The Role of Atmospheric Rivers in East Antarctic Precipitation and Accumulation: Merging Remote Sensing Techniques and Modelling

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8th EGU Leonardo Conference: From evaporation to precipitation: the atmospheric moisture transport
Ourense, Spain, 25–27 October 2016

Antarctic surface mass balance:

SMB = S ± SUs – SUds ± TR – MR

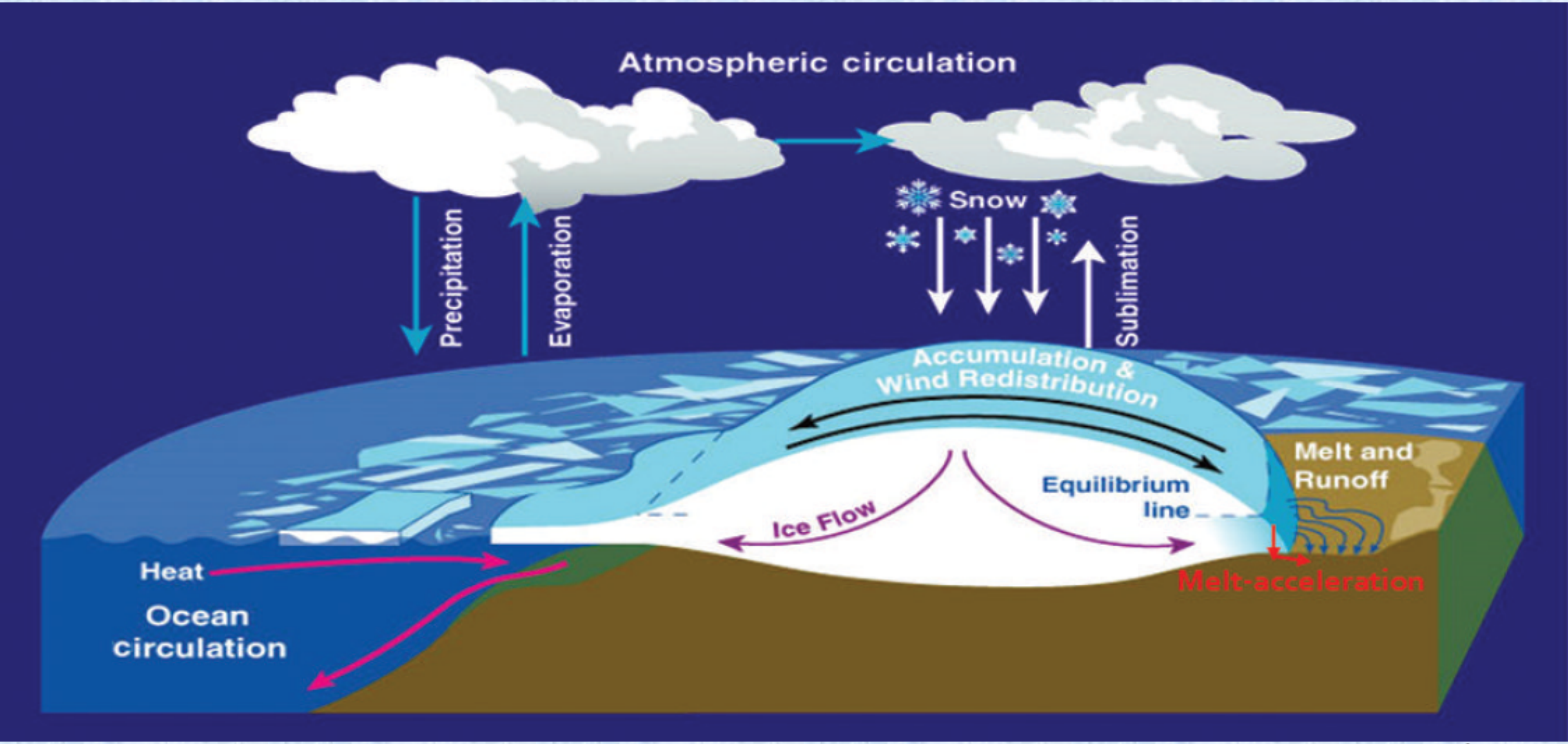
S = snowfall (+)

SUs = surface sublimation/deposition (+/-)

SUds = drifting snow sublimation (-)

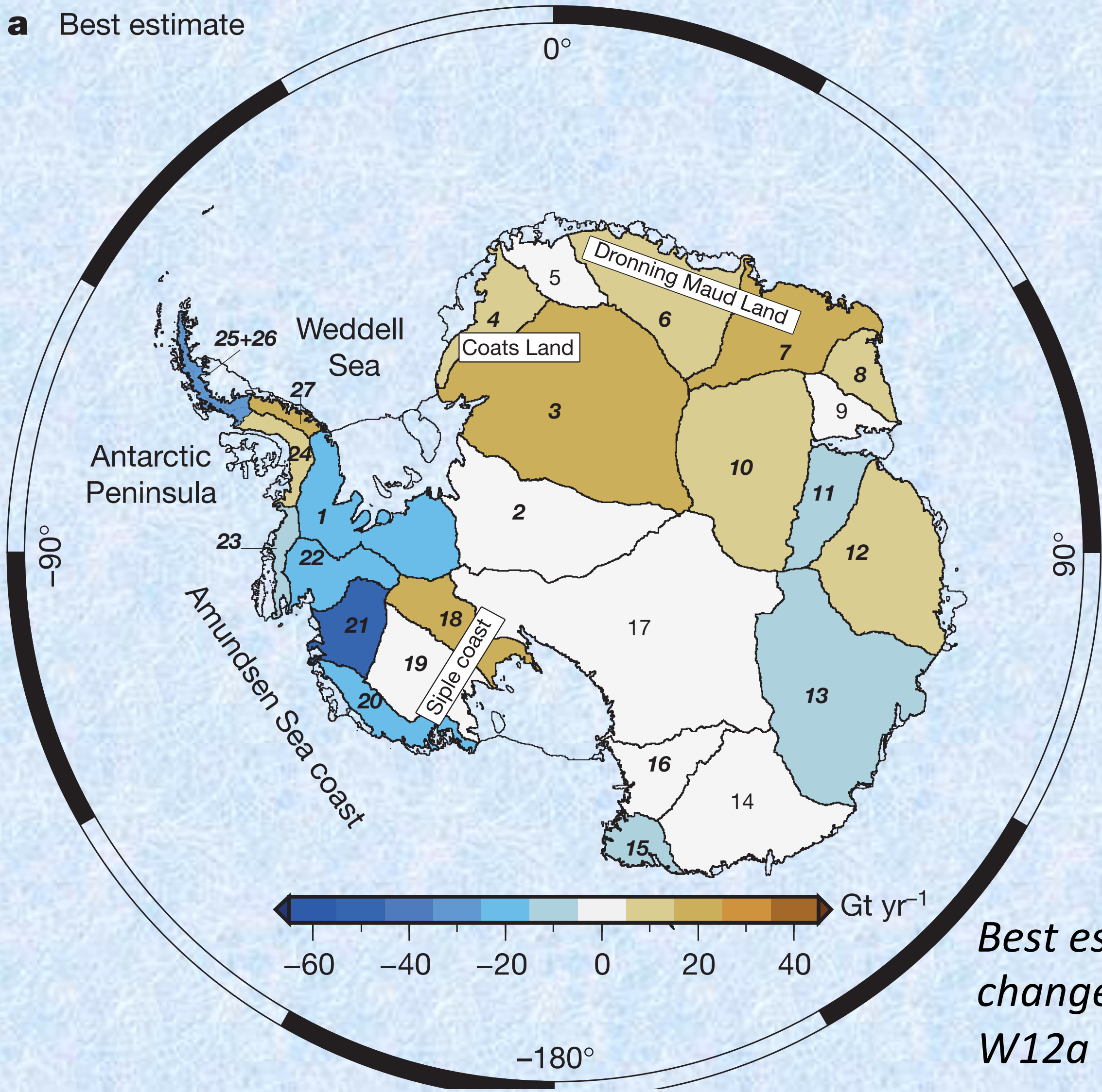
TR = erosion or deposition of snow due to the wind-driven transport (+/-)

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

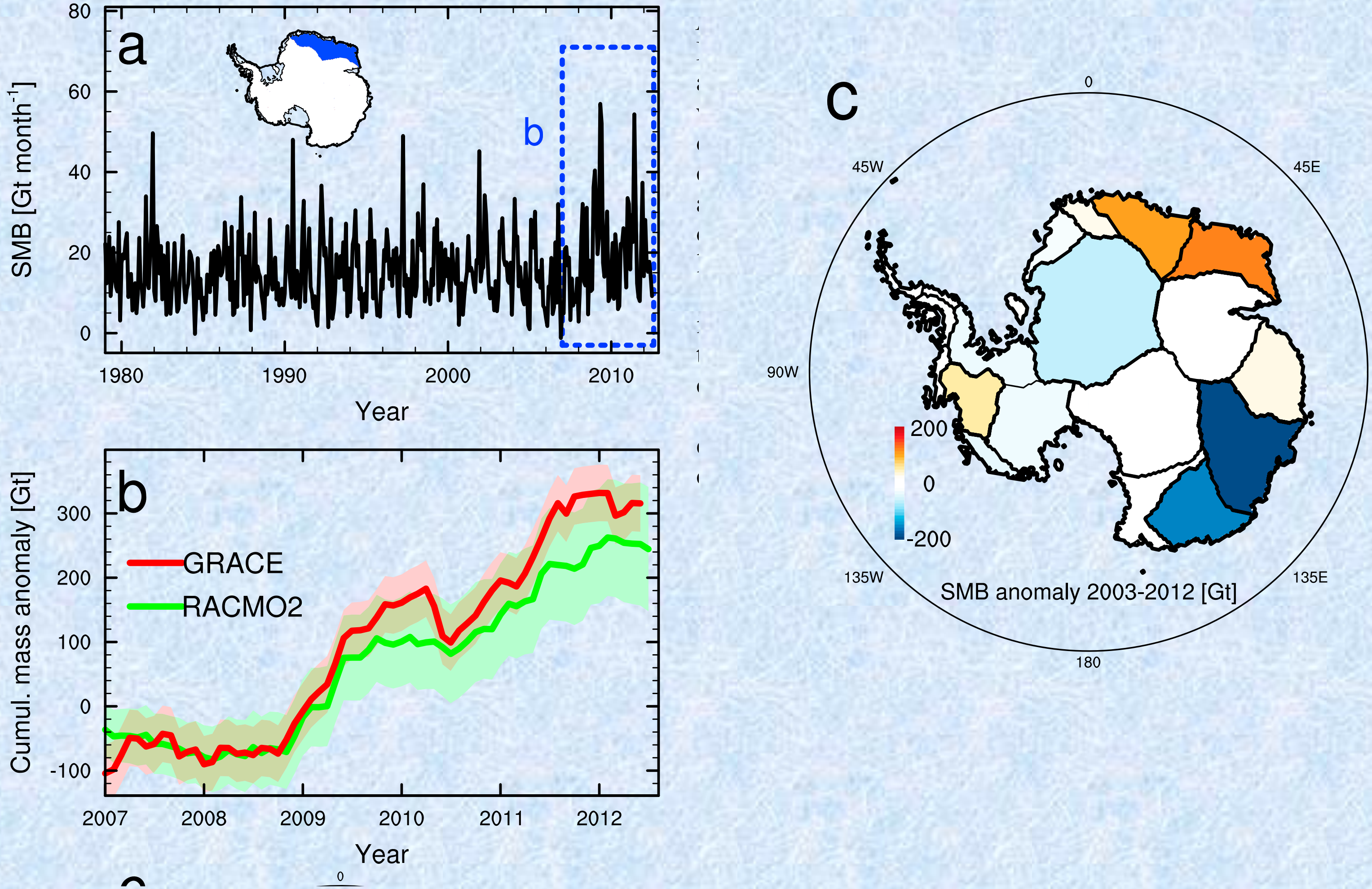
- Mass **loss**: mostly in Amundsen sea basins

- 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)

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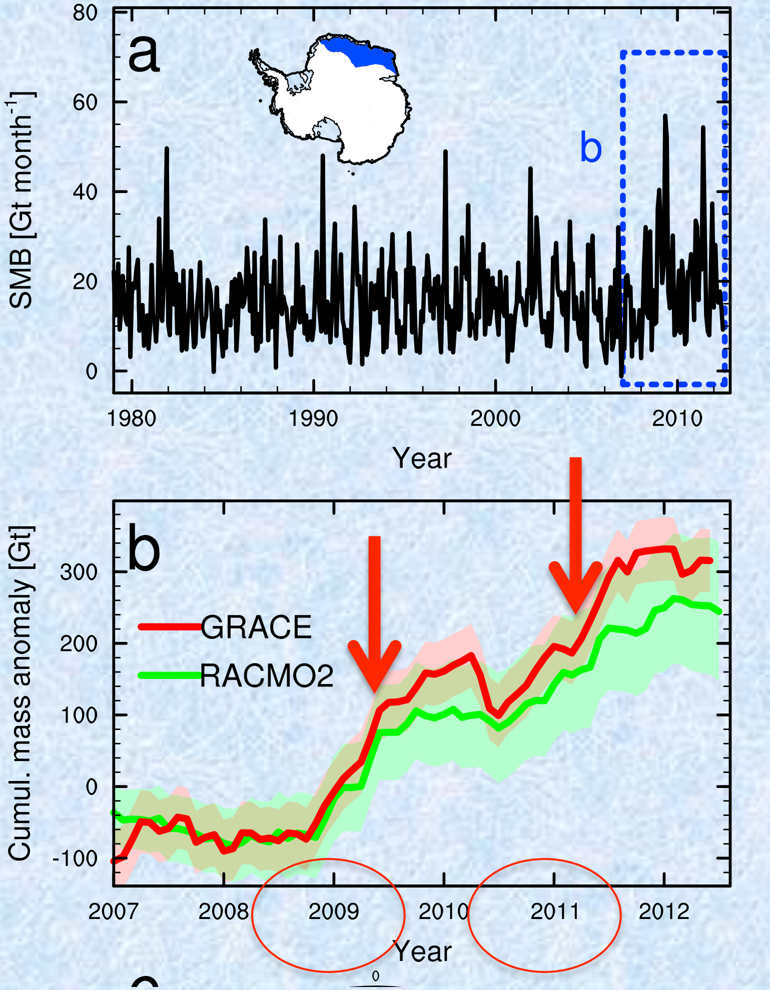
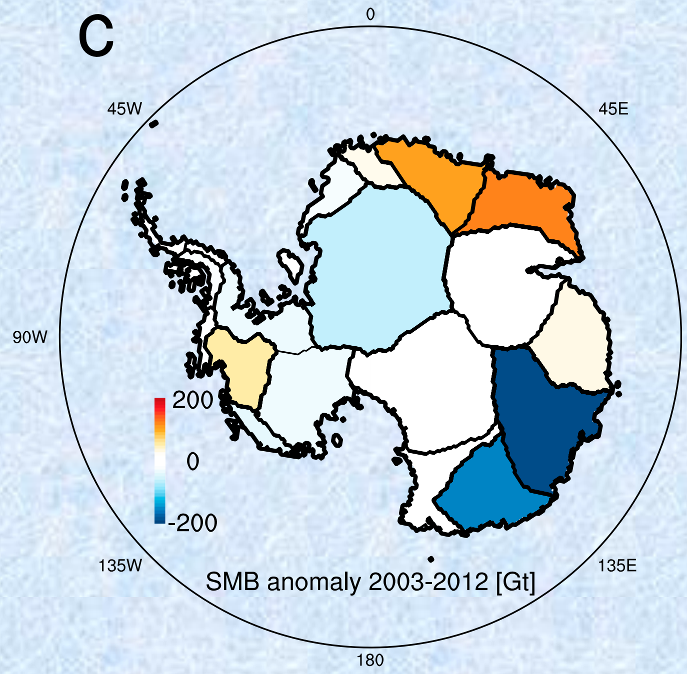
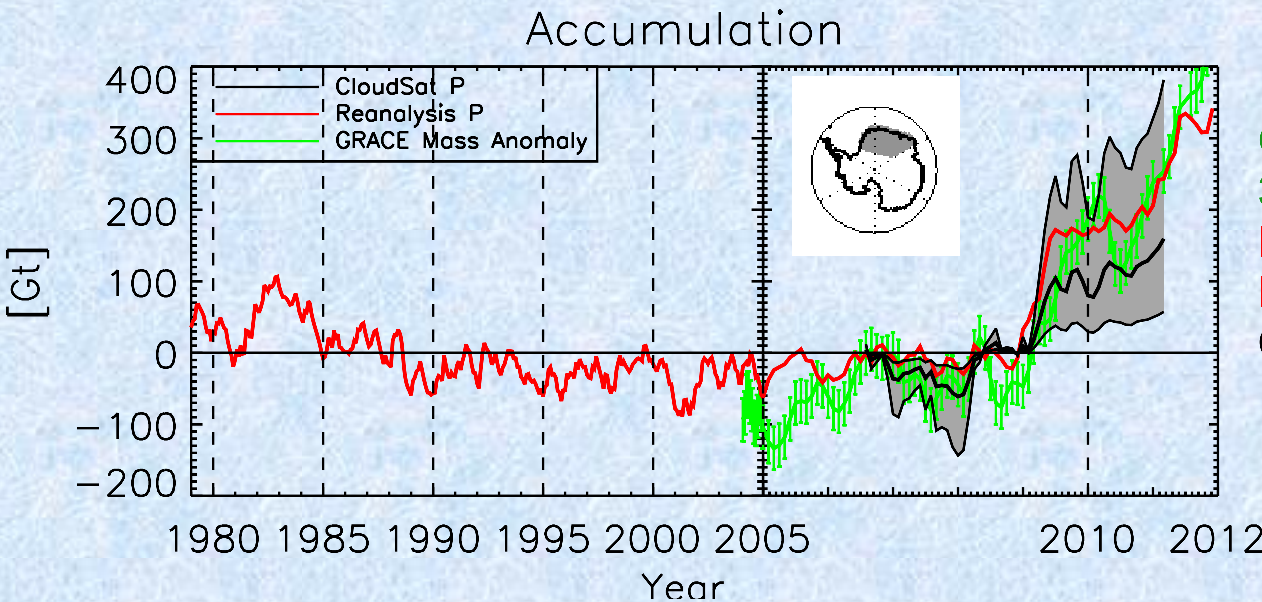




Lenaerts et al. (2013)

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

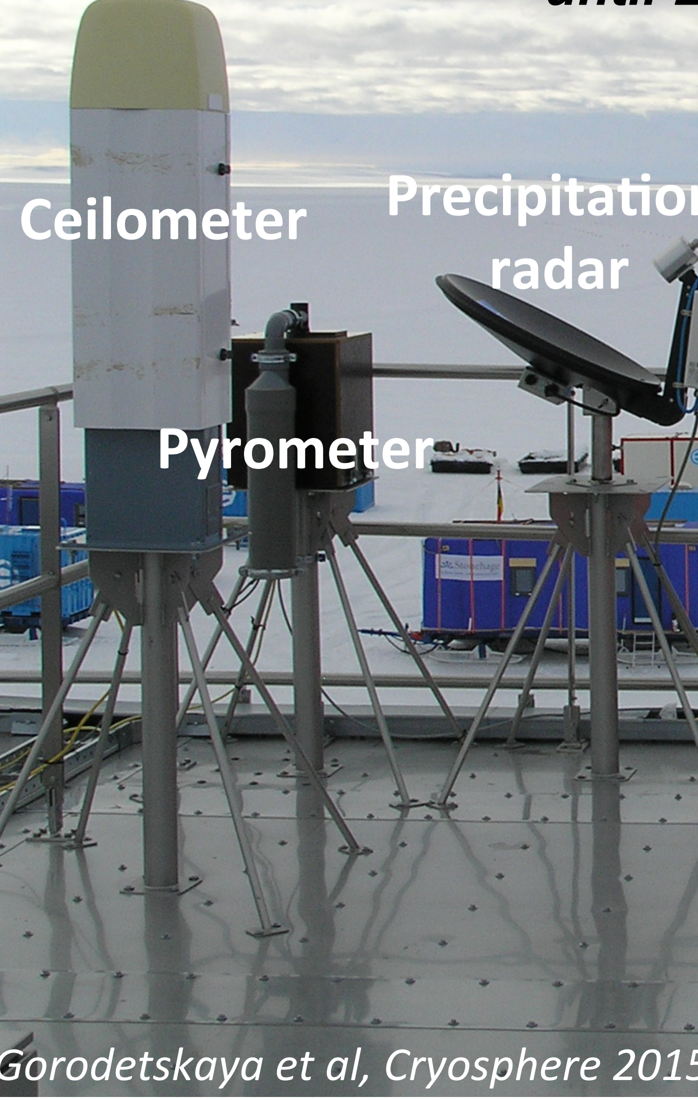
GRACE mass average over 30W-60E, 65S-80S
Integrated net precipitation (ERA-Interim)
CloudSat accumulated snowfall

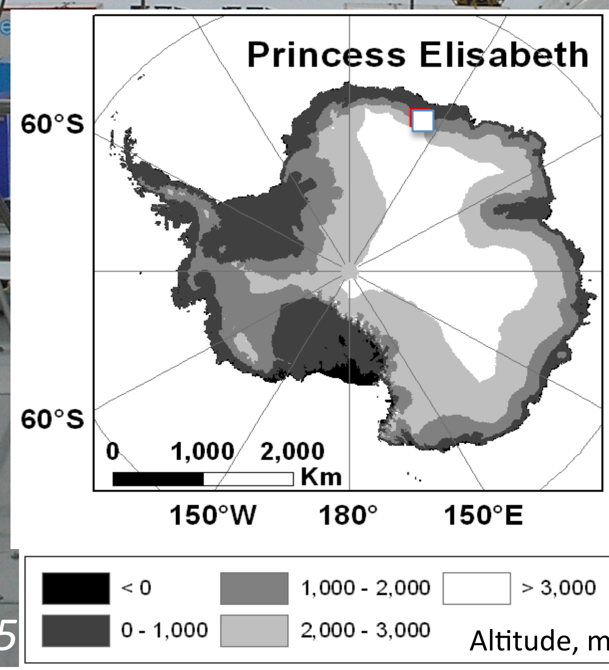
Meteorology-cloud-precipitation observatory at Princess Elisabeth base in Dronning Maud Land, East Antarctica

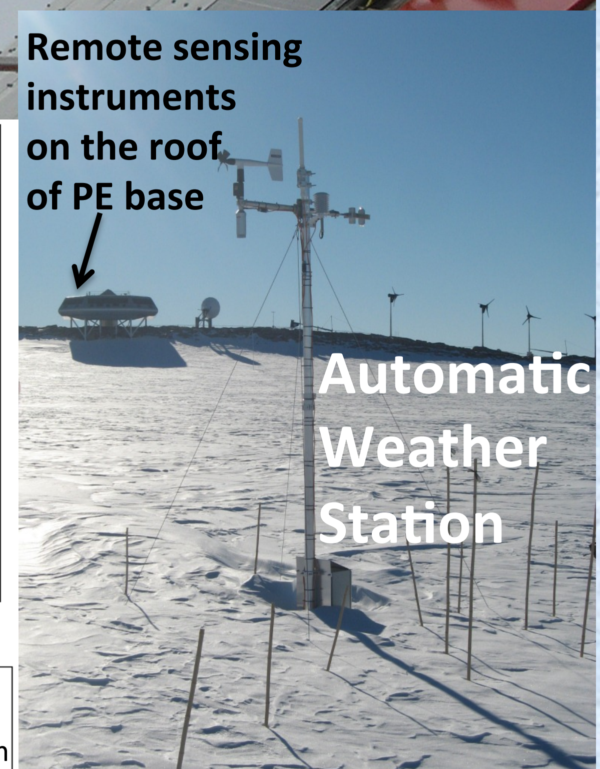
installed within the Belspo HYDRANT project ***in 2009-2010***

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

until 2018 *(and hopefully beyond)*







Gorodetskaya et al, Cryosphere 2015

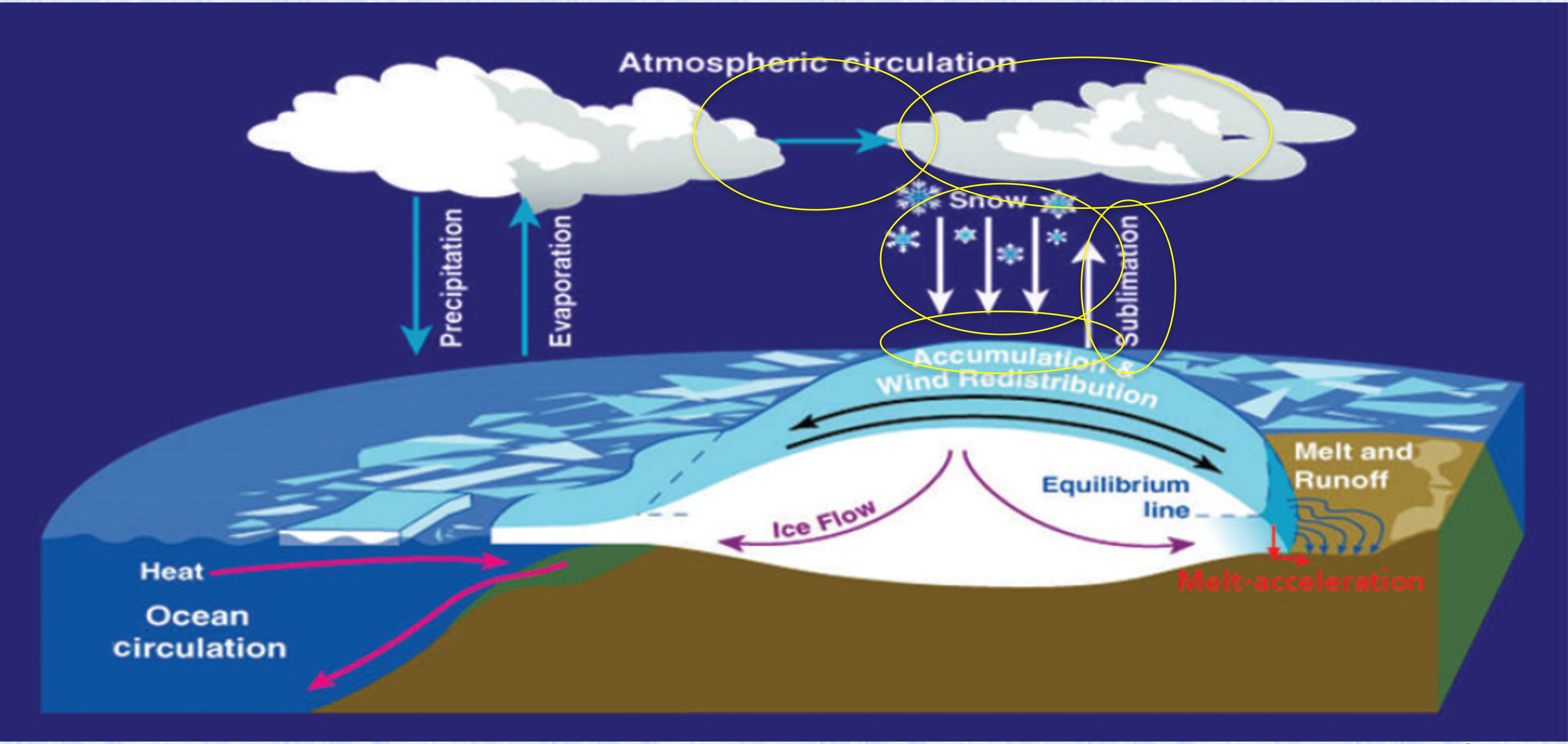
Antarctic surface mass balance:

SMB = S ± SUs – SUds ± TR – MR

Project HYDRANT (now continued as AEROCLOUD)

The atmospheric branch of the hydrological cycle in Antarctica

funded by the Belgian Science Policy



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

HYDRANT/AEROCLOUD Ground-based measurements: remote sensing

http://ees.kuleuven.be/hydrant/aerocloud/instruments/

Cloud properties

- pulsed diode laser in near IR (910nm)
- vertical backscatter profiles and cloud base height detection up to 7.5 km

- range resolution = 10m
- report interval = 15s (transfer time of accumulated signal)
- PT algorithm for polar cloud detection/cloud base height (Van Tricht et al AMT, 2015)

- passive radiometer: equivalent blackbody brightness temperature in 8-13 micron atm window

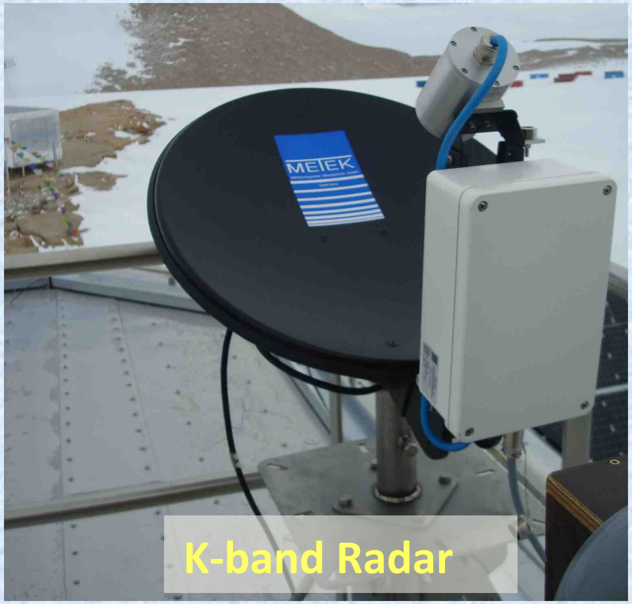
⇒effective cloud base temperature (assuming ε=1)

Gorodetskaya et al, Cryosphere 2015

HYDRANT/AEROCLOUD Ground-based measurements: remote sensing

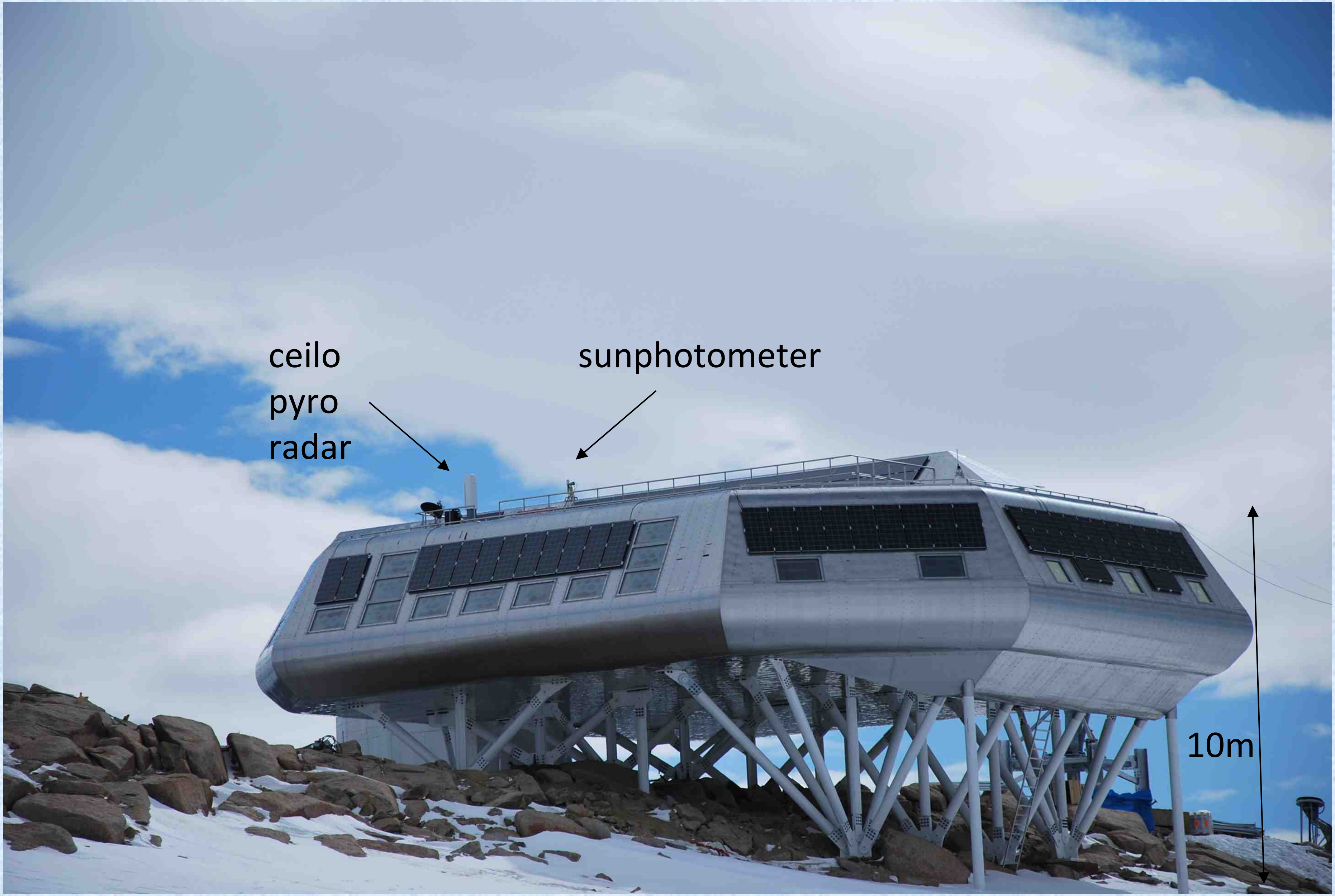
http://ees.kuleuven.be/hydrant/aerocloud/instruments/

Snowfall rate

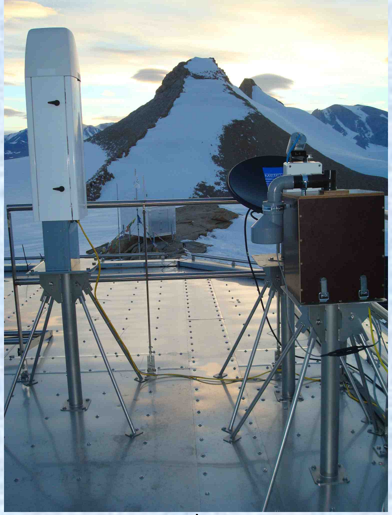


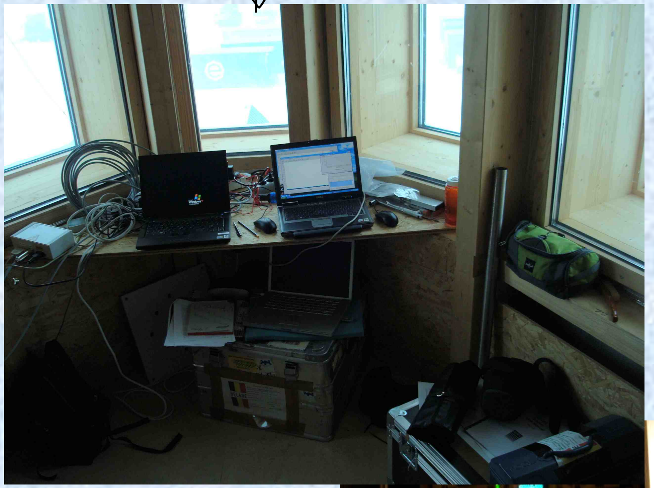
- 24 GHZ FM-CW Doppler radar
- Vertically (!) pointing
- Vertical reflectivity profile up to 3500m at 100m range resolution
- Reflectivity from hydrometeors (drifting snow, falling snow)
- profile information:
  depth of the layer in which snow is present
- distinguish events where only blowing snow was present from precipitation events

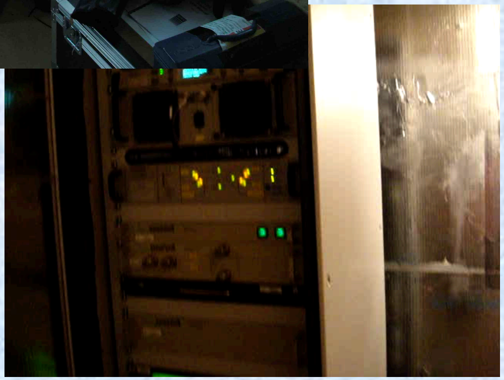
Gorodetskaya et al, Cryosphere 2015; Maahn et al JGR 2014 (Cloudsat blind zone eval)


ceilo
pyro
radar
sunphotometer
10m

Data flow..



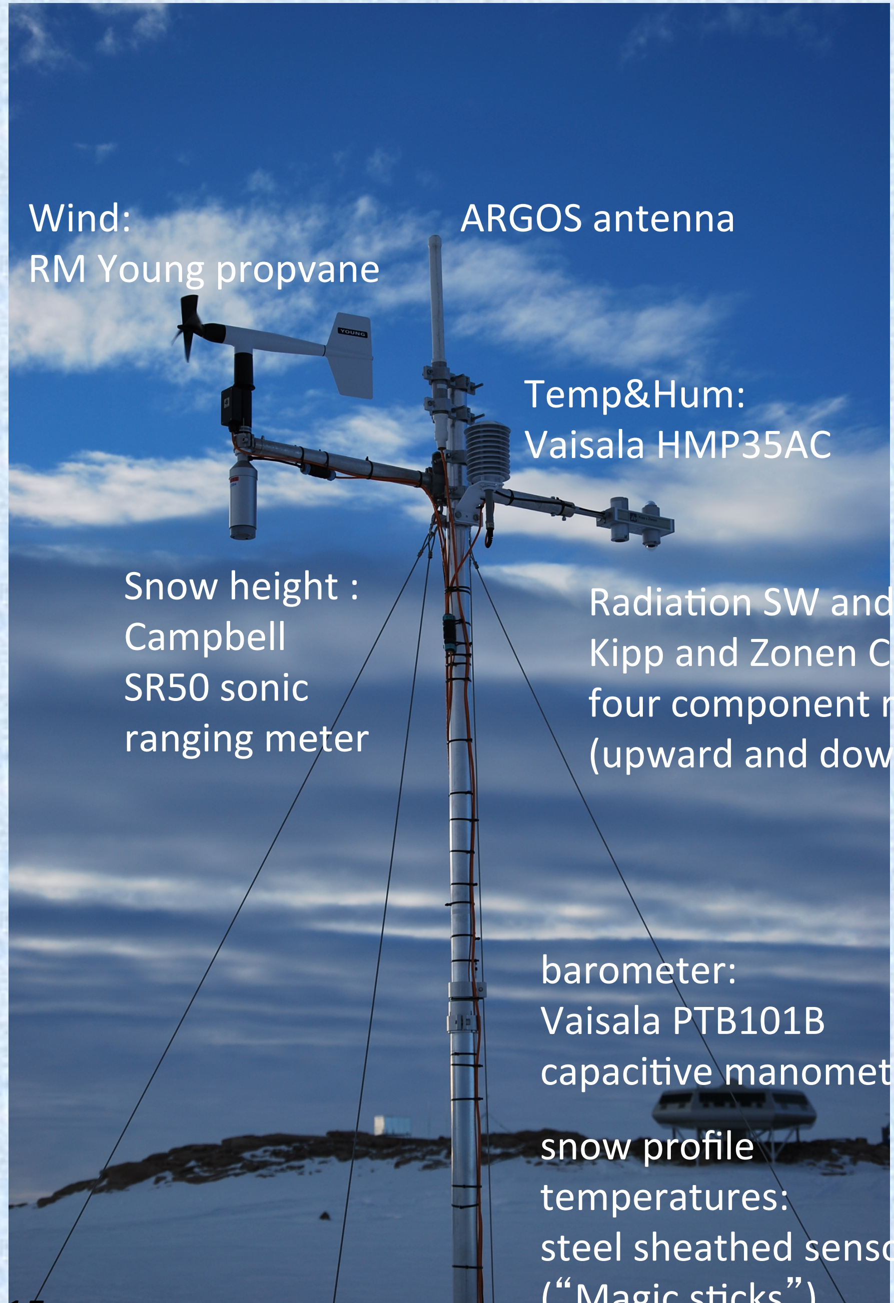




KU Leuven, Belgium...

Automatic Weather Station :

- **AWS16 designed by IMAU** (Utrecht University, The Netherlands)
- **Installation and maintenance by KU Leuven and RMI**
- **Installation: February 2009**
- **Instrument infromation:** http://ees.kuleuven.be/hydrant/aerocloud/instruments/
- **Real time meteo:** https://www.projects.science.uu.nl/iceclimate/aws/



Gorodetskaya et al, JGR 2013, Cryosphere 2015

AWS16 at Utsteinen:
300m east of the PE base

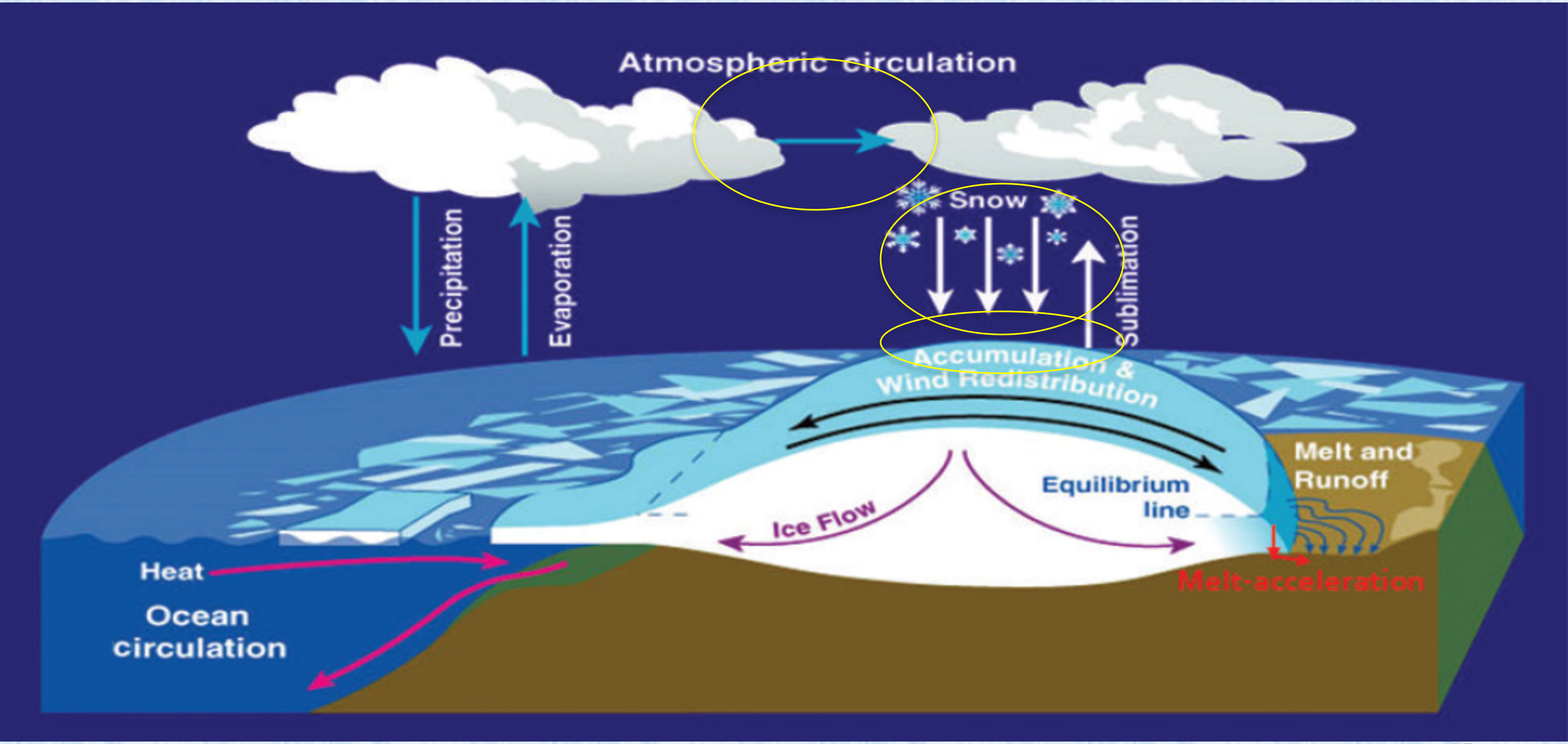
Antarctic surface mass balance:

SMB = S ± SUs – SUds ± TR – MR

Project HYDRANT

The atmospheric branch of the hydrological cycle in Antarctica

funded by the Belgian Science Policy



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

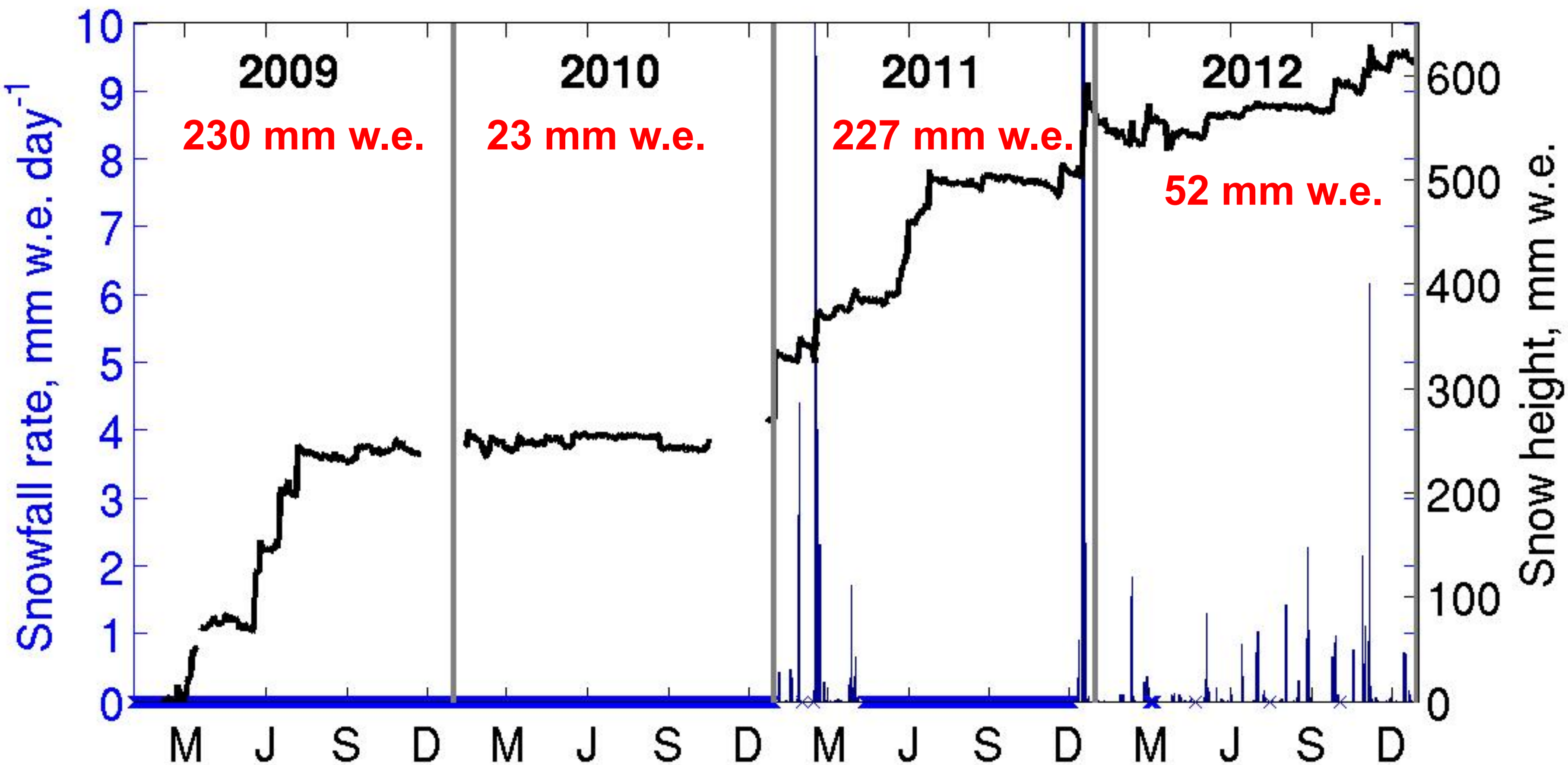
2009 and 2011:

Two anomalously high accumulation years (annual total 230 and 227 mm w.e.)

Compare:

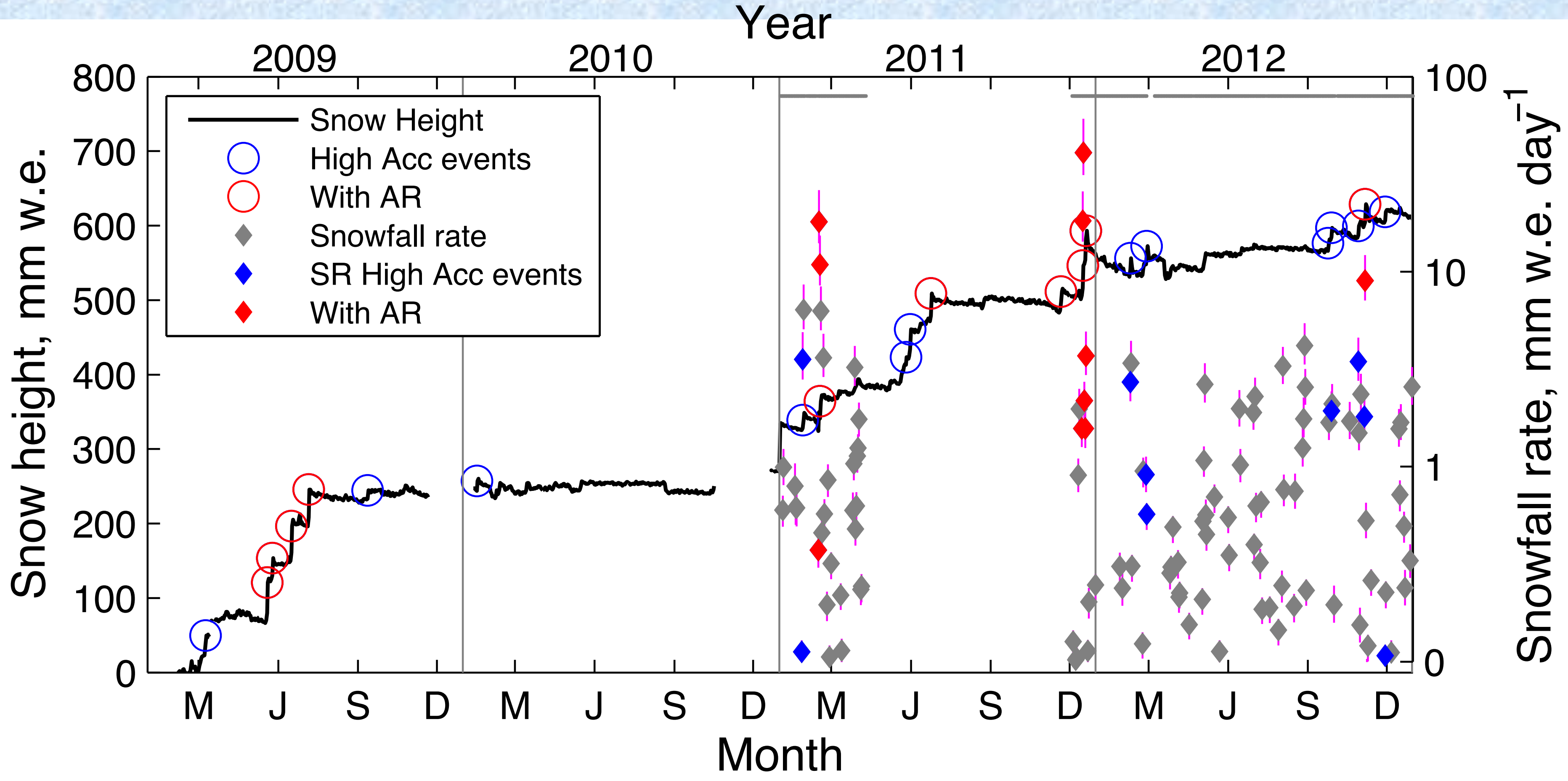
long-term stake measurements in the vicinity of Sør Rondane mountains

=> year total accumulation **~50-150 mm w.e.** (Takahashi et al. 1994)



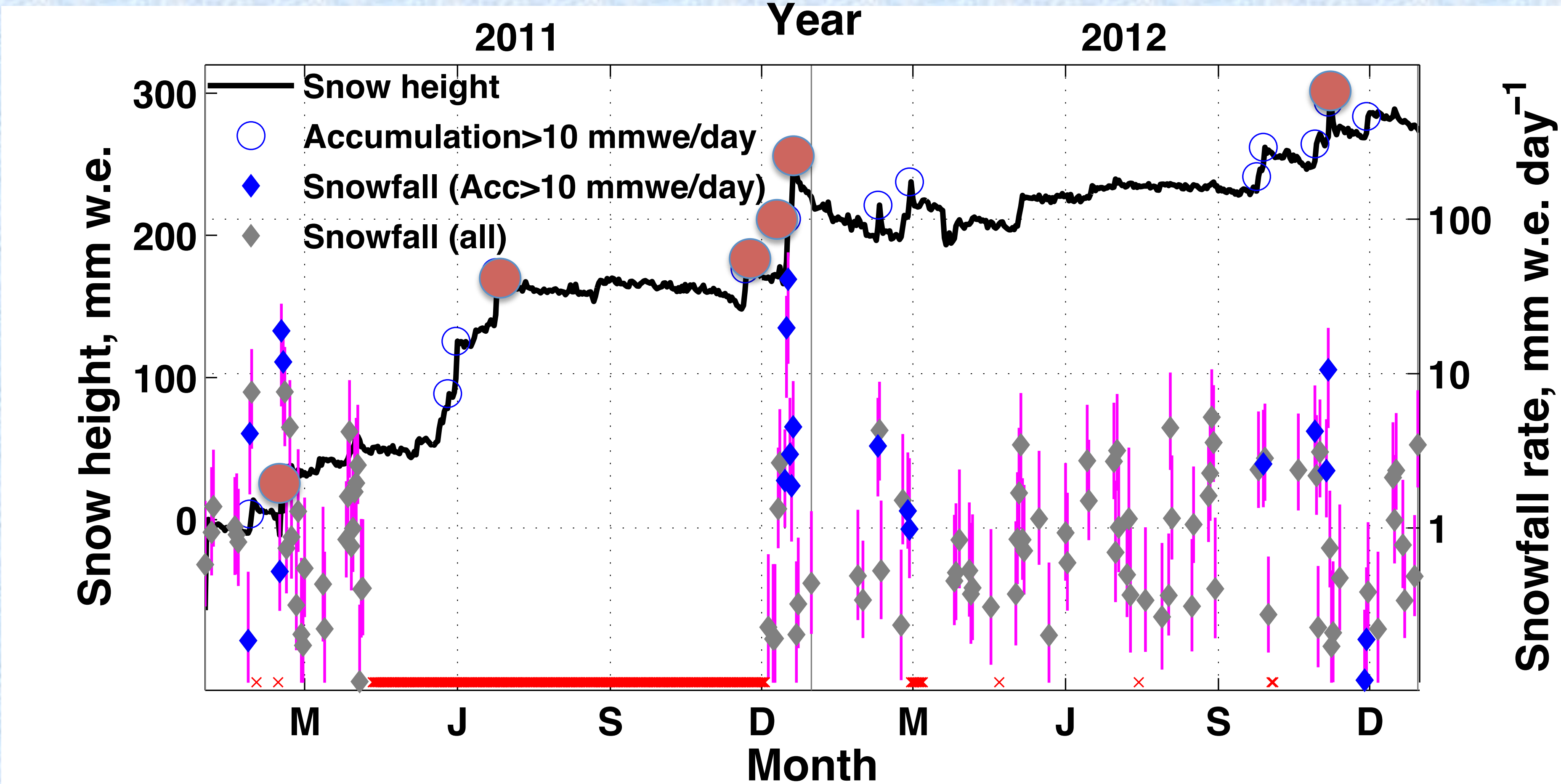
Daily snow accumulation (black line) and snowfall rate (blue bars) at PE during 2009-2012

Snow height and snowfall rate during 2009-2012



Gorodetskaya et al. 2014, GRL

Daily snowfall and snow height:
extreme events = atmospheric rivers



- *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)*

Defining AR events in East Antarctica...

Defining AR events in East Antarctica

- Low temperature saturated air condition:

$$IWV_{sat} = \int_{900}^{300hPa} q_{sat}(T)dp$$

- IWV > threshold depending on IWV_{sat}
(~1 cm IWV at 70°S)

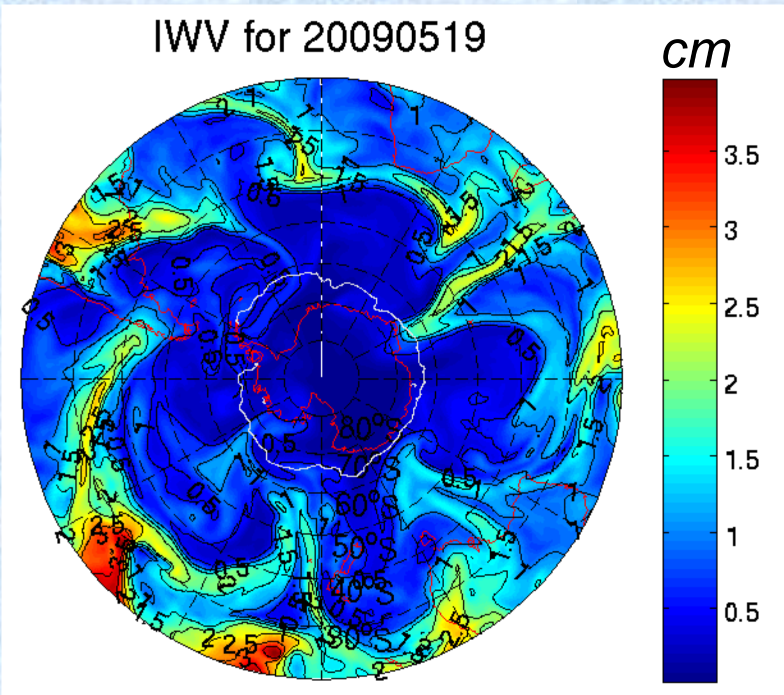
- Extends at least 20° lat (> 2000 km)

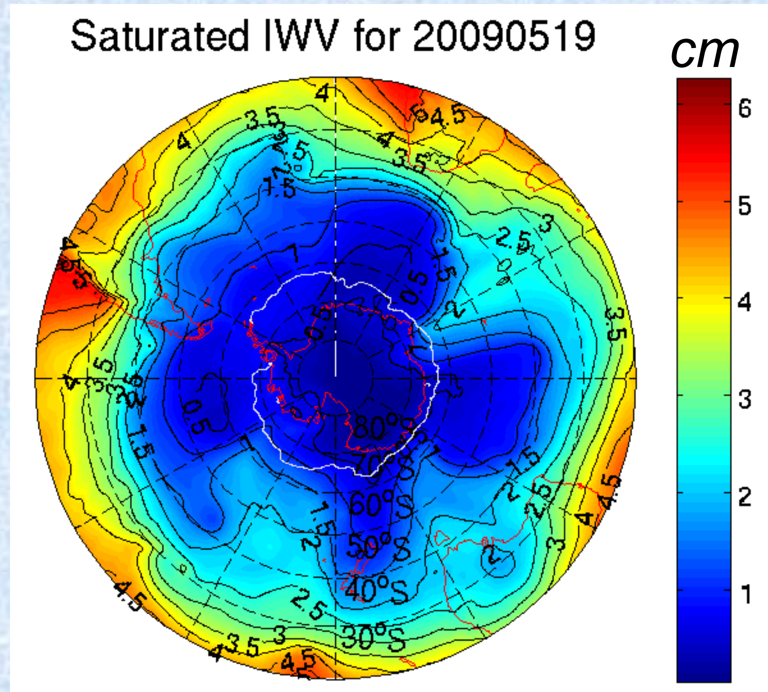
using ERA-Interim re-analysis data

Gorodetskaya, et al., GRL 201

Identifying Antarctic ARs:

1) **Maps of IWV and IWV_{sat} are calculated for each day 2009-2012 using ERA-Interim**





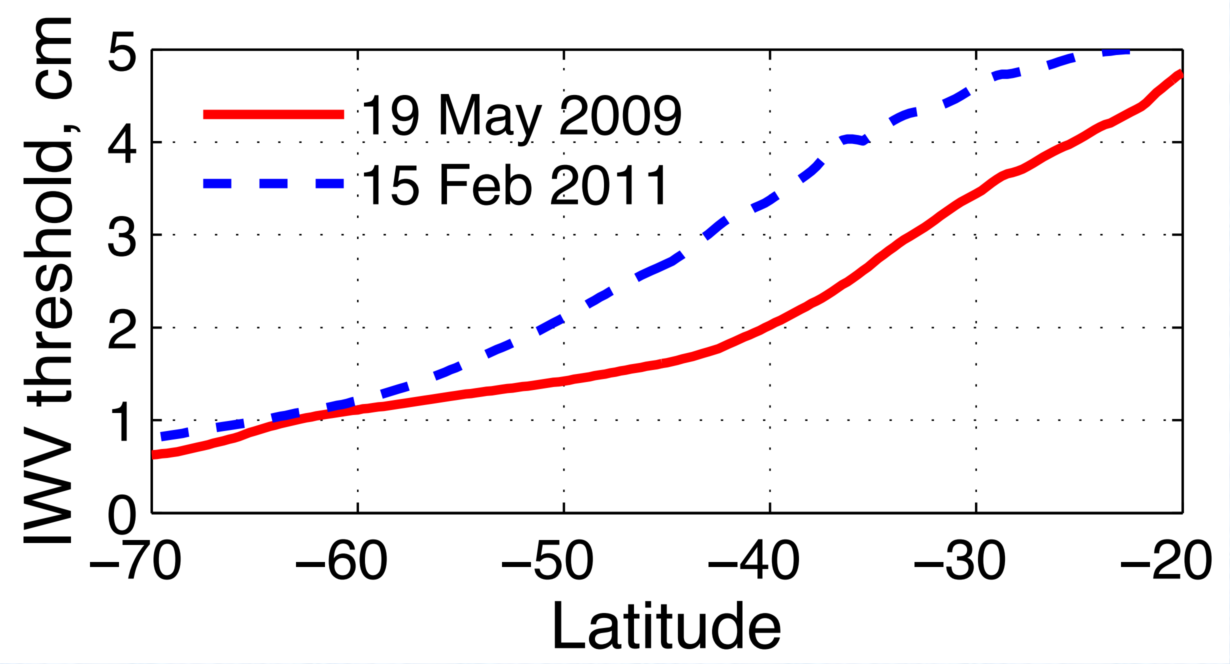
grey line = daily mean 50% sea ice concentration

Identifying Antarctic ARs:

2) IWV threshold to find excessive IWV within ARs is calculated for each latitude:

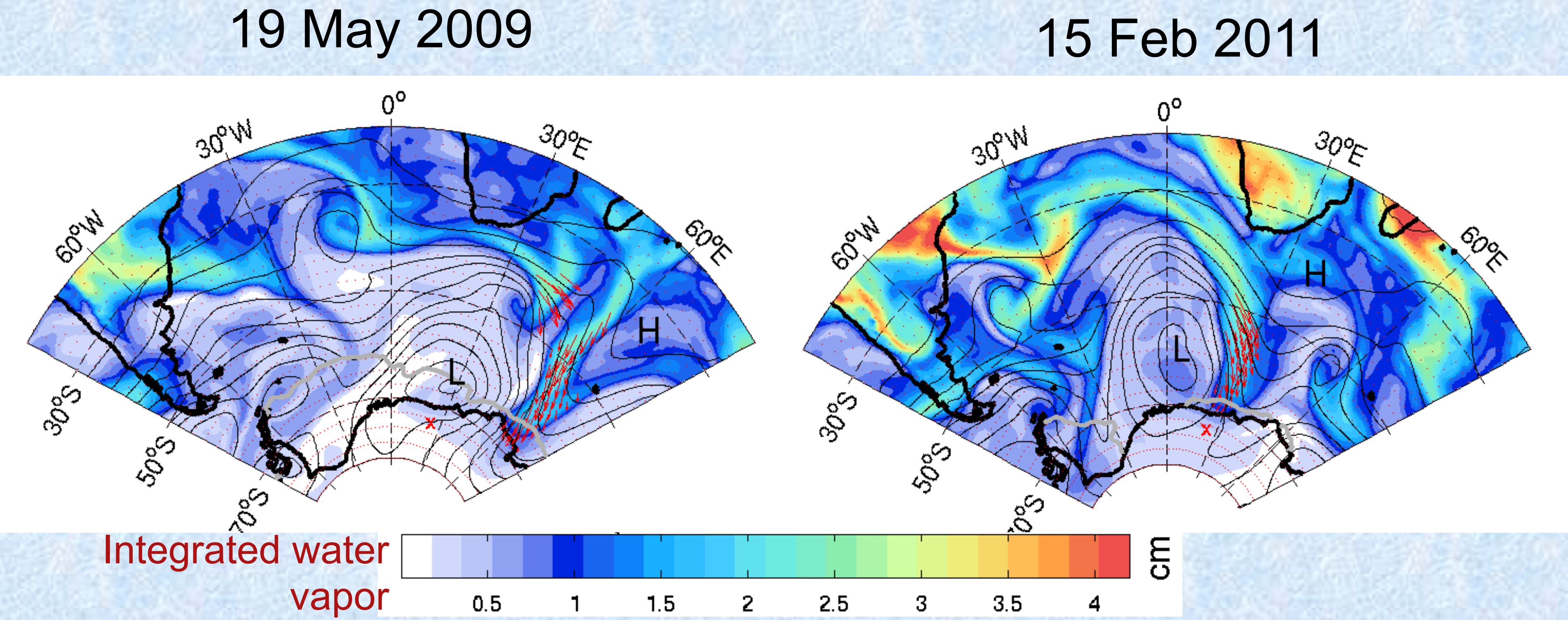
$$IWV_{thresh} = IWV_{sat,mean} + AR_{coeff}(IWV_{sat,\max} - IWV_{sat,mean}),$$

AR_{coeff} determines relative strength of an AR (= 0.2 in this study)



- ***Instead of using a fixed threshold of 2 cm suitable for mid-latitudes (Ralph et al. 2004), our IWV threshold varies with latitude depending on the temperature and saturation capacity***

Atmospheric rivers identified using a new definition adapted for Antarctica



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)*

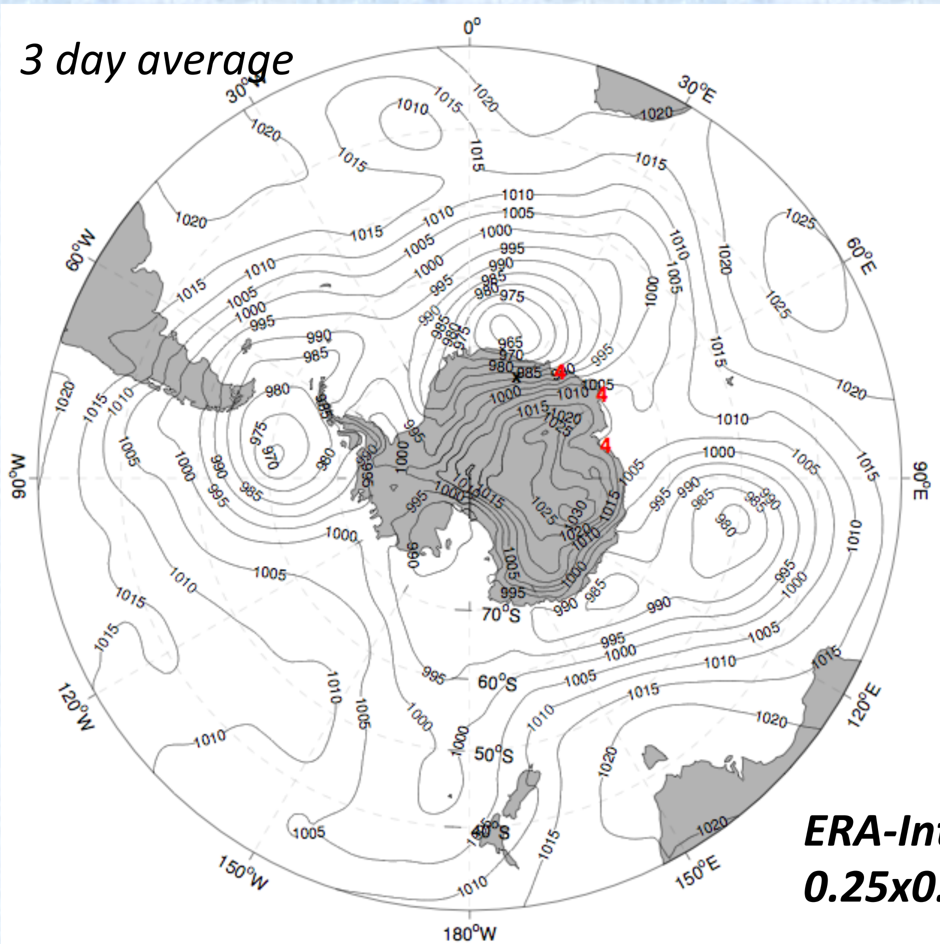
Mean sea level pressure composites

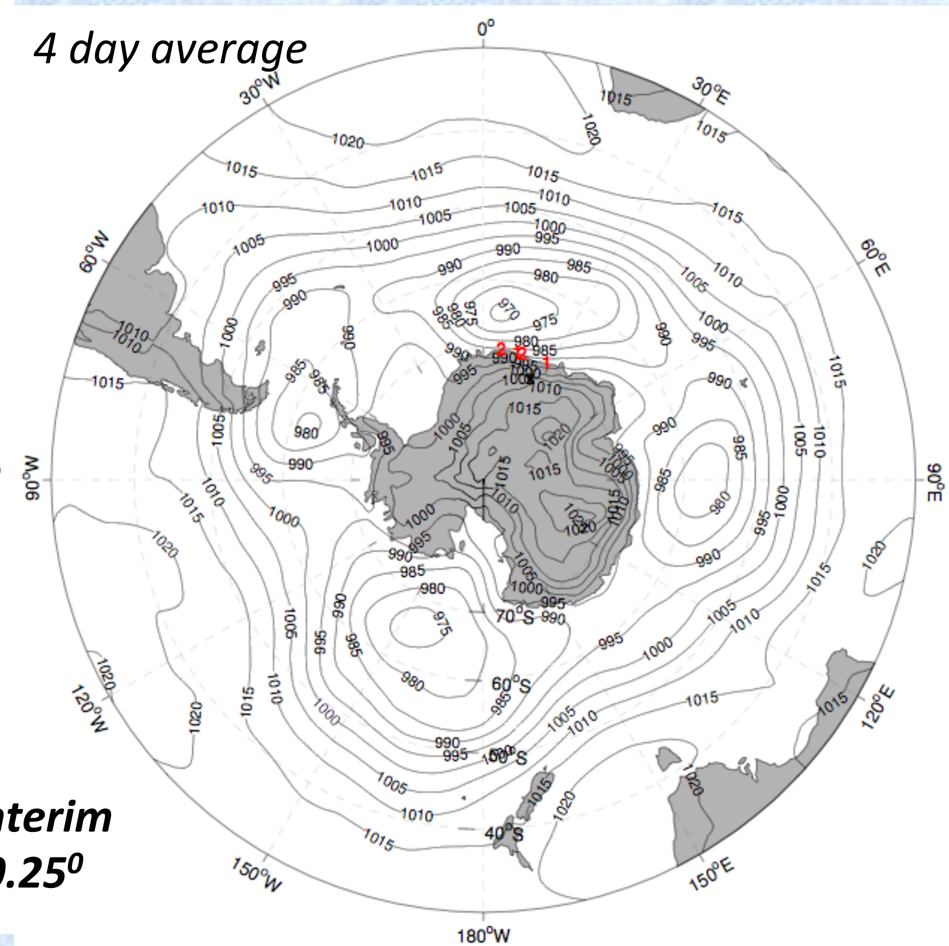
HIGH accumulation events

2009

SMALL accumulation events

2010





ERA-Interim
0.25x0.25⁰

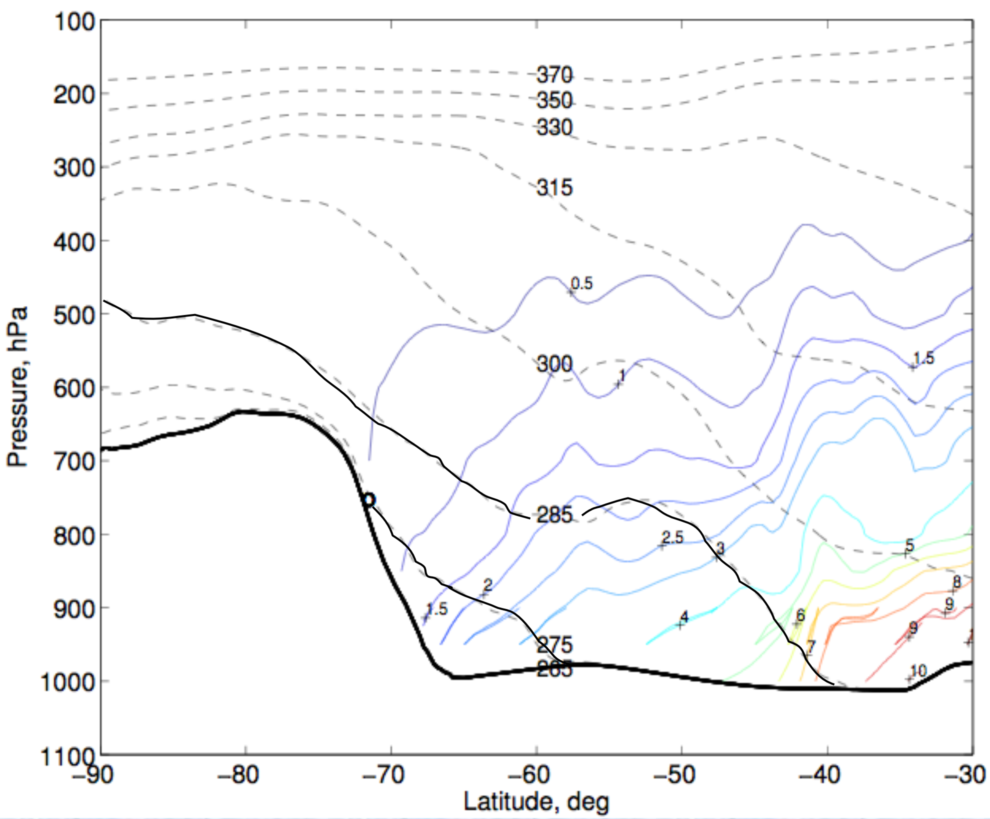
Gorodetskaya et al (AMOMFW 2011)

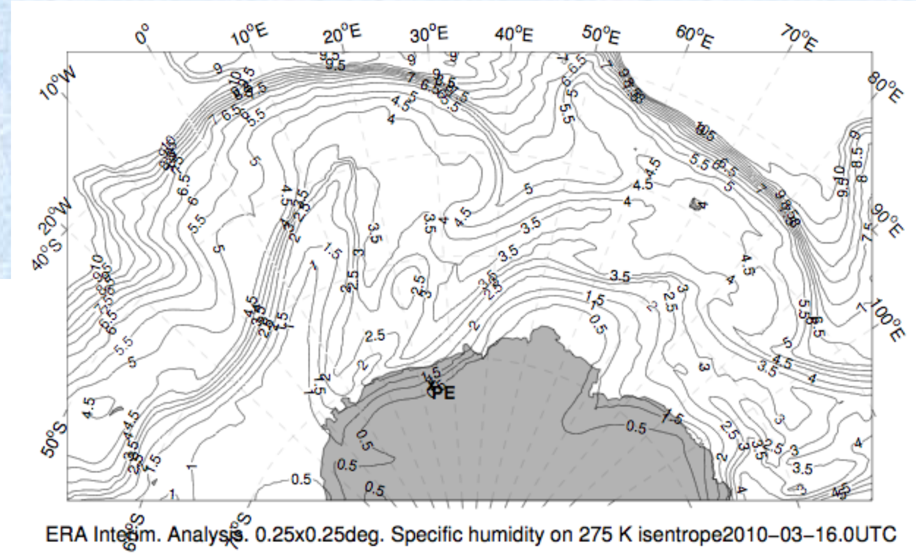
Isentropic analysis for selected positive accumulation days during warm events

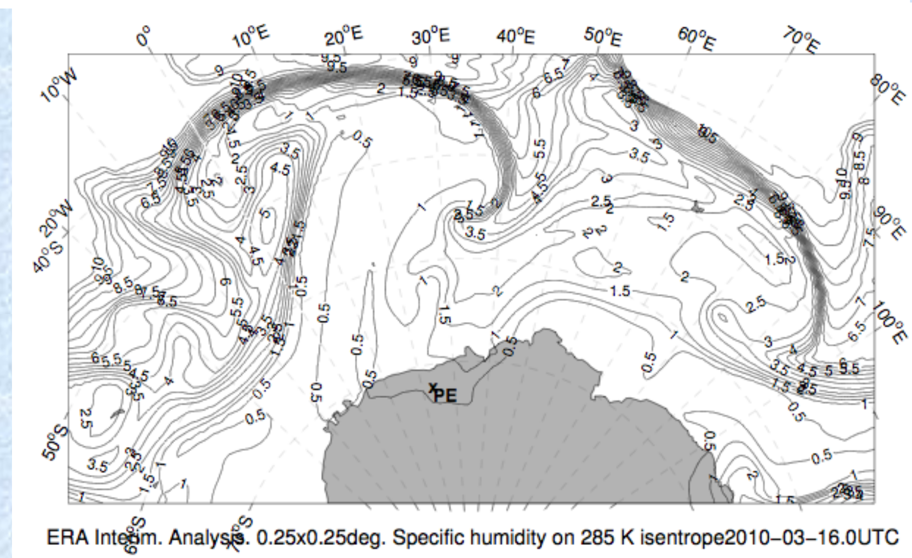
1. High accumulation:
May 19, 2009: 40 mmwe/day

2. Small accumulation:
March 16, 2010: 0.3 mmwe/day

Isentropic analysis for LOW accumulation event (march 16, 2010)







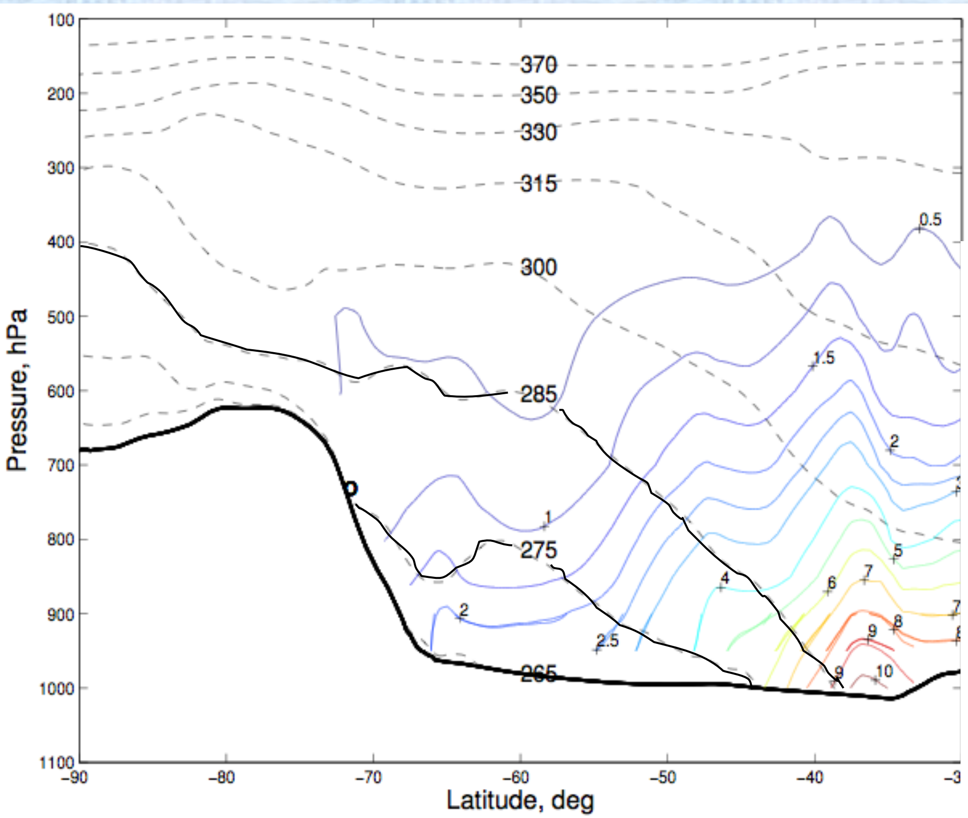
Mean meridional cross-section (20-60^{0}E) of isentropic surfaces with specific humidity color contours

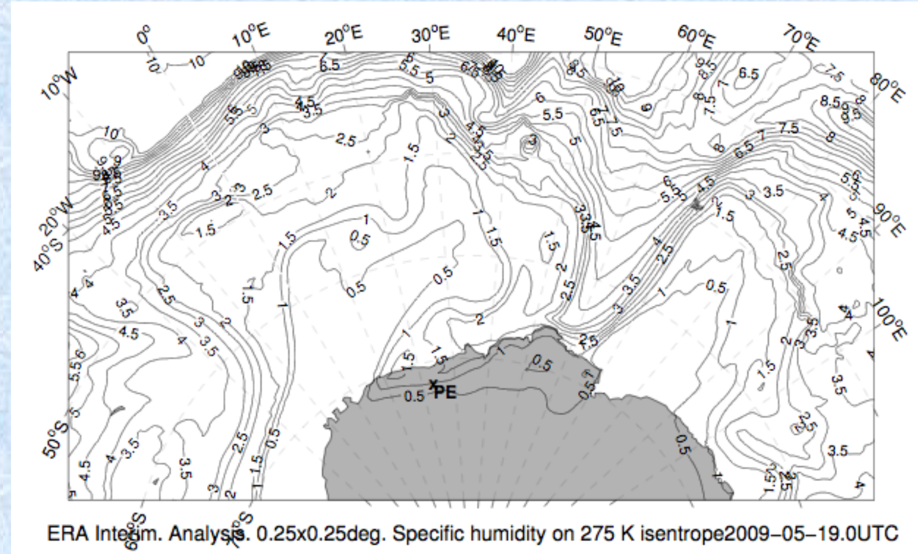
Specific humidity on 275K and 285K isentropic surfaces

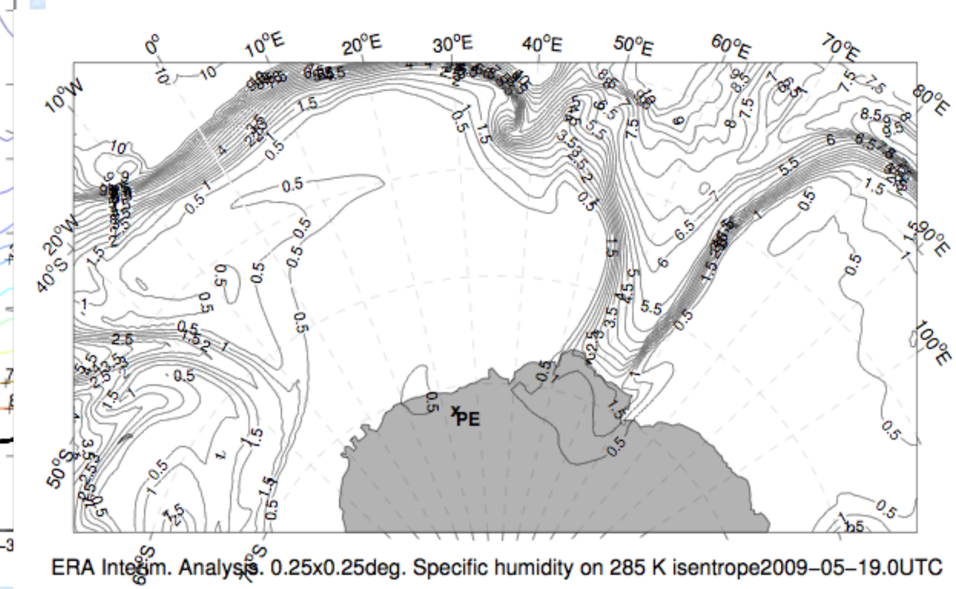
Gorodetskaya et al (AMOMFW 2011)

ERA-Interim

Isentropic analysis for HIGH accumulation event (may 19, 2009)







Mean meridional cross-section (20-60°E) of isentropic surfaces with specific humidity color contours

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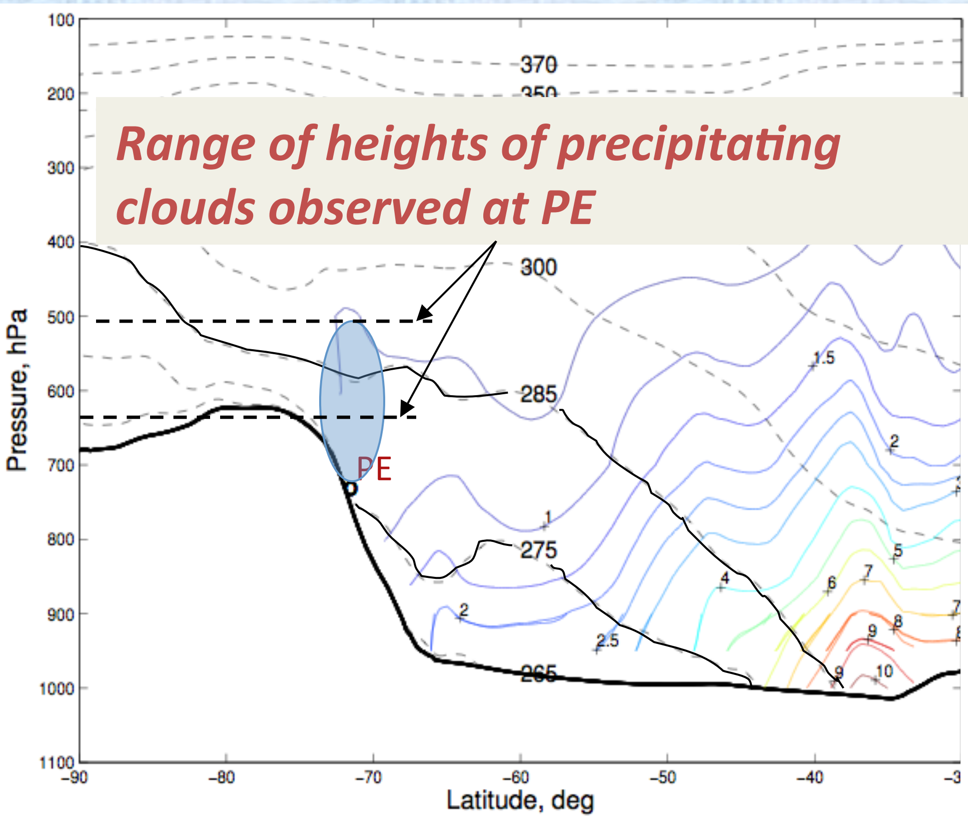
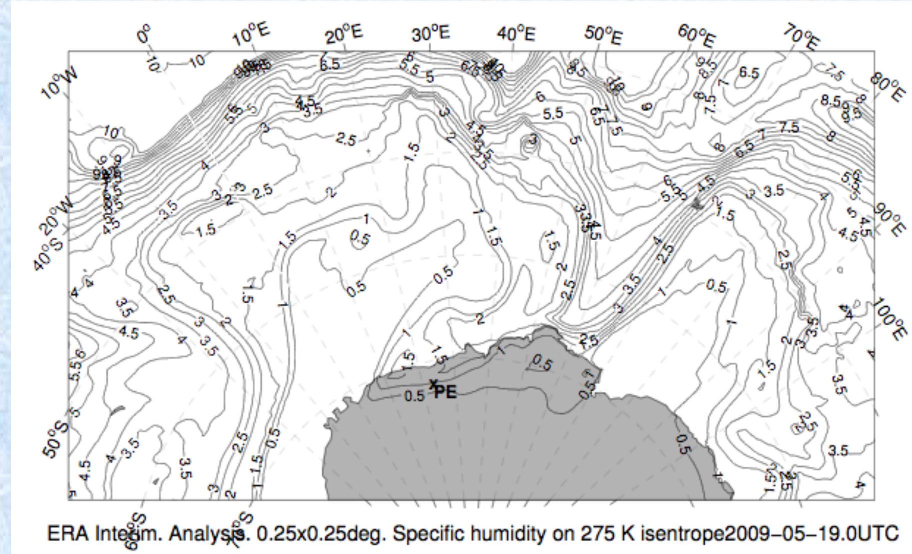
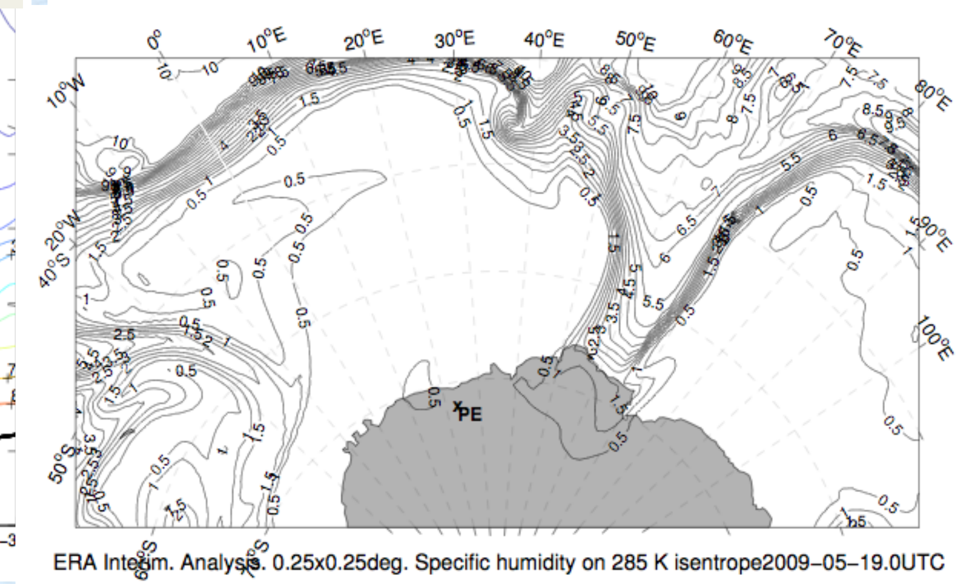




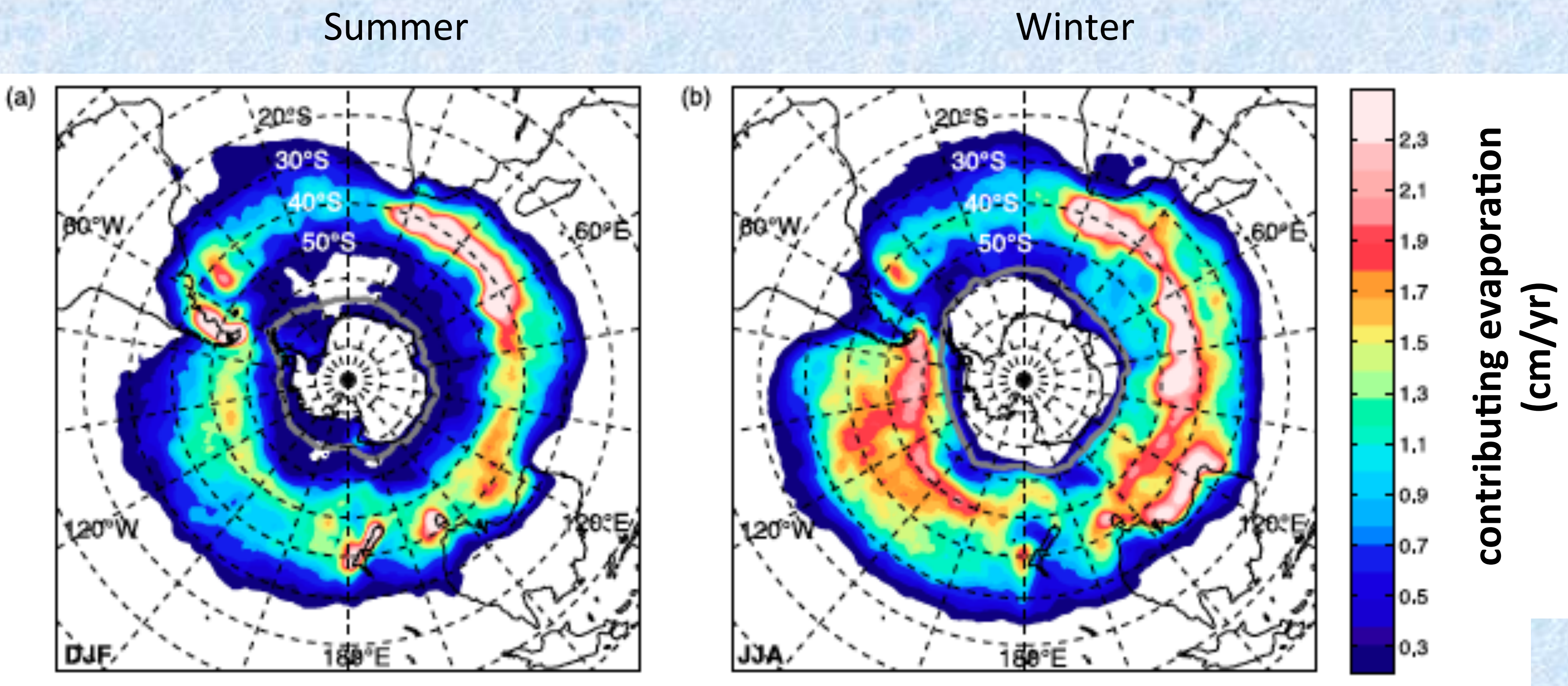


Mean meridional cross-section (20-60^{0}E) of isentropic surfaces with specific humidity color contours

Specific humidity on 275K and 285K isentropic surfaces

Gorodetskaya et al (AMOMFW 2011)

Mean moisture source regions for Antarctica

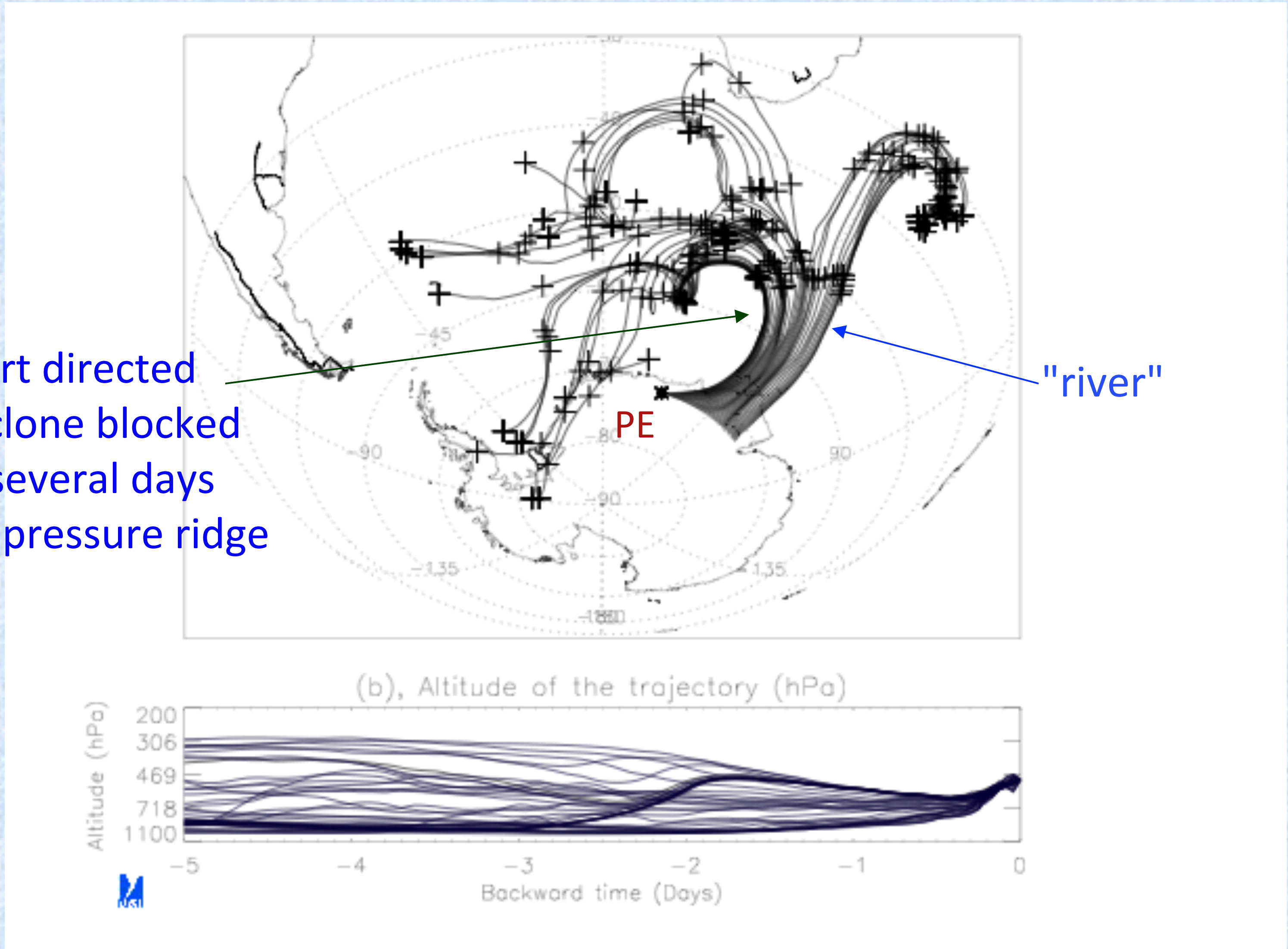


- Lagrangian long-rage moisture source diagnostics tracing water vapor transport for 20 days backward in time
- The highest altitudes of the East Antarctic ice shield, where major ice cores have been drilled, have mean source latitudes of 45 – 40°S year-round
- Consistent with findings from general circulation models with tagged tracers

Sodemann and Stohl, GRL 2009

5-day back-trajectories *initiated at a range of locations at 72°S, from 23°E to 63°E*

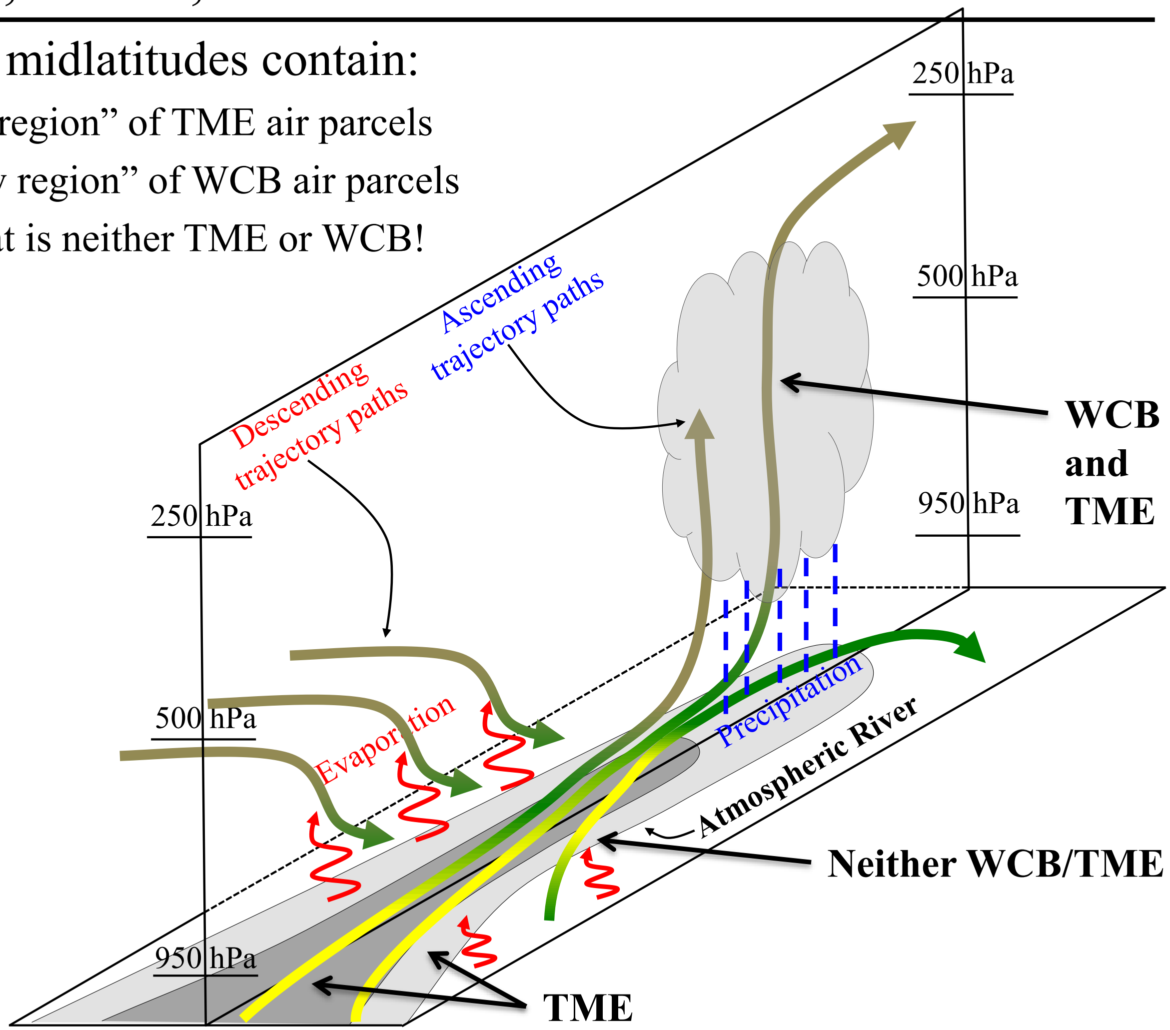
00UTC 19 may 2009



transport directed by a cyclone blocked during several days by high pressure ridge from Jason Cordeira's talk at the AR conference in San Diego Aug 2016...

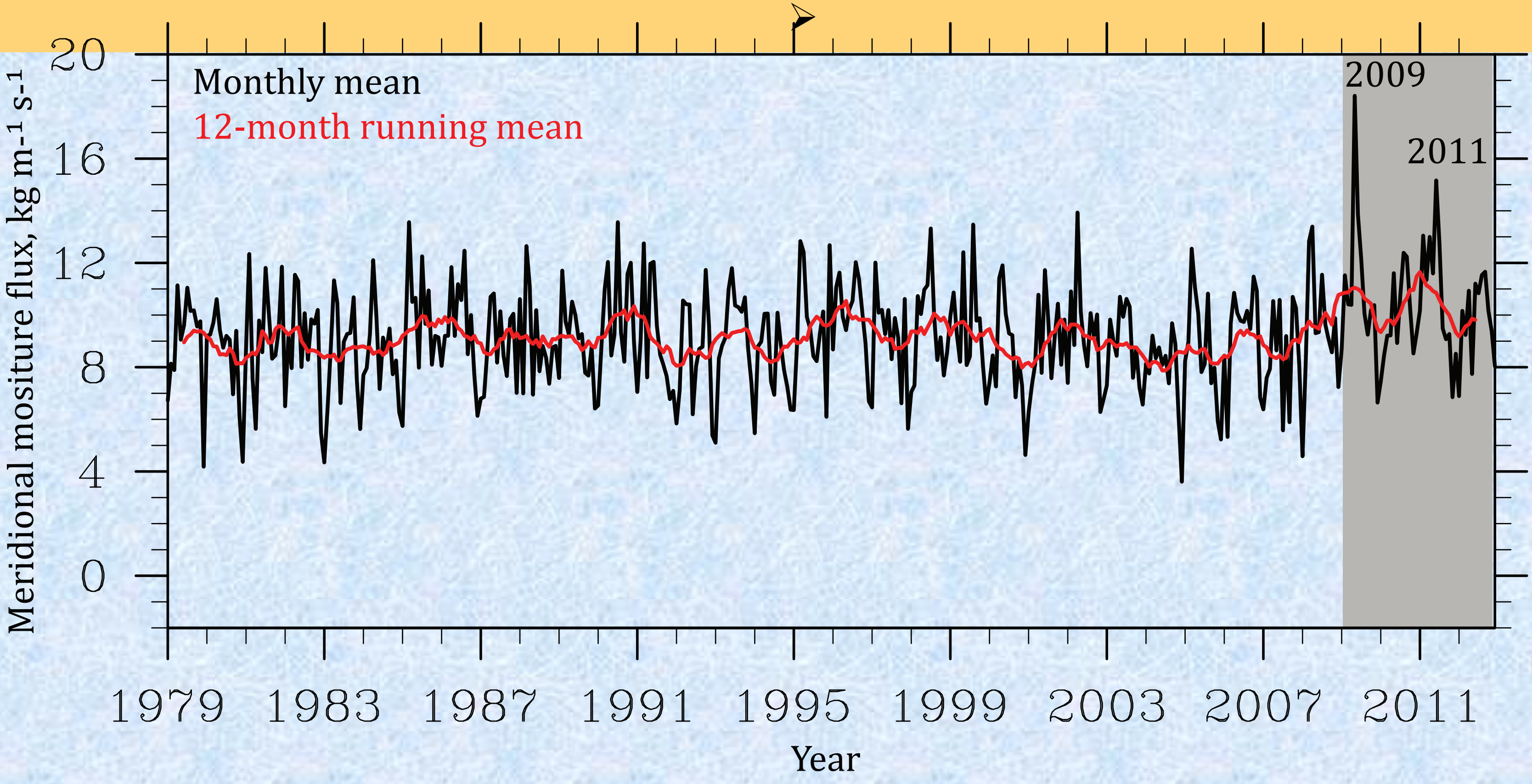
Part 2 - ARs, TMEs, and WCBs

- Some ARs in midlatitudes contain:
  - An "inflow region" of TME air parcels
  - An "outflow region" of WCB air parcels
  - A region that is neither TME or WCB!



Compare 2009 and 2011 to longer time series of total meridional moisture fluxes towards DML

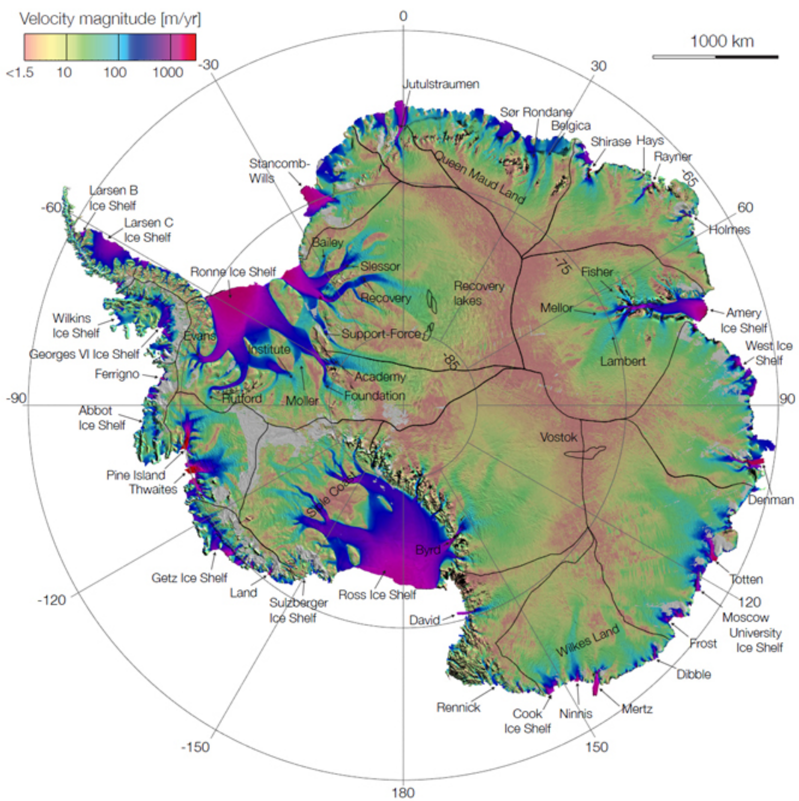
- 2009 and 2011 years stand out as anomalous during 1979-2012 period
  - **ARs correspond to anomalous moisture transport years**



Meridional moisture flux (ERA-Interim, seasonal cycle removed) towards the East Antarctic ice sheet averaged over 50-72ºS, 0-90ºE sector

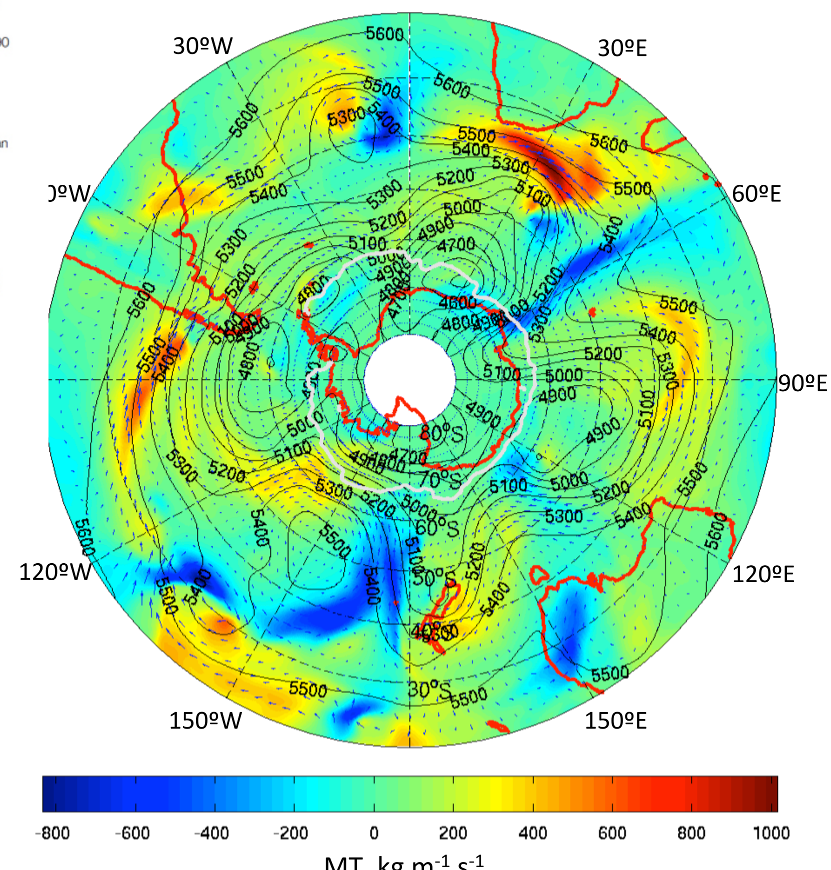
Gorodetskaya et al. 2014, GRL
Tsukernik and Lynch 2013

Pathways [of moisture/snow] IN and [of ice] OUT?



Map of the speed and direction of ice flow in Antarctica, derived from radar interferometri data. Image credit: NASA/JPL-Caltech/UCI

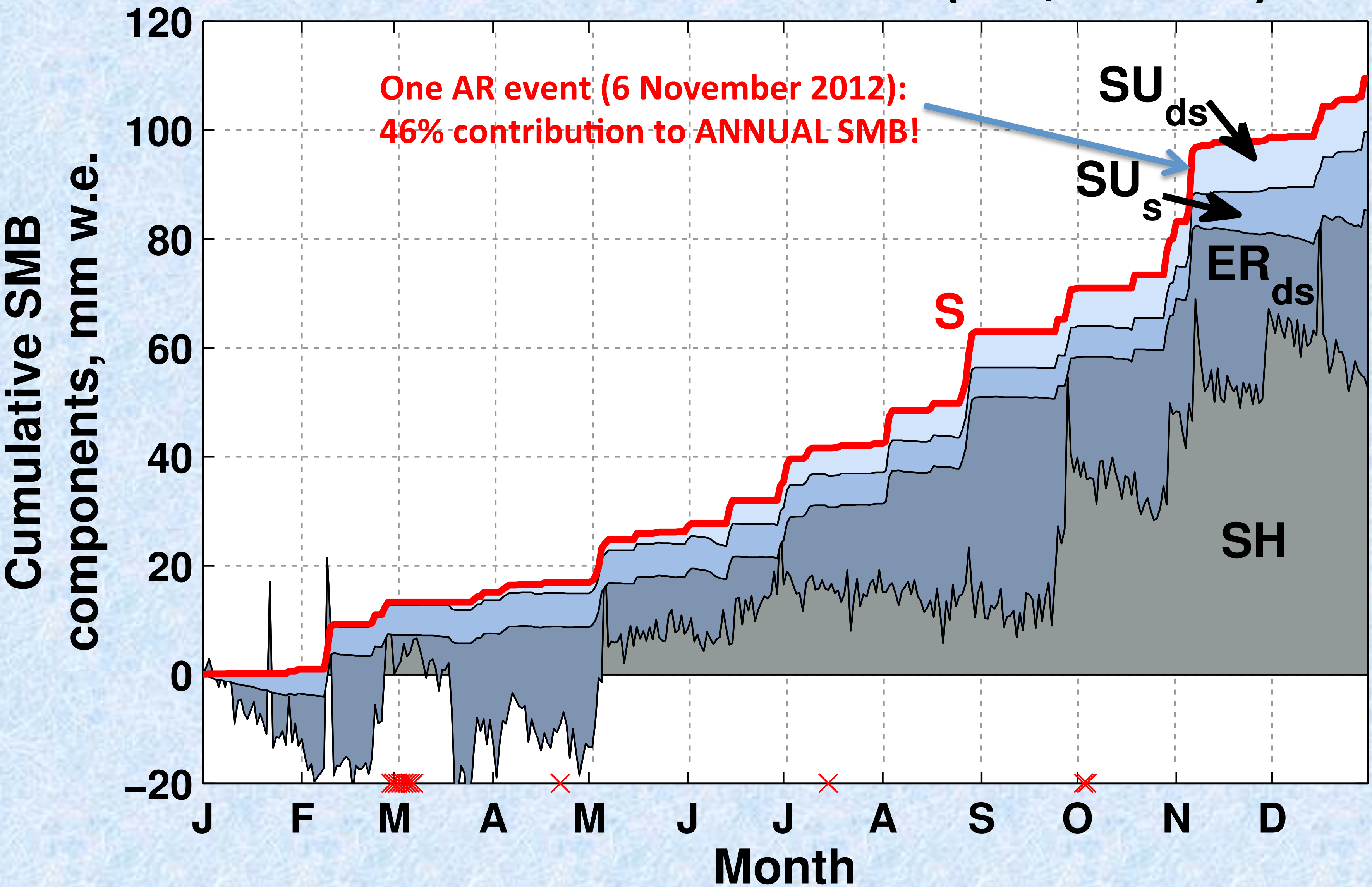
Rignot et al 2011



Vertically integrated atmospheric moisture transport on 19 May 2009

Gorodetskaya et al 2014

Surface mass balance (PE, 2012)

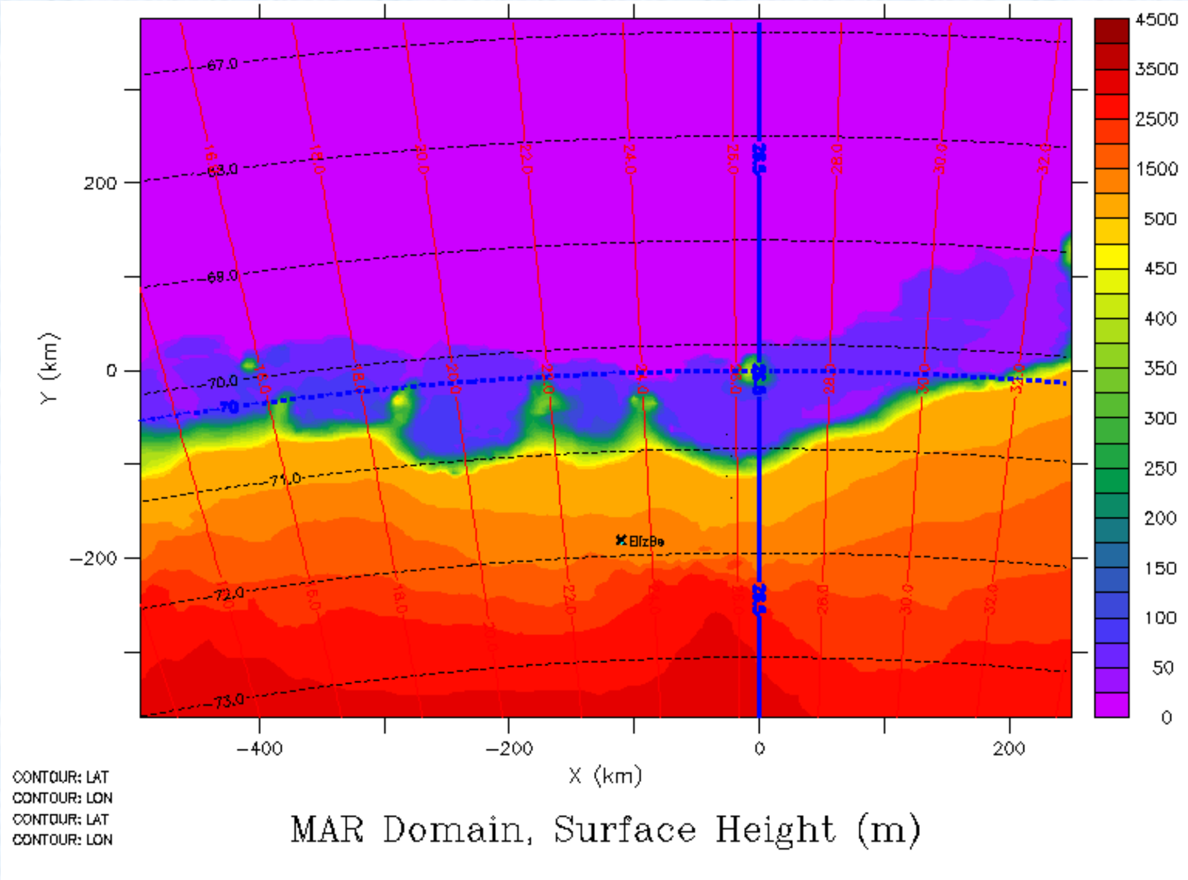


- *Gorodetskaya et al "Cloud and precipitation properties from ground-based remote sensing instruments in East Antarctica", Cryosphere 2015*
- *Thiery et al " Surface and snowdrift sublimation at Princess Elisabeth station, East Antarctica, Cryosphere (2012)*

...in regional climate models work in progress!!!

Modèle Atmosphéric Régional (MAR)

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



➢ 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)

Regional climate model RACMO2.3-ANT

- **New model version RACMO2.3**, simulation over Dronning Maud Land 5.5x5.5 km horiz resolution

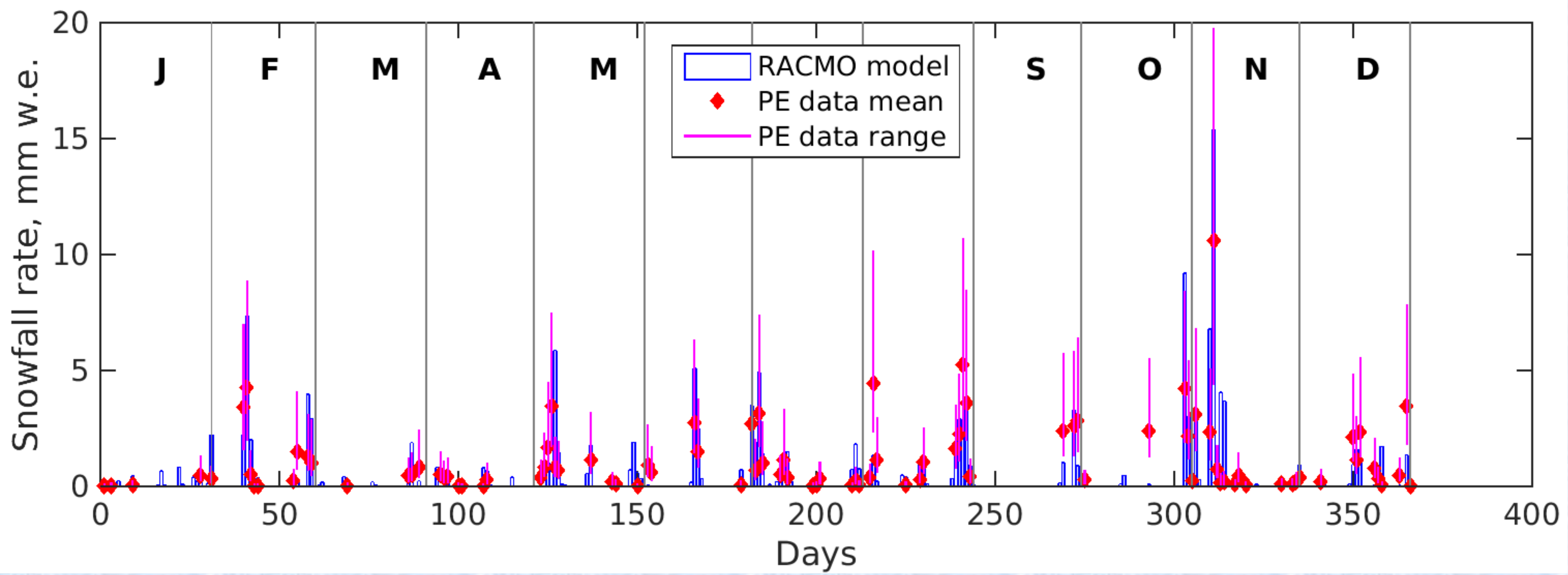
- **Updates in this model version** (*Van Wessem et al. TC 2013*):

➢ cloud ice super-saturation (Tompkins and Gierens 2007)
➢ precipitation formation (increase in auto-conversion coeff)
➢ radiative flux scheme (McRad, Morcrette et al. 2008)
➢ turbulent flux scheme (EDMF, Siebesma et al. 2007)

Snowfall evaluation:

RACMO-ANT – within the measurements uncertainty range also for extreme events (including ARs)

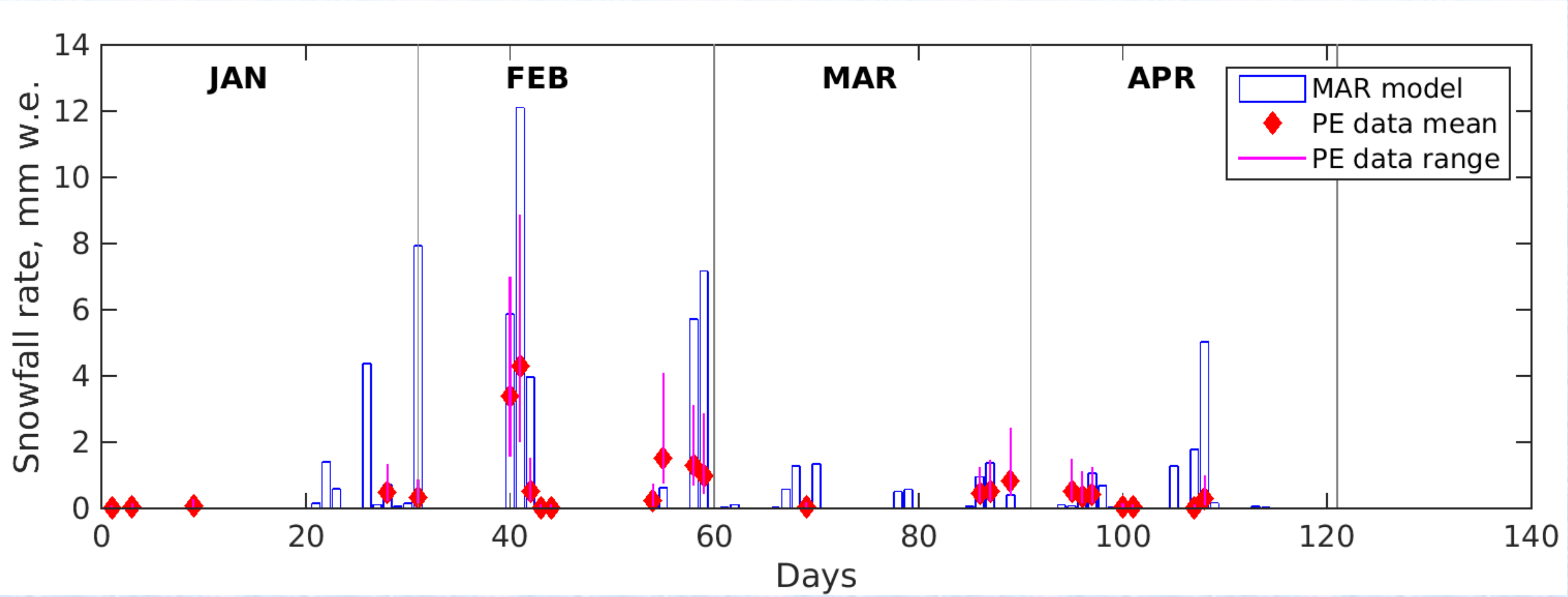
RACMO model



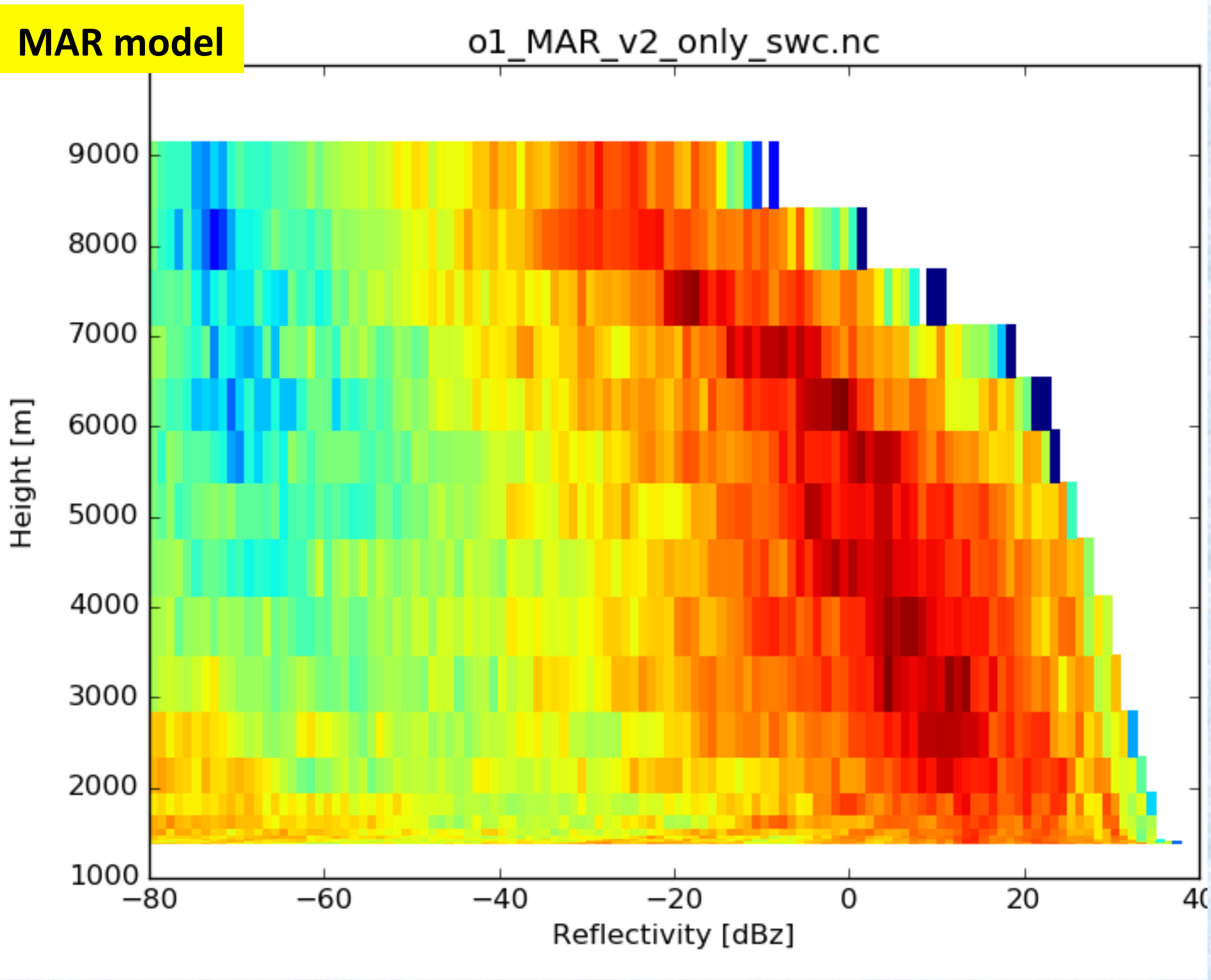
Snowfall evaluation:

MAR tends to overestimate snowfall rate for intense events (including ARs)

MAR model



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



Forward model
PAMTRA – Passive and Active Microwave radiative transfer model

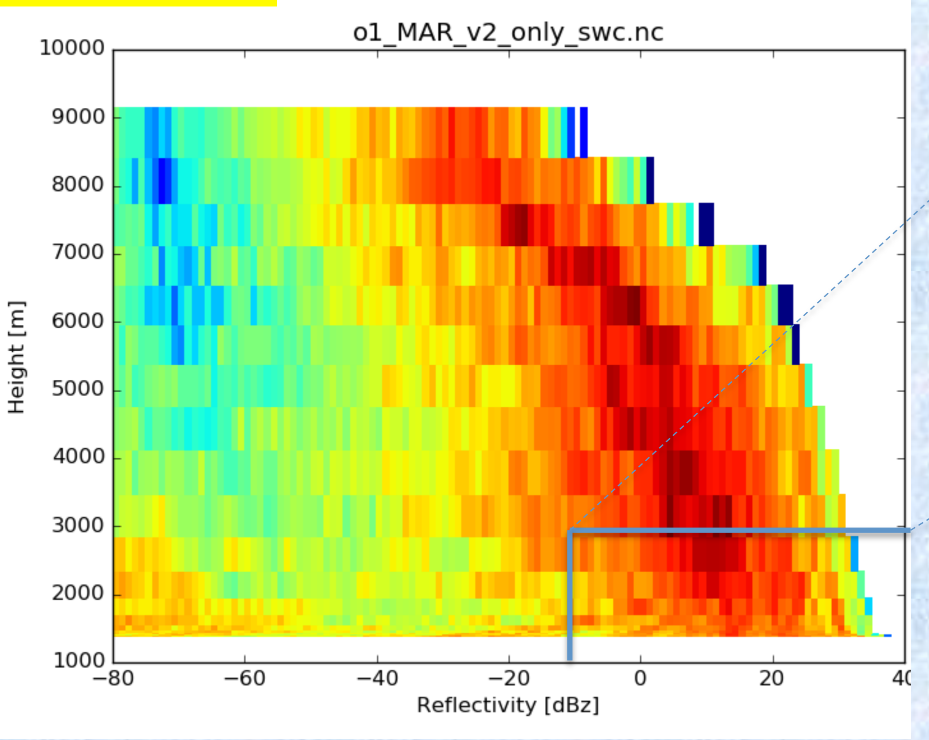
- ➢ Used to synthesize Ze at 24 GHz (MRR) for MAR model

MAR parameters used:

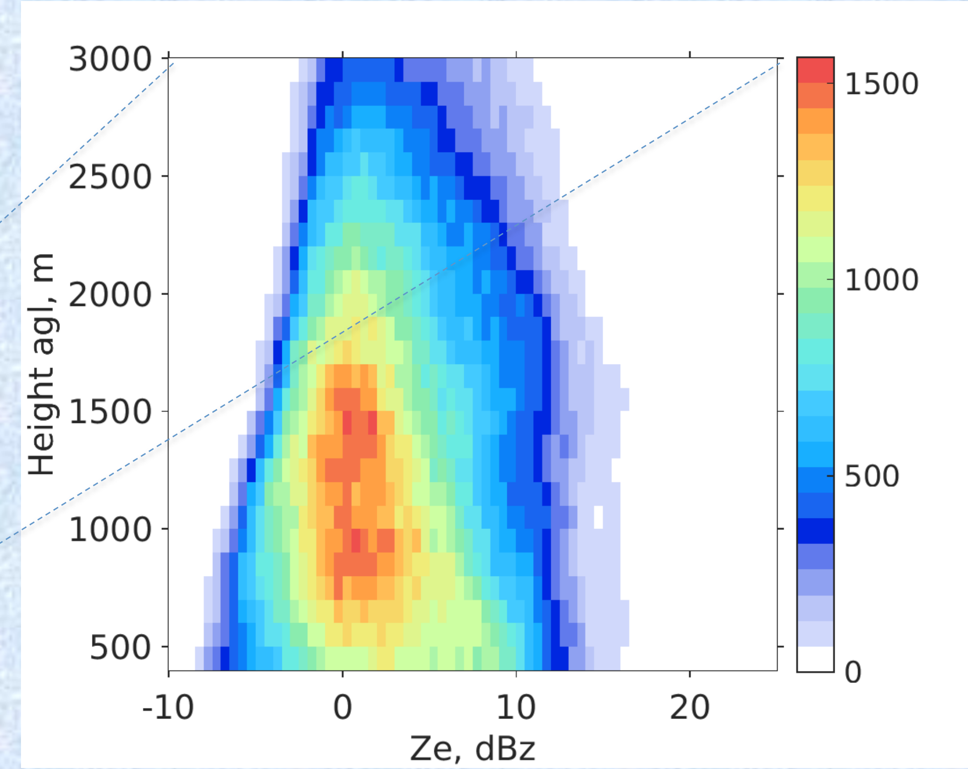
- V(D) for snow based on graupel-like snow of hexagonal type from Locatelli&Hobbs (1974)
- m(D): fixed snow density = 100 kg m^{-3}
- Snowfall N(D): exp (Marshall-Palmer)

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 => outlook

- *Atmospheric rivers explain the majority of extreme precipitation events in the escarpment zone of East Antarctica (Dronning Maud Land) during 2009-2012*

  => need longer record...

- *Large contribution of atmospheric rivers to Dronning Maud Land surface mass balance => difference in the regional total annual SMB is determined by the frequency of occurrence of ARs.*

- **Regional climate models** used to simulate Antarctic climate (MAR, RACMO) simulate intense snowfall events **within Z-S uncertainties with some events overestimated**

  => model parameterization improvements AND constrained snowfall rates derived from radar AND more radars in Antarctica...

  => Need to understand the dynamics and ocean-atmosphere linkage behind atmospheric rivers

Work continued...
ACE expedition
observations+modeling

Collaboration with:

- **Katie Leonard (EPFL, Switzerland)**
- **Marty Ralph (Scripps, USA)**
- **Innsbruck, Cologne, Wisc-Mad, Brown, KUL**

➢ Chasing... or being chased by the **Atmospheric Rivers:**

✧ Radiosonde measurements

✧ Precipitation

- Synoptic conditions
- Stable isotope measurements
- Back trajectories
- Sea ice and SST conditions

Thank you for your attention!
Questions? Feedback?

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