Arctic Oscillation and Polar Vortex Analysis and Forecasts

September 15, 2022

Special recap of winter 2019/20

Summary

- Winter 2019/20 was characterized by widespread warmth across the mid-latitudes continents including the United States (US), Southern Canada and especially Europe and Northern Asia. In contrast it was relatively cold across the North American Arctic including Alaska, Northern Canada, Greenland, parts of Eastern Siberia and the Central Arctic.
- The phase of the El Niño/Southern Oscillation (ENSO) had a warm bias but in general remained neutral that winter. ENSO did not seem to be a big factor that winter.
- October Siberian snow cover was fast to advance early in the month, then stalled and finished the month with a rapid spurt. October Siberian snow cover extent (SCE) was well above normal and more than most recent years. SCE was also above normal across North America. As I have argued much of my career above normal SCE in the fall across Siberia is favorable for disrupting the polar vortex.
- Arctic sea ice was below normal during the fall but focused in the North Pacific sector more so than in the Barents-Kara seas. This pattern of sea ice anomalies is not thought conducive to disrupting the polar vortex (PV).
- Unusual for the PV, there was little variability all winter with the PV locked in an undisturbed state. The only meaningful disruption was in late November and early December, and it was minor and I believe was a reflective or stretched PV event.
- Overall, during the winter, the PV was strong to record strong. The strong PV was for much of the winter coupled with a positive to even record positive Arctic Oscillation (AO). The pattern of Northern Hemisphere (NH) surface temperature anomalies was consistent with a strong PV and positive AO and contributed to the warmest overall winter across the NH continents in recent years.

<u>Boundary Forcings</u>

The climate community focuses on El Niño/Southern Oscillation or ENSO in making seasonal forecasts and a mostly neutral event was predicted by the models for winter 2019/20 and therefore ENSO was not much of a factor in the winter forecasts. In **Figure 1** I show the forecasts from dynamical models that show general warmth across the NH and do not exhibit the iconic northwest North America/Southern US dipole associated with ENSO variability.

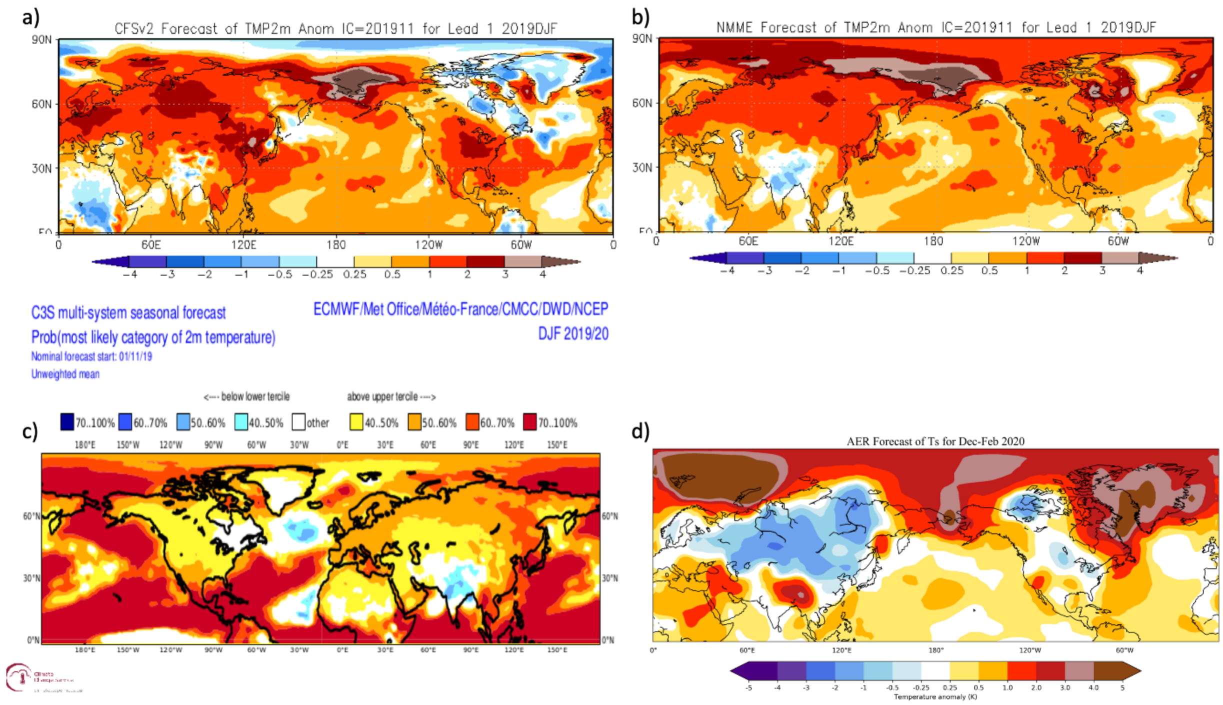

Figure 1. The winter 2019/20 surface temperature anomalies forecast for the Northern Hemisphere from the a) NOAA CFSv2, b) the North American Multi-model Ensemble (NMME), c) the C3S model ensemble (ECMWF, UK Met and Meteo France models) and d) the AER statistical model.

I will no longer discuss ENSO in the remainder of the blog post as the observed surface temperature anomaly pattern for the winter much more closely resembled that related to a positive AO more so than either phase of ENSO. However, I do want to mention that the Indian Ocean Dipole (IOD) was near record positive in the fall and early winter. This is not a teleconnection pattern that I usually pay attention to, nor do I know much about it. But it is plausible that it did contribute to a lack of high latitude blocking and a strong PV that winter, especially in the absence of strong ENSO forcing.

At AER we use ENSO in producing seasonal forecasts, but in addition we have pioneered the use of Arctic boundary forcings in winter seasonal forecasting including Arctic sea ice but especially Eurasian snow cover in October. We have demonstrated using observational analysis and model perturbation experiments that extensive Eurasian October snow cover is related to/can force a strengthened Siberian high, increased poleward heat flux, a weak stratospheric polar vortex (PV), which culminates in an extended period of a negative Arctic Oscillation (AO). A negative AO is associated with below normal temperatures in the Eastern US and Northern Eurasia including Northern Europe and East Asia. Scientists including those at AER, have shown a similar atmospheric response to low Arctic sea ice. In our recent paper Cohen et al. (2021) we also argued that above normal Eurasian SCE can favor reflective or stretched PV events that result not in a negative AO but rather a negative Nort Pacific Oscillation (NPO) pattern that favors widespread cold across North America east of the Rockies and Central/East Asia but not Europe.

There are different ideas how variability in Arctic sea ice might influence winter hemispheric weather but the trend has been a convergence to a similar set of mechanisms first proposed for Eurasian snow cover. Also, there is growing consensus that it is Barents-Kara sea ice in the late fall and early winter that has the greatest impact across Eurasia. Similarly, low Arctic sea ice in the Chukchi-Bering Seas might favor colder temperatures downstream across North America.

October 2019 Eurasian snow cover extent (SCE) was above normal even when compared to recent Octobers (**Figure 2a**). Snow cover advance was relatively fast in early and late October but stalled mid-month but for the entire month SCE was well above normal. I also compute the snow advance index (SAI) which is a measure of the pace or speed of the snow cover advance across Eurasia (see Cohen and Jones 2011 for more detail). The value was also above normal but not as high as the SCE for October.

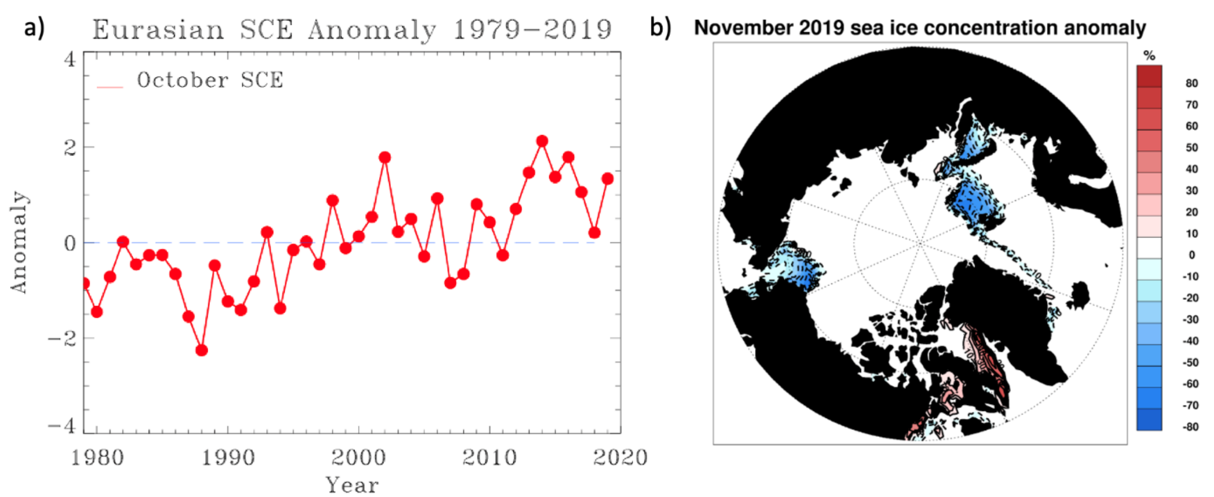

Figure 2. a) Standardized snow cover extent anomaly across Eurasia for October 1979-2019 **b)** Observed Arctic sea ice extent anomalies November 2019. Negative anomalies shown in blue shading.

Fall 2019 Arctic sea ice was below normal (**Figure 2b**) however Barents-Kara sea ice was only slightly below normal in November and higher that most recent Novembers with the exception of 2014. Therefore, Arctic sea ice was probably not as favorable for forcing a sudden stratospheric warming (SSW and where the zonal mean zonal wind reverses from westerly to easterly at 60°N and 10 hPa) often followed by a negative AO and cold temperatures across the NH mid-latitudes compared to other recent years.

The quasi-biennial oscillation (QBO) was in its westerly phase that winter. The QBO is a periodic oscillation of the zonal winds in the equatorial stratosphere and in the westerly phase the zonal winds are stronger. The westerly phase is thought to favor a stronger PV, which favors milder temperatures across the NH continents. It is plausible that the westerly QBO contributed to the overall mild winter.

And of course, the near record warm global atmosphere and ocean provided an overall warm backdrop heading into the winter of 2019/20.

Late fall/very early winter

As mentioned above, October 2019 Eurasian snow cover extent was above normal due to an early and late month surge in snow cover advance. Above normal snow cover across Siberia in October favors a strengthened Siberian high in November with the largest positive sea level pressure (SLP) anomalies northwest of the climatological center (see **Figure 3a** taken from Cohen et al 2014). The rapid advance of snow cover at the end of October favored the northwestward expansion of the Siberian high in November which dominated the monthly mean for November (**Figure 3b**). Below normal sea ice in the Barents-Kara seas is also associated with the northwestward expansion of the Siberian high and the combination of the rapid advance in snow cover at the end of October and low Barents-Kara sea ice contributed to an episode of blocking centered over the Urals for the months of November. From **Figure 3**, the northwestward expansion of the Siberian high is clearly evident as well as the "classic" tripole SLP anomaly pattern with relatively high pressure near Scandinavia/Urals and low pressure in both the North Atlantic and North Pacific Ocean basins that is the hemispheric circulation that is most favorable for disrupting the stratospheric PV.

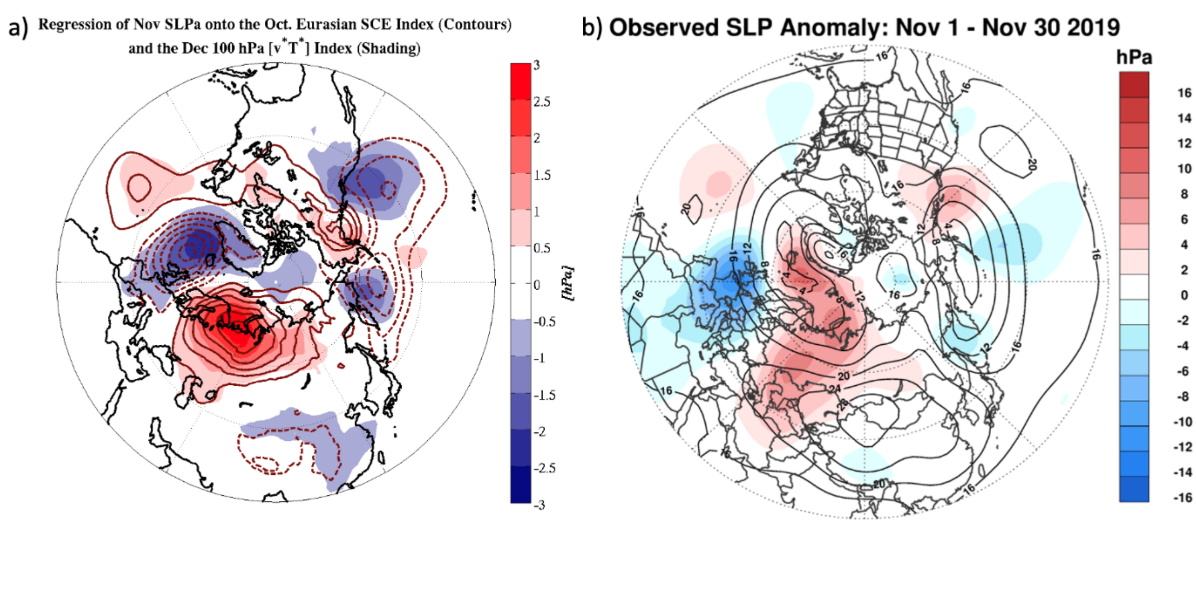

Figure 3. a) Regression of November sea level pressure (SLP) anomalies (hPa) onto October monthly mean, October Eurasian SCE (contouring) and December meridional heat flux anomalies at 100 hPa, averaged between 40-80°N (shading). **b)** Observed average sea level pressure (hPa; contours) and sea level pressure anomalies (hPa; shading) across the Northern Hemisphere from November 1-30, 2019.

This tripole pattern is optimal for forcing increased vertical transfer of Rossby wave energy (vertical wave activity flux or WAFz) and poleward heat flux. The WAFz plot in **Figure 4** shows active WAFz throughout November first in the troposphere and then in the stratosphere. The period of active WAFz, peaked the last week of November in the stratosphere.

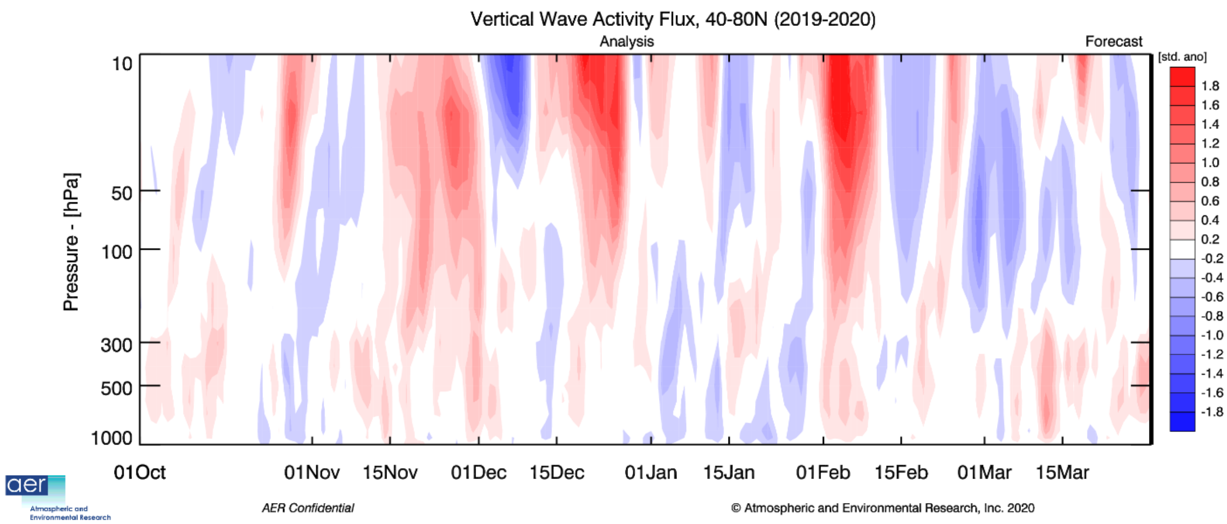

Figure 4. Observed daily vertical component of the wave activity flux (WAFz) standardized anomalies, averaged poleward of 40-80°N from October 1 through March 31 (data for first week is missing).

As I have discussed in the blog and in past winter summaries one of my focuses of my research has been to demonstrate that behavior of the stratospheric PV is not just binary, i.e., a strong PV and a weak or disrupted PV that is only really considered when a major mid-winter warming (MMW) is observed, which is identified when the zonal mean zonal wind reverses from westerly to easterly at 60°N and 10 hPa.

It turns out that the tropospheric response to a polar vortex disruption where WAFz is “reflected” is quite different from when WAFz is “absorbed.” The tropospheric response to a PV disruption where the WAFz is absorbed is the “classic” response to stratospheric PV disruptions. The tropospheric response is characterized by Greenland blocking, negative North Atlantic Oscillation (NAO), relatively cold temperatures across northern Eurasia and milder across North Africa, the Middle East and the North American Arctic. Also, the tropospheric response is usually delayed relative to the

WAFz pulses and the response can be of long duration, lasting of up to two months. In contrast the tropospheric response to a PV disruption where the WAFz is "reflected" is characterized by blocking near Alaska, relatively cold across much of Canada, the Eastern US and Central Asia and mild across Alaska and Europe. The response is not associated with a negative NAO but rather a negative North Pacific Oscillation (NPO). Also, the tropospheric response is usually rapid relative to the WAFz pulses and the response is of relatively short duration lasting on the order of days and up to two weeks. This will be a of more important consequence in winter 2020/21.

It is not until winter 2021/22 did we regularly produce the WAFz diagnostics that demonstrate reflective events so I what I now argue is somewhat circumstantial. In November and December there are two observed examples of positive WAFz pulses quickly followed by negative WAFz pulses - first in at the very end of October and early November and then again in late November and early December (**Figure 4**). This is strongly suggestive of a reflective events that involve upward WAFz pulses over Asia that reflect off the polar vortex and then are directed downward over North America. As I just mentioned, reflective WAFz results in blocking/high pressure as well as warming near Alaska with upstream and downstream troughing and cold temperatures across Central and Eastern Asia and North America east of the Rockies first in the stratosphere and quickly followed in the troposphere. In **Figure 5,** I present the geopotential heights for both 10 hPa and 500 hPa from November 1-15, 2019. **Figure 5a** closely matches the "reflective" cluster 4 for the stratospheric PV (see Figure 1 from Kretschmer et al. 2018) with a stretched PV from Asia to North America and positive geopotential height anomalies centered near the Dateline, Eastern Siberia and the North Atlantic with downstream negative geopotential heights across Asia but especially North America. And at 500 hPa there is strong ridging stretching along the West Coast of North America including Alaska and into Eastern Siberia with another ridge in the North Atlantic. The main troughs are in East Asia and eastern North America. There is another trough in Western Europe.

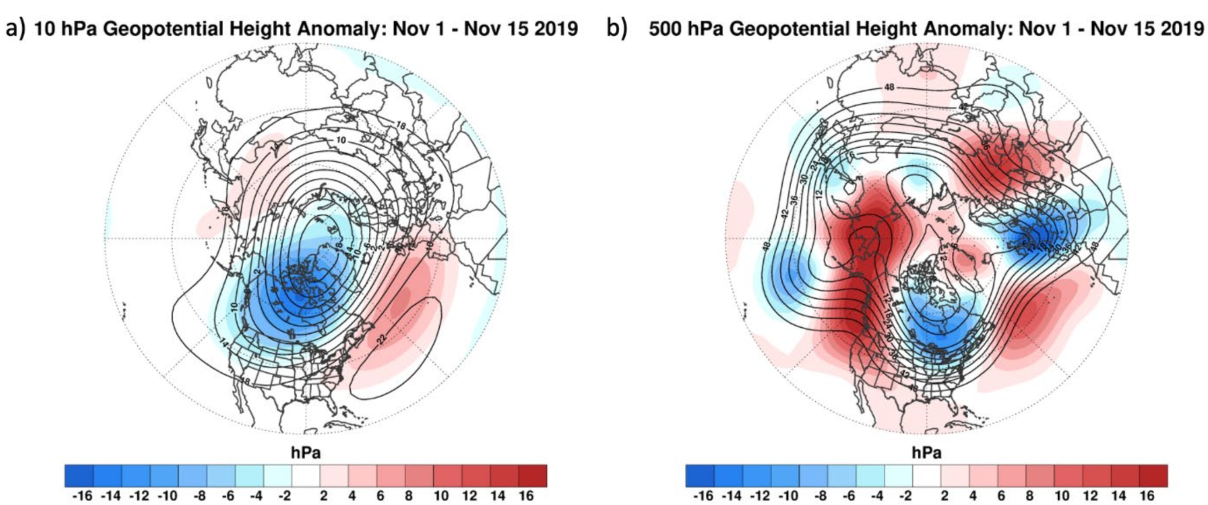

Figure 5. a) Observed average 10 hPa geopotential heights (dam; contours) and geopotential height anomalies (m; shading) across the Northern Hemisphere for November 1- 15, 2019. **b)** Observed average 500 hPa geopotential heights (dam; contours) and geopotential height anomalies (m; shading) across the Northern Hemisphere from November 1 - 15, 2019.

This pattern results in below normal temperatures in Northern Asia, Western Europe and especially Eastern Canada and the Eastern US (see **Figure 6**). On the flip side there are relatively warm temperatures under the mdi-tropospheric ridging along the West Coast of North America, Eastern Siberia Greenland and Eastern Europe.

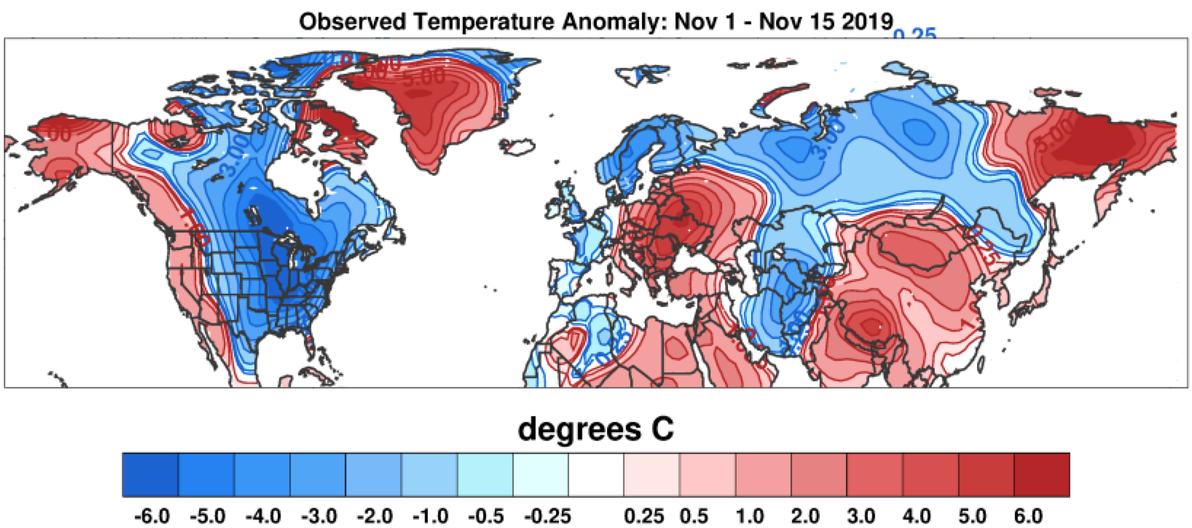

Figure 6. a) Observed average surface temperature anomalies (°C; shading) for November 1 - 15, 2019.

Another stretched PV or reflective event takes place in late November and early December. I show the NH geopotential height pattern for the first half of December both at 10 hPa and 500 hPa in **Figure 7**. The pattern in the stratosphere looks more like a Canadian warming than a starched PV but if you look ahead at **Figure 9a** for late November it looks much more a typical stretched PV event. In the mid-troposphere (which is usually a bit delayed relative to the response in the stratosphere) the pattern better resembles that associated with stretched or reflective PV events with strong ridging near Alaska with troughs across Asia and eastern North America that extends into the North Atlantic.

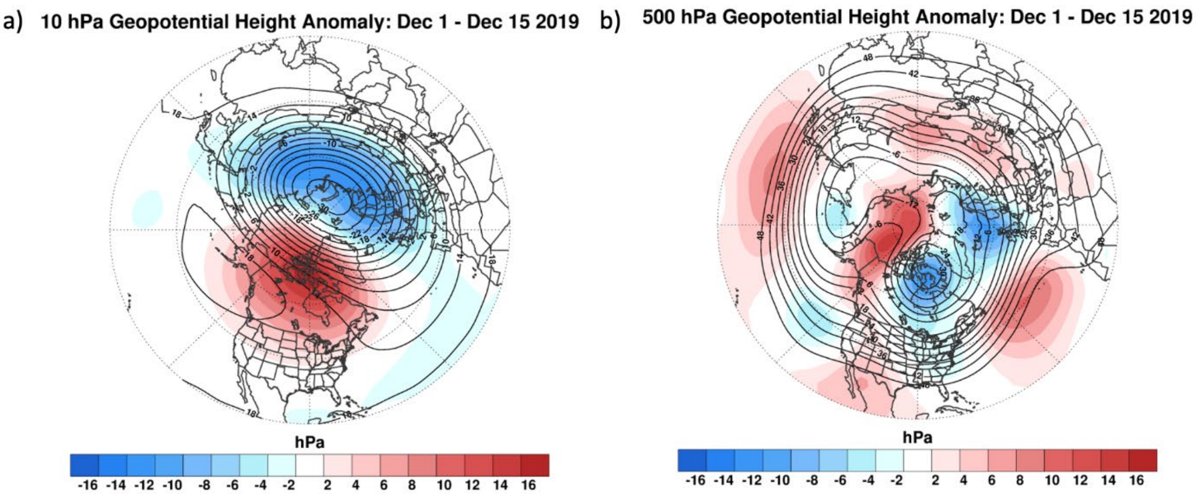

Figure 7. a) Observed average 10 hPa geopotential heights (dam; contours) and geopotential height anomalies (m; shading) across the Northern Hemisphere for December 1- 15, 2019. **b)** Observed average 500 hPa geopotential heights (dam; contours) and geopotential height anomalies (m; shading) across the Northern Hemisphere from December 1 - 15, 2019.

The surface temperature anomaly pattern also resembles that associated with a stretched PV with cold temperatures in East Asia (though not very impressive this period but the cold became more expansive in late December – see ahead to **Figure 10b**) and Eastern Canada and the Northeastern US (see **Figure 8**). It was also relatively warm in western North America, Europe, Western and Central Asia. However overall, the stretched/reflective PV event of early December is not as clean or as strong as the event in early November.

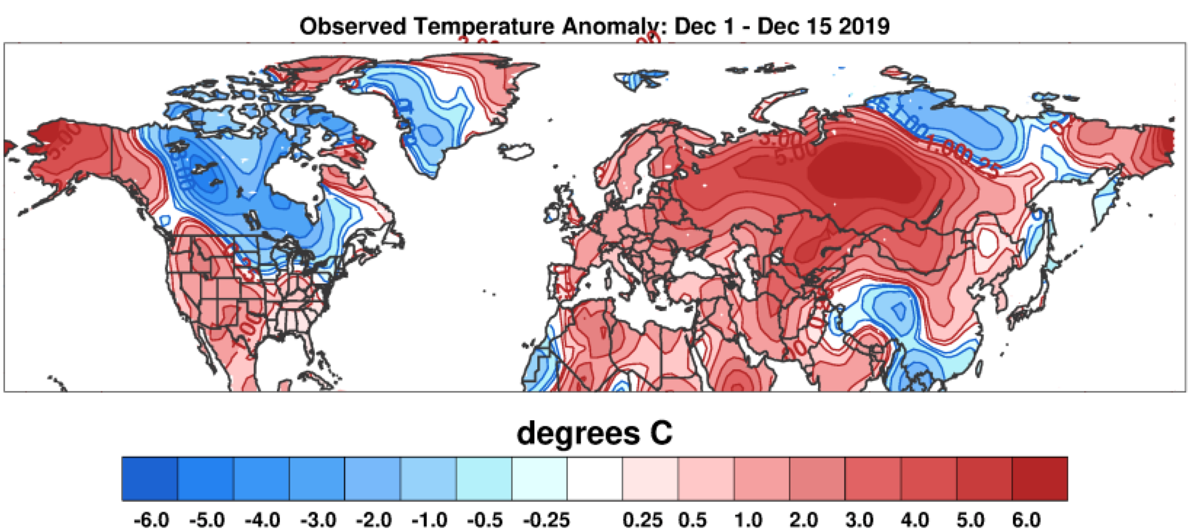

Figure 8. a) Observed average surface temperature anomalies (°C; shading) for December 1 - 15, 2019.

The tropospheric response to stretched/reflective PV events is relatively short on the order of one to two weeks. And after the stretched/reflective PV events in early November and December the tropospheric circulation and surface temperature anomaly patterns relax in late November and December with some residual impacts. The stratospheric PV seems to remain in a stretched configuration for much of November and December (see **Figure 9a&b**). However, in the troposphere, the ridging centered near Alaska and Eastern Siberia abates and the troughs in eastern North America are replaced with ridges (see **Figure 9c&d**). Still, ridging near the Urals helps to maintain troughing in East Asia and relatively cold temperatures dominate Central and East Asia while milder temperatures overspread eastern North America in late November and December (see **Figure 10a&b**). And with strong westerly flow in both periods across Europe, Europe remains mild for both periods.

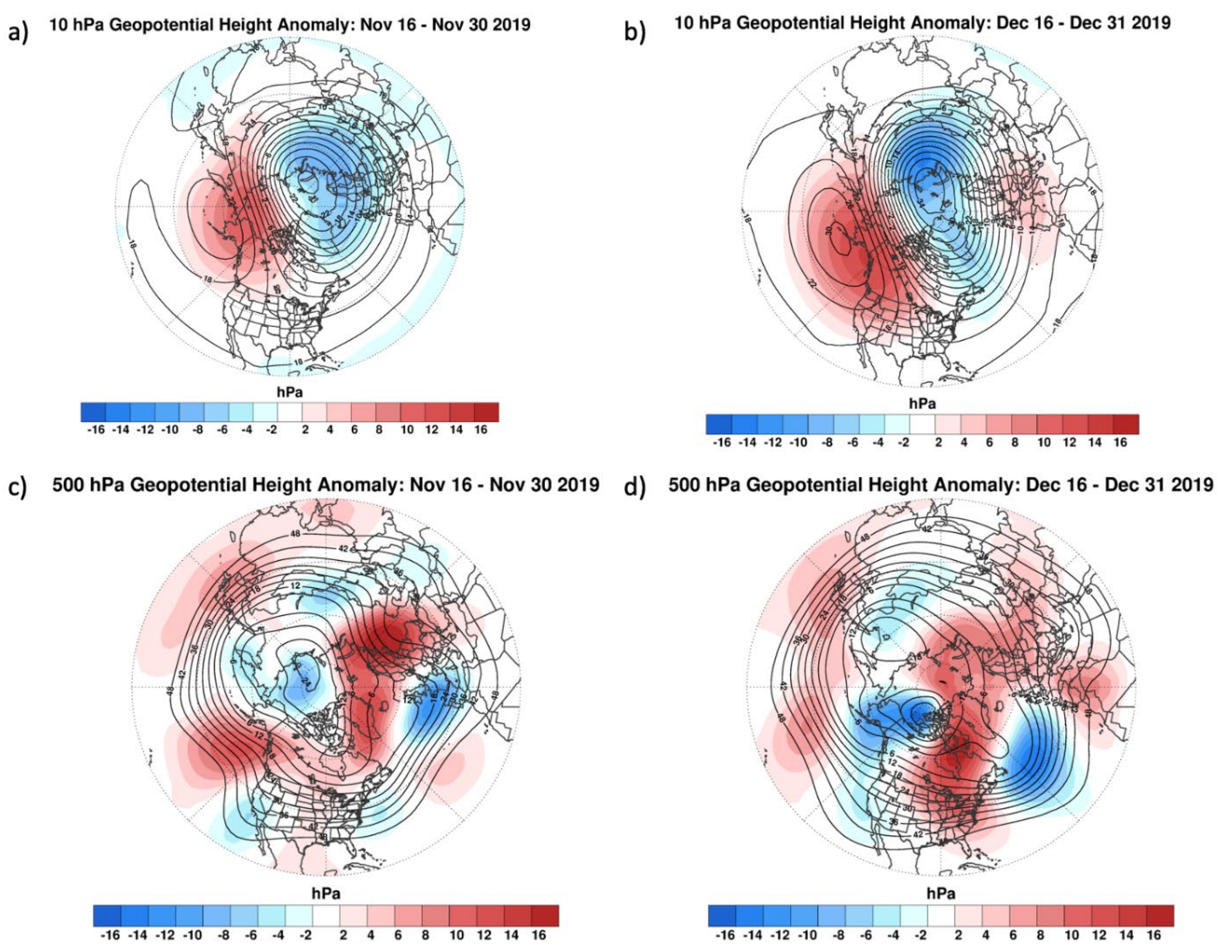

Figure 9. a) Observed average 10 hPa geopotential heights (dam; contours) and geopotential height anomalies (m; shading) across the Northern Hemisphere for November 16- 30, 2019. b) Observed average 500 hPa geopotential heights (dam; contours) and geopotential height anomalies (m; shading) across the Northern Hemisphere from November 16 - 30, 2019. **c)** Observed average 10 hPa geopotential heights (dam; contours) and geopotential height anomalies (m; shading) across the Northern Hemisphere for December 16- 31, 2019. **d)** Observed average 500 hPa geopotential heights (dam; contours) and geopotential height anomalies (m; shading) across the Northern Hemisphere from December 16 - 31, 2019.

From **Figure 9a**, it does look like the PV is vulnerable to further weakening and the potential does exist for an SSW and not just stretching, especially given that the WAFz remained active for the last three weeks of December (see **Figure 4**). And looking back on my blog posts in late November I was discussing the possibility of an SSW in late December (see blog from 29 Nov 2019). In winter 2018/19 the PV transitioned from a stretched PV to a mature SSW while in 2019/20 the PV transitioned from a stretched PV to an absolute beast and what accounts for the difference, I don't really know. It is possible that the QBO was easterly in 2018/19 but westerly in 2019/20. Another difference (but with little support in the literature) is that the IOD was strongly positive in fall 2019 but not in fall 2018.

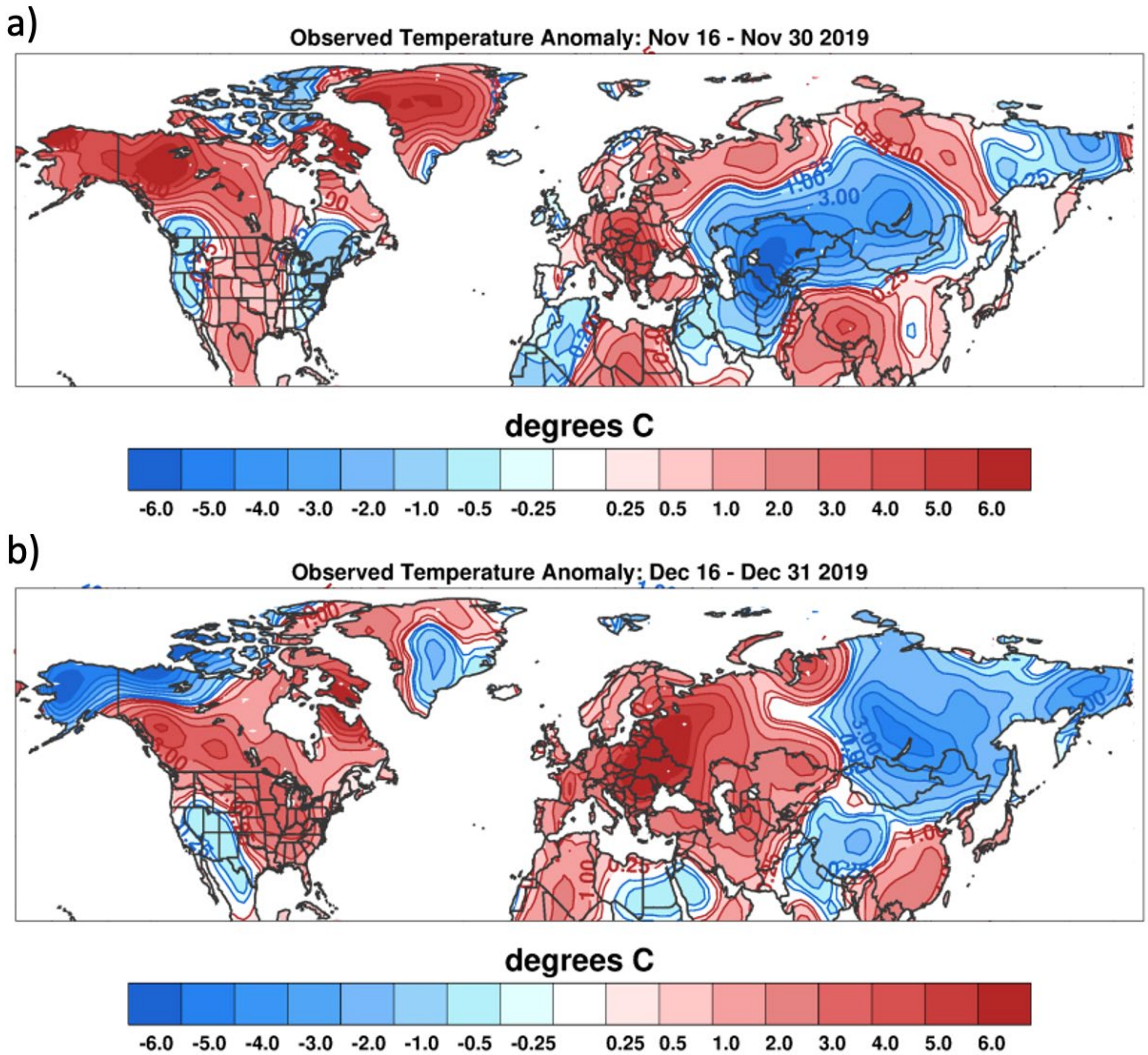

Figure 10. a) Observed average surface temperature anomalies (°C; shading) for **a)** November 16 - 30, 2019 and **b)** December 16-31, 2019.

Mid winter

A reflective layer in the stratosphere inhibits WAFz from penetrating to higher levels in the stratosphere that can shield the PV from disruption and often following stretched PV events the PV will strengthen. I believe a very good example of this is winter 2010/11. A strong reflective event took place in January but starting at the end of January the PV started to wind up and was in beast mode for the remainder of the winter and into early April before a rapid demise. The strong PV even contributed to the first-ozone-hole recorded in the Northern Hemisphere. That is where I want to end the similarities between winters 2010/11 and 2019/20 since the timing and what preceded the PV spin-up were very different.

The lack of active WAFz at the end of December through early February and the reflective layer in the stratosphere allowed the PV to strengthen represented by cold/negative polar cap geopotential height anomalies (PCH) observed in the stratosphere shown in **Figure 11**. Meanwhile a deficit of high latitude blocking represented by cold/negative PCHs in the troposphere accompanied or followed the strengthening PV (**Figure 11**). The strong PV and the lack of high latitude blocking/positive AO mutually reinforced each other for the remainder of the winter, represented by the cold/negative PCHs throughout the atmospheric column. The strong PV helped delay the Final Warming until May contributing to the NH's [largest-ever-ozone-hole]() ever observed.

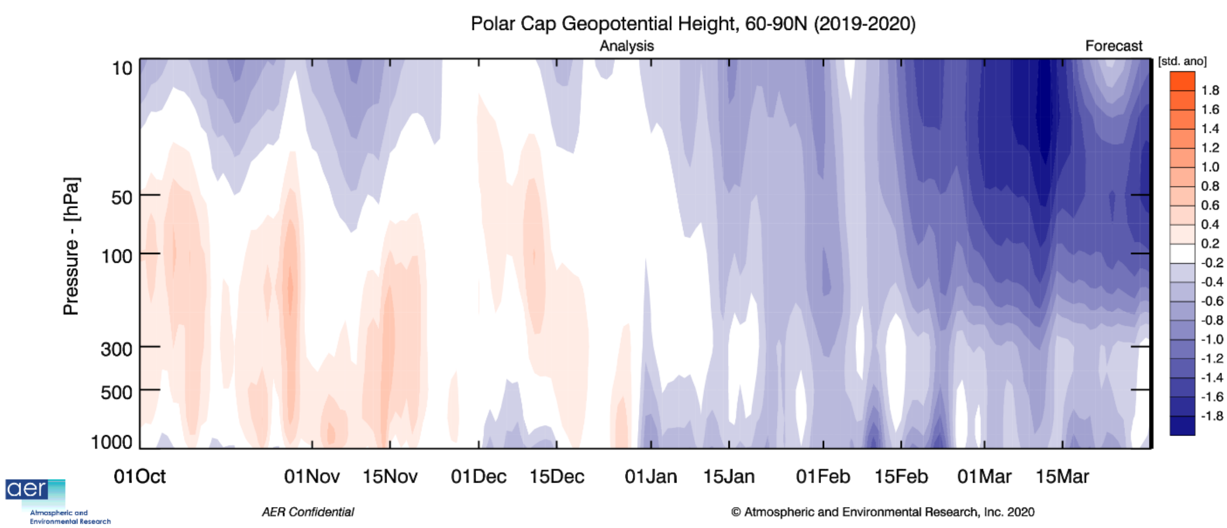

Figure 11. Observed daily polar cap height (i.e, area-averaged geopotential heights poleward of 60°N) standardized anomalies from October 1 2019 through March 31 2020.

The remainder of the winter was dominated by a strong PV, characterized by a circular PV with the most negative geopotential height anomalies in the center of the PV (**Figure 12a**). The tropospheric circulation resembled an annulus with relatively low geopotential heights over the Arctic ringed by relatively high geopotential heights across the mid-latitudes (**Figure 12b**). There was an uncharacteristic lack of waves in the troposphere or highly anomalous zonal flow that kept cold Arctic air and milder air to the south well separated.

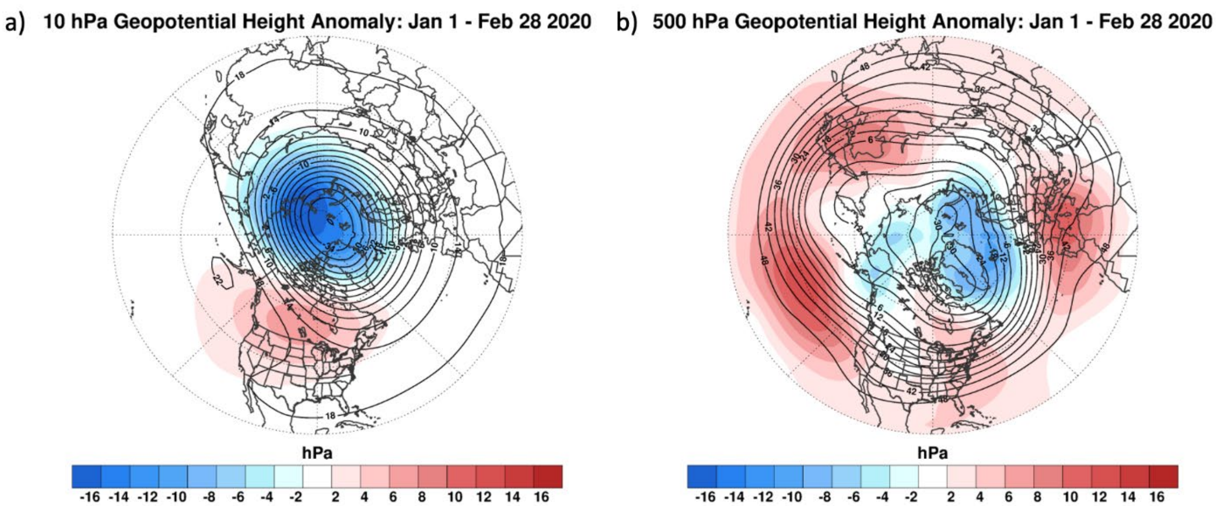

Figure 12. a) Observed average 10 hPa geopotential heights (dam; contours) and geopotential height anomalies (m; shading) across the Northern Hemisphere for January 1- February 28, 2020. **b)** Observed average 500 hPa geopotential heights (dam; contours) and geopotential height anomalies (m; shading) across the Northern Hemisphere from January 1- February 28, 2020.

Both North America but especially Eurasia were dominated by above to well above temperatures the remainder of the winter with the exceptions of Eastern Siberia, Alaska, Northern Canada and Greenland (**Figure 13**).

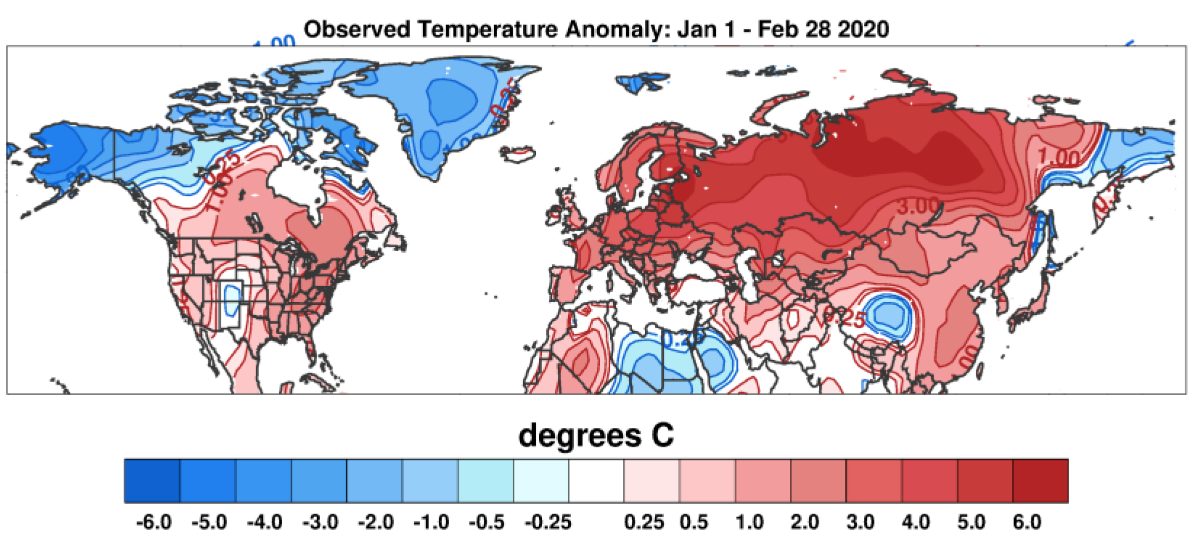

Figure 13. a) Observed average surface temperature anomalies (°C; shading) for January 1- February 28, 2020.

The only meaningful period of active WAFz for the remainder of that winter was in early February (**Figure 4**). Any other winter this would be hardly worth a mention, but it did seem to result in stretched/ reflective PV event in early February (**Figure 14a**). In the mid-troposphere ridging developed in the Gulf of Alaska with downstream troughing east of the Rockies (**Figure 14b**).

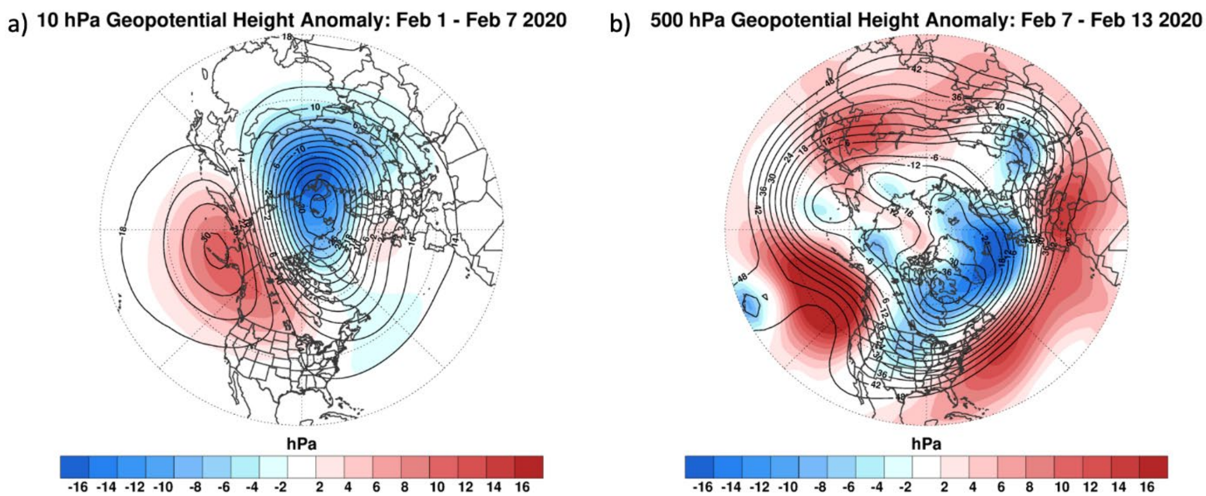

Figure 14. a) Observed average 10 hPa geopotential heights (dam; contours) and geopotential height anomalies (m; shading) across the Northern Hemisphere for February 1- 7, 2020. **b)** Observed average 500 hPa geopotential heights (dam; contours) and geopotential height anomalies (m; shading) across the Northern Hemisphere from February 7- 13, 2020.

It would be a stretch to say it brought a meaningful period of cold weather to the US but maybe at least a respite from record warm temperatures, certainly to the Plains (**Figure 15**). Meanwhile no letting up from the record warm temperatures across Europe and Asia.

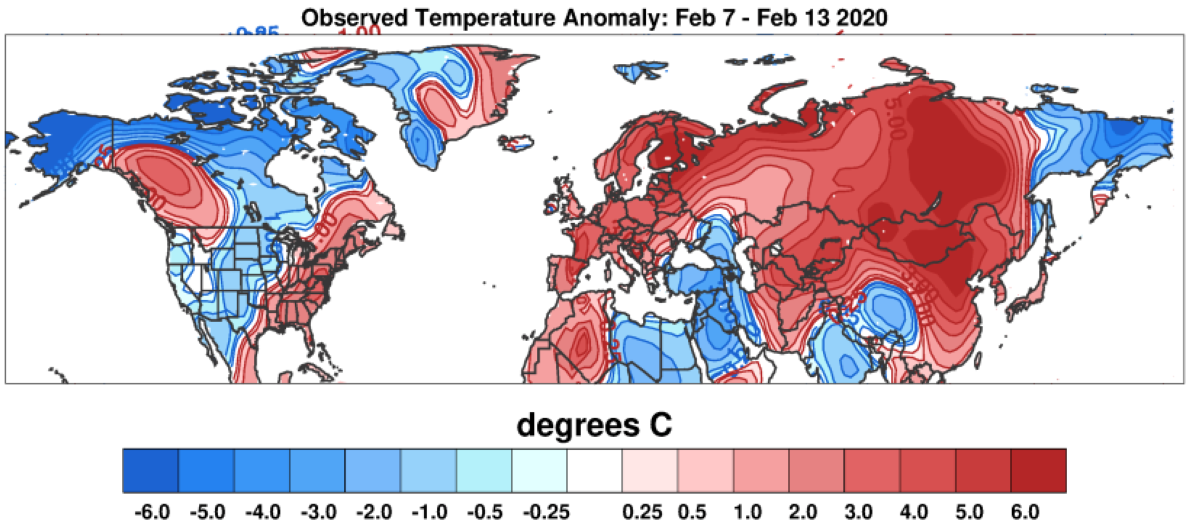

Figure 15. a) Observed average surface temperature anomalies (°C; shading) for February 7- 13, 2020.

Late winter

I see little reason to discuss the late winter period as it was a continuation of January and February as seen in **Figure 11**. The mostly circular shape of the PV and the deep negative geopotential height anomalies over the Arctic (**Figure 16a**) are characteristic of a strong PV as observed throughout January and February. Meanwhile the mid-tropospheric pattern mostly resembles an annulus or donut with low heights over the Arctic ringed by high heights across the mid-latitudes (**Figure 16b**).

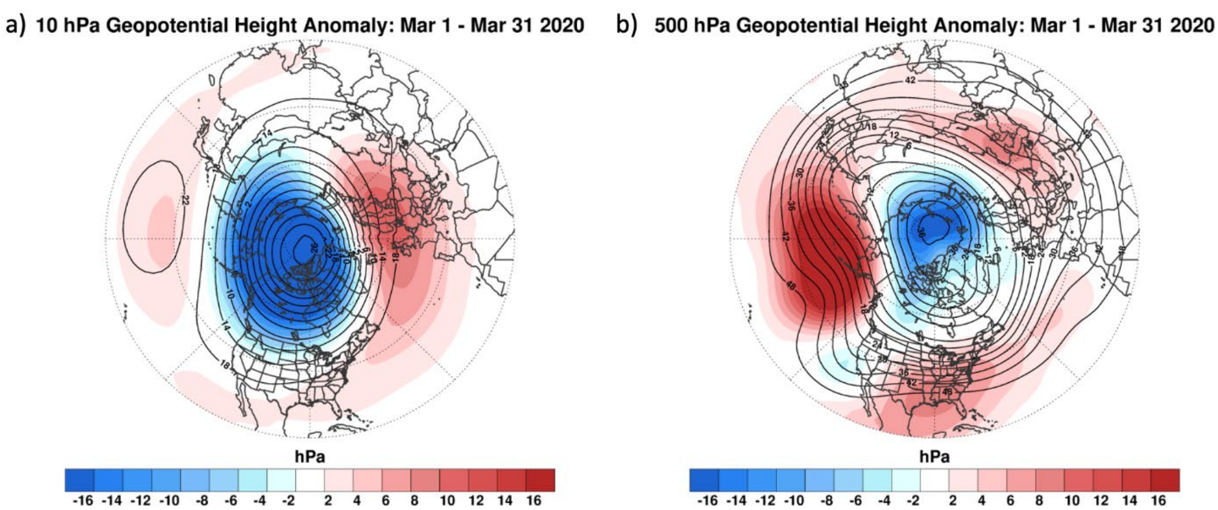

Figure 16. a) Observed average 10 hPa geopotential heights (dam; contours) and geopotential height anomalies (m; shading) across the Northern Hemisphere for March 1- 31, 2020. **b)** Observed average 500 hPa geopotential heights (dam; contours) and geopotential height anomalies (m; shading) across the Northern Hemisphere from March 1- 31, 2020.

Given the strong PV/positive AO not surprisingly the Eastern US, Europe and Northern Asia are all mild (**Figure 17**).

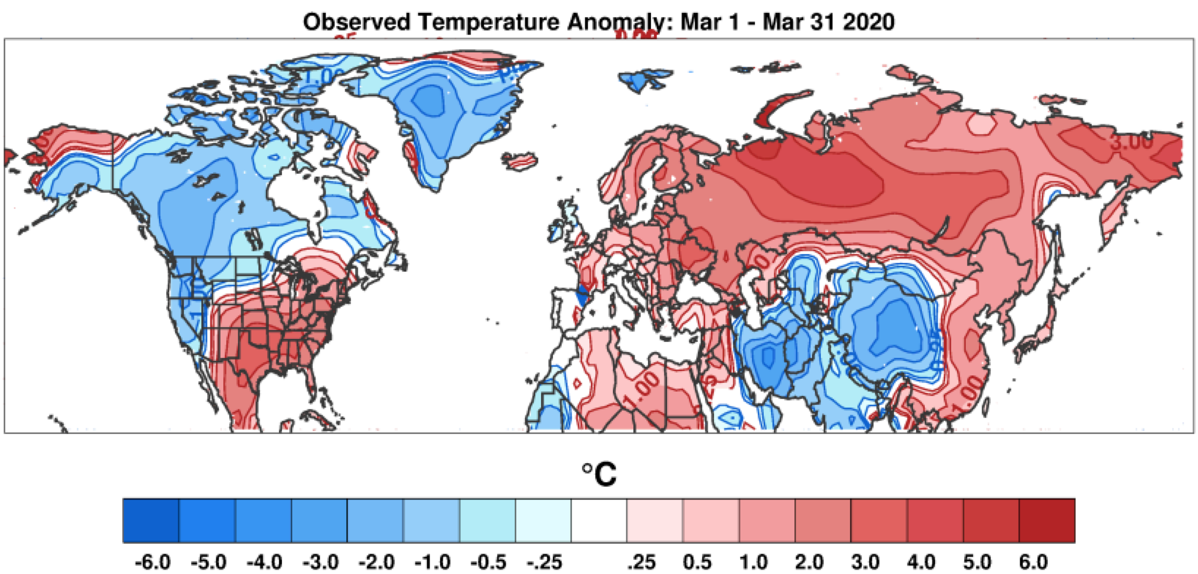

Figure 17. a) Observed average surface temperature anomalies (°C; shading) for March 1 - 31, 2020.

<u>Observed winter circulation</u>

In **Figure 18** I show the winter mean (December-February) circulation in the mid-stratosphere (10 hPa geopotential heights) and mid-troposphere (500 hPa geopotential heights). The strong stratospheric PV in January and February is evident on the winter mean anomalies. Negative height anomalies cover the Arctic with positive height anomalies across the mid-latitudes readily recognizable as a classic strong PV/positive AO pattern. The coupling of this pattern clearly translates into a related pattern in the troposphere. The Central Arctic is characterized by negative height anomalies with mostly positive height anomalies across the mid-latitudes. This is a classic example of downward propagation of geopotential height anomalies from the stratosphere to the troposphere related to a positive AO in both the stratosphere and troposphere. I would just add that the PV is not perfectly circular in shape and suggests some elongation or stretching towards North America. This is probably some residual from the weak disruptions of the PV related mostly to wave reflection in December and to a lesser extent in February.

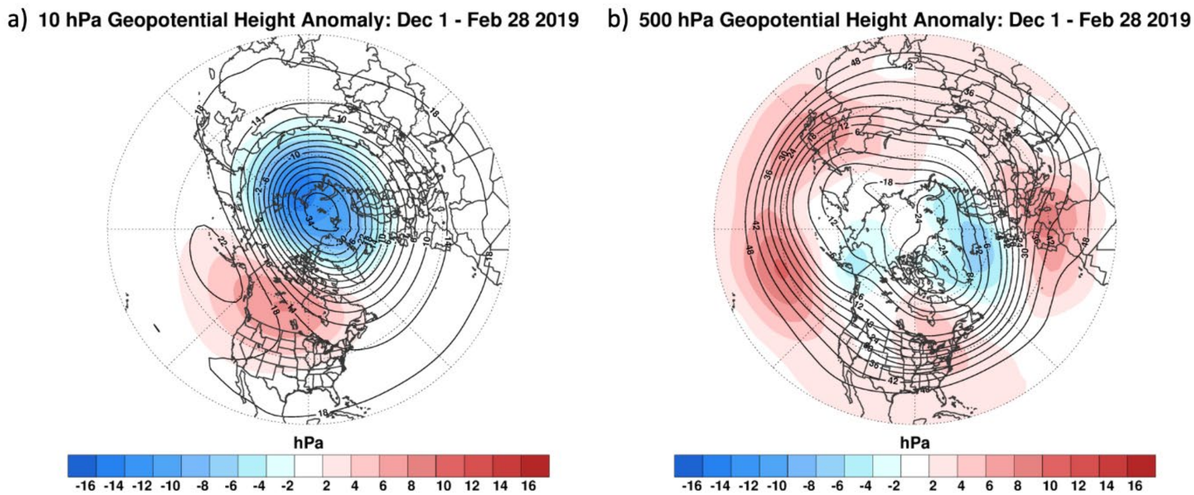

Figure 18. a) Observed average 10 hPa geopotential heights (dam; contours) and geopotential height anomalies (m; shading) across the Northern Hemisphere for December 1, 2019 - February 28, 2020. **b)** Observed average 500 hPa geopotential heights (dam; contours) and geopotential height anomalies (m; shading) across the Northern Hemisphere from December 1, 2019 - February 28, 2020.

Given the strong even classical positive AO both in the troposphere and the stratosphere it is not surprising that the surface temperature anomaly pattern for the winter projects strongly on to the surface temperature pattern associated with a positive AO. Above normal temperatures are nearly universal across the US, Europe and Asia (**Figure 19**). The one region of below normal temperatures is across the North American Arctic including Alaska, Northern Canada and Greenland. Below normal temperatures were also observed in parts of Eastern Siberia. The observed cold Greenland and warm Northern Europe is also the classical temperature anomaly pattern associated with a positive North Atlantic Oscillation.

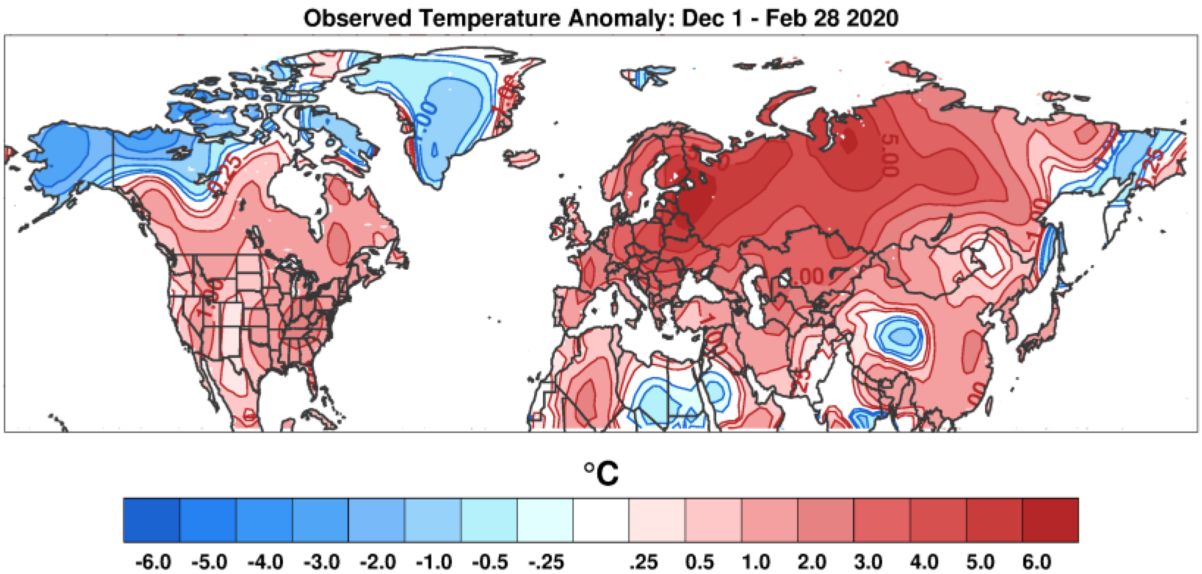

Figure 19. a) Observed average surface temperature anomalies (°C; shading) for December 1, 2019 - February 28, 2020.

Winter forecasts

The main predictors in the AER winter forecast are October Eurasian SCE, the Arctic sea ice anomaly and El Niño. The dynamical models rely strongly on ENSO that was neutral and therefore were mostly forced by global warming (my opinion). The AER forecast and those from key dynamical models for NH winter surface temperature anomalies are shown in **Figure 1** and the observed temperature anomalies are shown in **Figure 19**. Dynamical models include the national multi-model ensemble (NMME- an ensemble of North American models) forecast for NH temperatures, the NOAA CFSv2 and the European model ensemble (C3S) in **Figure 1**.

As is the case every winter now, the dynamical models predict almost universal above normal temperatures across the NH continents. The AER forecast was colder especially across Asia. But in a digression or divergence from other recent winter forecasts, the warmer the forecast the better, and clearly the dynamical models performed better than colder AER forecast. Of the four forecasts shown, the warmest CFS likely performed best, at least by my eye.

Concluding remarks

I believe that Arctic boundary forcings are the best available predictors of the possible behavior of the polar vortex. I do think that the extensive snow cover across Eurasia in the fall favored a more disrupted PV relative to a strong PV. Though Arctic sea ice was low, sea ice extent in the Barents Kara Seas was near normal and this did not favor a more disrupted PV at least relative to recent winters. My recent work would suggest that extensive fall Eurasian snow cover but relatively more extensive Barents-Kara sea ice would favor more stretching/reflection PV events rather than the large disruptions associated with SSWs. The PV was stretched for much of November and December but then went into beast mode with a lack of high altitude blocking in the troposphere and the strong PV and lack of high latitude blocking seeming to feed off each other leading to almost a runaway warm pattern that strongly projects onto the positive AO across the NH continents, especially Eurasia.

It is understood that to form a stretched PV a reflective layer is required in the stratosphere which can shield the PV from upwelling standing or Rossby wave energy from the troposphere allowing the PV to strengthen or accelerate. I think an almost textbook example of this is winter 2010/11. I would add that 2019/20 is another textbook example of this. But had high altitude blocking remained in place, stretched or reflective PV events would have continued over the course of the winter, even if the PV remained strong, this occurred in winter 2021/22. Why high latitude blocking completely disappeared with only one minor stretched event in early February, I don't have any good answers, just guesses.

In my mind, the winter of 2019/20 is the exception that proves the rule. The winter of 2019/20 cannot be the paradigm for climate change winters simply because Arctic amplification all but disappeared. Arctic amplification is well established in theory and in the dynamical model climate projections. Why did the Arctic "circle the wagons" sort of speak, locking any cold air in the Central and North American Arctic, I don't have a good answer. I could throw out strongly positive IOD but that is without any support from the literature as far as I know and certainly has no support from my own research. Of course, one can always attribute a poor forecast to noise or intrinsic variability of the climate system, but I always find that answer unsatisfying.