Simulations of Föhn in Antarctica with WRF for the Antarctic Mesoscale Prediction System AMPS

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UKRI Natural Environment Research Council
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IMAU Institute for Marine and Atmospheric research Utrecht

Sharing is encouraged

Background: Why Föhn, why here?

Location: Where are we?

Data and methods: What data is used?

Data and methods: How is Föhn identified?

Results: Föhn vs no Föhn

Results: Observations vs Model

Upstream conditions and flow characteristics

Results: The Role of Clouds

Thank you!

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Background:

Föhn:

The Antarctic Peninsula is one of the fastest warming regions in the world.

There are regional and seasonal differences, with winter winter warming strongest on the western side, and strong warming in summer and autumn on eastern side.

A mechanism to explain these seasonal and regional differences are Föhn winds.

A positive trend in the Southern Annular Mode (SAM) supports this. A stronger SAM index leads to stronger circumpolar westerly winds. Instead of being blocked by the mountain range, these stronger winds are more likely to overcome the barrier. This in turn leads to Föhn effect on the lee side of the Antarctic Peninsula.

Larsen Ice Shelves:

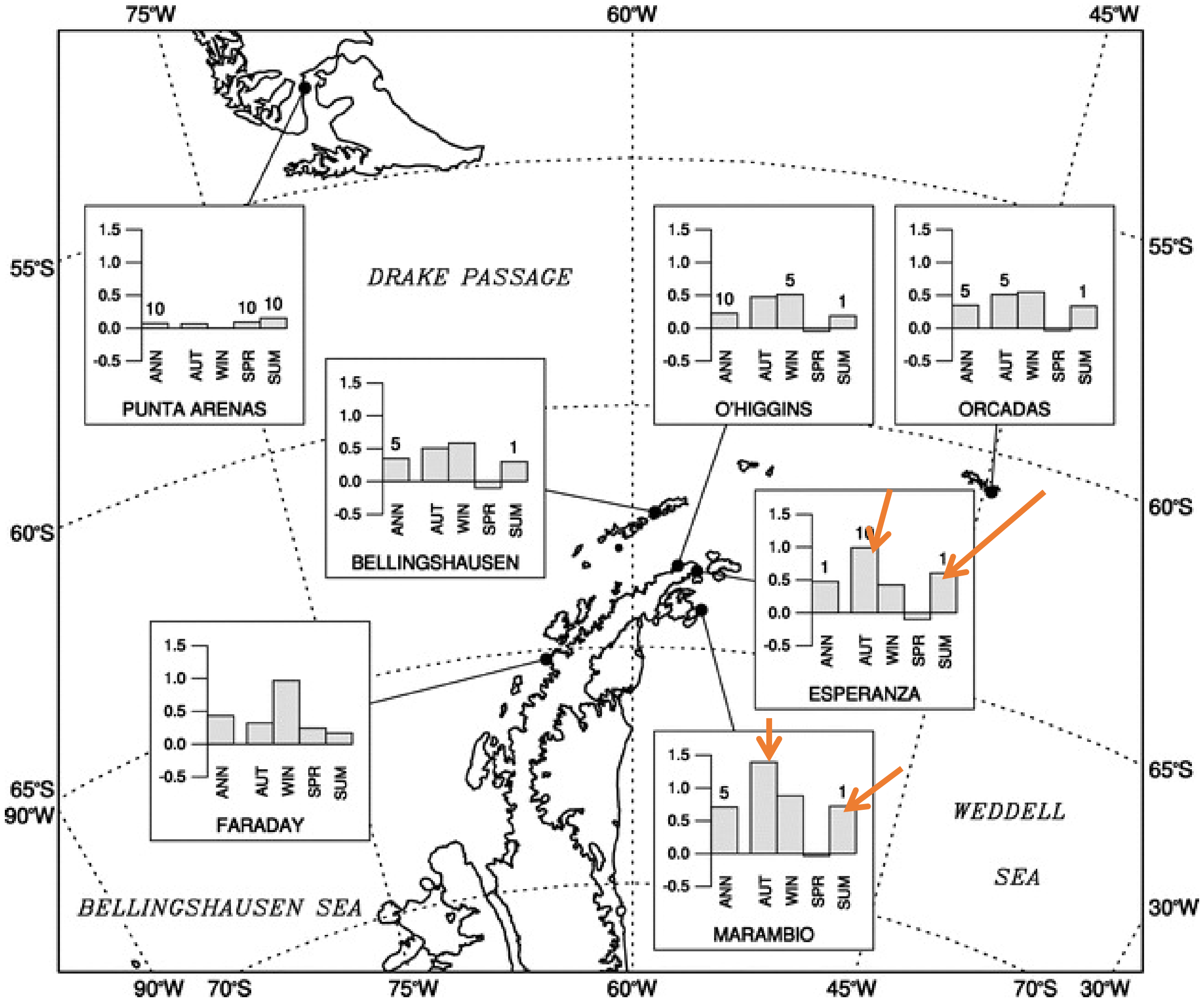
The dominant feature on the leeside of the Antarctic Peninsula is the Larsen Ice Shelf.

Its northern parts Larsen A and Larsen B have collapsed in 1998 and 2002 respectively.

Warm, dry Föhn winds are thought to have provided the atmospheric conditions that have led to the collapse through hydro-fracturing (Scambos et al., 2004).

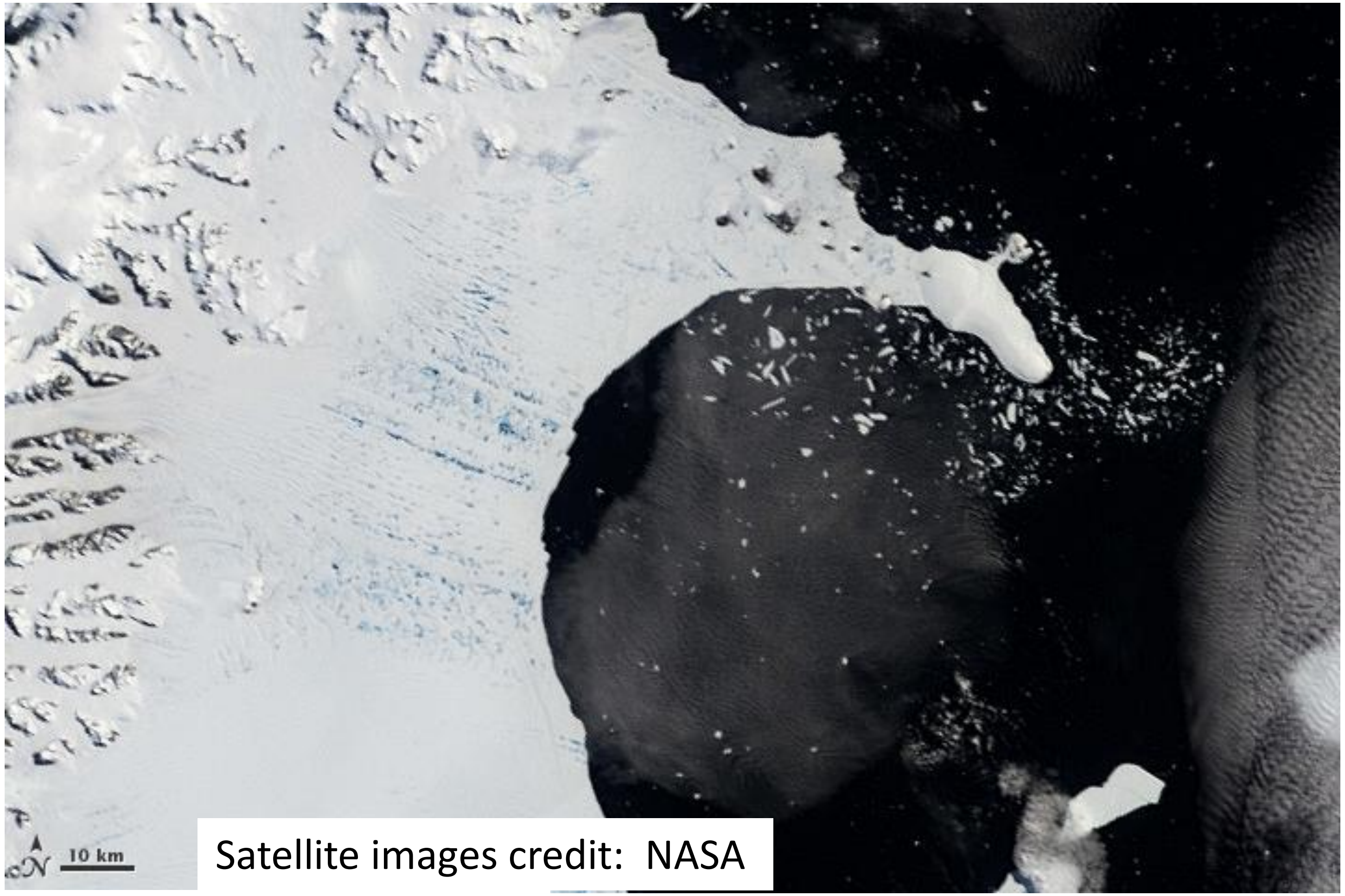
Föhn winds are a major influence on the stability of the remaining Larsen C ice shelf.

- Antarctic Peninsula has warmed more rapidly than global average
- regional and seasonal differences
- winter warming strongest on the western side
- strong warming in summer and autumn on eastern side



Marshall et al (2006), Journal of Climate

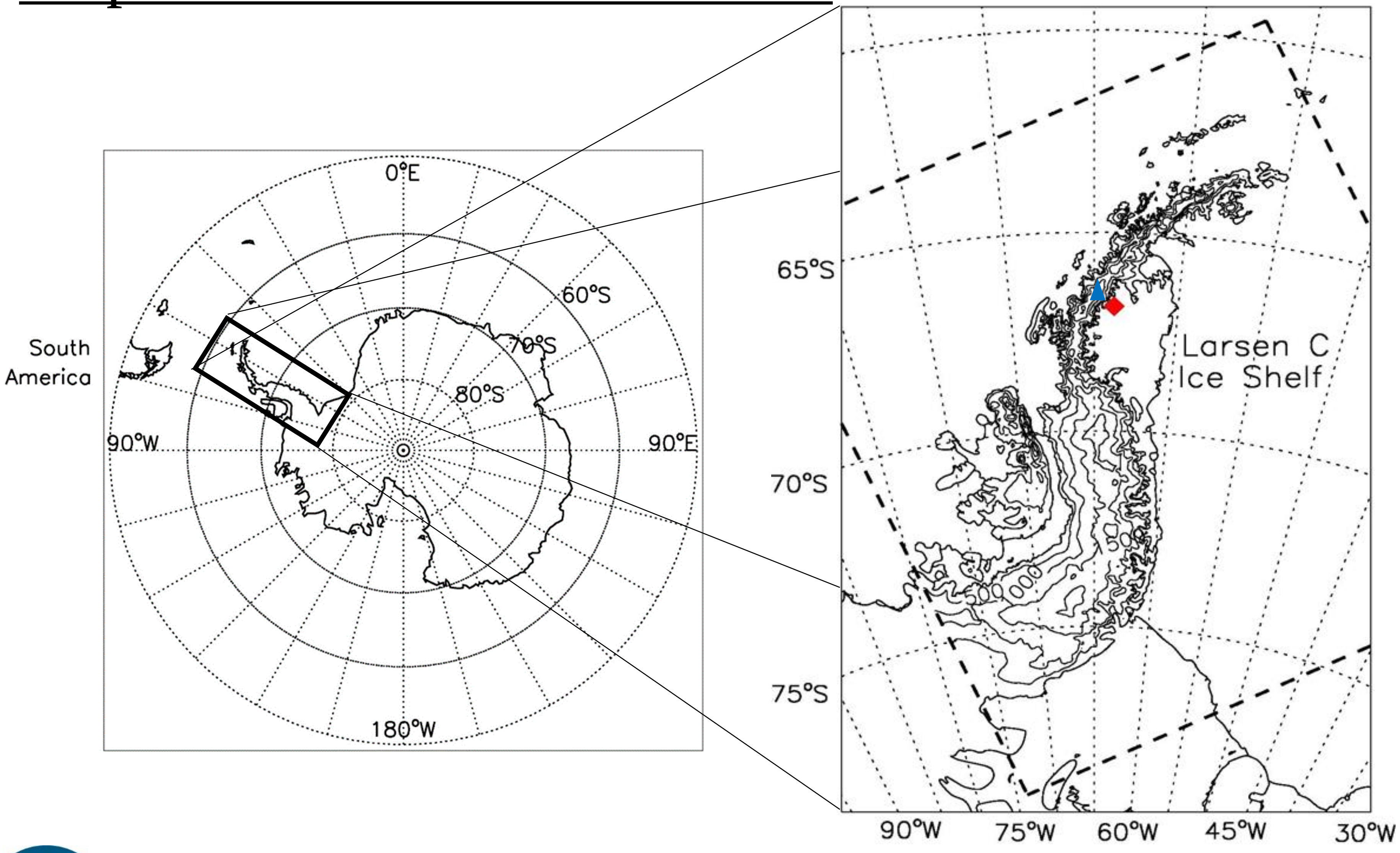
Animation of the collapse of Larsen B Ice Shelf collapse over the period from Jan 31st to April 13th 2002



Satellite images credit: NASA

It is widely accepted that hydrofracturing, the widening of crevasses due to the excess hydrostatic pressure exerted by meltwater which accumulates inside them, is the mechanism behind the break-up of the Larsen A and Larsen B ice shelves (e.g. Scambos et al, 2004).

Map of the Antarctic Peninsula



Dashed lines mark the model domain of the Antarctic Mesoscale Prediction System.

◆ Cole Peninsula AWS

▲ Avery Plateau AWS

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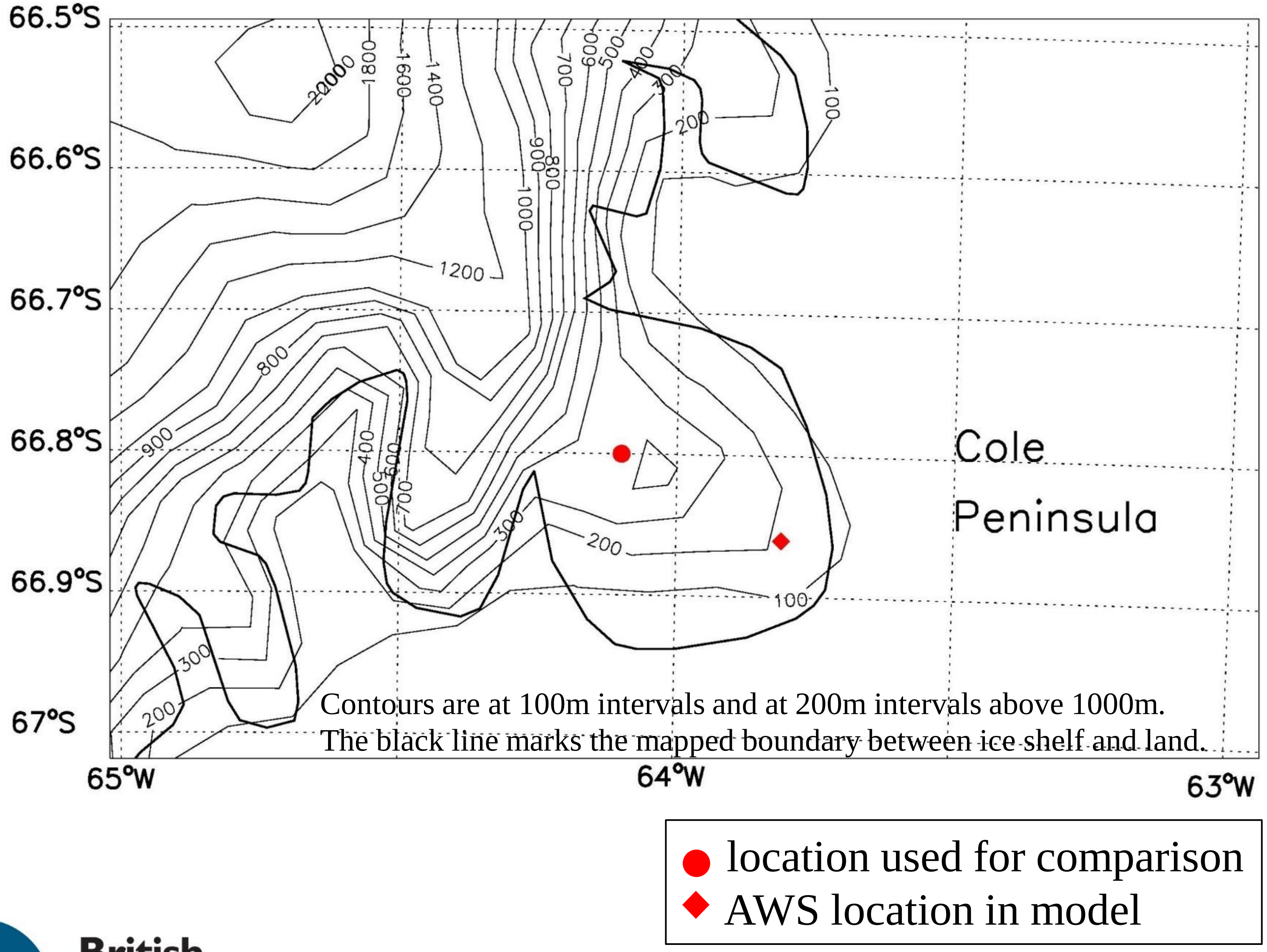

The model orography in the area of Cole Peninsula differs from reality.

The diamond marks the GPS location of the AWS projected on model orography. The circle marks the location chosen for the comparison between measurements and model output, as it more closely resembles the AWS location in reality (424m asl).

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Observations

- Automatic Weather Station at Cole Peninsula
- Temperature & Relative Humidity
- Wind speed and direction
- Air pressure
- Solar powered with battery back up
- Data transmission via Iridium short burst messages
- 10 min measurements collated to six hour mean values

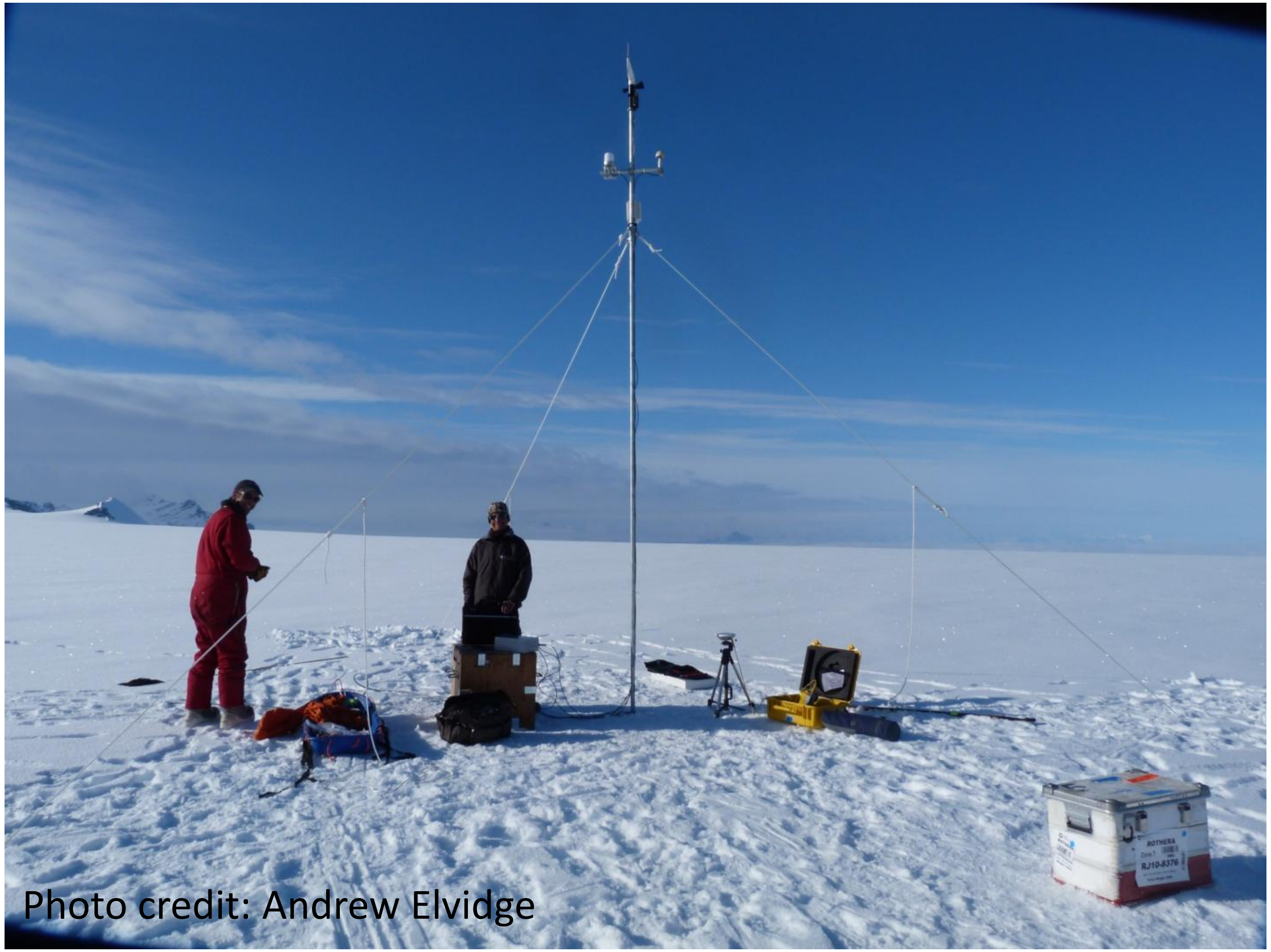
Data available at: https://catalogue.ceda.ac.uk/
(search for “AWS”, “Antarctic Peninsula”

Model data

- Antarctic Mesoscale Prediction System AMPS
- Weather, Research and Forecasting model WRF
- 5km resolution
- 44 model levels
- output of initialisations at 00UTC and 12UTC combined to 6 hourly artificial time series.

Data available: www.earthsystemgrid.org

Automatic Weather Stations at Cole Peninsula and Avery Plateau



- RM Young prop vane (4m above surface)
- GPS and Iridium antenna at 3.5m
- Humicap HMP45D at 3m
- Pressure sensor buried with logger box at the foot of the AWS.

Automatic Weather Station at Cole Peninsula

Operational from Jan 21st 2011 – Jan 4th 2012

Location: 66°51'48''S, 63°48'39''W
424m above sea level

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Automatic Weather Station at Avery Plateau

Operational from Jan 9th 2011 – July 4th 2011 (then buried by snow)

Location: 66°52‘38''S, 65°27‘23''W
1813m above sea level

Photo: Amélie Kirchgaessner

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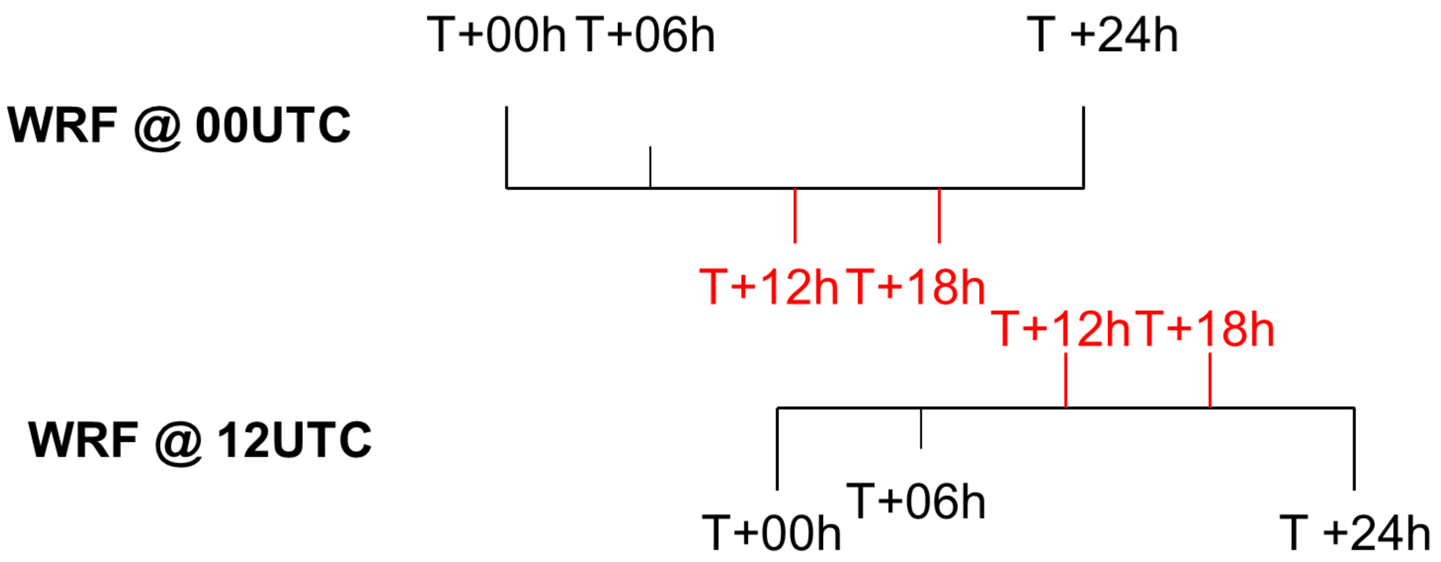
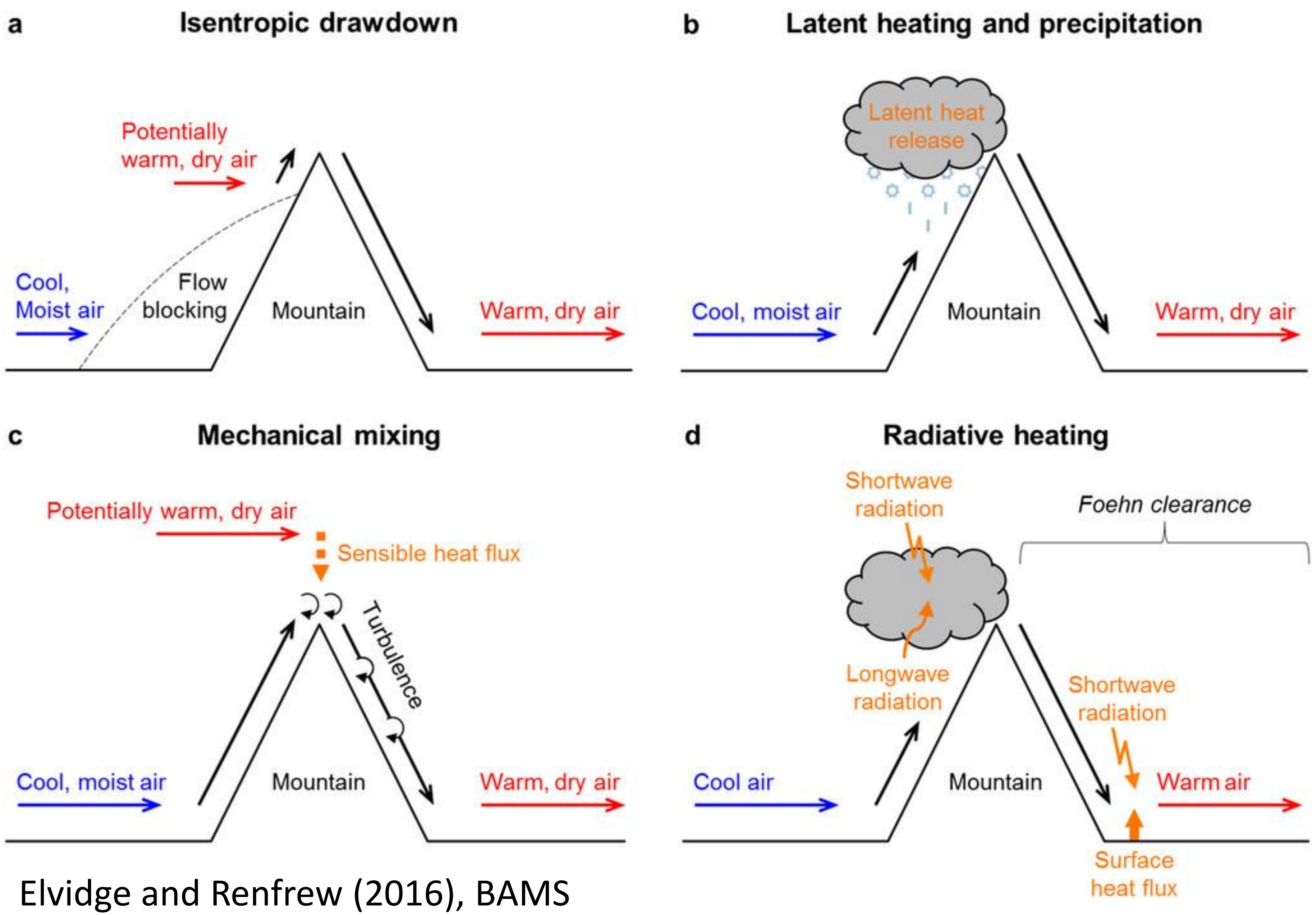
Schematic of how the two daily initialisations of the model runs were combined into a 6 hourly time series. E.g. Seefeldt and Cassano (2008) have shown that up to 12 hours are needed for the model to adjust to topography.



Föhn mechanisms that lead to warming in the lee of mountains:

- ❄ Isentropic drawdown
- ❄ Latent cooling and precipitation
- ❄ Mechanical mixing
- ❄ Additional radiative heating



Elvidge and Renfrew (2016), BAMS

How do we identify Föhn cases?

In the observations:

We use thresholds empirically obtained from measurements during an intensive aircraft field campaign.

either RH < 65%
or RH < 70% and 3K temperature increase or decrease over 12 hours.

For the comparison only data points are considered that are identified as Föhn in observations and simulations.

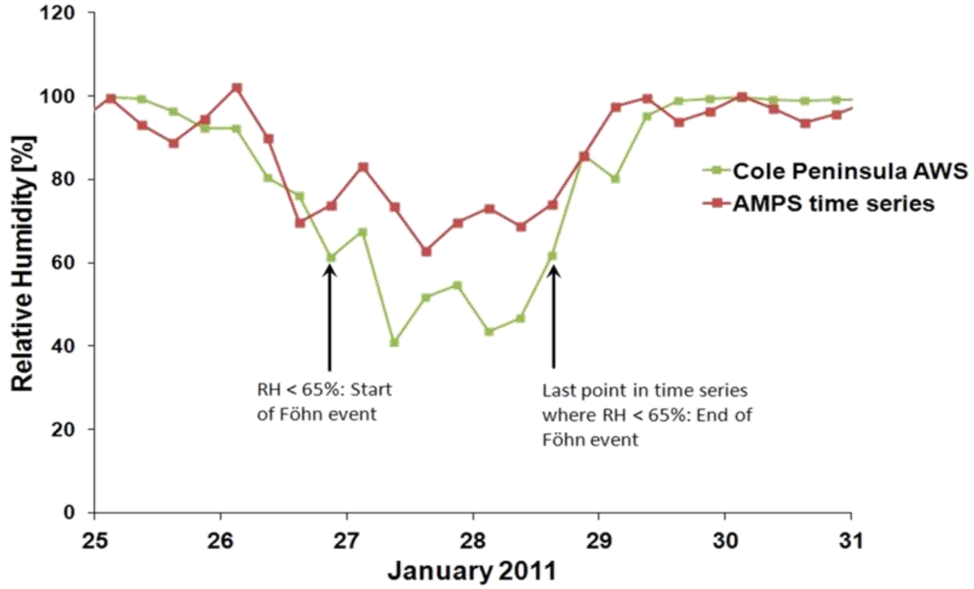
In the model simulations:

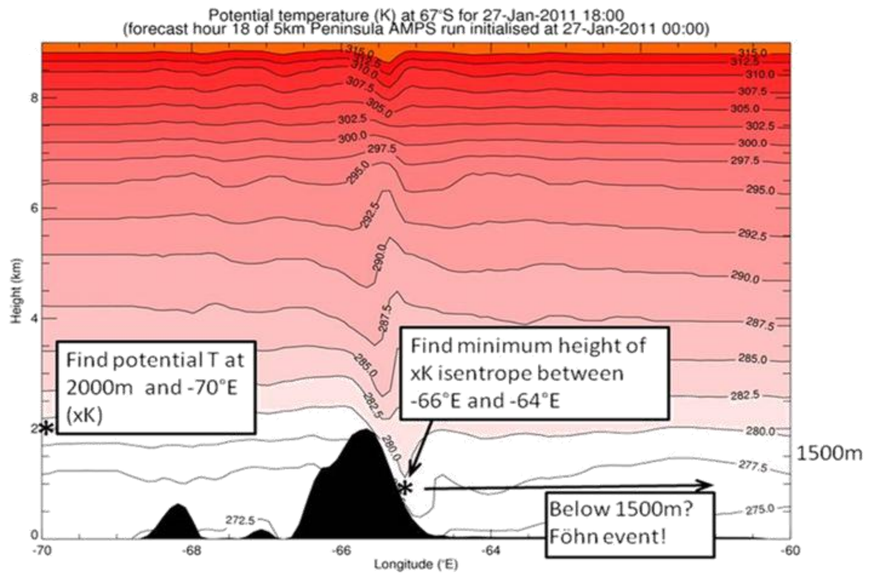
We extract the potential temperature at 70°W and 66.8°S (to match the latitude of the AWS) at 2000m height.

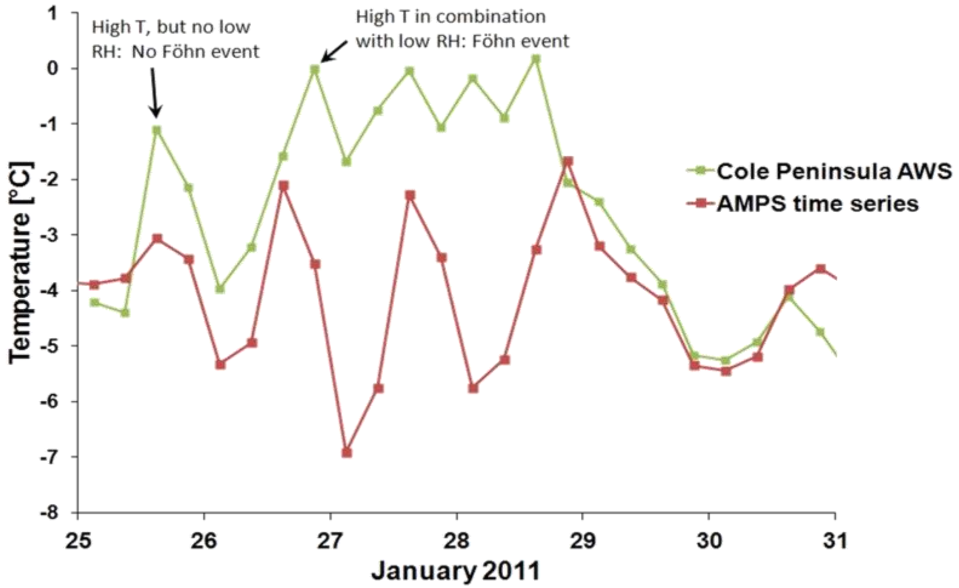
The point at 70°W is about one Rossby radius upwind of the AP, and therefore can be considered representative of the undisturbed upwind flow under westerly conditions.

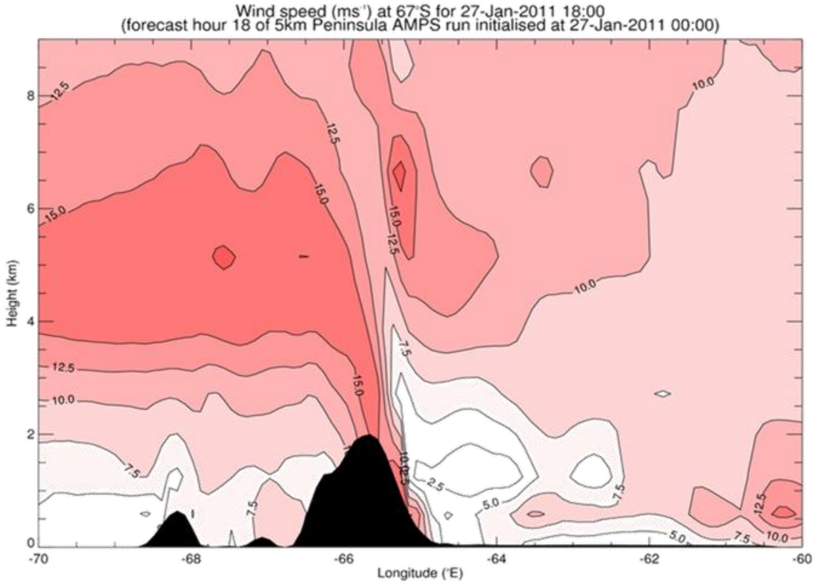
Then the minimum height of this potential temperature value on the lee side of the mountains along 66.8°S was determined in the section between 64°W and 66°W.

If this minimum height was lower than 1500m (signifying a drawdown of at least 500m), this data point was classified as Föhn.









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Obs vs Sim

Observations vs simulations
Cole Peninsula

- AMPS overestimates the near surface Temperature
- AMPS underestimates near surface Relative Humidity
- Wind speed and direction do not agree that well. In such complex terrain this is not unexpected.
- **Generally the model does a good job simulating conditions at Cole Peninsula**

n = 1352	T [° C]	p [hPa]	RH [%]	u [m/s]	v [m/s]	ff [m/s]
AWS	-12.3 ±10.3	942.7 ±11.9	84 ±23	1.5 ±4.2	-1.8 ±1.7	3.9 ±3.3
AMPS	-11.8 ±8.6	942.5 ±12.2	81 ±19	3.8 ±4.5	1.2 ±4.9	6.6 ±4.7
Mean bias	0.5	-0.2	-2	2.3	3.0	2.7
Correlation	0.93	0.99	0.76	0.28	-0.07	0.49
RMSE	3.88	1.59	15.6	5.68	6.07	5.05

Kirchgaessner et al (2019), JGR-A

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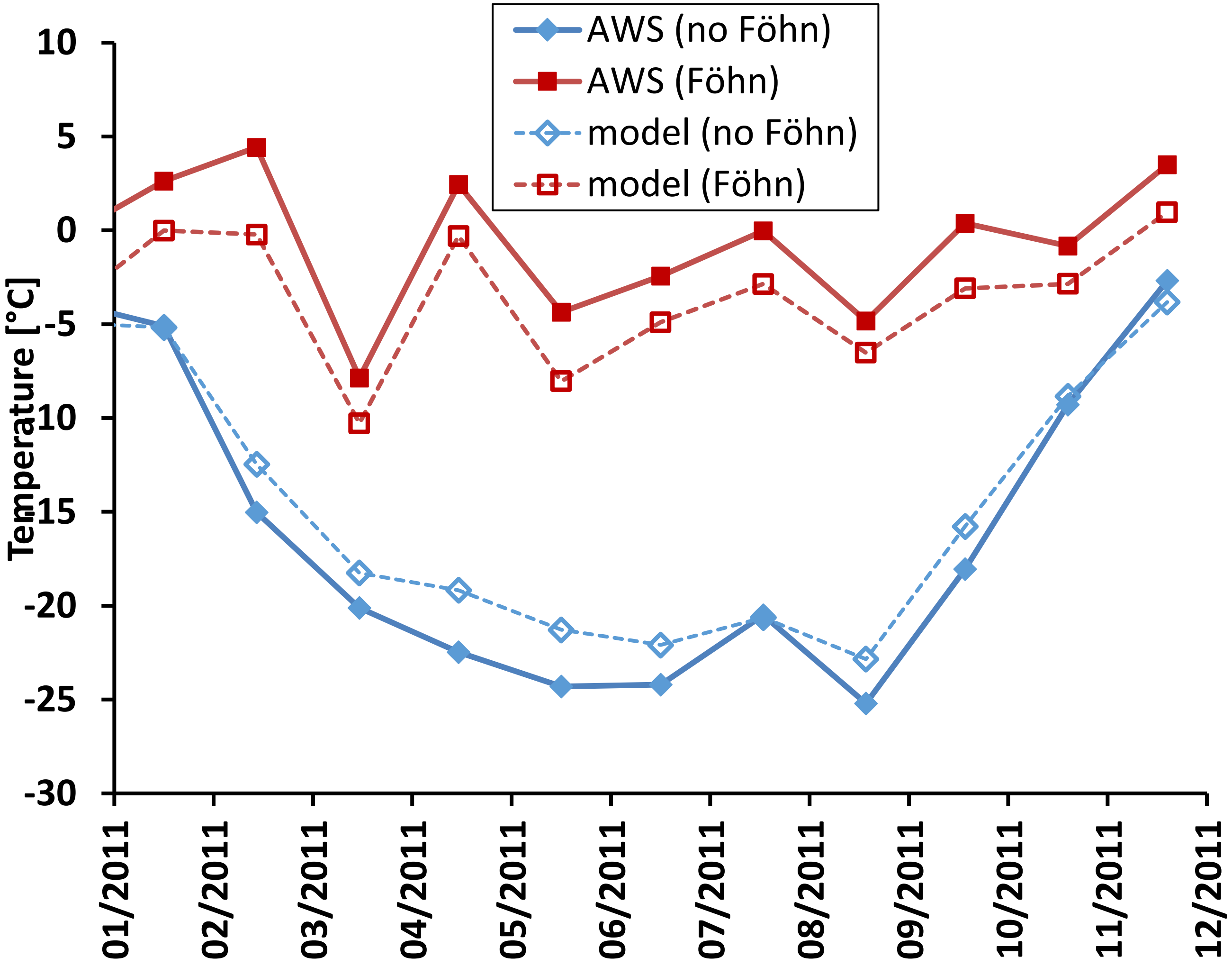
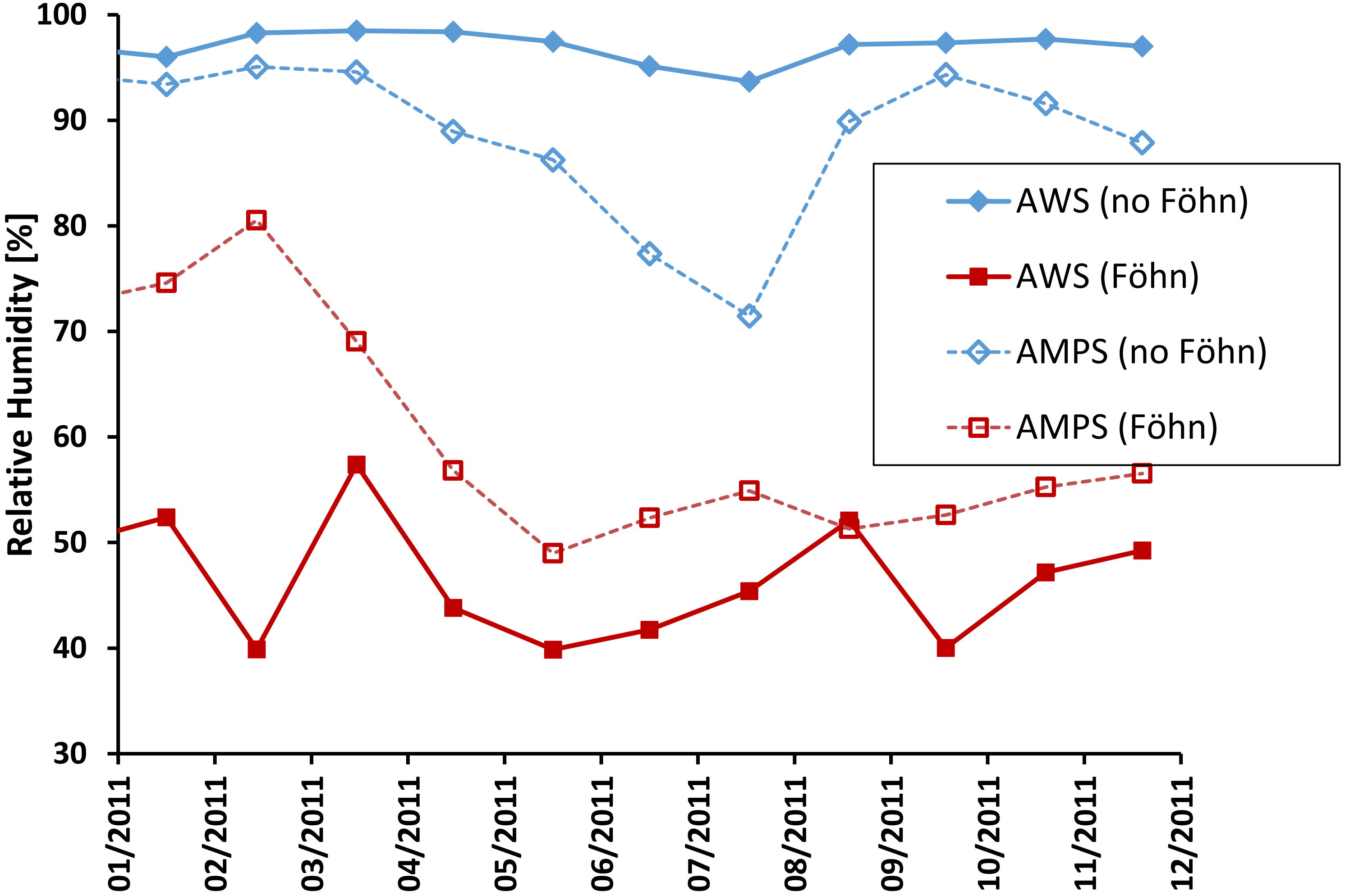
Temperature



- generally model and observations agree well
- for „no Föhn“ data points the model **over**estimates temperature
- for „Föhn“ data points the model **under**estimates the temperature

Kirchgaessner et al (2019), JGR-A

Relative humidity



- generally good agreement, less so in winter
- for „no Föhn“ data points the model **under**estimates RH
- for „Föhn“ data points the model **over**estimates RH

Kirchgaessner et al (2019), JGR-A

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Föhn vs no Föhn

Föhn versus no Föhn

- Significantly higher T during Föhn than no Föhn in both data sets
- Significantly lower RH during Föhn than no Föhn in both data sets
- AMPS underestimates T during Föhn
- AMPS overestimates RH during Föhn

	T [° C]	p [hPa]	RH [%]	a [g/m^3]	u [m/s]	v [m/s]	ff [m/s]
no Föhn (AWS):	-16.9± 8.8	942.9±11.8	97 ± 5	2.9±0.8	2.3 ± 4.0	-1.7 ± 1.5	3.8 ± 3.4
Föhn (AWS)	-0.4 ± 4.9	943.4 ±11.4	46 ± 13	2.2±0.6	-0.9 ± 2.6	-2.2 ± 2.6	3.4 ± 2.7
Difference (AWS)	16.5K	0.5	-51	-0.7	-3.2	-0.5	-0.4
no Föhn (AMPS):	-15.3 ±7.9	942.6 ±12.0	91 ± 13	1.5±1.0	2.7 ± 2.7	3.0 ± 3.7	5.4 ± 3.0
Föhn (AMPS):	-3.2 ± 4.6	942.7 ±11.8	60 ± 13	2.3±0.9	7.6 ± 7.2	-4.4 ± 4.5	10.4 ± 7.4
Difference (AMPS)	12.1K	0.1	-31	0.8	4.9	-7.4	5.0

Kirchgaessner et al (2019), JGR-A

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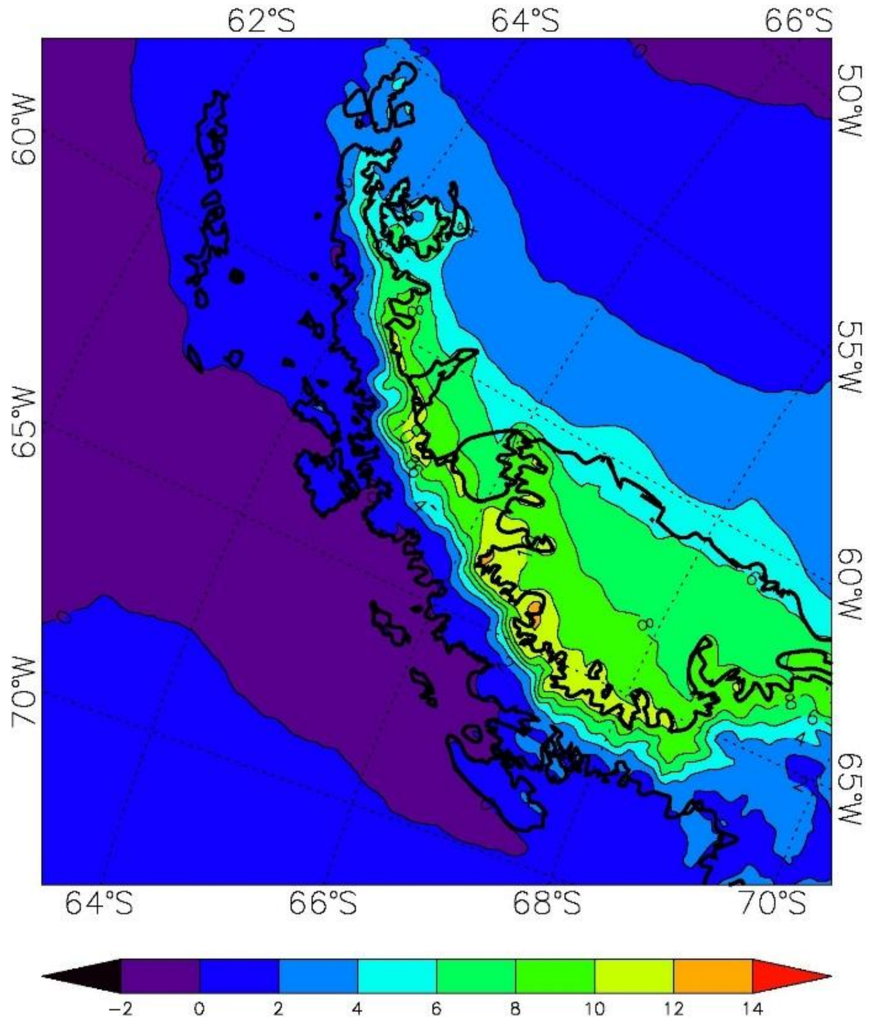
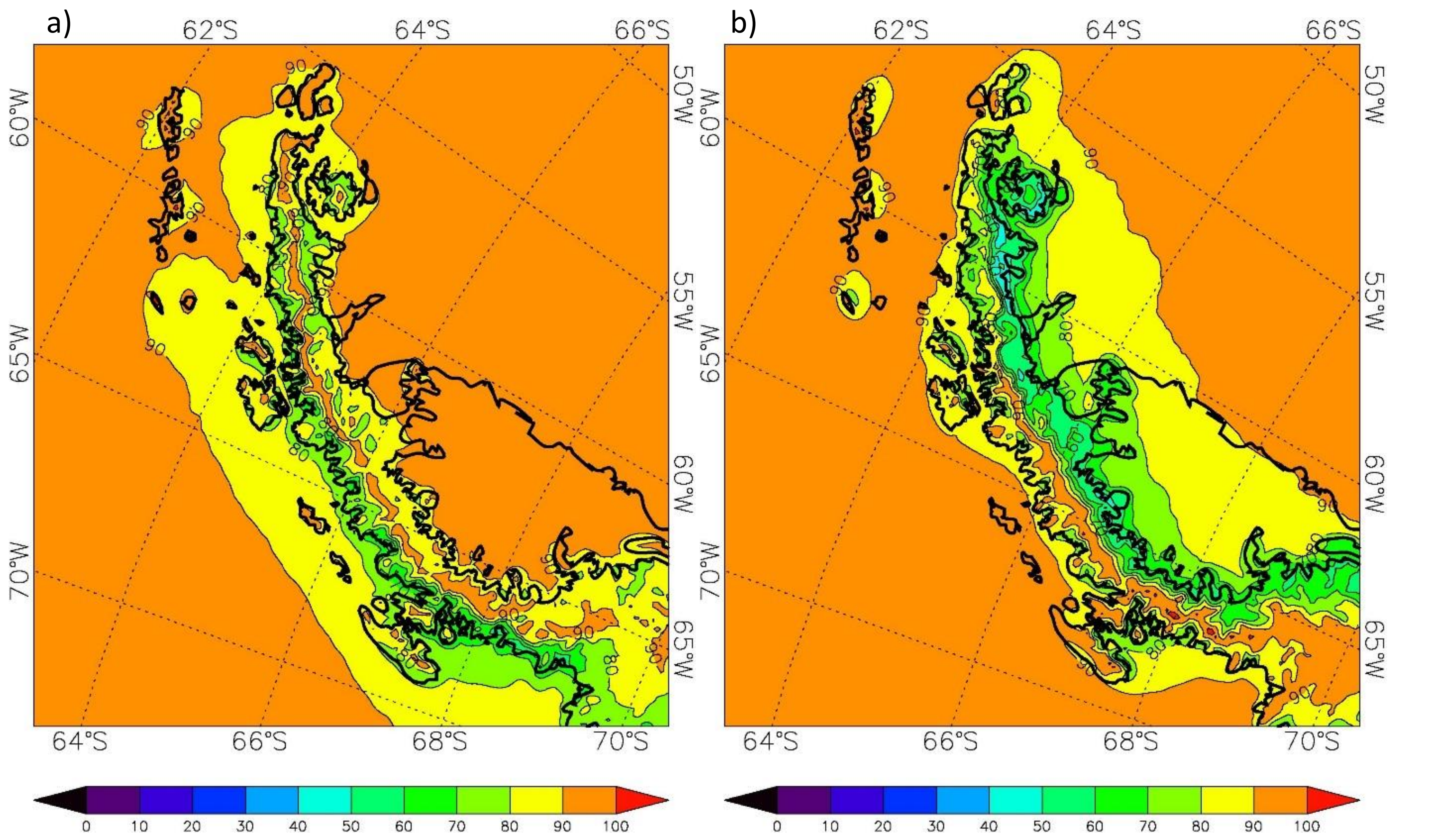


Difference in modelled 1.5 m temperature (K) between composites for Föhn and no Föhn conditions.

Up to 12K difference in surface near air temperature are shown in model output between Föhn and no Föhn conditions.

The largest difference occurs at the foot of the Antarctic Peninsula mountains.

Kirchgaessner et al (2019), JGR-A

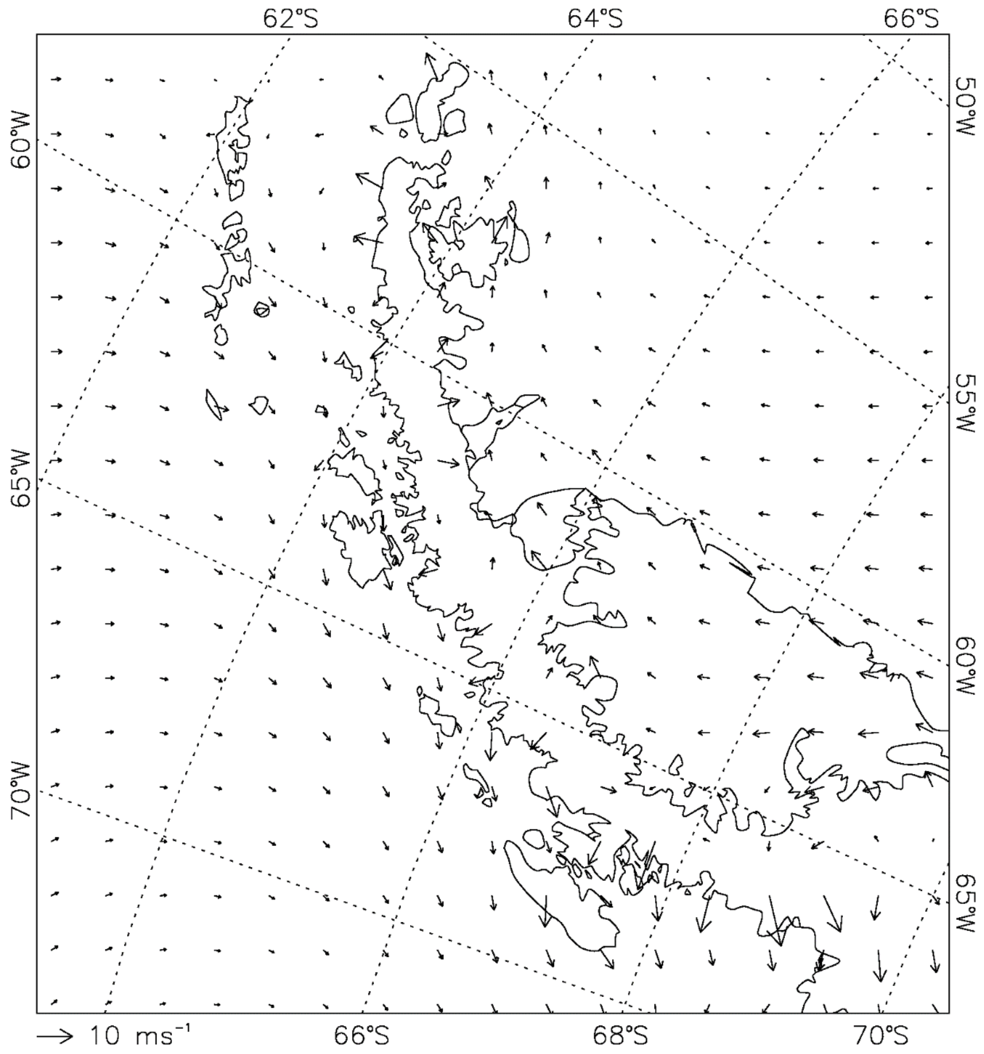


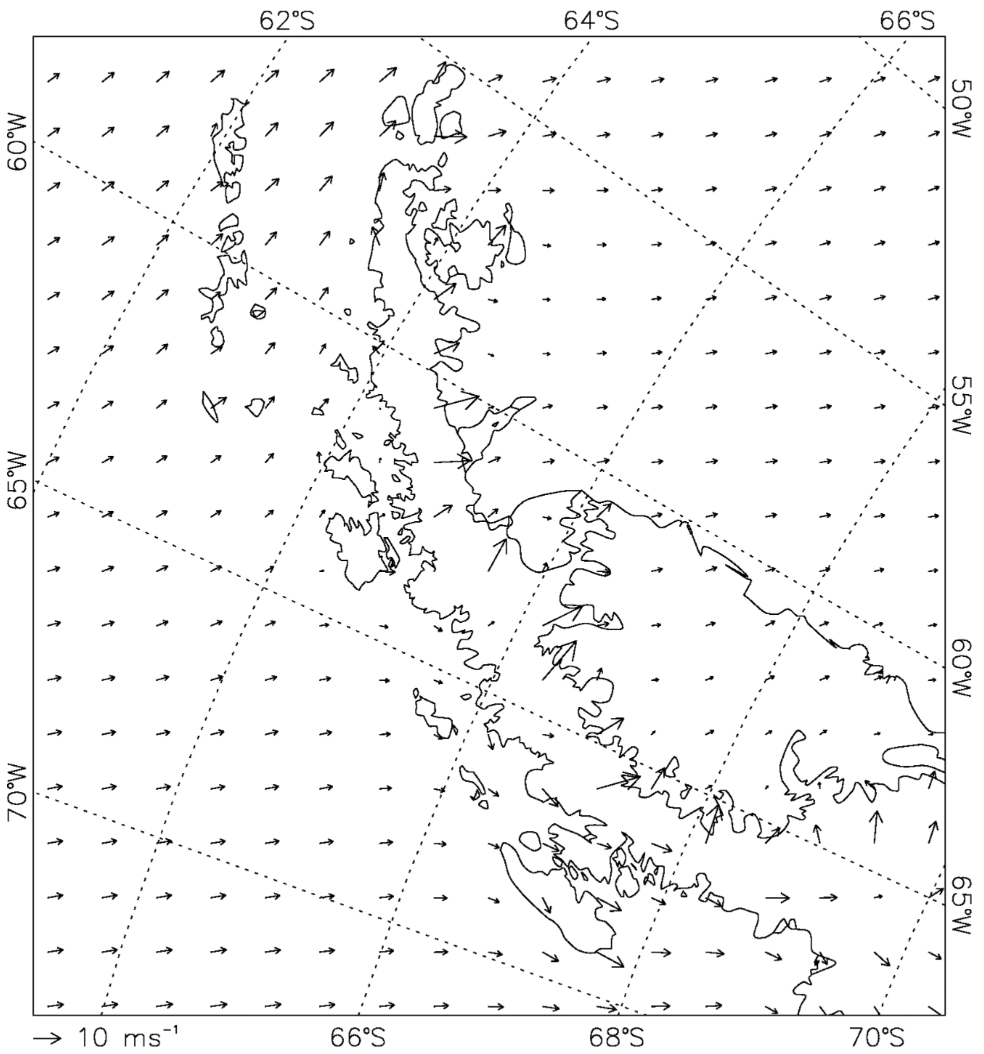
Simulated RH shows a stark contrast between Föhn and no Föhn conditions.

Largest differences are found in the direct lee of the spine of the Antarctic Peninsula mountains.

Composite plots of relative humidity with respect to ice for non-Föhn (a) and Föhn (b) conditions based on AMPS data (lowest model level, ~16m).

Kirchgaessner et al (2019), JGR-A





The blocking effect of the mountain range during normal conditions is clearly visible (left).

Strong cross barrier winds from NW to W dominate during Föhn conditions (right).

Composite plots of the wind speed and direction at 10m height for non-Föhn (left) and Föhn (right) conditions during 2011, based on AMPS data.

Kirchgaessner et al (2019), JGR-A

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Clouds

The Role of Clouds

Surface energy balance comparison by King et al. (2015) indicate WRF simulates

- low level clouds that are optically too thin.

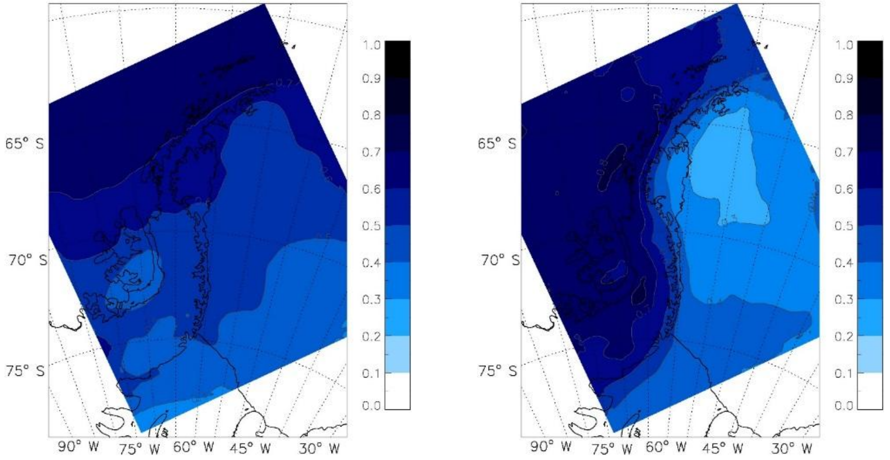
Experiments by C. Listowski show that independent of cloud scheme, the model

- underestimates the fraction of low level cloud, on the windward side. Hence the
- cloud clearing effect of Föhn is likely smaller, and thus
- the effect on T and RH is also reduced.

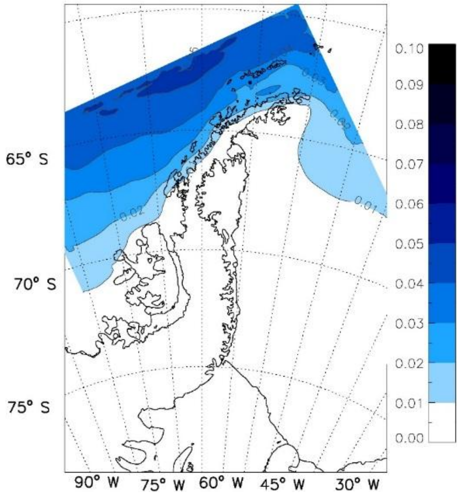
Possible reason is the absence of any liquid water in clouds in the area in the simulations.

Studies by Grosvenor et al. (2012) and Lachlan-Cope et al. (2016) have shown that, in reality, a significant amount of liquid water is present in clouds on both sides of the Antarctic Peninsula.

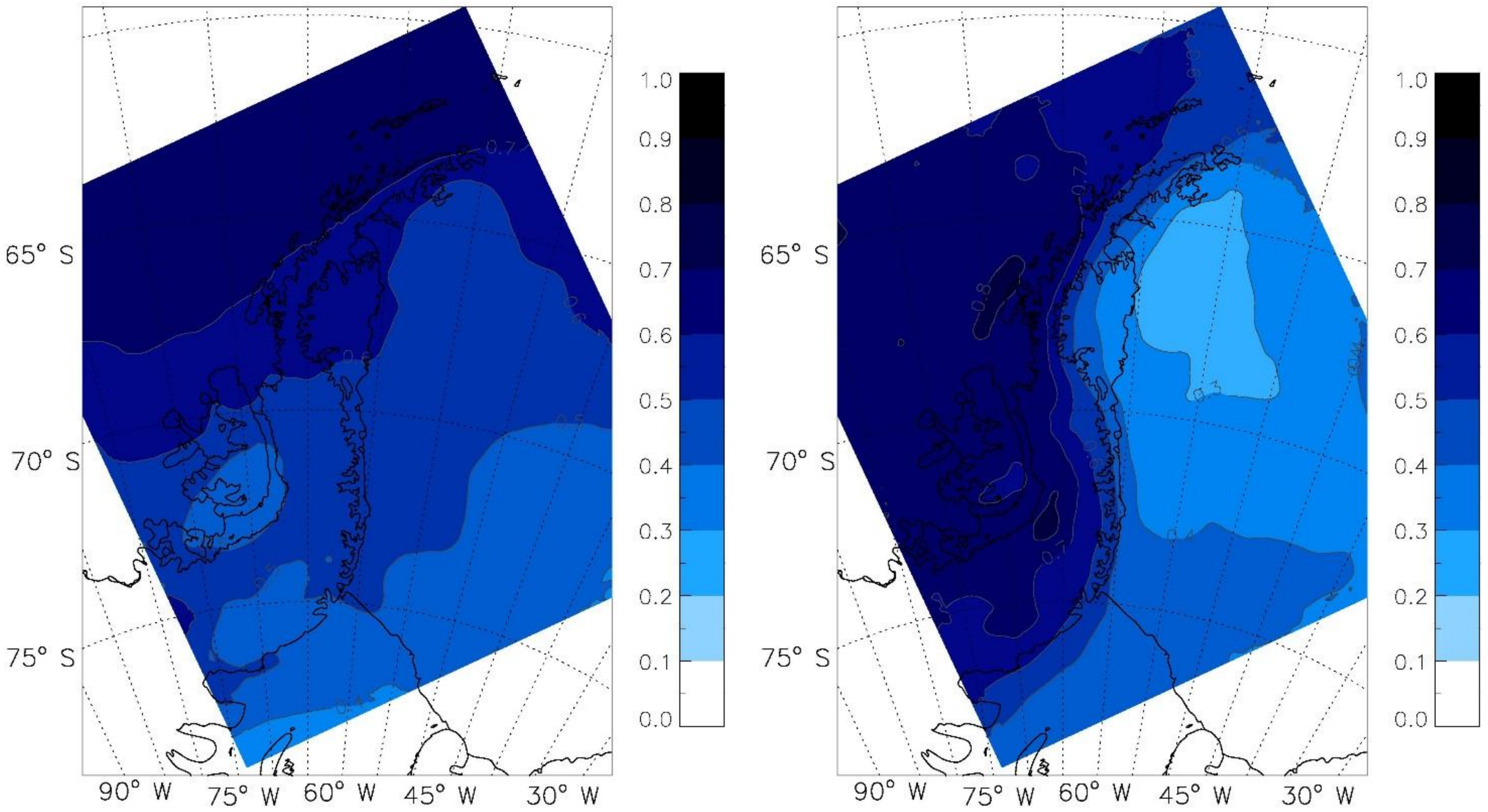
Kirchgaessner et al (2019), JGR-A



No Föhn   Cloud fraction   Föhn



Liquid cloud water (all data points)



This comparison of simulated cloud fraction between no Föhn and Föhn shows that the model generally reproduces a cloud clearing effect through Föhn in the lee of the mountain range.

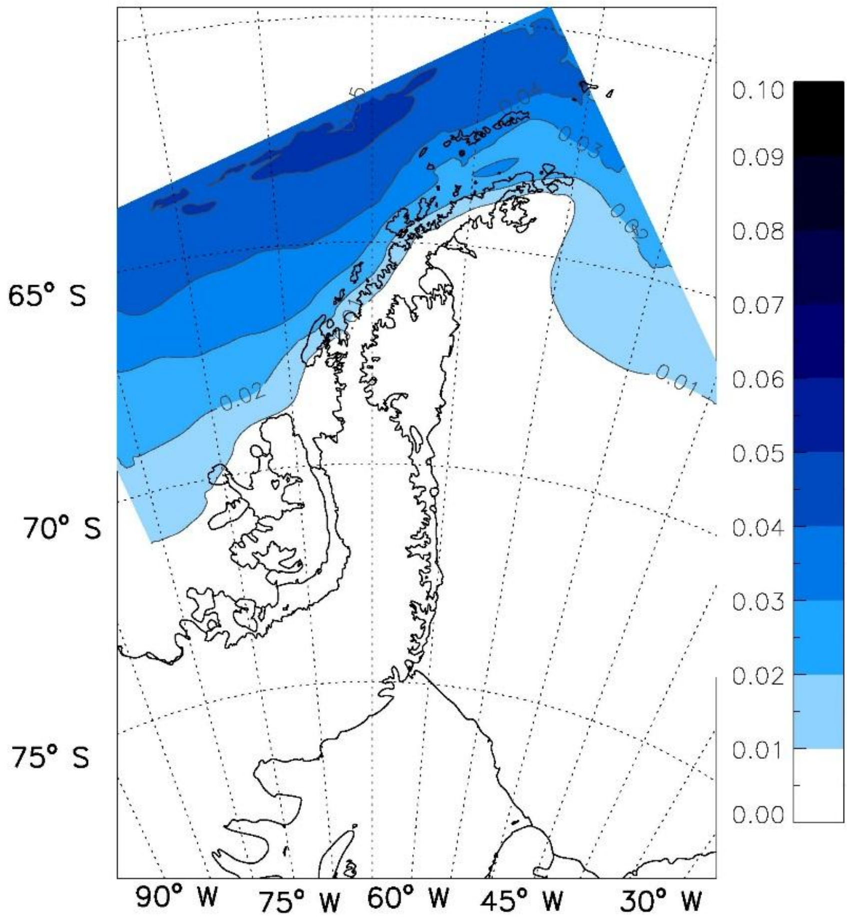
Composite plots of cloud fraction for non-Föhn (left) and Föhn (right) in AMPS in 2011.

Kirchgaessner et al (2019), JGR-A

The model though does not simulate any liquid cloud or rain water south west of a line from 70°S and 75°W to 65°S and ~62°W.

According to the model all clouds over our study area are ice clouds, which are optically thinner than liquid water or mixed-phase clouds with the same water content.

Studies by Grosvenor et al. (2012) and Lachlan-Cope et al. (2016) have shown that, in reality, a significant amount of liquid water is present in clouds on both sides of the Antarctic Peninsula.



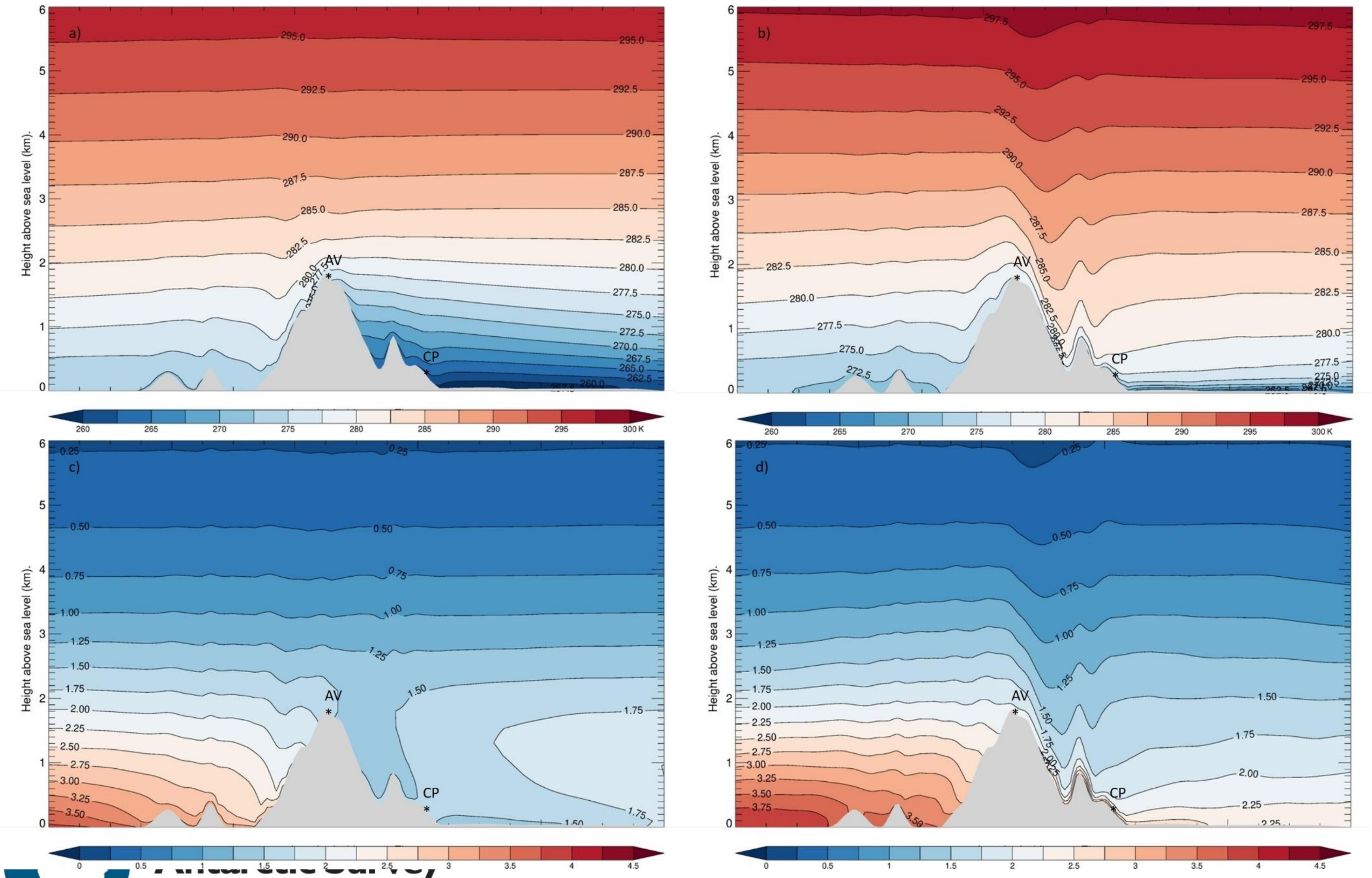
Kirchgaessner et al (2019), JGR-A

Upstream flow

Upstream conditions: Avery Plateau

No Föhn

Föhn



The blocking effect of the Antarctic Peninsula is clearly visible for “No Föhn“ composites of potential temperature (top), and absolute humidity (bottom).

The effect of isentropic drawdown is equally apparent in “Föhn” composites of potential temperature (top), and absolute humidity (bottom).

Kirchgaessner et al (2021), JGR-A

Upstream conditions: Avery Plateau

	Cole Peninsula		Avery Plateau	
	Föhn	No Föhn	Föhn	No Föhn
Potential temperature [K]	277.8	260.7	279.7	277.1
Absolute humidity [g/m^3]	2.2	2.9	2.1	1.7

Kirchgaessner et al (2021), JGR-A

During Föhn air from the crest of the Antarctic Peninsula at Avery Plateau descends to Cole Peninsula undergoing adiabatic warming.

This leads to comparatively similar values of potential temperature and absolute humidity.

During non Föhn the air masses are distinctly different.

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Froude number and flow characteristics:

The non-dimensional Froude number Fr, defined by

$$Fr = U/NH \qquad (1)$$

is often used to describe the upstream conditions. In Eq.(1) H is the height of the mountain barrier, and U and N are, respectively, the component of wind perpendicular to the mountain barrier and the Brunt-Vaisala frequency, which are both characteristics of the undisturbed flow upstream of the barrier.

Non-linear versus linear flow conditions:

At a critical Froude number Fr_c (here ≥0.4), the upstream flow changes from non-linear (partially blocked) to linear (flow-over) regime.

Non-linear Föhn:

- mountain wave breaking
- accelerated downslope wind
- extreme warming in the immediate lee of the mountains
- Less effect further downwind on the ice shelf

Linear Föhn:

- Föhn wind flows at low levels across the entire ice shelf
- Mechanical mixing of the near surface air
- Prevention of a stable boundary layer
- large sensible heat flux to the ice shelf
- increased potential for warming and melt

We have found that during the time considered here, the majority of Föhn cases is non-linear.

-> Stronger circumpolar westerlies may lead to more linear Föhn cases, and increased melt on the Larsen C Ice Shelf.

Many thanks for your interest!

The work presented here was supported by the UK Natural Environment Research Council (NERC) under grant NE/G014124/1 “Orographic Flows and the Climate of the Antarctic Peninsula” and by the Netherlands Organisation for Scientific Research under grant 818.01.016. Thanks also go to the Mesoscale and Microscale Meteorology Division at NCAR for giving us access to the AMPS forecast archive, and BAS staff at Rothera Research Station for supporting the field measurement programme.

See also:

Kirchgaessner, Amelie , King, John, Gadian, Alan. (2019) The representation of Föhn events to the east of the Antarctic Peninsula in simulations by the Antarctic Mesoscale Prediction System (AMPS). Journal of Geophysical Research: Atmospheres, 124. 17 pp. 10.1029/2019JD030637

Kirchgaessner, Amélie , King, John C., Anderson, Philip S. (2021) The impact of Föhn conditions across the Antarctic Peninsula on local meteorology based on AWS measurements. Journal of Geophysical Research: Atmospheres, 126. 10.1029/2020JD033748

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