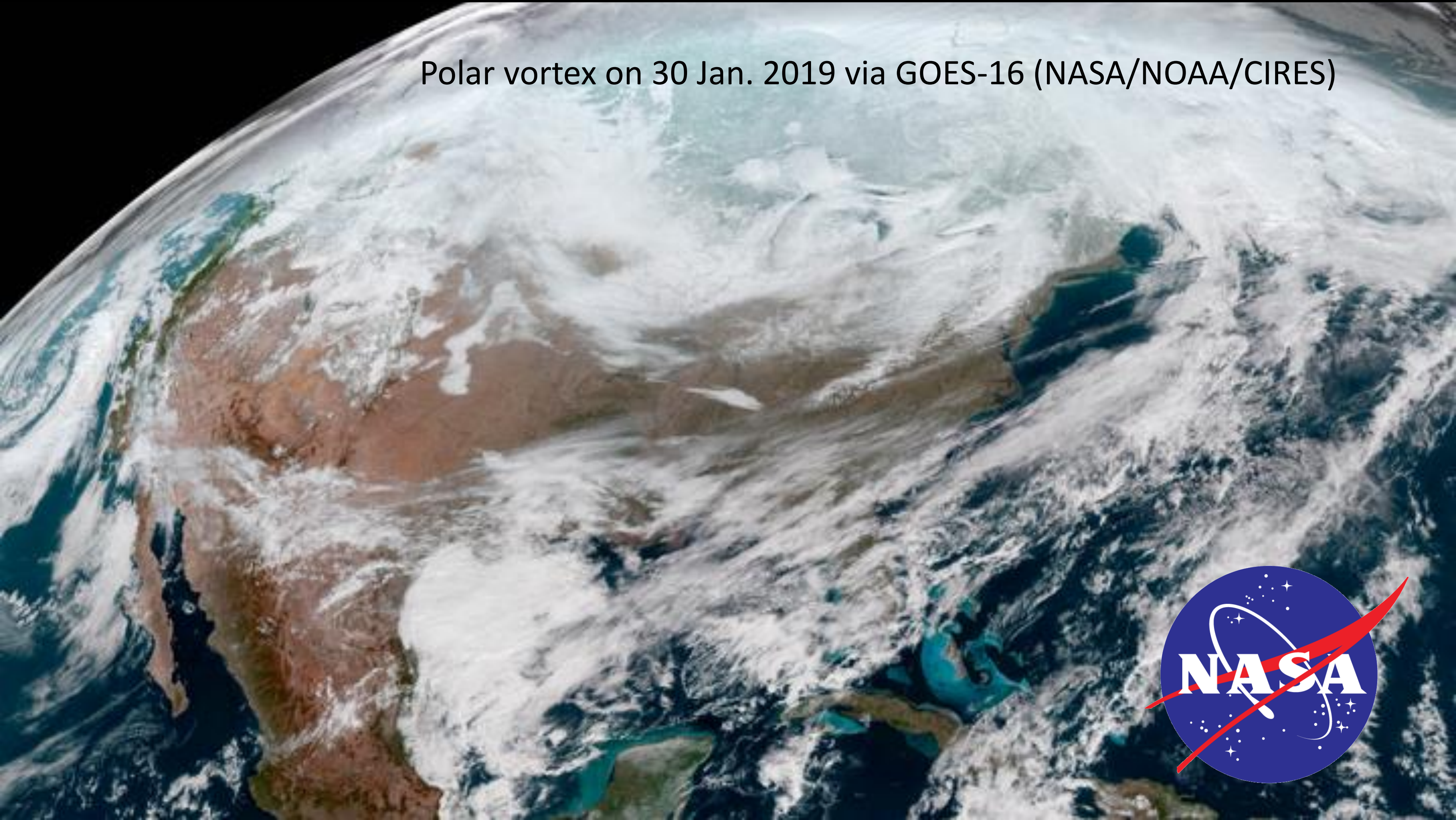
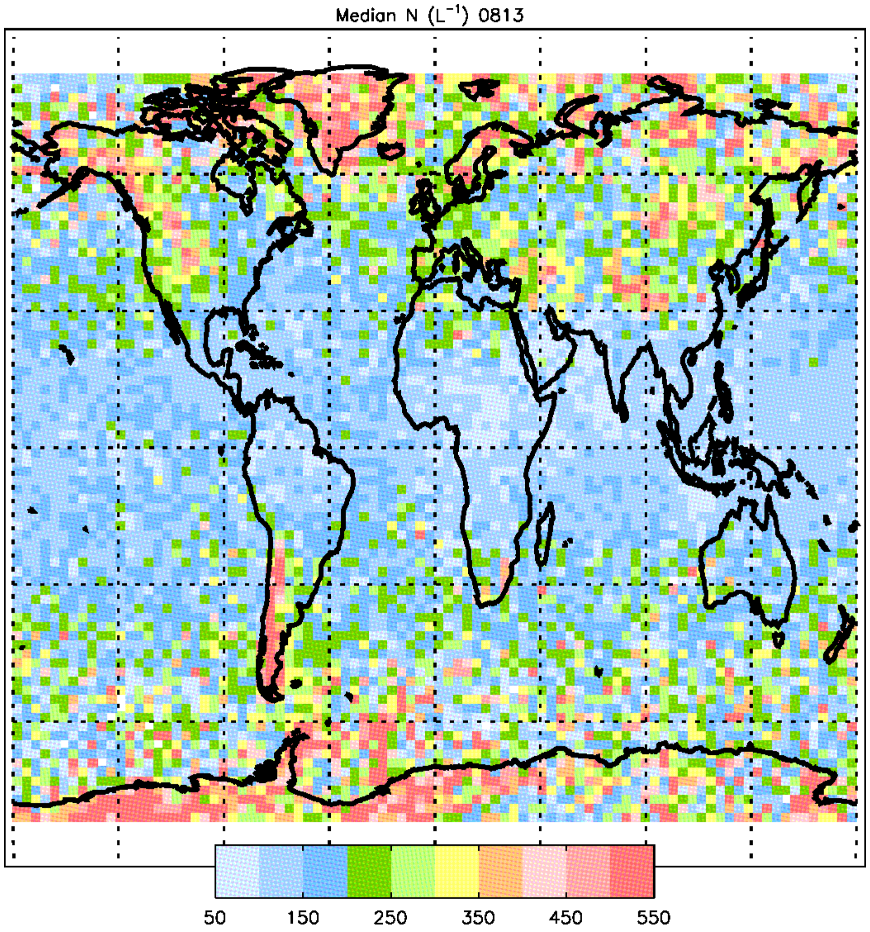
On the Potential Role of Arctic Cirrus Clouds in Producing Anomalous Mid-latitude Weather and Climate

David Mitchell, John Mejia and Yuta Tomii (DRI) and Anne Garnier (SSAI)



Polar vortex on 30 Jan. 2019 via GOES-16 (NASA/NOAA/CIRES)

Left: Our CALIPSO retrieval, median N (L^{-1}) for 2008 & 2013. Right: From Gryspeerdt et al. (2018, ACPD), using a lidar-radar CALIPSO-CloudSat retrieval for N (L^{-1}) at -50°C. Results are similar to our study in terms of latitude and topography dependence of N.



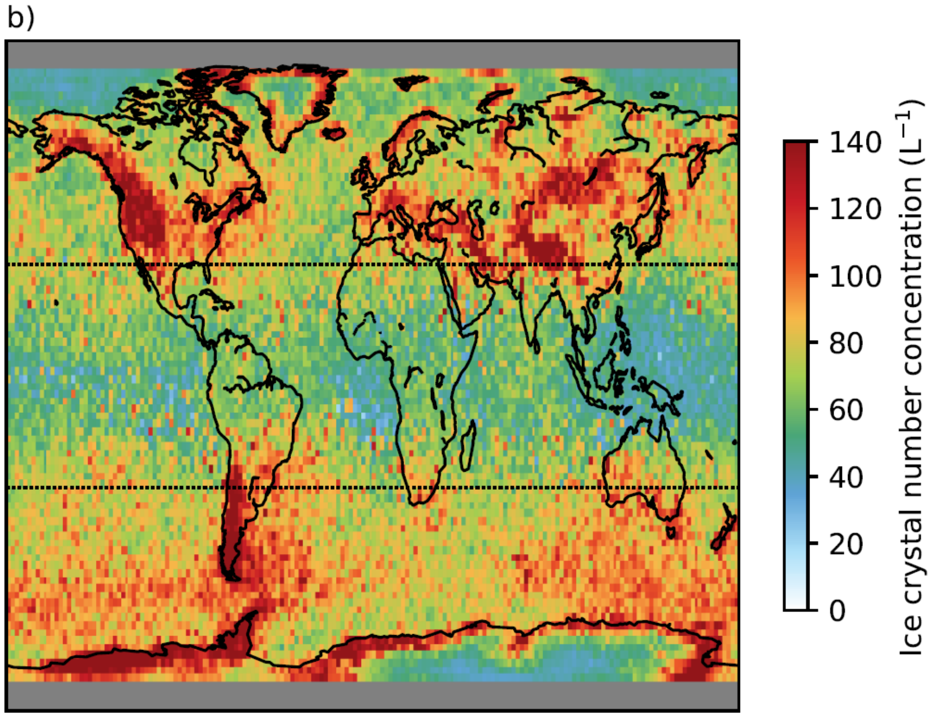
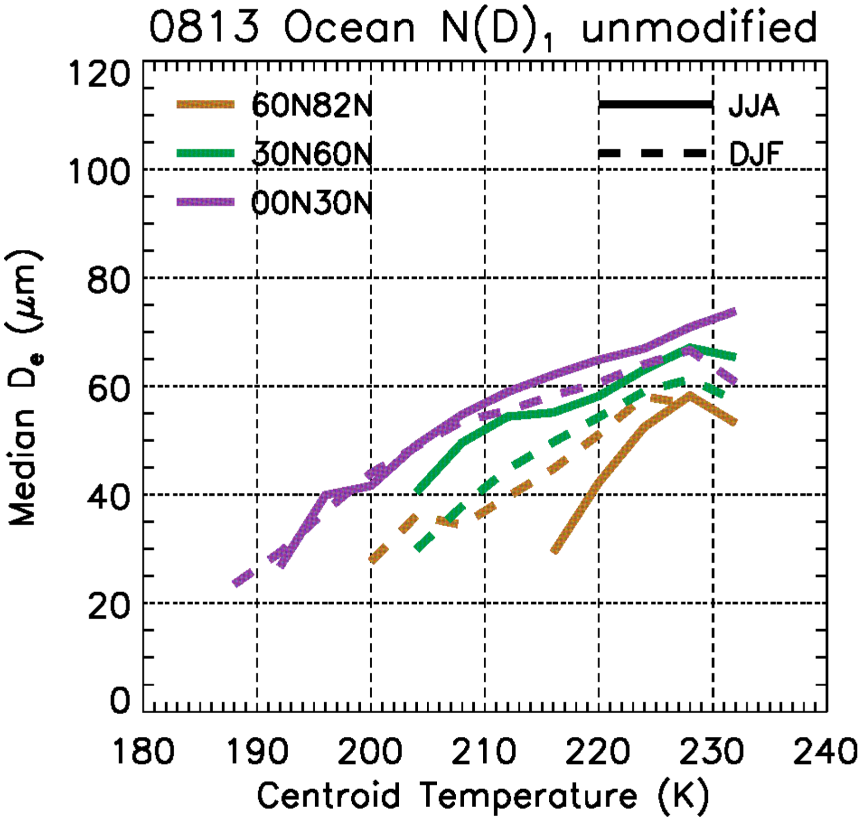


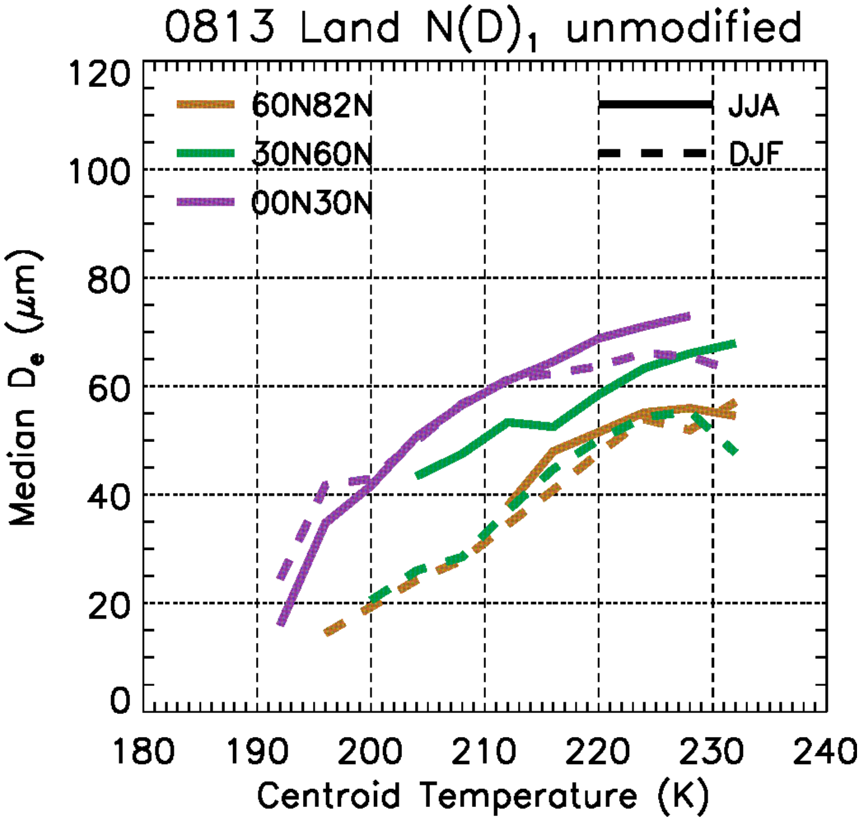
Figure 1. a) The zonal mean DARDAR-LIM cloud top N_i ($N_{i(top)}^{5\mu m}$) for crystals larger than 5 μm as a function of temperature from DARDAR-LIM data for the period 2006-2013. Temperatures warmer than -35°C are in greyscale. b) The mean $N_{i(top)}^{5\mu m}$ at -50°C. Grey indicates missing data.

CAM5 Experiment

CALIPSO simulation: $D_e(T)$ based on CALIPSO observations

Het simulation: based on tropical (30 °S – 30 °N) cirrus $D_e(T)$ only





Cirrus cloud radiative forcing depends on D_e, IWC and cloud fraction, which is greater for the CALIPSO simulation having lower fall speeds. CALIPSO cloud radiative effect (CRE) is greater than Het.

…CAM5 Experiment

- **We adapted CAM5-MG1.5 to use prescribe CALIPSO retrieved**

  D_e = f(T, latitude, season, surface(land vs. ocean)) => 48 D_e(T)
- **Used integrated treatment of ice fall speeds, ice water content and cirrus cloud coverage:**

$$V_{\text{mass-weighted}} \ \& \ V_{\text{number con.-weighted}} = f(D_e, T, p)$$

based on Mishra et al. (2014, JGR); applied to cloud ice & snow

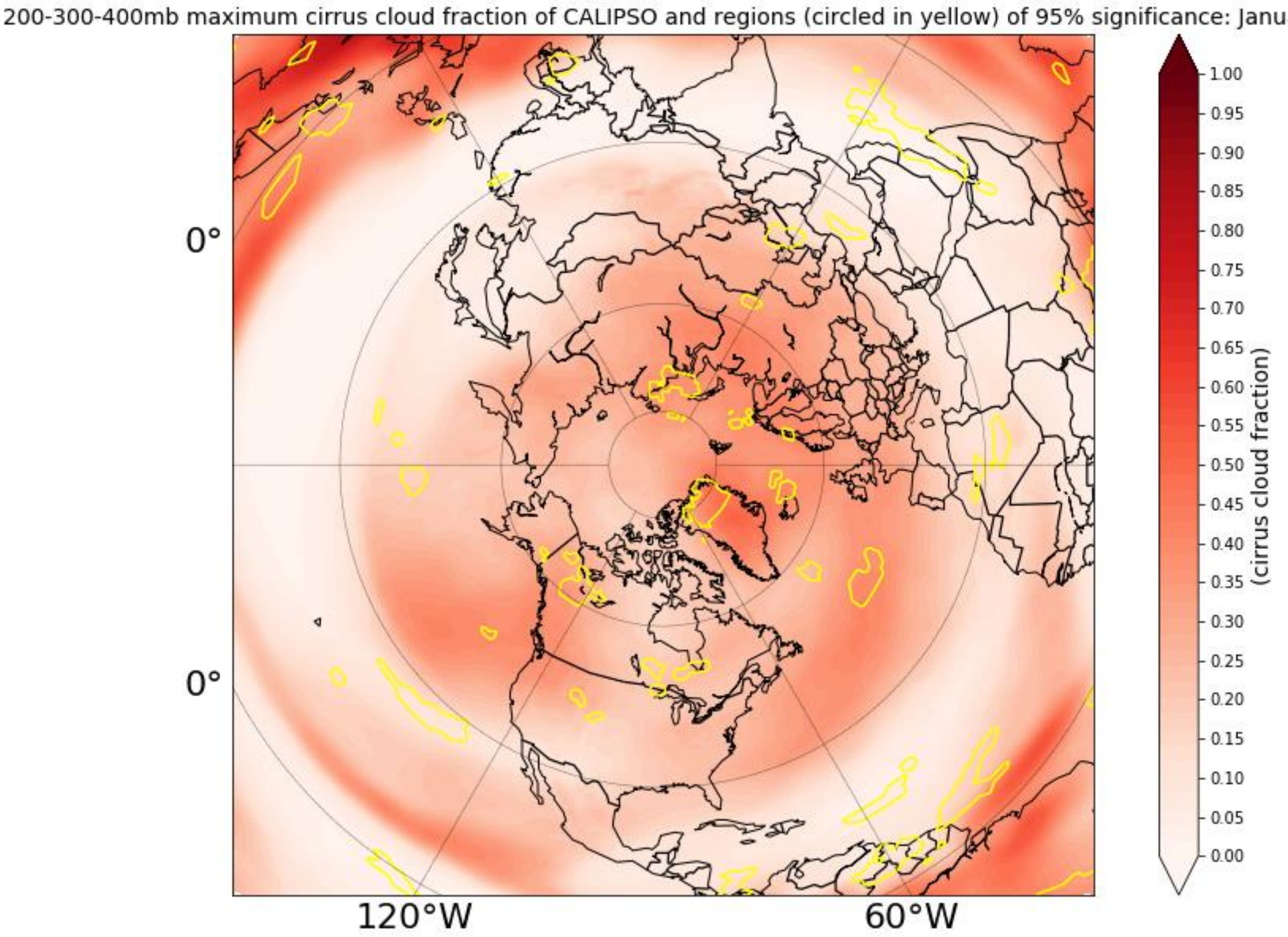
$$\text{IWC} = f(V_m, V_n)$$

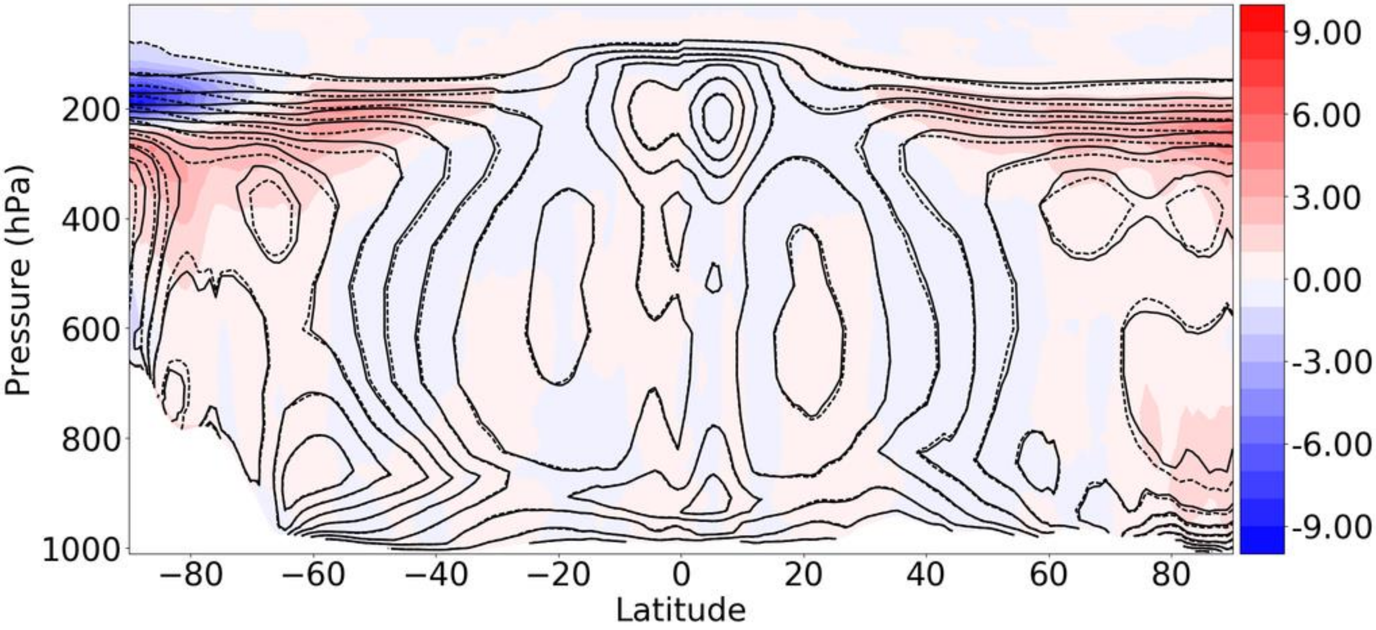
$$\text{cirrus cloud coverage} = f(V_m, V_n)$$

- **In-cloud mixing ratio and number concentration tendency terms updated every time step; sedimentation is calculated over grid-scale quantities to ensure conservation constraints.**
- **1.125 deg_arc, 10-year long simulations (2000-2009)**

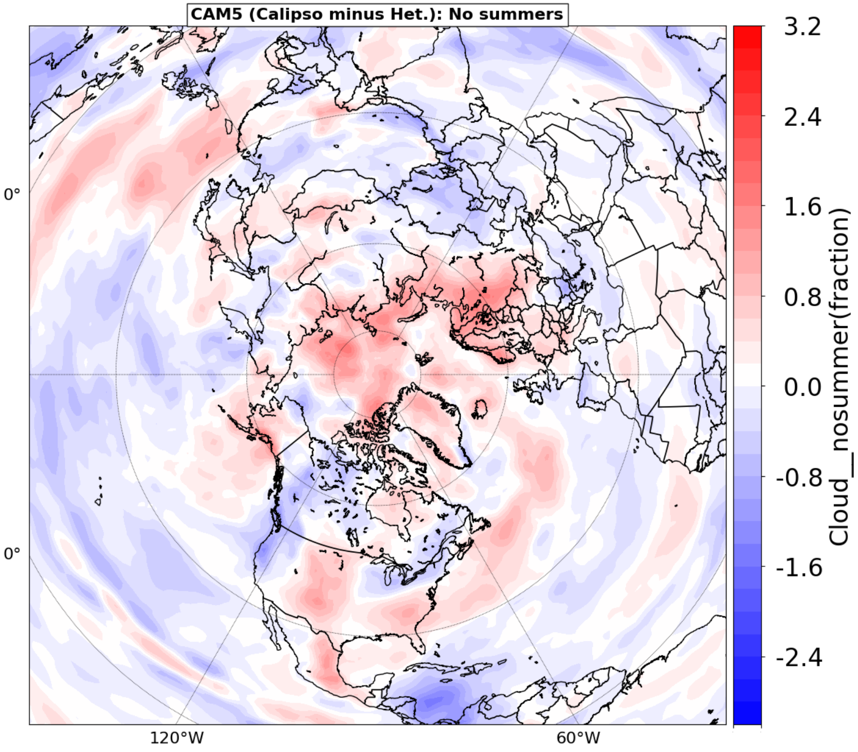
Key point: CALIPSO minus Het differences are used to infer the impact of increasing cirrus cloud coverage, which was observed to at least double in the Arctic during winter for 0.3 < OD < 3.0.

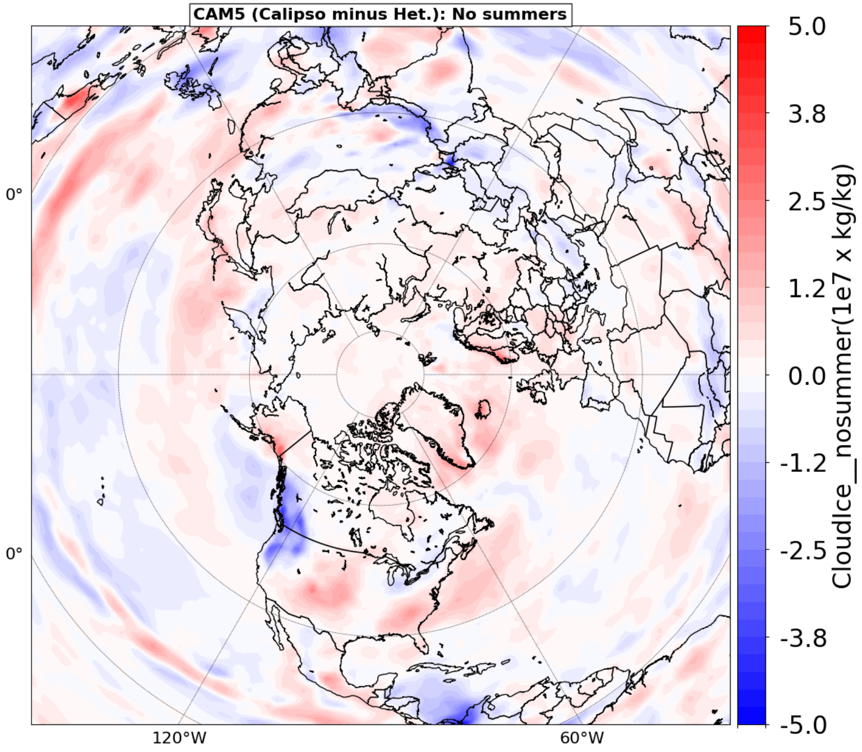
Maximum cirrus cloud fraction between 200 & 400 hPa for January for the CALIPSO simulation. Yellow contours => 95% signif. wrt Het.

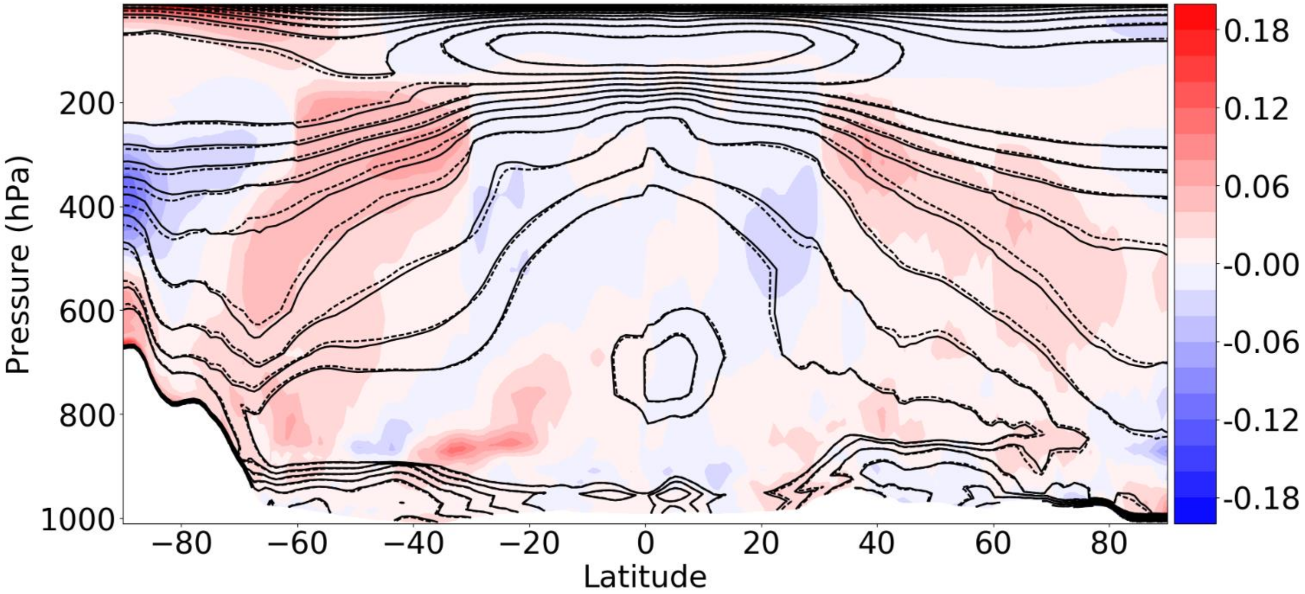




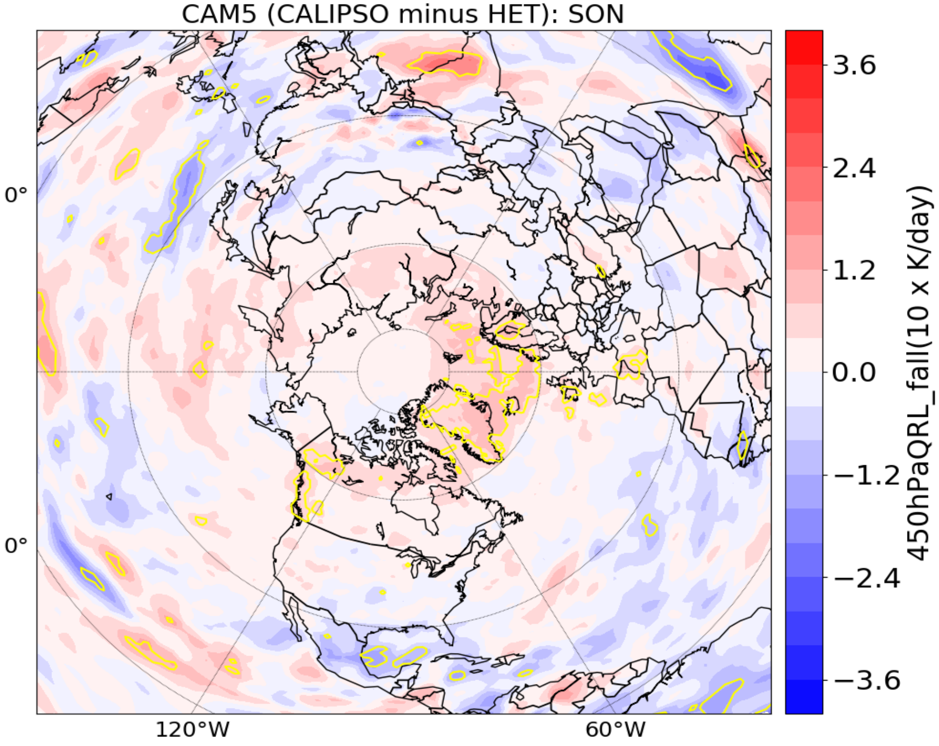
Percent increase in cloud fraction (upper & lower left) and increase in cloud ice (lower right) for the CALIPSO simulation relative to the Het simulation for non-summer months.

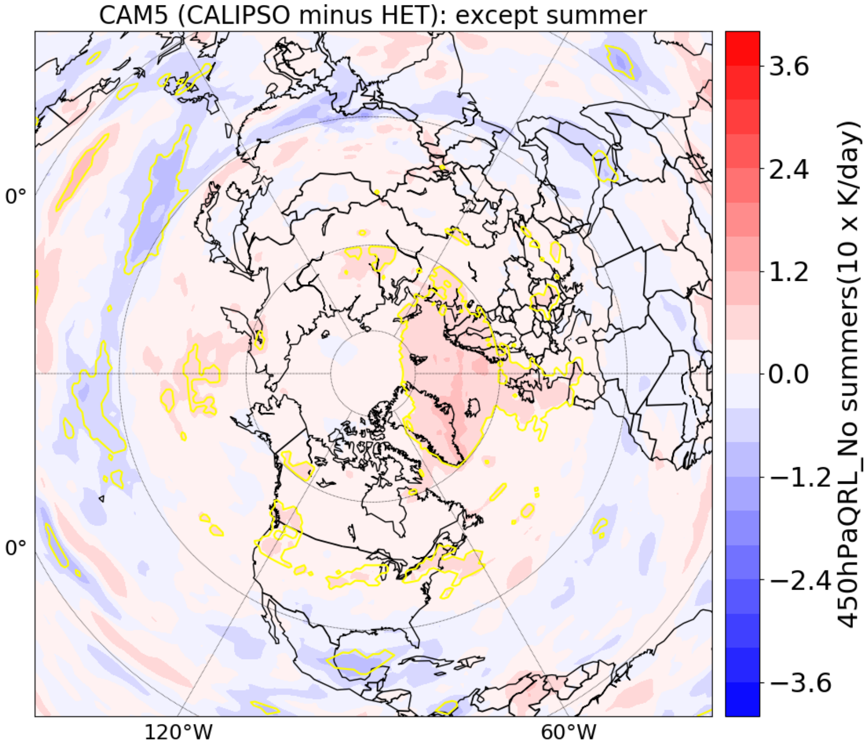




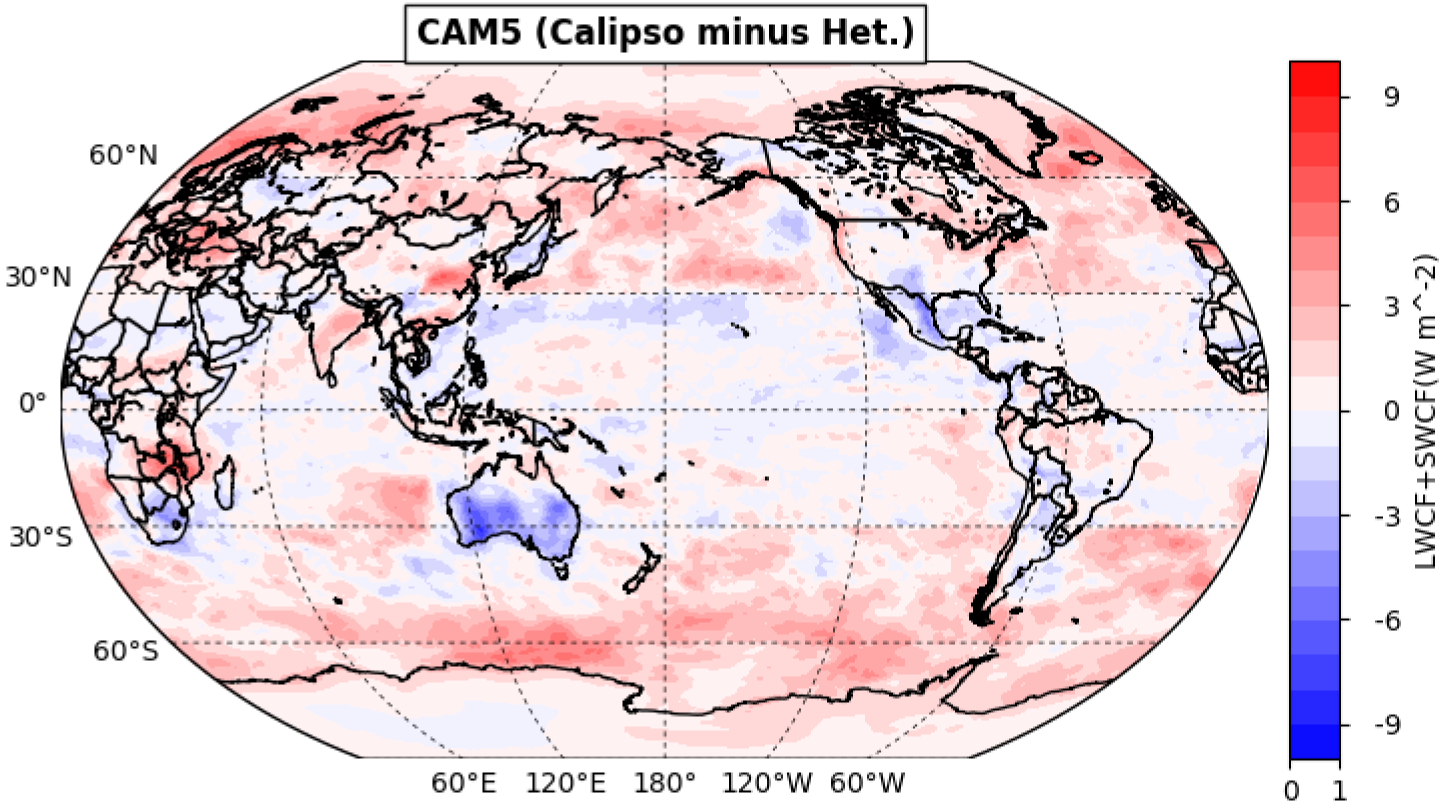


Increase in ice cloud heating rates for CALIPSO relative to the Het simulation for annual zonal means (left), fall (lower left) and non-summer months (lower right). Yellow contours indicate 95% significance.


CAM5 (CALIPSO minus HET): SON


CAM5 (CALIPSO minus HET): except summer

The net cirrus cloud radiative effect: annual

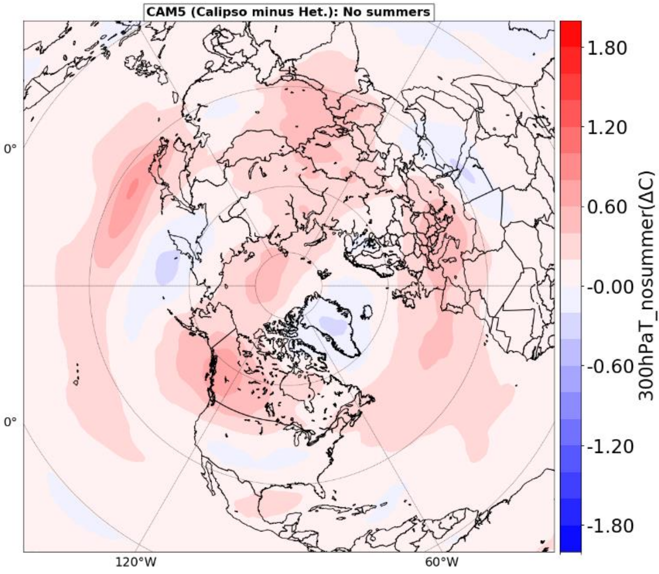


	All Seasons ($W\ m^{-2}$)	Non-Summer ($W\ m^{-2}$)
Global	0.69	0.87
S.H. (-30,-90)	1.28	1.49
N/H. (+30,+90)	1.14	1.30

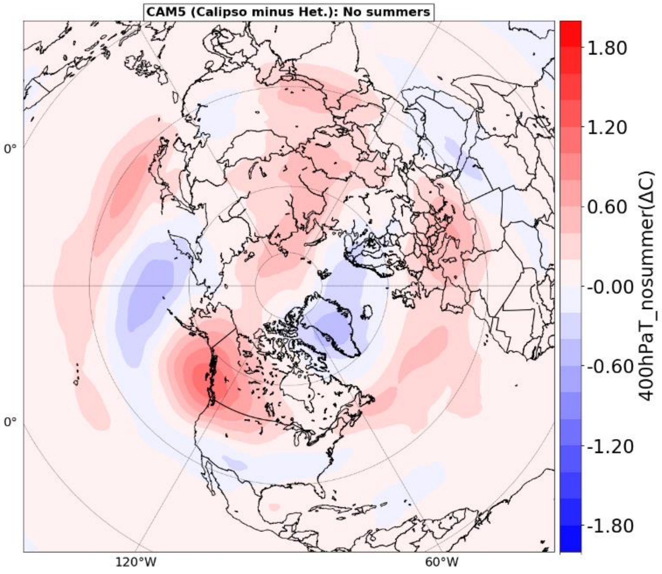
The natural CALIPSO cirrus tend to trap more heat than the het cirrus.

CALIPSO minus Het temperature differences at 4 pressure levels for non-summer months

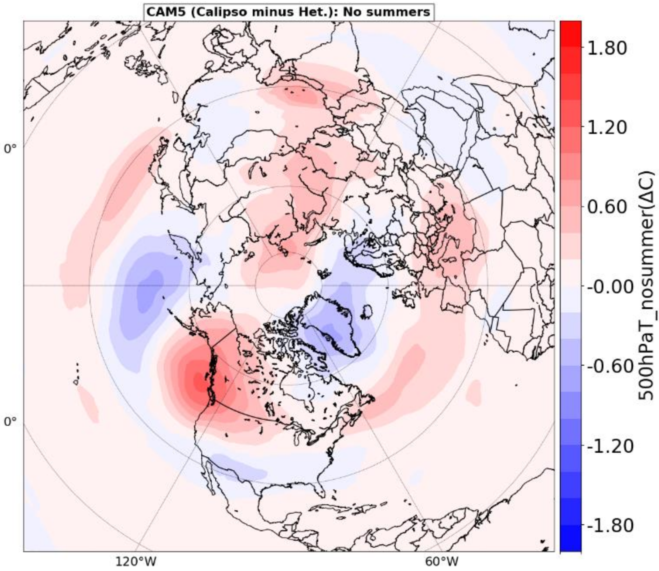
300 hPa



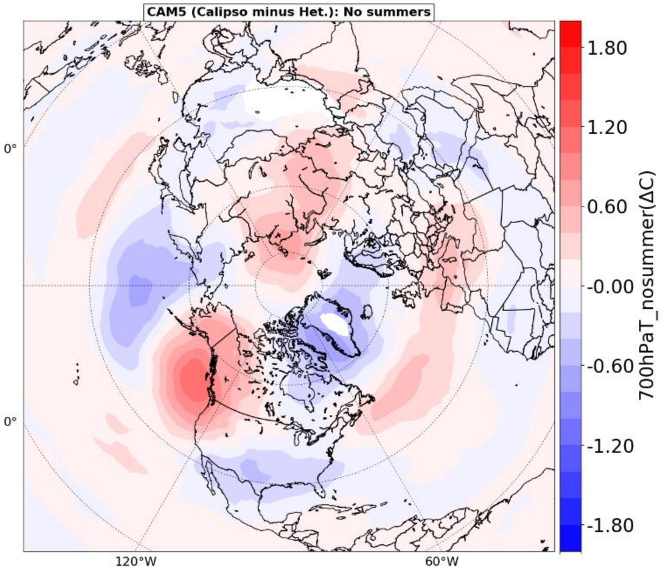
400 hPa

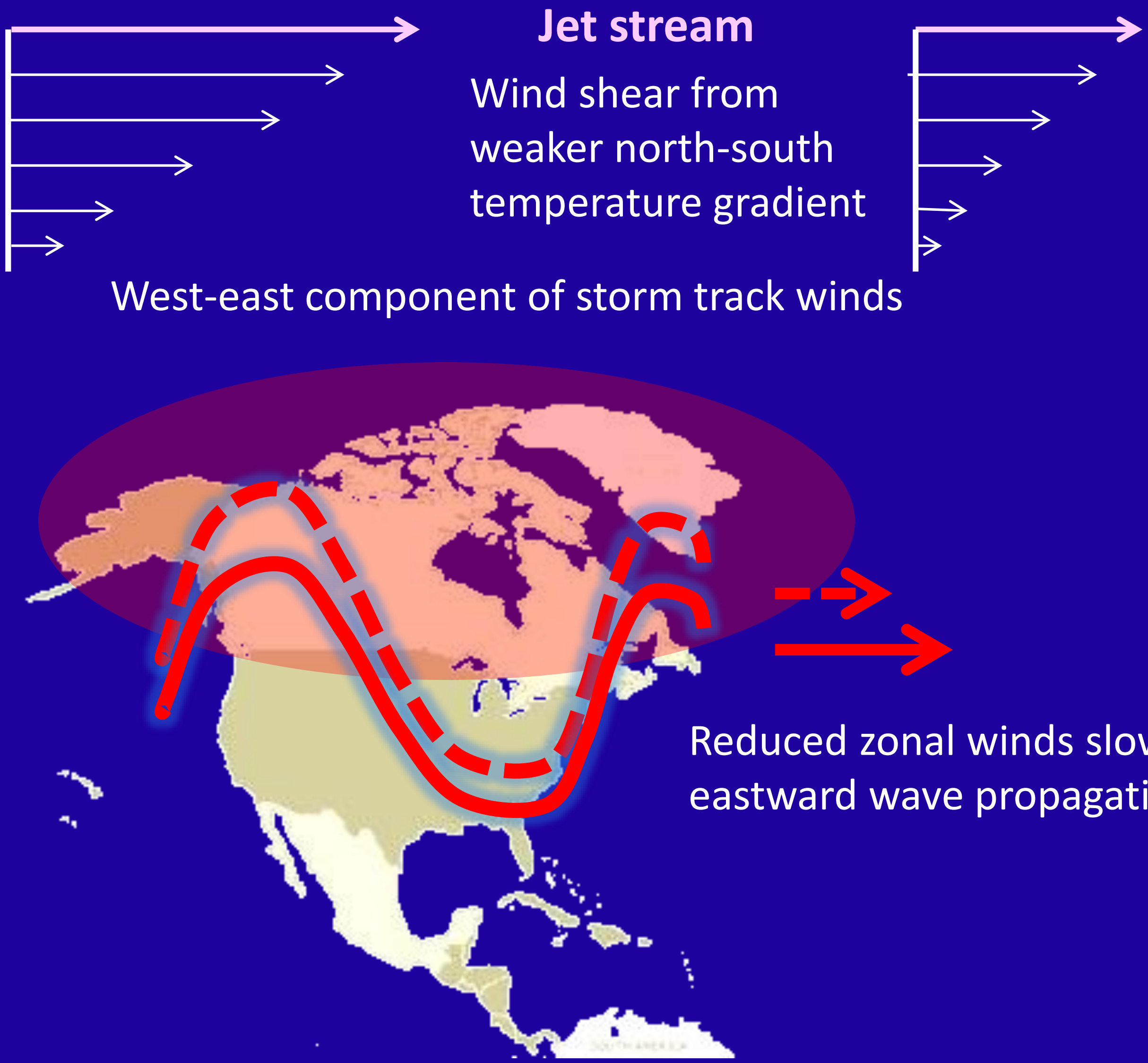


500 hPa



700 hPa





Wind shear produced by normal north-south temperature gradient

Jet stream

Wind shear from weaker north-south temperature gradient

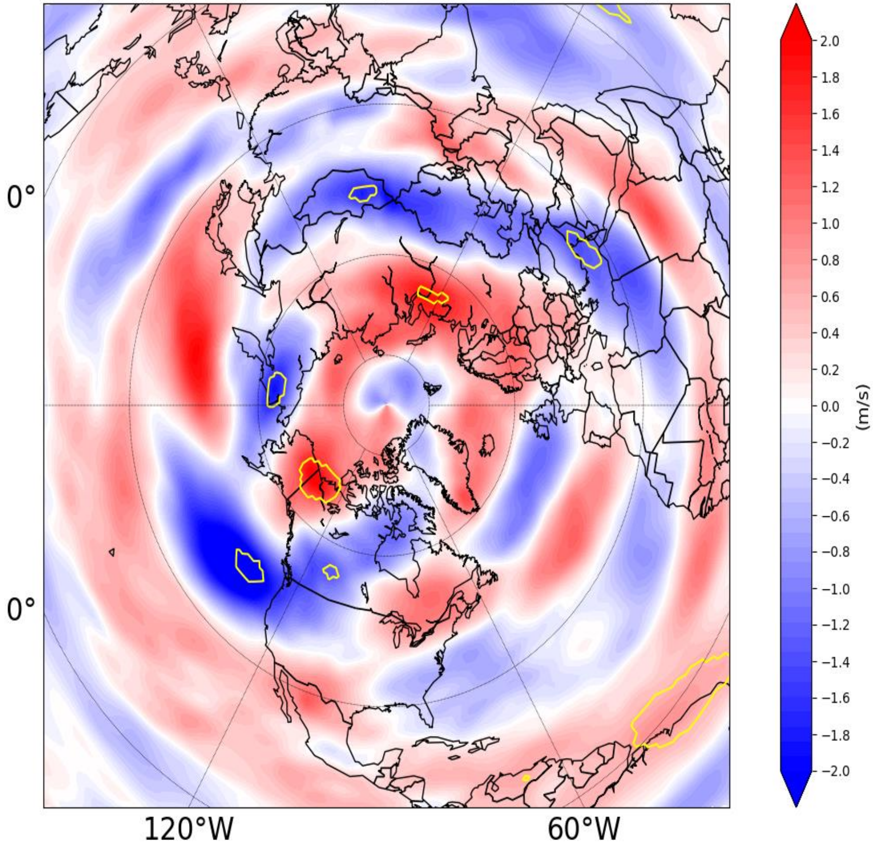
West-east component of storm track winds

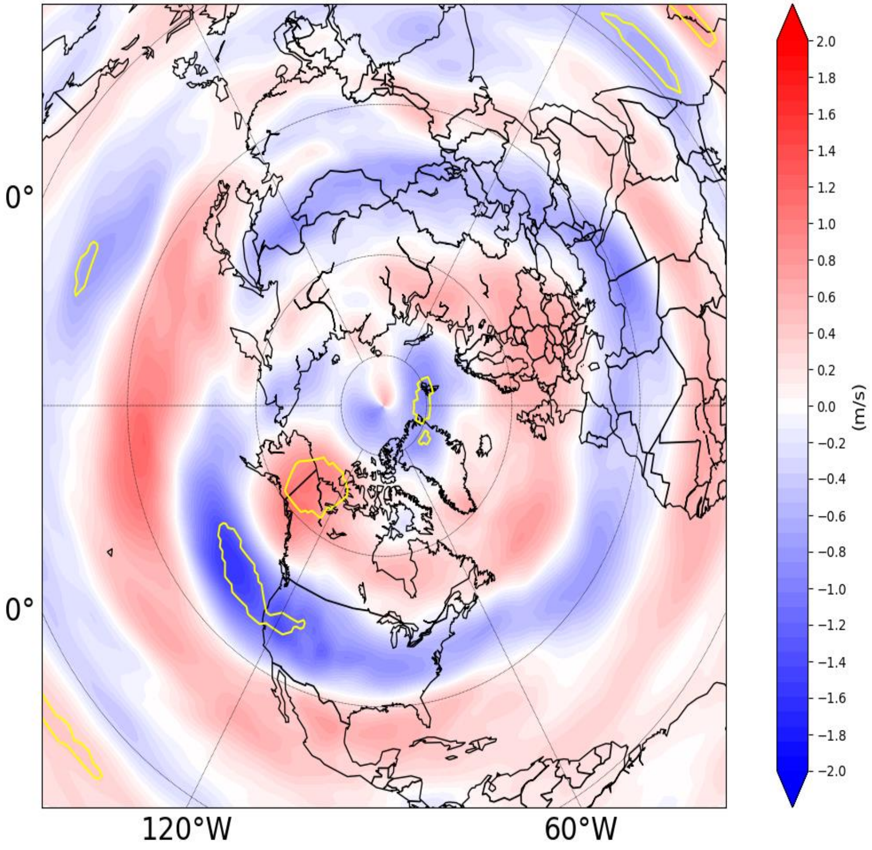
Amplitude of planetary waves (controlling the jet stream & storm track) increase as a result of a weaker north-south temperature gradient.

Reduced zonal winds slow the eastward wave propagation.

Francis and Vavrus, GRL 2012

CALIPSO – Het differences in mean 500-600 hPa zonal winds


500-600mb averaged CALIPSO-HET in U and regions (circled in yellow) of 95% significance: SON


500-600mb averaged CALIPSO-HET in U and regions (circled in yellow) of 95% significance: No summers

Fall season

Non-summer months

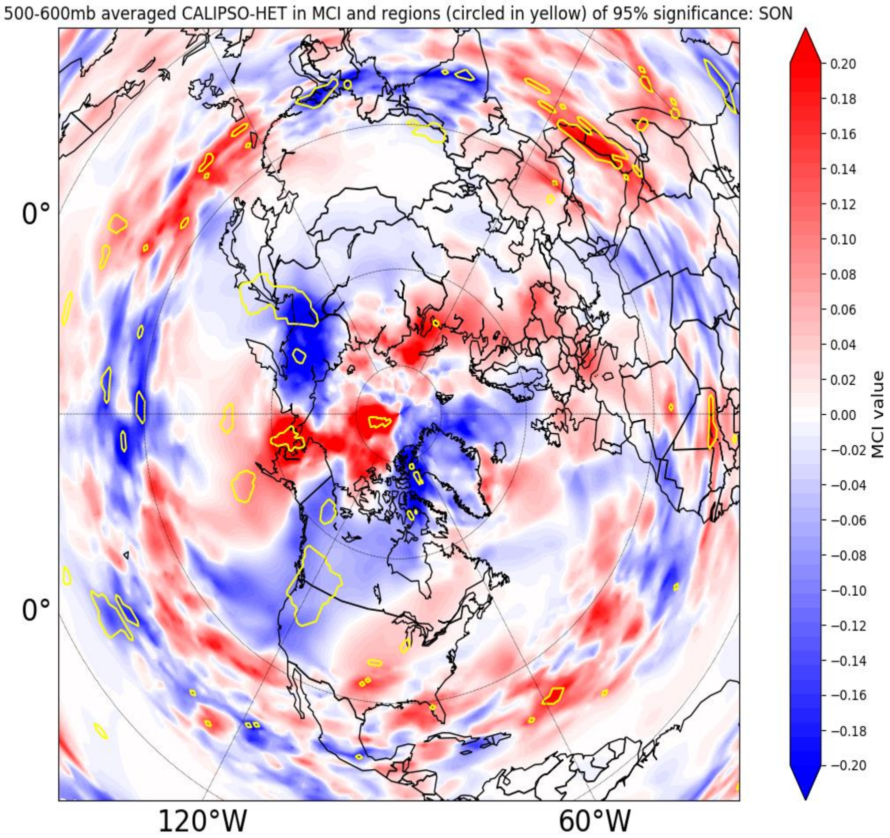
Yellow contours indicate 95% significance within enclosed region

Adopted the practice of Francis and Vavrus (2015) of characterizing meridional flow using the meridional component index, or MCI:

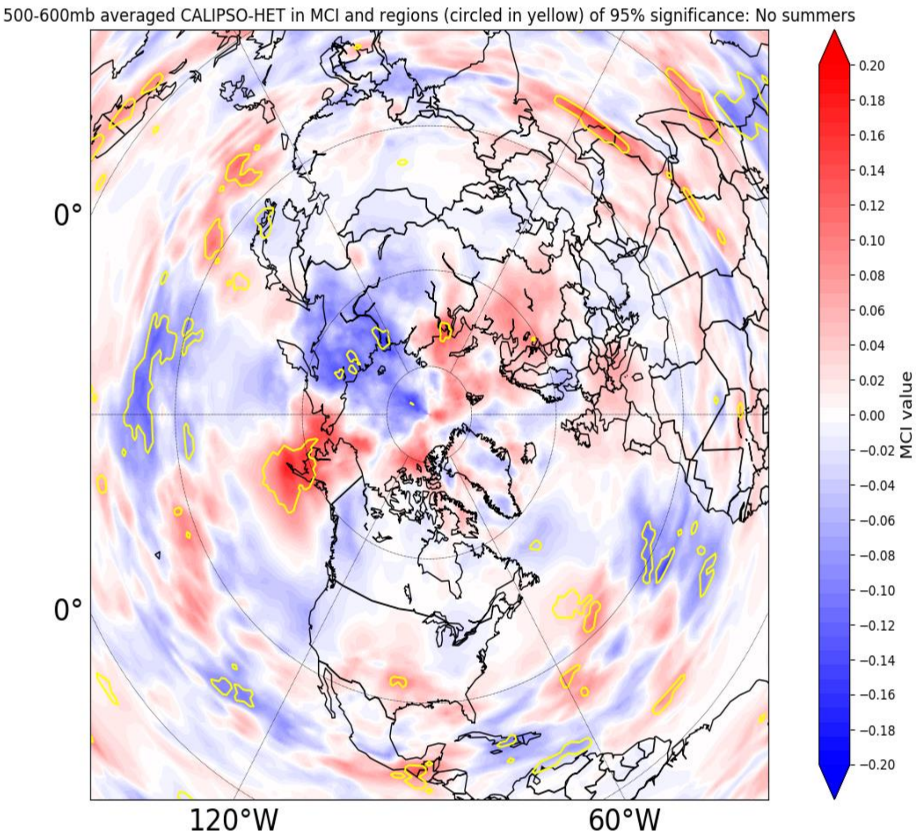
$$\mathrm{MCI} = \frac{v\ |v|}{u^2 + v^2}$$

Positive MCI = poleward transport
Negative MCI = equatorward transport

CALIPSO – Het differences in mean 500-600 hPa MCI



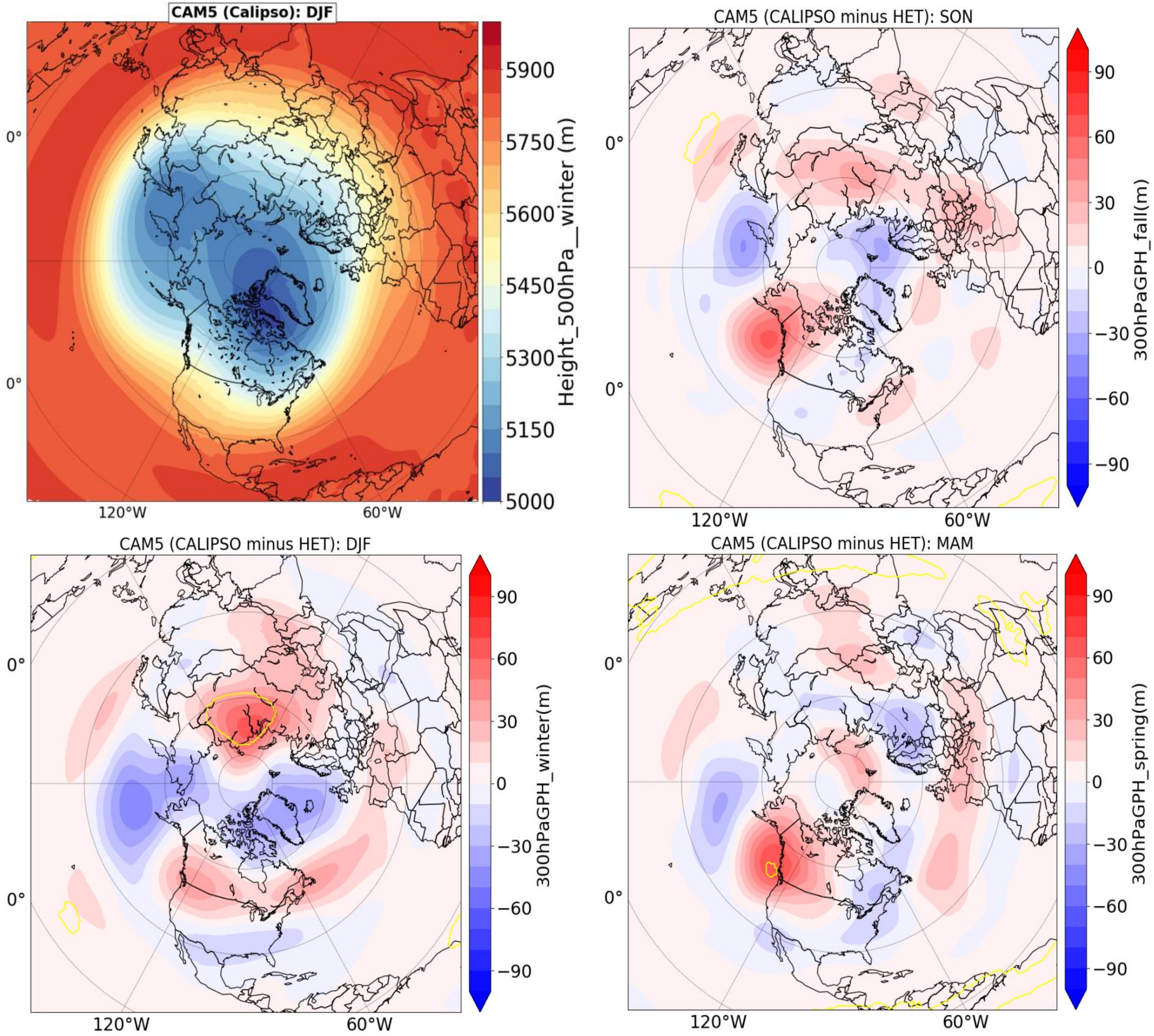
500-600mb averaged CALIPSO-HET in MCI and regions (circled in yellow) of 95% significance: SON



500-600mb averaged CALIPSO-HET in MCI and regions (circled in yellow) of 95% significance: No summers

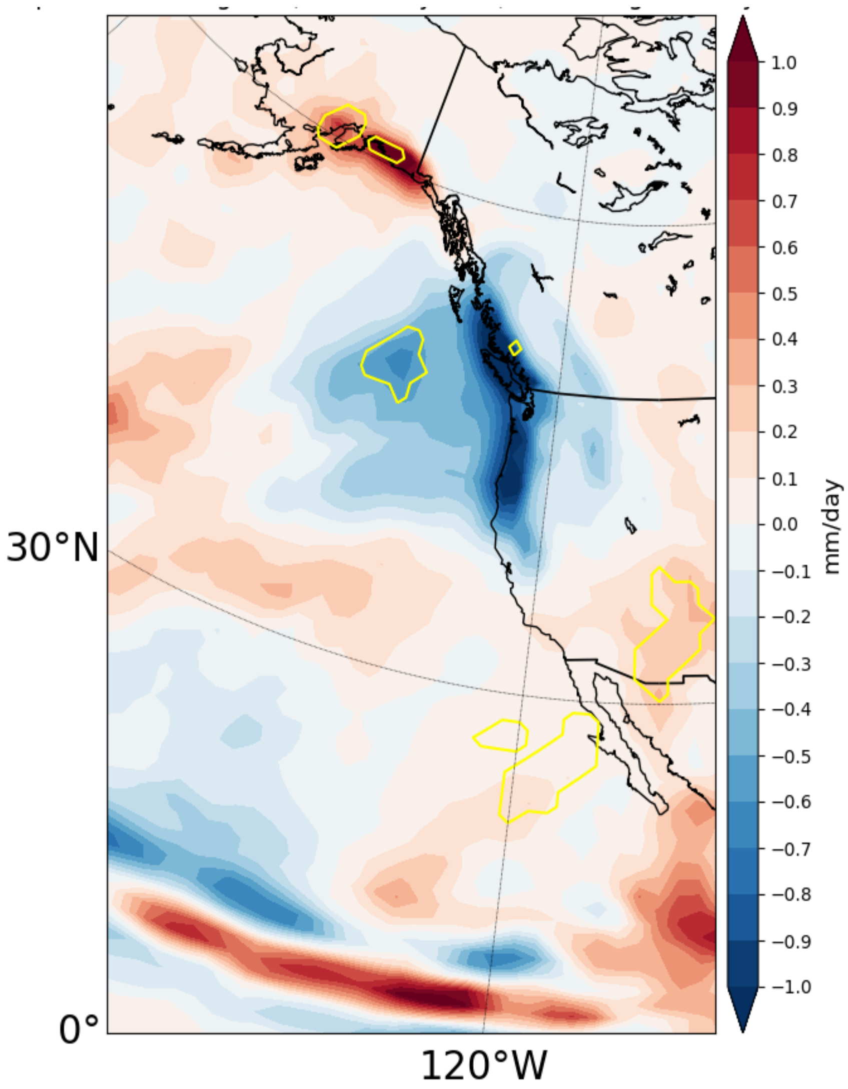
Fall season **Non-summer months**

Yellow contours indicate 95% significance within enclosed region

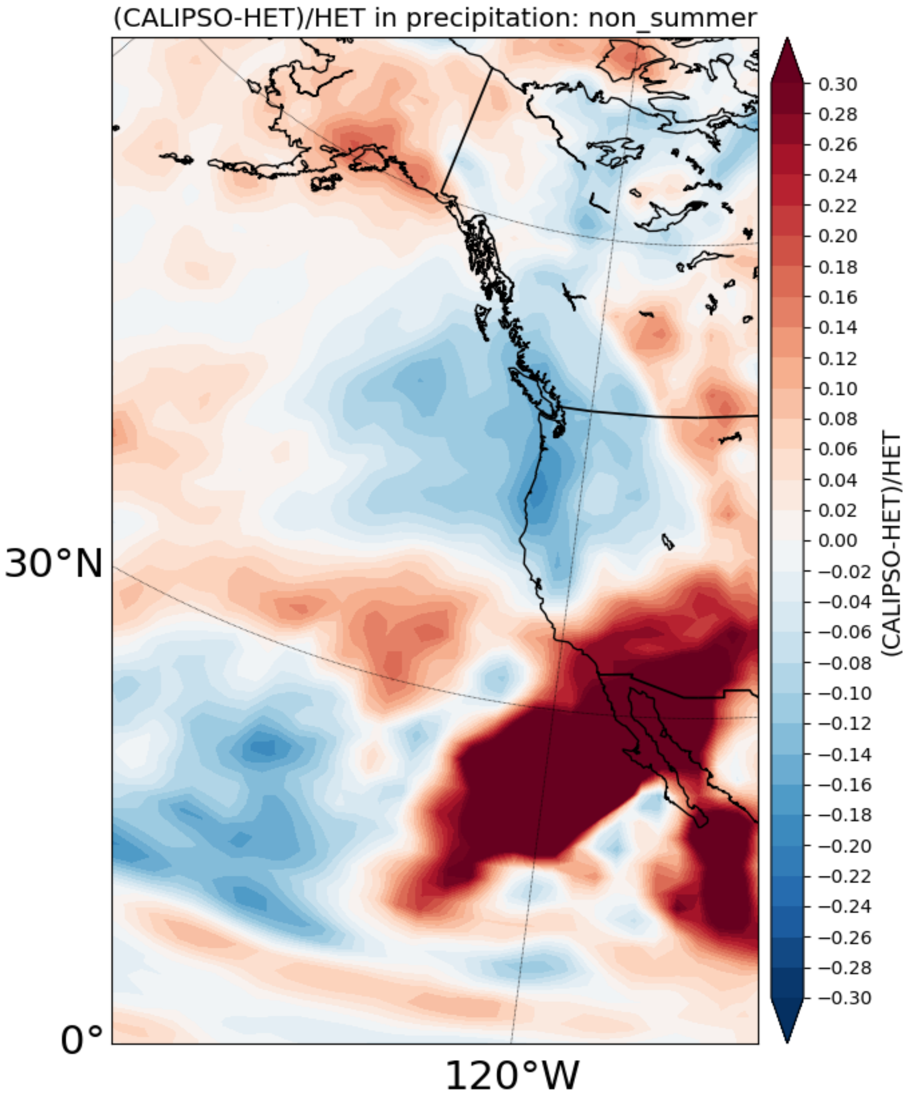


500 hPa winter geopotential height (m), and CALIPSO – Het differences in 300 hPa geopotential height for fall (upper R), winter (lower L) and spring (lower R). Yellow contours indicate 95% significance within enclosed region.

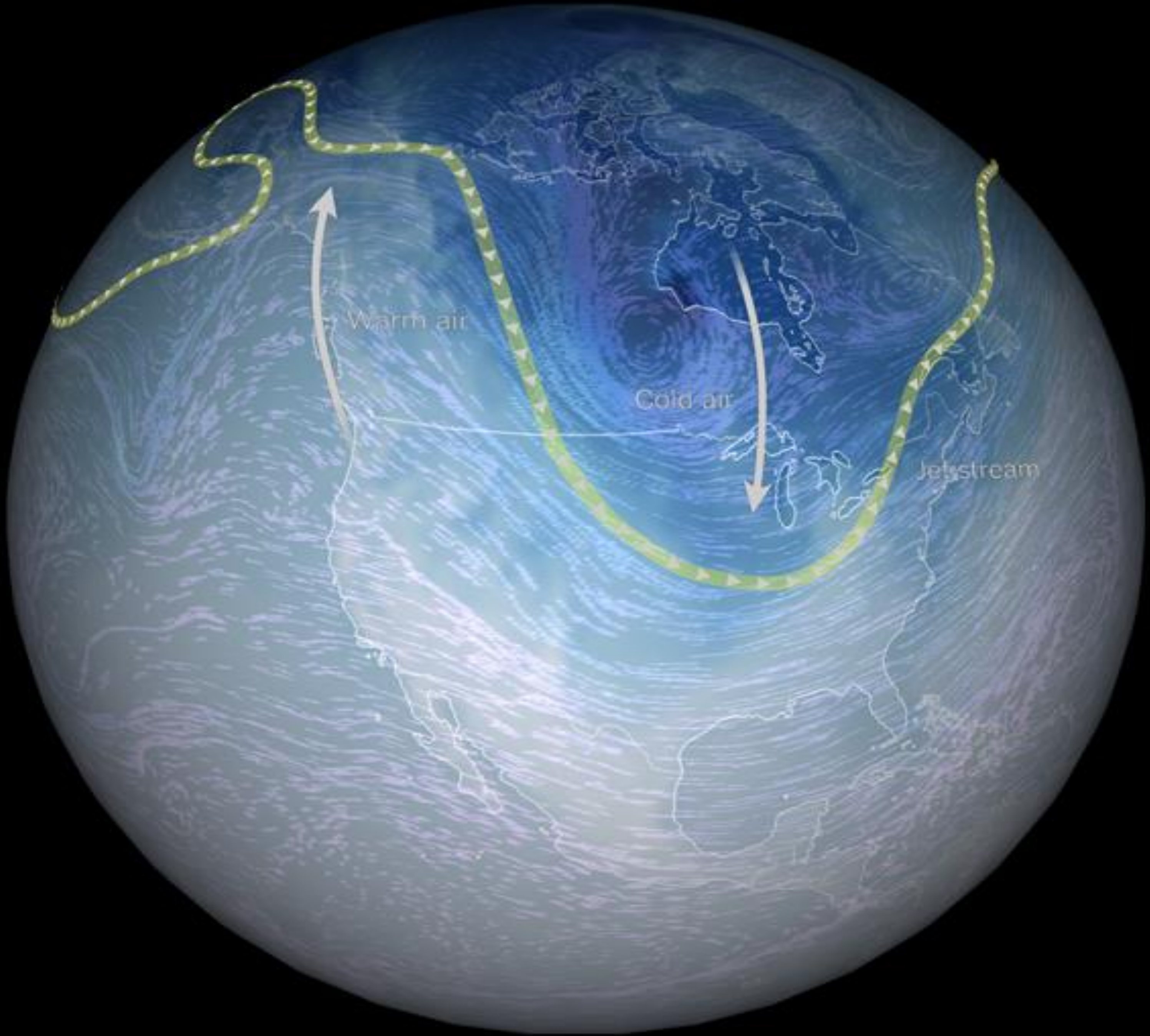
CALIPSO – Het differences in precipitation; non-summer months



mm/day differences

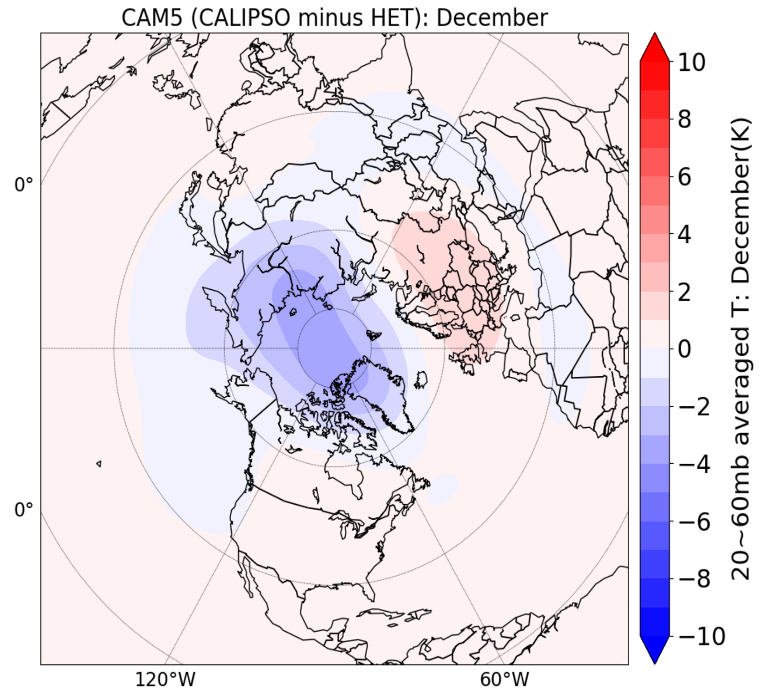

(CALIPSO-HET)/HET in precipitation: non_summer

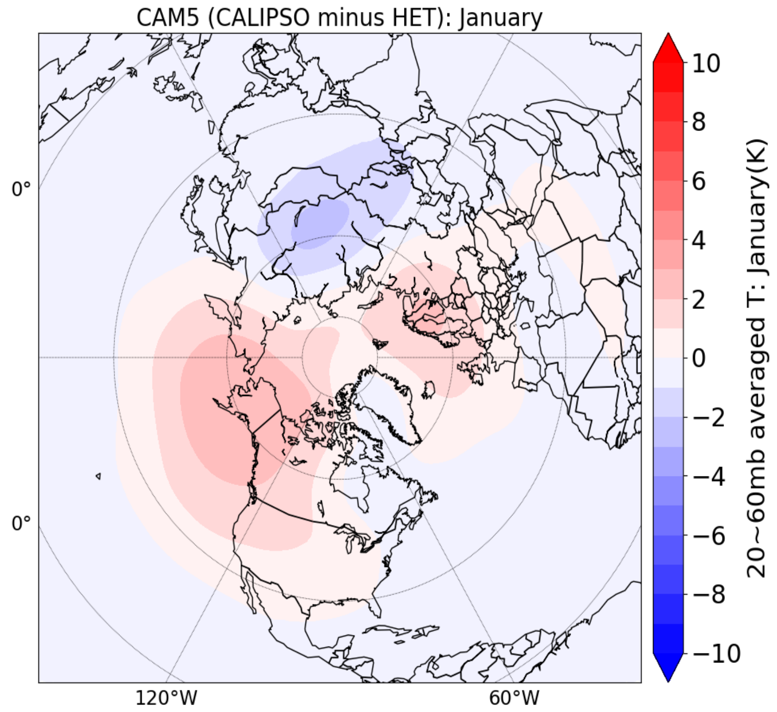
(CALIPSO-Het)/Het

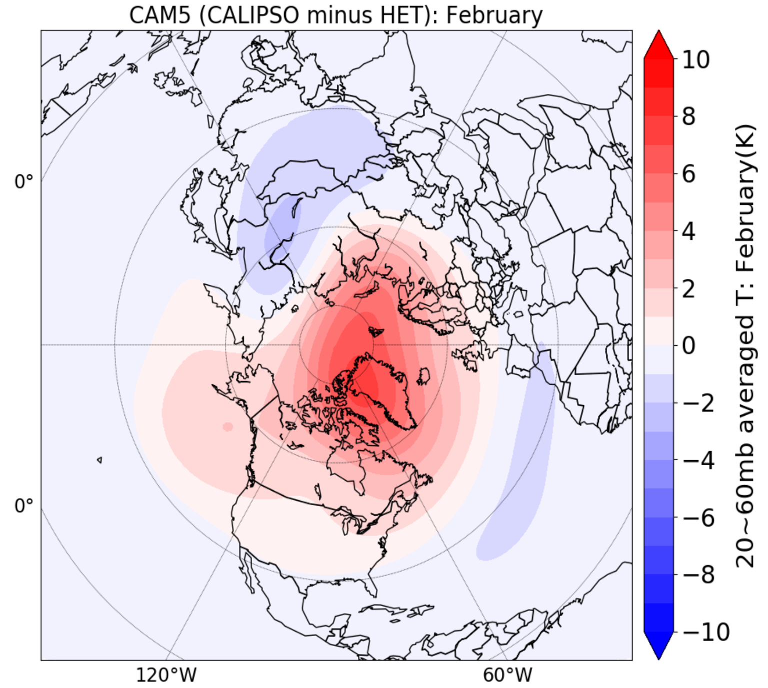


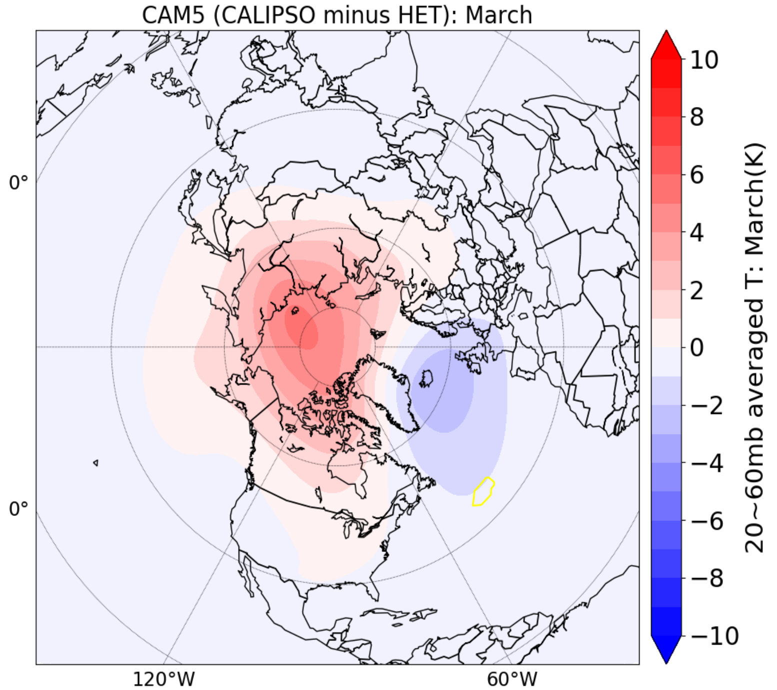
The polar vortex split on 3 January 2019, producing the jet-stream pattern shown here on 29 Jan. 2019.

Image from NY Times









20-60 hPa CALIPSO – Het temperature differences, showing more stratospheric warming in the CALIPSO simulation. 10 hPa temperature changes were very similar.

SSW analysis:

SSW climatology => 6 SSWs per decade (duration of simulations)
Assume Het => 5 SSWs; CALIPSO => 7 SSWs
Assume all SSWs produce stratospheric temperature max. of 50 K

"Cumulative SSW T" for CALIPSO = 7 × 50 = 350 K
"Cumulative SSW T" for Het = 5 × 50 = 250 K
Cumulative CALIPSO – Het SSW T = 100 K
Mean CALIPSO – Het SSW T = 10 K (based on maximum T)

Monthly mean CALIPSO – Het SSW T < 10 K

Therefore, 7 K difference appears indicative of more SSWs in CALIPSO relative to Het.

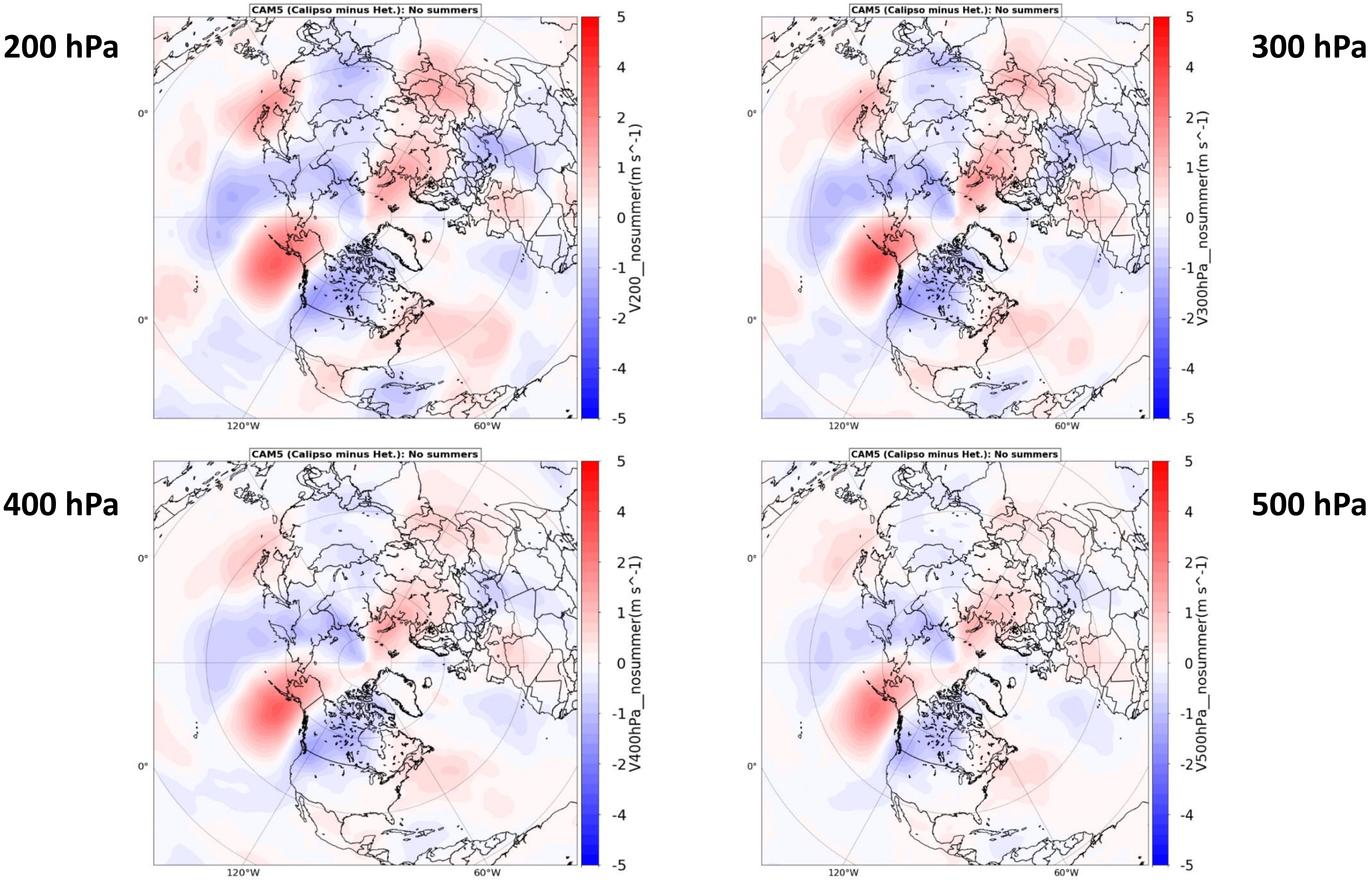
SUMMARY

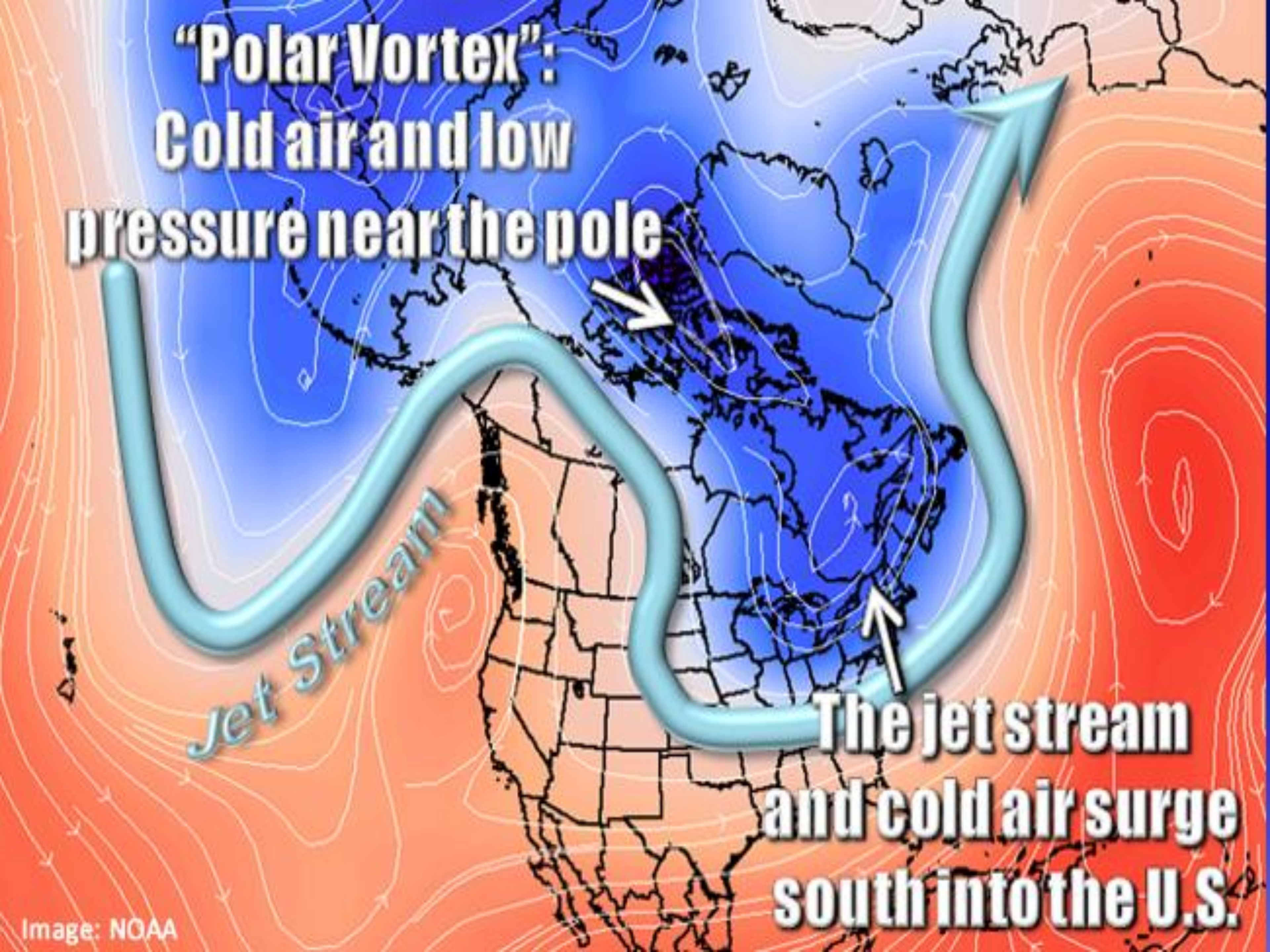
1. Enhanced ridging of large-scale planetary waves during CALIPSO (relative to Het)
2. Enhanced ridging over western North America resulted in warmer and drier conditions, possibly contributing to drought and wild fires.
3. These amplified planetary waves (i.e. wavier jet stream) may produce more extreme winter weather.
4. These amplified planetary waves appeared to disrupt the stratospheric polar vortex, resulting in stratospheric warming. A disrupted stratospheric vortex can gradually drift downwards to produce extreme winter weather.
5. Improved model representation of high latitude cirrus clouds may improve sub-seasonal forecasts and climate prediction.

Acknowledgements

This research was supported by a NASA CloudSat CALIPSO grant and the NASA CALIPSO project.

CALIPSO – Het meridional winds at 4 pressure levels (non-summer months)

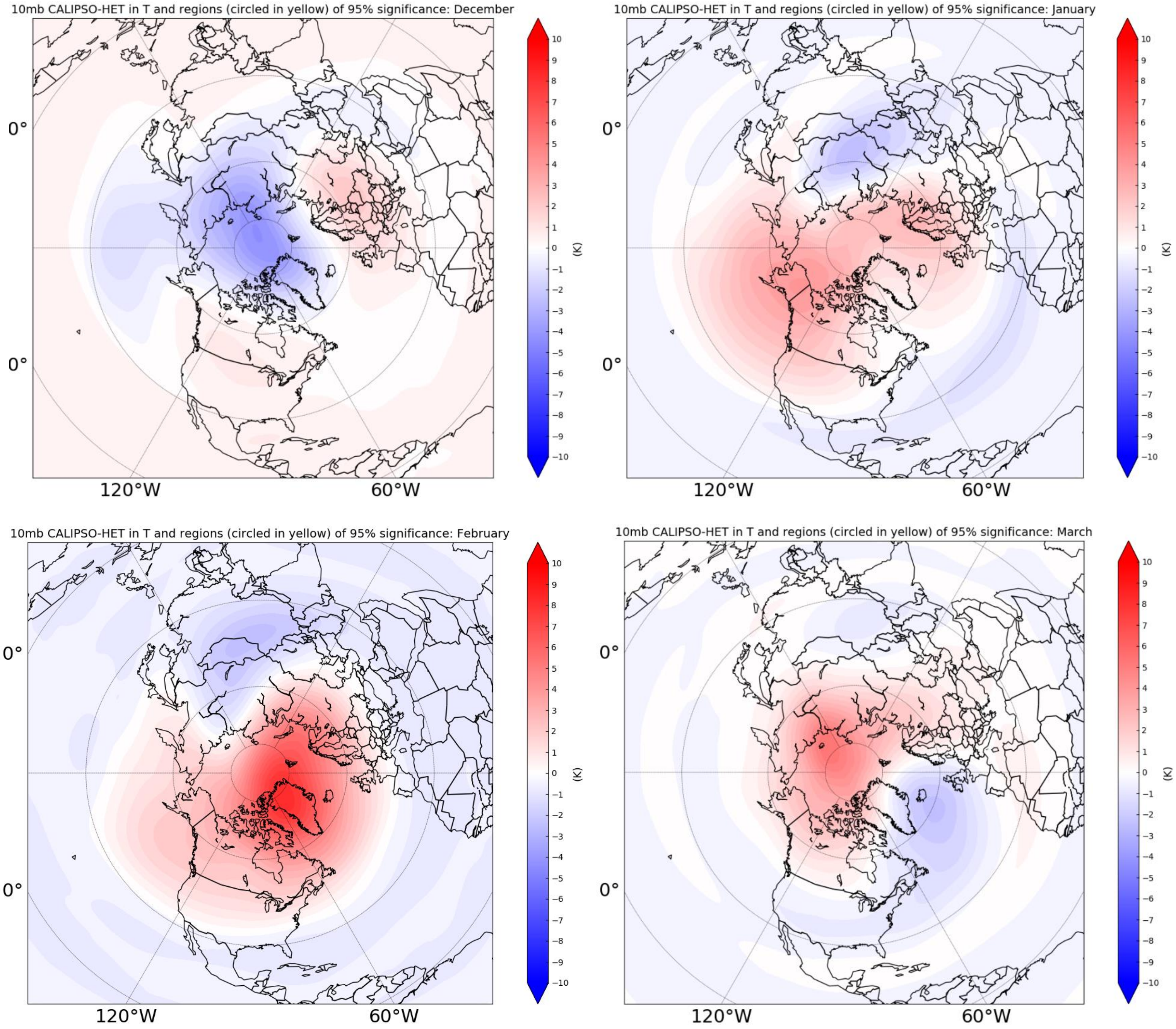




“Polar Vortex”: Cold air and low pressure near the pole

The jet stream and cold air surge south into the U.S.

Image: NOAA



10mb CALIPSO-HET in T and regions (circled in yellow) of 95% significance: December

10mb CALIPSO-HET in T and regions (circled in yellow) of 95% significance: January

10mb CALIPSO-HET in T and regions (circled in yellow) of 95% significance: February

10mb CALIPSO-HET in T and regions (circled in yellow) of 95% significance: March

10 hPa CALIPSO – Het temperature differences, showing more stratospheric warming in the CALIPSO simulation (up to 7 K in February). 20-60 hPa temperature changes were very similar.

RELEVANT MECHANISM FOR EXTREME WEATHER (from Cohen et al., 2014, Nature)

Sea-ice loss warms atmosphere => high pressure => suppress jet stream southwards ⇒ more snow over Eurasia

Sea ice loss in Barents/Kara seas => strong surface heating ⇒ increased mid-level high pressure => distorted tropos. polar vortex => vertical waves into stratosphere

Ascending waves weaken strat. polar vortex => strat. warming ⇒ circulation anomalies in strat. & troposphere with more extreme mid-latitude weather

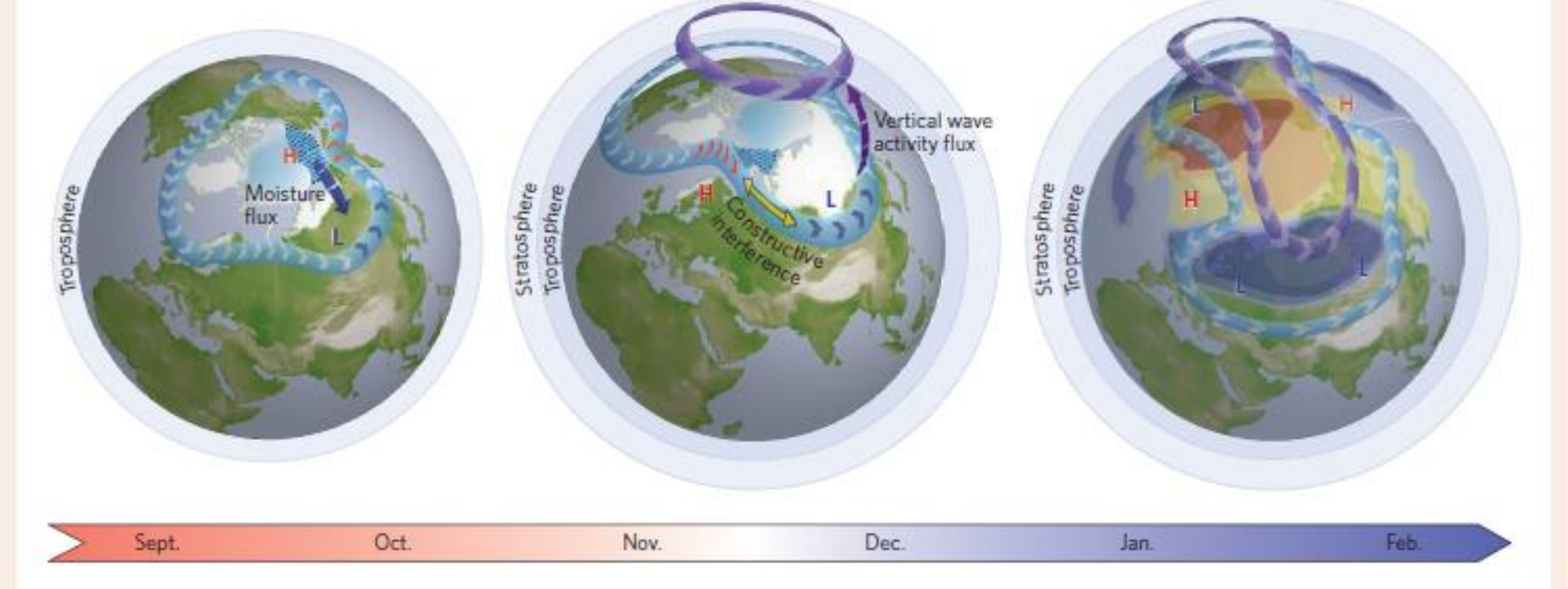
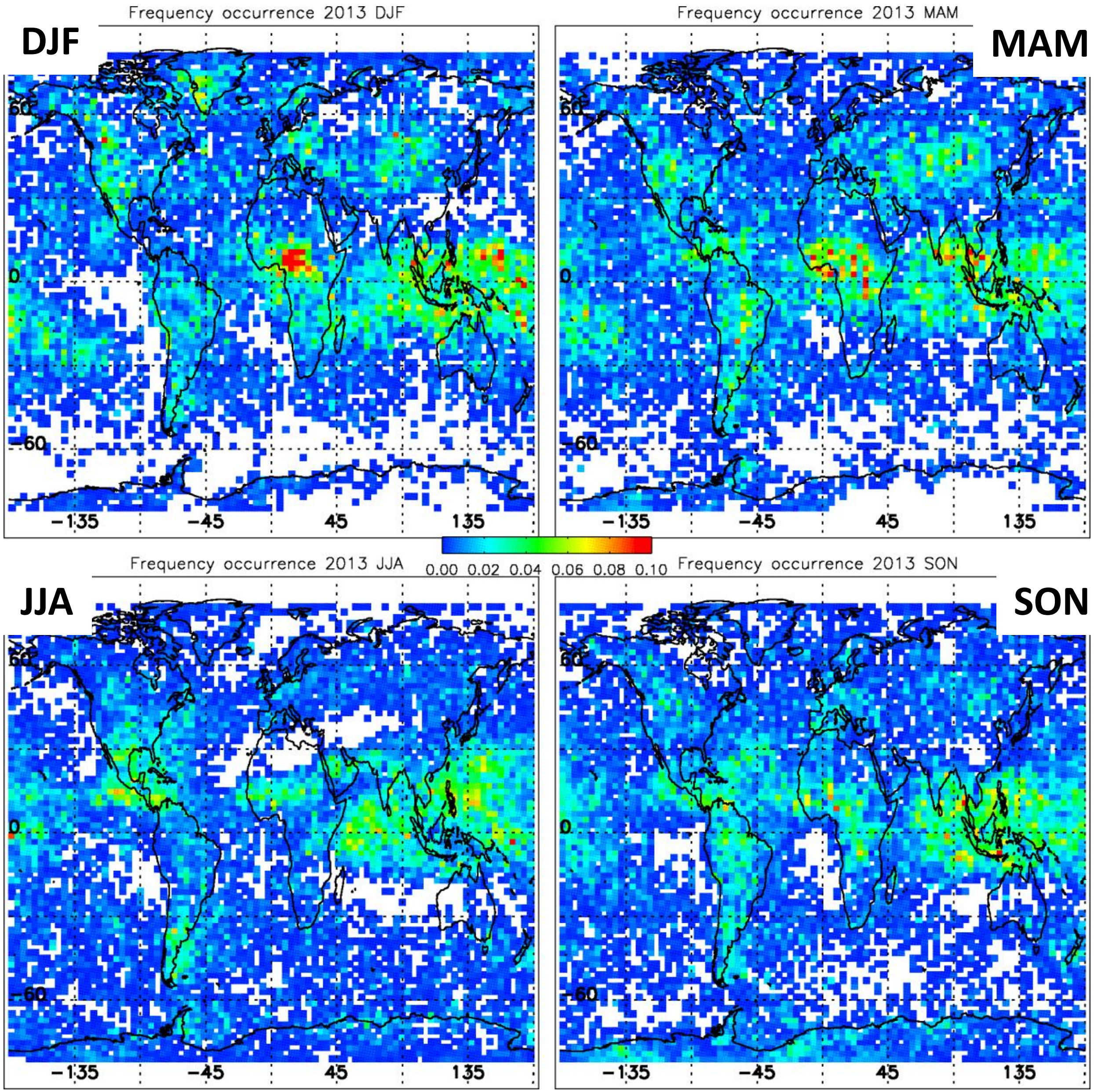


Figure B2 | Synthesis of proposed cryospheric forcings. The schematic highlights a proposed way in which Arctic sea-ice loss in late summer through early winter may work in concert with extensive Eurasian snow cover in the autumn to force the negative phase of the NAO/AO in winter. Snow is shown in white, sea ice in white tinged with blue, sea-ice melt with blue waves, high and low geopotential heights with red 'H' (red represents anomalous warmth) and blue 'L' (blue represents anomalous cold) respectively, tropospheric jet stream in light blue with arrows, and stratospheric jet or polar vortex shown in purple with arrows. On the right globe, cold (warm) surface temperature anomalies associated with the negative phase of the winter NAO/AO are shown in blue (brown). See Box text for detailed explanation.

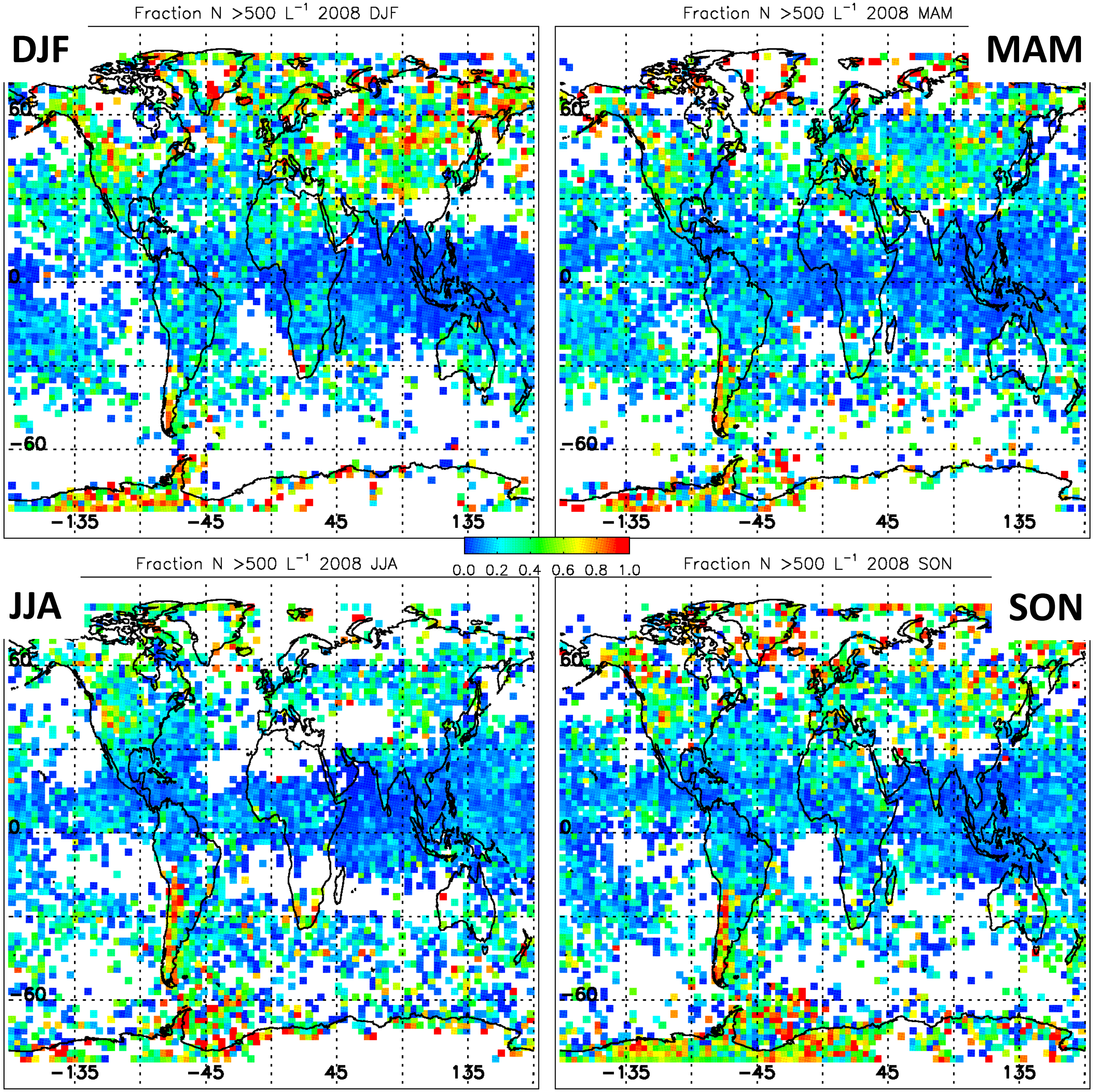
Frequency of occurrence of sampled cirrus clouds for 2013



Frequency of occurrence of high latitude (60-90°) cirrus clouds is at least 2 x greater during boreal winter relative to any other season.

Over British Columbia and regions nearby, the cirrus frequency of occurrence is highest during winter.

The Seasonal Cirrus Cloud N_i Cycle for 2008



Results for 2008: Fraction of cirrus clouds having N > 500 liter^{-1}. Such cirrus are most likely formed by homogeneous ice nucleation (hom), and the fraction of these cirrus are shown for each season.

Results are consistent with Cziczo et al. (2013, Science).

From Mitchell et al., 2016, ACPD.