Navigating the uncertainty of studying Arctic atmospheric rivers with global reanalyses

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Motivations

- **Arctic amplification:** The rise in Arctic near-surface air temperature has been almost twice as large as the global average in recent decades (e.g., Johannessen et al., 2004; Serreze and Francis, 2006; Serreze et al., 2009).
- Several physical processes underlying Arctic amplification remain uncertain: e.g., surface-albedo feedback, greenhouse effects associate with changes in clouds and water vapor, changes in poleward energy transport.
- These physical processes are intertwined, especially the major poleward moisture transport, such as atmospheric rivers (AR).
- Quantify Arctic AR's climatological characteristics and associated effects at the surface

Questions

1. Is there a climate change of Arctic AR frequency of occurrence? Has Arctic AR occurrence frequency increased?

2. Have Arctic ARs transported more moisture into the Arctic? Is there a climate change of proportion of poleward integrated water vapor transport attributed to ARs?

3. Are there recurring spatial patterns of ARs?

4. What are the regional effects of ARs at the surface?

Data

- ERA5 & NASA MERRA-2
  - Sampled at 3 hourly intervals from Jan. 1980 to Dec. 2019
  - 0.25° x 0.25° (ERA5) & 0.5° latitude x 0.625° longitude (MERRA-2)
  - Integrated Water Vapor Transport (IVT), Integrated Water Vapor (IWV), 2m Temperature (T2m), Mean Sea Level Pressure (SLP)
- NOAA daily indices of Arctic Oscillation (AO), North Atlantic Oscillation (NAO), and Pacific/North America (PNA): Positive/Negative phase: +/- 0.5
- The Clouds and the Earth's Radiant Energy System (CERES) SYN1deg products from 2000 to 2019: adjusted all-sky profile fluxes surface longwave flux down
- Monthly & daily Sea Ice Concentration (SIC) from the National Snow and Ice Data Center (1990-2019)

Multifactorial AR detection algorithm

- Algorithm was based on detection criteria in Zhang et al. (2021) and AR event tracking method developed by Guan & Waliser (2019)
- Zhang et al. (2021) found that climate thresholds and moisture fields had a more significant impact on the generation of AR index and AR-related surface hydrometeorological impacts.
- An ensemble of 6 Arctic AR indices based on IVT or IWV, applied with three climate thresholds (75th, 85th, and 95th percentiles) and geometry (1500 km length & length/width>=2) and duration (18 hours) criteria was created from Jan.1980 to Dec. 2019 in ERA5 and MERRA-2, respectively.
- AR detection was made possible by distributed-parallel computing, specifically, the divide-and-recombine approach using the R-based DeltaRho backended by a Hadoop system.

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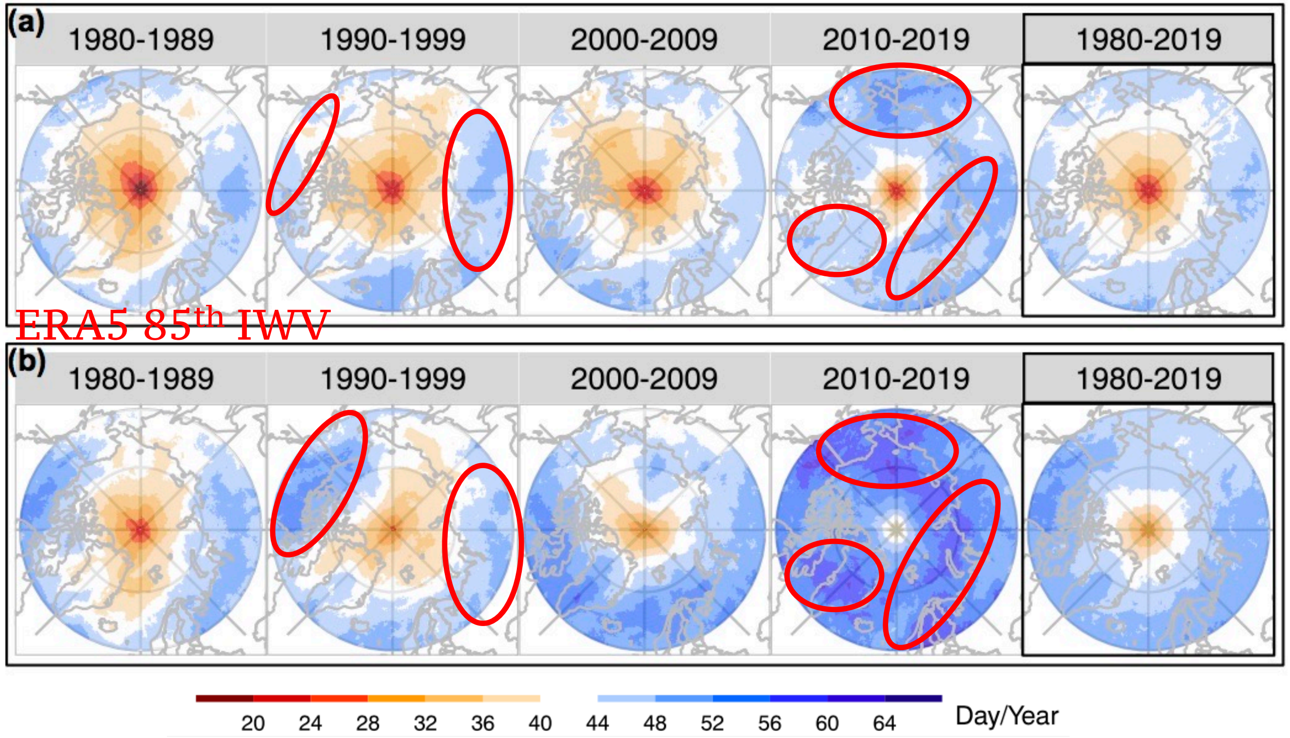
Result 1 (Arctic AR climatology): Increased ARs over the Arctic regions from the Pacific, across the Arctic, to the Atlantic side in the recent 20 years, coinciding with sea ice retreat

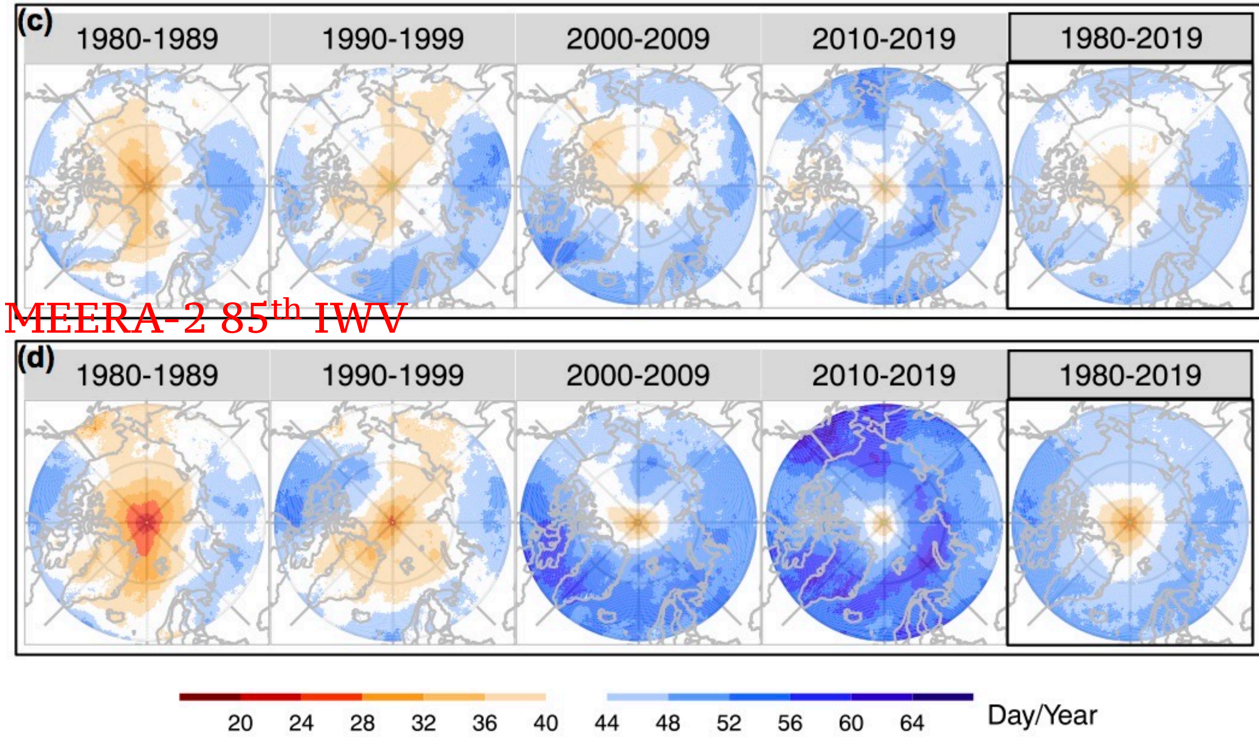
ERA5 85th IVT

ERA5 85th IWV

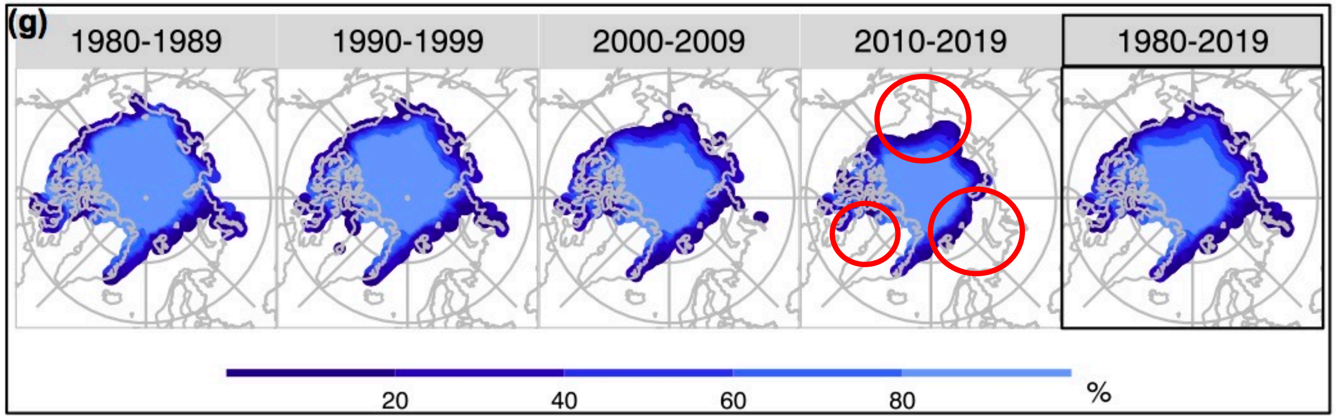


MEERA-2 85th IVT

MEERA-2 85th IWV



Average September sea ice concentration (SIC): Only greater than 15% SIC are shaded to outline the sea ice margins



coinciding with the retreat of sea ice margins

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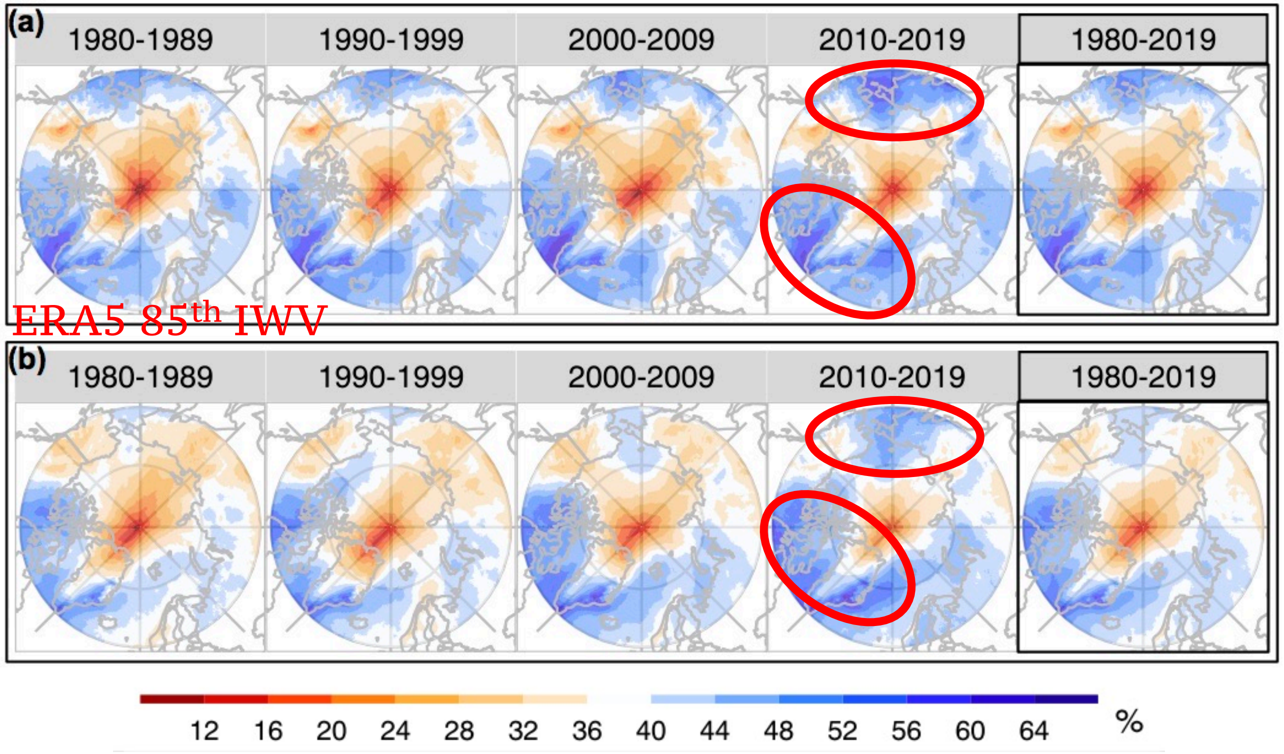
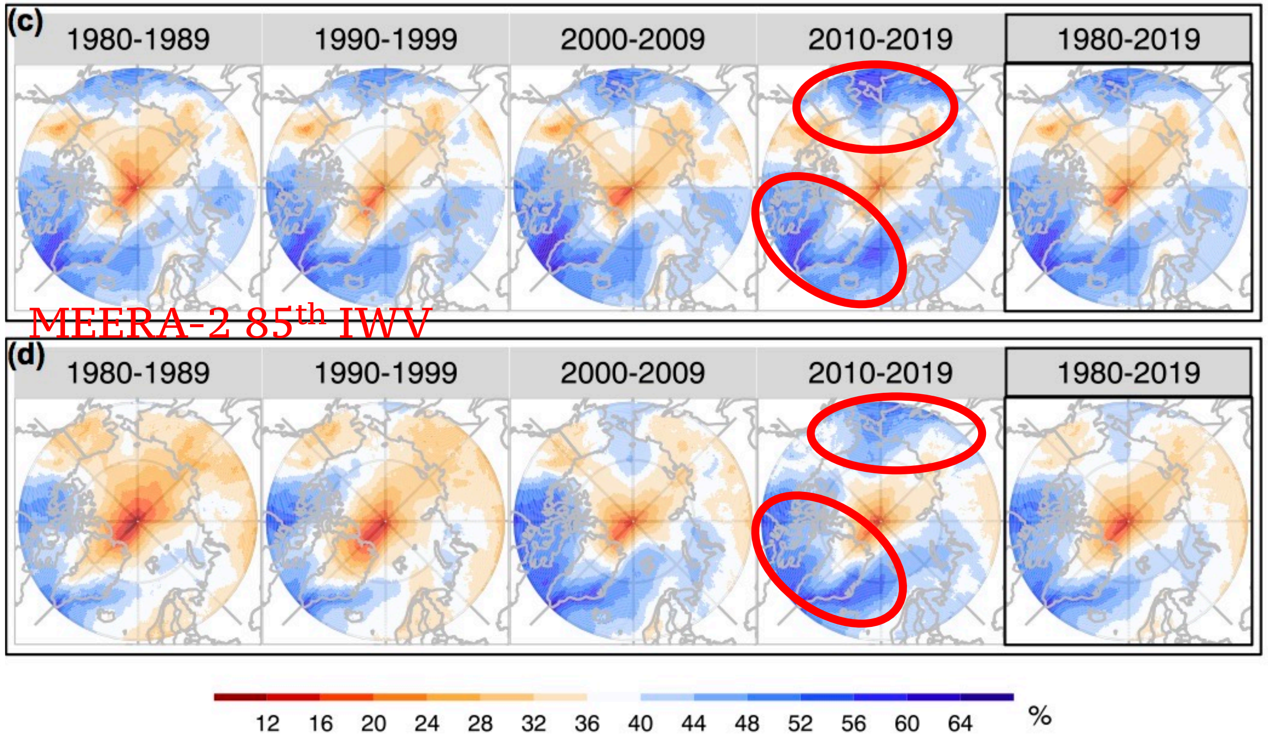
Result 2: Proportion of increasing poleward moisture transport attributed to ARs has been increasing

ERA5 85th IVT

MEERA-2 85th IVT





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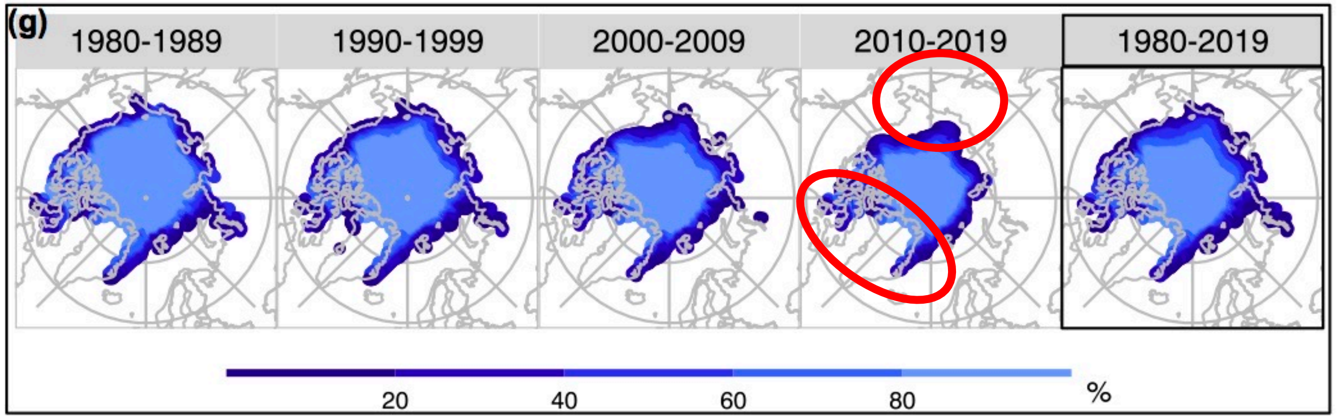

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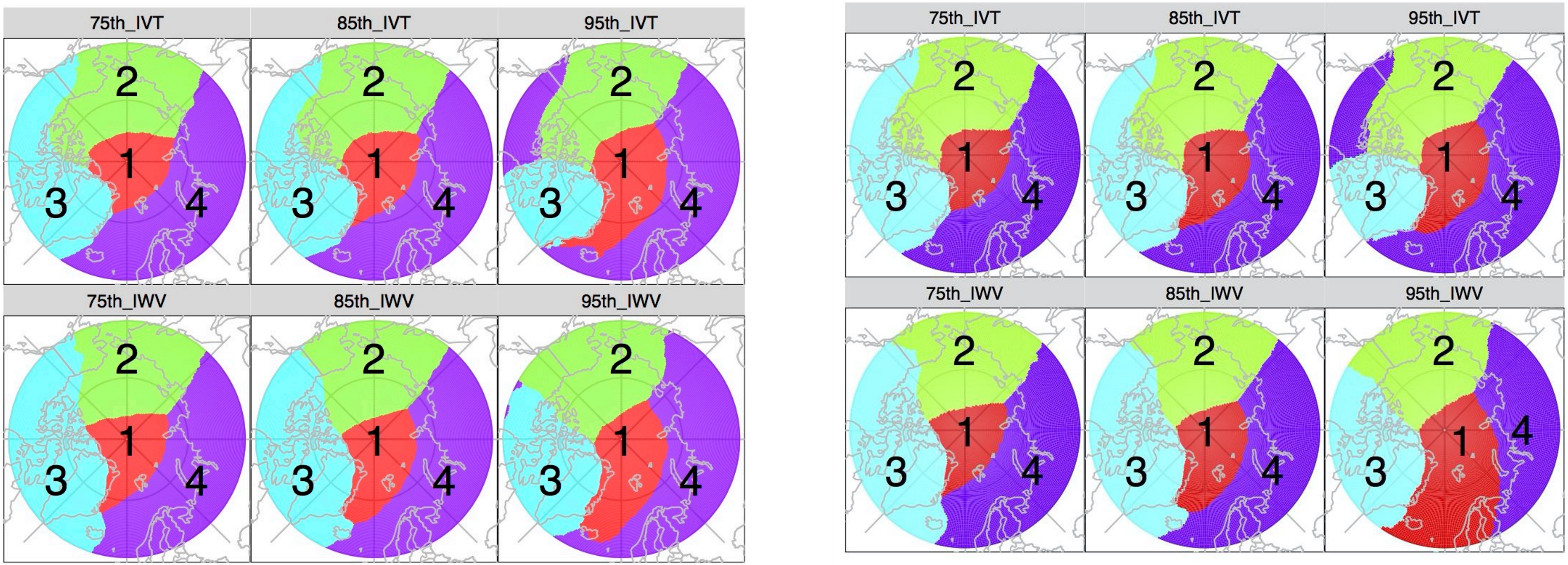
3. Are there recurring spatial patterns of ARs?
   - AO, NAO, PNA strongly modulate regional AR activities
   - The results of K-means effectively reflect the teleconnection patterns' modulation of ARs

4. What are the regional effects of ARs at the surface?

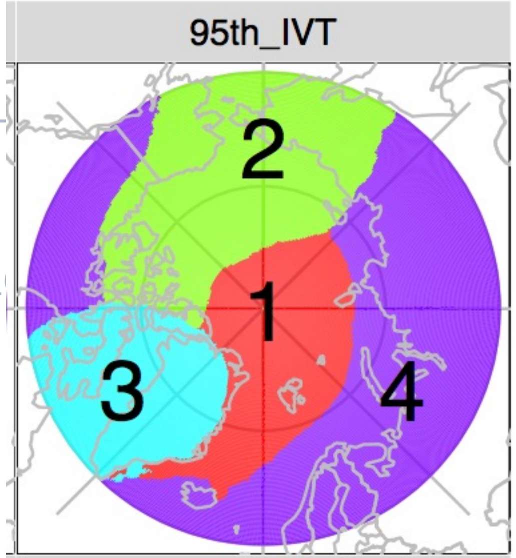
Result 3: K-means analysis of monthly AR occurrence (unit: counts/month) reflected the regional modulations of teleconnection patterns

ERA5 MEERA-2



- The results of K-means analysis are qualitatively consistent among the 12 AR indices in the two reanalyses: Region 1: central Arctic;
  Region 2: Pacific sector;
  Region 3: Northeast Canada + Greenland;
  Region 4: Atlantic sector + part of Eurasian Continent

Questions



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4. What are the regional effects of ARs at the surface?
   - Arctic Pacific AR's effects (Region 2) conditional on the phase of PNA during winter
   - Northeast Canada/Greenland ARs' regional effects (Region 3) conditional on the phase of NAO during winter
   - Arctic Atlantic AR's regional effects (Region 4) conditional on the phase of AO during winter

Result 4: Arctic Pacific AR's regional effects conditional on the phase of PNA during winter (composite analysis of major AR events in Region 2 based on 95th IVT in ERA5)

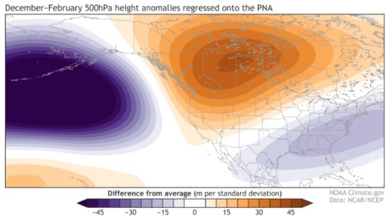
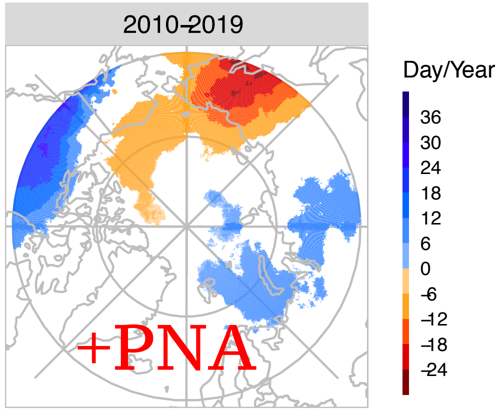
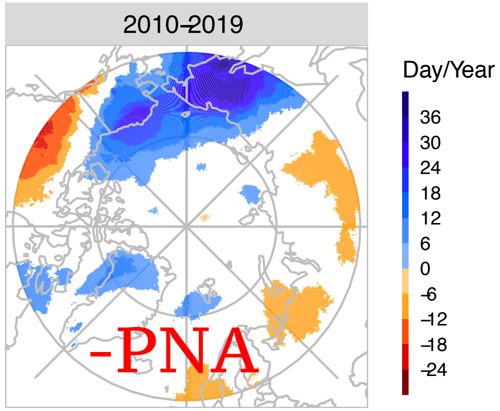
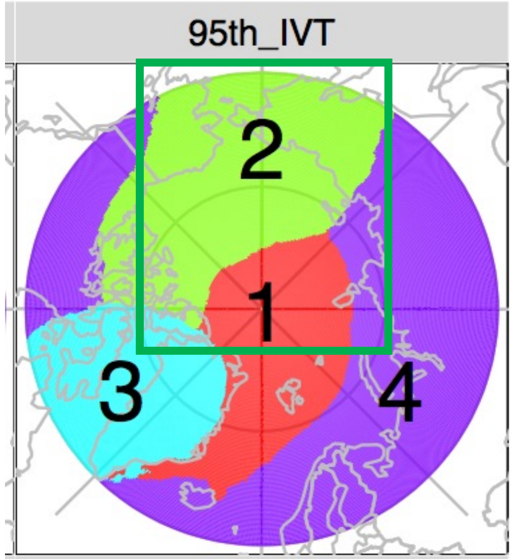


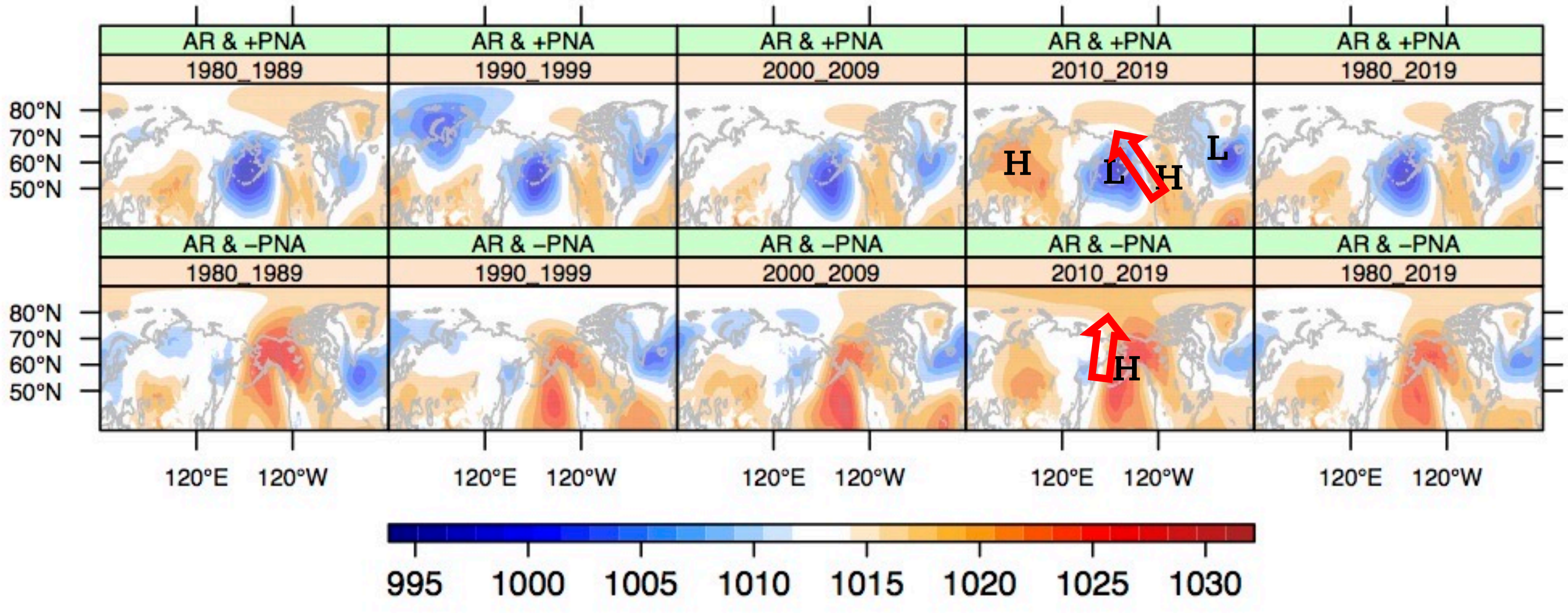
Figure source :
NOAA Climate gov.





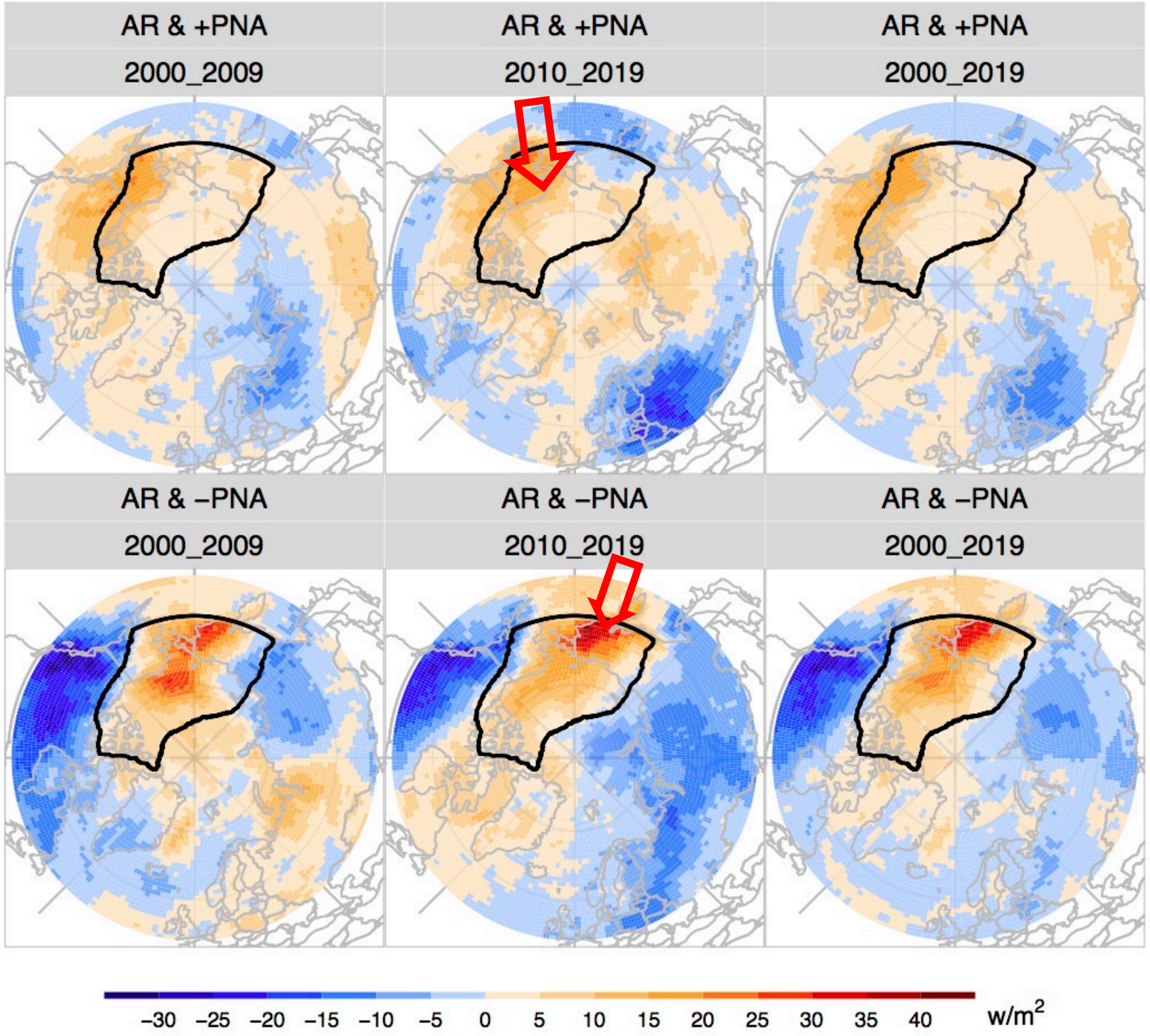


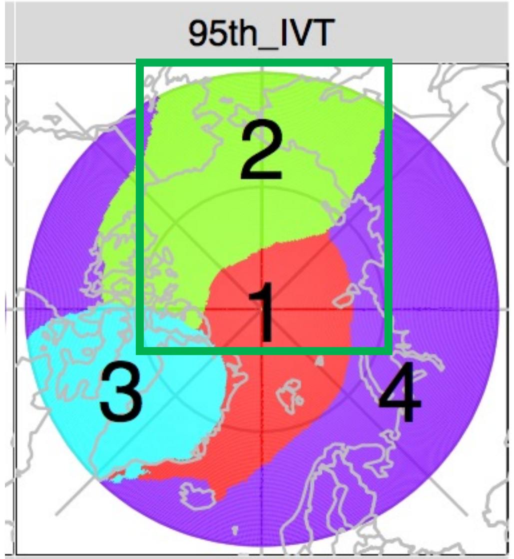
(a): Sea Level Pressure (unit: hPa)



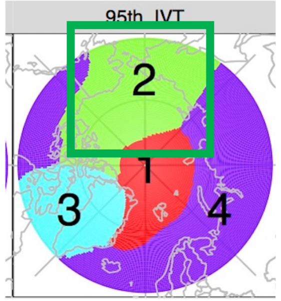
Result 4: Arctic Pacific AR's regional effects conditional on the phase of PNA during winter (composite analysis of major AR events in Region 2 based on 95th IVT in ERA5)

(b): surface downward LW radiation anomalies
(unit: w/m2)

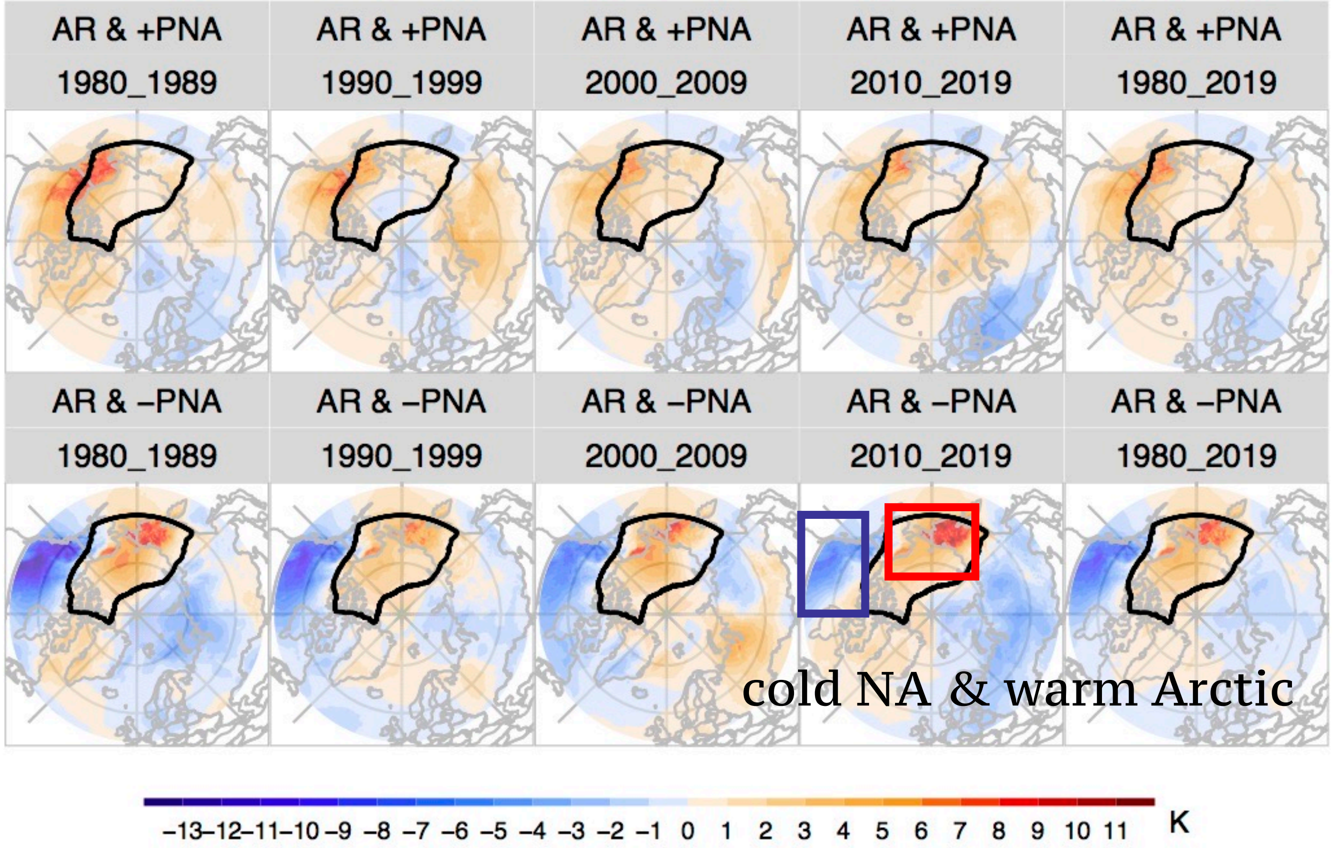




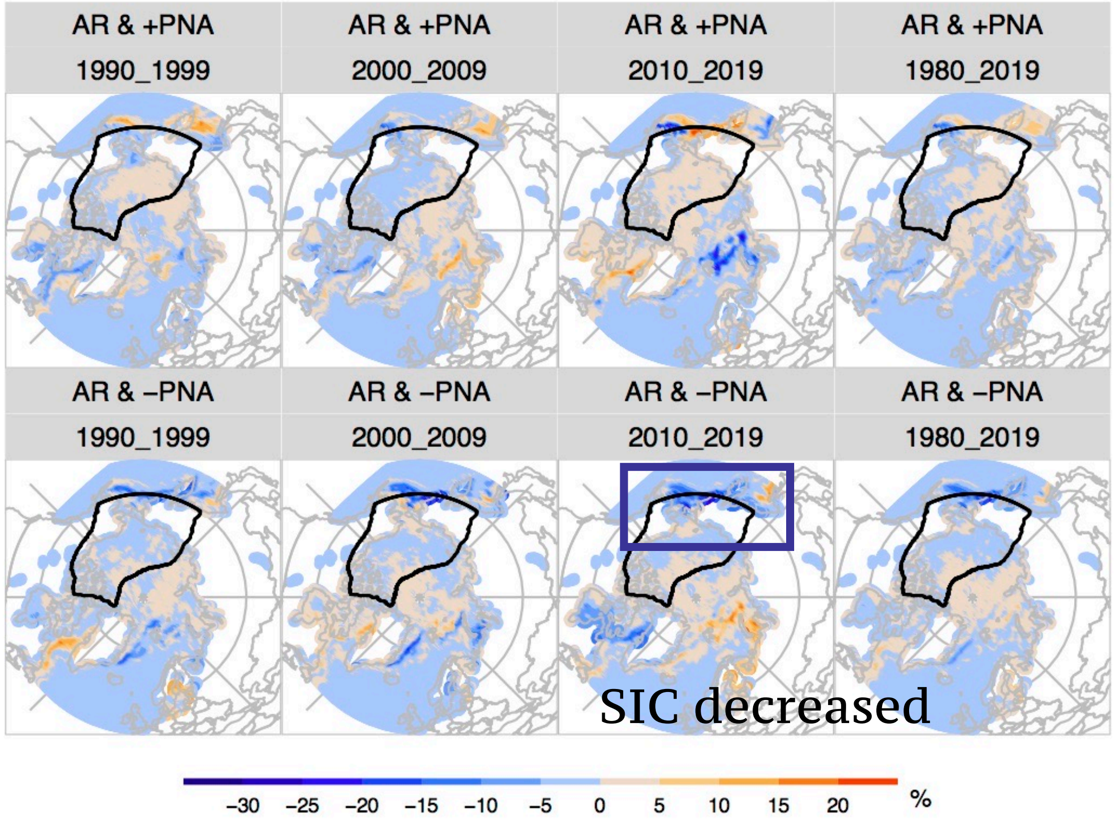
Result 4: Arctic Pacific AR's regional effects conditional on the phase of PNA during winter (composite analysis of major AR events in Region 2 based on 95th IVT in ERA5)



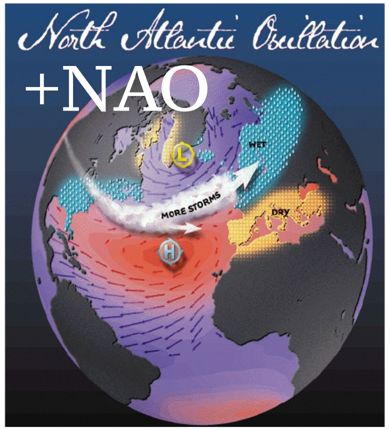
(c): surface T2m anomalies (unit: K)

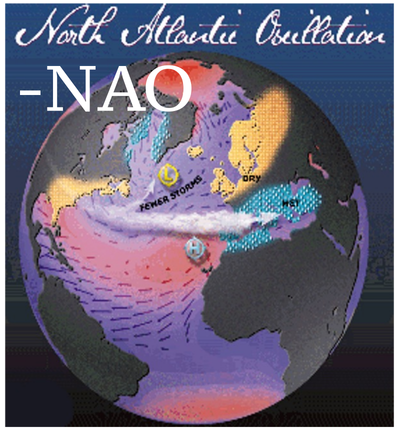


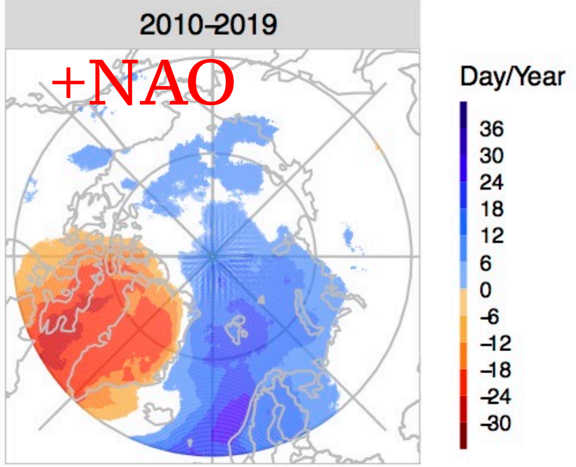
(d): SIC anomalies (unit: %)

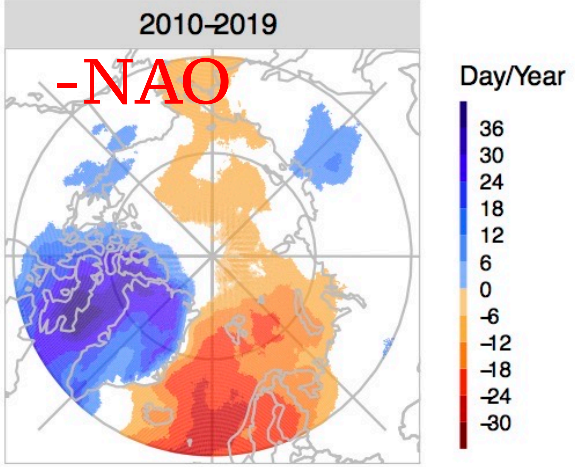


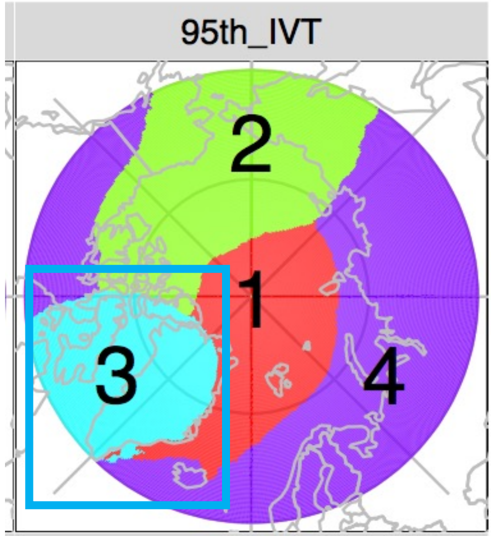
Result 5: Northeast Canada/Greenland AR's regional effects conditional on the phase of NAO During winter (composite analysis of major AR events on the region 3 based on 95th IVT in ERA5)



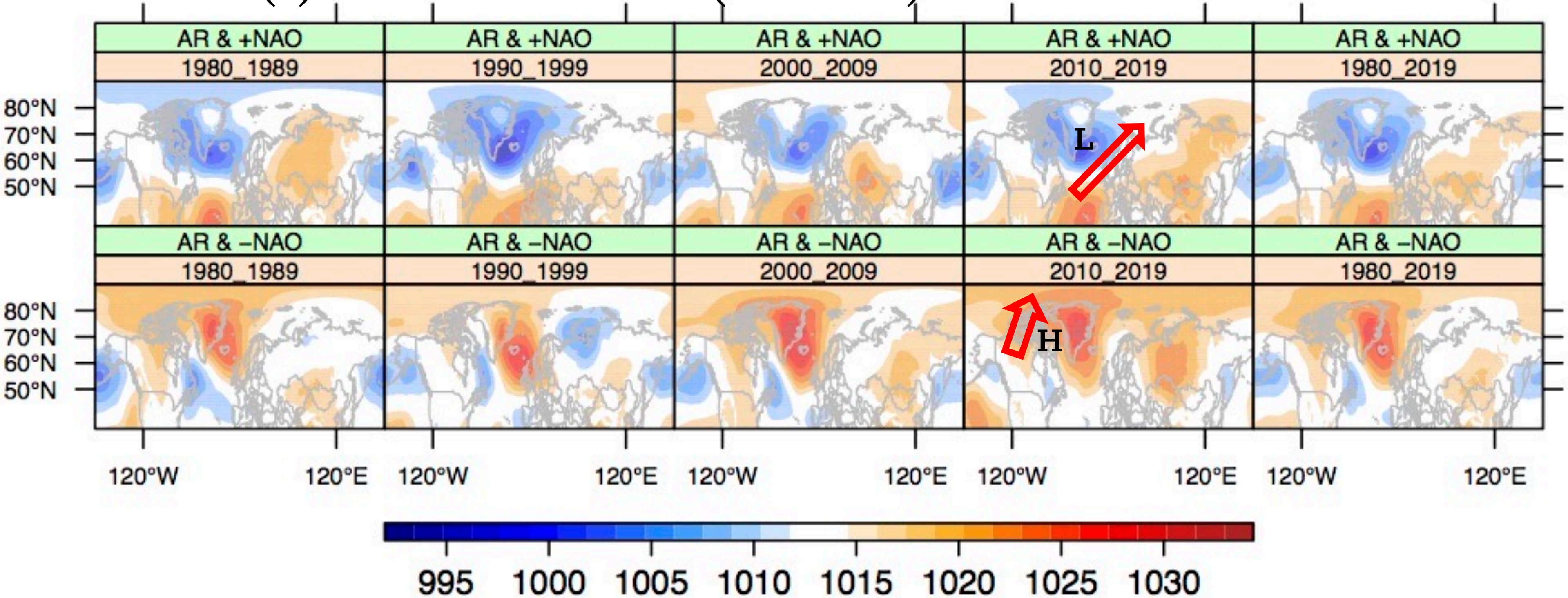






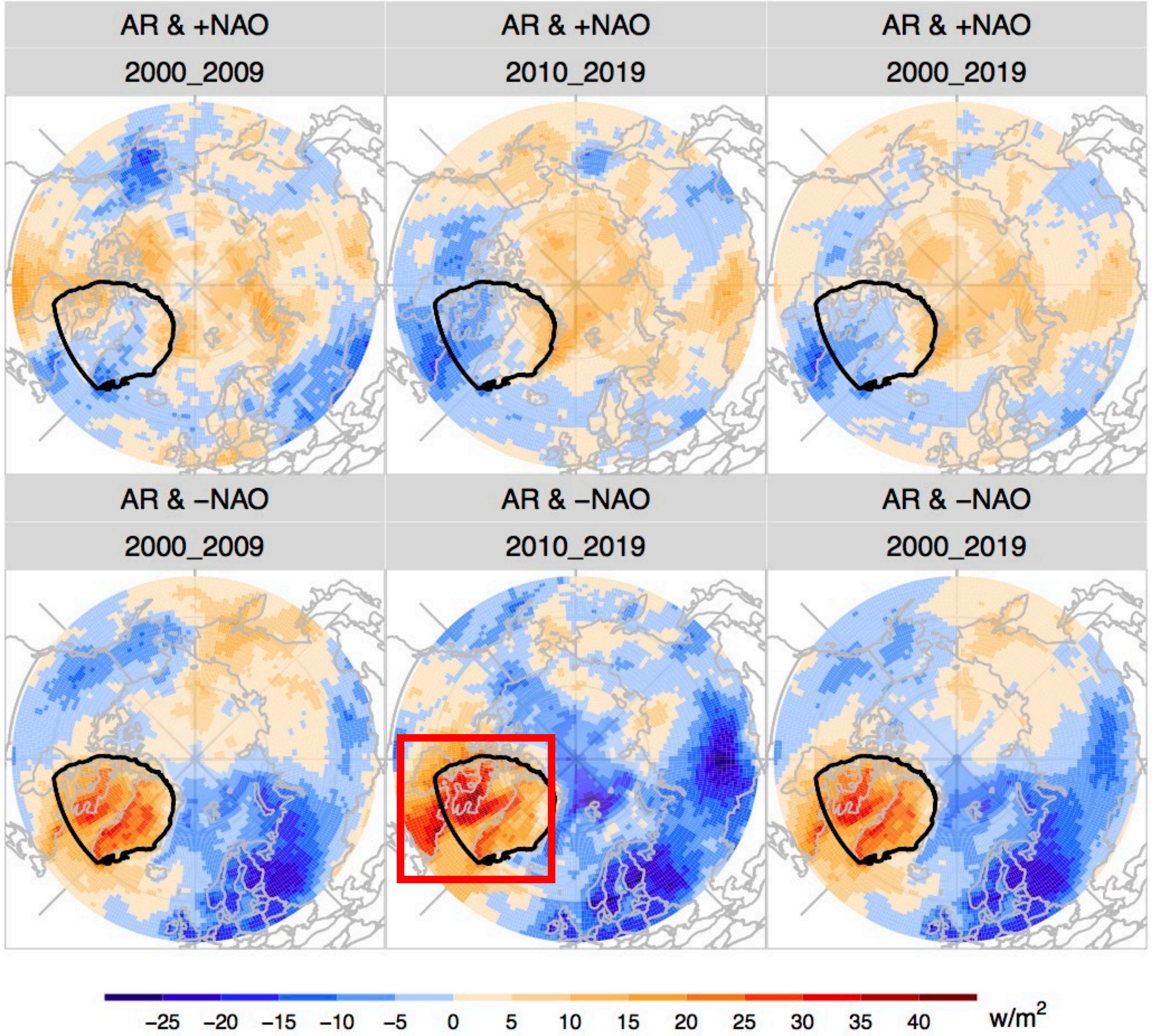


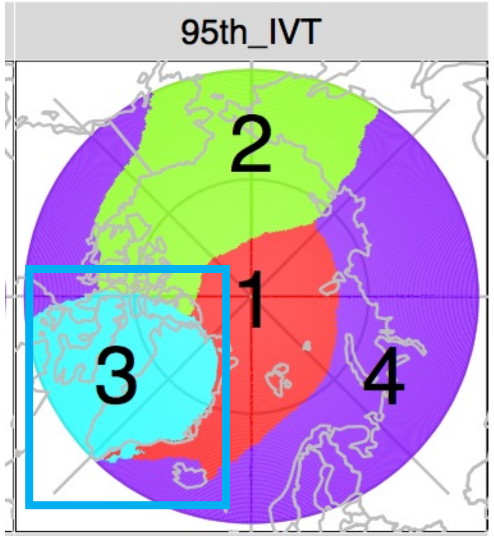
(a): Sea Level Pressure (unit: hPa)



Result 5: Northeast Canada/Greenland AR's regional effects conditional on the phase of NAO During winter (composite analysis of major AR events on the region 3 based on 95th IVT in ERA5)

(b): downward longwave radiation anomalies
(unit: W/m2)





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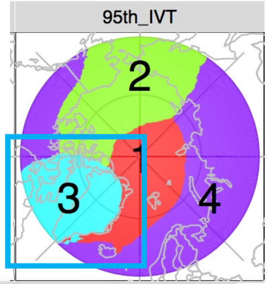
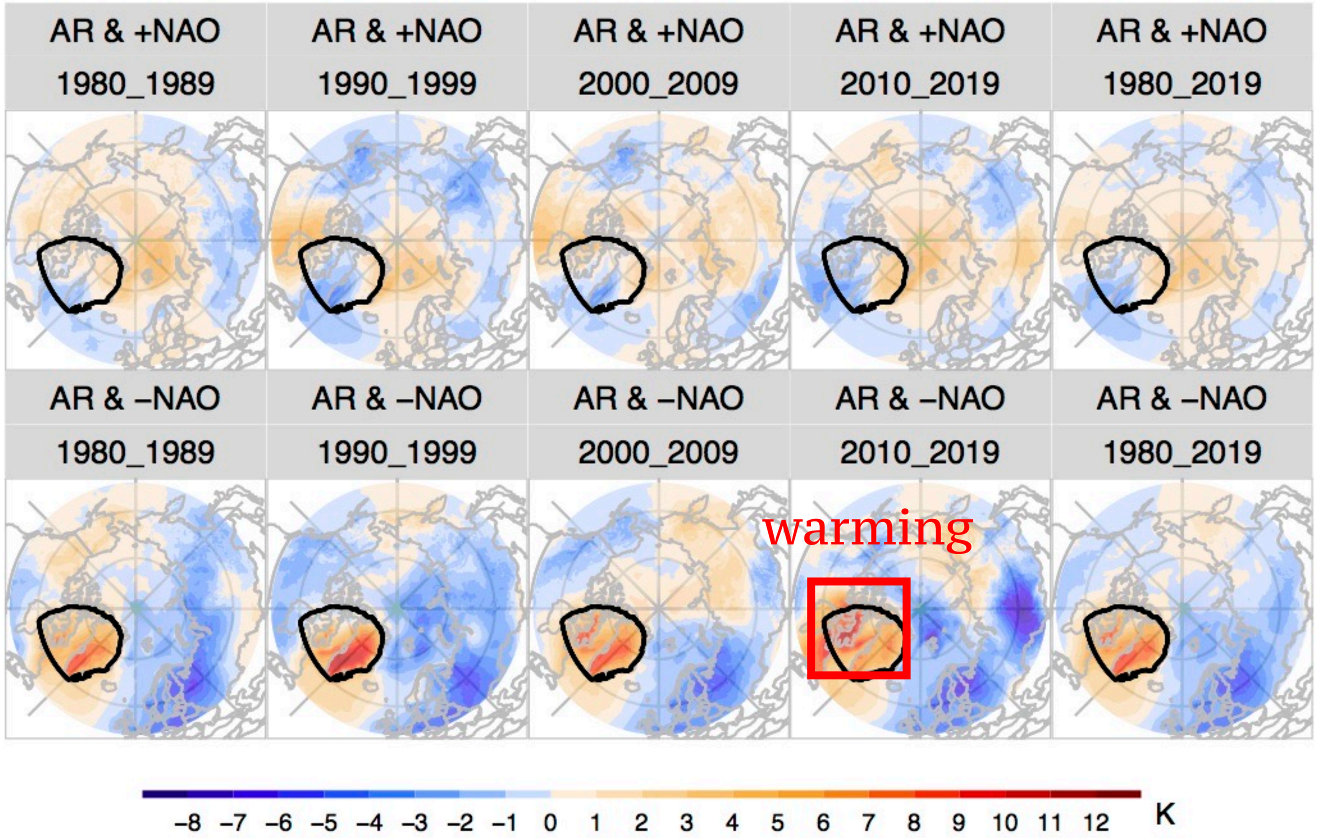
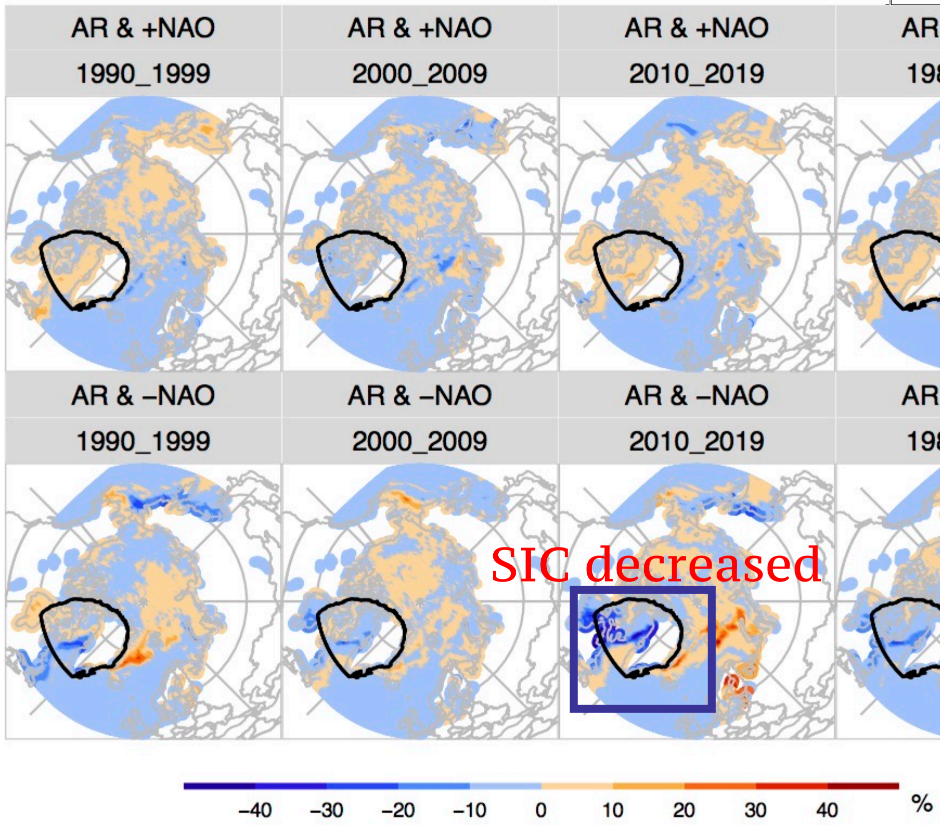


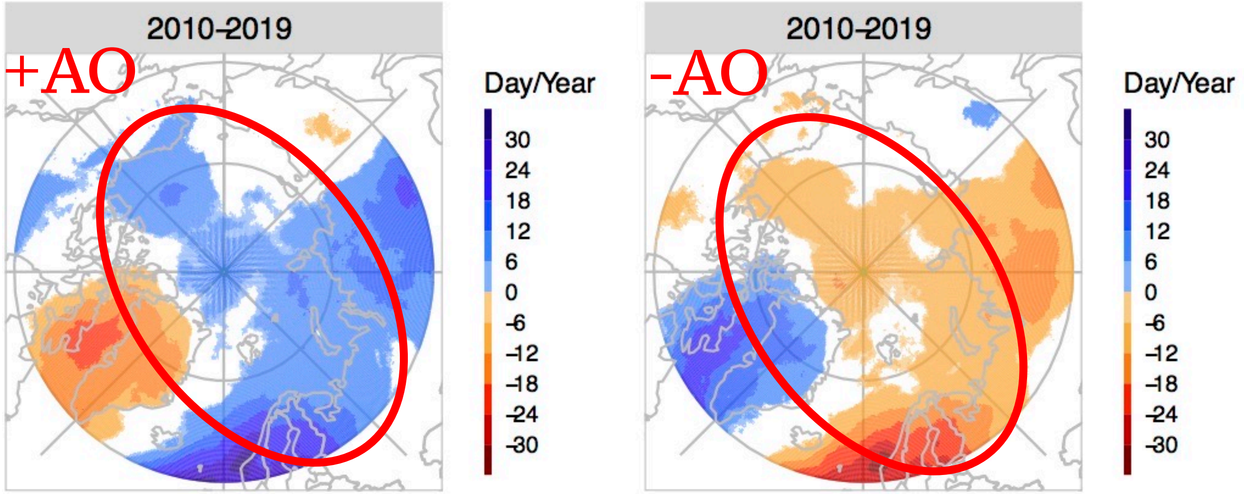
(c): surface T2m anomalies (unit: K)



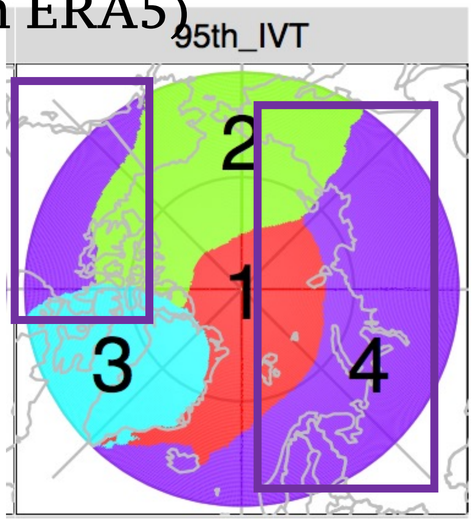
(d): SIC anomalies (unit: %)



Result 6: Arctic Atlantic AR's regional effects conditional on the phase of AO during winter (composite analysis of major AR events on the Region 4 based on 95th IVT in ERA5)



Results of spatial clustering analysis of AR occurrence reflected the modulation of teleconnection patterns.



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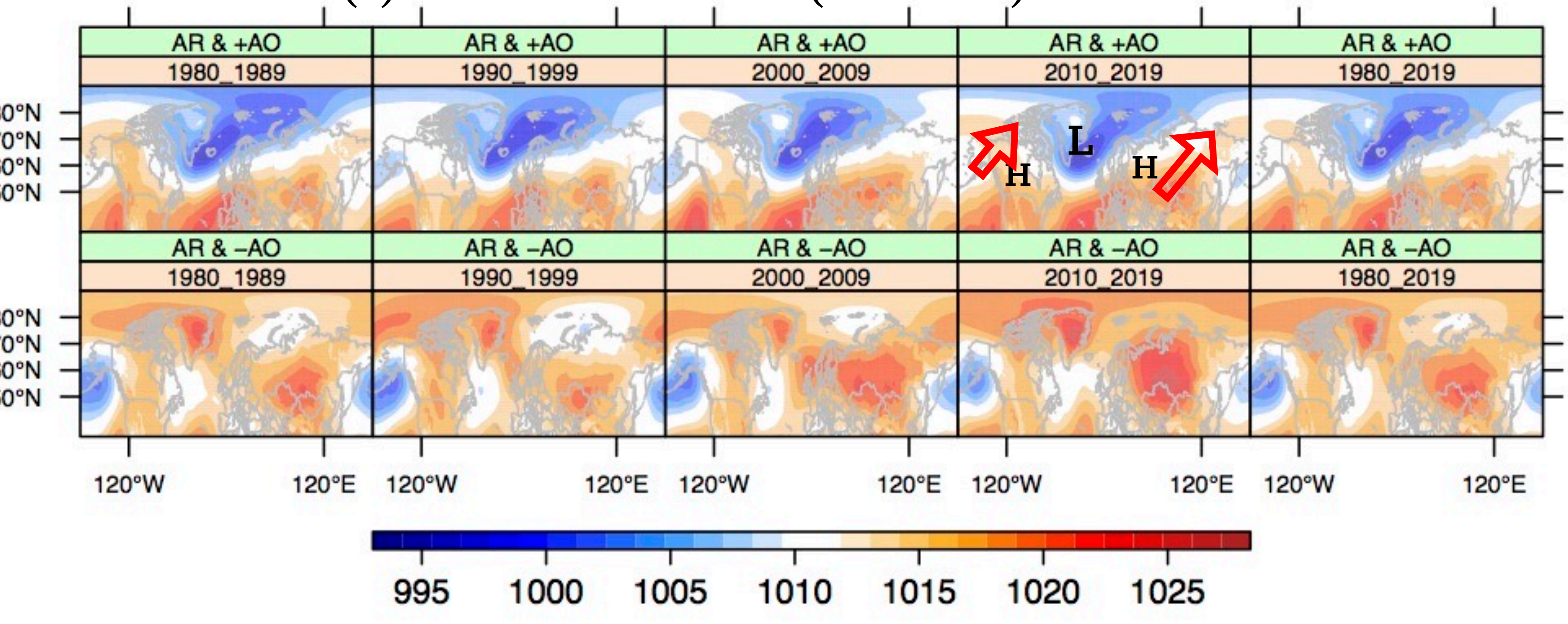
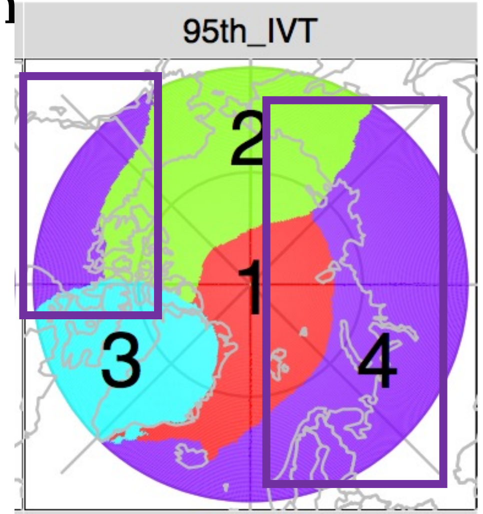


Result 6: Arctic Atlantic AR's regional effects conditional on the phase of AO during winter (composite analysis of major AR events on the Region 4 based on 95th IVT in



(b): surface downward LW radiation anomalies
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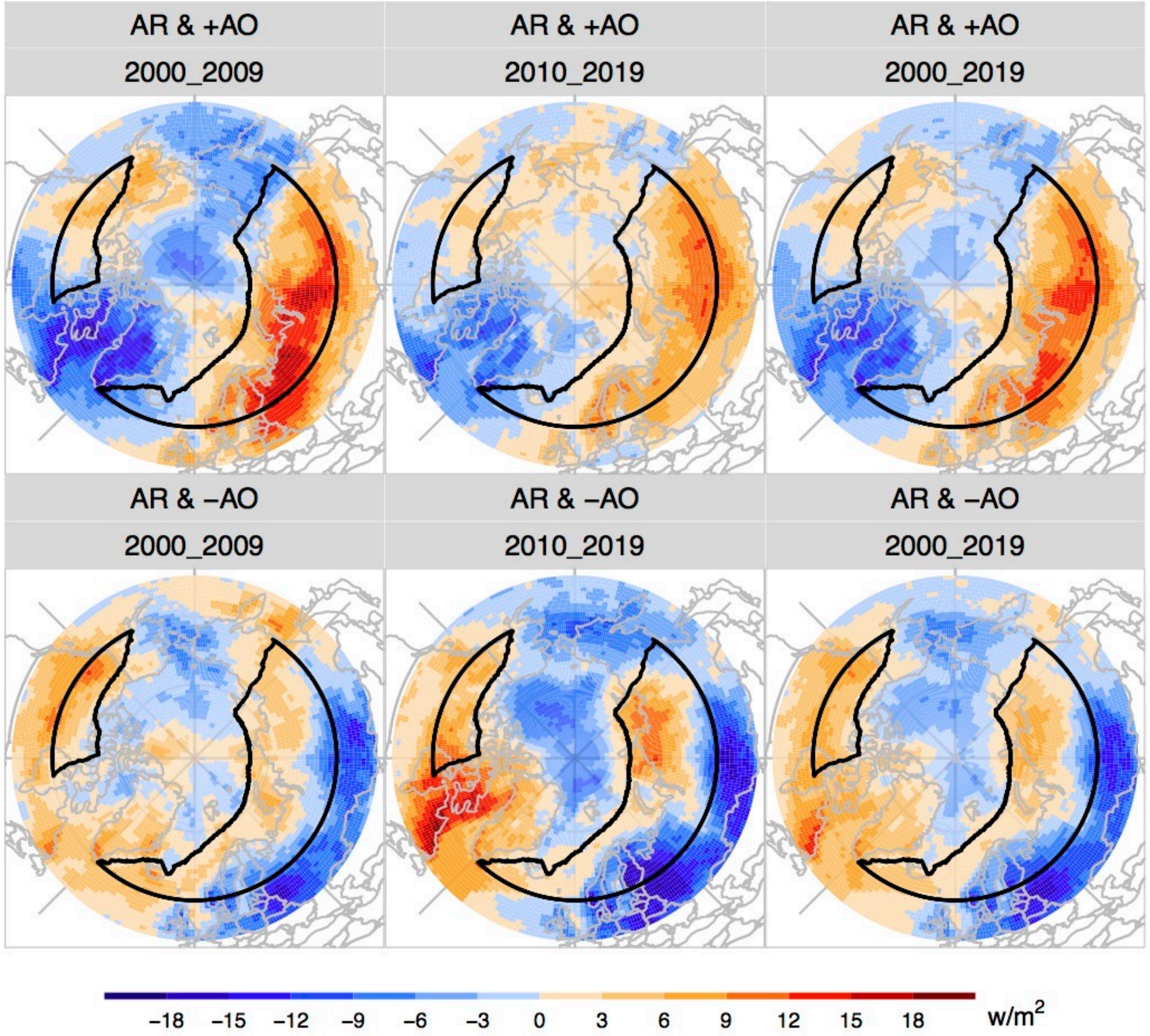

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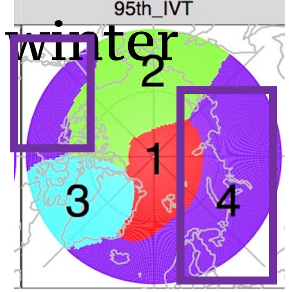
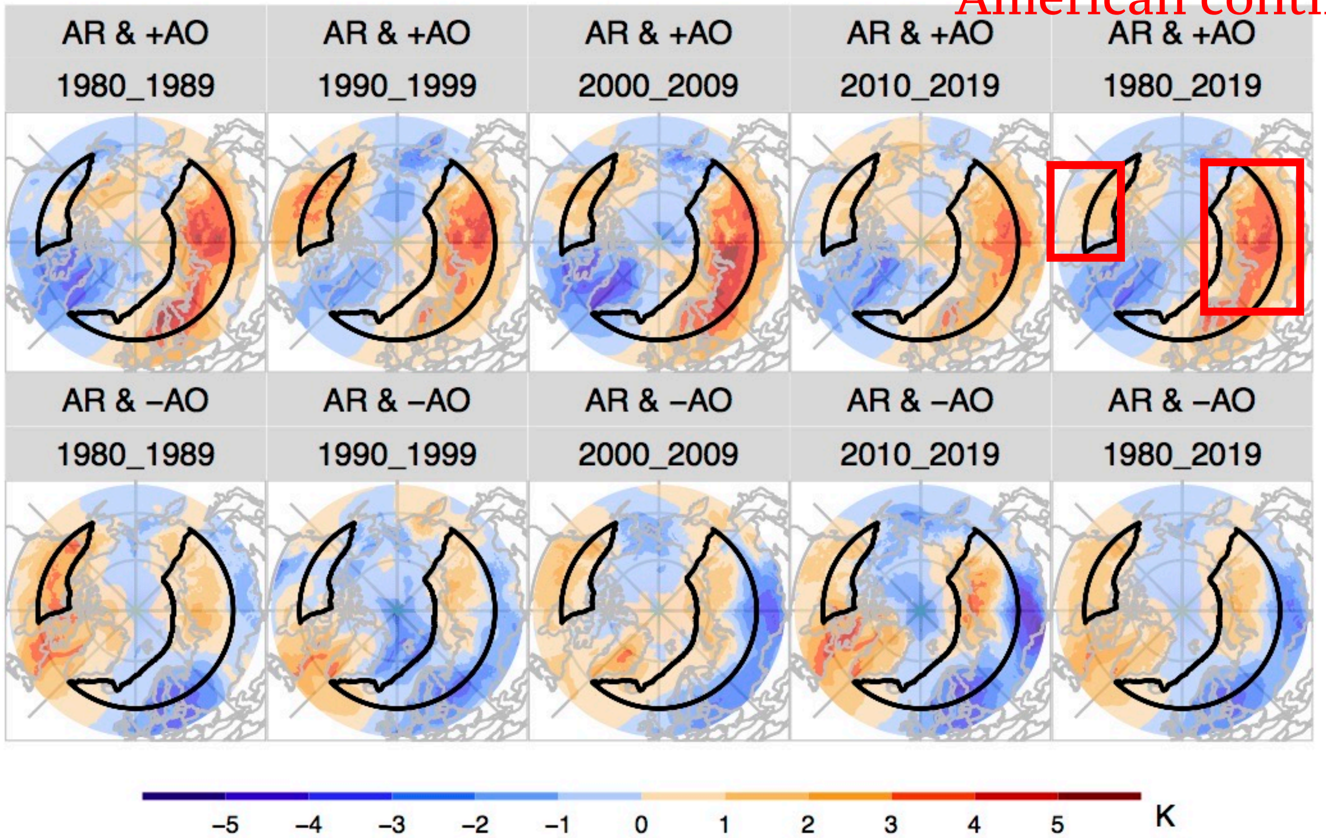
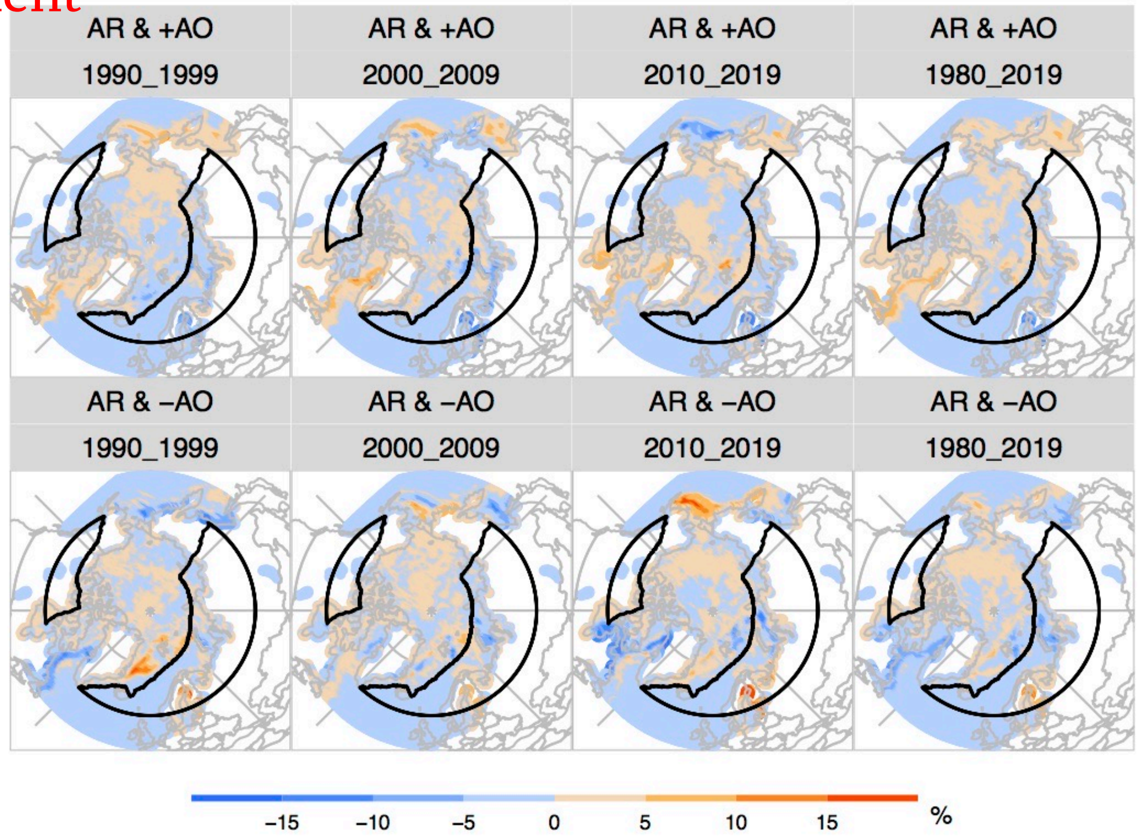


(c): surface T2m anomalies (unit: K)

warm Eurasian and North American continent



(d): SIC anomalies (unit: %)



Conclusions

1. Arctic ARs detected by 12 MERRA-2- and ERA5-based indices have consistent climatology
   - Increased AR over the Arctic regions from the Pacific, across the Arctic, to the Atlantic side in the recent 20 years, coinciding with sea ice retreat

   (The range of mean AR occurrence frequency: 38-107 days/year (75^{th} –based indices), 16-67 days/year (85^{th} –based indices), 3-23 days/year (95^{th} –based indices)).
   - AR's proportion of increasing poleward moisture transport also increased

   (The range of AR's contribution to poleward moisture transport: 18%-79% (75^{th} –based indices), 9%-67% (85^{th} –based indices), 1%- 37% (95^{th} –based indices)).
2. AO, NAO, & PNA strongly modulate regional AR activities, with strongest signals in north Atlantic and Pacific sectors
   - Consistent with AR spatial recurrence from K-mean clustering analysis with all 12 indices
3. Synoptic circulations associated with teleconnection patterns, jet stream, and storm track modulated major AR events into the Arctic according to the 95^{th} IVT-based index in ERA5 and MERRA-2.
   - Accompanied with ARs, enhanced warming and moistening, increased downward longwave radiation, and associated sea ice concentration decline were observed.
   - During -PNA, Arctic Warming-North America Continent cooling.
   - During –NAO, Northeast Canada/Greenland warming
   - During +AO, North America-Eurasian warming simultaneously.

Thank you!
Questions?

Result 3a: AR frequency anomalies are modulated by the teleconnection patterns
Arctic Oscillation (AO)

+AO: jet stream is shifted north,
so are storm tracks

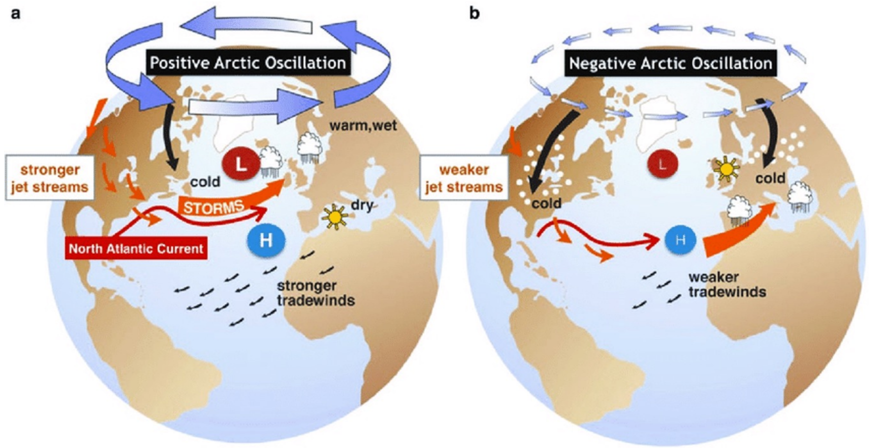
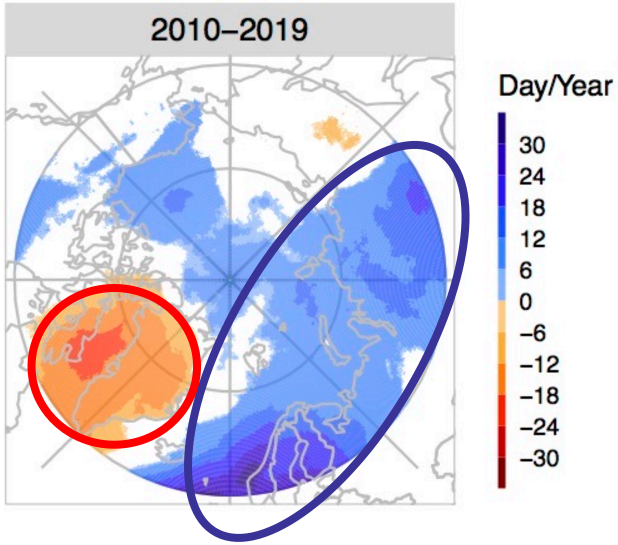


Figure source : Campos and Horn, 2018

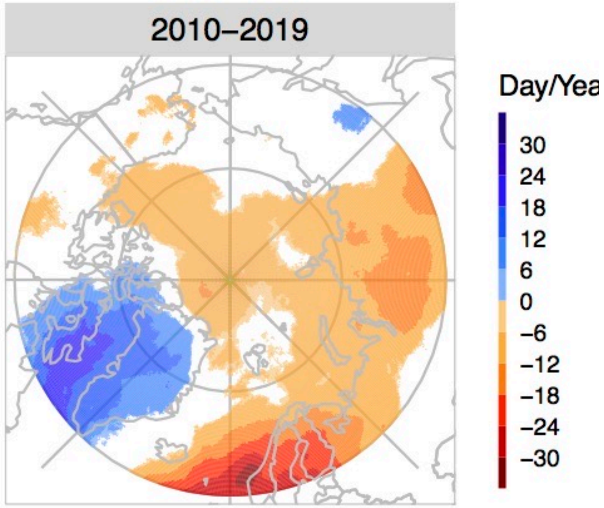
ERA5 85th IVT

MERRA-2 85th IVT

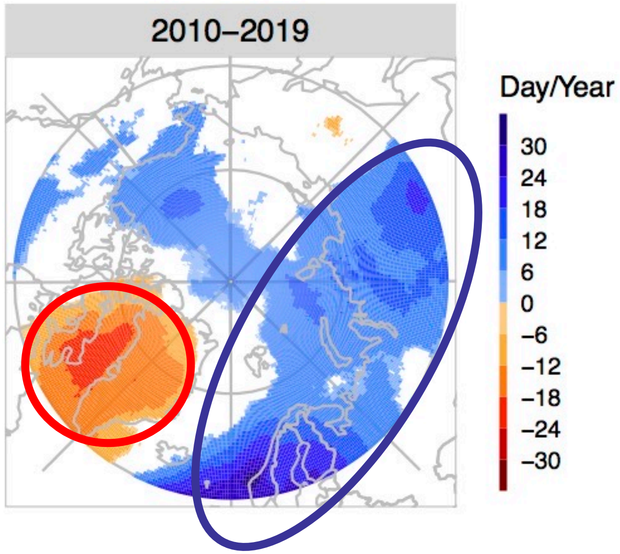
+AO



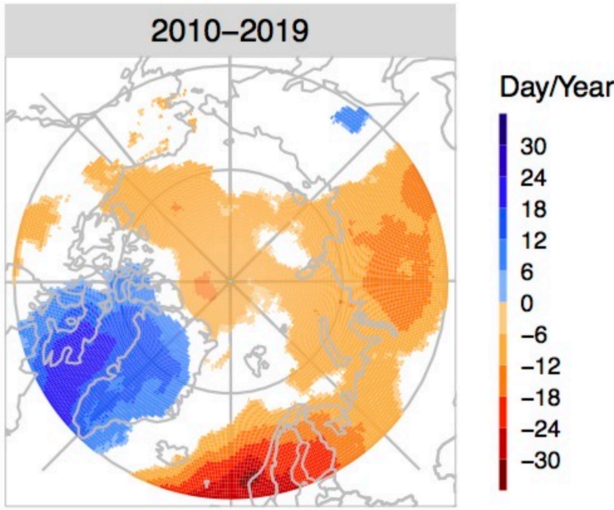
-AO



+AO



-AO



Only values within 95% confidence interval are shown

Result 3b: AR frequency anomalies are modulated by the teleconnection patterns

North Atlantic Oscillation (NAO)

+NAO: jet stream and storm tracks associated with Icelandic Low moved northward

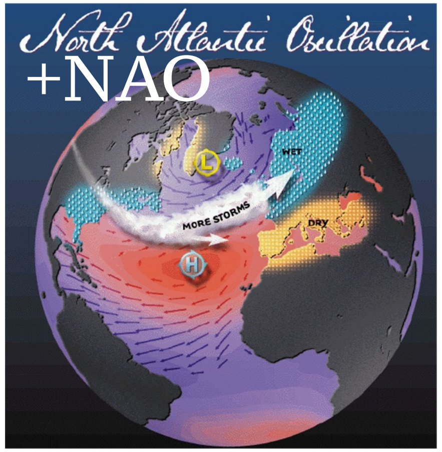
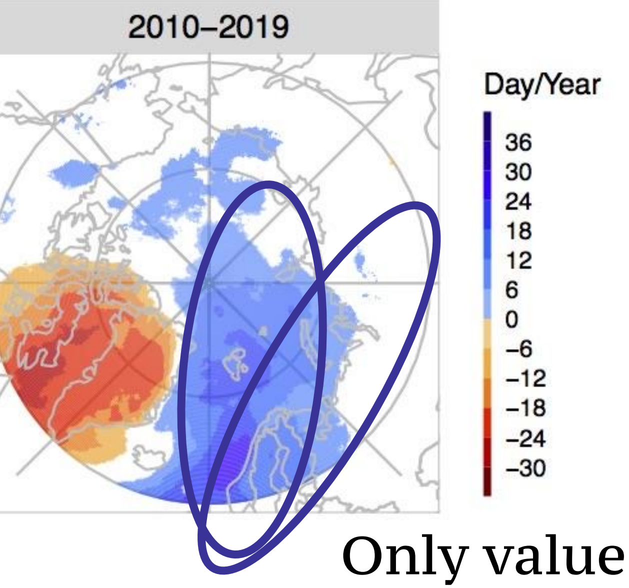


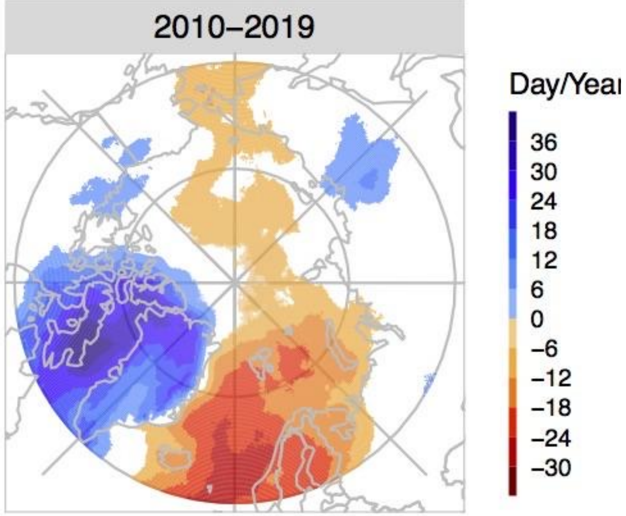
Figure source : https://www.ldeo.columbia.edu/res/pi/NAO/

ERA5 85th IVT

+NAO

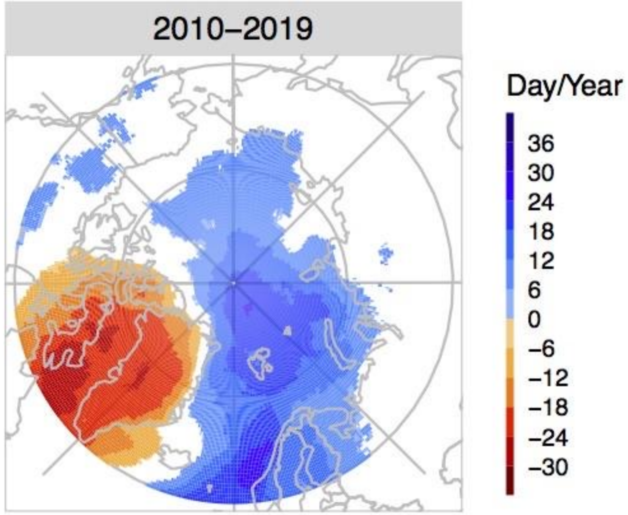


-NAO

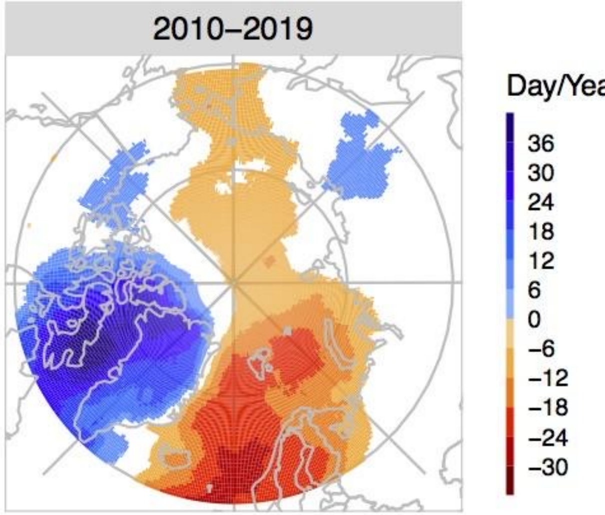


MERRA-2 85th IVT

+NAO



-NAO

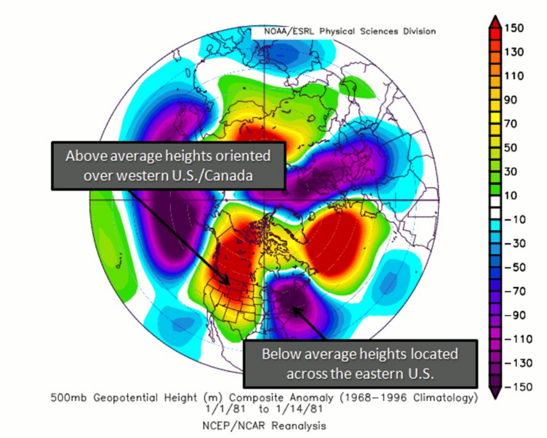


Only values within 95% confidence interval are shown

Result 3c: AR frequency anomalies are modulated by the teleconnection patterns

Pacific North America (PNA)

+PNA: anomalous high/low over central Canada/Aleutian Islands



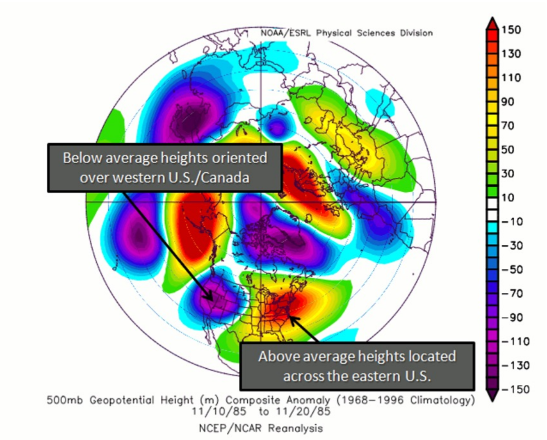
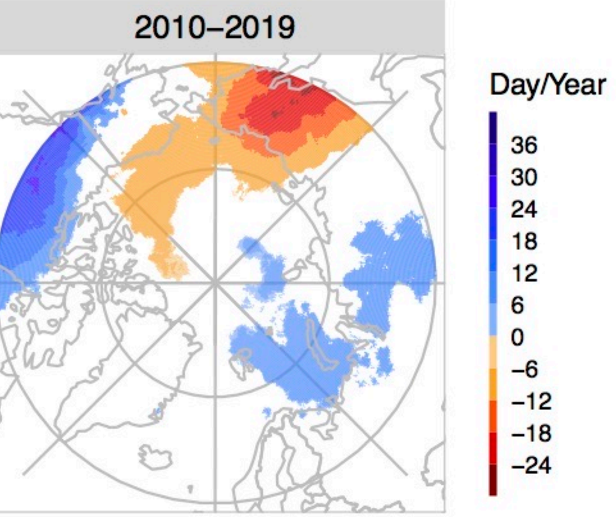


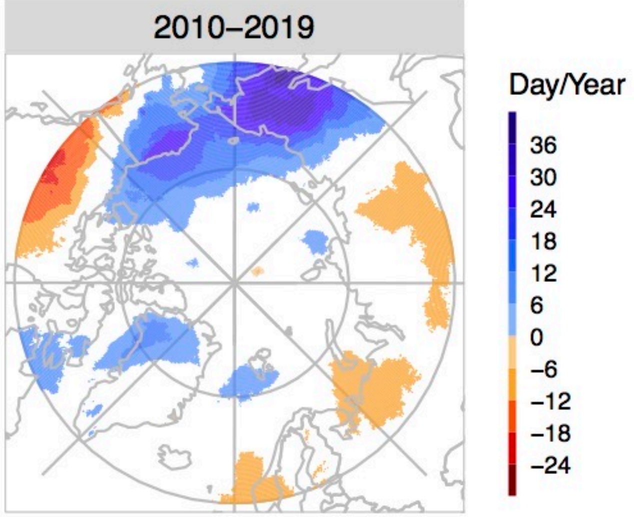
Figure source : North Carolina Climate Office: https://legacy.climate.ncsu.edu/climate/patterns/pna

ERA5 85th IVT

+PNA

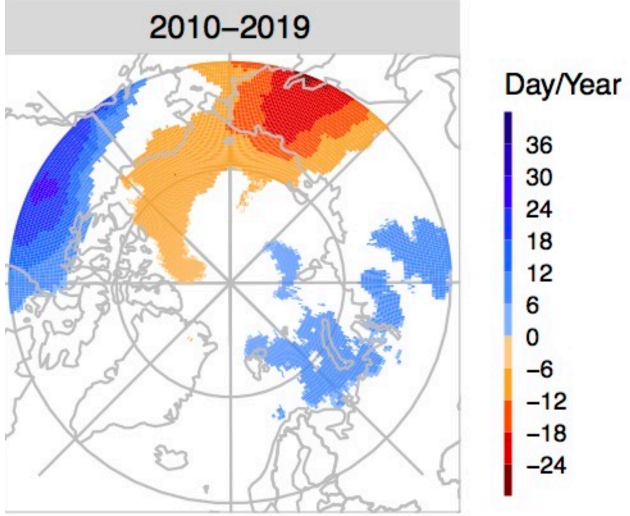


-PNA



MERRA-2 85th IVT

+PNA



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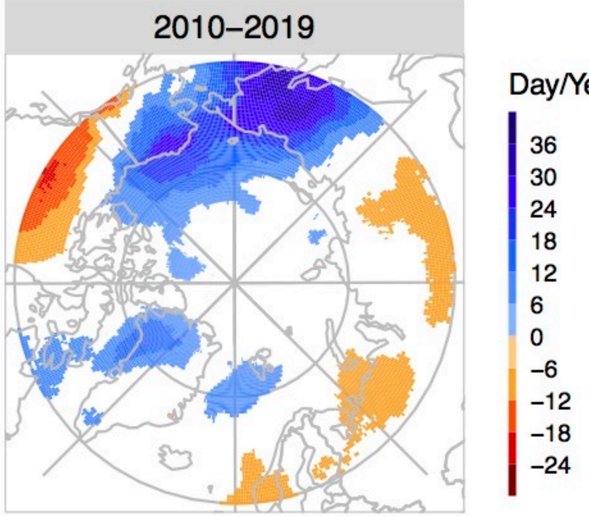
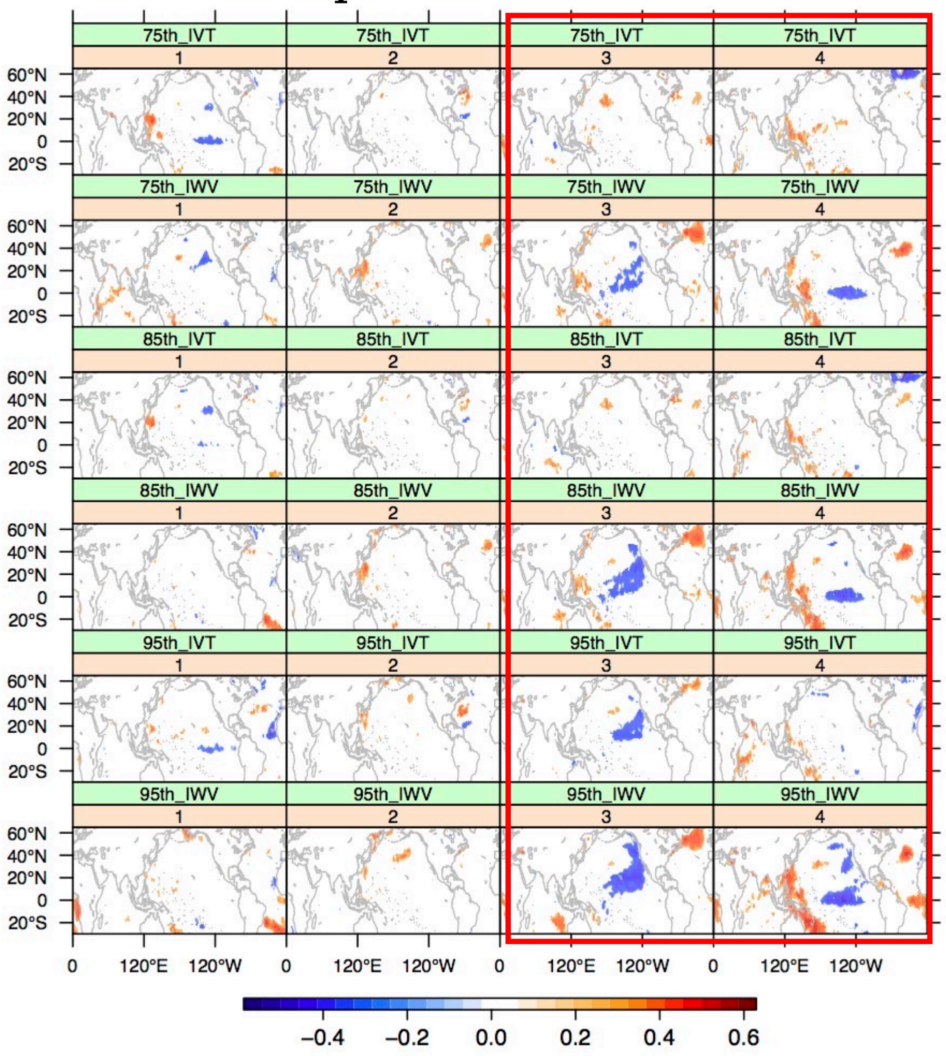


Only values within 95% confidence interval are shown

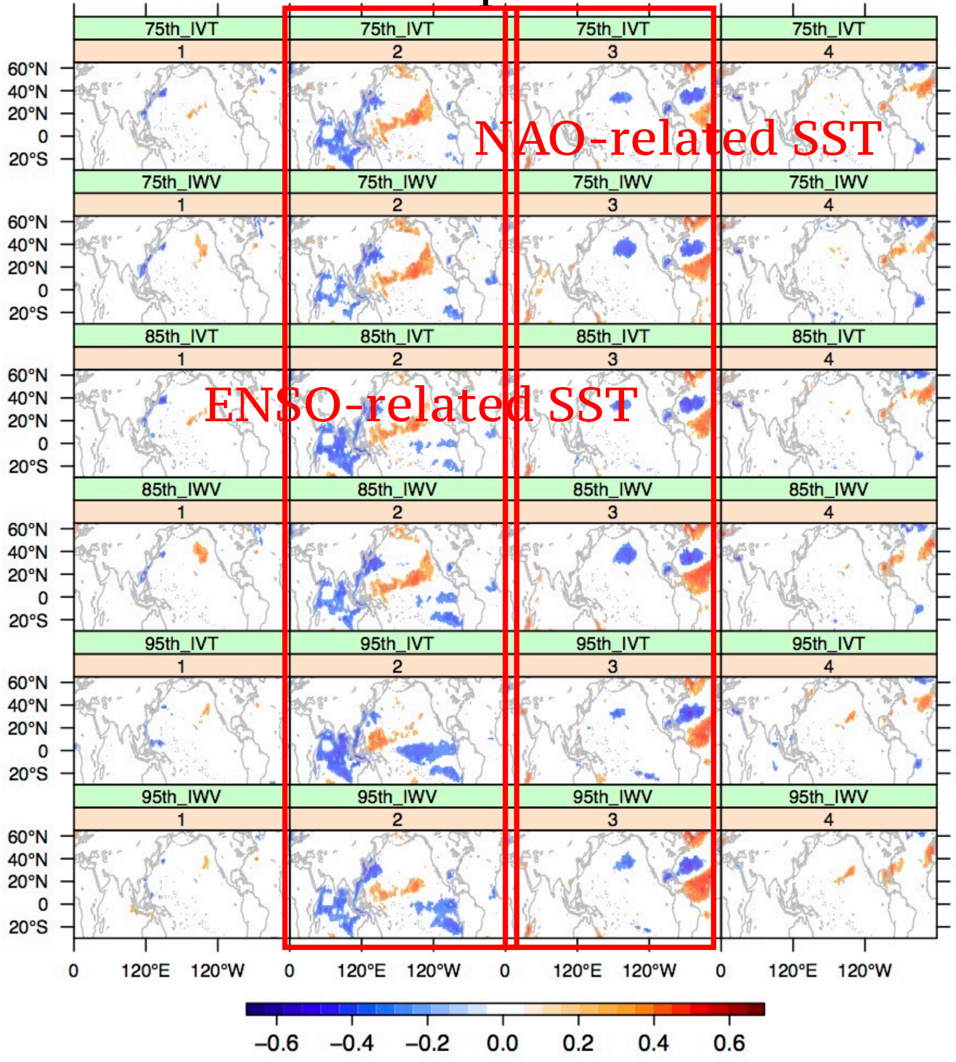
Ongoing work: The Tropical Excited Arctic warming Mechanism, TEAM
(e.g., Lee et al., 2012, 2014).

Observed AR SST pattern in the divided four regions, derived by regressing the detrended SST anomalies on the observed detrended AR frequency in each region from 1980 to 2019 based on the 6 AR indices in ERA5. Only regression values within the 95% confidence interval are shaded.

AR SST pattern in summer



AR SST pattern in winter



Ongoing work:

- ARs over Arctic Pacific was associated with ENSO-related SST pattern in the tropics
  - Planetary waves serve as an effective mechanism for moisture transport from the tropics and maintain Arctic warming (the Tropical Excited Arctic warming Mechanism, TEAM (e.g., Lee et al., 2012, 2014).
  - In our finding, ARs are accompanied by teleconnection patterns, which may serve as an essential role in communicating the changes in the tropics to those in the Arctic.