Atmospheric rivers impact on the East Antarctic surface mass balance during recent years

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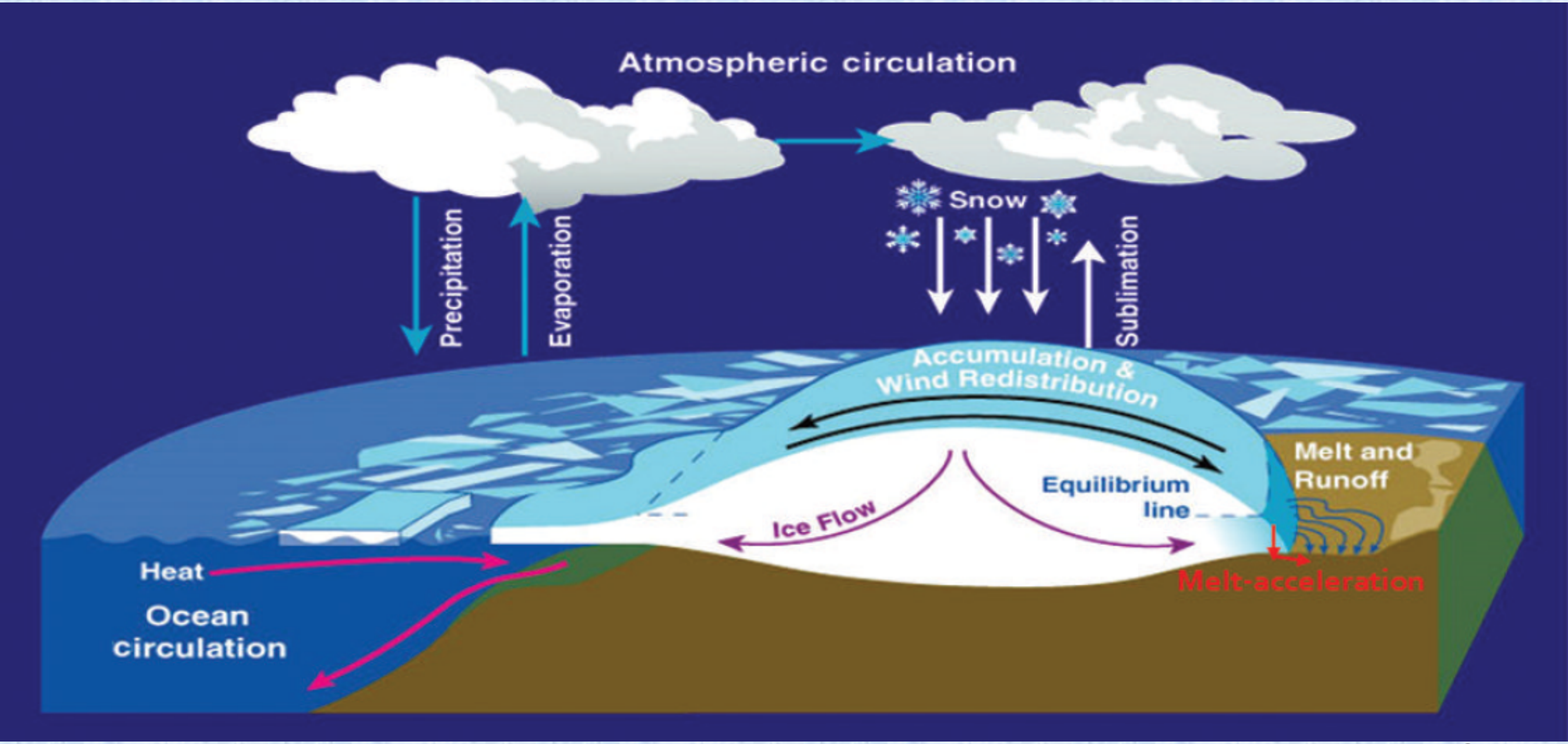
Antarctic surface mass balance:

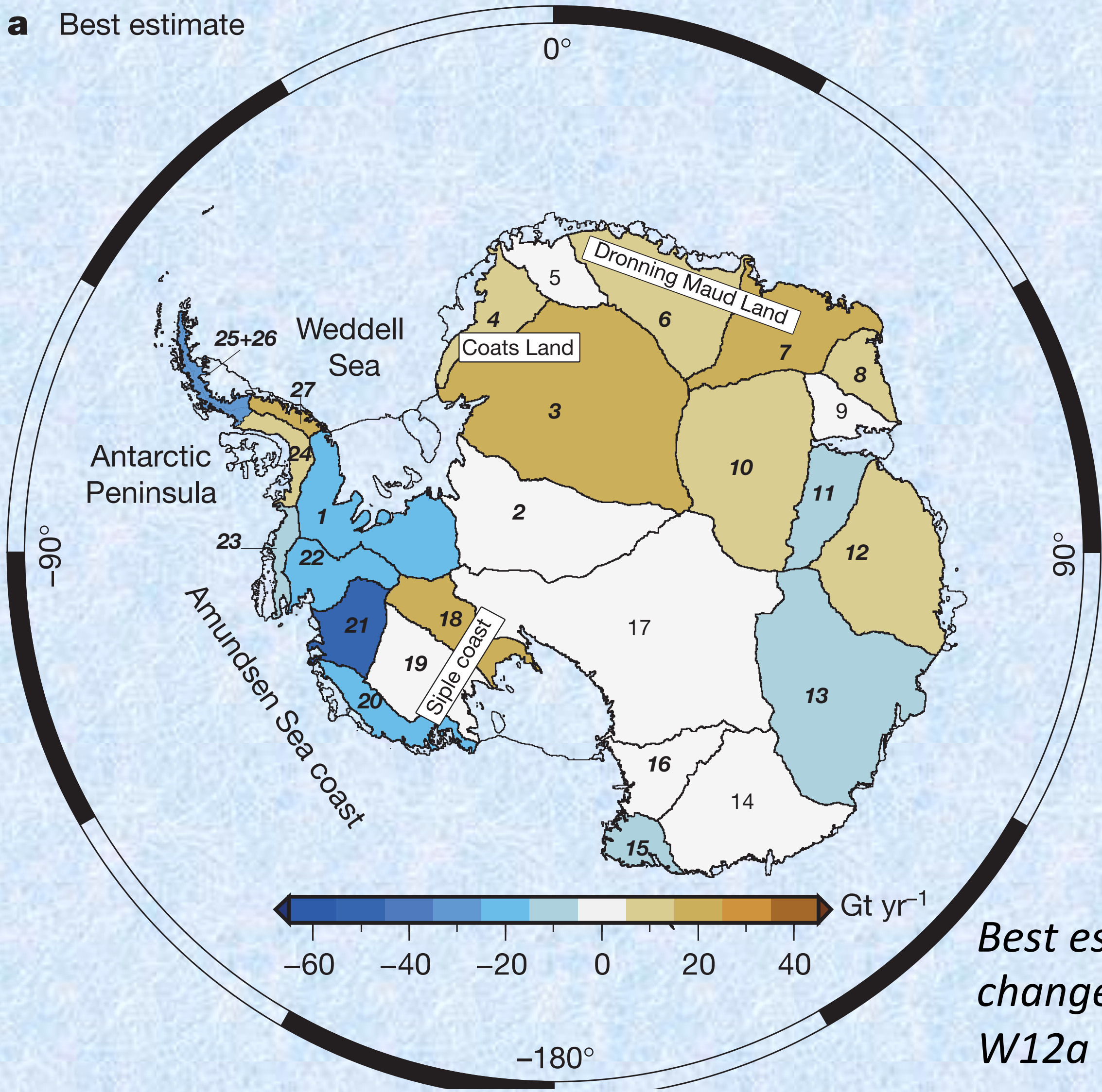
SMB = S ± SUs – SUds ± TR – MR

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

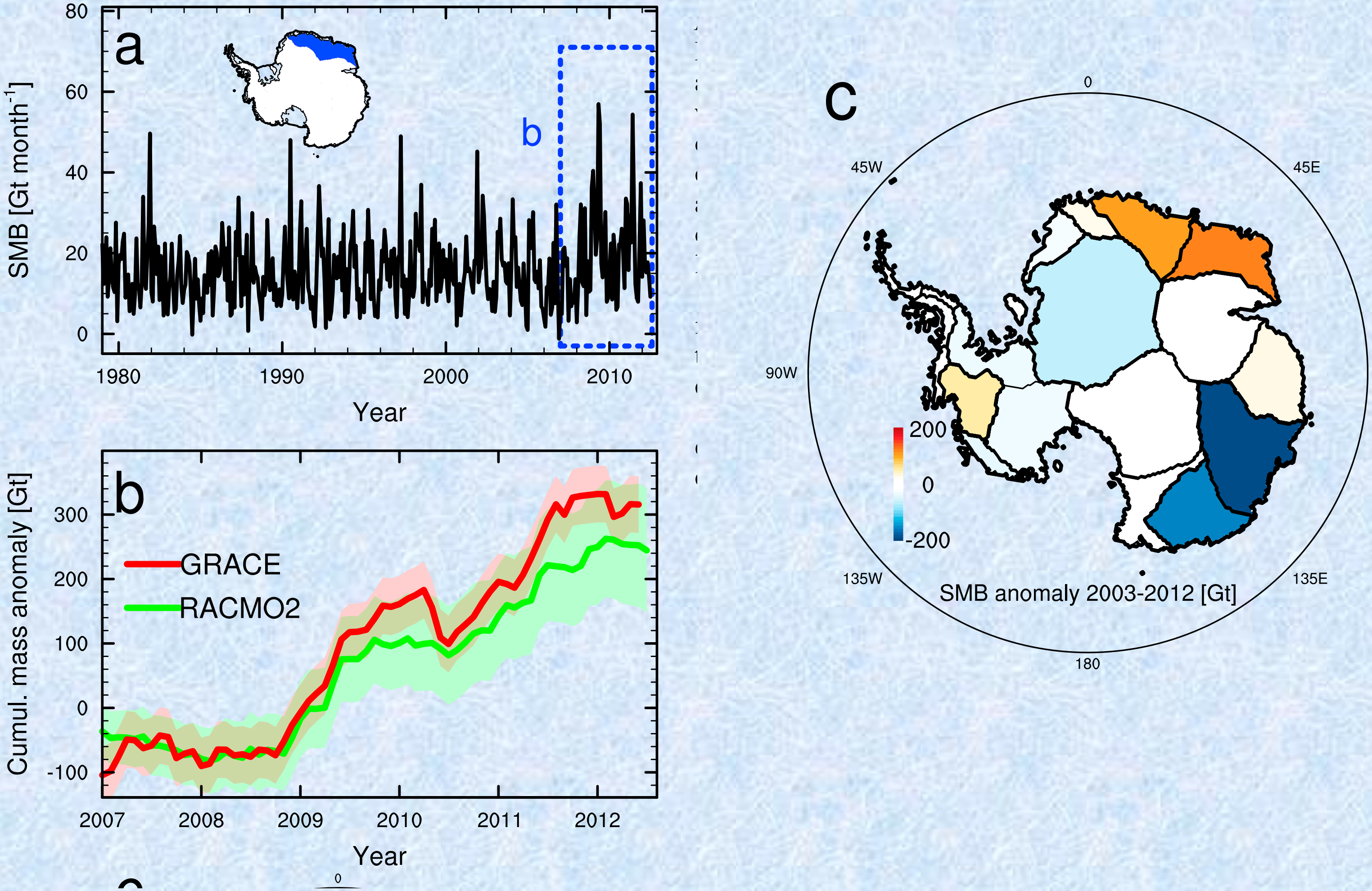
- Mass **loss**: mostly in Amundsen sea basins

- 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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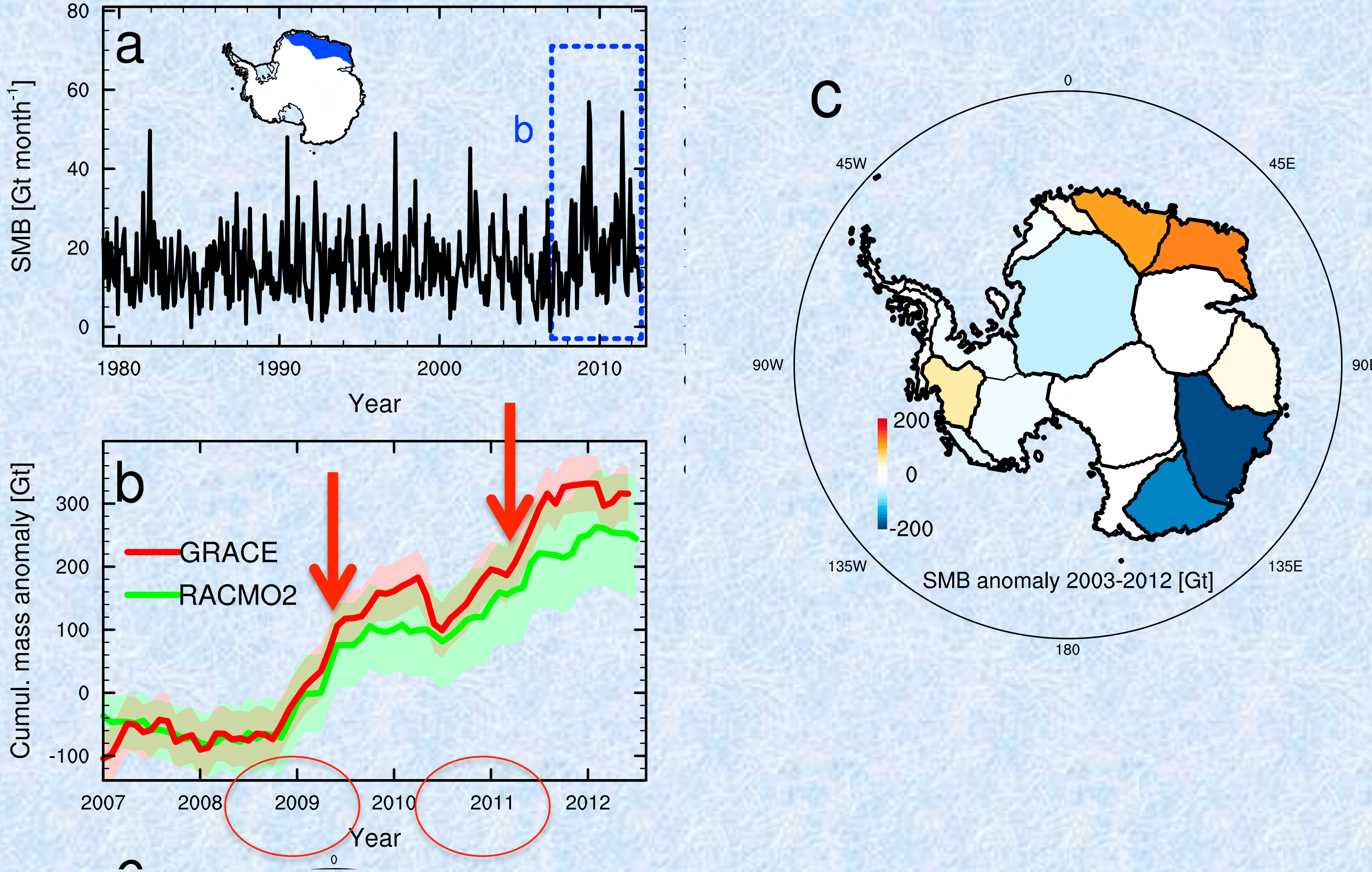
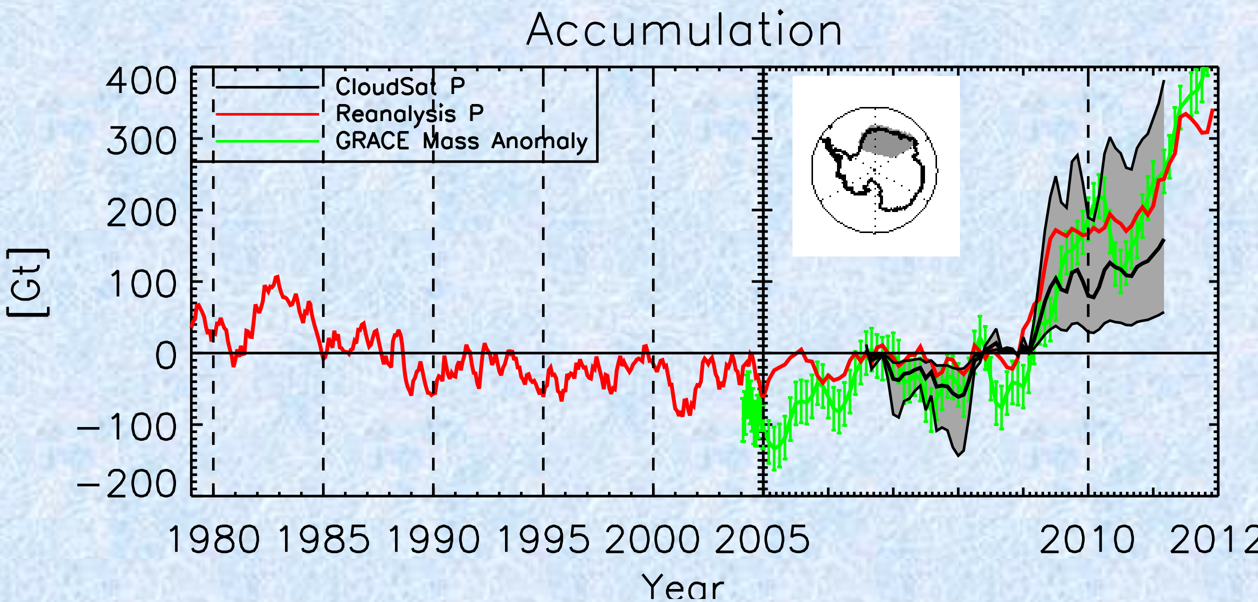


Lenaerts et al. (2013)

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

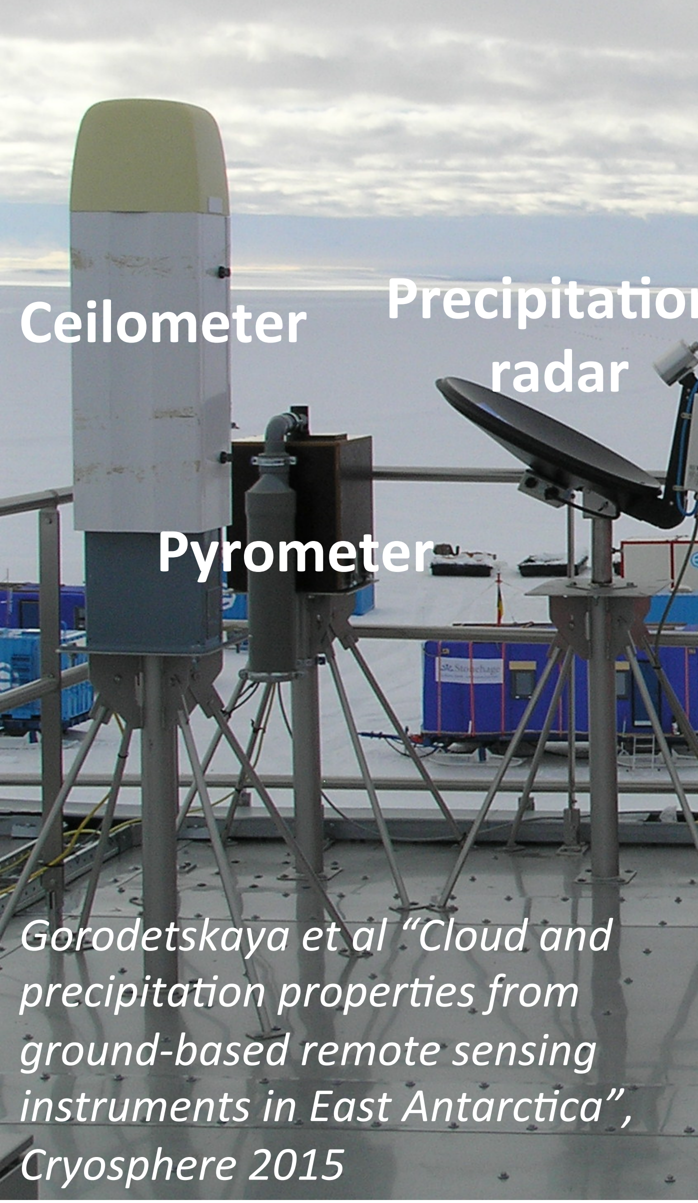
GRACE mass average over 30W-60E, 65S-80S

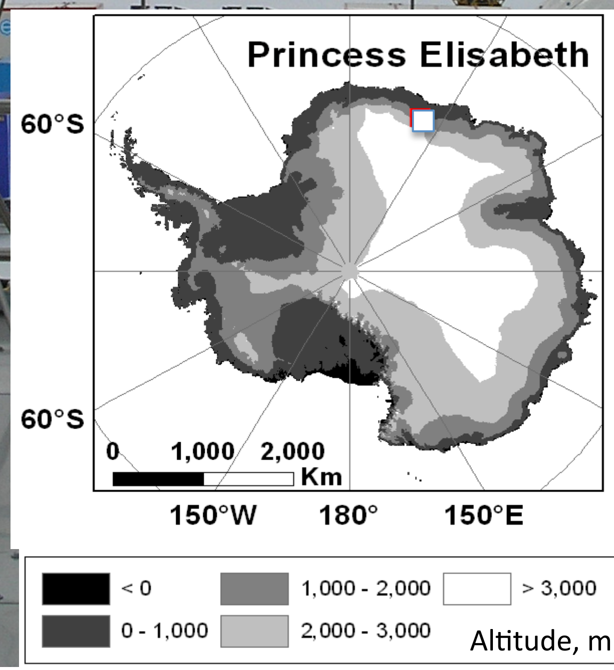
Integrated net precipitation (ERA-Interim)

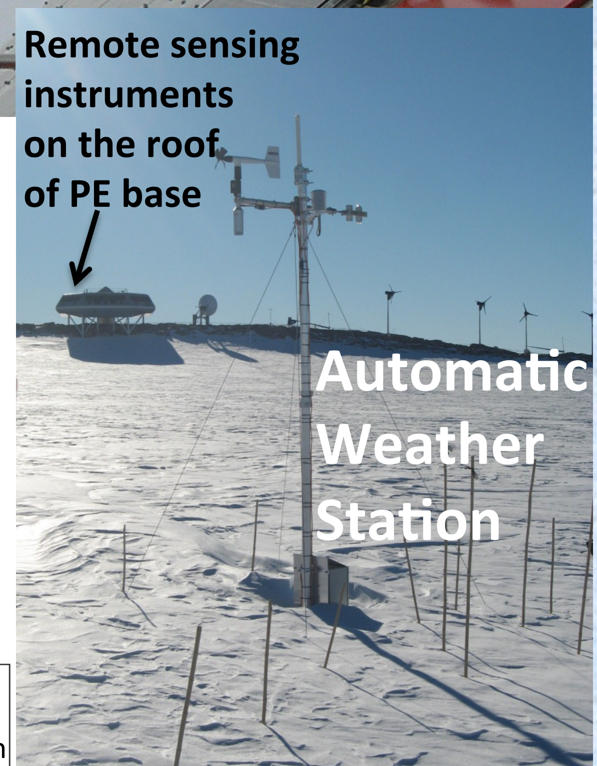
CloudSat accumulated snowfall

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

installed within the HYDRANT project







Gorodetskaya et al "Cloud and precipitation properties from ground-based remote sensing instruments in East Antarctica", Cryosphere 2015

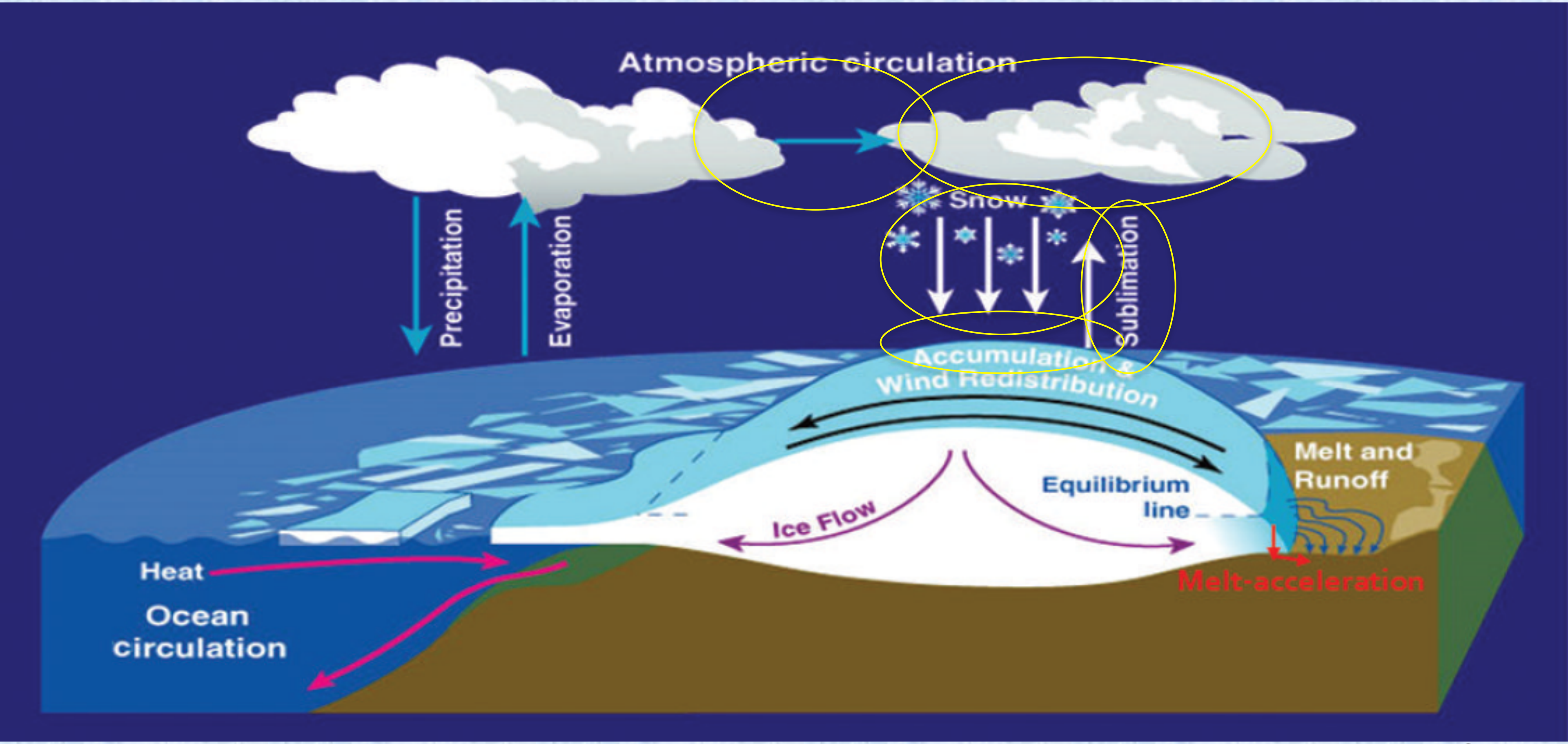
Antarctic surface mass balance:

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 (credit: NASA)

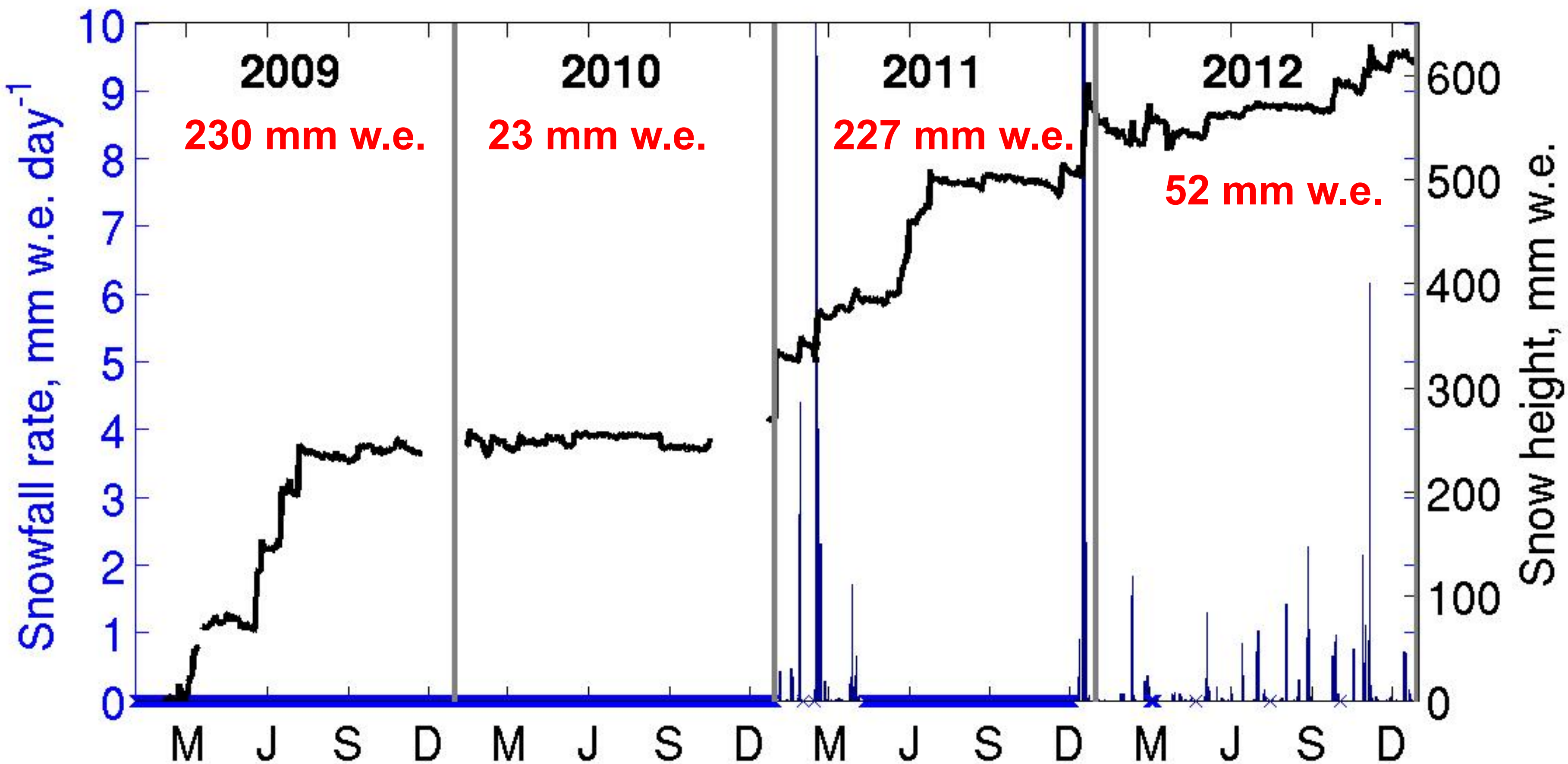
2009 and 2011:

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

Compare:

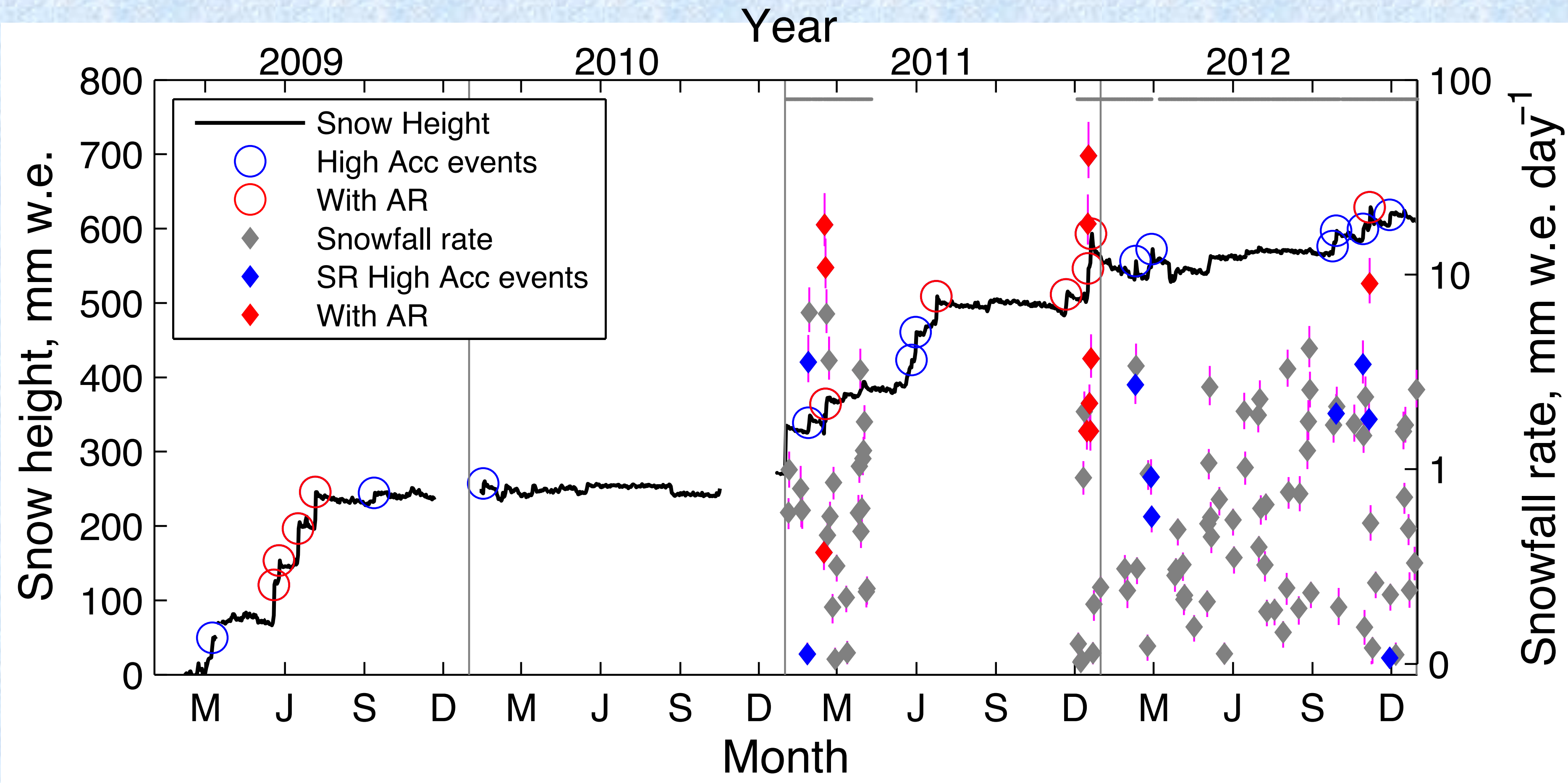
long-term stake measurements in the vicinity of Sør Rondane mountains

=> 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

Defining AR events in East Antarctica

- Low temperature saturated air condition:

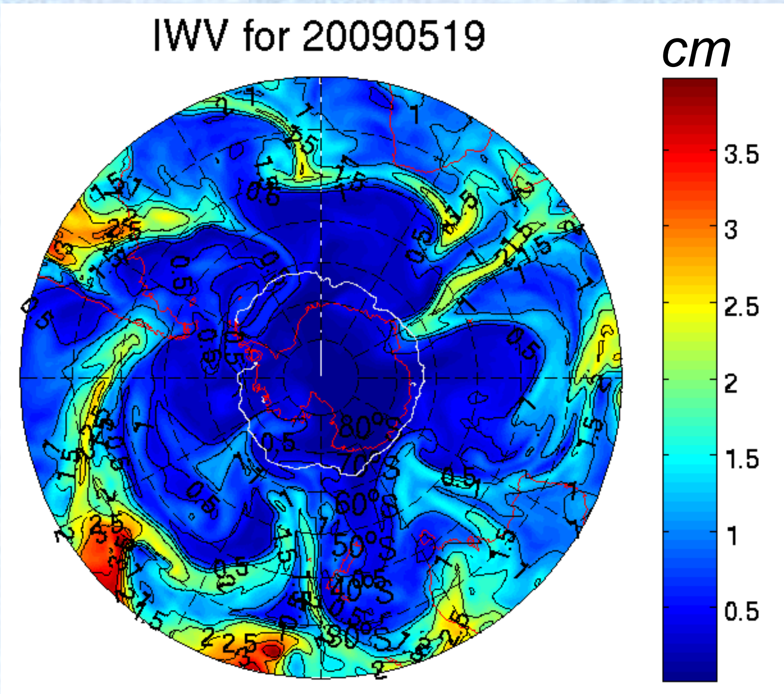
$$IWV_{sat} = \int_{900}^{300hPa} q_{sat}(T)\,dp$$

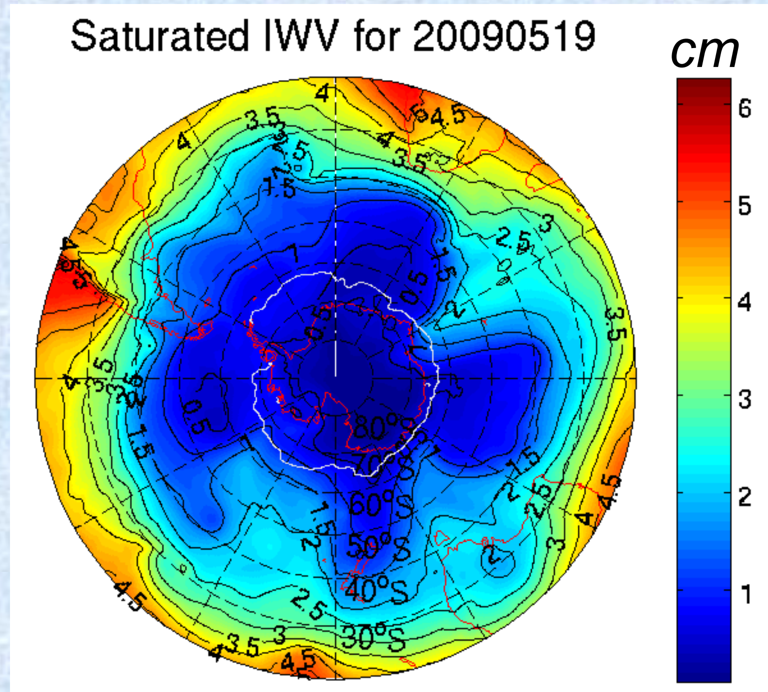
- IWV > threshold (~1 cm IWV at 70°S)
- Extends at least 20° lat (> 2000 km)
- More ARs discovered in 2009 and 2011
- **ARs correspond to anomalous moisture transport years**

Gorodetskaya, et al., 2014

Identifying Antarctic ARs:

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





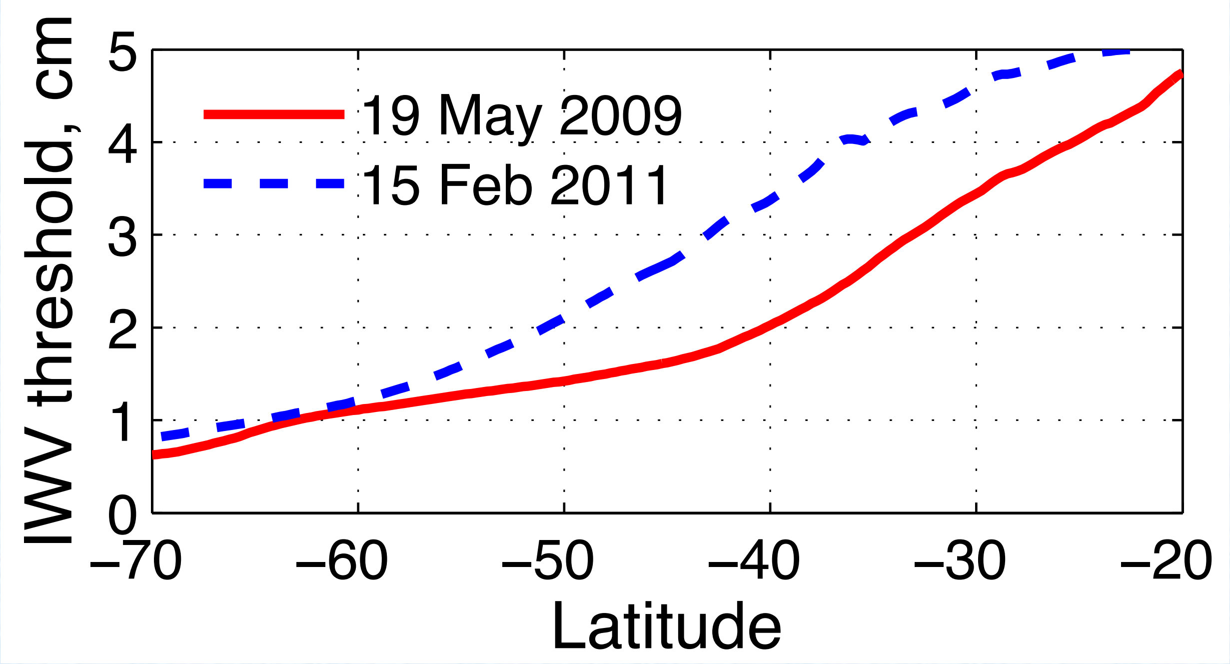
grey line = daily mean 50% sea ice concentration

Identifying Antarctic ARs:

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

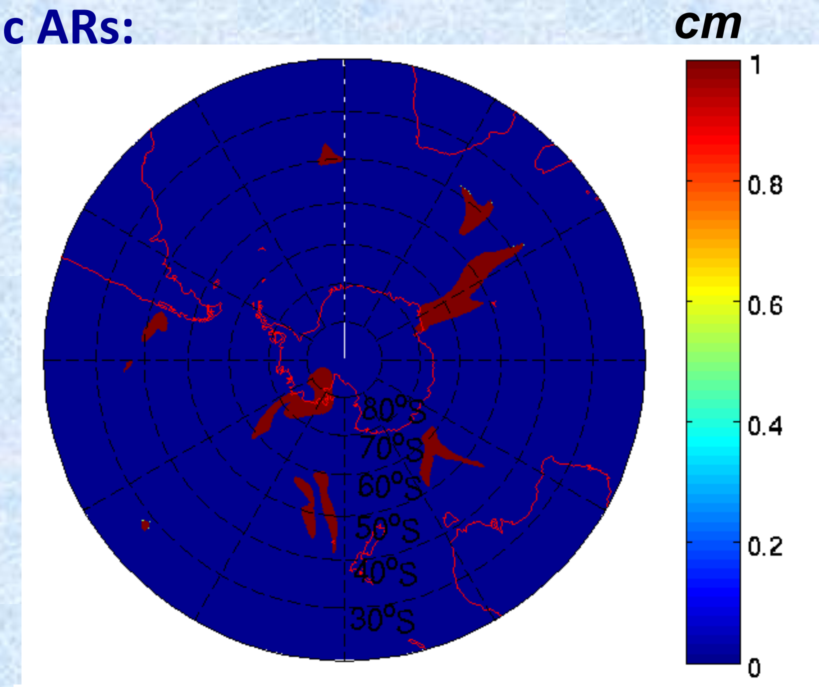
$$IWV_{thresh} = IWV_{sat,mean} + AR_{coeff}\,(IWV_{sat,\max} - IWV_{sat,mean}),$$

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



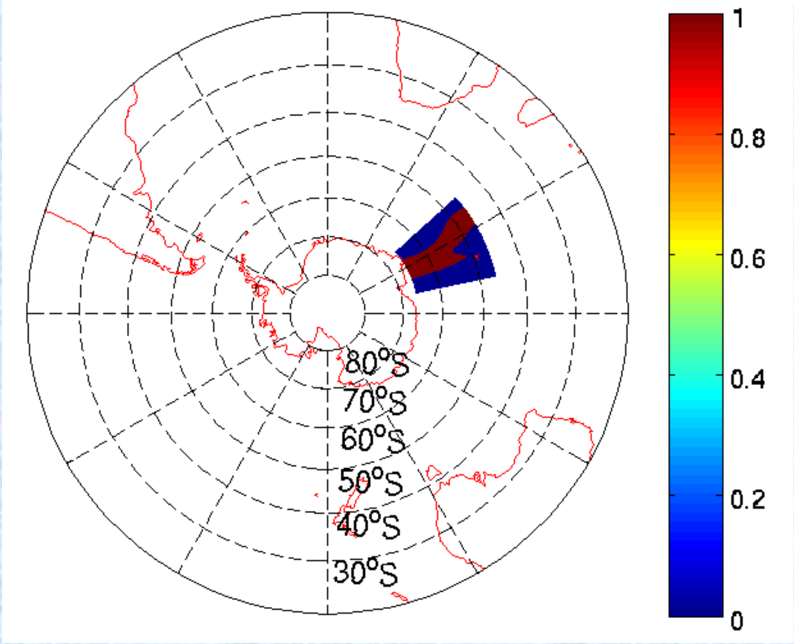
- ***Instead of using a fixed threshold of 2 cm suitable for mid-latitudes (Ralph et al. 2004), our IWV threshold varies with latitude depending on the temperature and saturation capacity***

Identifying Antarctic ARs:



3) Find excessive IWV based on IWVthresh:

4) Identify ARs with the potential to influence DML and neighboring sectors (20W-90ºE):

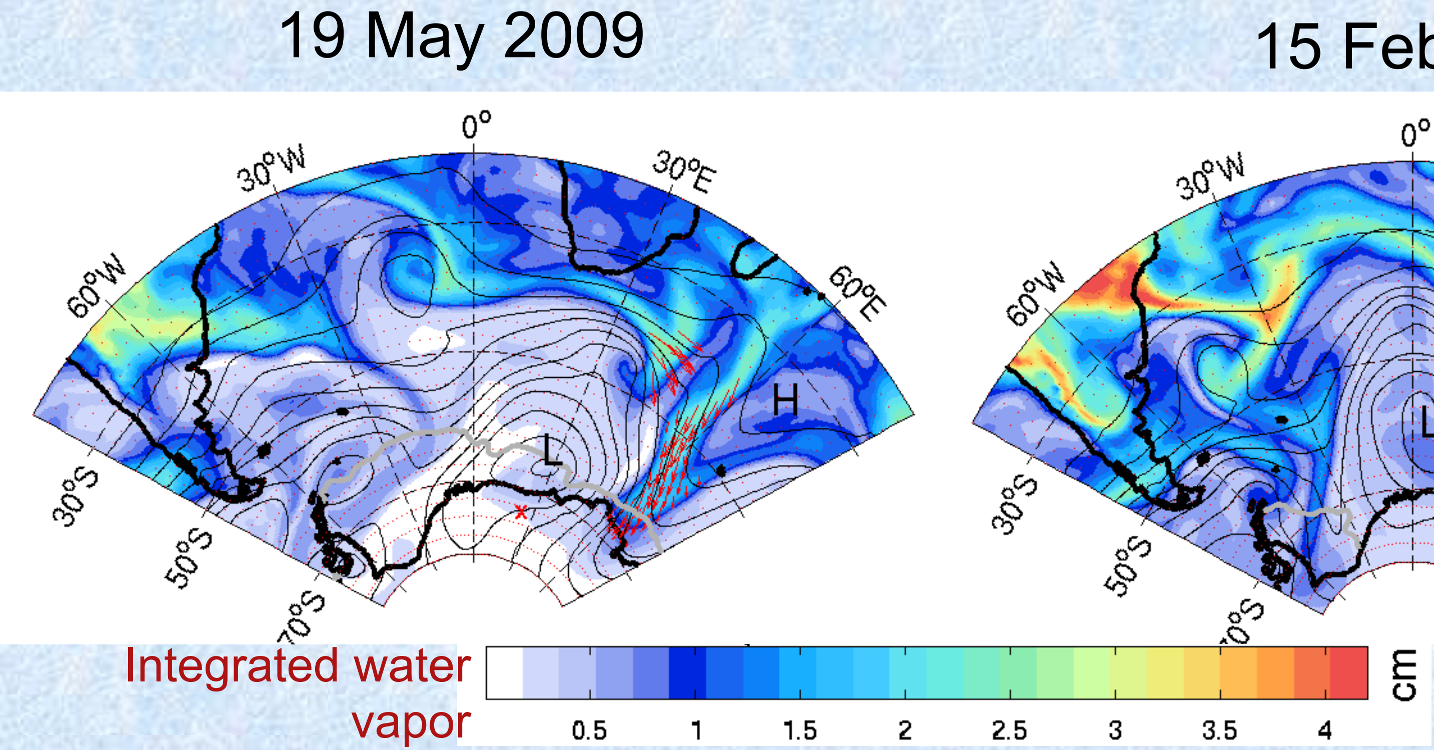


- identify location where **band of excessive IWV hits the coast** :
(longitude dependent) => average (L_{mean})

- define **sector within which AR** should be located:
L_{mean}+/- 15º longitude, lat coast + 20º latitude

- if **$IWV>IWV_{thresh}$ continuously** at each latitude within this sector **=> AR**

Atmospheric rivers identified using a new definition adapted for Antarctica

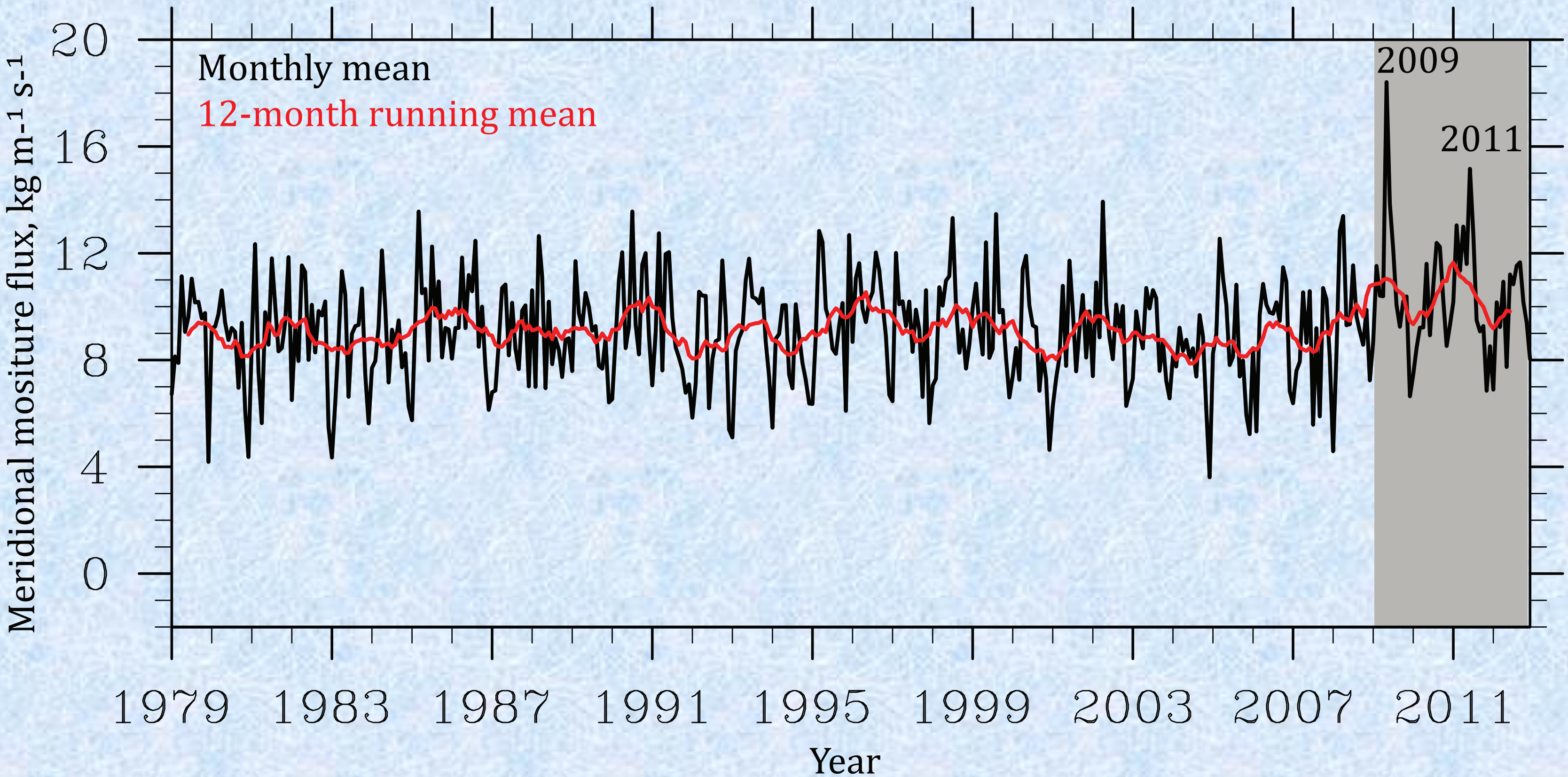


Colors = integrated (900-300hPa) water vapour
Red arrows = total integrated moisture transport within ARs
black contours = 500 hPa geopotential height

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

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

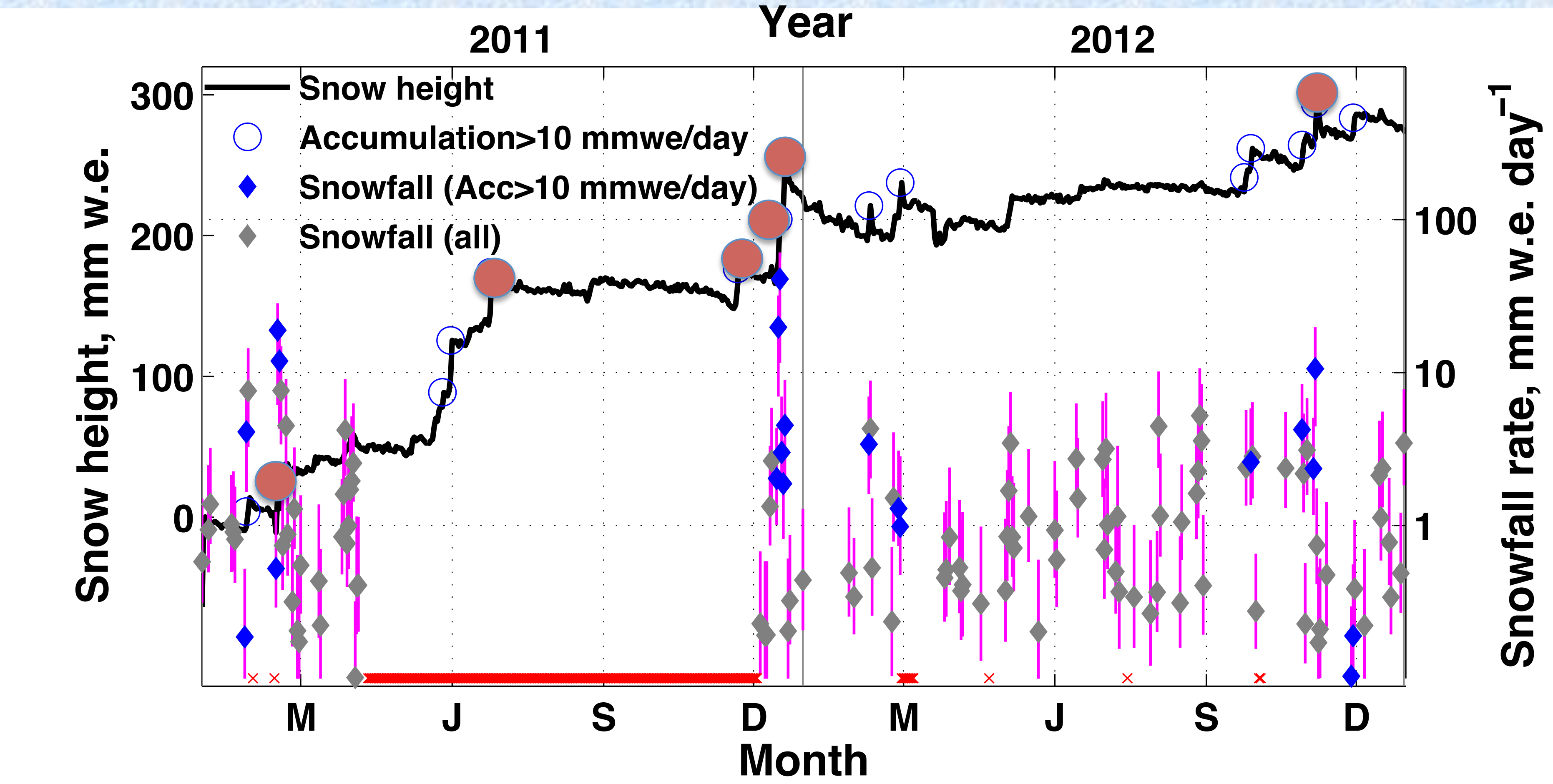
- 2009 and 2011 years stand out as anomalous during 1979-2012 period



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

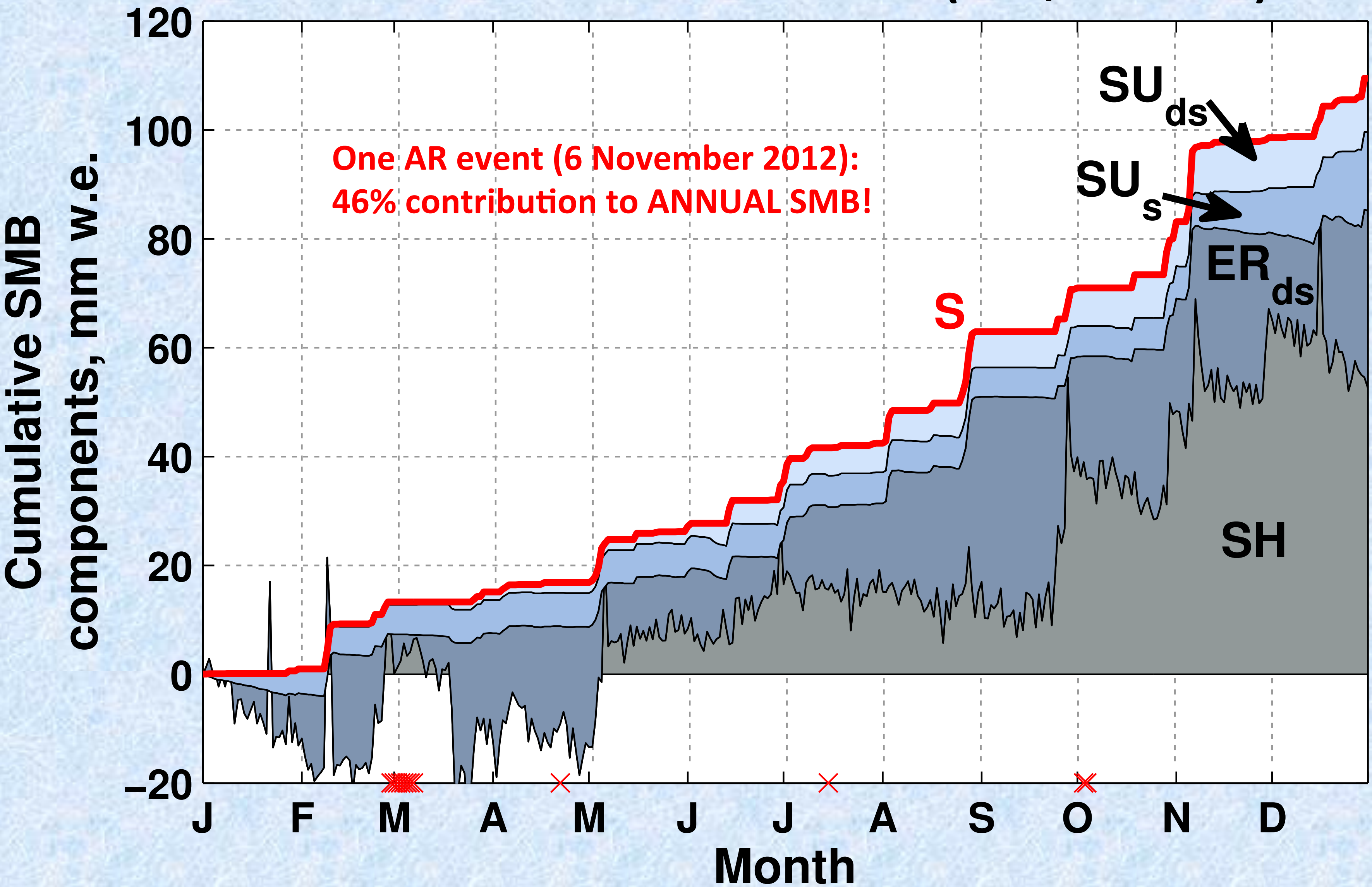
- *Gorodetskaya et al. 2014, GRL*

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)*

Surface mass balance (PE, 2012)

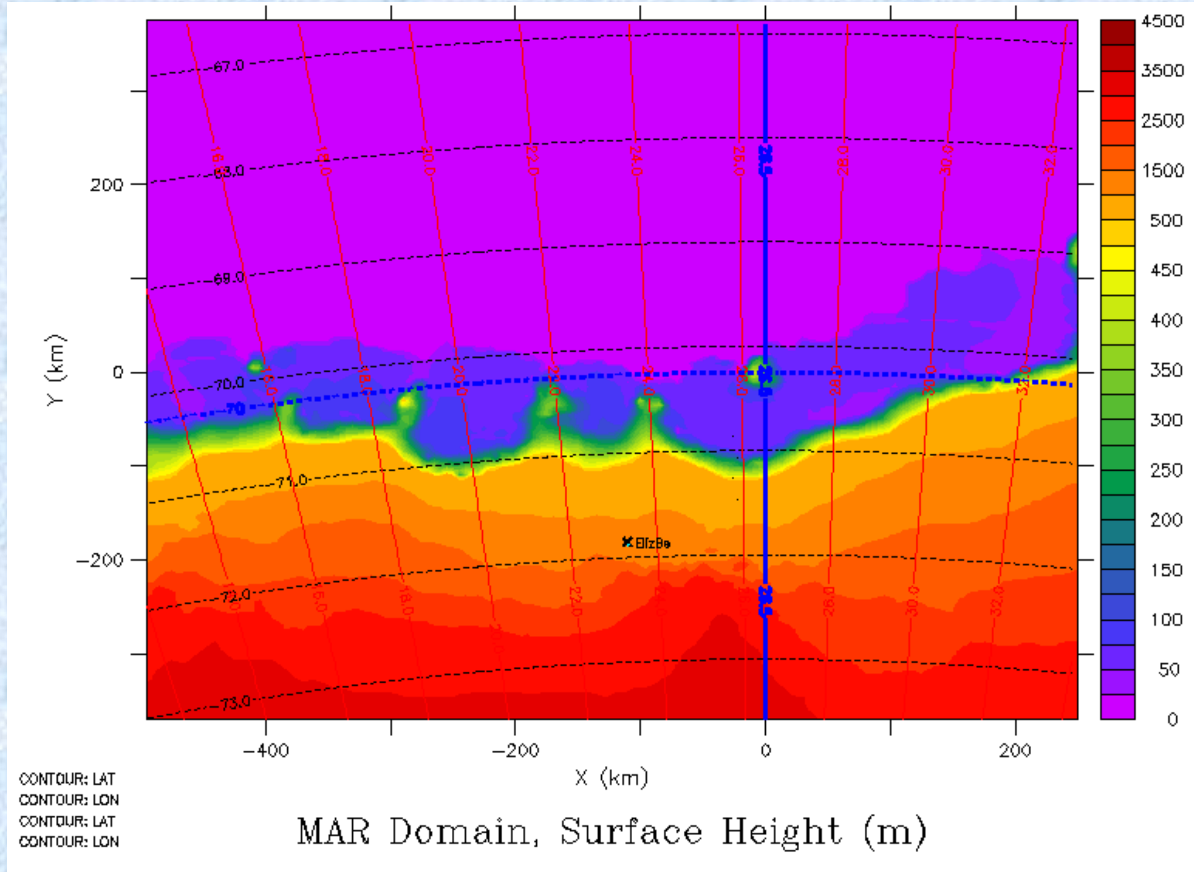


- Gorodetskaya et al "Cloud and precipitation properties from ground-based remote sensing instruments in East Antarctica", Cryosphere 2015
- Thiery et al " Surface and snowdrift sublimation at Princess Elisabeth station, East Antarctica, Cryosphere (2012)

...in regional climate models

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)

Case study using COSMO-CLM

MODEL:

Regional climate model CCLM 5.0 (COSMO model in climate mode)

Domain: Dronning Maud Land and adjacent Southern Ocean

Horiz. Res: 0.44º (~50 km); domain size: 100x100 grid points

Run length: one month (February 2011)

Forcing: NCEP reanalysis

- 6 prognostic moisture variables in the atmosphere:
  water vapour, cloud water, cloud ice, rain, snow and graupel

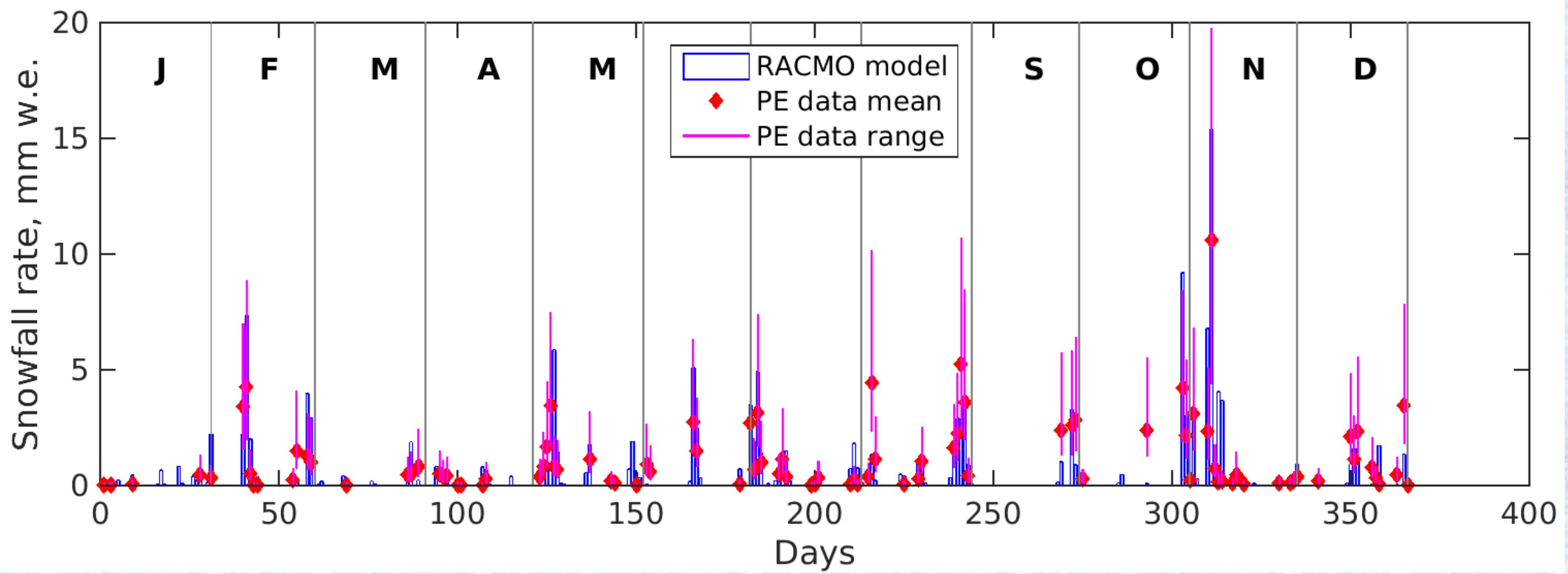
- Grid-scale precipitation scheme computes the effects of precipitation formation on temperature and the prognostic moisture variables in the atmosphere as well as the precipitation fluxes of grid-scale rain and snow at the ground

- Cloud microphysics: a two-category ice scheme (5 water categories qv, qc, qr, qs, qi); snow = rimed aggregates of ice crystals; cloud ice = small hexagonal plates

Snowfall evaluation:

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

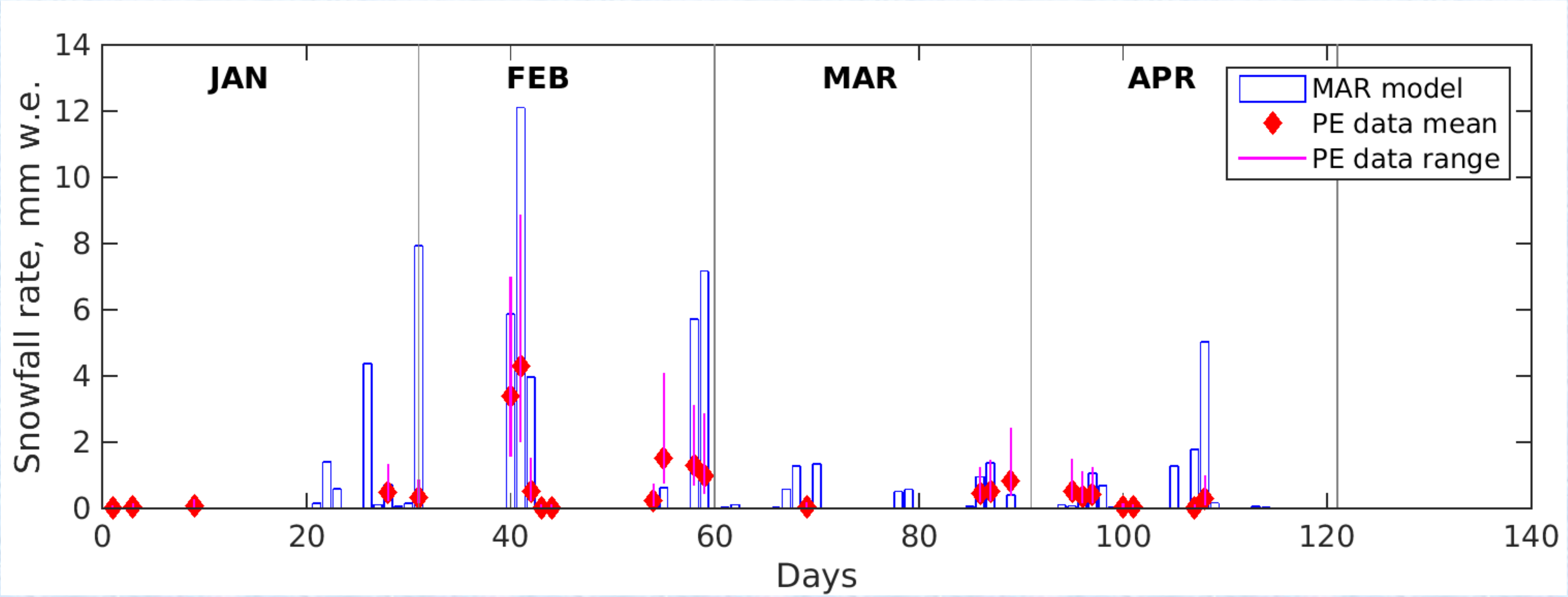
RACMO model



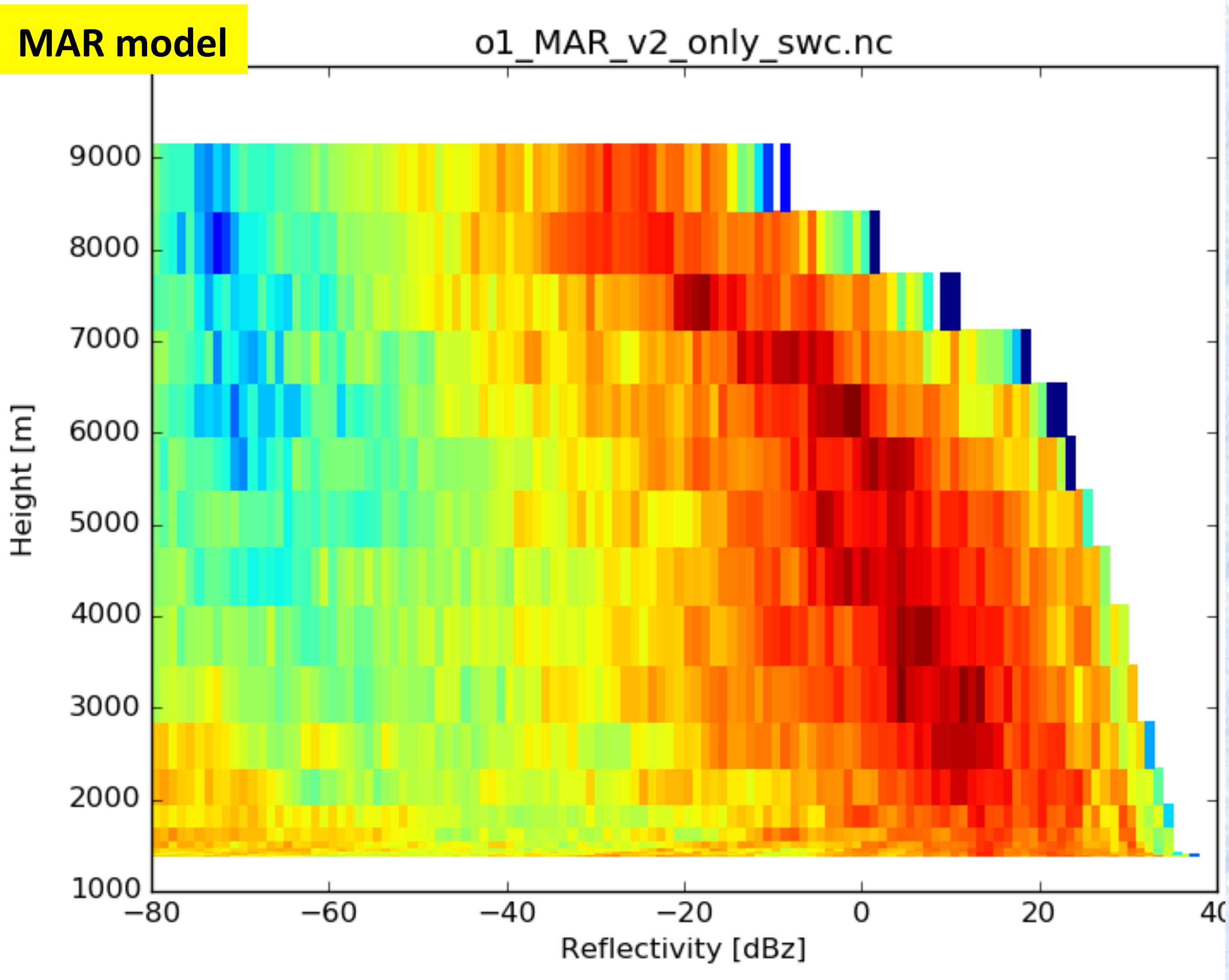
Snowfall evaluation:

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

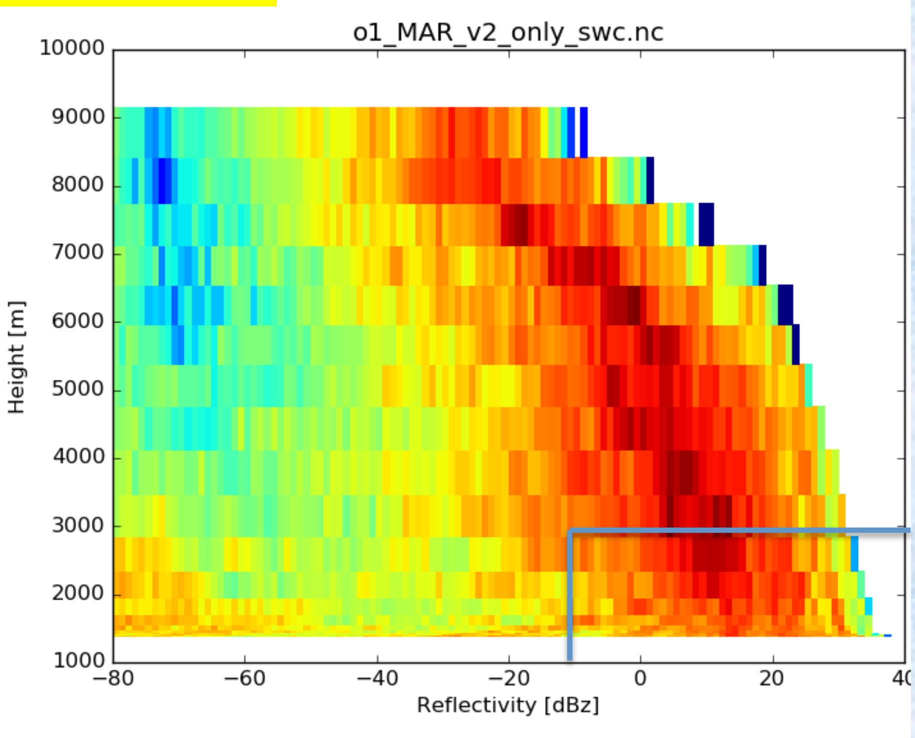
- Used to synthesize Ze at 24 GHz (MRR) for MAR model

MAR parameters used:

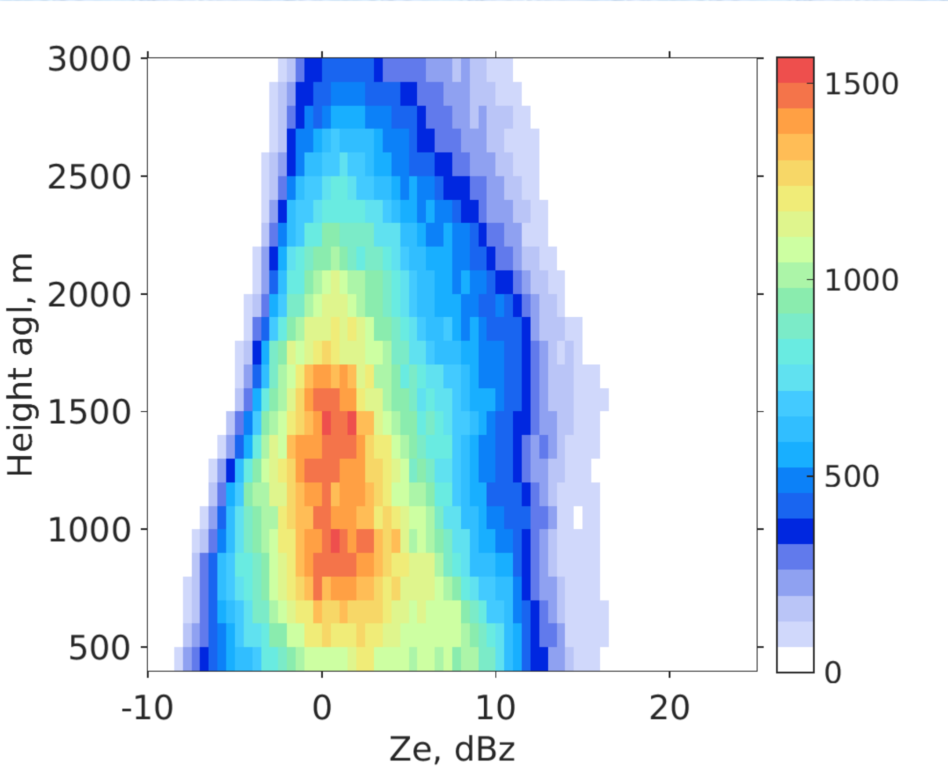
- V(D) for snow based on graupel-like sow of hexagonal type from Locatelli&Hobbs (1974)
- m(D): fixed snow density = 100 kg m^{-3}
- Snowfall N(D): exp (Marshall-Palmer)

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

MAR model



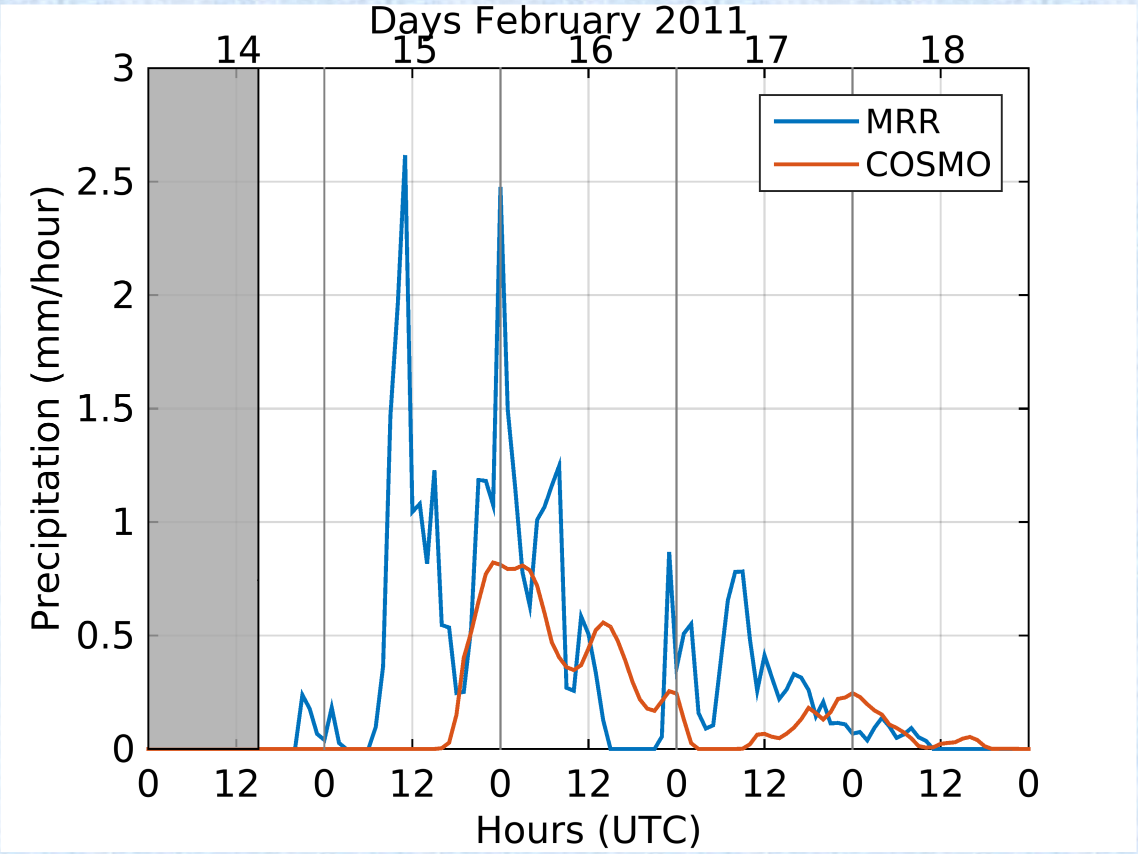
Ze forward-modeled using PAMTRA for MAR RCM snowfall (full model rage)



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

CCLM model

Comparing modeled and observed precipitation



Snowfall rates derived from MRR at PE* and simulated by CCLM (nearest to PE gridbox).

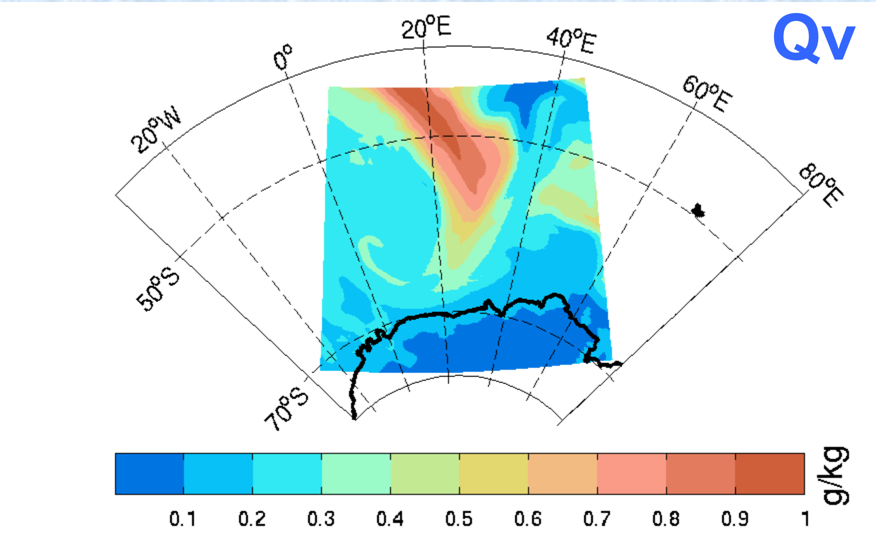
*Snowfall rate is calculated using nine Z-S relationships for dry snow from Kulie&Bennartz 2009 and Matrosov 2007, see Gorodetskaya et al 2015)

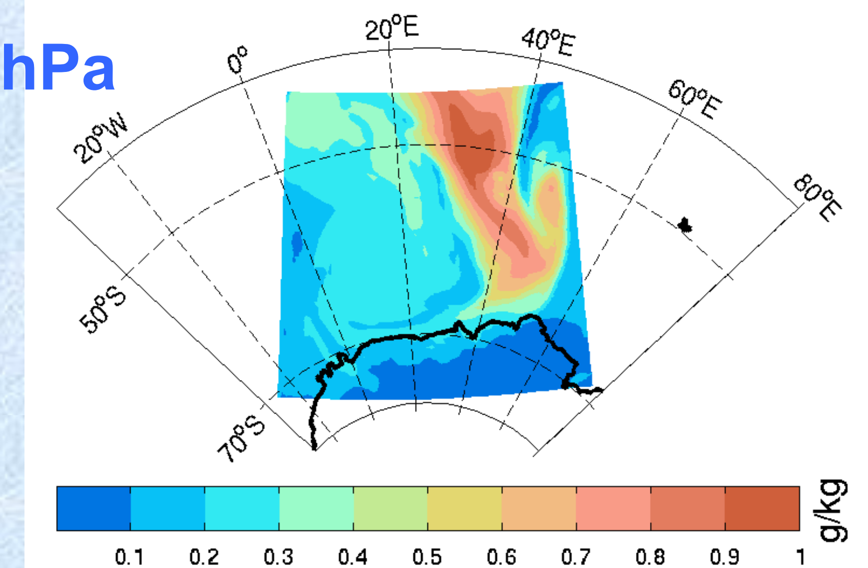
CCLM model

CCLM:
underestimates precipitation during AR case

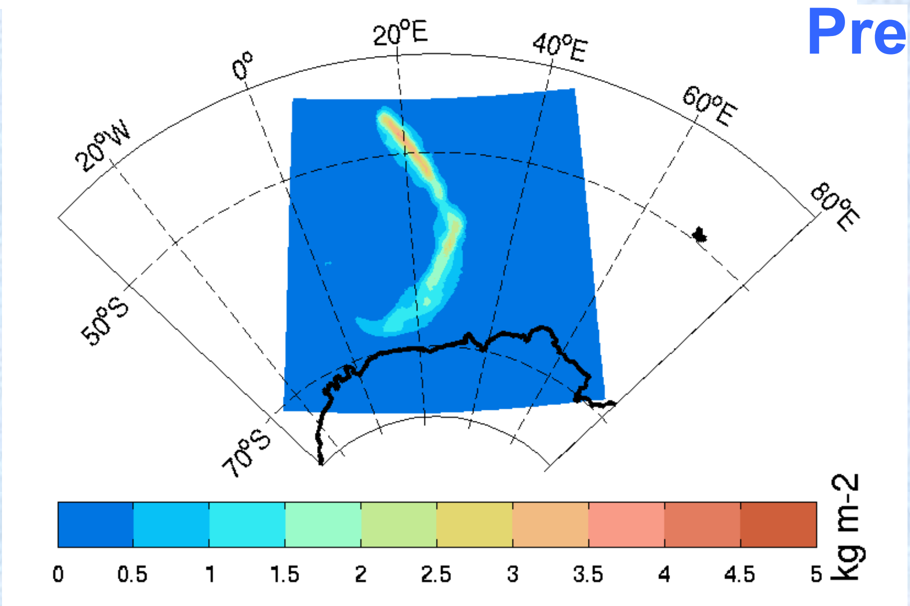
15 Feb 2011 **16 Feb 2011**

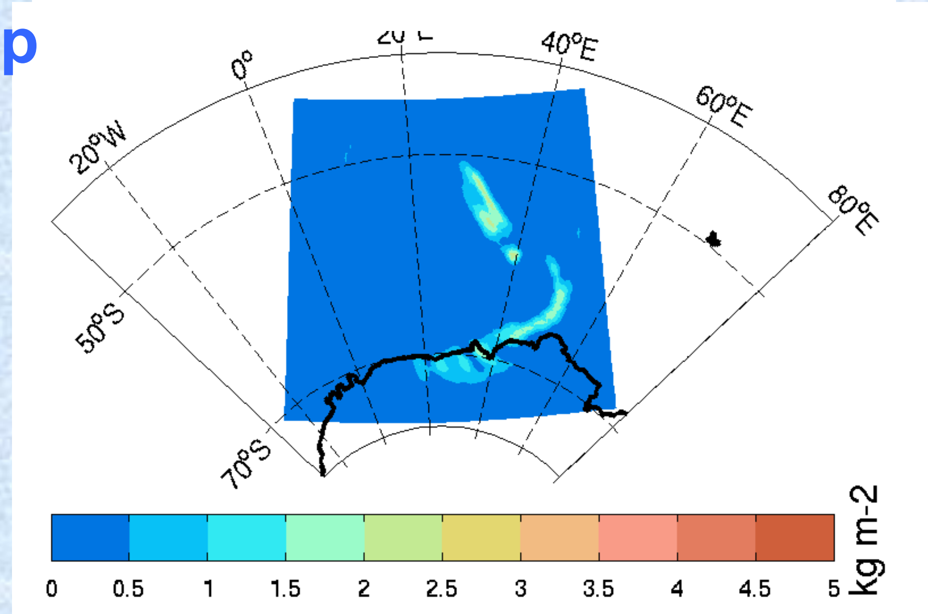
Qv 850 hPa



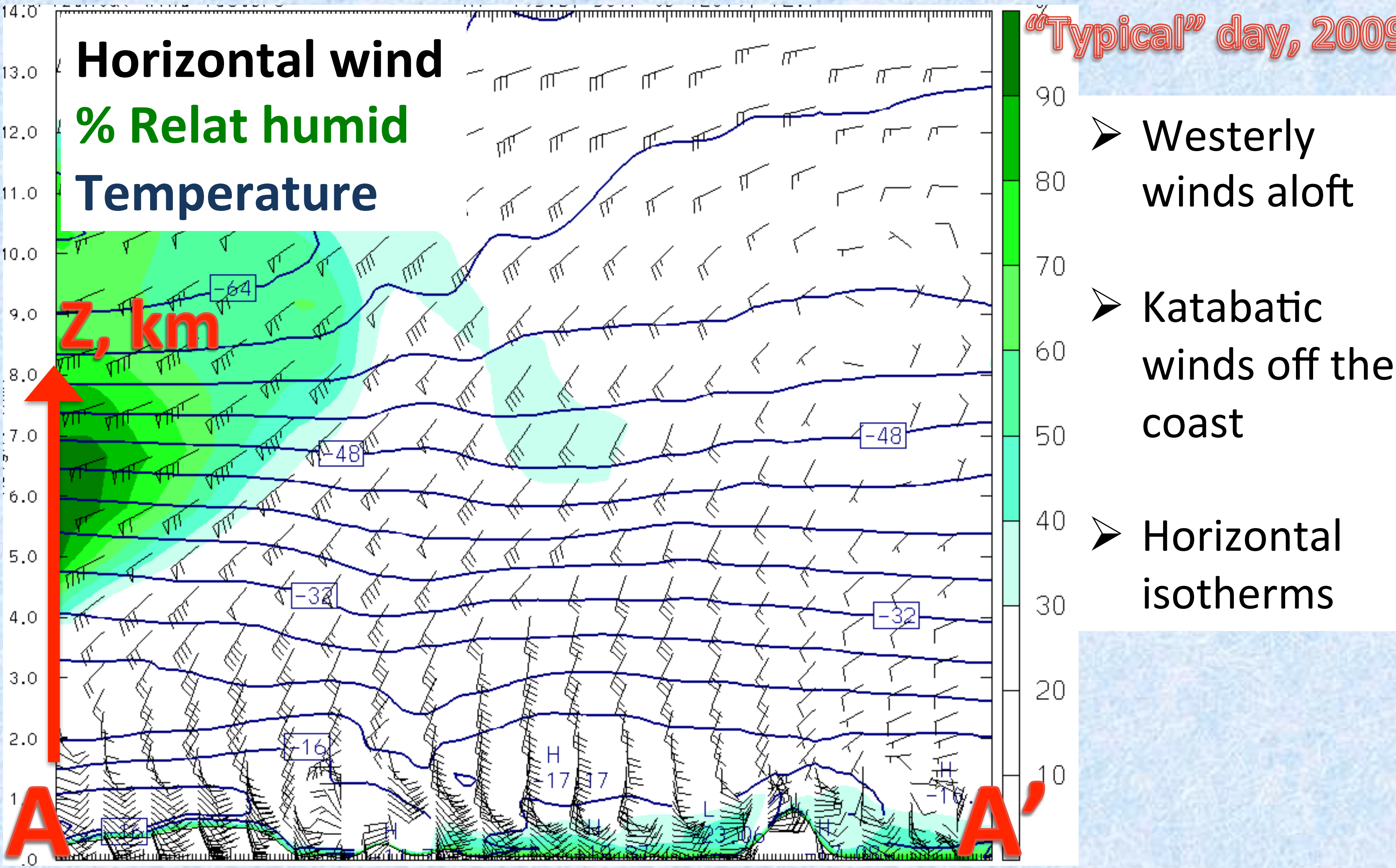


Precip





Vertical profile along DML coast (10°E – 50°E)

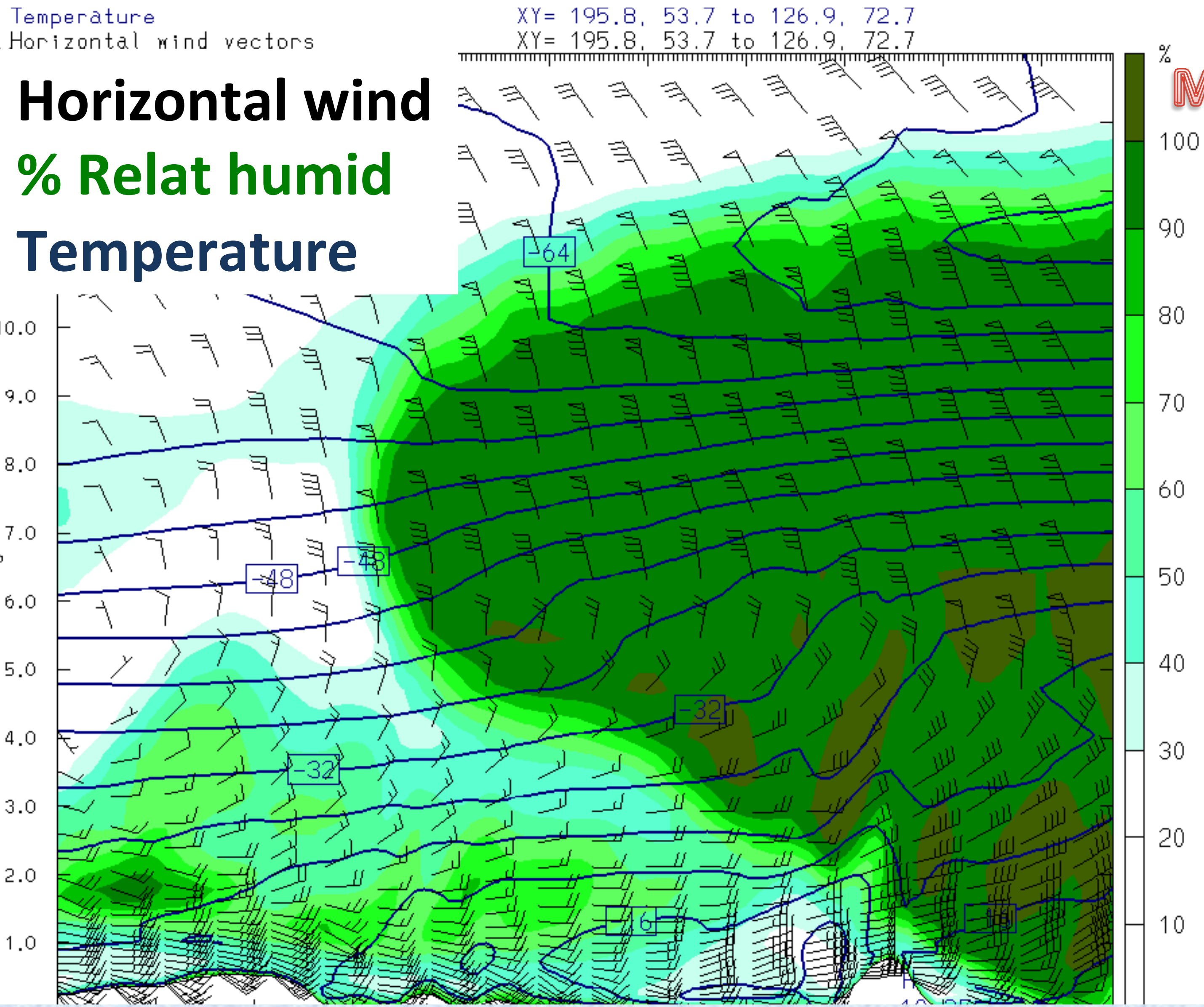


- Westerly winds aloft
- Katabatic winds off the coast
- Horizontal isotherms

WRF model

Tsukernik et al., in prep

Vertical profile along DML coast (10°E – 50°E)



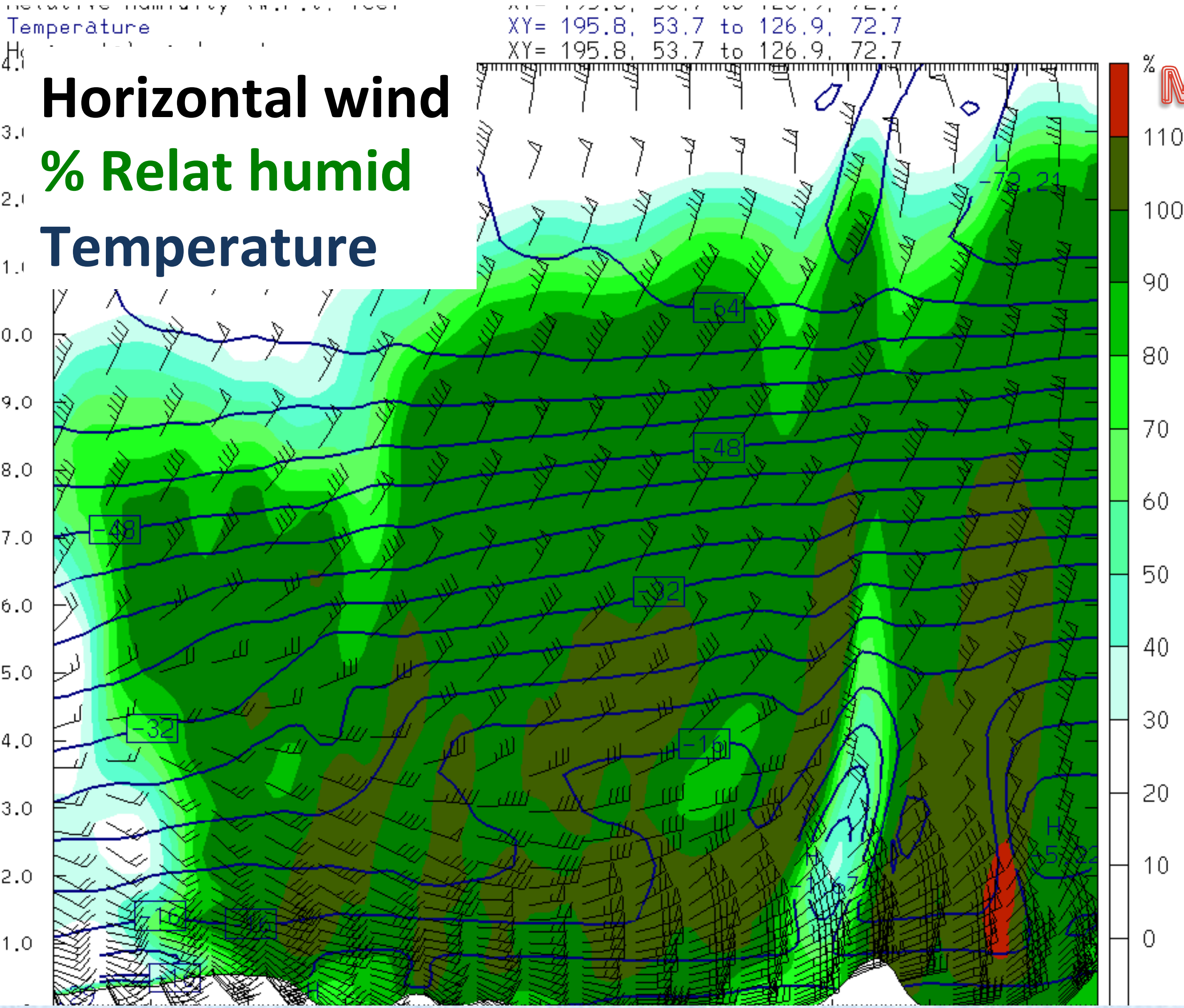
May 18, 2009 @ 00

- Approaching storm
- Warm temperature advection
- Saturated air
- Easterly flow along the coast

Tsukernik et al., in prep

WRF model

Vertical profile along DML coast (10°E – 50°E)

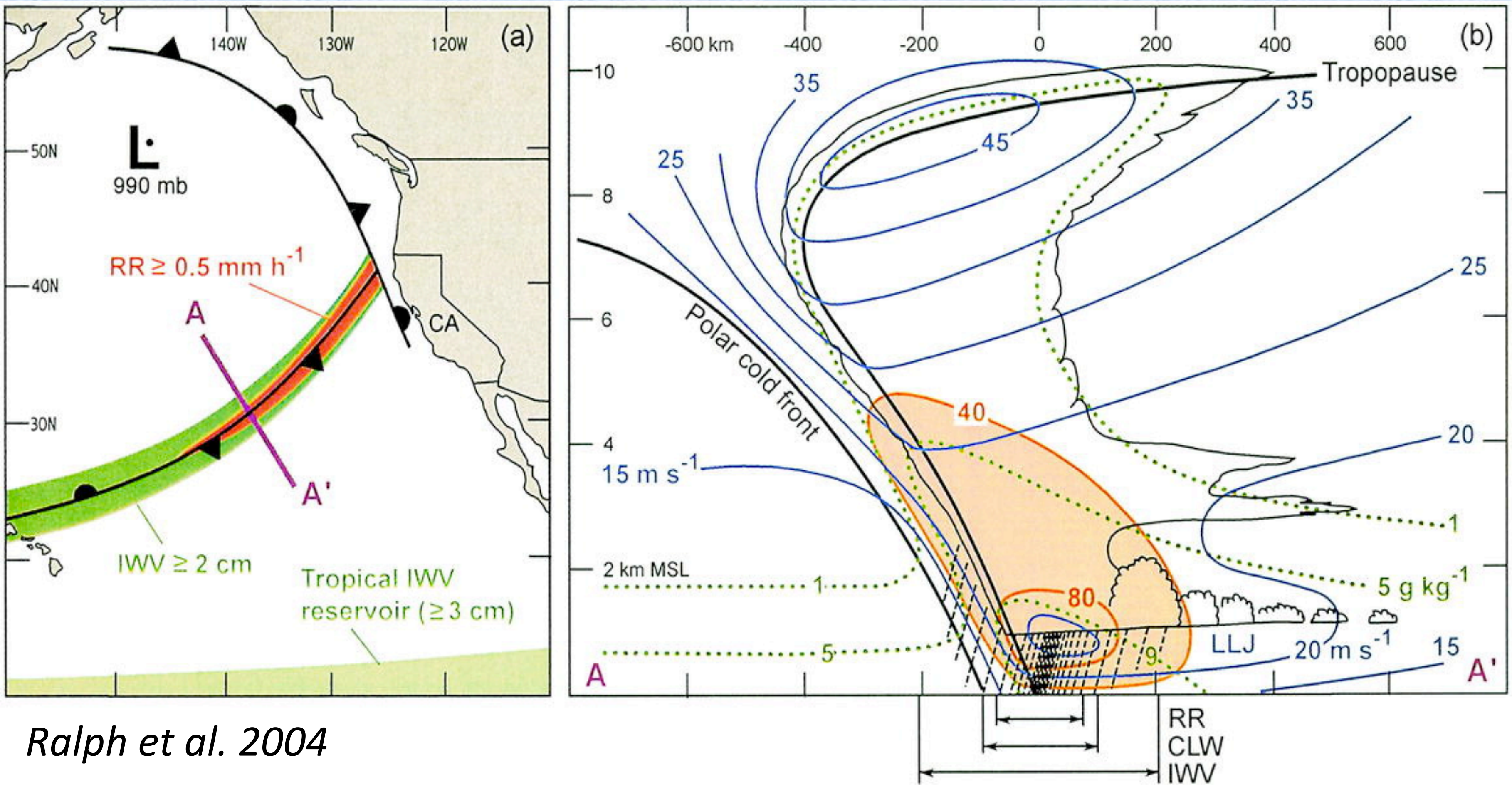


May 18, 2009 @ 12

- Warm temperature advection @ low levels
- High moisture content
- LLJ with northerly component

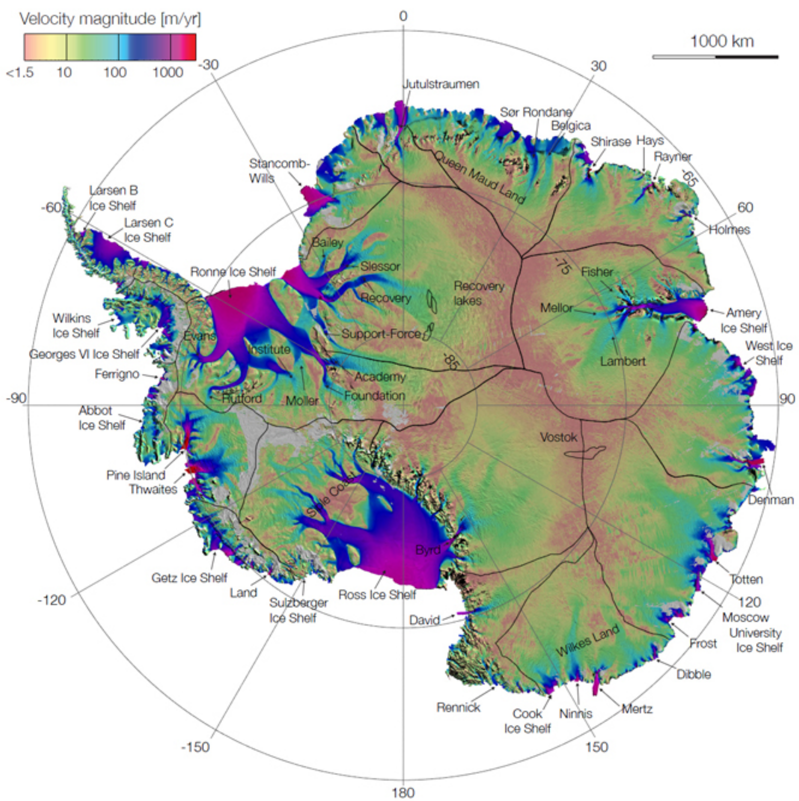
Tsukernik et al., in prep

Vertical cross section of a typical midlatitude atmospheric river



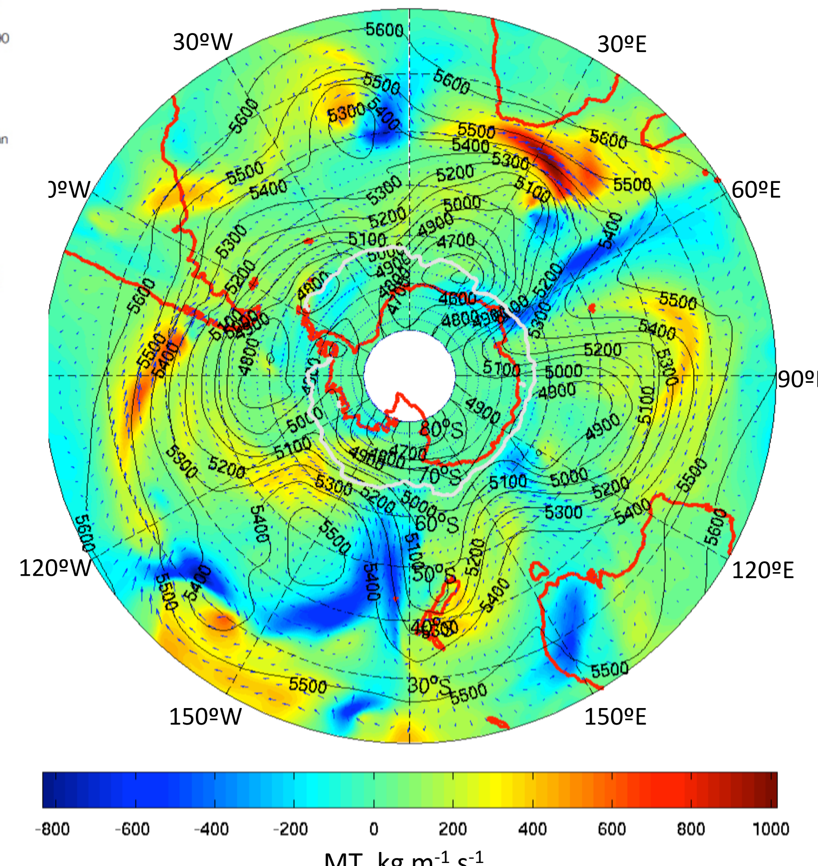
Ralph et al. 2004

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 astmospheric moisture transport on 19 May 2009

Gorodetskaya et al 2014

Conclusions

- *Atmospheric rivers explain the majority of extreme precipitation events in such coastal areas as Portugal, California and escarpment zone of East Antarctica*

- *Antarctica: The large contribution of atmospheric rivers to Dronning Maud Land surface mass balance implies that the difference in the regional total annual SMB is determined by the frequency of occurrence of ARs.*

- *Influence of an atmospheric river on specific watersheds and river flow in mid latitudes will also strongly depend on its characteristics (landfall, strength, orientation,...) and local surface characteristics (complex terrain*

- *High resolution modeling (best at convection-permitting scales <4 km) is needed to resolve orographically-forced precipitation and its influence on the local hydrology*

- *Need to understanding the ocean-atmosphere linkage behind atmospheric rivers*

Conclusions cont-ed

- **Antarctic surface mass balance** is dependent on many processes => integrated measurements and analysis are needed for model evaluation and process understanding
- **New observatory installed within HYDRANT project in East Antarctica**

  provides ground-based remote sensing of clouds and precipitation,

  + meteorological parameters, snow accumulation and radiative fluxes
- **Derived parameters include:**

- Cloud/precipitation base height
- Cloud types (ice clouds and virga, mixed-phase clouds)
- Snowfall rate
- SMB components (sublimation – sfc and drifting; wind erosion)

- **MRR measurements** => high-resolution estimates of snowfall rate and relationship to SMB + direct comparison using forward modeling (avoids uncertainties in SR estimates)
- **Regional climate models** tend to overestimate intense snowfall events => need for parameterization improvements

Thank you for your attention!
Questions? Feedback?

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