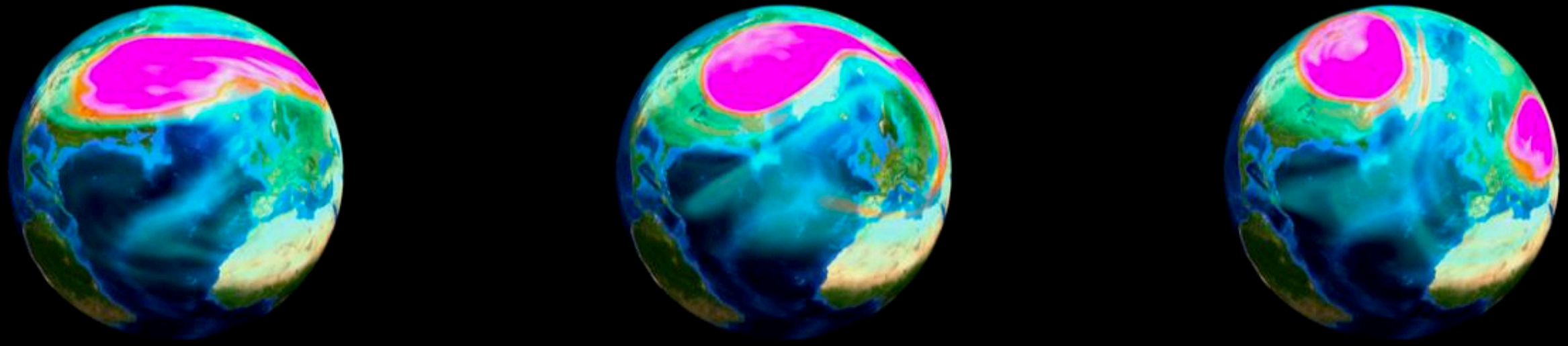


The Role of the Stratosphere in Extended-Range Prediction: Mechanisms, Modeling and Impacts

Daniela Domeisen

with contributions from

Wolfgang Wicker, Alexander Wollert, Hilla Afargan-Gerstman, Ole Wulff, Rachel Wu, Ying Dai, Peter Hitchcock, Alexey Karpechko, Frederic Vitart, Inna Polichtchouk, Amy Butler, Blanca Ayarzagüena, Erik Kolstad, Andrew Charlton-Perez

and many more

COLD EXTREMES

With climate change, cold extremes will become less frequent.
However, not all regions will experience fewer cold spells, in fact some parts of Eurasia have experienced a wide range of cold spells over the past years.
(e.g. Tyrlis et al 2019,2020,2021)

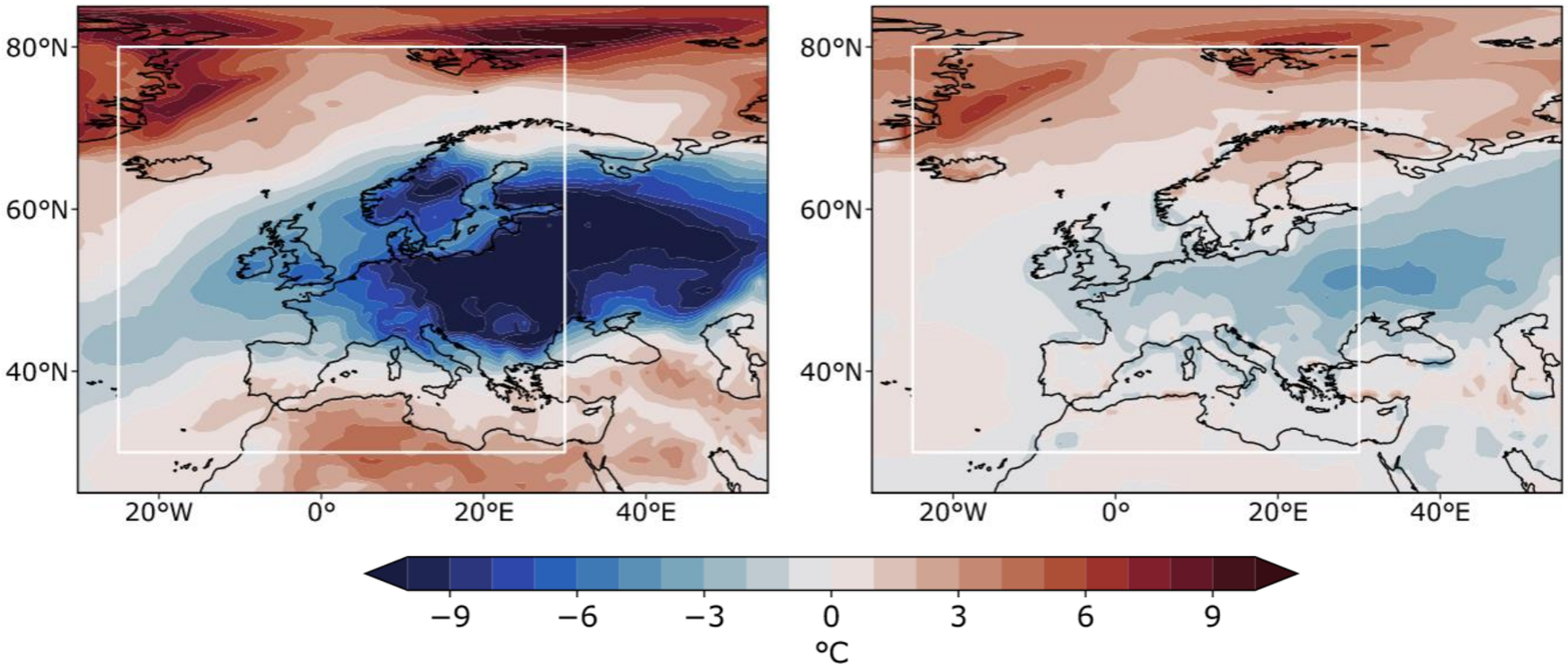
weathemation.com

THE COLD SPELL IN FEBRUARY 2018

ERA5

ECMWF forecast (3 weeks lead time)

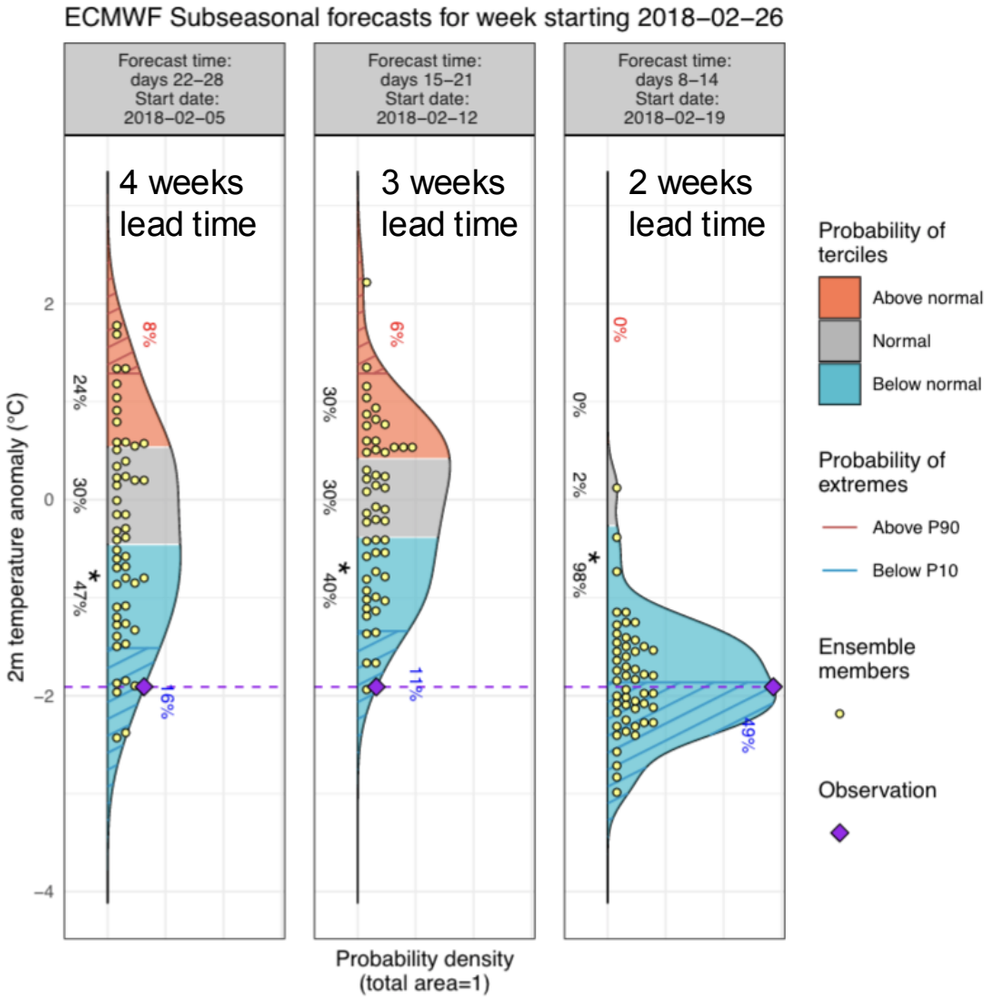
Initialization: Feb 12, 2018



2m temperature anomalies for the target week (26 Feb – 4 March 2018)

Figure: Domeisen et al, BAMS, 2022

HOW WELL PREDICTED WAS THE 2018 COLD SPELL?



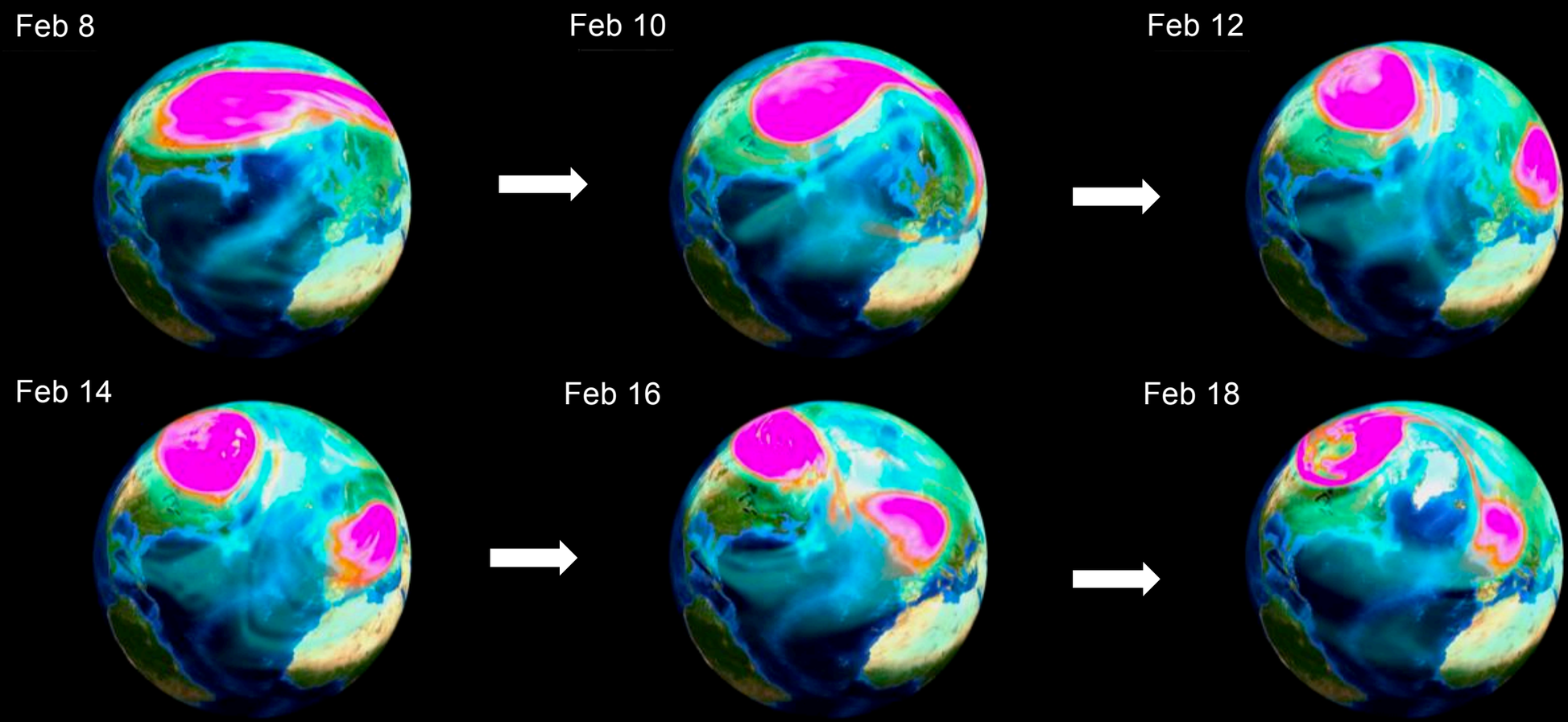
4 weeks before the cold spell:
only **16%** of the ensemble members already predict temperatures below the 10th percentile. This number even reduces to 11% at 3 weeks lead time.

2 weeks before the cold spell, the model provides an accurate prediction of the event, with close to **50%** of the ensemble members below the 10th percentile.

What happened between the week-3 and the week-2 forecasts that changed the prediction of the cold spell?

Figure: Domeisen et al, BAMS, 2022

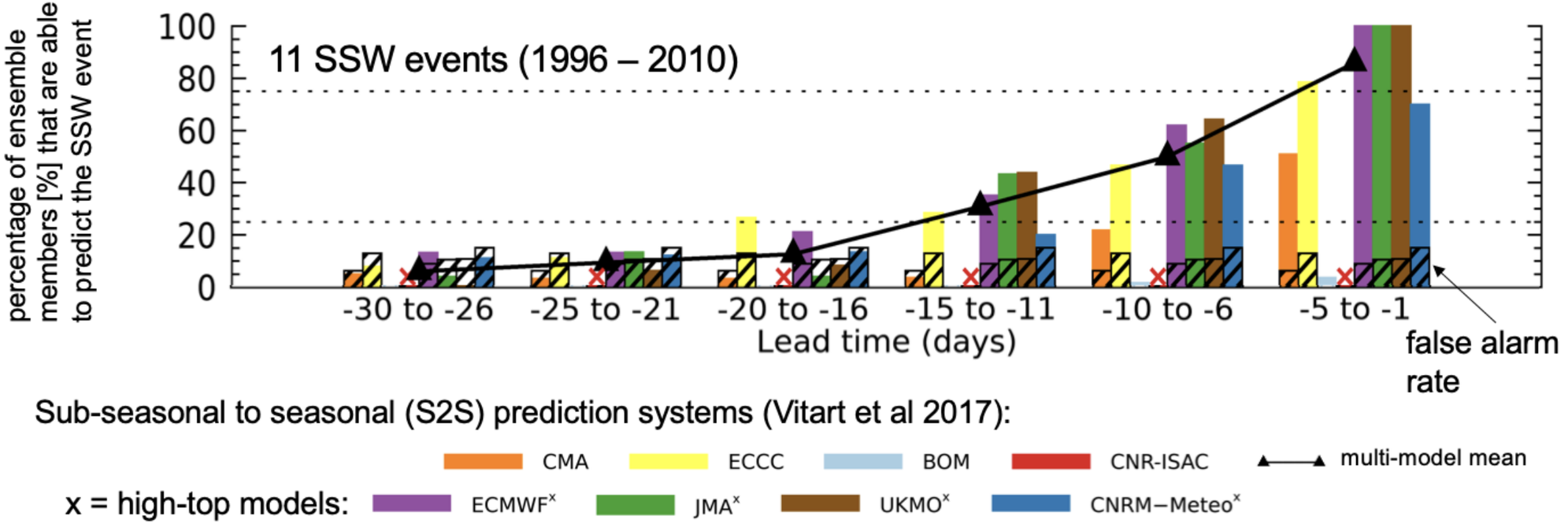
THE SUDDEN STRATOSPHERIC WARMING EVENT ON FEBRUARY 12, 2018

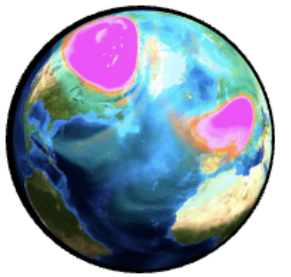


Figures: potential vorticity at 10hPa by Alexander Wollert

HOW PREDICTABLE ARE SUDDEN STRATOSPHERIC WARMING (SSW) EVENTS?

The occurrence of sudden stratospheric warming (SSW) events is generally predictable about 1-2 weeks before their onset in dynamical models.





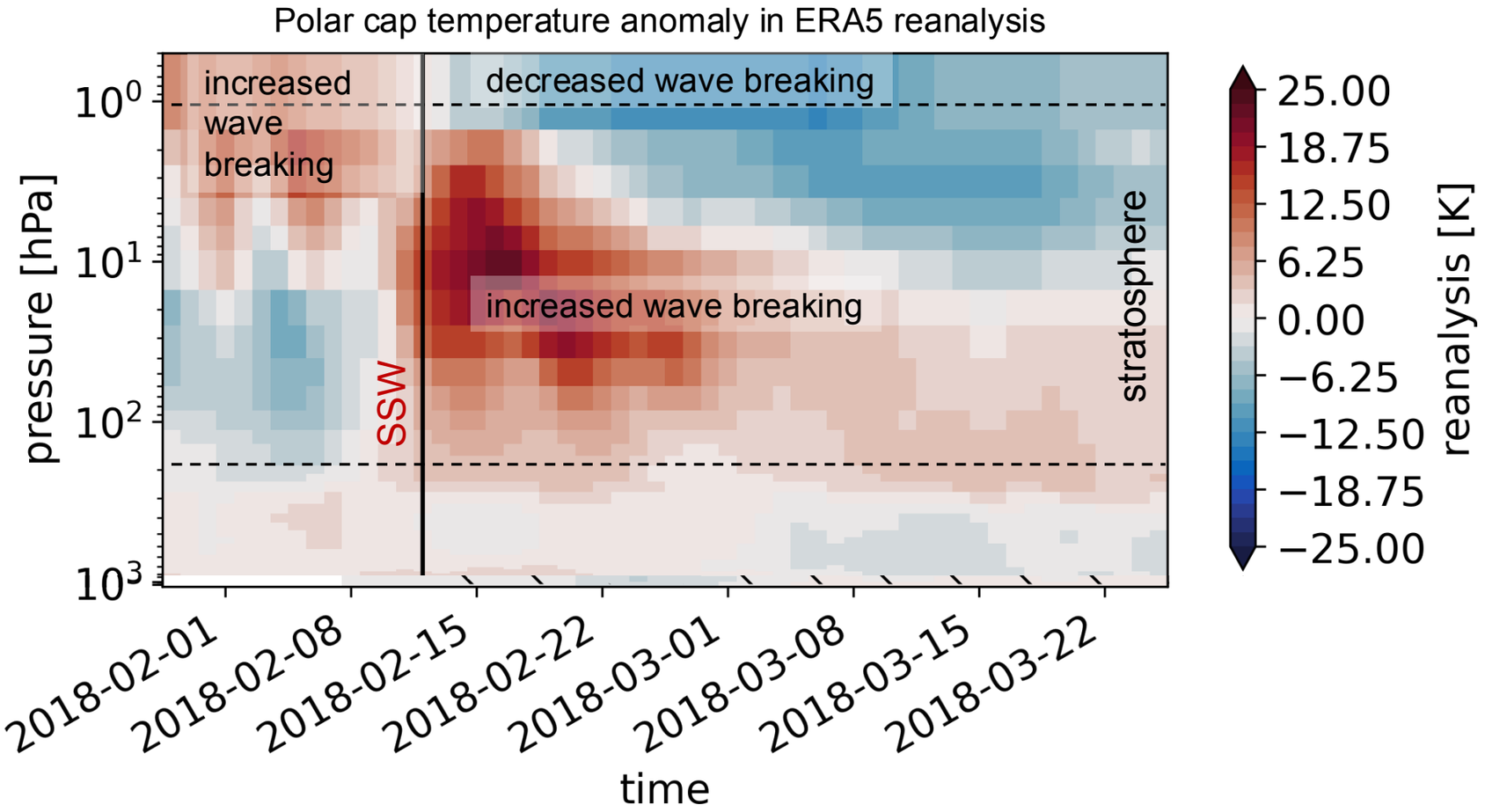
High resolution in the stratosphere is an important component of stratospheric predictability.

Figure: Domeisen et al., 2020, JGR special issue on S2S prediction

TESTING THE EFFECT OF VERTICAL RESOLUTION IN THE STRATOSPHERE

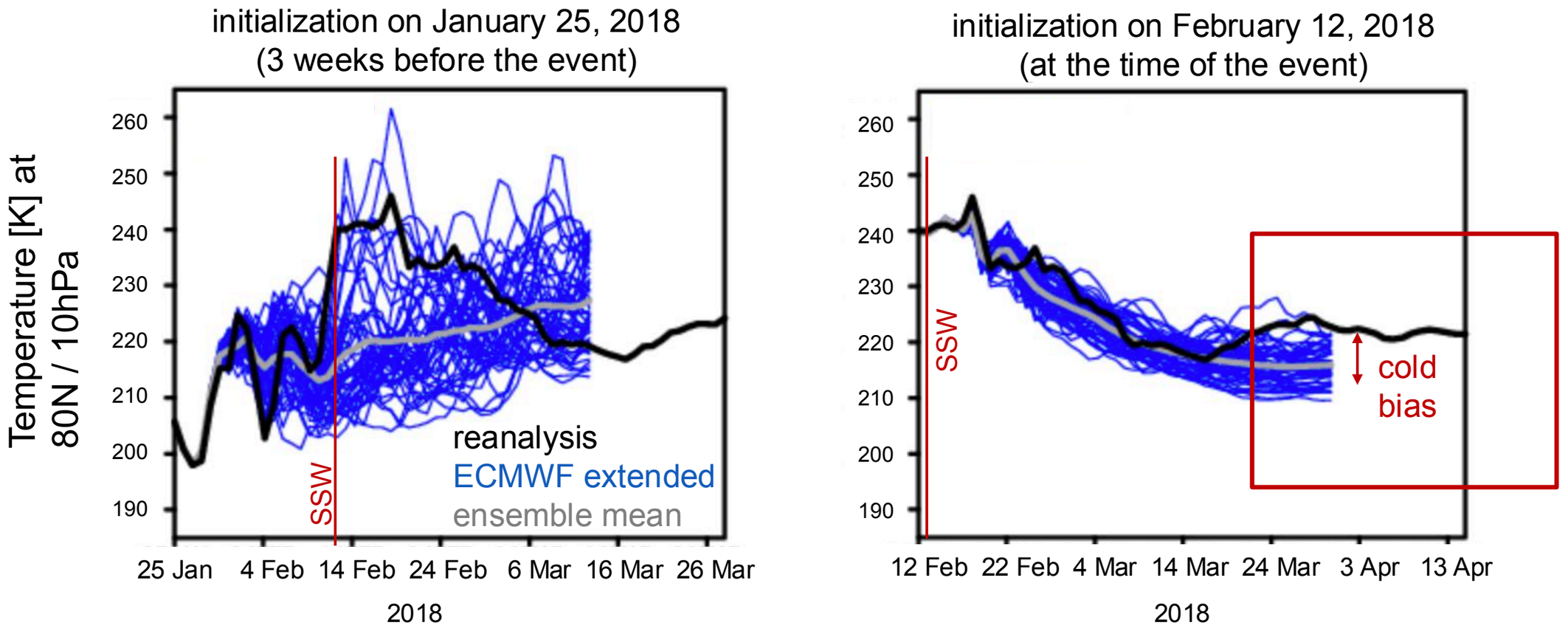
After stratospheric event, waves tend to break further down in the atmosphere, slowing the zonal winds and warming the stratosphere.

If the wave breaking and hence the warming in the stratosphere is not correctly predicted, this can lead to major forecast busts, as e.g. in winter 2019.



Wicker, Polichtchouk, Domeisen, 2023. Increased vertical resolution in the stratosphere reveals role of gravity waves after sudden stratospheric warmings, Weather and Climate Dynamics

THE COLD BIAS AFTER THE EVENT LIMITS THE PREDICTABILITY OF THE DOWNWARD IMPACT ON OUR WEATHER



Figures: M. Matsueda, S2S Museum

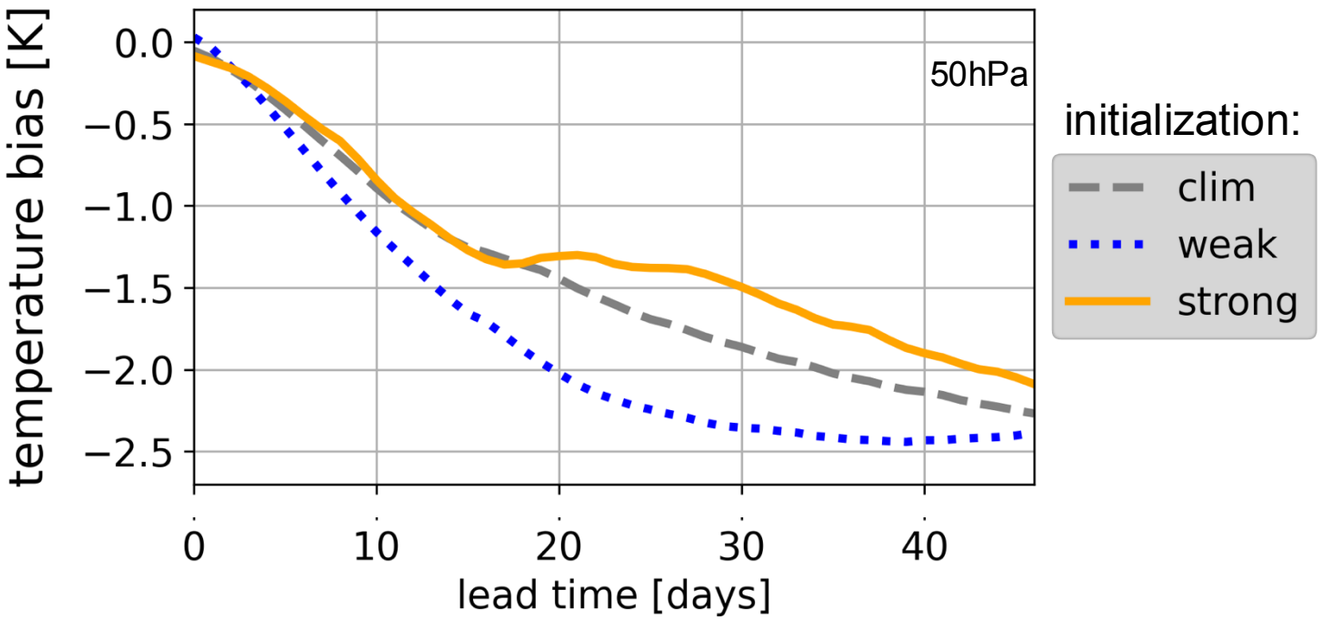
THE COLD BIAS IS PARTICULARLY STRONG AFTER WEAK VORTEX EVENTS

Funding / collaboration: ECMWF

Enhanced cold bias during weak vortex initializations and reduced cold bias during strong vortex conditions
(in line with findings of Lawrence et al. 2022)

Climatology: 21’000 ensemble members

Initialization during:
Weak vortex: 2761 ensemble members
Strong vortex: 4191 ensemble members

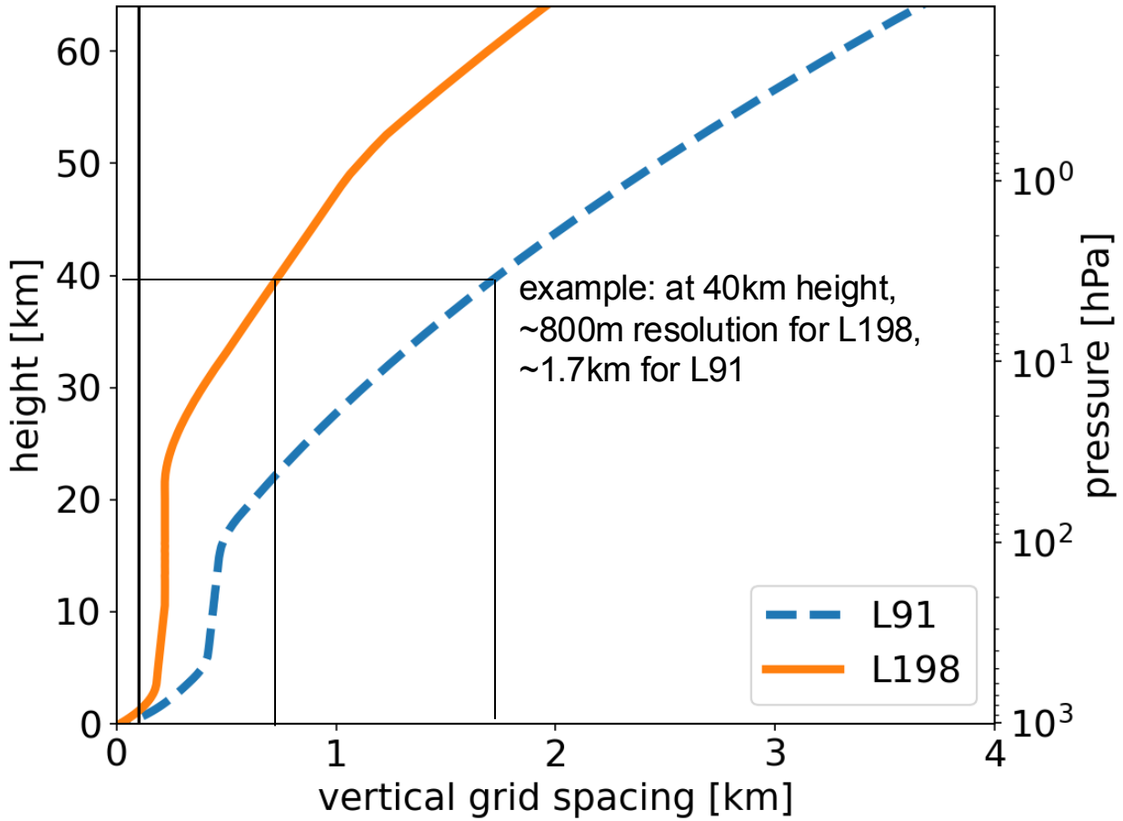


Wicker, Polichtchouk, Domeisen, 2023. Increased vertical resolution in the stratosphere reveals role of gravity waves after sudden stratospheric warmings, Weather and Climate Dynamics

CAN INCREASED VERTICAL RESOLUTION IMPROVE THE COLD BIAS BY BETTER RESOLVING WAVE BREAKING?

Systematic comparison of vertical resolution in hindcasts of the ECMWF IFS system

- 51 ensemble members
- initialized on 8 Feb 2018 (5 days prior to the SSW on 12 February 2018), when the onset of the event can be skillfully predicted
- length of simulations: 46 days
- horizontal resolution: TCo639 ~ 18 km
- **different vertical resolutions** (L91, L198)



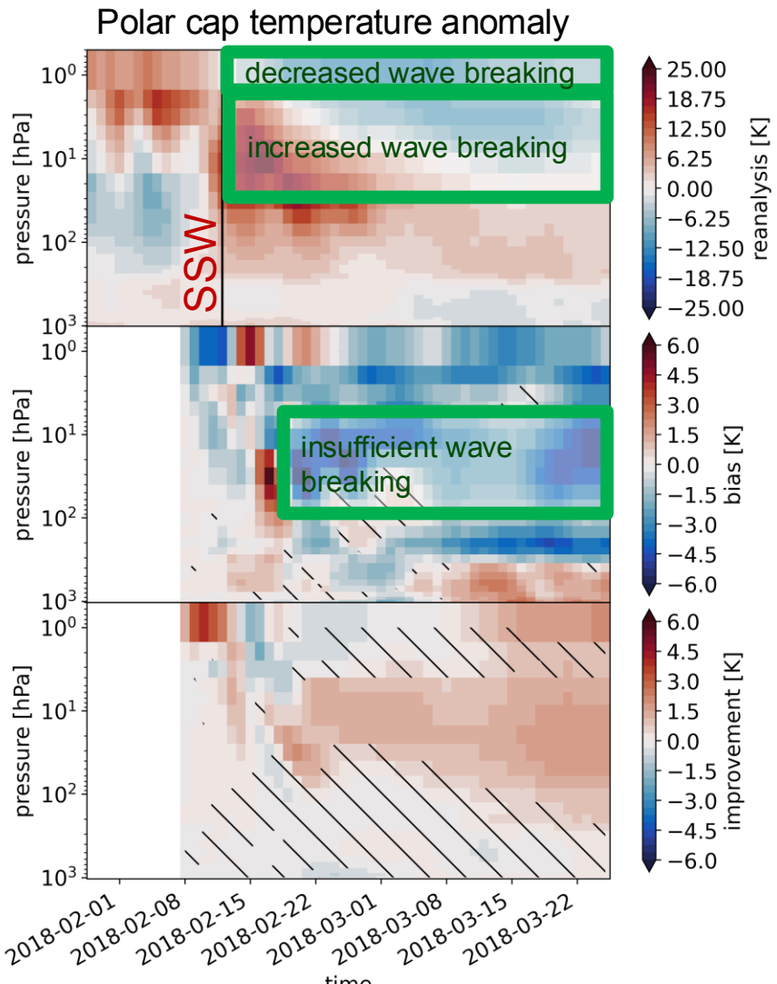
Wicker, Polichtchouk, Domeisen, 2023. Increased vertical resolution in the stratosphere reveals role of gravity waves after sudden stratospheric warmings, Weather and Climate Dynamics

REDUCTION OF COLD BIAS FOR HIGHER VERTICAL MODEL RESOLUTION

Typical warming of the lower stratosphere after SSW event

Cold bias: Low vertical resolution configuration (L91) strongly underestimates prolonged positive polar cap temperature anomalies by 2-4K

At increased vertical resolution (L198) stratospheric cold bias is reduced by ~50%, leading to increased predictability up to 6 weeks



ERA5 (our "truth")

cold bias: low (L91) – ERA5

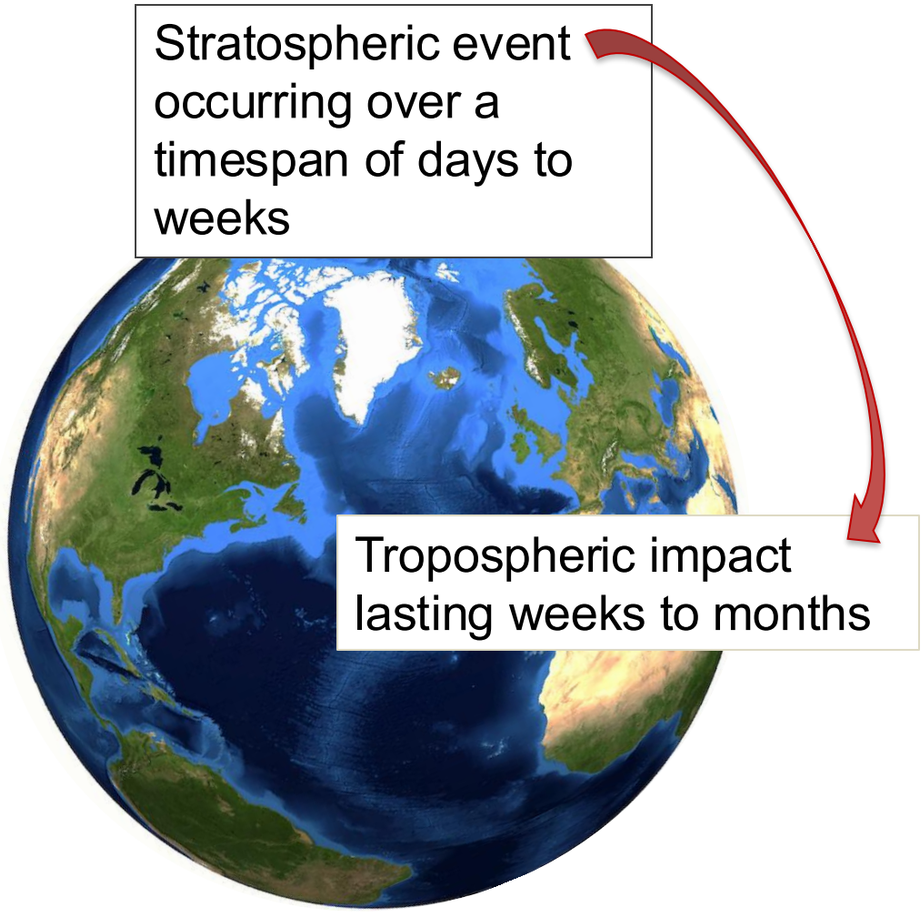
improvement: high (L198) – low (L91)

Wicker, Polichtchouk, Domeisen, 2023. Increased vertical resolution in the stratosphere reveals role of gravity waves after sudden stratospheric warmings, Weather and Climate Dynamics

WHY DO WE CARE?
THE SURFACE IMPACT OF STRATOSPHERIC EVENTS

A correct prediction of the lower stratosphere after SSW events is crucial for surface prediction.

The surface impact of stratospheric events can lead to weather extremes, including cold spells over northern Europe, which can lead to severe impacts on human health.
(e.g. Charlton-Perez et al, 2019)



STRATOSPHERIC EXTREMES CAN INDUCE A RANGE OF SURFACE EXTREME EVENTS

Kolstad et al (2010). The association between stratospheric weak polar vortex events and cold air outbreaks in the Northern Hemisphere, QJRMS

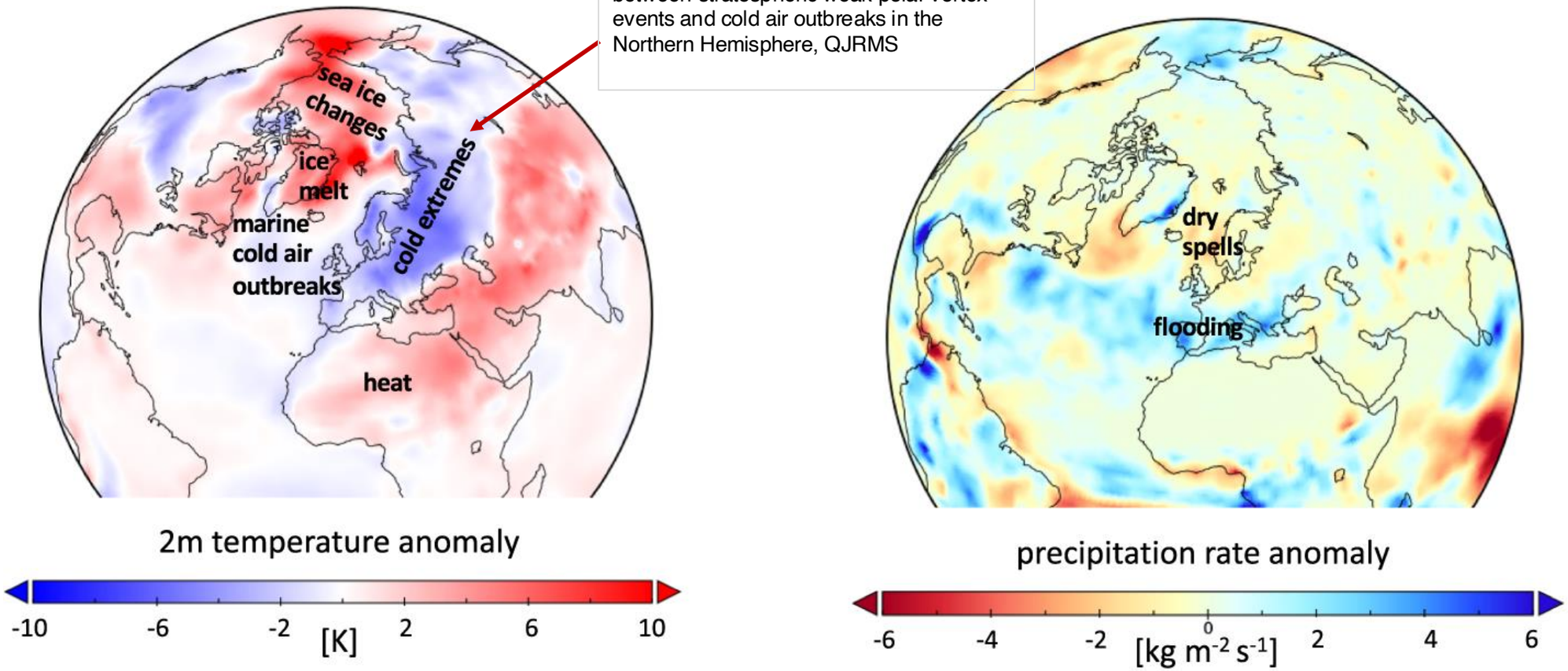


Figure: examples for surface extremes after SSW events, shading: anomalies after 2018 SSW

From: Domeisen & Butler, *Stratospheric drivers of extreme events*, Comms E & E (2020)

IMPACTS: COLD AIR OUTBREAKS

Large increases in the frequency of cold air outbreaks after weak vortex events

State of the stratospheric event:

Peak
Days 0-14

Mature
Days 15 - 29

Decline
Days 30 - 44

Decay
Days 45 - 59

The anomalous number of cold days:

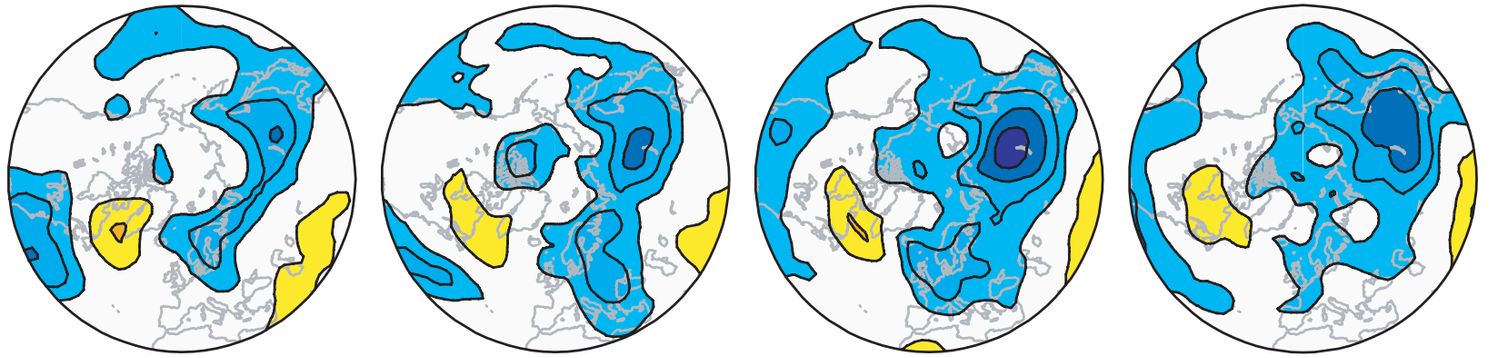
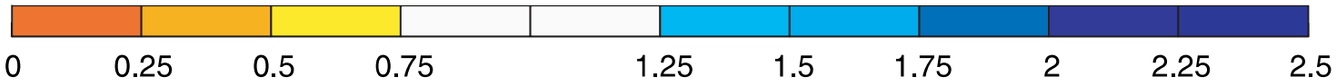


Figure: Kolstad et al., 2010



50% more cold days as compared to normal

double the number of cold days as compared to normal

Link to increased mortality after weak vortex events:

Charlton-Perez et al. (2019). Winter pressures on the UK health system dominated by the Greenland Blocking weather regime. *Weather and Climate Extremes.*

Charlton-Perez et al. (2020). Impact of Sudden Stratospheric Warmings on United Kingdom mortality, Atmos. Sci. Lett.

STRATOSPHERIC EXTREMES CAN INDUCE A RANGE OF SURFACE EXTREME EVENTS

Afargan-Gerstman, H. et al (2020). Stratospheric influence on North Atlantic marine cold air outbreaks following sudden stratospheric warming events. *WCD*

Kolstad et al (2010). The association between stratospheric weak polar vortex events and cold air outbreaks in the Northern Hemisphere, QJRMS

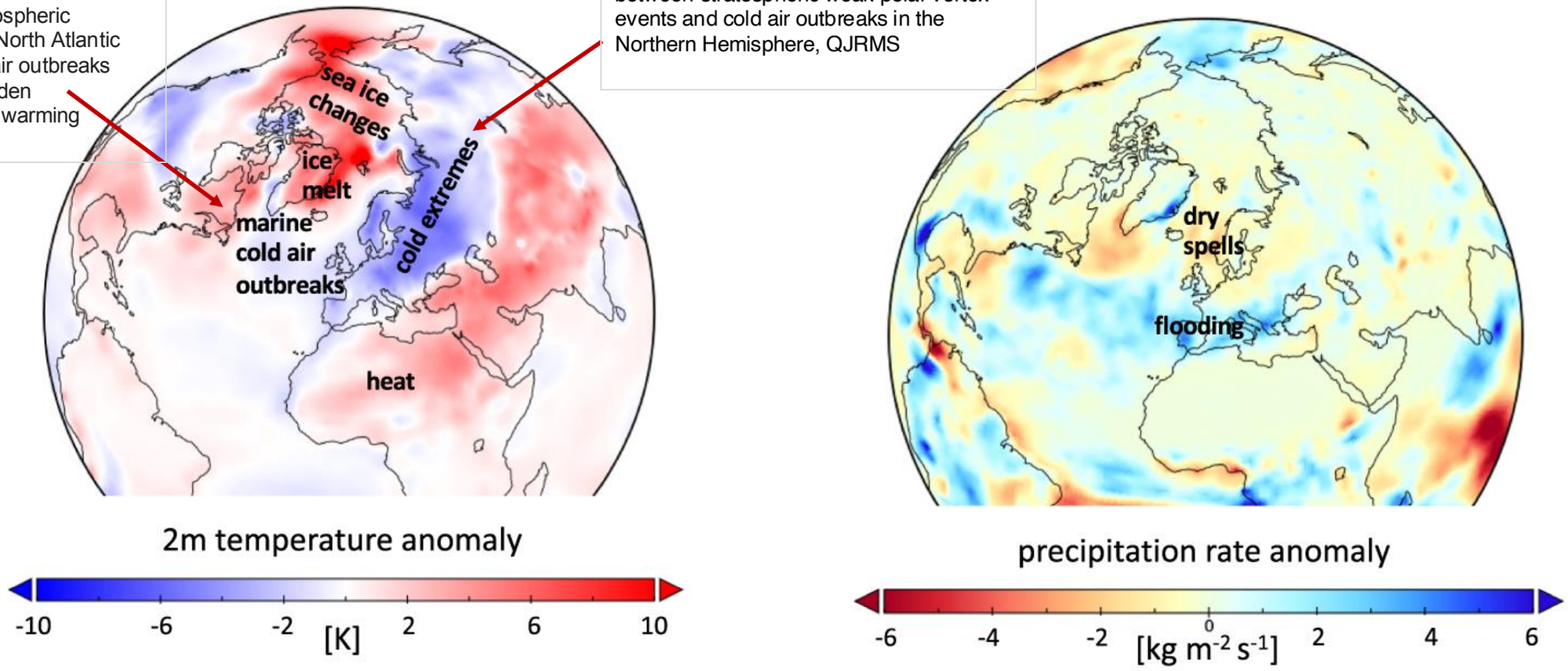
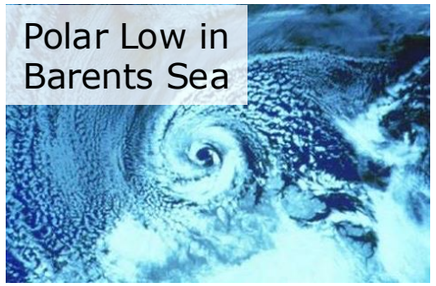


Figure: examples for surface extremes after SSW events, shading: anomalies after 2018 SSW

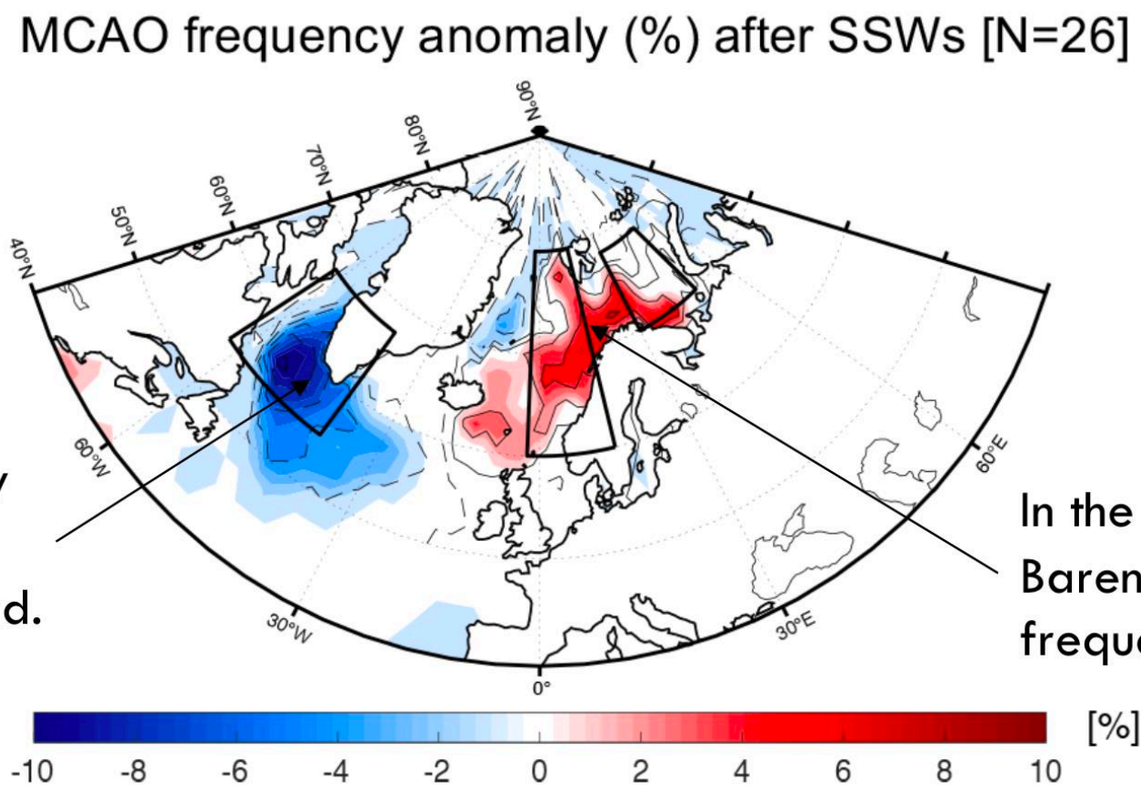
From: Domeisen & Butler, *Stratospheric drivers of extreme events*, Comms E & E (2020)

OCEAN IMPACTS: MARINE COLD AIR OUTBREAKS (MCAO)



MCAOs act as favorable environments for polar lows, also called «Arctic hurricanes», which can endanger Arctic shipping and infrastructure

Reduction most notably over Labrador sea and south of Greenland.



In the Norwegian and Barents Seas MCAO frequency is increased.

Averaged over a period of 30 days after SSWs

Afargan-Gerstman, H. et al (2020). Stratospheric influence on North Atlantic marine cold air outbreaks following sudden stratospheric warming events. *Weather and Climate Dynamics*, *1*(2), 541-553.

STRATOSPHERIC EXTREMES CAN INDUCE A RANGE OF SURFACE EXTREME EVENTS

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Kolstad et al (2010). The association between stratospheric weak polar vortex events and cold air outbreaks in the Northern Hemisphere, QJRMS

Dai et al. (2022). Stratospheric impacts on dust transport and air pollution in West Africa and the Eastern Mediterranean. *Nature Comms.*

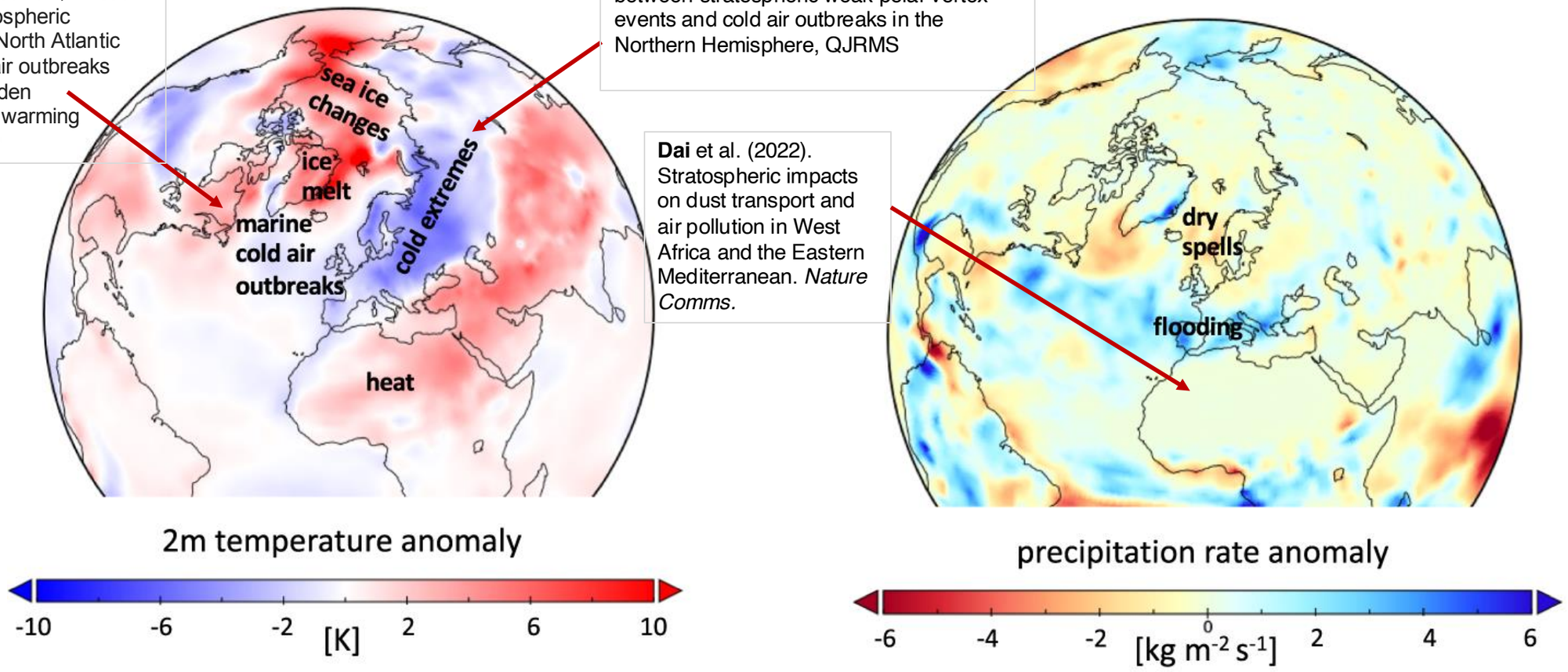

Figure: examples for surface extremes after SSW events, shading: anomalies after 2018 SSW

From: Domeisen & Butler, *Stratospheric drivers of extreme events*, Comms E & E (2020)

IMPACTS OF THE STRATOSPHERE ON DUST AND AIR POLLUTION

Anomalous dust transport towards the eastern Mediterranean following SSW events

On average, a single SSW is estimated to cause up to 2500 additional premature deaths in the Eastern Mediterranean and prevents up to 2000 premature deaths in West Africa from exposure to dust-source fine particulate ($PM_{2.5}$).

Due to the extended-range predictability of the downward impact of stratospheric events, the stratosphere represents an important source of subseasonal predictability for air quality over West Africa and the Eastern Mediterranean

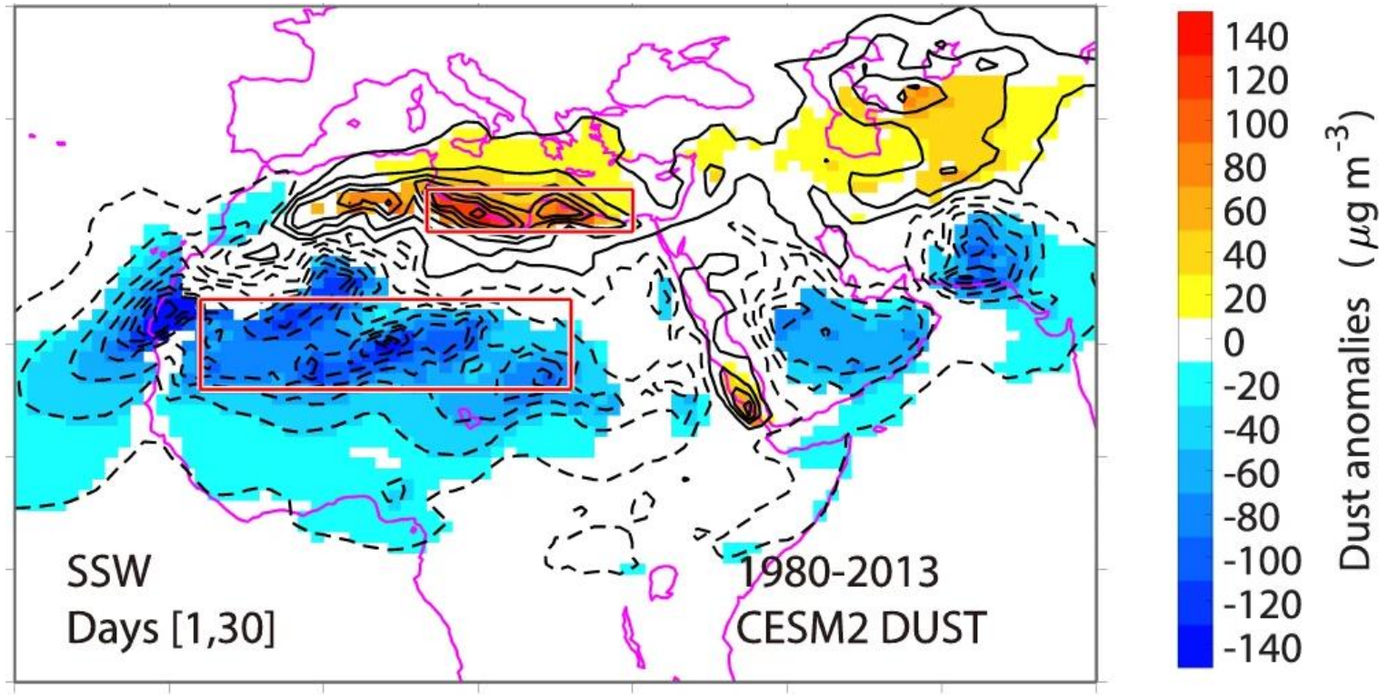

Figure:
CESM2 surface dust concentrations during SSW episodes

Dai et al. (2022). Stratospheric impacts on dust transport and air pollution in West Africa and the Eastern Mediterranean. *Nature Comms.*

STRATOSPHERIC EXTREMES CAN INDUCE A RANGE OF SURFACE EXTREME EVENTS

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Kolstad et al (2010). The association between stratospheric weak polar vortex events and cold air outbreaks in the Northern Hemisphere, QJRMS

Dai et al. (2022). Stratospheric impacts on dust transport and air pollution in West Africa and the Eastern Mediterranean. *Nature Comms.*

Ayarzagüena et al. (2018). Stratospheric Connection to the Abrupt End of the 2016/2017 Iberian Drought. *GRL*

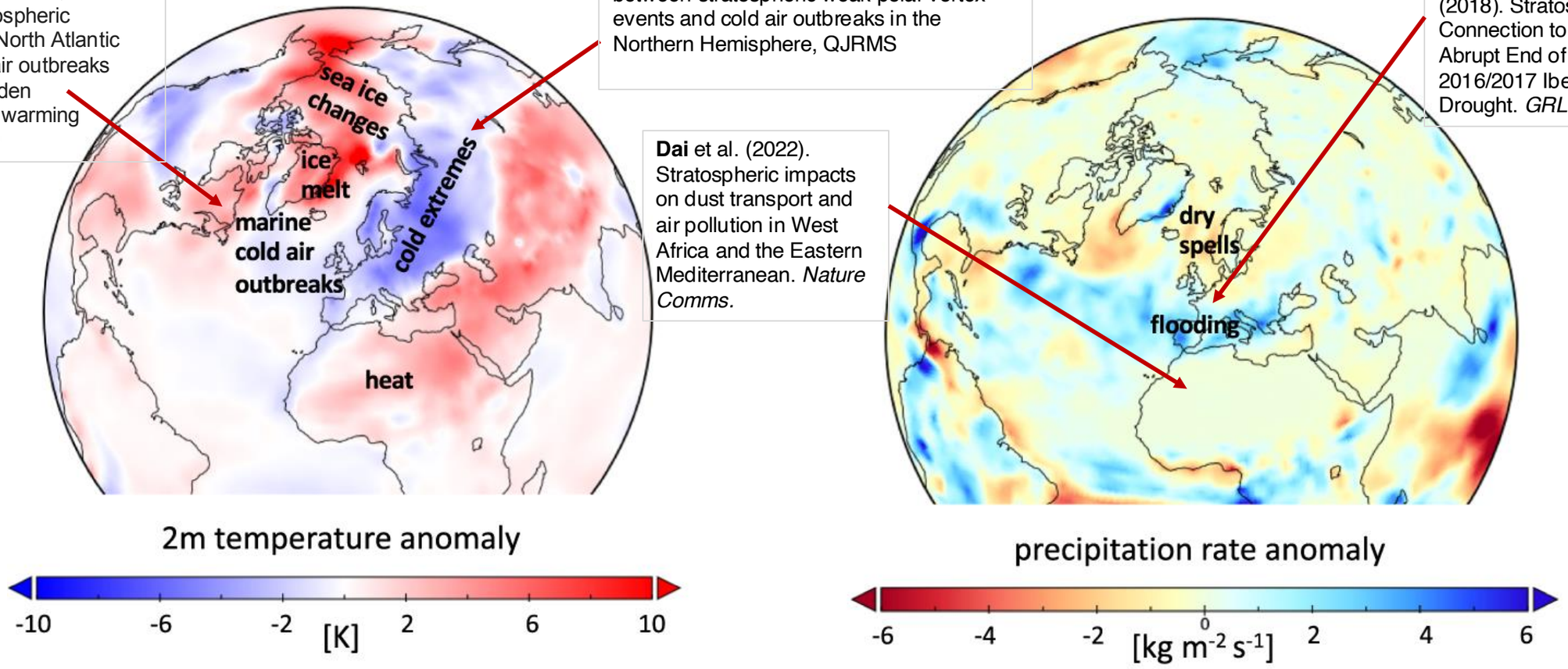


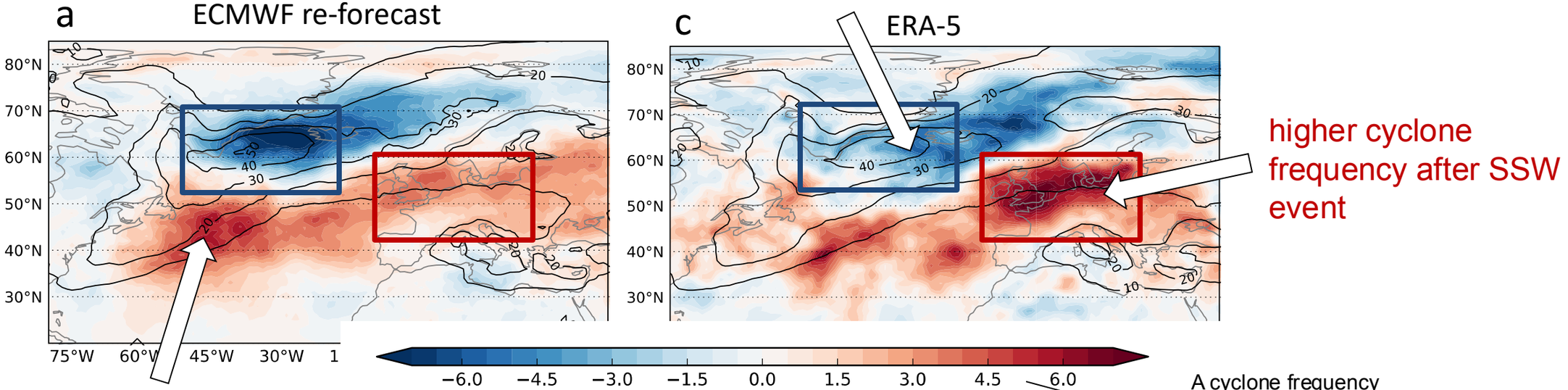
Figure: examples for surface extremes after SSW events, shading: anomalies after 2018 SSW

From: Domeisen & Butler, *Stratospheric drivers of extreme events*, Comms E & E (2020)

VARIABILITY IN THE STORM TRACK RESPONSE TO SSW EVENTS IN SUBSEASONAL FORECASTS

After SSW events (14 events, averaged over days 1-30), the re-forecasts **underestimate** the cyclone frequency response **over Europe and south of Greenland**. (model initialized 1±2 days after SSW central date)

lower cyclone frequency after SSW event



higher cyclone frequency after SSW event

higher cyclone frequency after SSW event

The percentage of cyclone frequency indicates the number of days (out of 28 days after SSW events) for which a grid point is part of a cyclone area.

A cyclone frequency increase by 5%. For comparison, the climatological cyclone frequency for DJF is 40%.

Afargan-Gerstman et al., *WCD, 2024*

APPLICATION: STORM DAMAGE

- In Europe alone, windstorms are one of the costliest hazards.
  Manning et al., 2022

- Damages caused by extratropical cyclones amounted to 77 billion Euros between 1998 and 2022.

https://www.waldwissen.net/assets/waldwirtschaft/schaden/sturm_schnee_eis/wsl_wintersturmschaeden_schweiz/wsl_wintersturmschaeden_schweiz_vivian2.jpeg

CHANGES IN STORMS AFTER STRATOSPHERIC EVENTS

Storms tend to shift south after SSW events, accompanied by higher precipitation and surface winds.

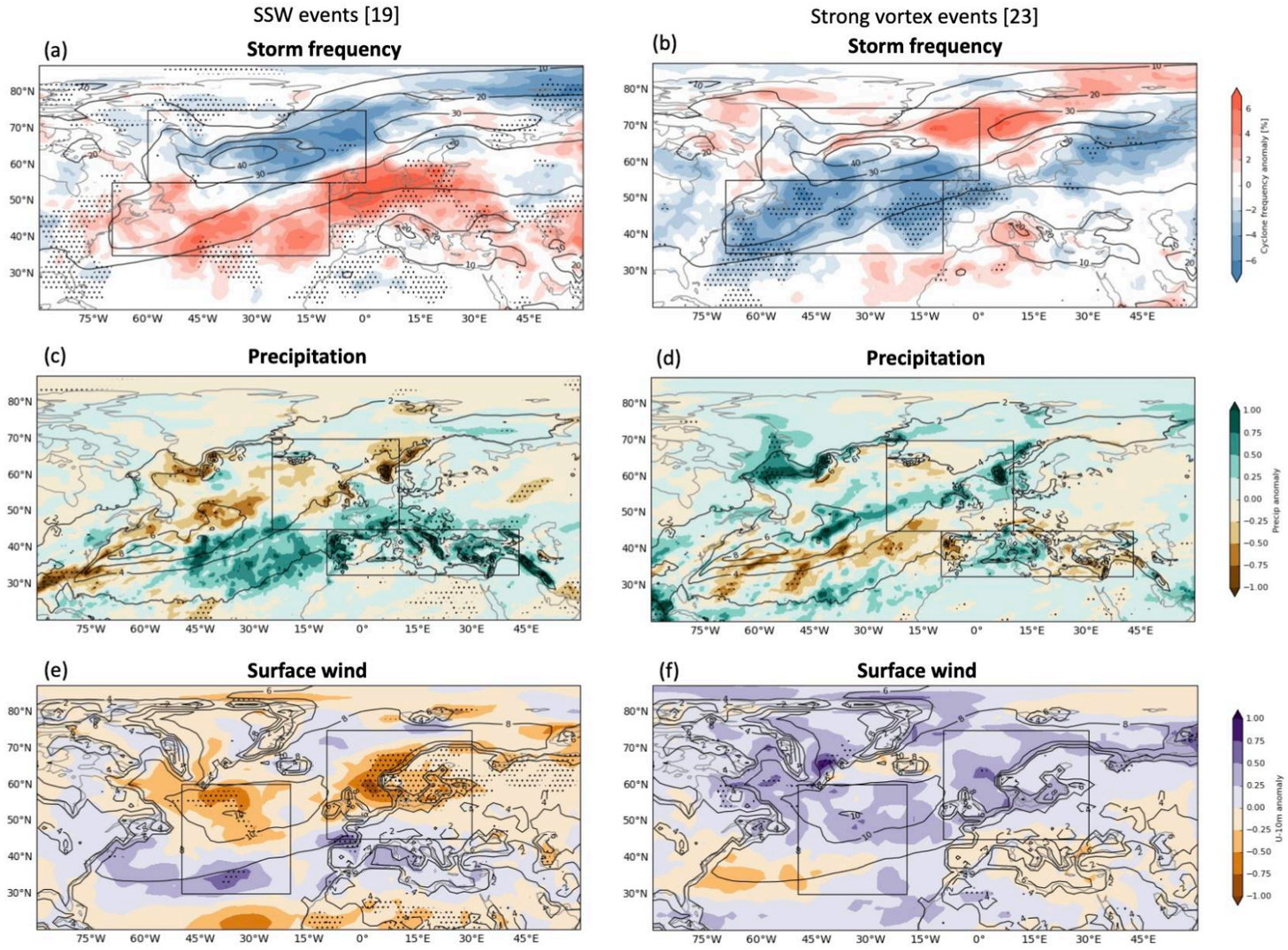


Figure: Afargan-Gerstman & Domeisen: “Stratospheric extreme events impact European storm damage”, in rev.

CHANGES IN STORM FOOTPRINT AFTER STRATOSPHERIC EVENTS

Higher wind gusts are experienced further south / north after SSW / strong vortex events.

Figure: The storm footprint (max 3s 10m wind gust [m/s] over 72-hour period).
Data: Copernicus database, 1998-2021

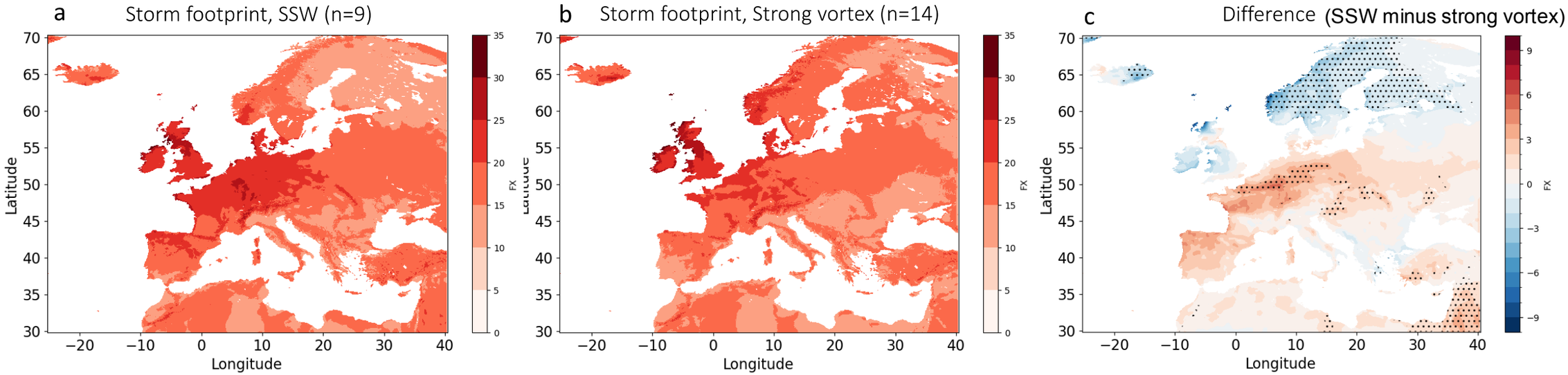


Figure: Afargan-Gerstman & Domeisen: “Stratospheric extreme events impact European storm damage”, in rev.

CHANGES IN STORM DAMAGE AFTER STRATOSPHERIC EVENTS

Storm damage generally shifts in the same way as storms after stratospheric events. Stratospheric surface impacts can be predictable several weeks in advance, which could benefit storm damage prediction.

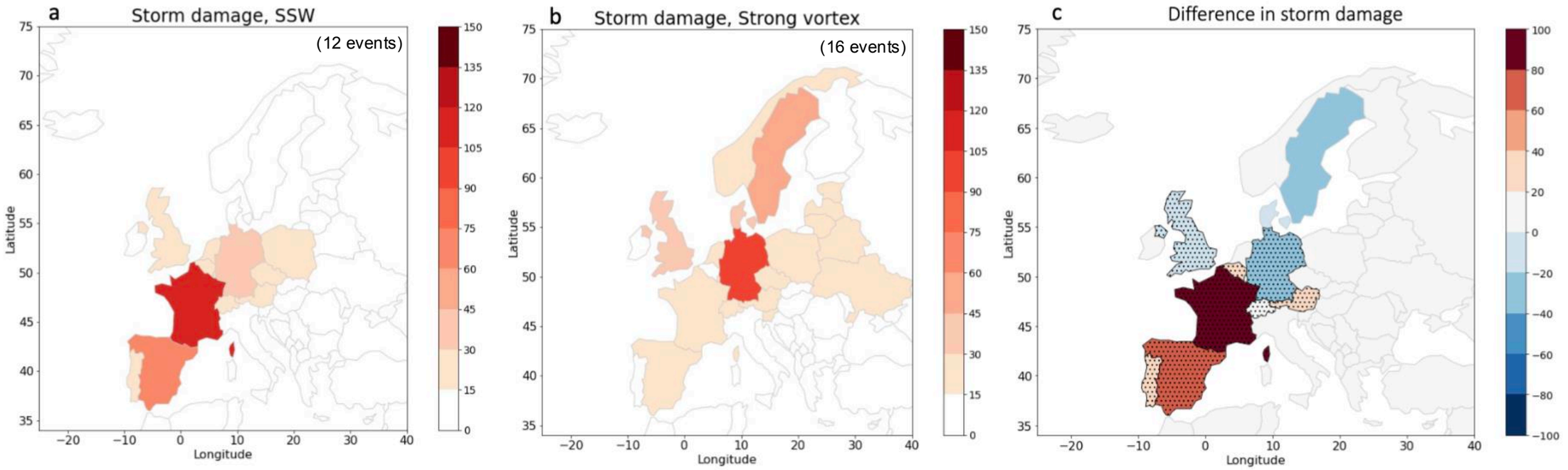


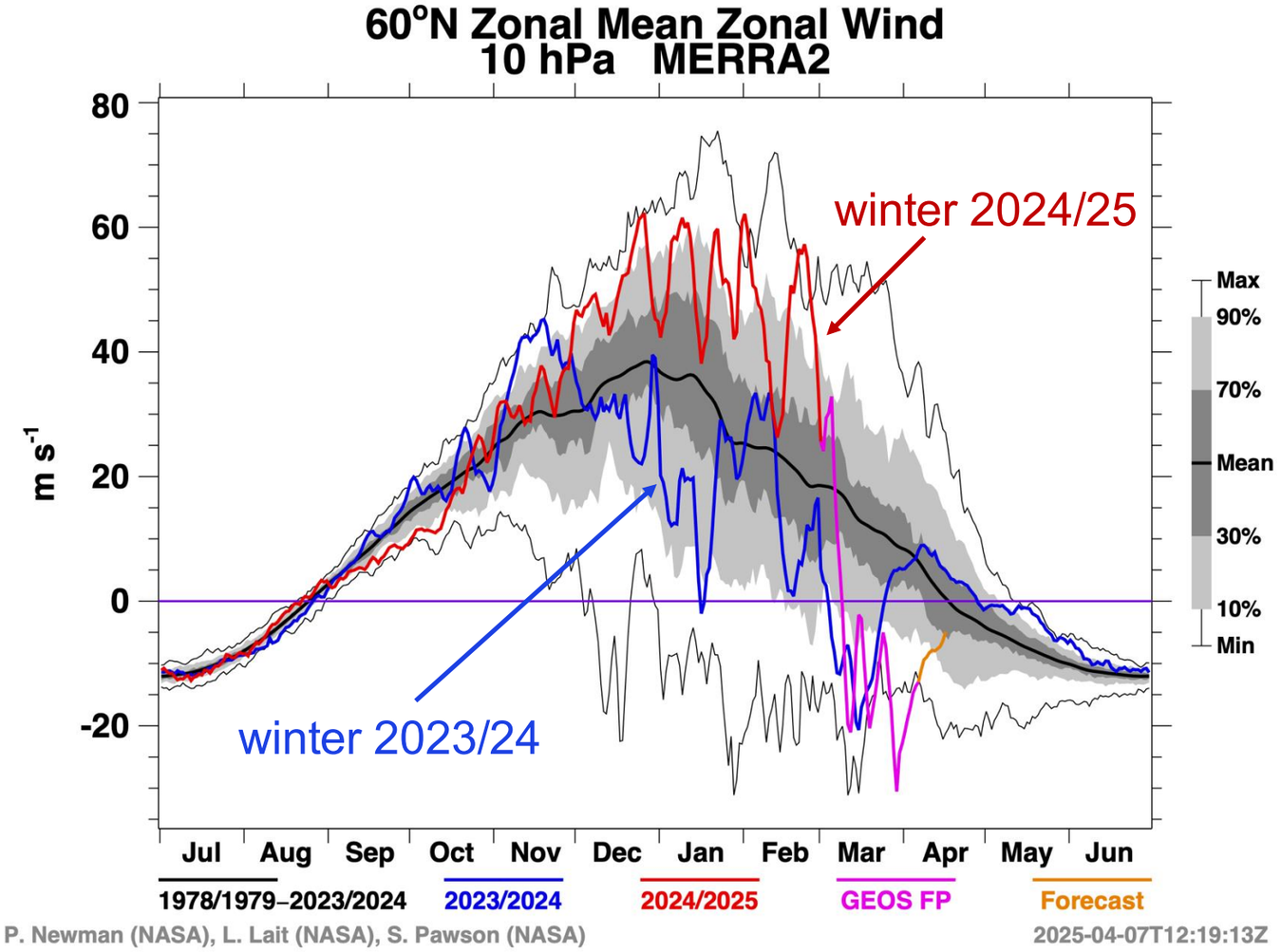
Figure: Total damage following stratospheric events in hundred millions of USD. Data: EM-DAT, 1998-2023.

Figure: Afargan-Gerstman & Domeisen: “Stratospheric extreme events impact European storm damage”, in rev.

WHAT HAS BEEN HAPPENING IN THE STRATOSPHERE THIS WINTER?

The stratospheric polar vortex has been very strong throughout winter 2024/25 – unlike in winter 2023/24, when the vortex was generally weak and variable and broke down twice!

But this winter showed a spectacular warming event (what will likely become the second-earliest final warming on record) with wind decelerations of roughly 70m/s in ~3 weeks from mid-February to early March, corresponding to a warming of about 45 C.



POTENTIAL SURFACE IMPACTS?

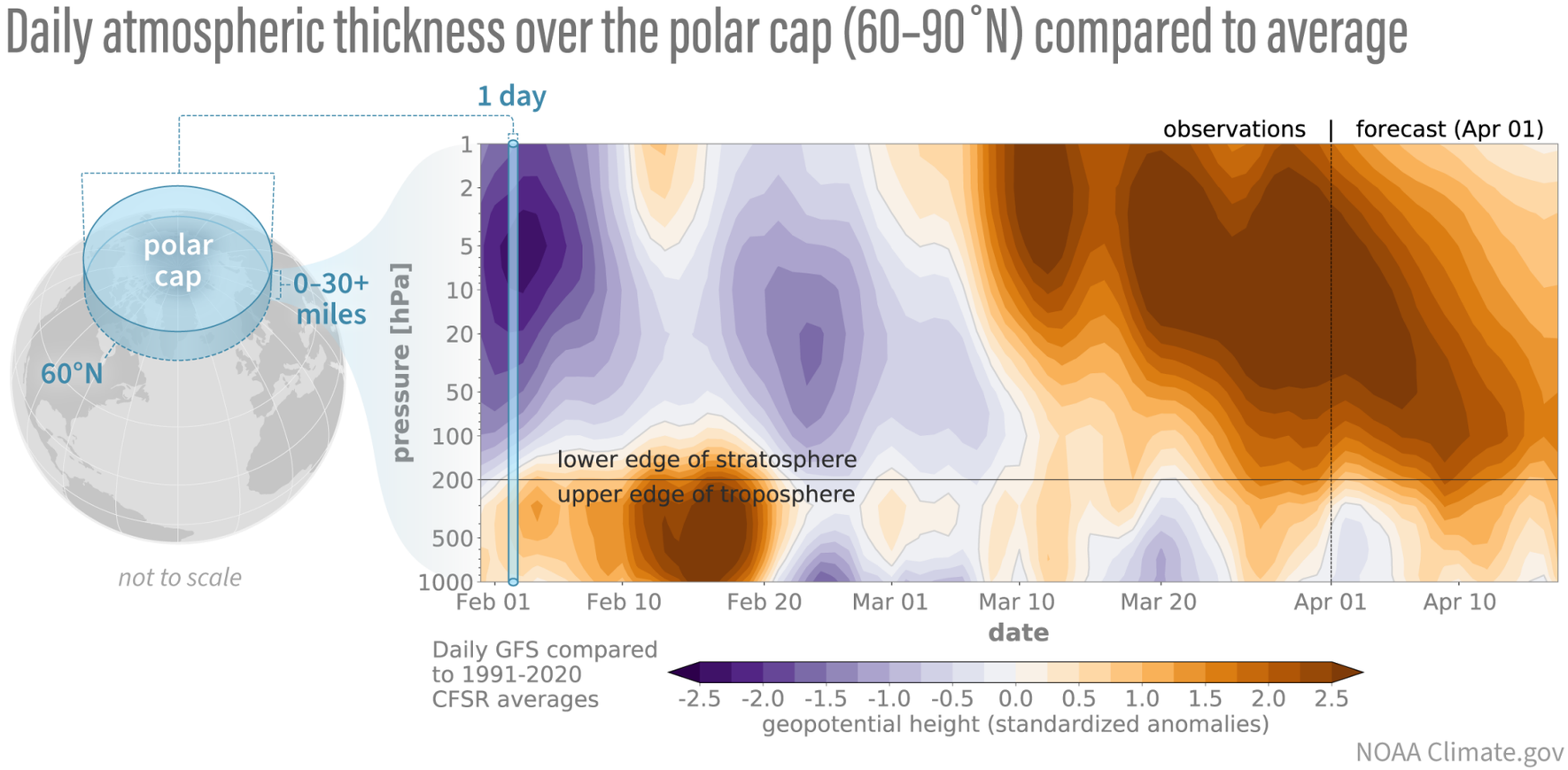
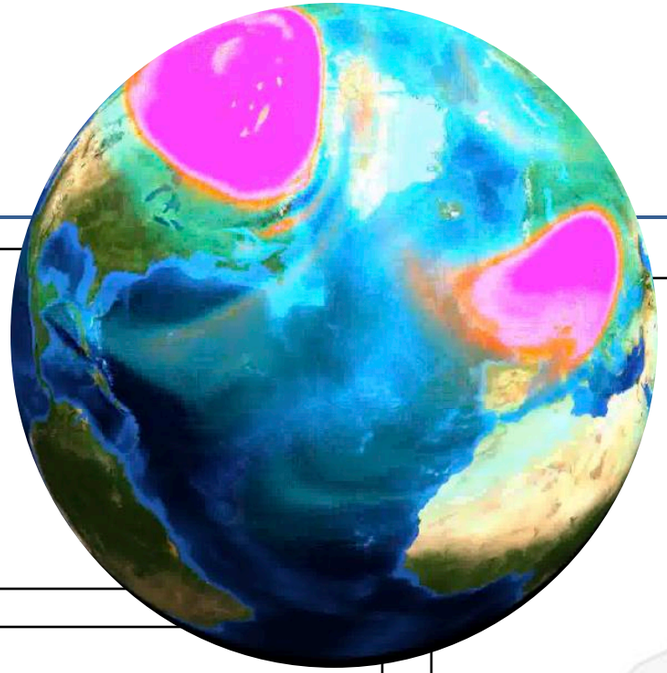
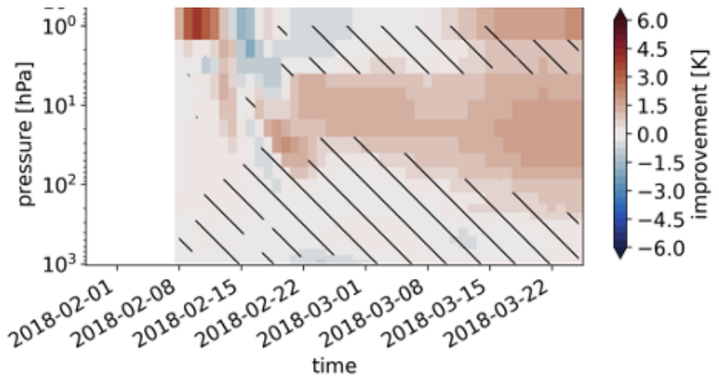


Figure: https://www.climate.gov/news-features/blogs/polar-vortex/early-interesting-end-2024-25-polar-vortex-season

SUMMARY

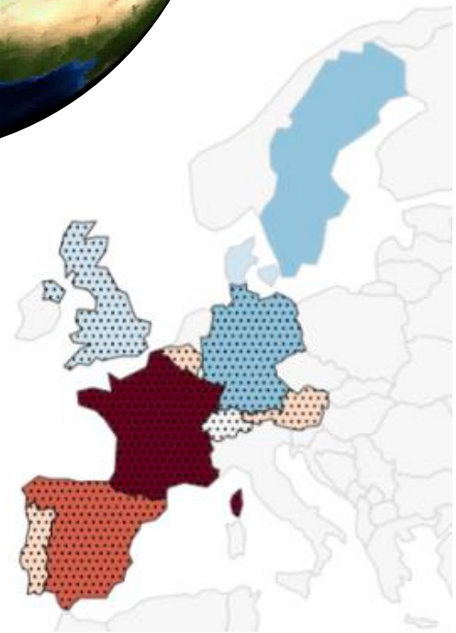


Stratospheric extremes are predictable on timescales of 5-10 days, but only in models with higher vertical resolution.



Improvement: High – Low ***vertical resolution***

Increased vertical resolution improves the cold bias and predictability of the stratosphere, with potential impacts on the predictability of our weather.



Stratospheric events lead to a wide range of surface impacts, including land and marine cold air outbreaks and anomalous dust transport impacting human mortality, flooding and windstorm damage.

The extended-range predictability of the stratosphere represents a window of opportunity for enhanced predictability of these surface impacts.

funding sources: