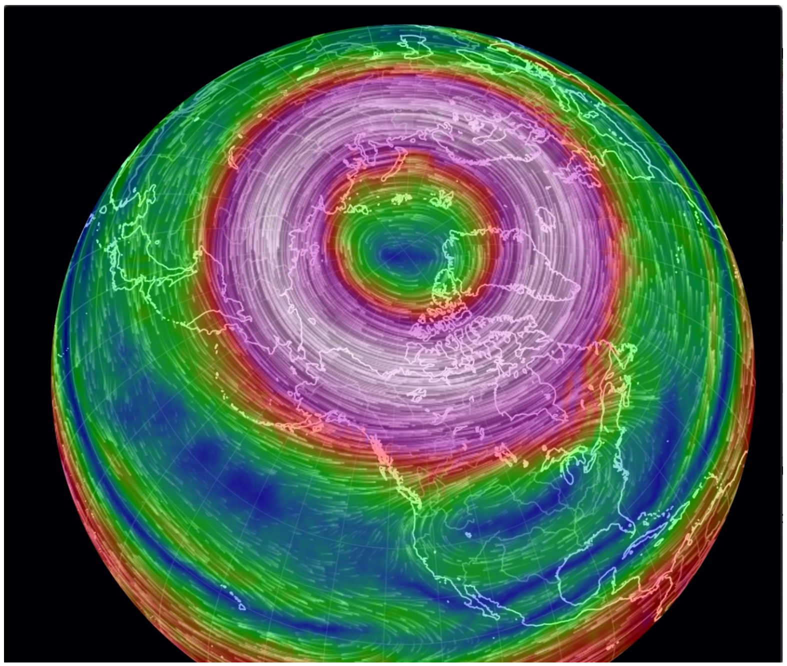
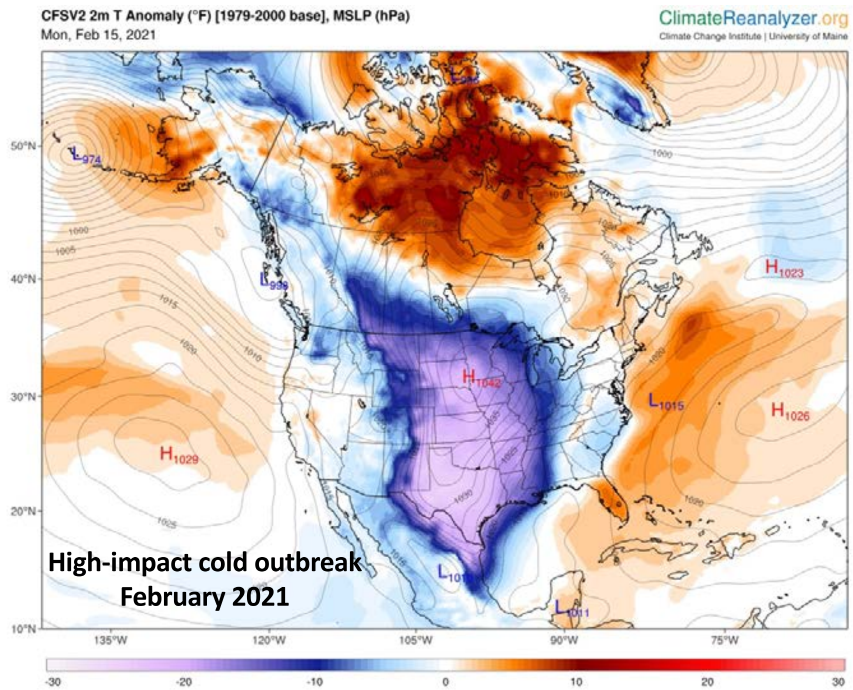
Wintertime Impacts of Polar Stratospheric Variability

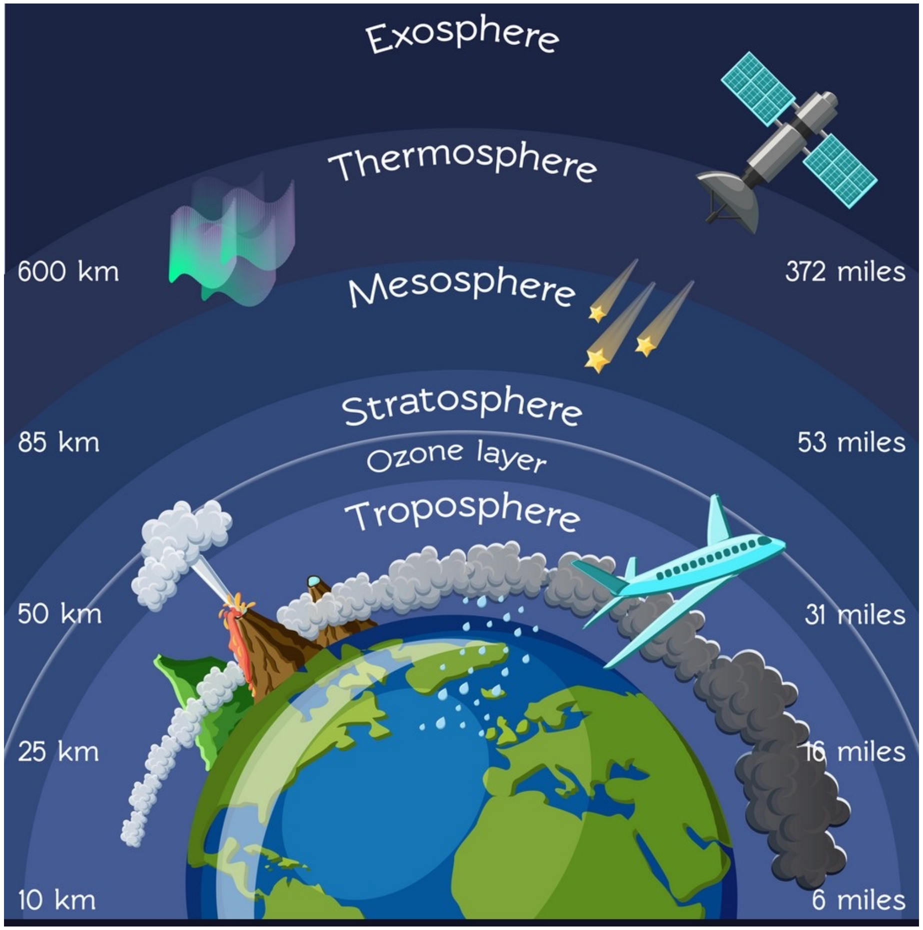
Dr. Amy H. Butler (NOAA Chemical Sciences Laboratory)

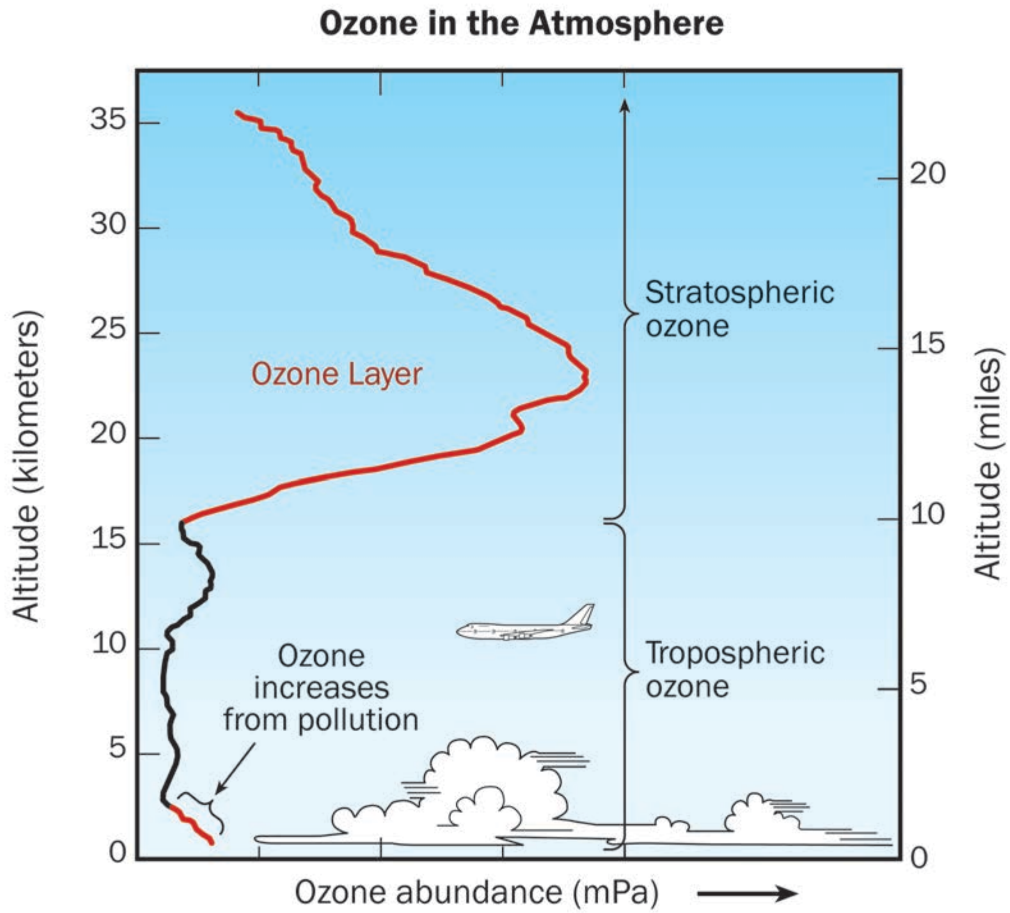
NWS Climate Services Webinar



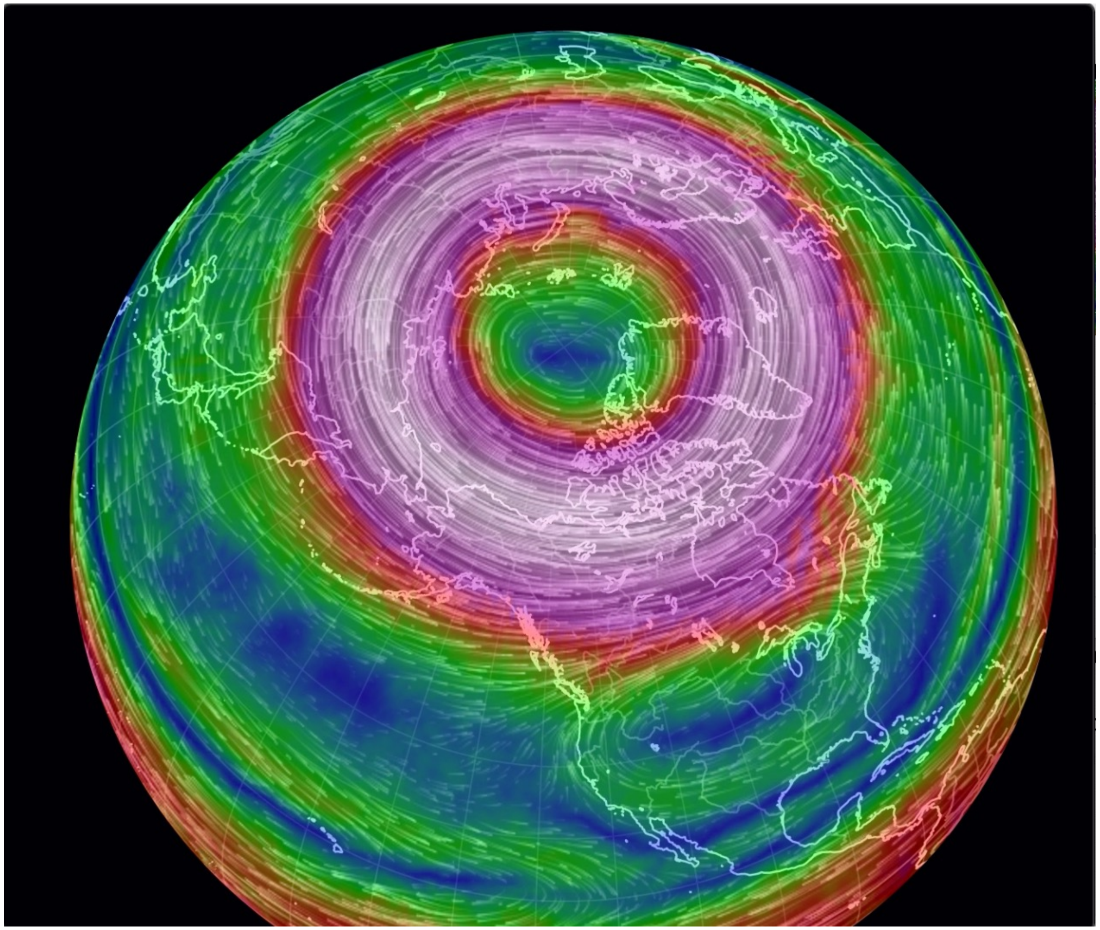


What is the Stratosphere?





What is the stratospheric polar vortex?

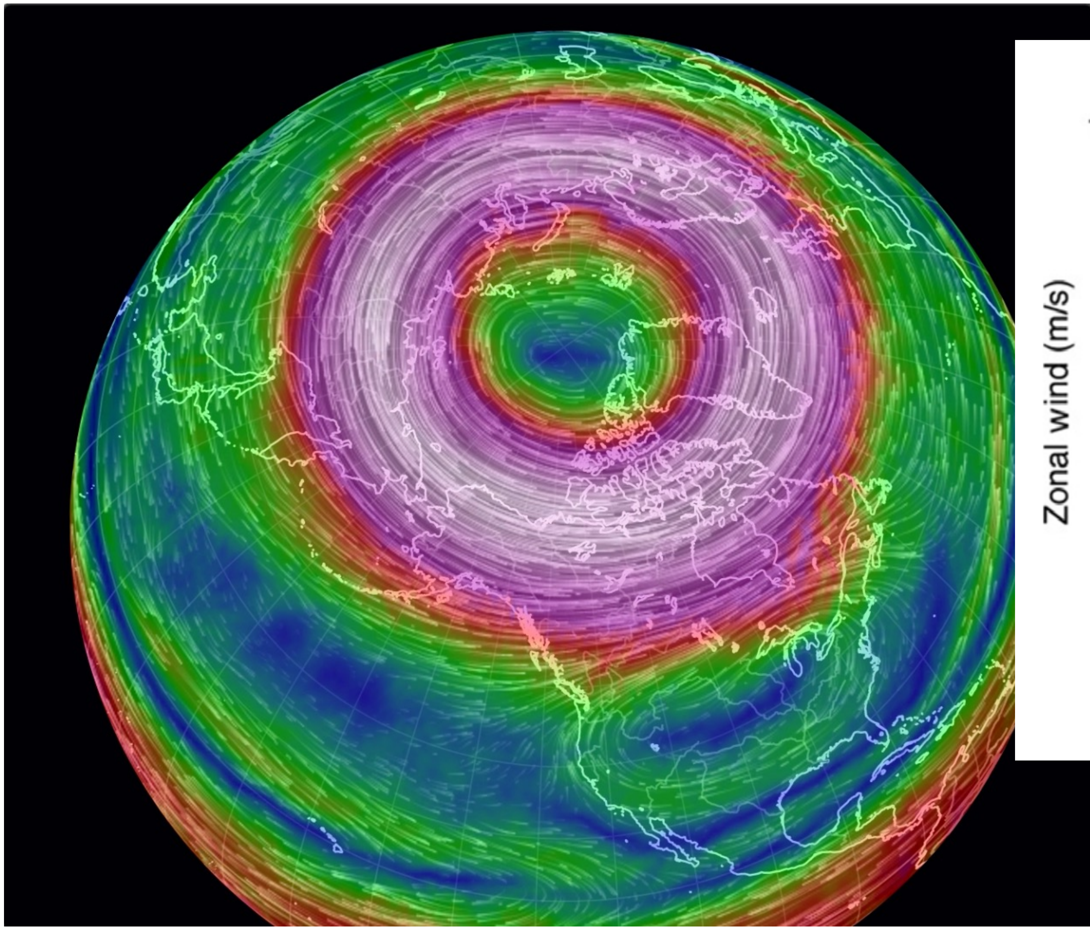


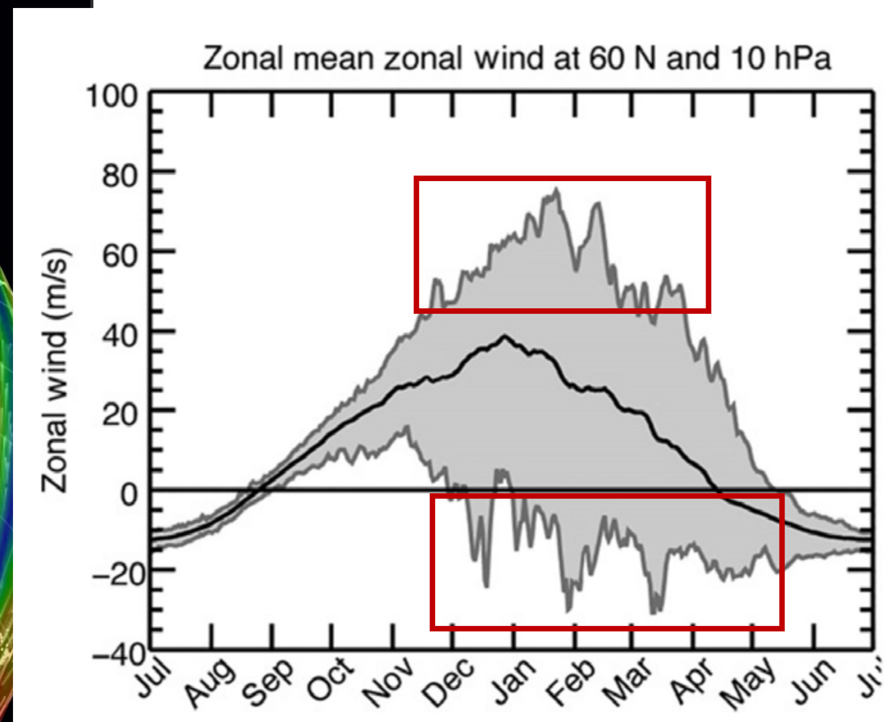
Westerly circumpolar winds in the winter hemisphere stratosphere.

These winds are due to seasonal changes in incoming amounts of sunlight.

From earth.nullschool.net,
Feb 16 2020

What is the stratospheric polar vortex?



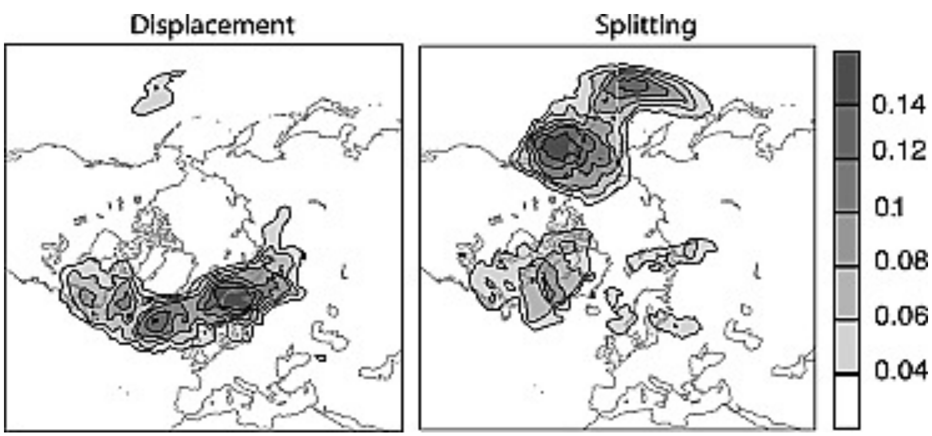


From earth.nullschool.net,
Feb 16 2020

The troposphere and the stratosphere interact with each other

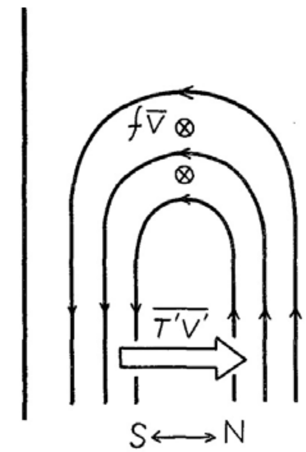
Weather systems (e.g., blocking patterns) and land-sea contrasts are associated with planetary-scale atmospheric waves that amplify into the stratosphere *[Matsuno 1971],* as long as the background flow is westerly *[Charney and Drazin 1961].*

Blocking precursors to polar vortex weakening



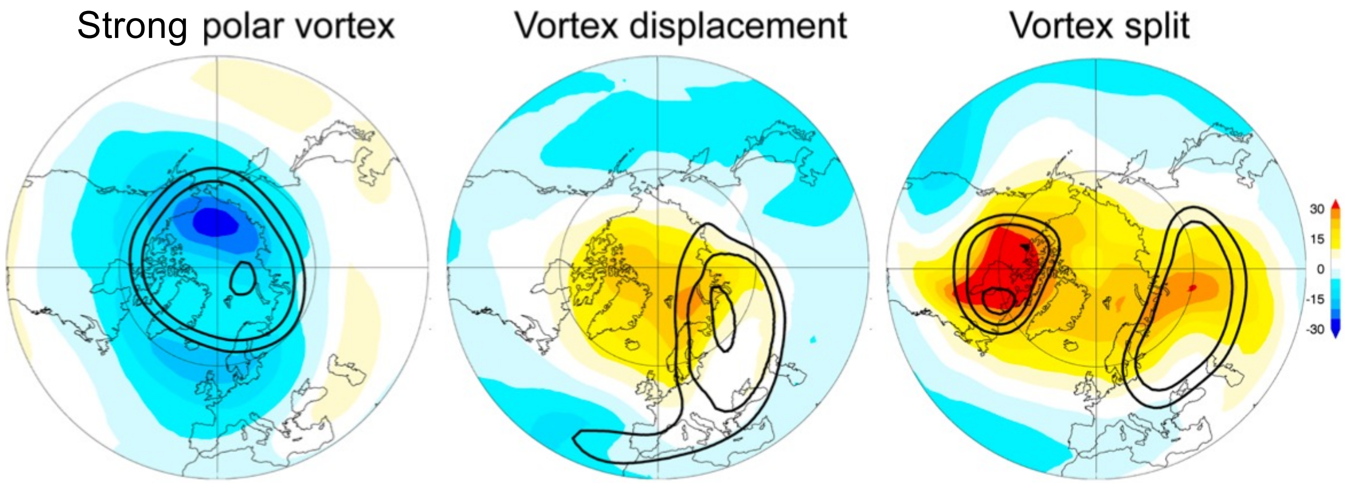
Martius et al. 2009

These vertically-propagating waves (positive v’T’) can dissipate or break, depositing easterly momentum and slowing the westerly polar vortex.



Matsuno 1971

Disruptions of the polar vortex (SSWs)



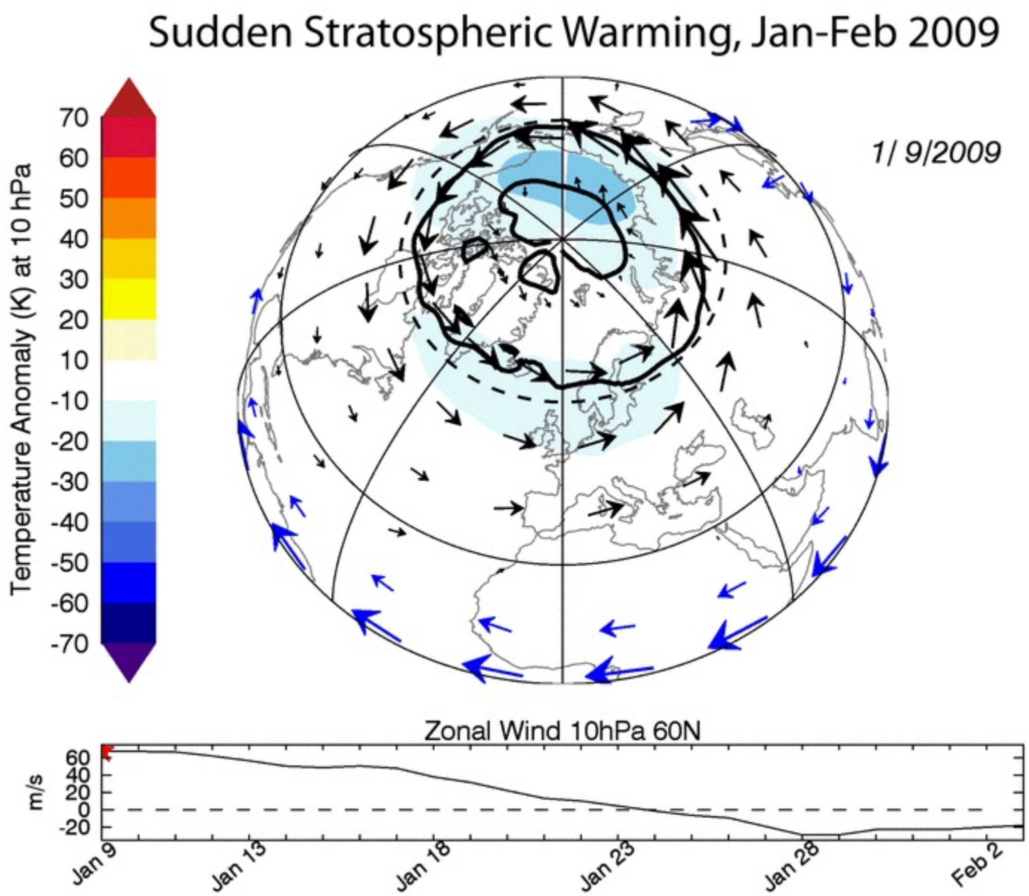
Butler et al 2017 ESSD
PV at 550K
Temp anoms [K], 10 hPa

Driven by a combination of **internal resonance** and momentum deposition from **planetary-scale atmospheric waves** that propagate into the stratosphere and break. In a "*major sudden stratospheric warming*" (**SSW**) event, the zonal-mean zonal wind at 10 hPa and 60N reverses.

The vortex can be **displaced** off the pole or **split** into two smaller vortices.

For a comprehensive review of Sudden Stratospheric Warmings, see Baldwin et al. 2021, Reviews of Geophysics

Disruptions of the polar vortex (SSWs)

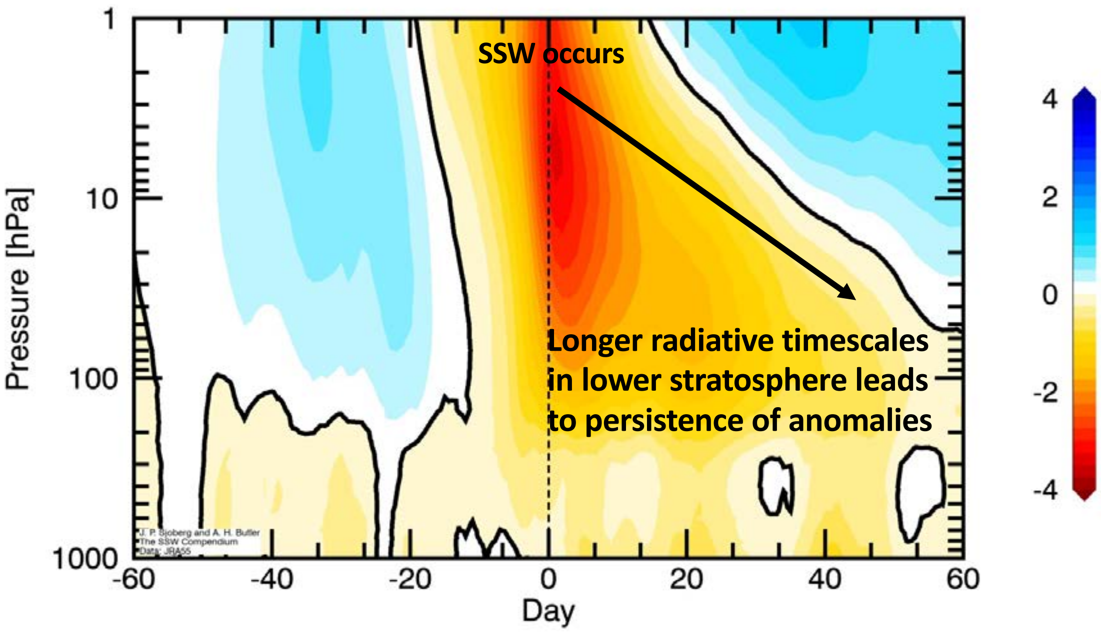


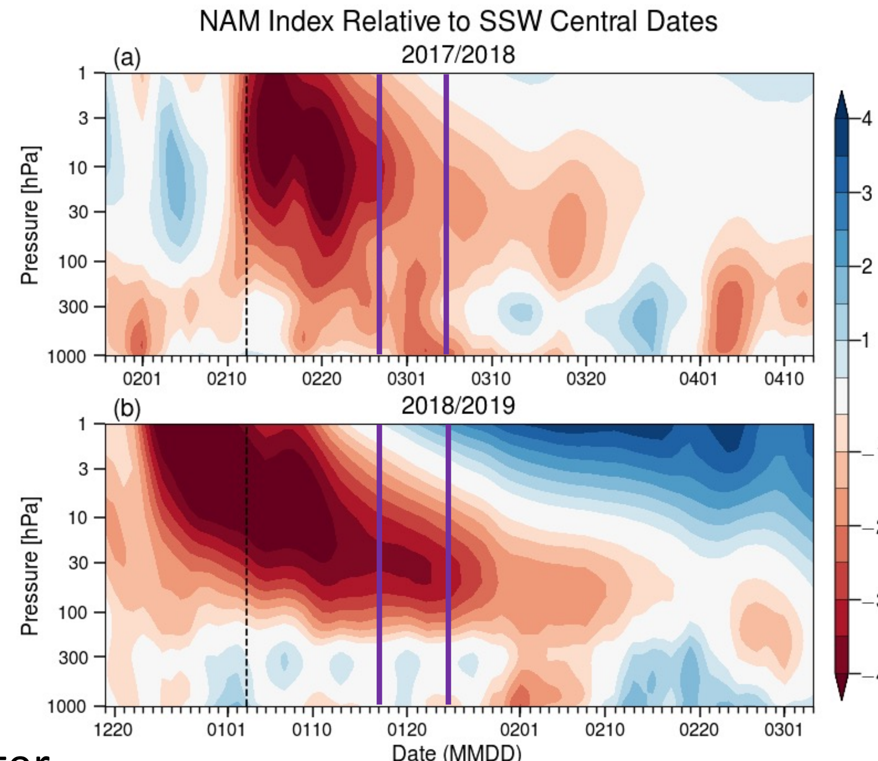
From Butler et al. 2015

Downward Influence of Polar Vortex Extremes

Butler et al 2017 ESSD

Northern Annular Mode index (stddev)

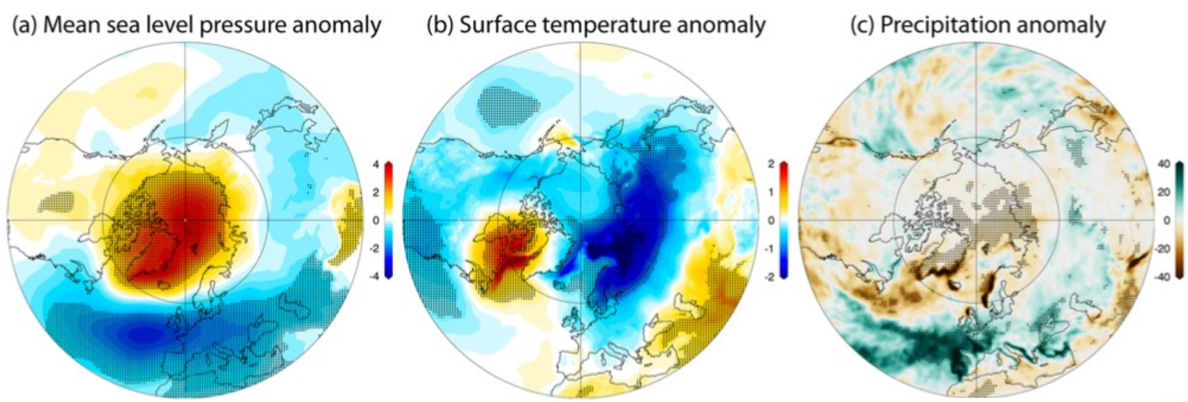




Butler et al. 2020 QJRMS

Downward influence can **persist** for **days to weeks** after the polar vortex breaks down or intensifies [e.g. *Baldwin and Dunkerton 2001*]. However, downward influence varies significantly on case to case basis.

Impact of polar vortex extremes on the surface



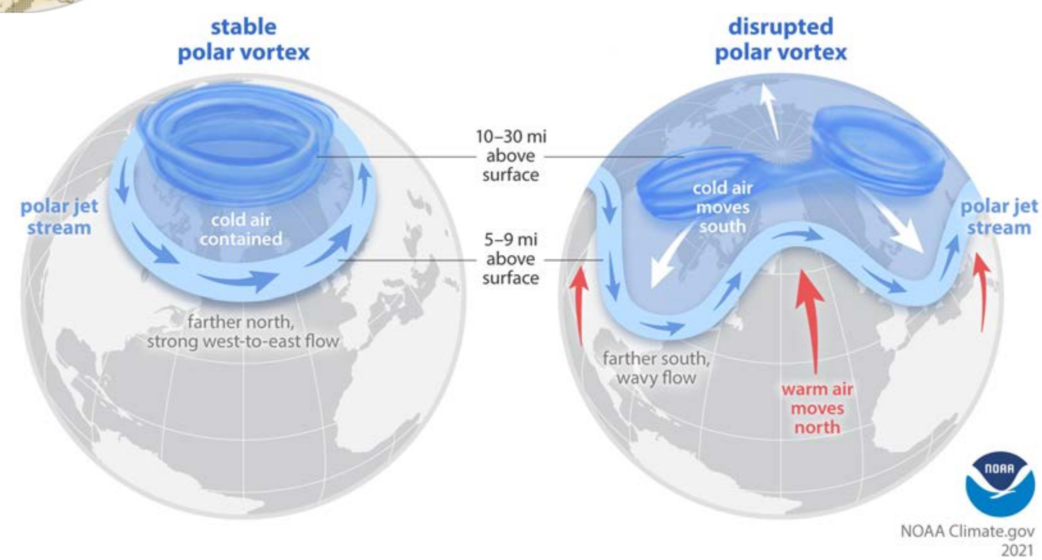
Butler et al 2017 ESSD

Averaged days 0-60 after historical SSWs

A weaker, disrupted polar vortex = cold mid-lat extremes and snowier weather, anomalously warm over Greenland and subtropical Asia, wetter over southern Europe BUT……

A stronger polar vortex = warmer winter weather over the eastern USA, Europe, and Asia, drier over southern Europe.

These weather changes are persistent and thus potentially predictable.



Quick aside on the term “polar vortex”

WEATHER OR NOT

Polar vortex might deliver early taste of winter to Tri-State area

The polar vortex may be on its way

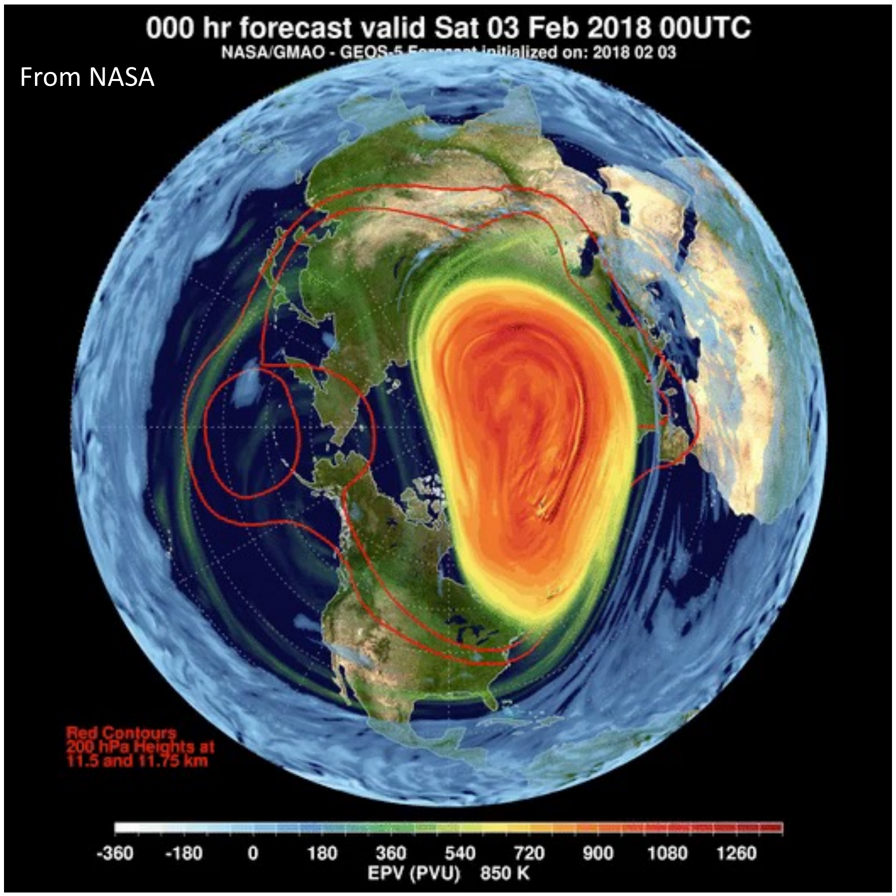
UK cold weather forecast: Mercury plunges sub-zero as polar vortex to strike Britain

Polar vortex brings most extreme winter weather in years

Caution! The term “polar vortex” is often used almost as a synonym for “cold air outbreak”. But scientists most often use “polar vortex” to refer to the climatological westerly wintertime winds in the stratosphere.

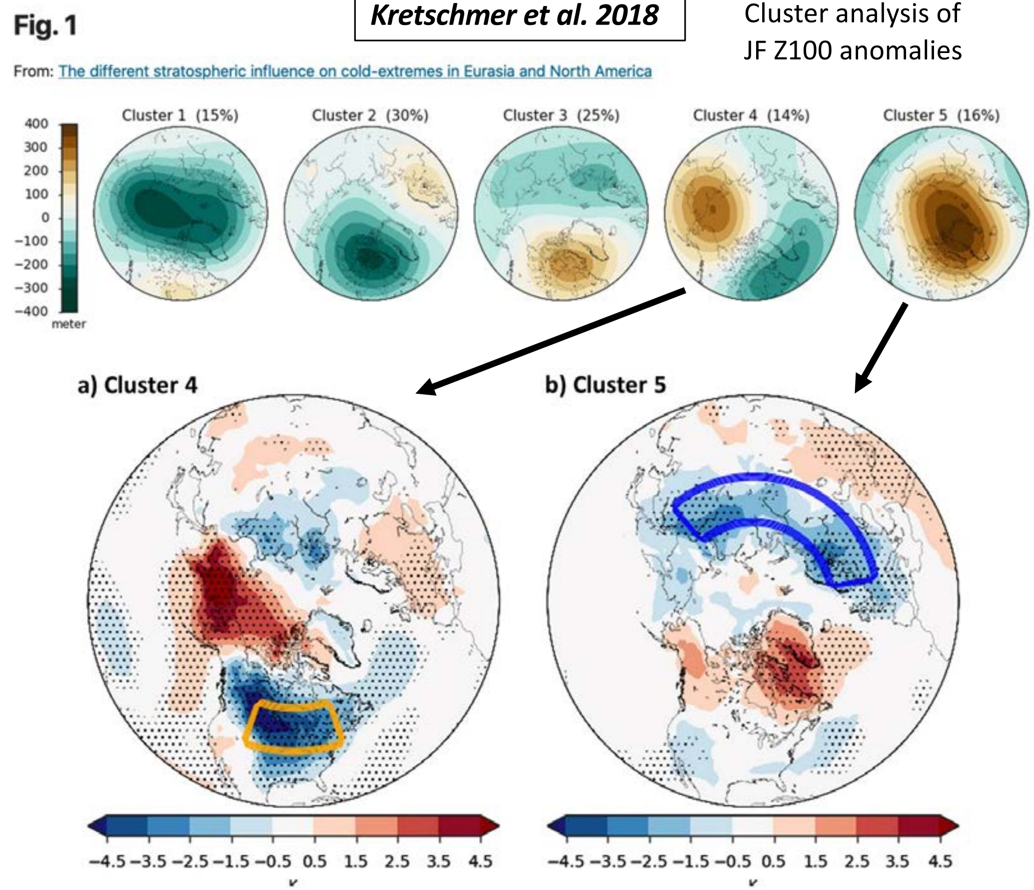
The polar vortex is a regular feature of the atmosphere. Usually it’s the *disappearance* or disruption of the polar vortex that make cold air outbreaks more likely. Cold air outbreaks can (and often do) occur independently of changes in the polar vortex.

Non-zonal downward influence likely relevant



Kretschmer et al. 2018

Cluster analysis of
JF Z100 anomalies

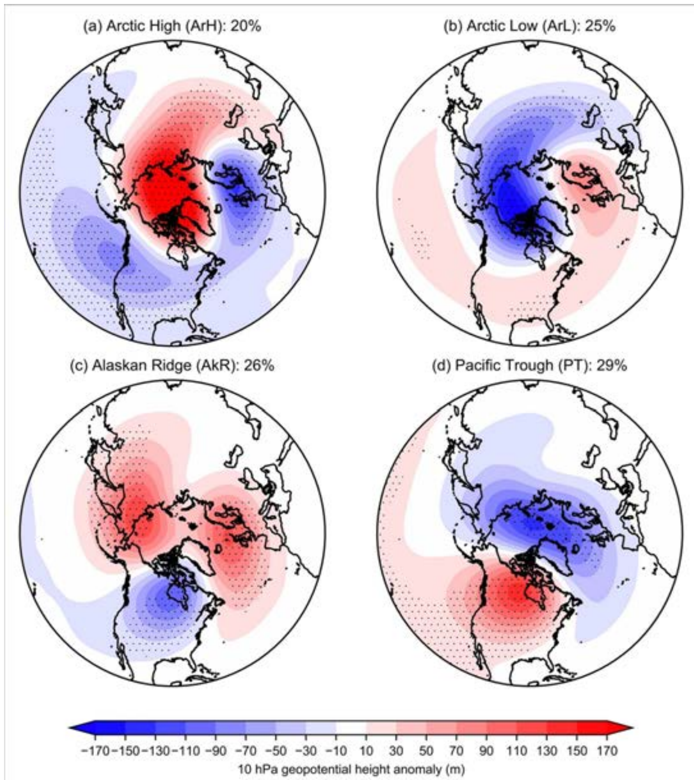


Primary influence of polar vortex on North American weather may not be from SSWs

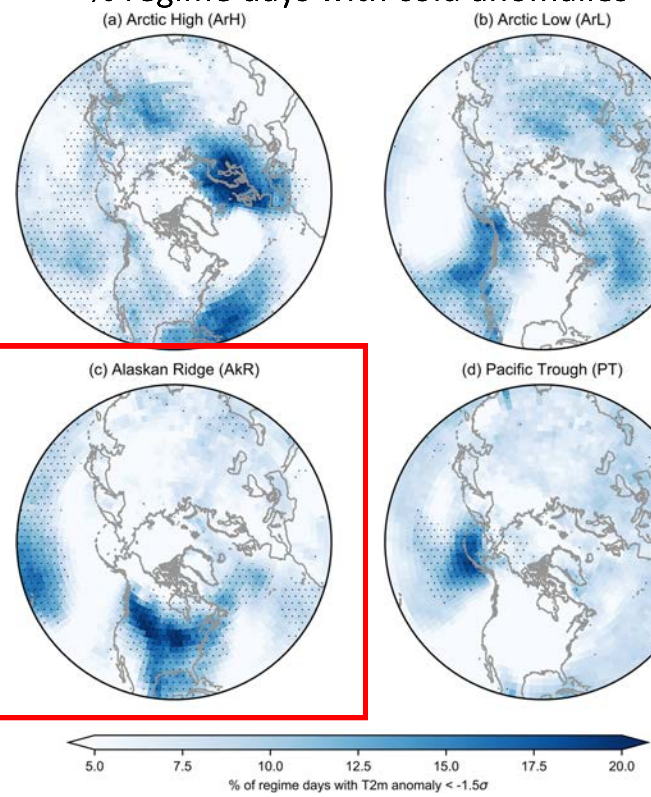
SSWs ->

Stretched polar vortex -> (see also, Cohen et al. 2021)

10 hPa height anomaly patterns

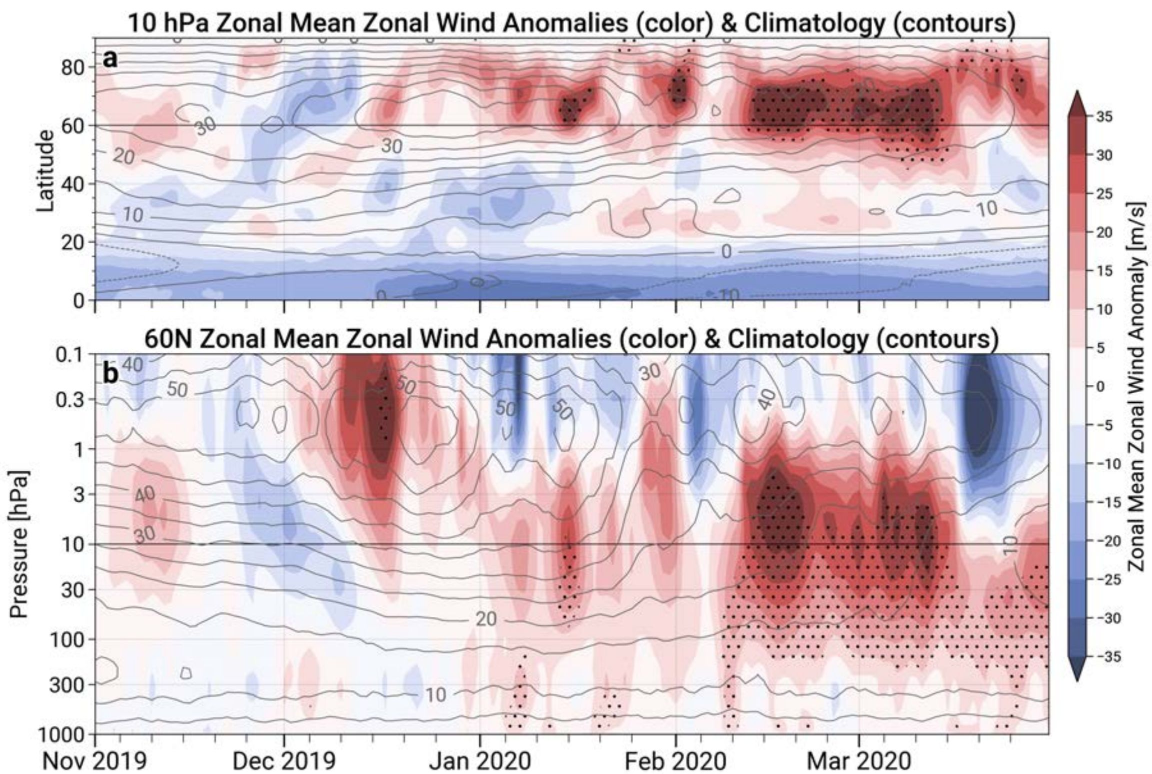


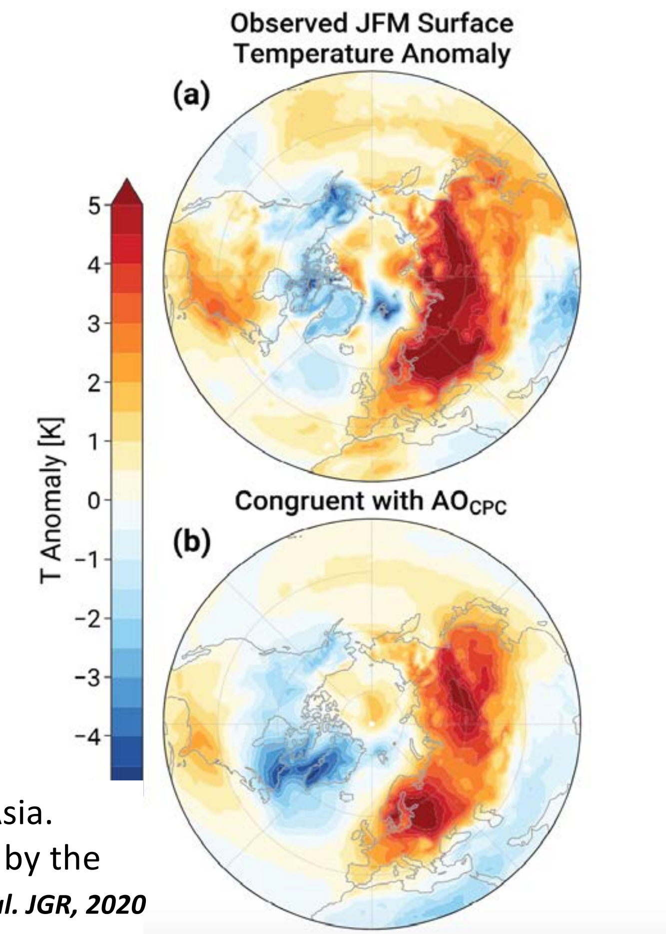
% regime days with cold anomalies



Lee et al. 2019, **Wintertime North American Weather Regimes and the Arctic Stratospheric Polar Vortex**

A strong polar vortex can also drive surface extremes





2020 was the record hottest winter in many locations, particularly Russia/Asia. However, about 2/3 of the warmth in the mid-latitudes could be explained by the extreme +AO, which was the highest in the 70-year record. ***Lawrence et al. JGR, 2020***

The WWRP/WCRP S2S Prediction Project

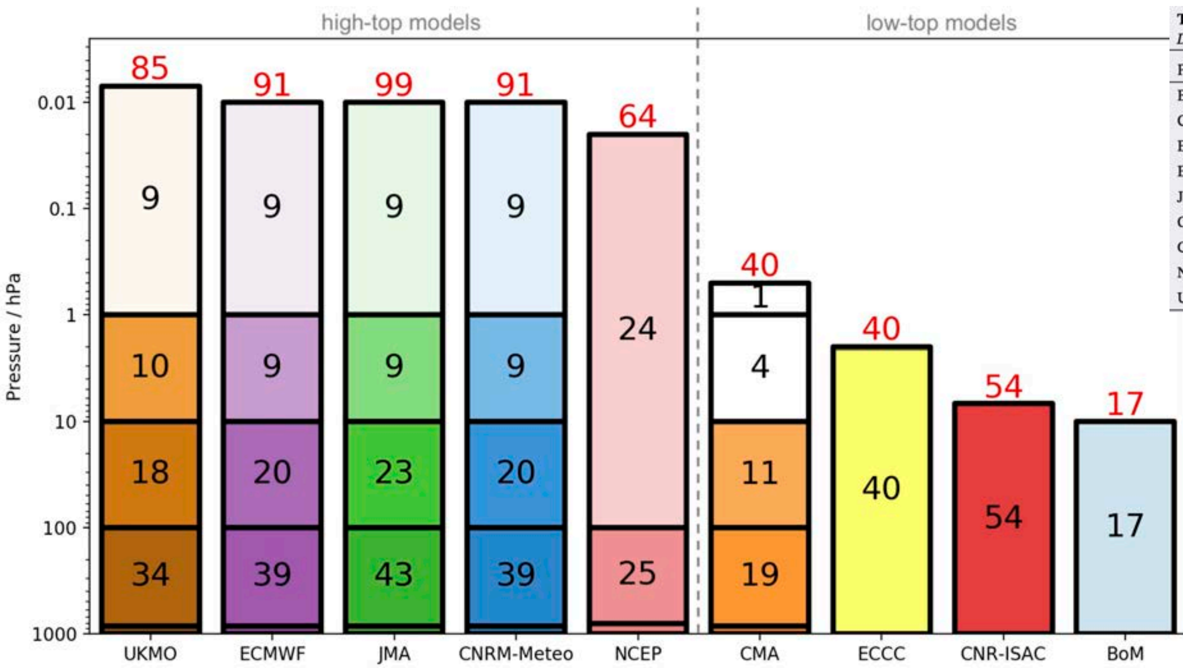


Table 1
Details of the Prediction Systems Considered in This Study, Based on the Data Available at the Time of Analysis

Prediction system	Initialization	Hindcast period	Ensemble size
BoM	ERA-interim/ALI	1981–2013	33
CMA	NCEP-NCAR R1	1994–2014	4
ECCC	ERA-interim	1995–2014	4
ECMWF×	ERA-interim	1997–2016	11
JMA×	JRA-55	1981–2010	5
CNRM-Meteo×	ERA-interim	1993–2014	15
CNR-ISAC	ERA-interim	1981–2010	1
NCEP×	CFSR	1999–2010	4
UKMO×	ERA-interim	1993–2015	2–7

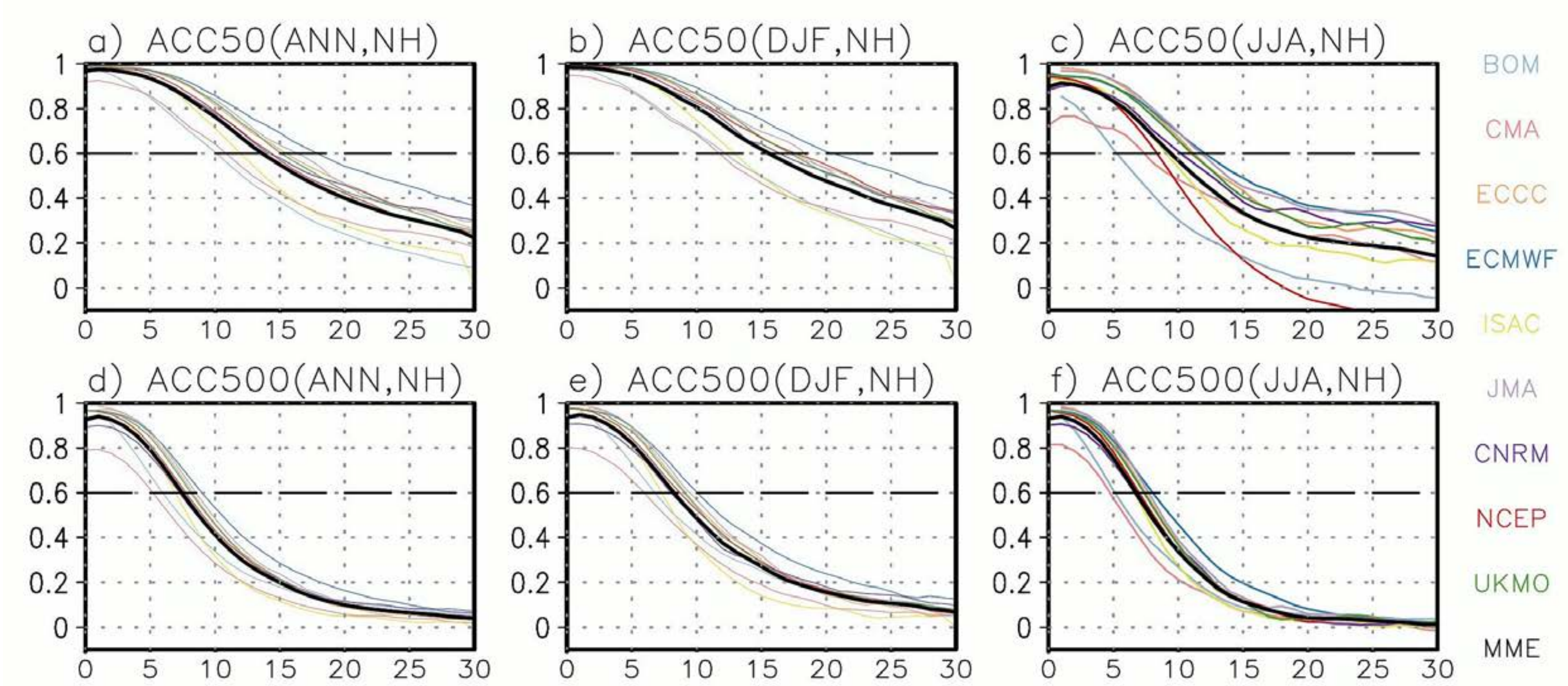
'x' indicates a high-top model => model top above 0.1 hPa and several model levels above 1 hPa

Data is from S2S Project (Vitart et al. 2017)

Domeisen, Butler et al. (2020), Part I

The majority of S2S prediction systems now have high model lids and are more vertically resolved above 100 hPa.

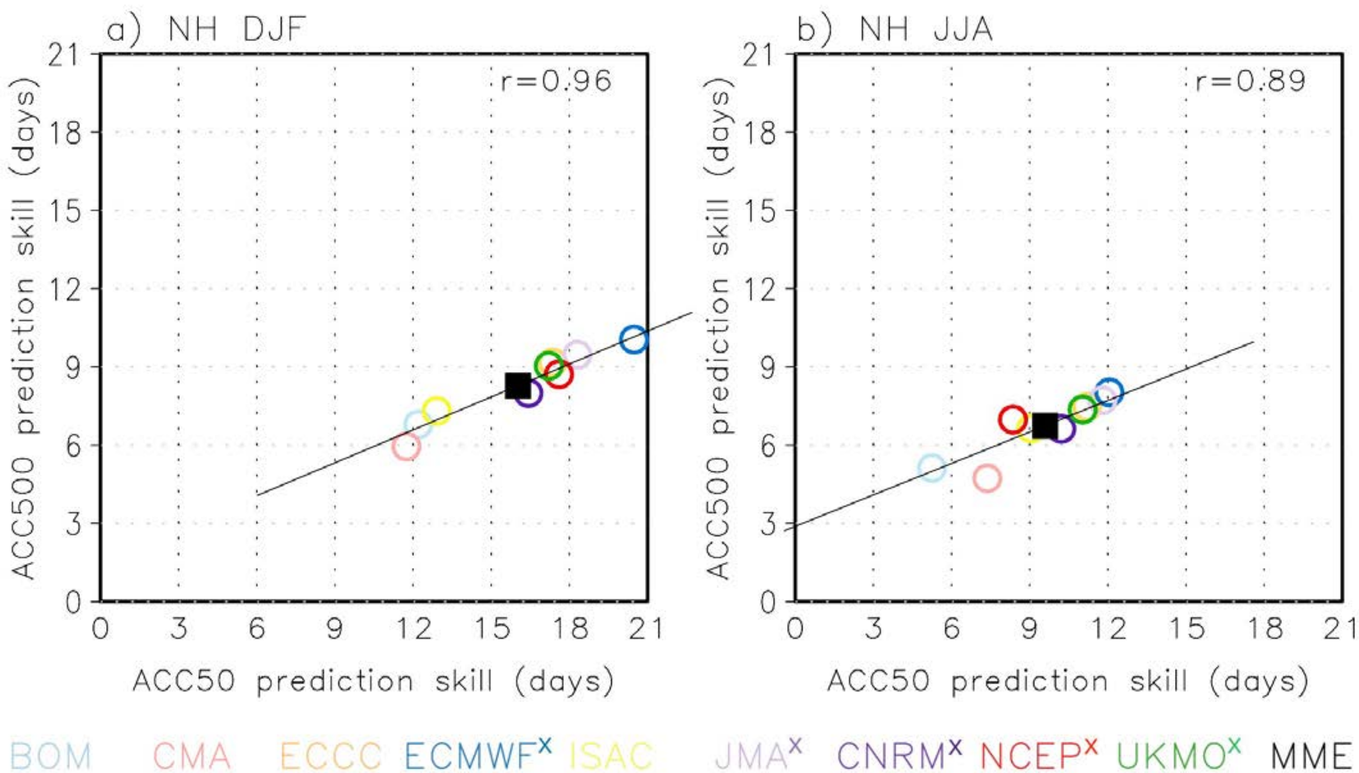
The stratosphere has longer memory than the troposphere



50 mb: 14 +/- 2.4 days	50 mb: 16 +/- 2.9 days	50 mb: 9.6 +/- 2.2 days
500 mb: 7.5 +/- 1.2 days	500 mb: 8.3 +/- 1.3 days	500 mb: 6.7 +/- 1.1 days

Domeisen et al. (2020), Part I.

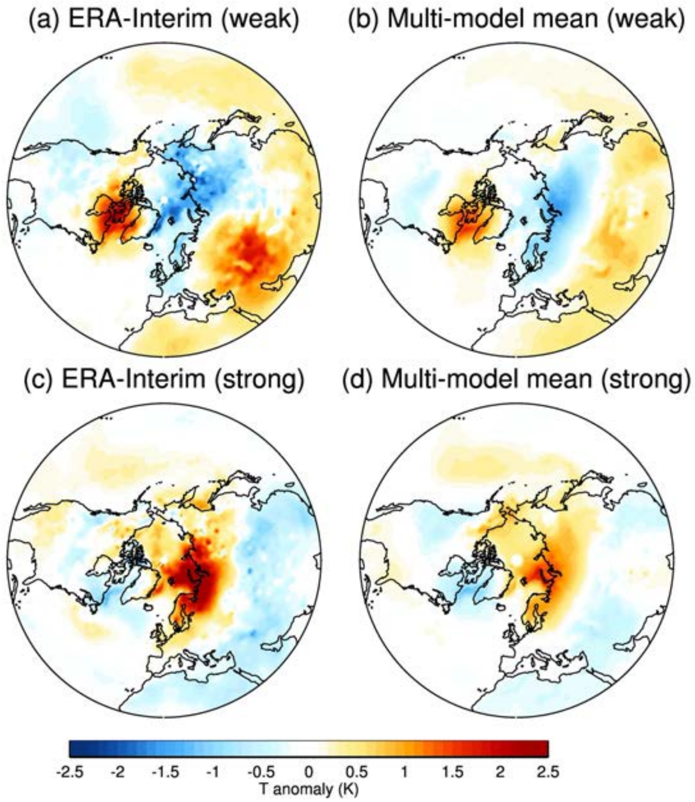
Models with longer prediction skill in the stratosphere have longer prediction skill in the troposphere



Domeisen et al. (2020), Part I.

The direction of causality here cannot be inferred. Can we look at "forecasts of opportunity" initialized when the polar vortex is weak or strong, compared to control forecasts?

Week 3-4 temperature response following polar vortex extremes in S2S systems



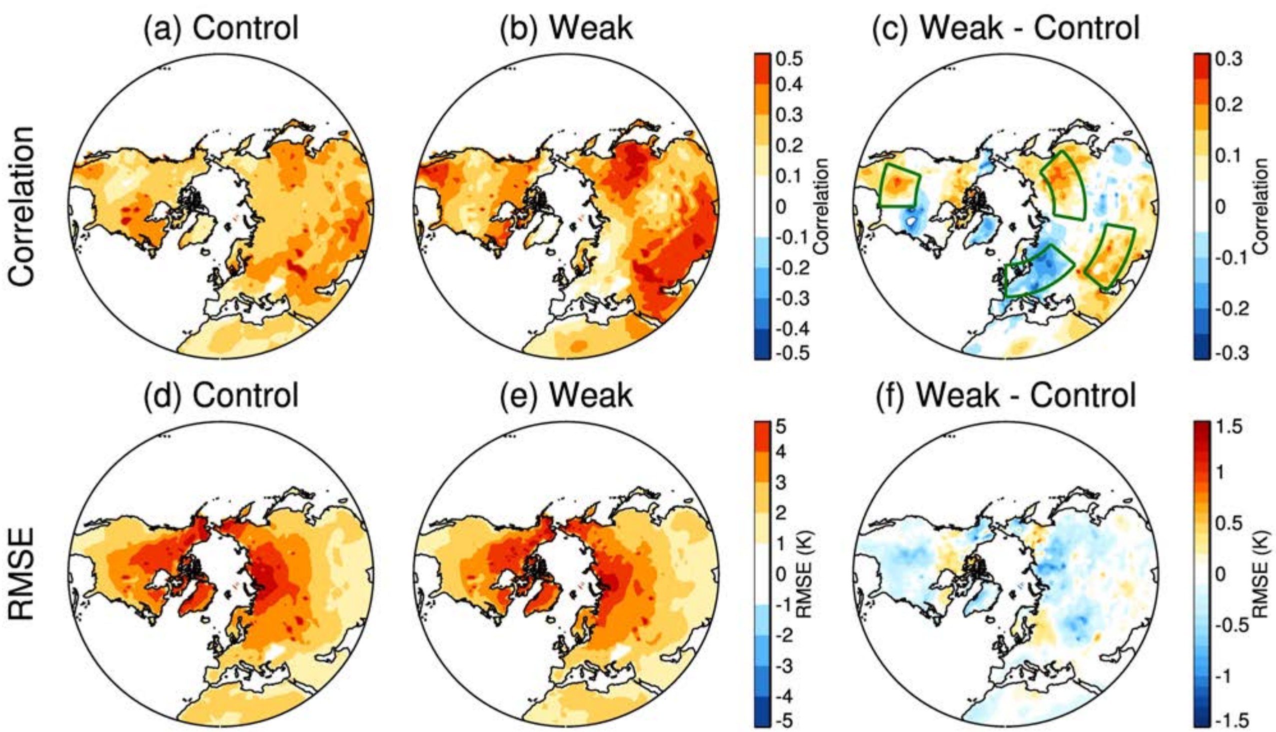
Domeisen et al. (2020), Part II

<u>Methodology</u>: Consider zonal-mean zonal winds at 10mb and 60N at time of initialization for all hindcasts from Dec-Mar.

Weak vortex: U < 5 m/s
Strong vortex: U > 40 m/s

S2S prediction systems generally capture the observed 2m-temperature response 3-4 weeks after weak and strong vortex events. Warm anomalies in ERA-interim are stronger compared to multi-model mean.

Does surface skill increase after weak vortex events?



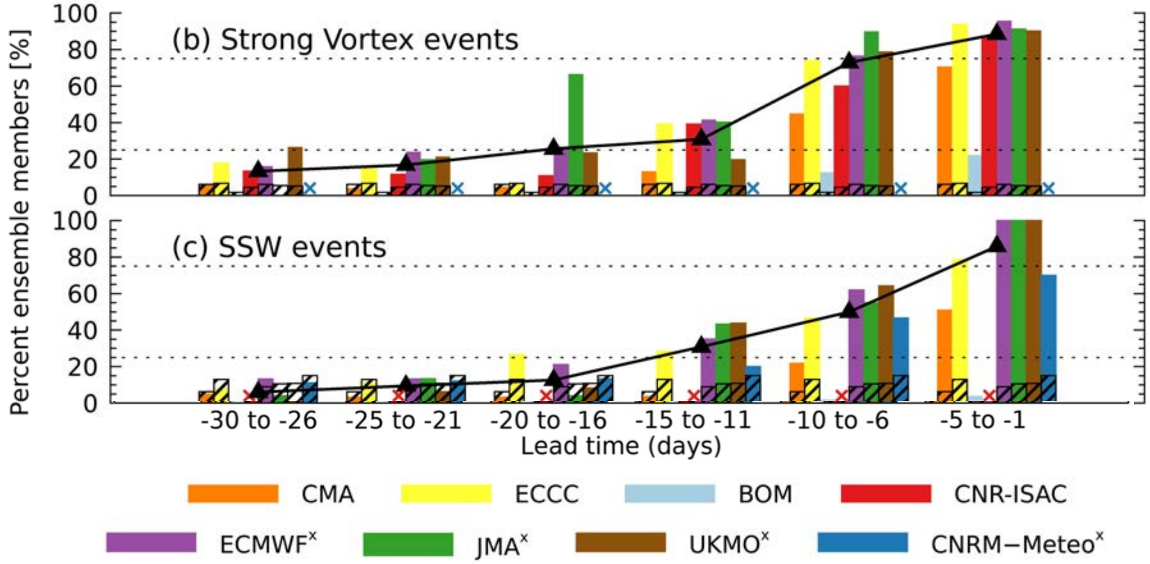
Domeisen et al. (2020), Part II

Week 3-4 correlation skill is increased in some regions, but not others.

Notably, there is a decrease in correlation skill over Europe relative to control forecasts.

Week 3-4 RMSE mostly decreases for forecasts initialized during weak vortex events.

Predictability of polar vortex extremes



Black striped bars indicate average 30-day "false alarm rate" (events that were predicted but not observed)

Accurate *(within +/- 3 days)* detection of event *(> 75% of members)* generally occurs at **10 days or less**. Strong vortex events have slightly higher rates of detection at longer leads than SSWs.

In general models with higher model top/vertical resolution detect events at longer lead times.

Domeisen et al. (2020), Part I; period of 1996-2010 is assessed

Can we make probabilistic forecasts of SSWs for seasonal forecasts?

… given the inherent limitations of deterministically forecasting SSWs?

Q: Are there factors that increase the probability of SSW events over a season?

El Nino-Southern Oscillation:

30% higher frequency of SSWs in El Nino (Butler et al. 2014, Polvani et al. 2017)

Madden-Julian Oscillation:

Higher chance of SSWs 1-3 weeks following phase 6/7 (Garfinkel et al. 2012)

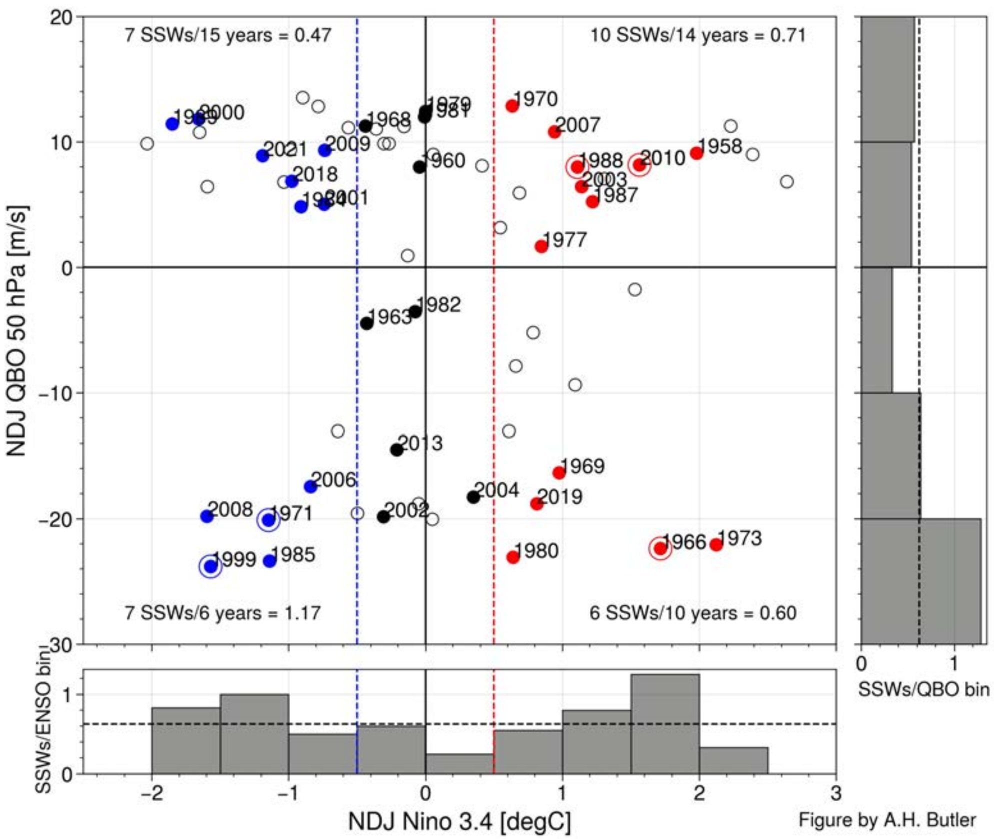
Quasi-biennial Oscillation:

More SSWs in easterly phase but may be modulated by solar cycle (Holton and Tan 1982, Labitzke and van Loon 1988)

Other factors: Eurasian snow cover, North Pacific SSTs, volcanoes, Arctic sea ice…

Can we make probabilistic forecasts of SSWs for seasonal forecasts?

A: Yes, but in practice it's messy

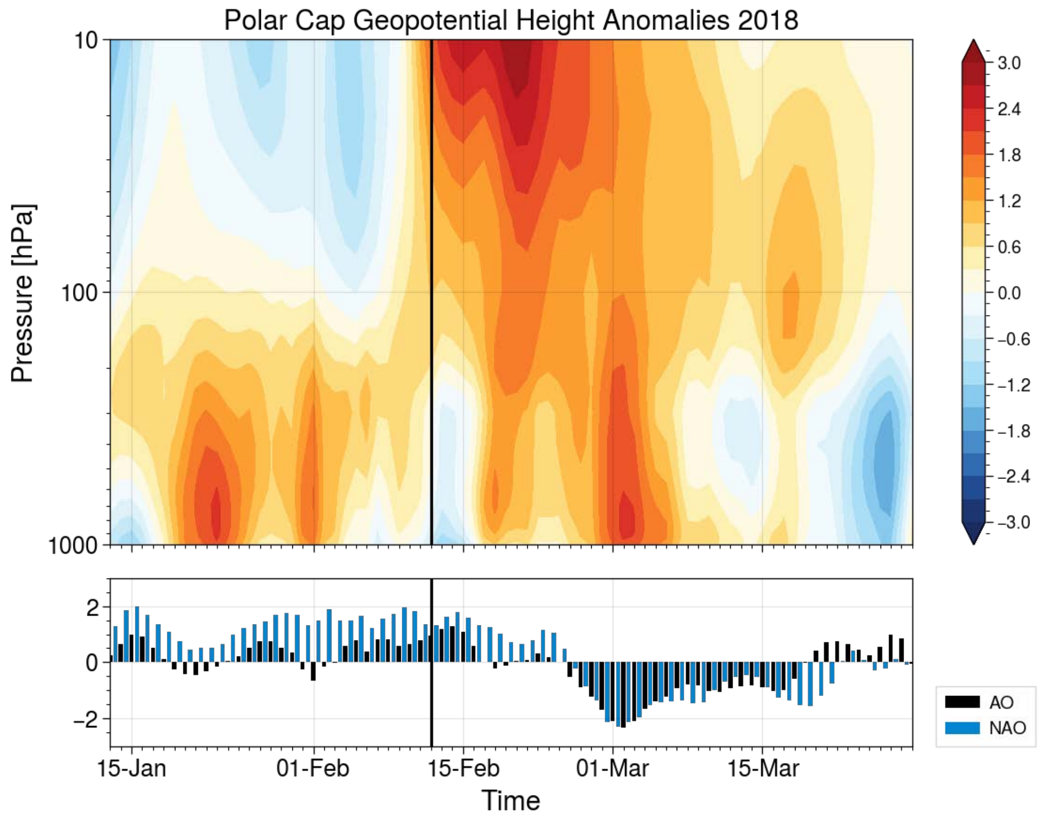


Colored dots show winters with SSWs, as a function of QBO and ENSO phase.

SSWs can occur in almost any phase of QBO/ENSO; however they've occurred with the highest frequency during easterly QBO and La Nina.

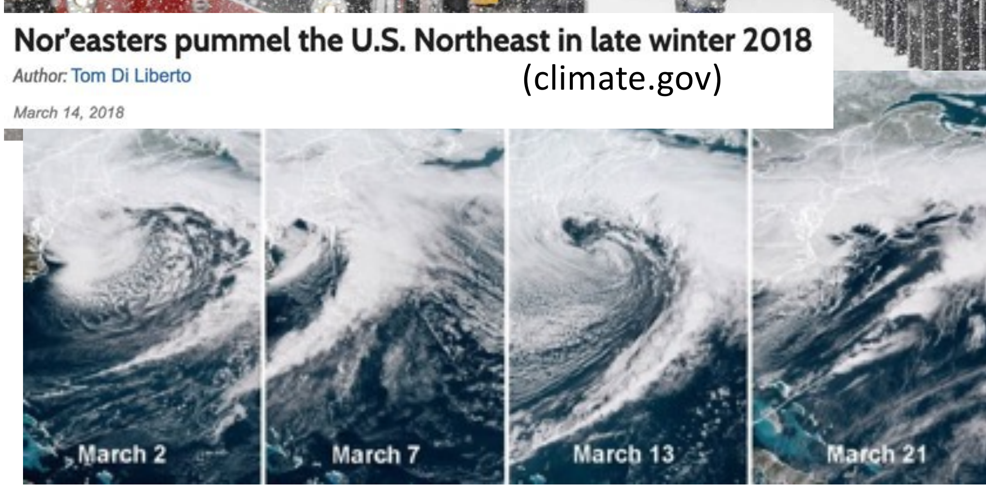
However this is the combination that has occurred the least often (maybe this winter?).

Case Study: February 12, 2018 SSW

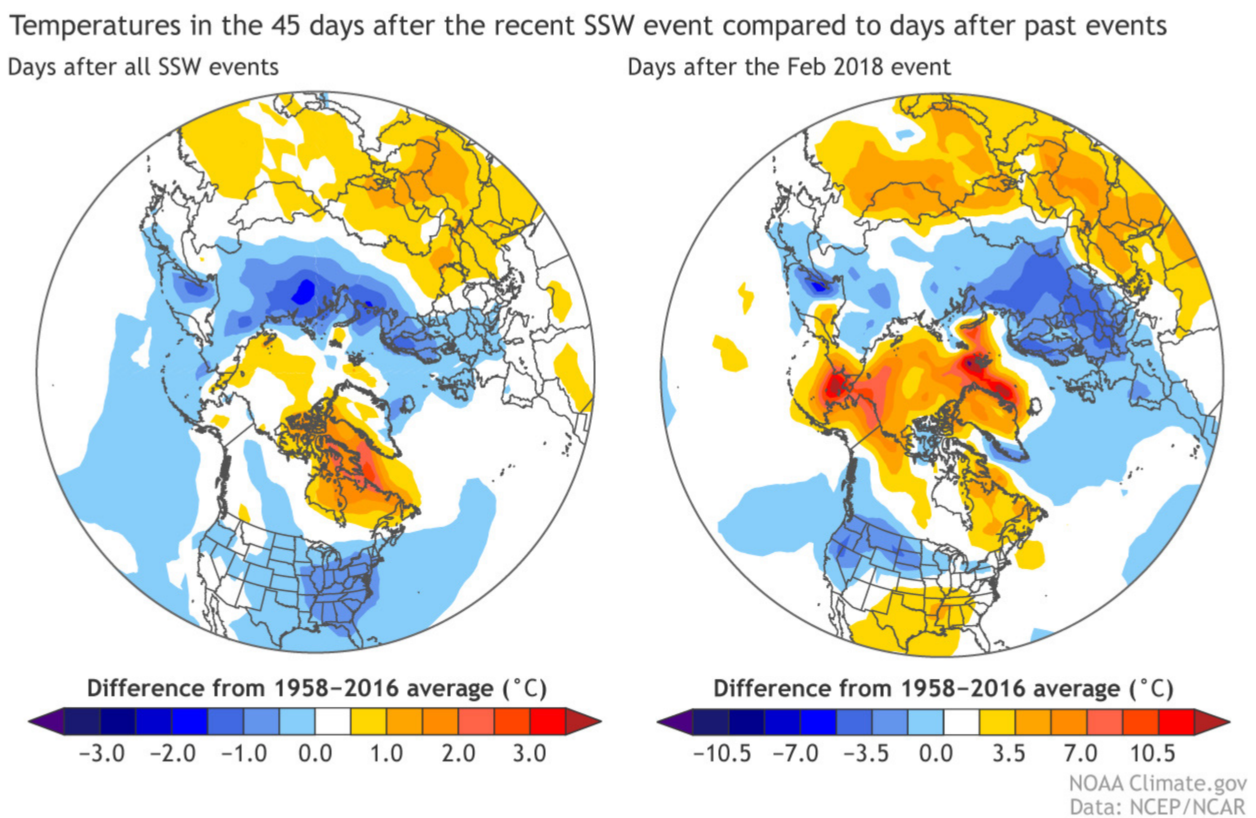


In the zonal-mean, coupling occurred ~6-7 days after the wind reversal in the stratosphere and was strongest from end of February through mid-March.

Cold, snowy weather following SSW 2018



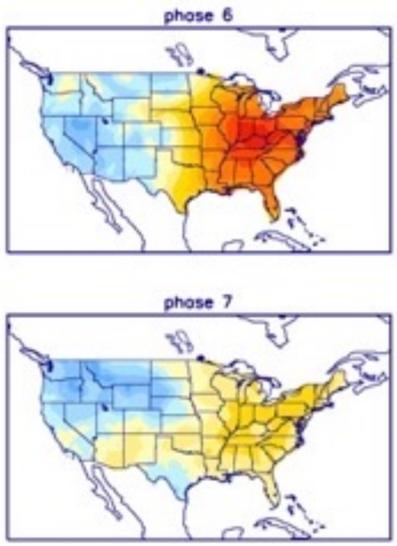
Case Study: February 12, 2018 SSW



Many similarities of the 2018 weather with the typical response following SSWs; but also some noticeable differences, particularly over the USA

SSW impacts occur in the context of other influences like MJO and ENSO

Strong amplitude phase 6/7 MJO



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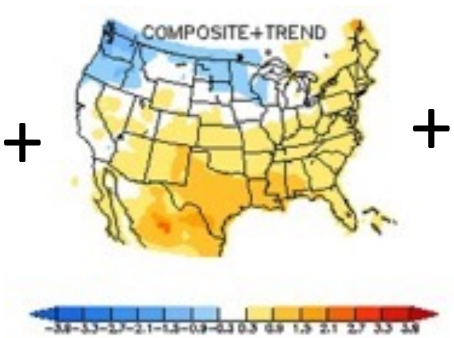
La Nina + trend



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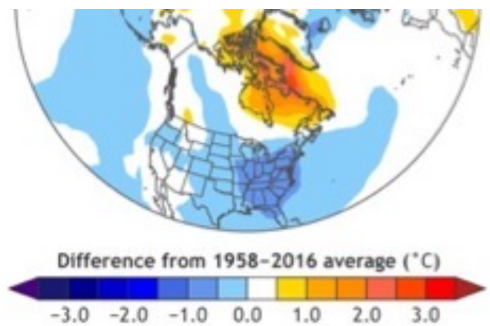
SSW



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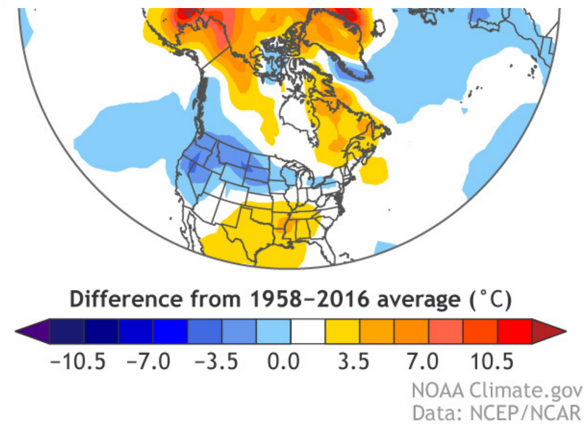
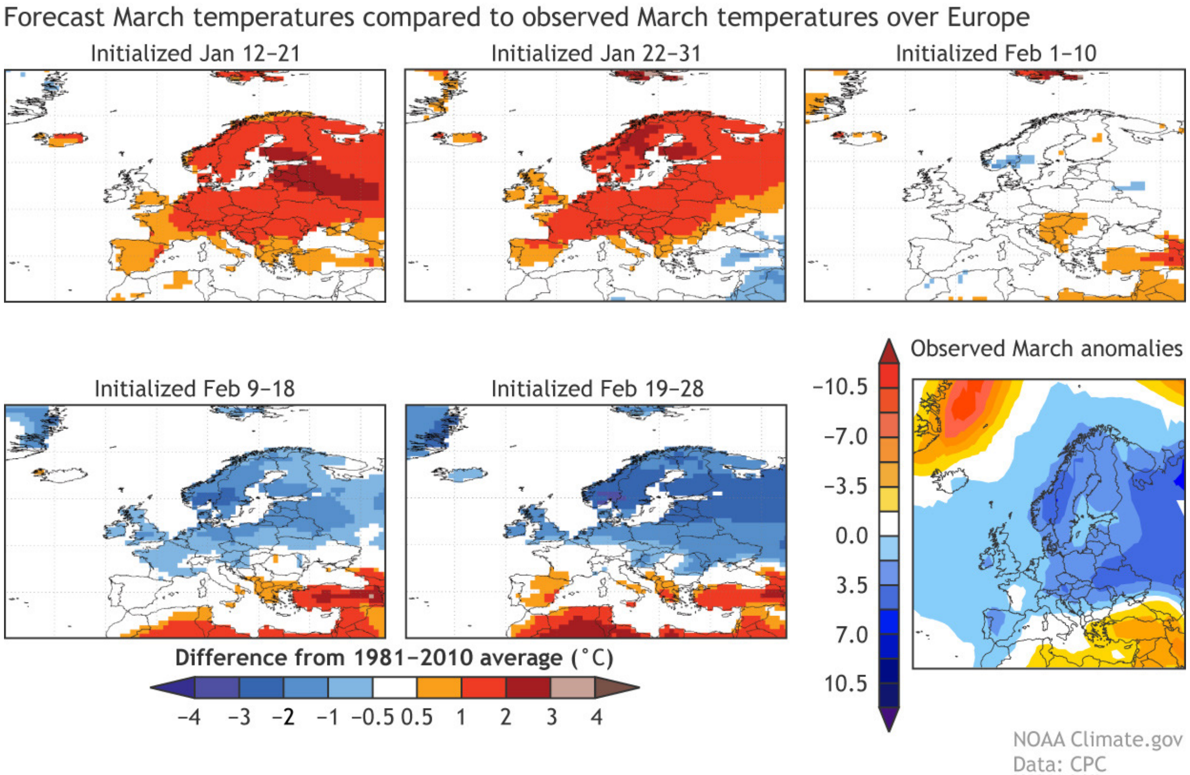
Observed temperature anomalies ?



Are these responses linear? Independent? What other factors matter? How much is just internal variability?

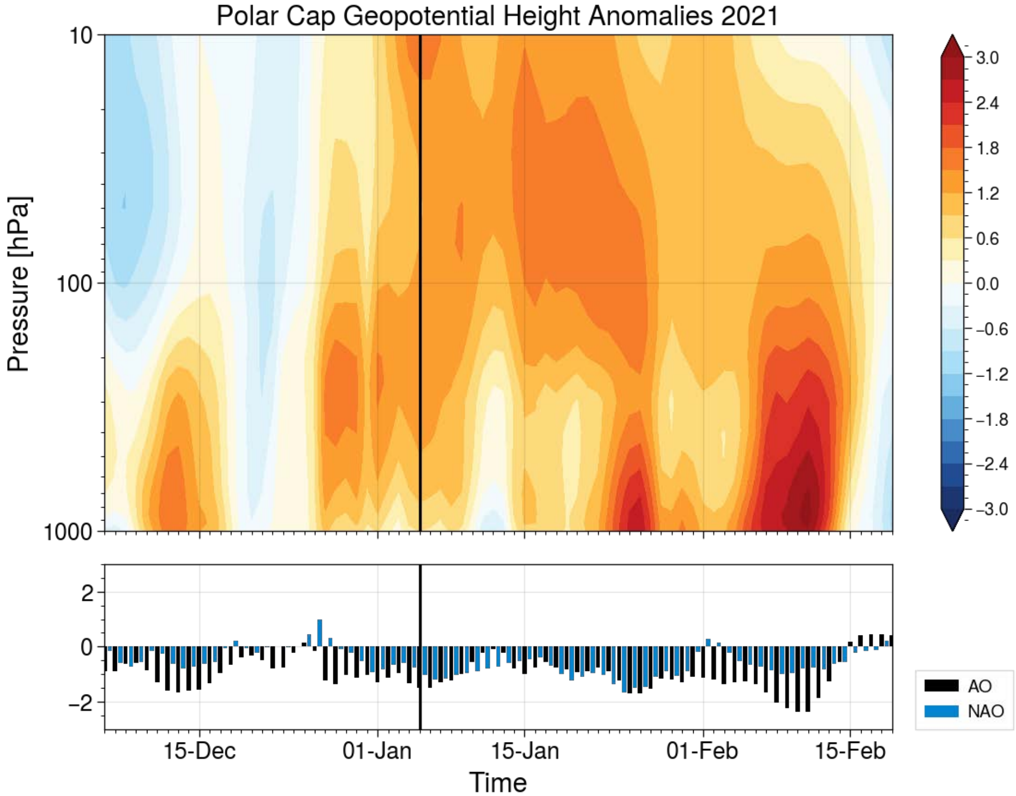
Inability to forecast SSWs >15 days out can have big impact on S2S timescales

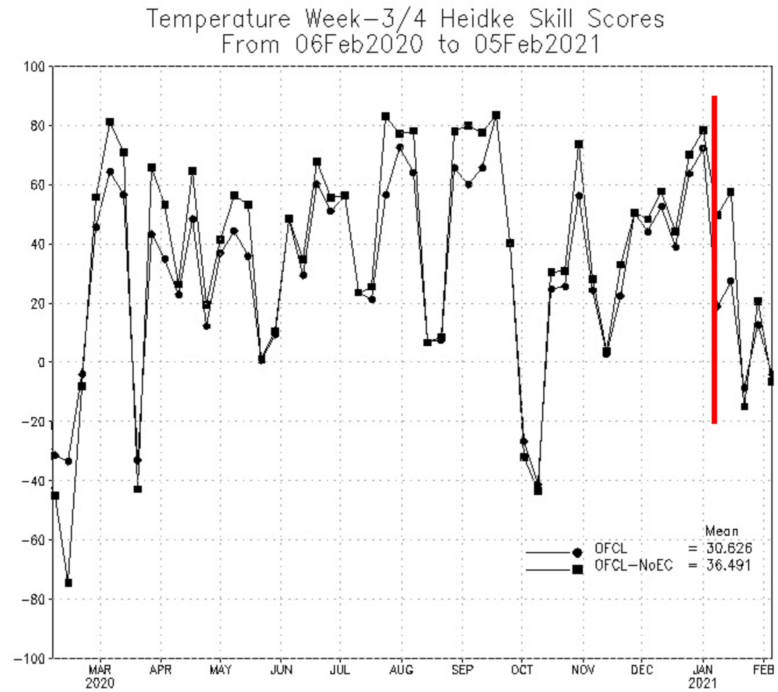


But, there was added skill over Europe 4-6 weeks after the SSW occurred.
Impact on skill was less clear over USA.

https://www.climate.gov/news-features/blogs/enso/february-and-march-madness-how-winds-miles-above-arctic-may-have-brought

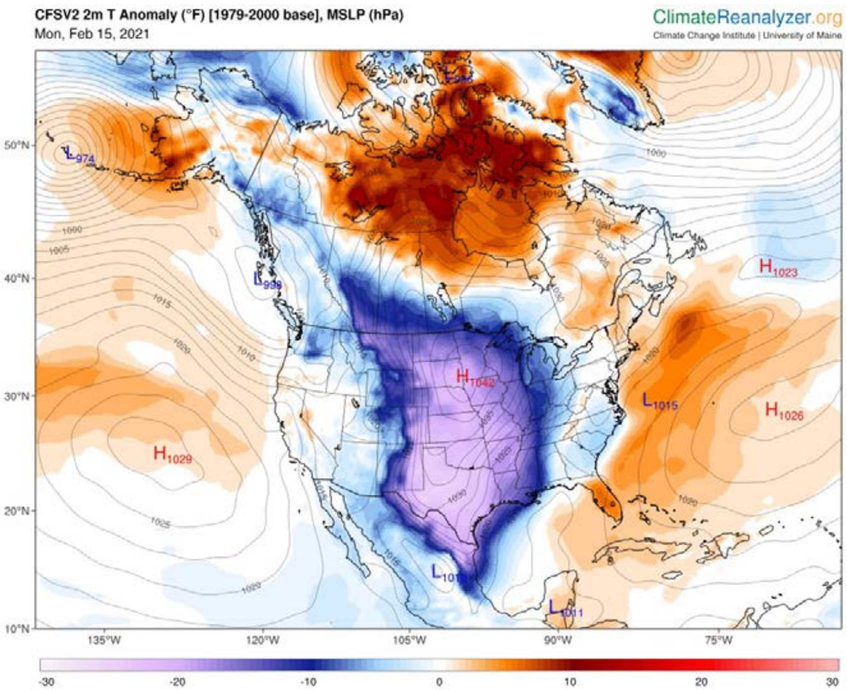
Recent Case Study: January 5, 2021 SSW





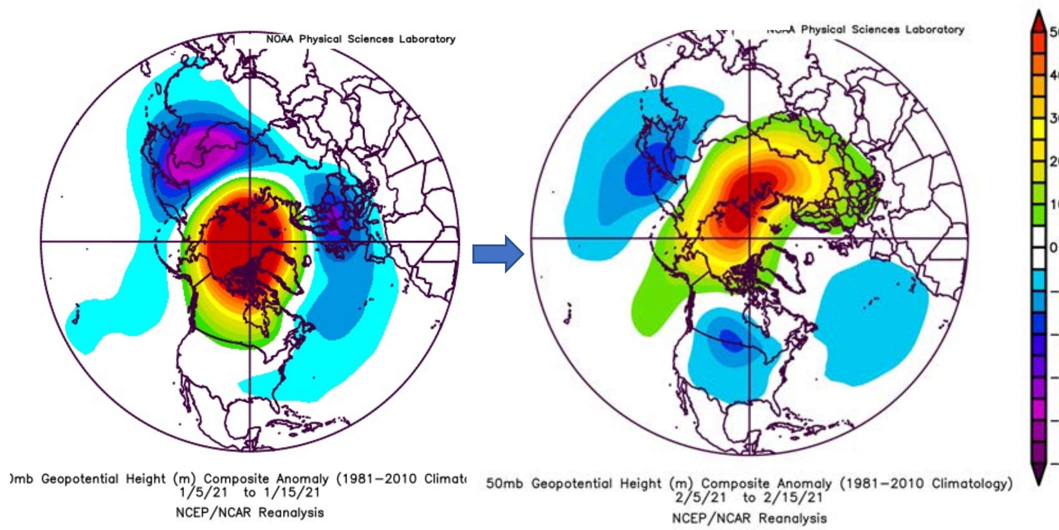
Negative AO/NAO phase persisted for several weeks after SSW. However, skill of week 3-4 temperature forecasts for CONUS actually went down after event (see S. Baxter's presentation last month)

Impact on extreme central U.S./Texas cold outbreak?



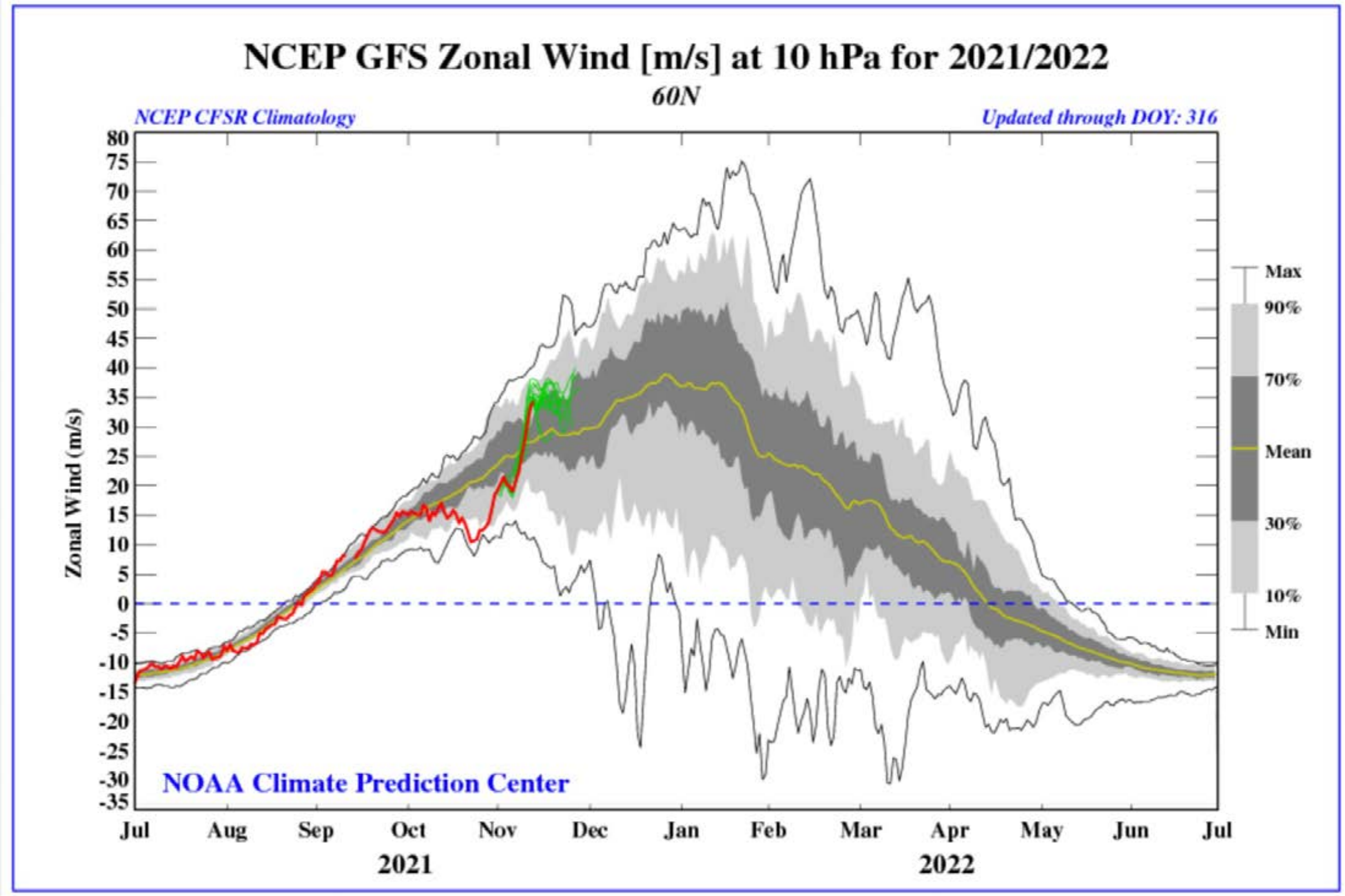
Extreme Cold Killed Texans in Their Bedrooms, Vehicles and Backyards

At least 58 people died in storm-affected areas stretching to Ohio, victims of carbon monoxide poisoning, car crashes, drownings, house fires and hypothermia. **NYT Feb 19 2021**



North American cold air outbreak didn't start to get underway until remnants of vortex moved over central Canada. Suggests that location/shape of vortex play important role.

What about this coming winter?



- La Nina (likely most important for US)
- Likely easterly QBO

- Multi-model S2S models forecasting positive NAO for Feb/Mar

- But, an SSW could upend these forecasts

Frequent Media Question: Is climate change making cold air outbreaks associated with a weaker polar vortex occur more often?

The idea is that Arctic sea ice loss can weaken the polar vortex, making cold air outbreaks occur more often even as the global climate warms.

Some points to keep in mind:

- In general if CO_2 concentrations continue to increase, winters will overwhelmingly become warmer everywhere, not colder
- There is no agreement across climate models even in the sign of the response of the strength of the stratospheric polar vortex to increased CO_2, even though all models show substantial sea ice loss.
- There is some indication of changes in the shape and/or location of the polar vortex in observations and future climate change scenarios.

Conclusions

- Information about the polar **stratospheric vortex is useful** (at a minimum, during windows of opportunity) for improving predictive skill on S2S timescales

- There are **inherent limitations** of S2S forecasts in regions where winter weather can be dominated for weeks by a polar vortex event itself only predictable at 10-15 day lead-times. But, once an event is underway, the stratosphere offers a significant, persistent source of skill for days to weeks.

- Some potential for **probabilistic forecasts** of these events at longer leads, but more work remains to determine how much skill can be gained.

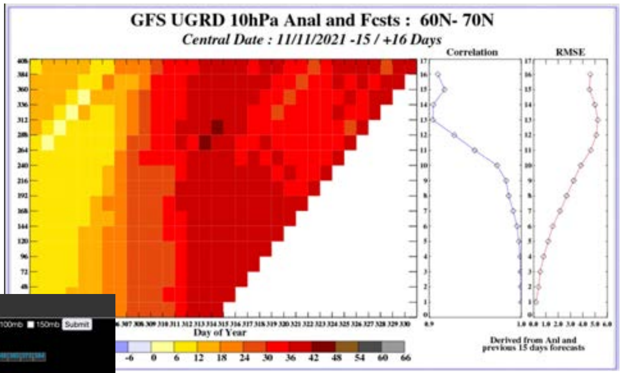
- Different types of **polar vortex characteristics** (beyond a typical SSW event) may be more useful for improving North American forecasts

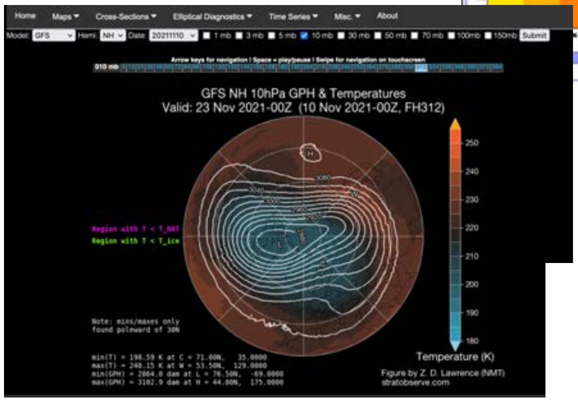
Resources for Stratospheric Monitoring/Prediction

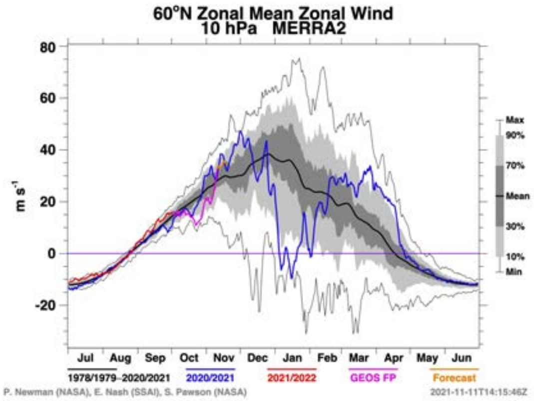
Climate Prediction Center: Forecasts of stratospheric zonal winds, temperatures, and eddy heat and momentum fluxes for GFS, CFS, and GEFSv12 (contact: Dr. Laura Ciasto)

StratObserve: Website by Zachary Lawrence (CIRES/NOAA PSL) with forecasts of many different stratospheric diagnostics, including the shape of the vortex

NASA Arctic Ozone Watch: Forecasts of stratospheric dynamics and ozone using GEOS

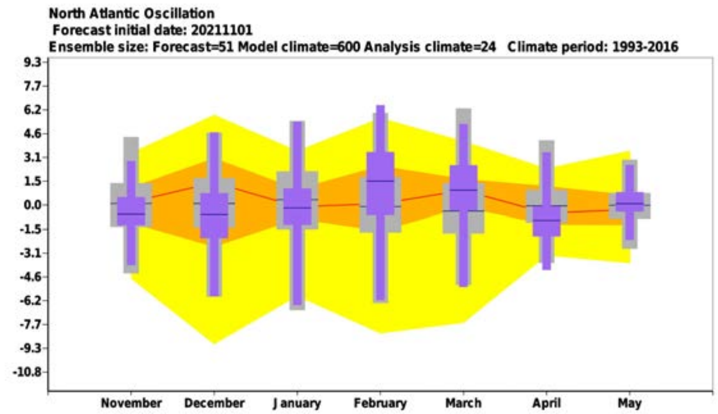




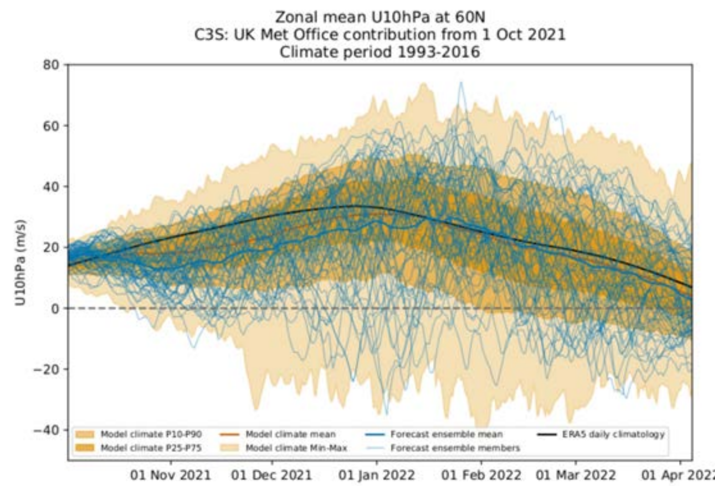


Resources for Stratospheric Monitoring/Prediction

ECMWF medium-range and long-range forecasting charts: monthly NAO predictions, 45-day forecast polar vortex winds, many other charts



C3S Copernicus Seasonal Forecasts: Multi-model comparisons of 10 hPa zonal winds, SSW risk, tropospheric fields



Zonal-mean zonal wind at 10hPa
The index is defined as the zonal average of the u component of wind at 10 hPa, at 60N.

ECMWF

References

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