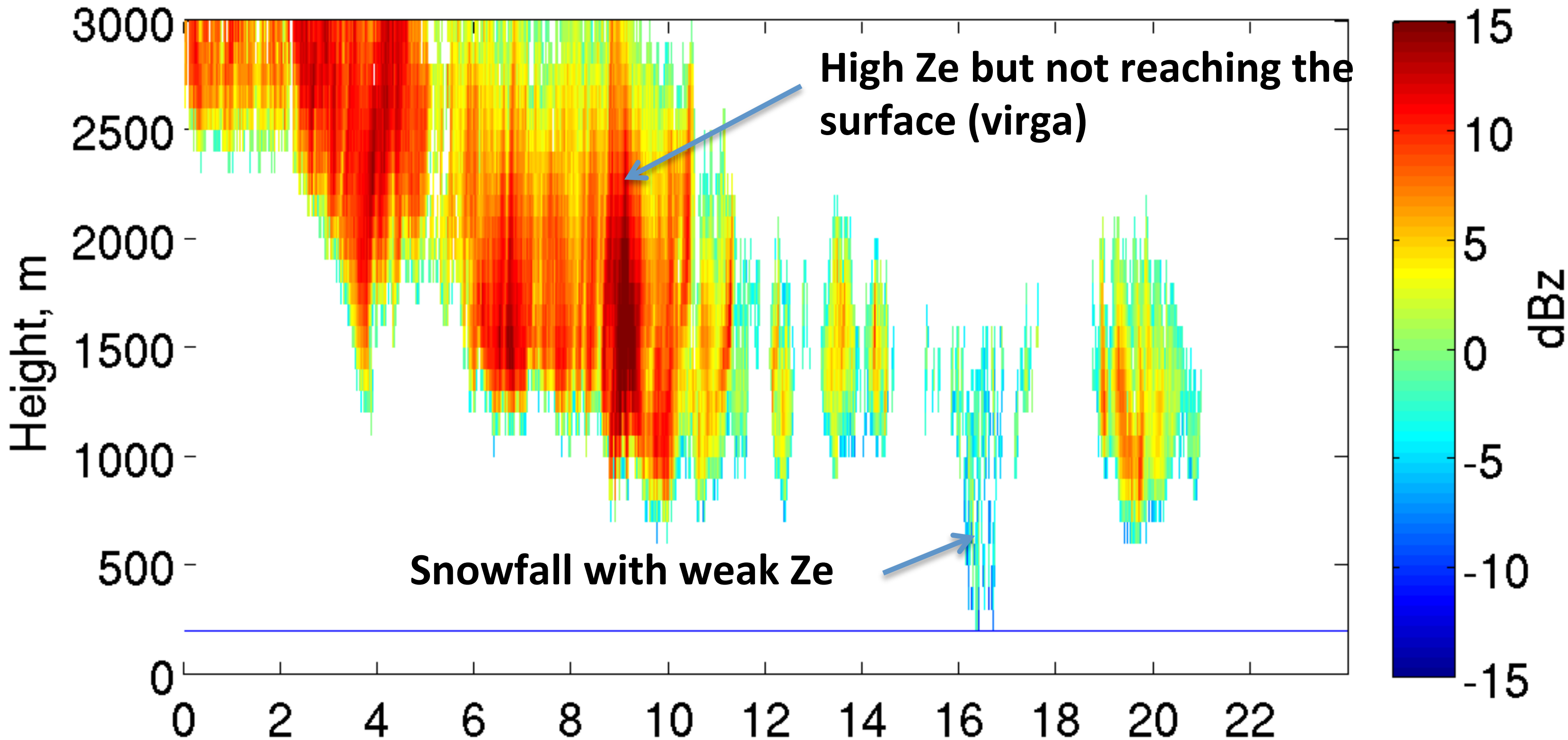


Effective cloud base temperature from pyrometer

(13 Feb 2012)

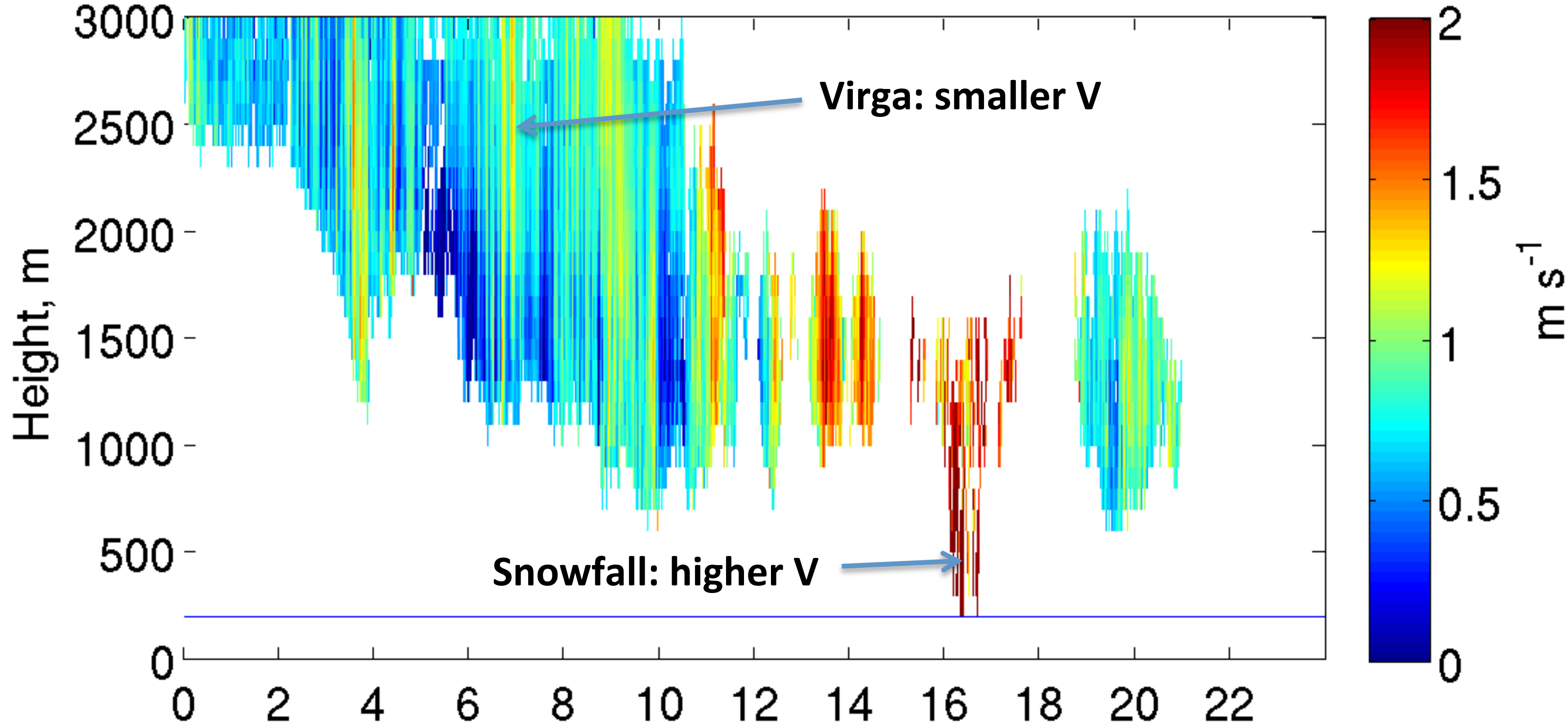


Radar effective reflectivity Ze from MRR
(13 Feb 2012)



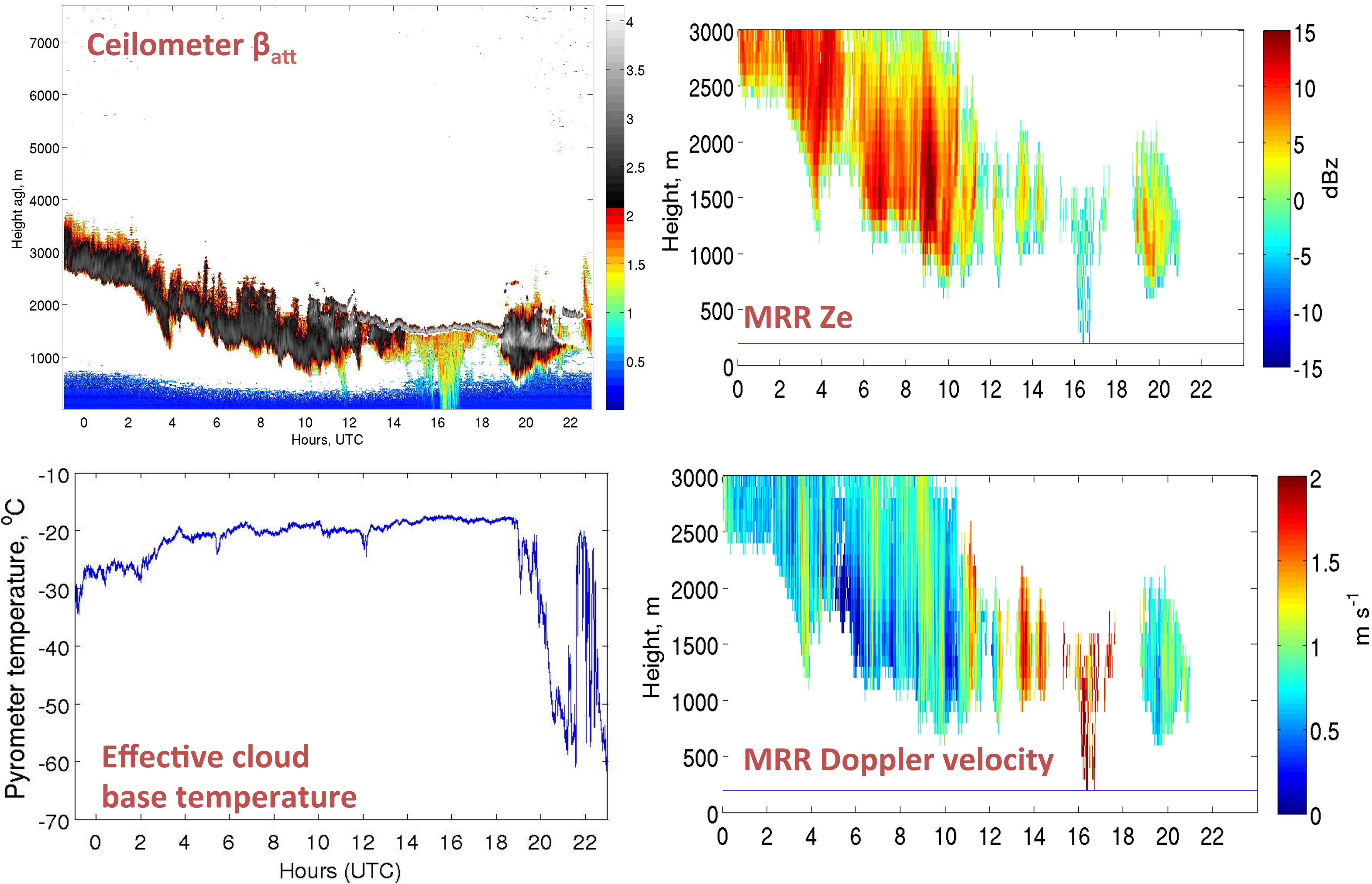
- ***Important also for Cloudsat, which misses the first 1-1.3 km above ground:***
- ***In this case virga will be considered as snowfall by Cloudsat and the shallow afternoon snowfall will be missed!***

Doppler velocity from MRR
(13 Feb 2012)



- *Doppler V = Particle fallspeed + air W*
- *Snowfall at PE: high V_{horiz} >> W => Doppler V ~ particle fallspeed*
- *Particle fallspeed = f(shape and size)*

13 February 2012 case:
ice cloud, virga, mixed phase cloud, snowfall

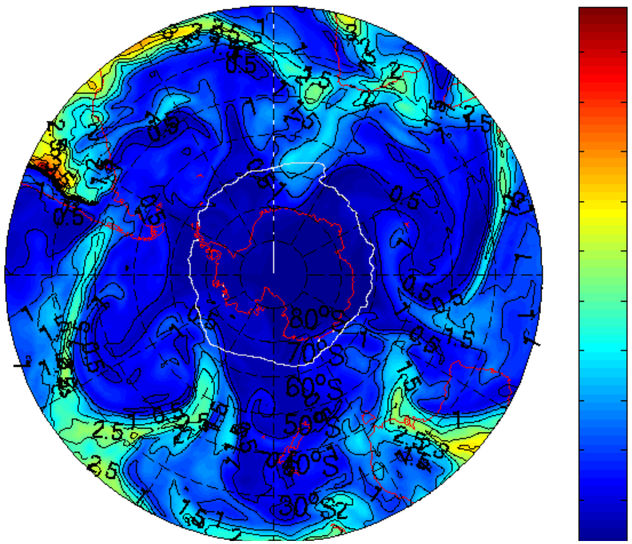


Case/process studies

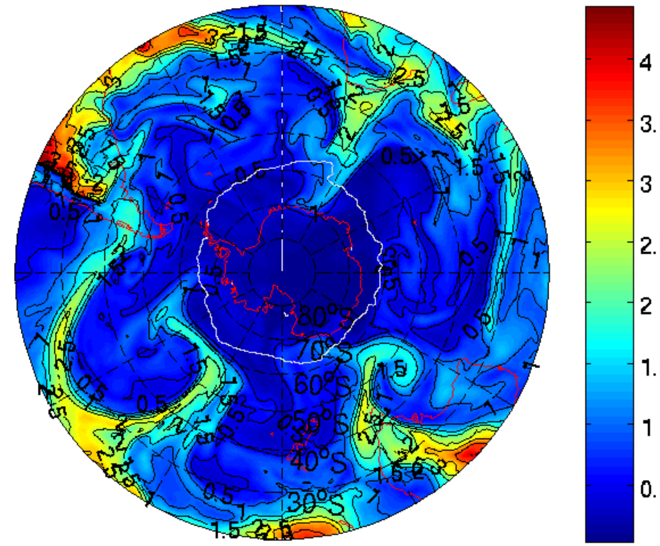
- **Case 2: 6 Nov 2012 - atmospheric river with extreme precipitation and accumulation**

Two days identified as one continuous AR event (Gorodetskaya et al. 2014, GRL)

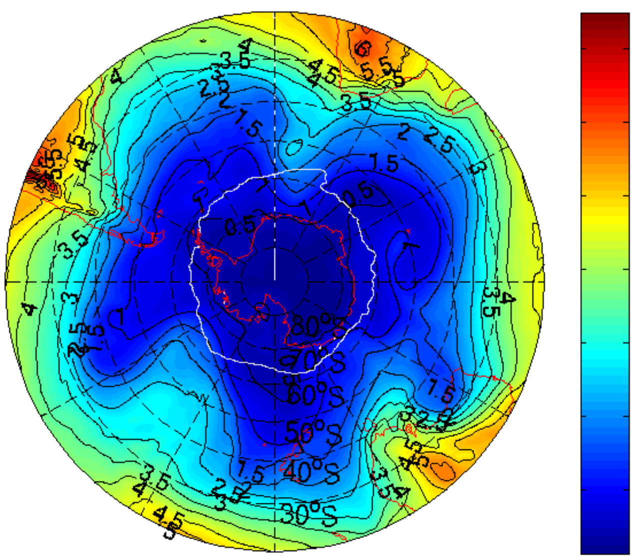
IWV for 20121105



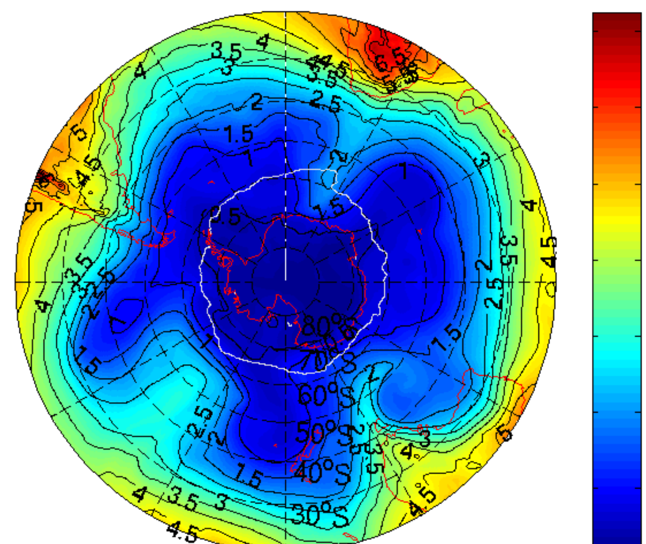
IWV for 20121106



Saturated IWV for 20121105

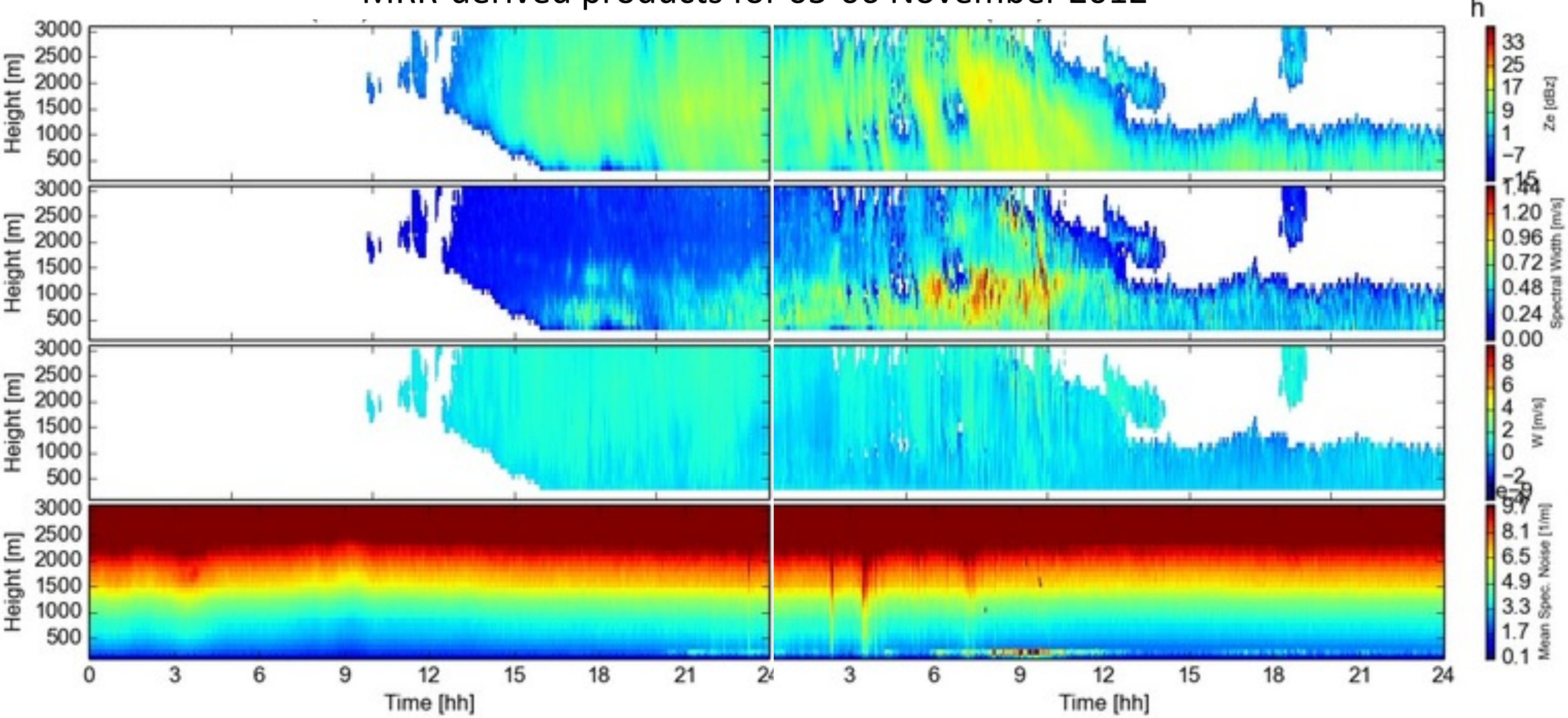


Saturated IWV for 20121106



Much stronger precipitation during an AR event

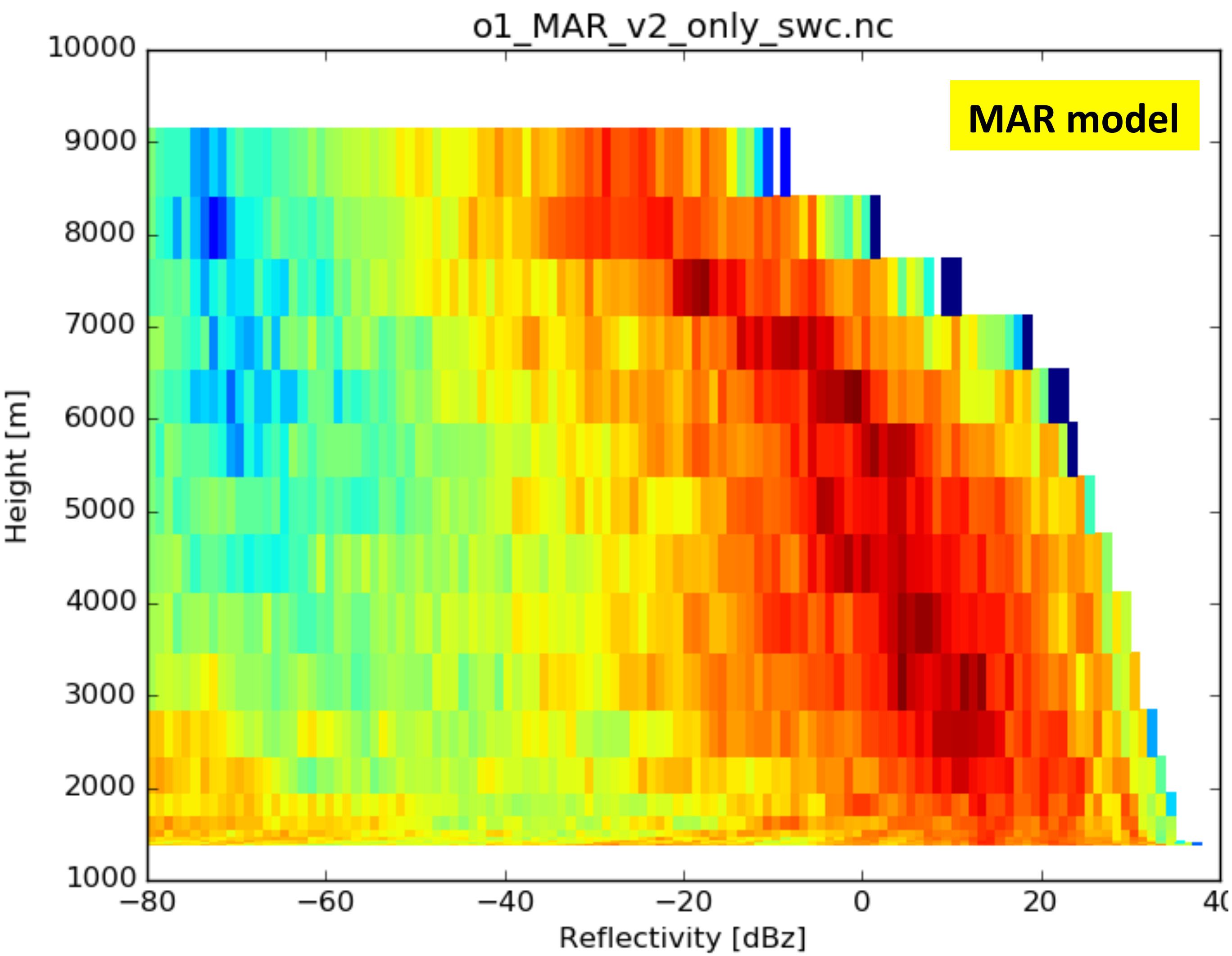
MRR-derived products for 05-06 November 2012



Raw data processing: Maahn and Kollias 2012)

Snowfall evaluation:

model-to-observations approach: comparing Ze from PE PE MRR and simulated by MAR model



Forward model PAMTRA – Passive and Active Microwave radiative transfer model

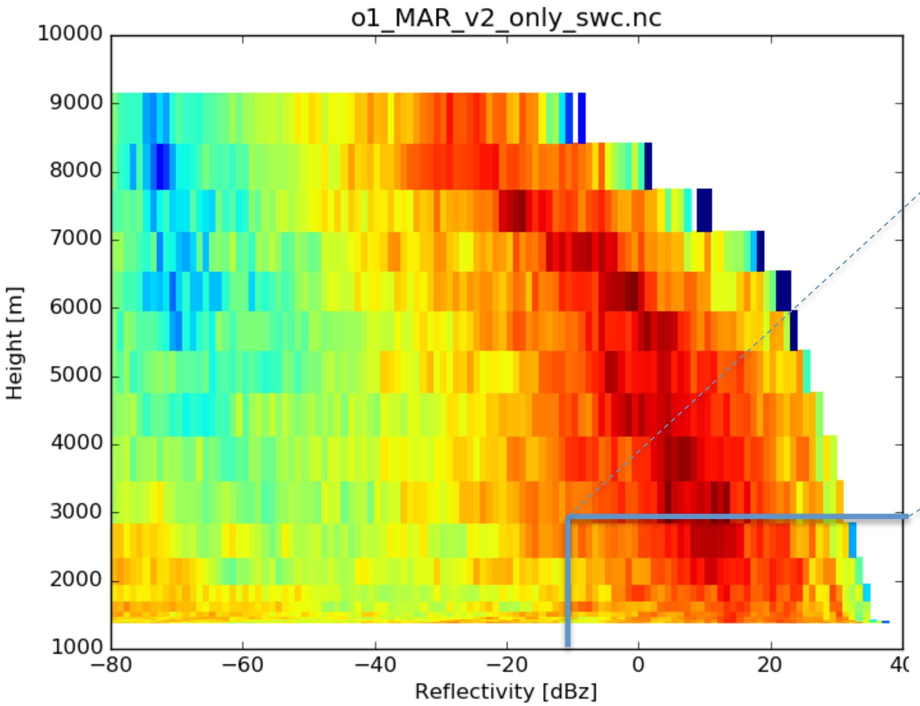
➢ Used to synthesize Ze at 24 GHz (MRR) for MAR model

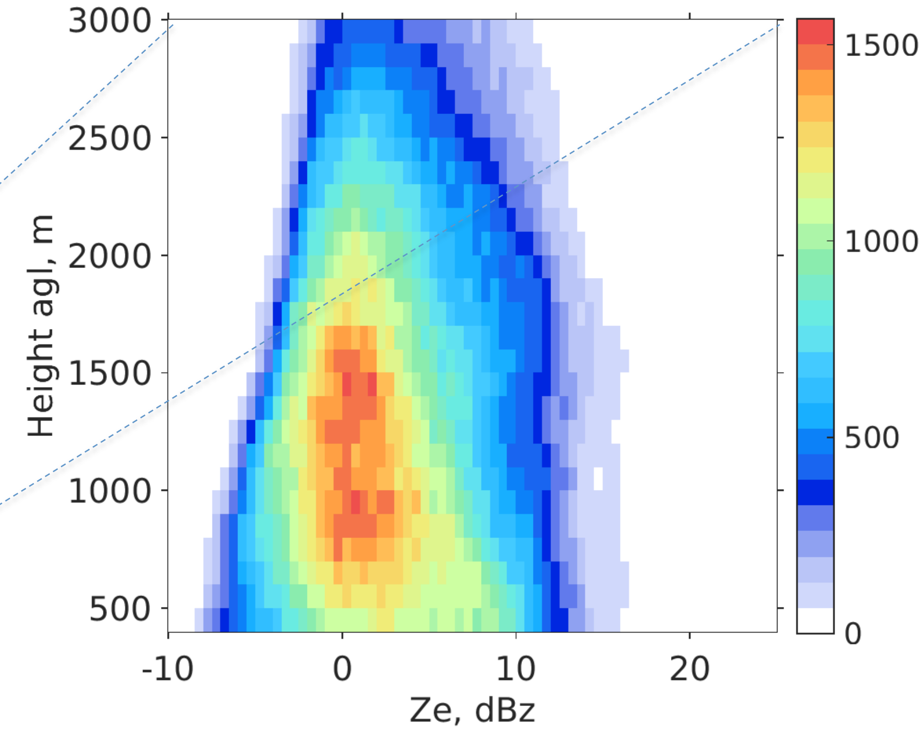
MAR parameters used:

- V(D) for snow based on graupel-like snow of hexagonal type from Locatelli&Hobbs (1974)
- m(D): fixed snow density = 100 kg m^{-3}
- Snowfall N(D): exp (Marshall-Palmer)

Snowfall evaluation:
model-to-observations approach: comparing Ze

MAR model





Ze forward-modeled using PAMTRA for MAR RCM snowfall (full model rage)

PE MRR Ze on 1-min scale during 2012
(from Gorodetskaya et al, Cryosphere 2015)

Conclusions

- Antarctic surface SMB is dependent on many processes => snowfall estimates are necessary for model evaluation and process understanding
- MRR measurements give an opportunity to obtain high-resolution estimates of snowfall rate and relate them to the snow accumulation on the ground
- Work is continued to reduce the uncertainty in the derived SR due to the range of possible Ze–S relationships => constrain Ze-S using SVI
- RCMs overestimate intense snowfall events => improve parameterizations
- Cloud properties can shed light to precipitation biases in models (tendency to overestimate snowfall and ice clouds – very fast conversion liquid to ice? Bergeron-Findeisen process in models – different parameterizations/parameters
- MAR BF process modification => improved results

Thank you for your attention!
Your questions and feedback are most welcome!

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