ИНСТИТУТ ФИЗИКИ АТМОСФЕРЫ ИМ. А.М. ОБУХОВА РАН

70 ЛЕТ

1956 – 2026

Warmest Congratulations on the 70th Anniversary of IAP RUS!

Long-term changes in Northern Hemisphere marine cold air outbreaks during boreal winter

Lin Wang

Institute of Atmospheric Physics, Chinese Academy of Sciences

A.M. Obukhov Institute of Atmospheric Physics Russian Academy of Sciences

Email: wanglin@mail.iap.ac.cn

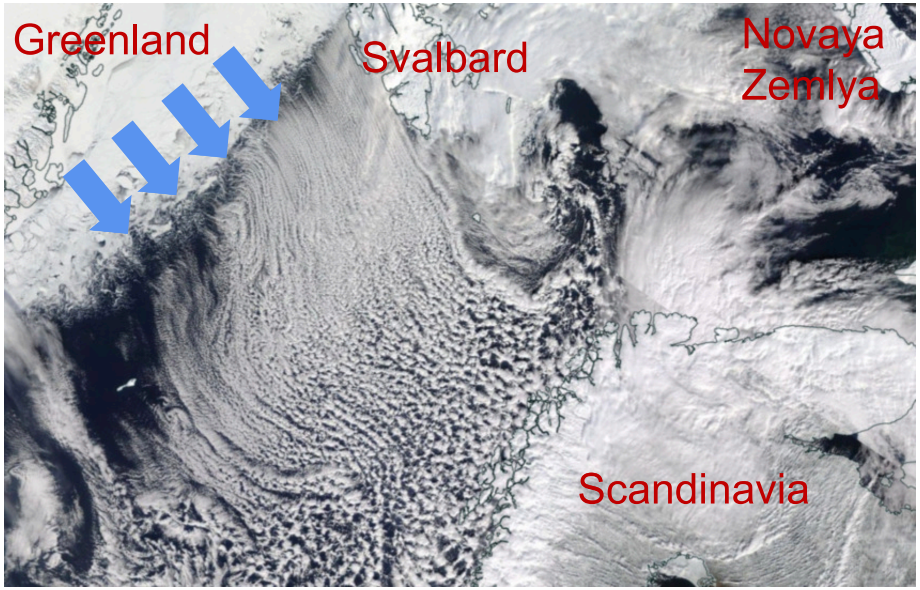
Outline

- Introduction
- Long-term trends and the underlying mechanism
- Interannual variability over the North Atlantic
- Summary

Marine cold air outbreak (MCAO)

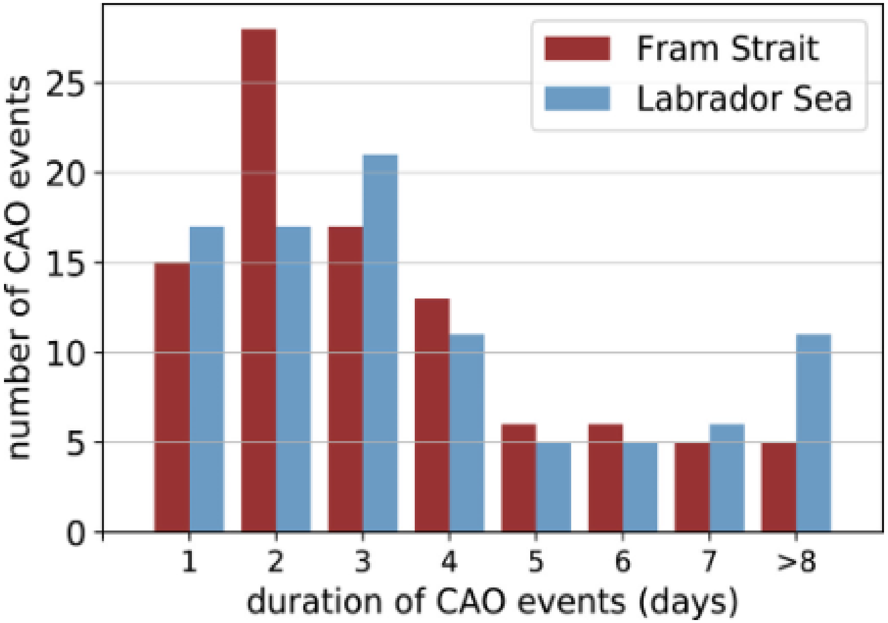
- Rapid movement of extremely cold, dry air from ice-covered or continental regions over relatively warm, open ocean waters.
- Synoptic phenomena with a median duration of ~2.5 days.
- Often associated with fronts and extratropical cyclones.

Clouds during a MCAO in March 2020



From NASA

Distribution of MCAO's duration

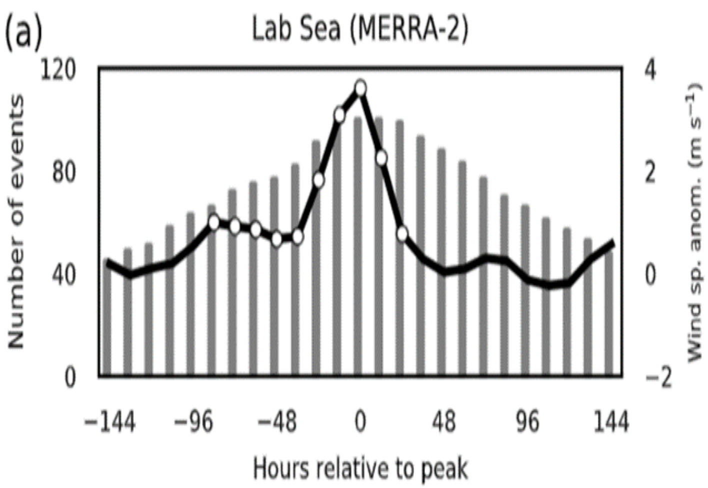


Terpstra et al. (2021)

Significance in the climate system

- Cause intense air-sea interaction via releasing turbulent heat flux.
  - Cool and salt the upper ocean
  - Heat and moisten the atmospheric boundary layer

Wind speed during MCAOs

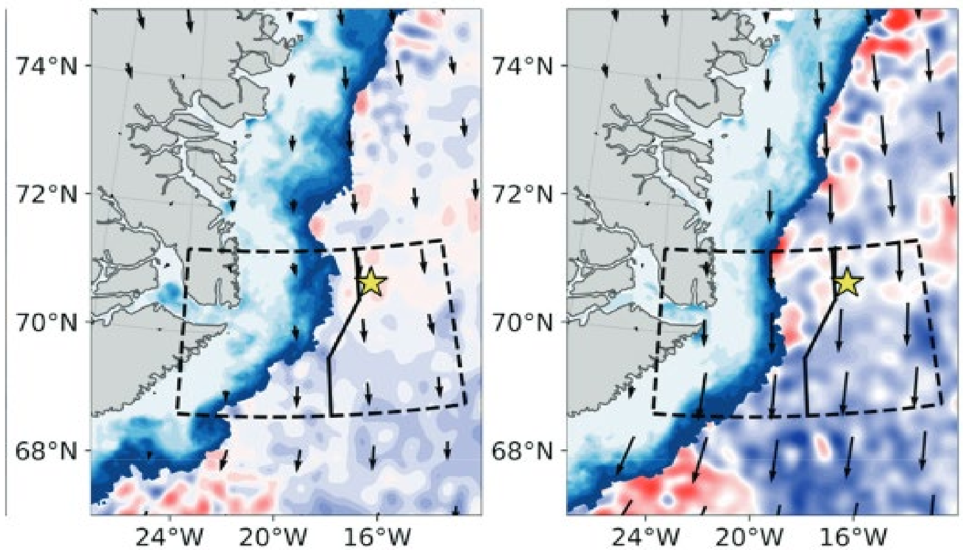


Kolstad et al. (2017)

SST during a MCAO

Before

After

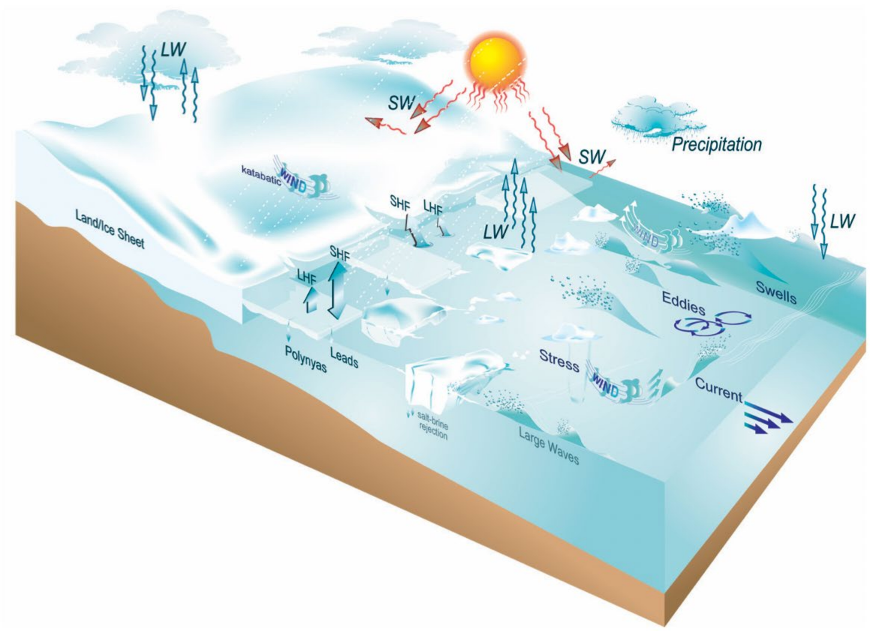


Renfrew et al. (2023)

Significance in the climate system

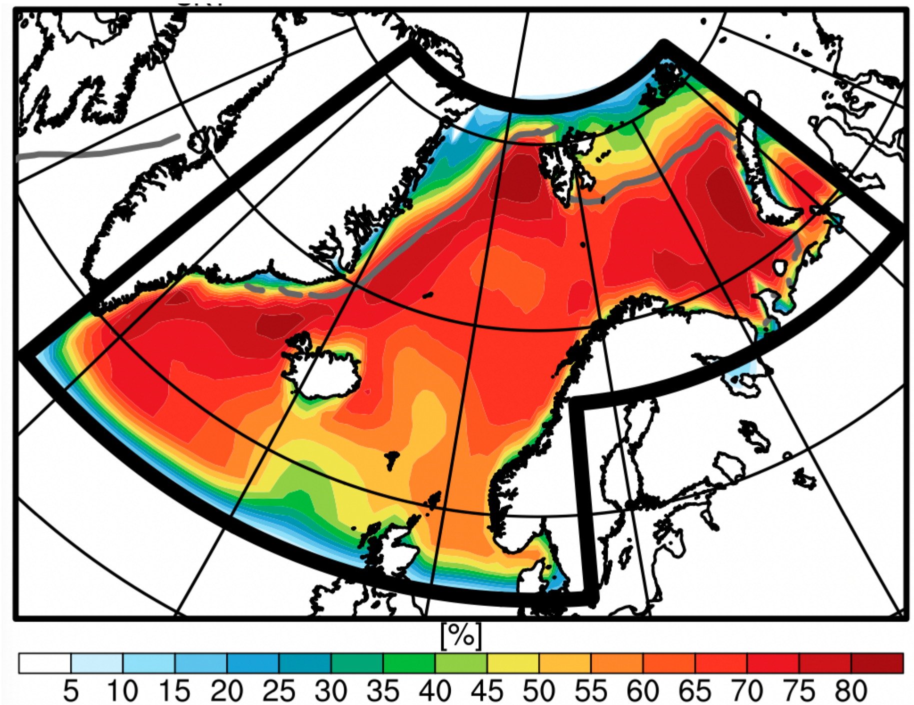
- MCAOs explain a large portion of high-latitude turbulent heat flux, which is highly sporadic

Schematic of surface fluxes and related processes for high latitudes



Bourassa et al. (2013)

Percentage of MCAO-related upward THF



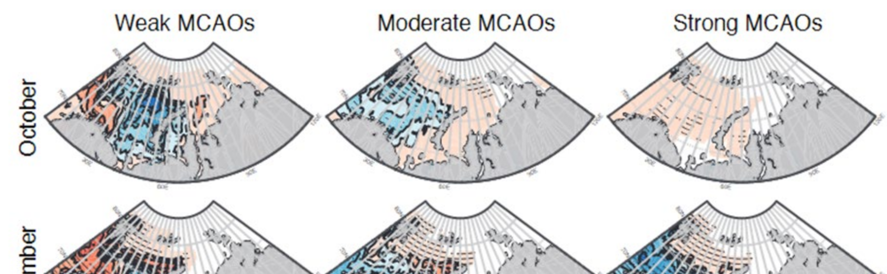
Papritz & Spengler (2017)

Possible changes with global warming

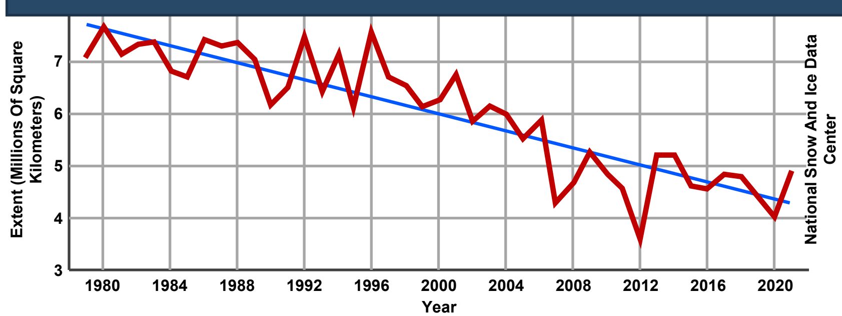
- Competing effects by declining Arctic sea ice & Arctic Amplification
  - Polar air is less cold: Weaker & less MCAO
  - More open water & wavy atmos. circulation: Stronger & more MCAO

Arctic sea ice extent

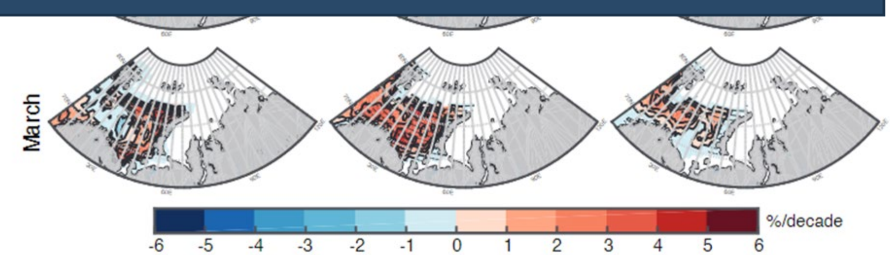
Trends of MCAO frequency



- How do MCAOs change during the past decades?
- What is the underlying mechanism?



From NSIDC

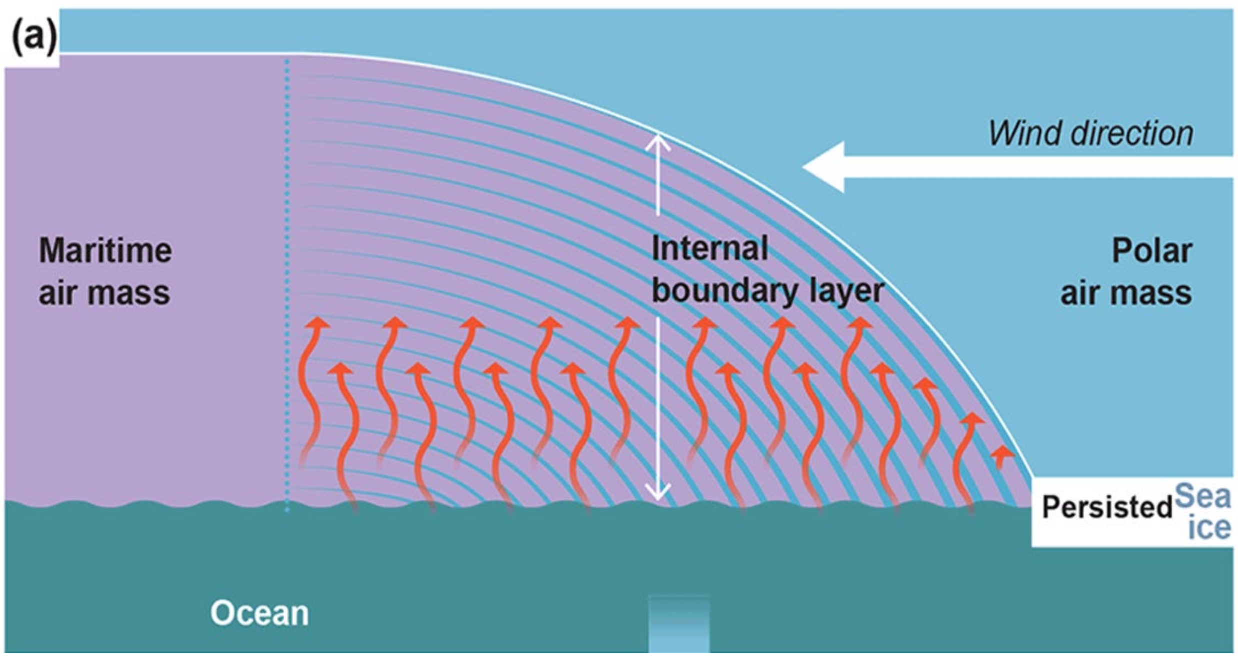


Narizhnaya et al. (2020)

Identification of MCAO in ERA5 data (1979-2020)

- MaCAO index: $M = \theta_{SST} - \theta_{850hPa}$
- Four categories:
  - Weak: $0 < M \leq 4$
  - Moderate: $4 < M \leq 8$
  - Strong: $8 < M \leq 12$
  - Very strong: $12 < M$

Schematic of MCAOs

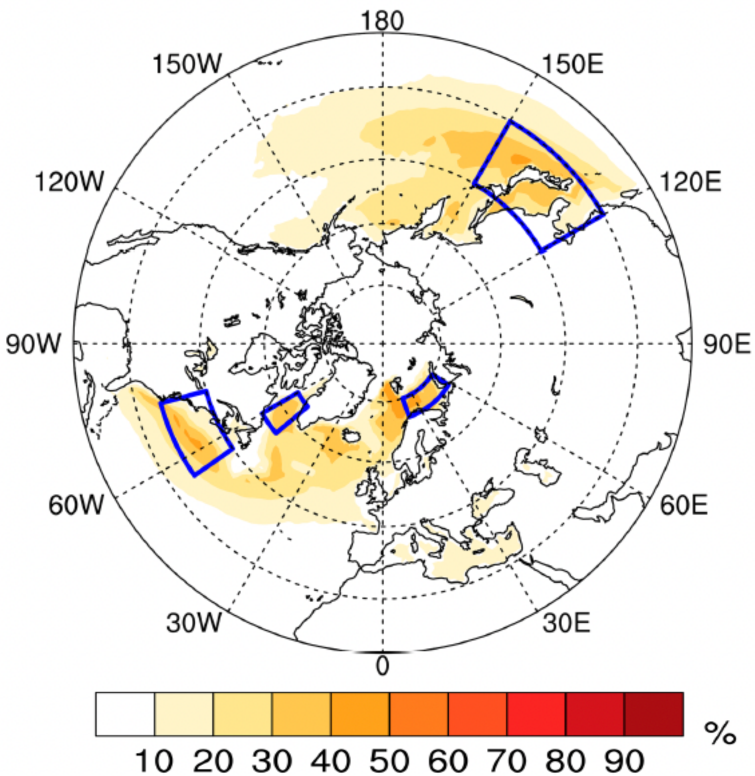


Day et al. (2022)

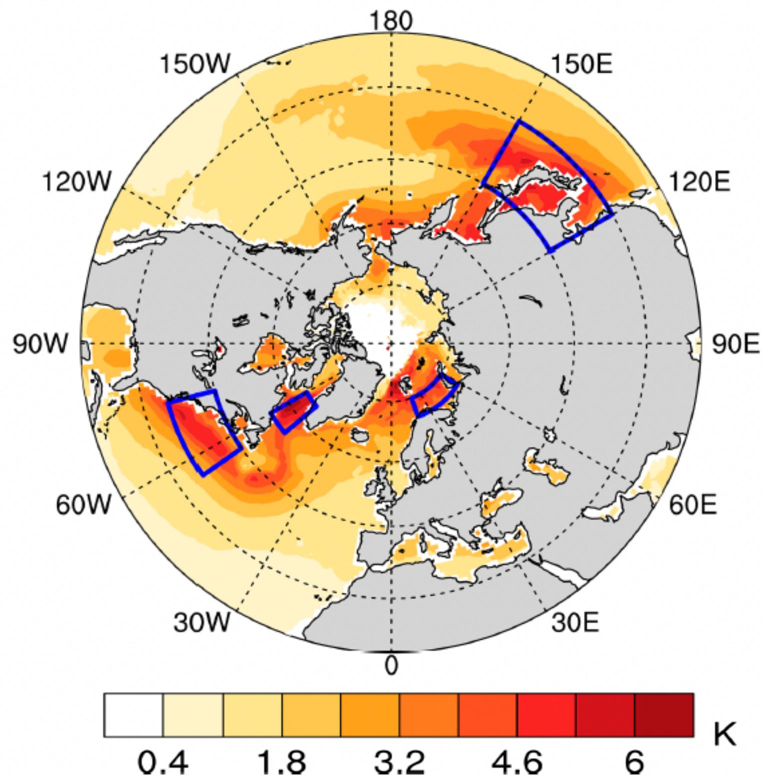
Climatology

- Most frequent & intense over
  - Western boundary currents (e.g., Gulfstream, Kuroshio extension)
  - Around Arctic (e.g., Barents Sea, Labrador Sea)

Annual frequency



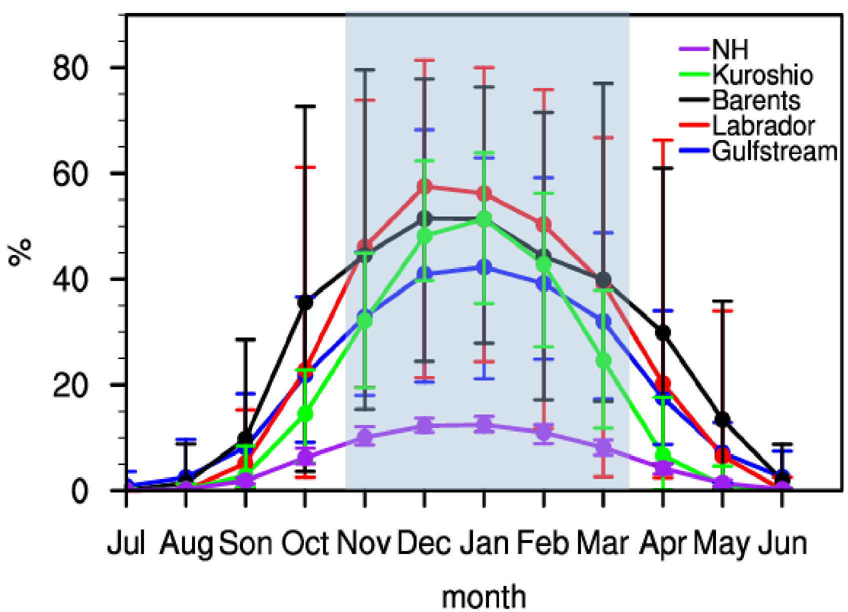
Annual mean intensity



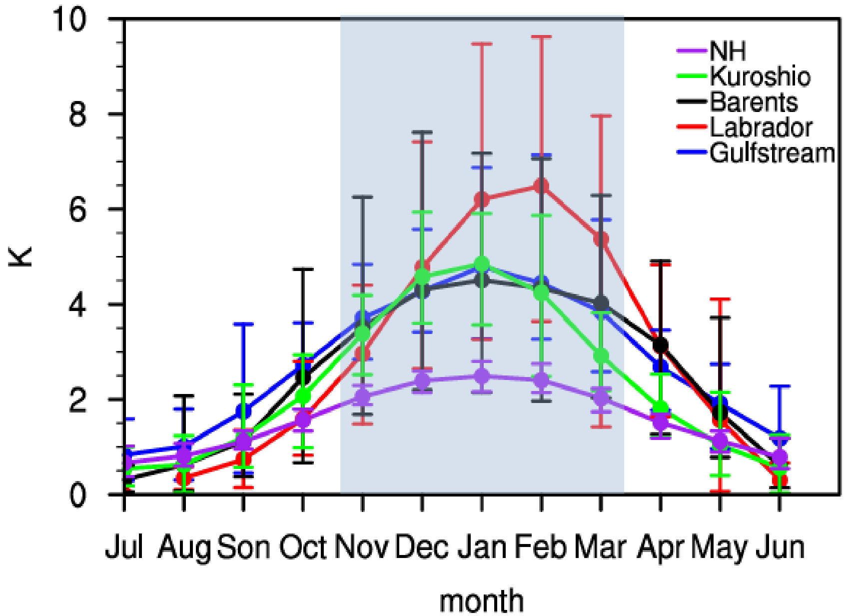
Annual cycle

- More frequent & intense in cold season
- There are some regionalities

Frequency



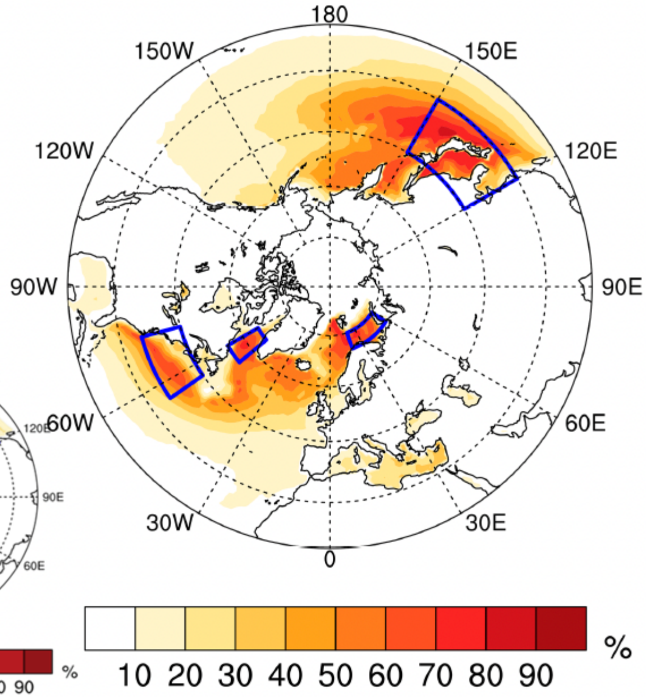
Intensity



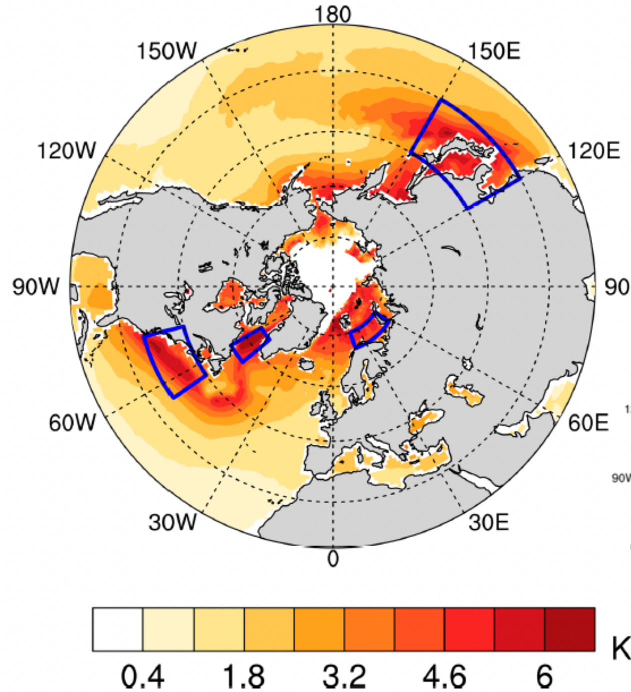
Winter climatology

- Similar patterns to the annual situation
- Much higher frequency
- Similar mean intensity, due to the small weighting in warm seasons

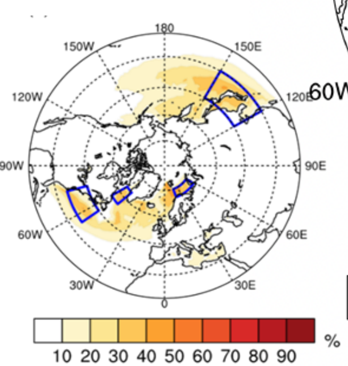
Winter frequency



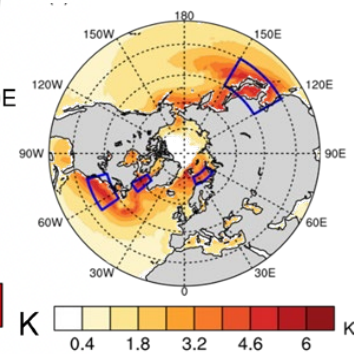
Winter mean intensity



Annual frequency

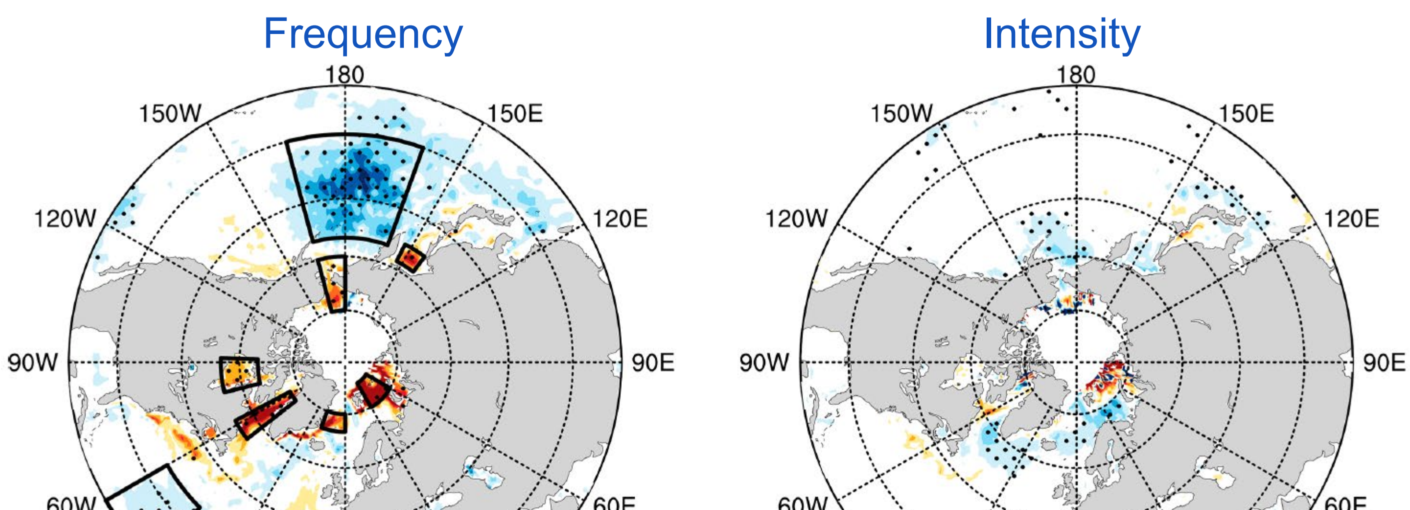


Annual mean intensity



Winter trends

- Frequency:
  - Increase surrounding the Arctic
  - Decrease over mid-latitude North Pacific & Atlantic
- Intensity:
  - Weaken surrounding the Arctic

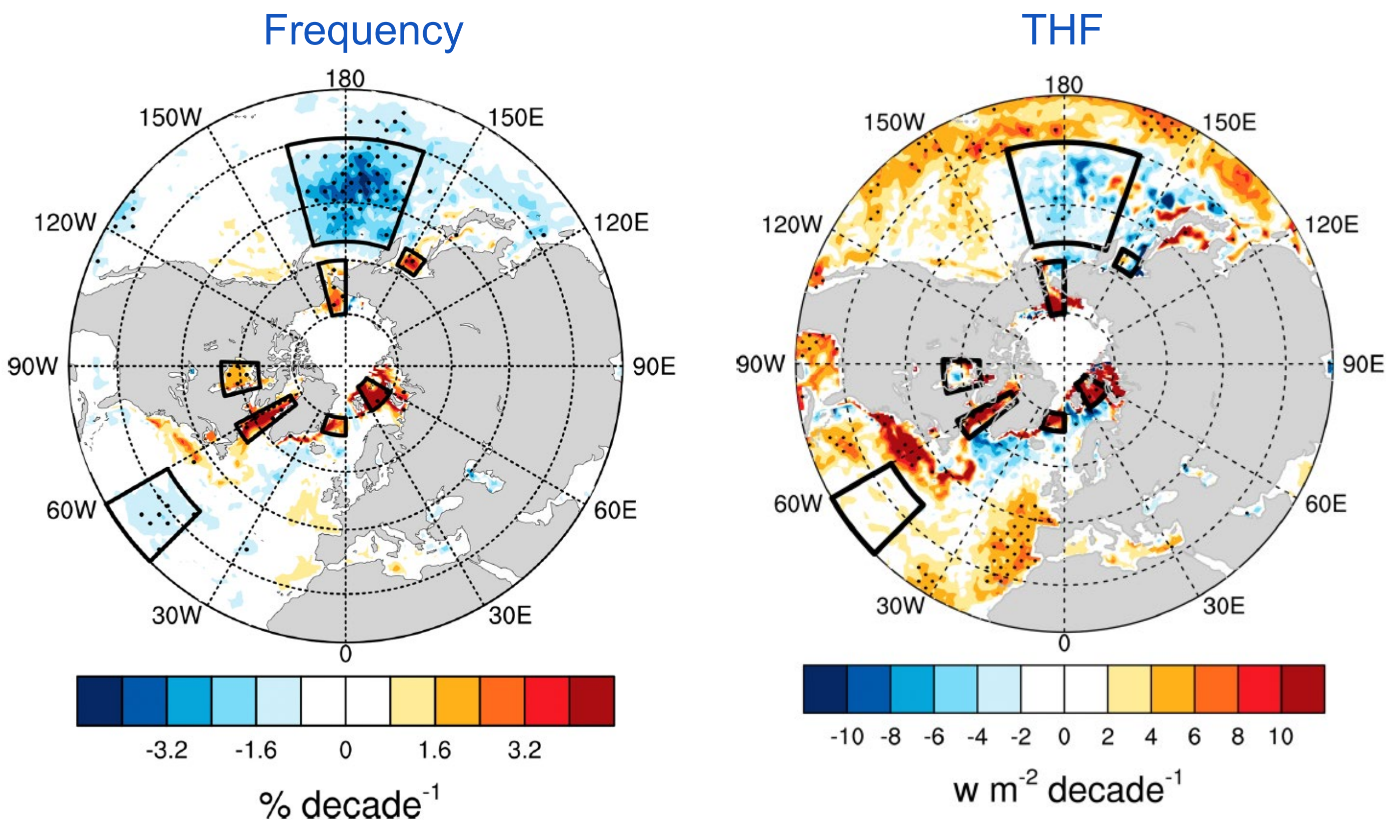


- How do MCAOs change during the past decades?
- Weaker but more frequent surrounding the Arctic
- Less frequent over mid-latitude N. Pacific & Atlantic

% decade^{-1} K decade^{-1}

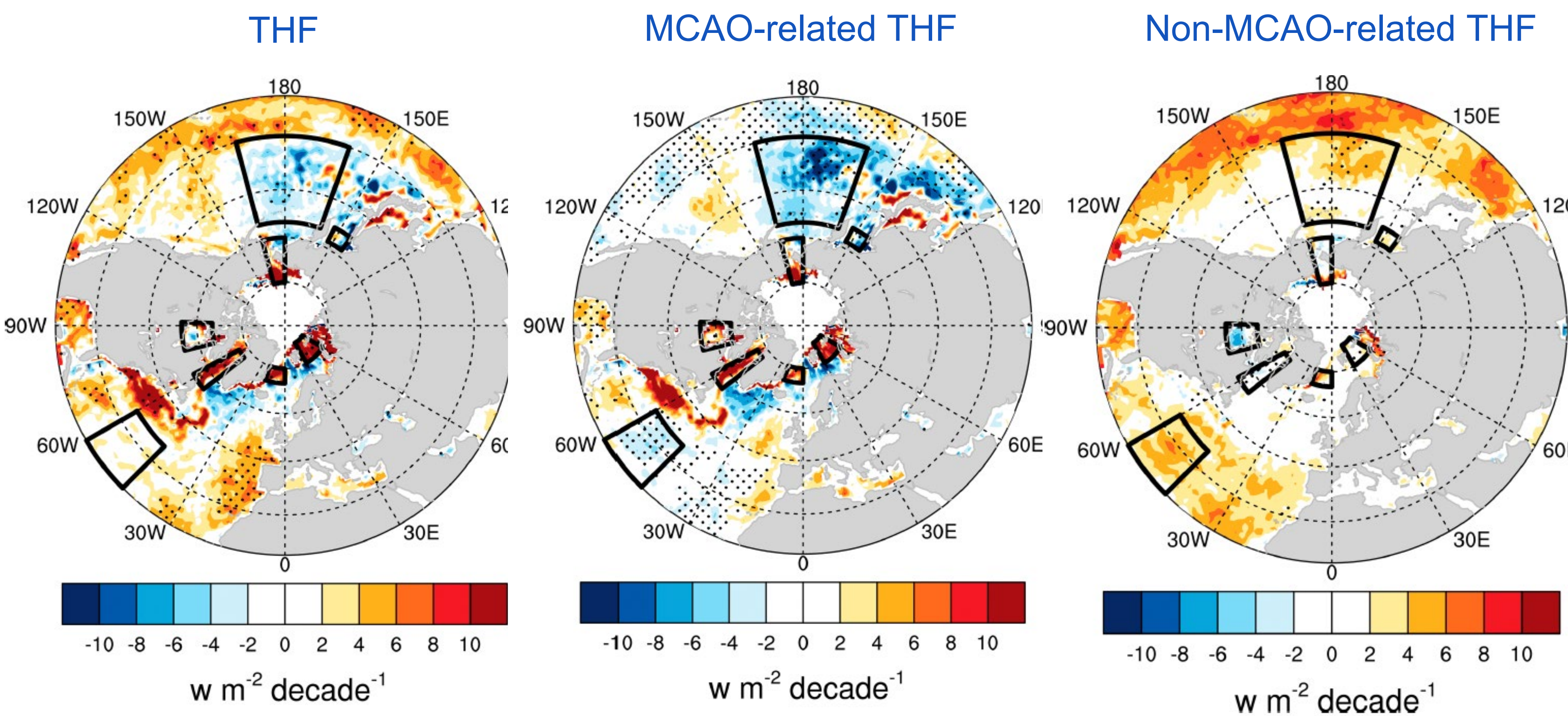
Contribution to trends in turbulent heat flux

- Good correspondence btw. MCAO frequency & THF:
  - More frequent MCAOs → Enhanced THF
  - Less frequent MCAOs → Weakened THF



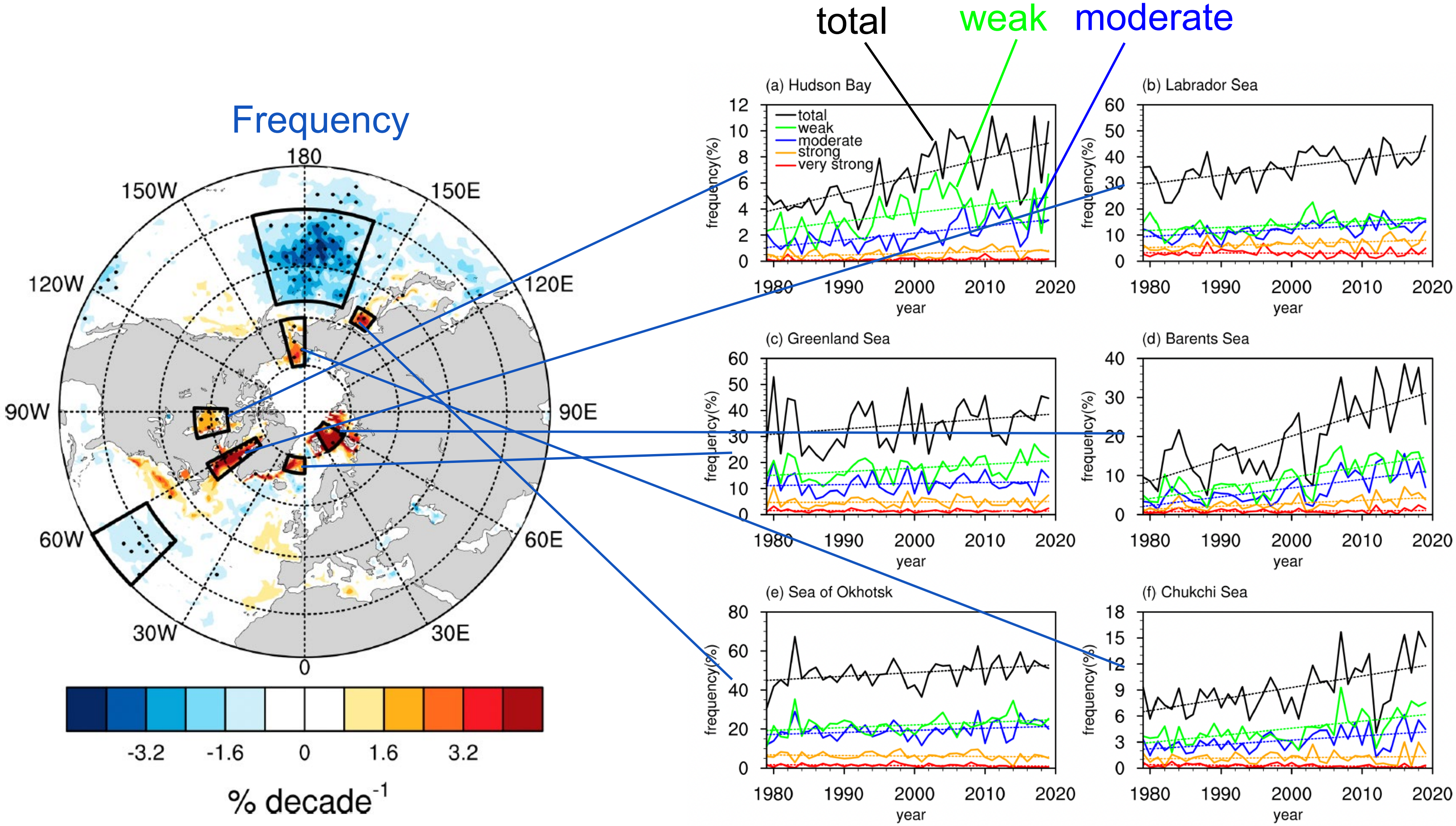
Contribution to trends in turbulent heat flux

- Trends in THF are mainly contributed by MCAOs



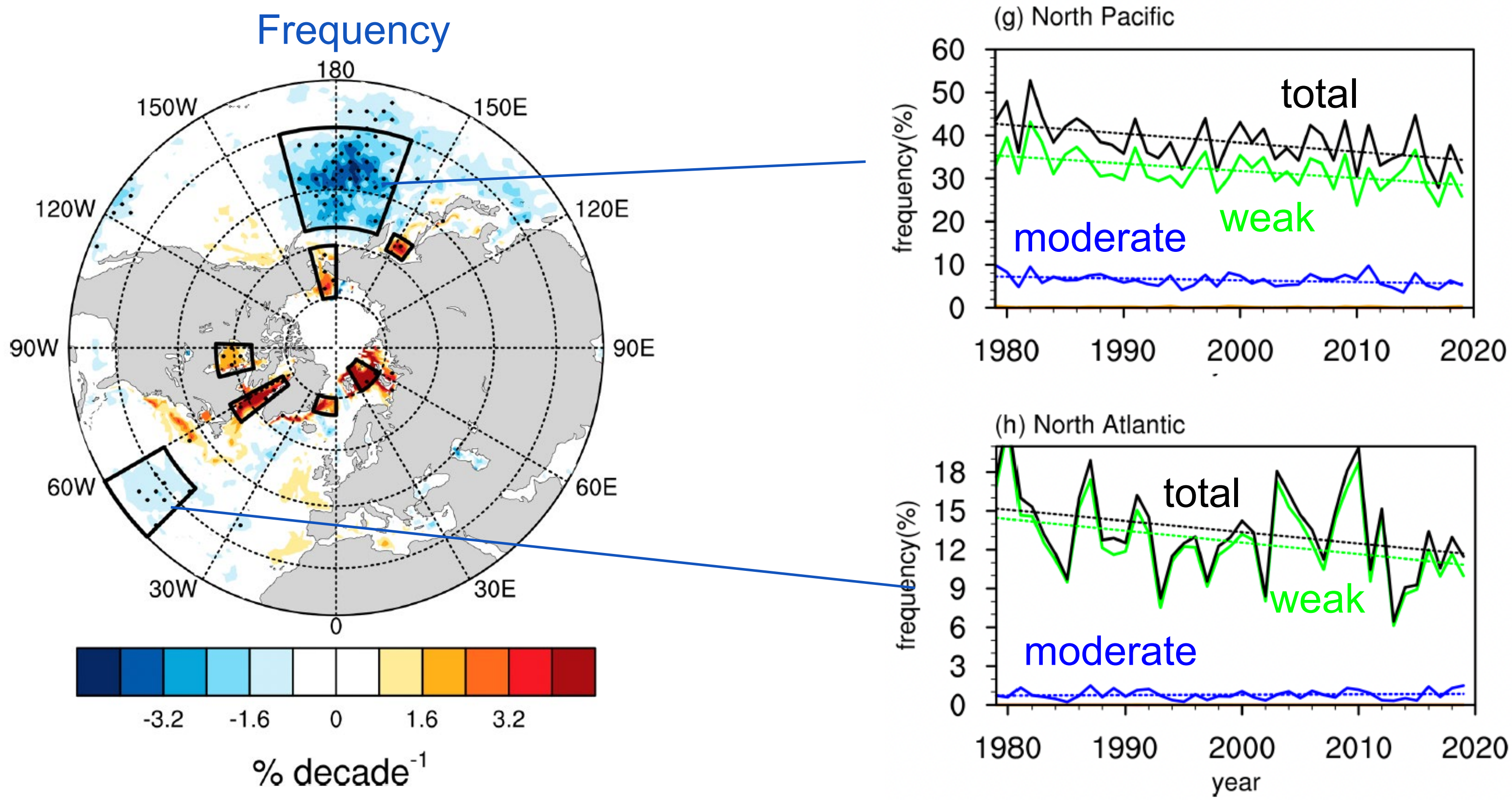
Causes of trends in frequency

- Weak & moderate MCAOs account for increased frequency
- Strong & very strong MCAOs do not change much
- Most MCAOs are weak and moderate ones



Causes of trends in frequency

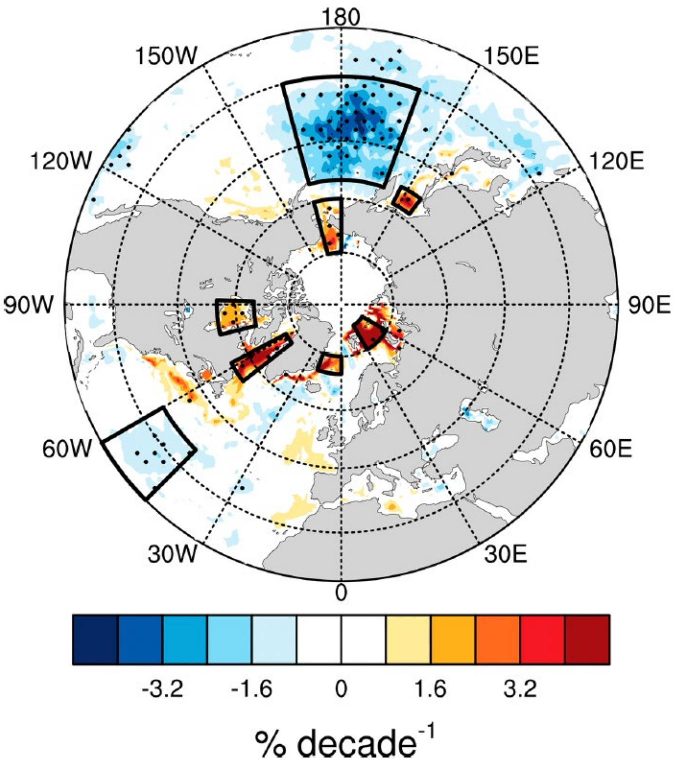
- Weak MCAOs account for decreased frequency



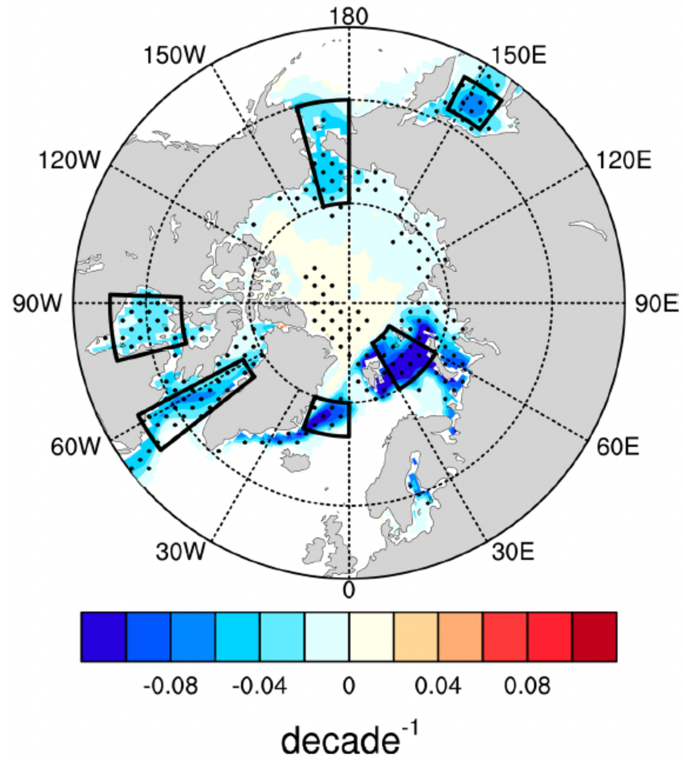
Role of declining sea ice: Arctic & sub-Arctic

- Increased MCAO frequency corresponds well with declining SIC

Trends in MCAO Frequency



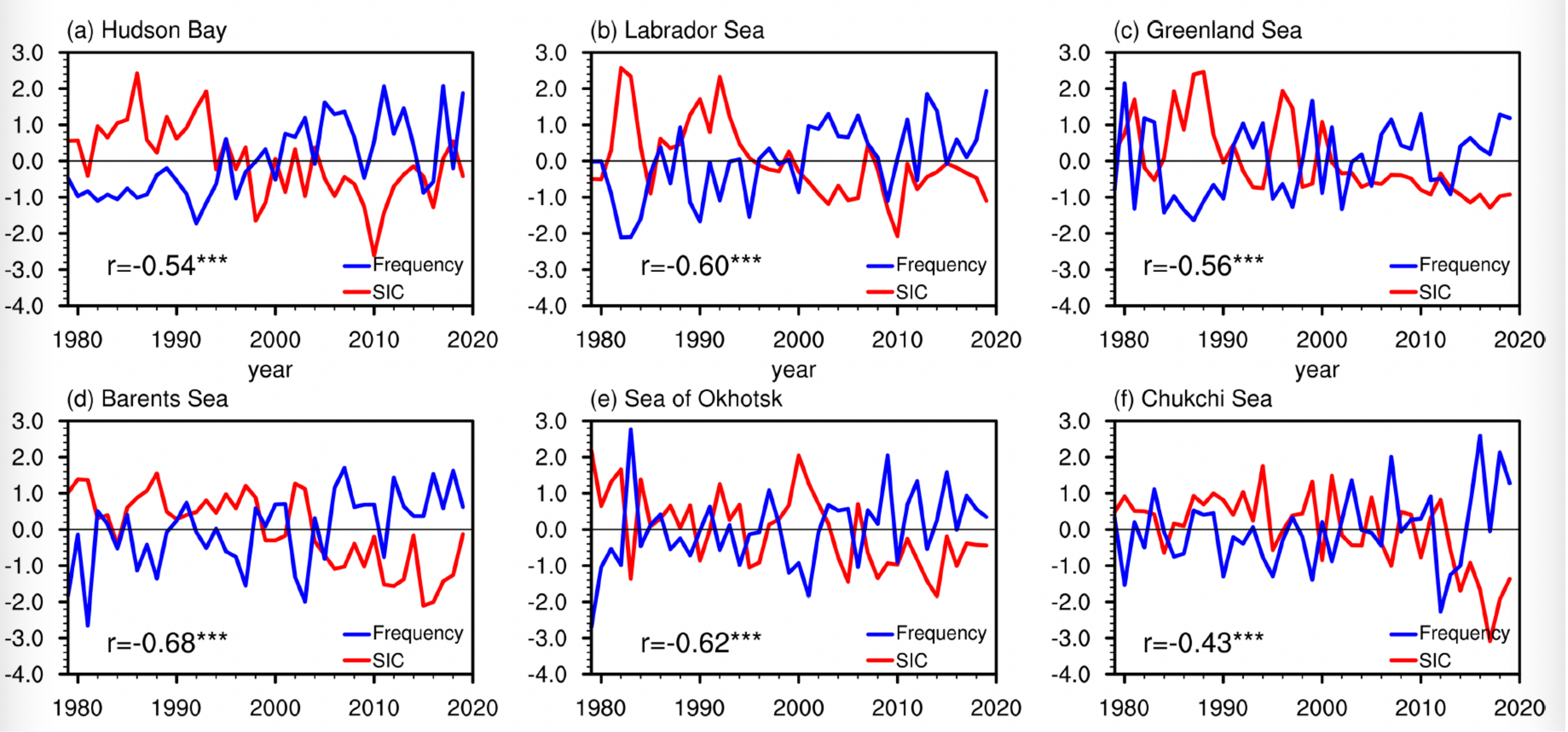
Trends in winter SIC



Role of declining sea ice: Arctic & sub-Arctic

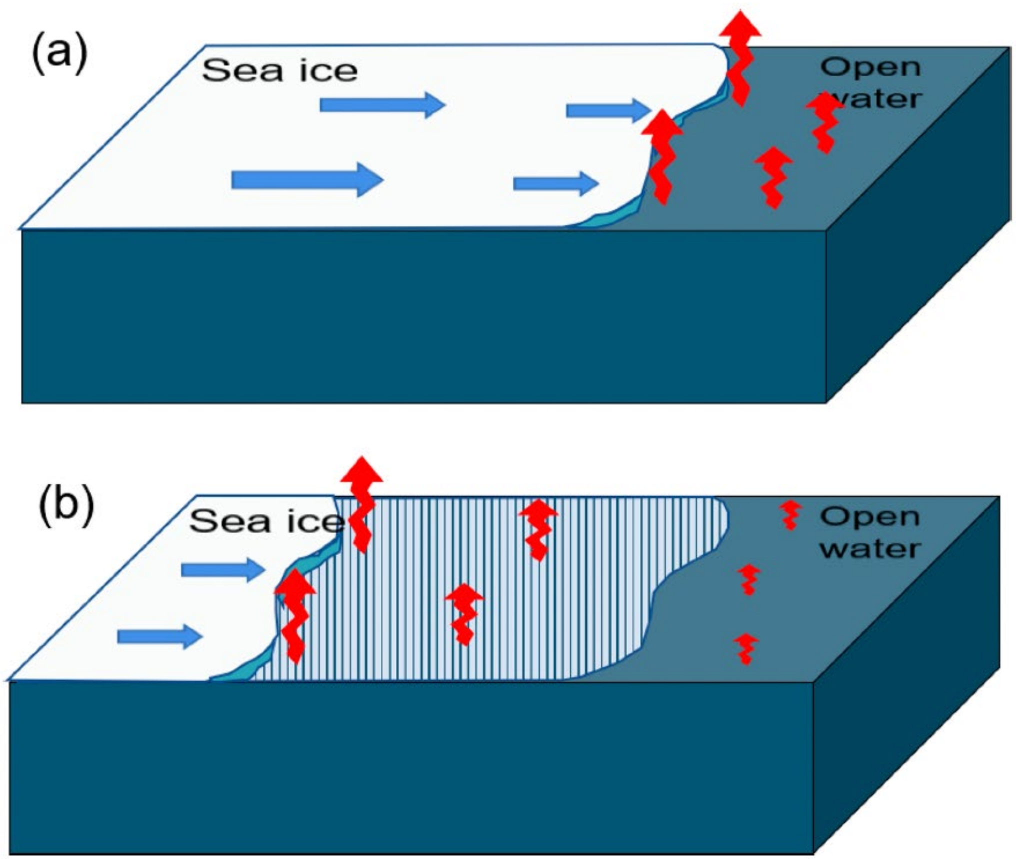
- Increased MCAO frequency corresponds well with declining SIC

Time series of MCAO Frequency & winter SIC



Role of declining sea ice: Arctic & sub-Arctic

- Reduced SIC → more open ocean → more grids with MCAO
- Stronger MCAOs occur near ice edge → location changes
- Weaker MCAOs occur over open ocean → frequency increases



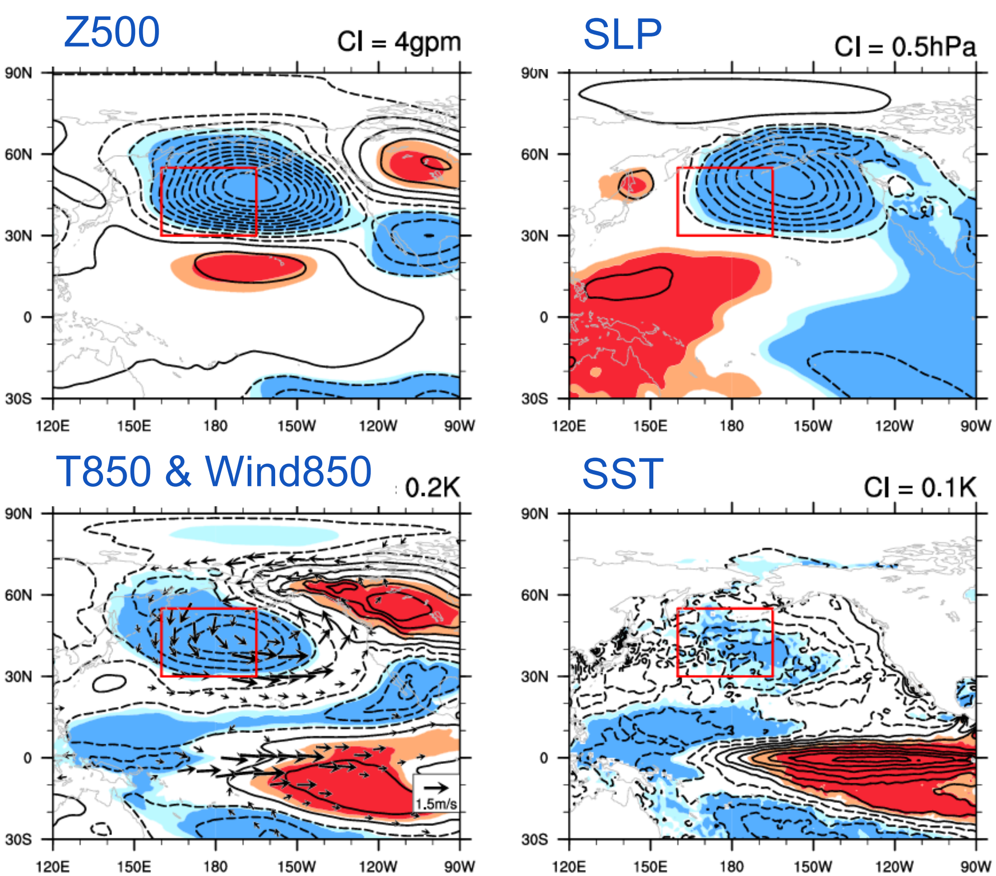
Original state

After sea ice decline

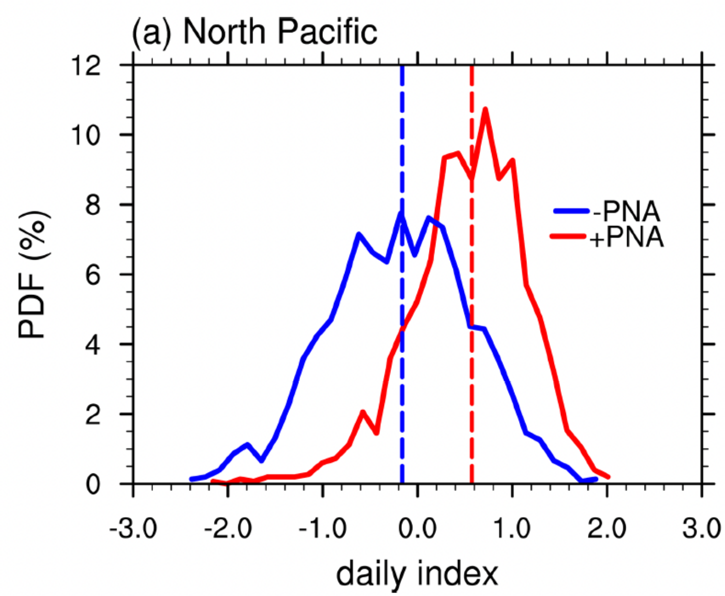
Role of atmospheric circulation: N. Pacific

- Winter with +PNA → more +PNA days → more frequent N. Pacific cyclone → more enhanced northerly → more MCAO

Winter means regression onto MCAO frequency

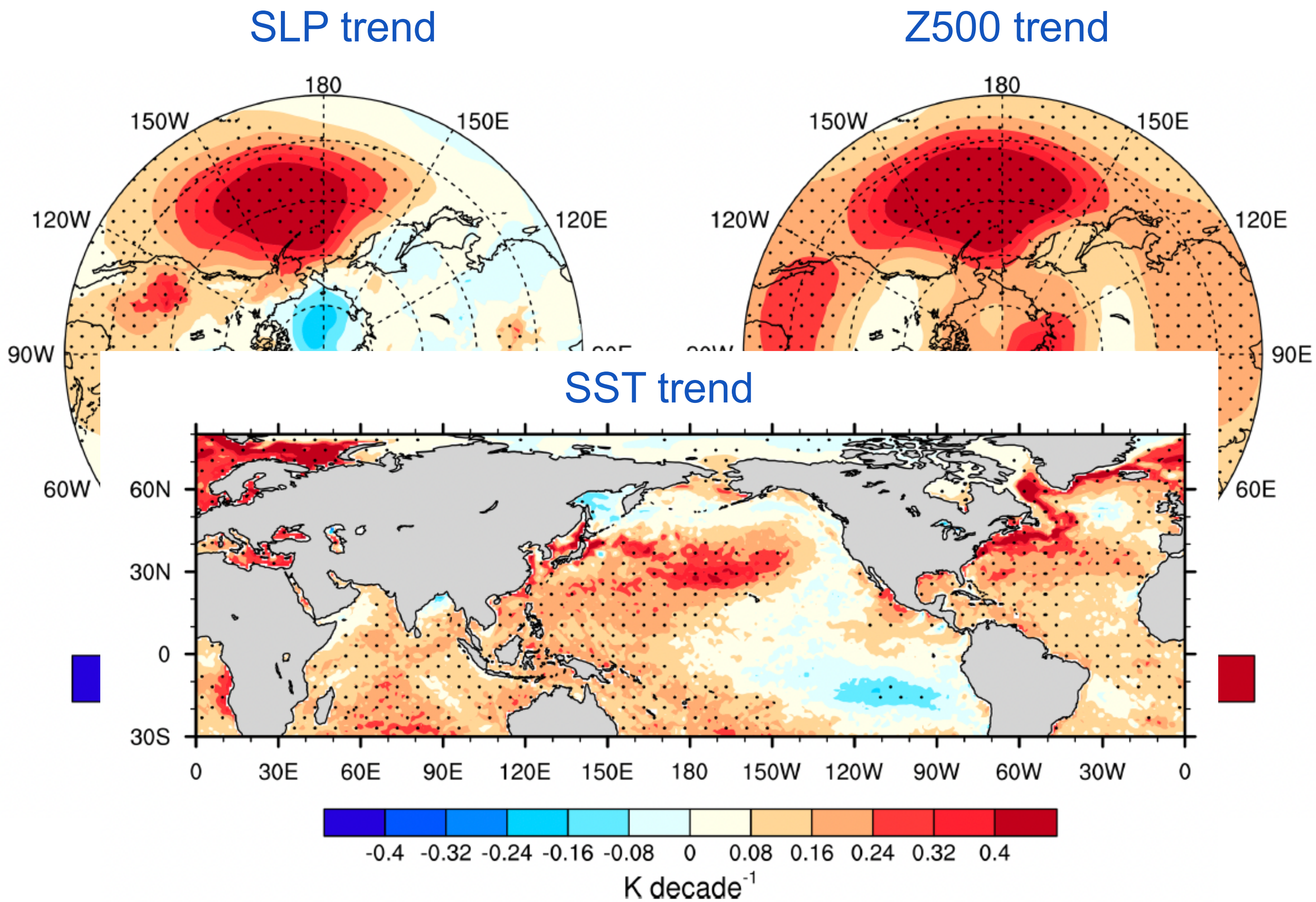


PDF of daily PNA index in winters with +/-PNA



Role of atmospheric circulation: N. Pacific

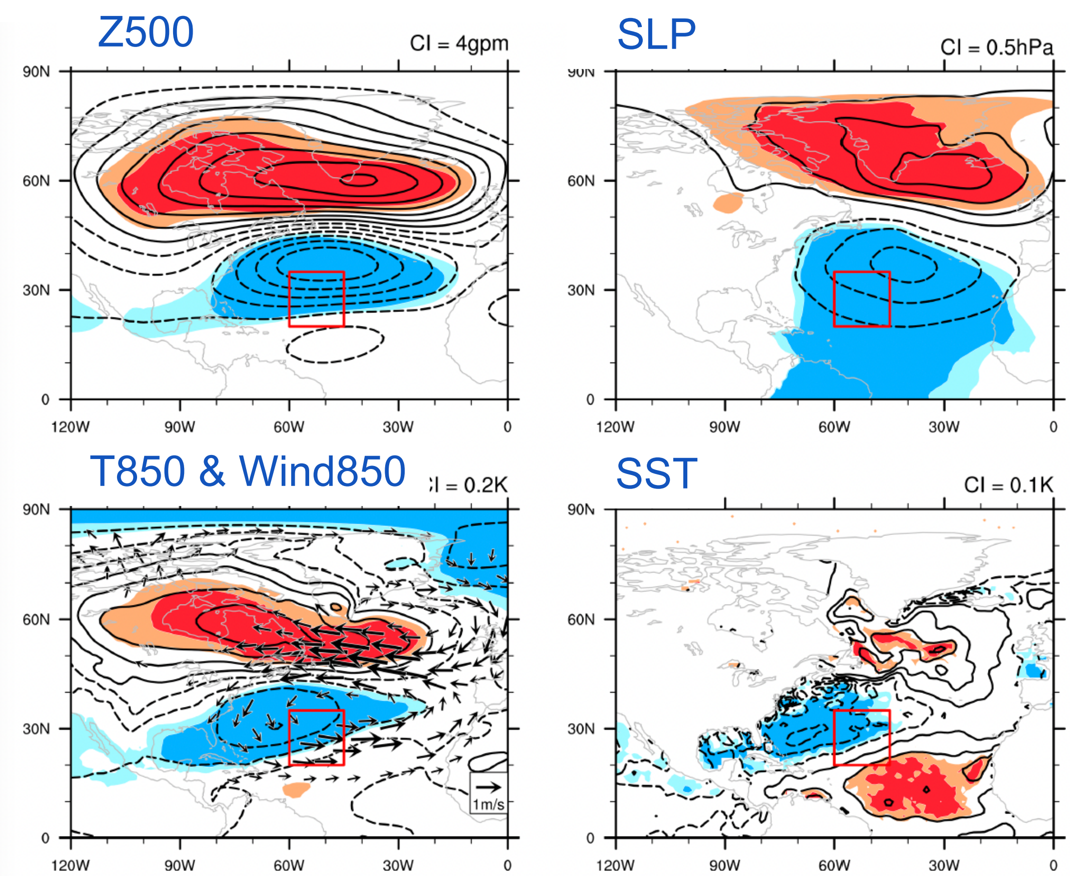
- Negative trend of PNA in obs → decreasing MCAO
- Partly attributed to La Nina-like trend



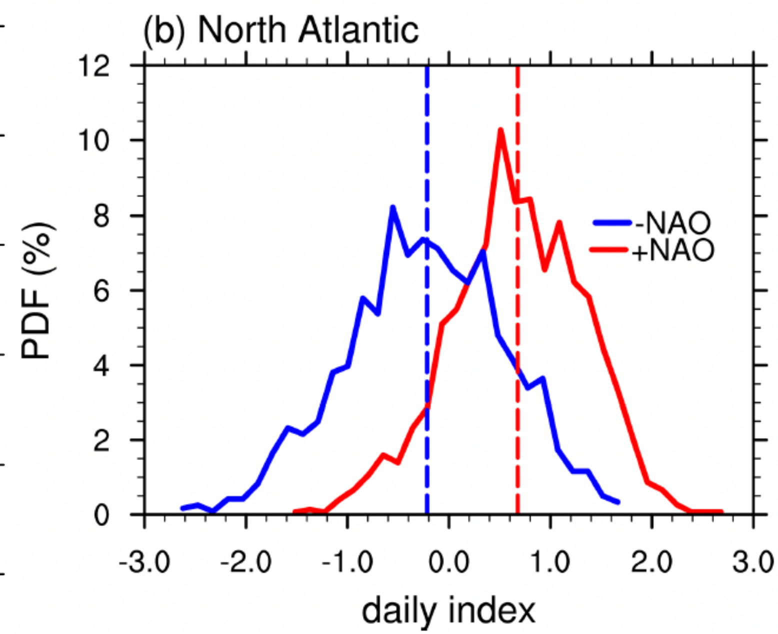
Role of atmospheric circulation: N. Atlantic

- Winter with -NAO → more -NAO days → more frequent N. Atlantic cyclone → more enhanced northwesterly → more MCAO

Winter means regression onto MCAO frequency

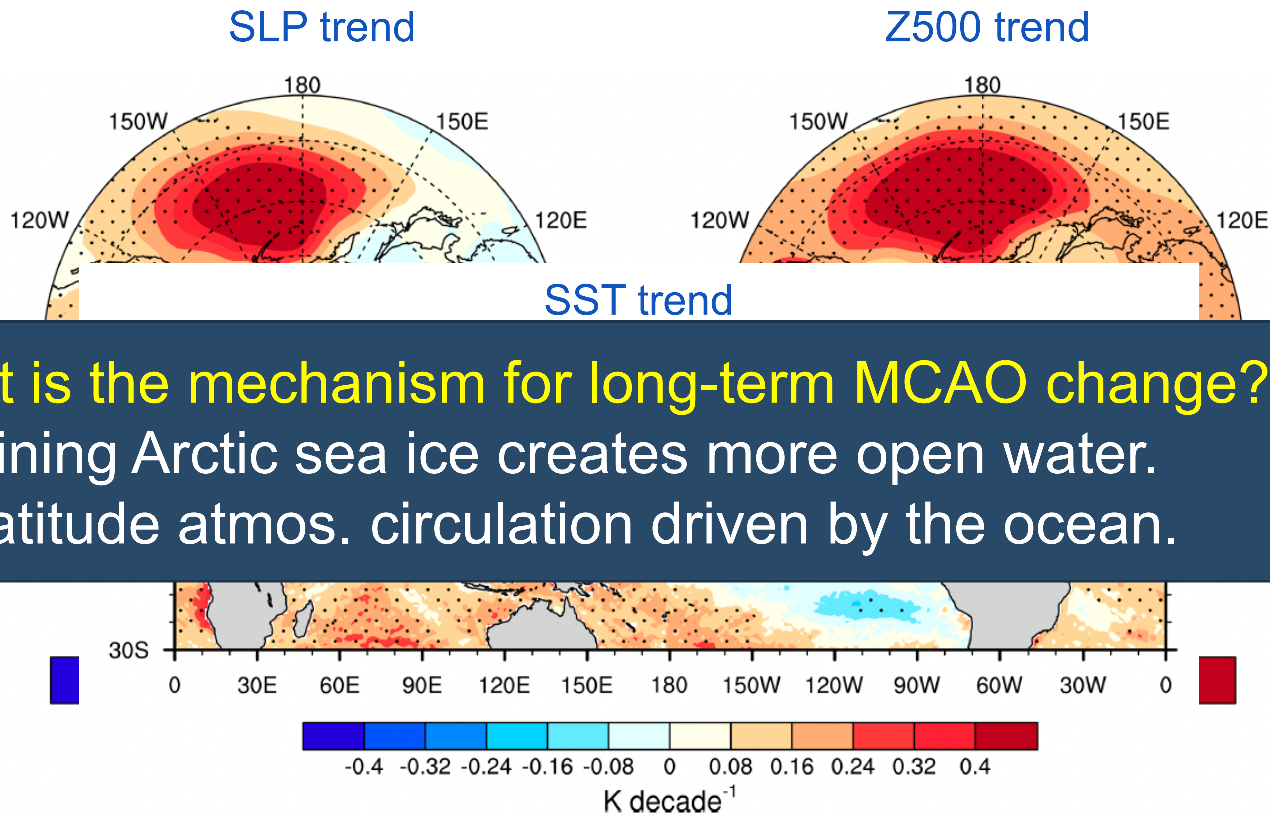


PDF of daily NAO index in winters with +/-NAO



Role of atmospheric circulation: N. Atlantic

- Trend of +NAO in obs → decreasing MCAO
- North Atlantic SST warming also facilitate decreasing MCAO

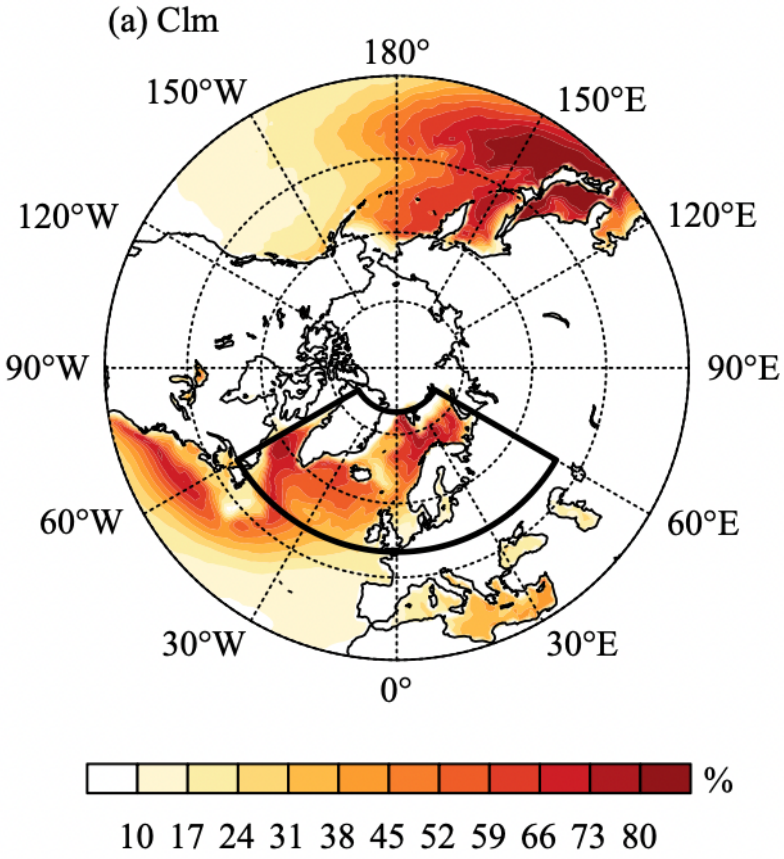


- What is the mechanism for long-term MCAO change?
- Declining Arctic sea ice creates more open water.
- Midlatitude atmos. circulation driven by the ocean.

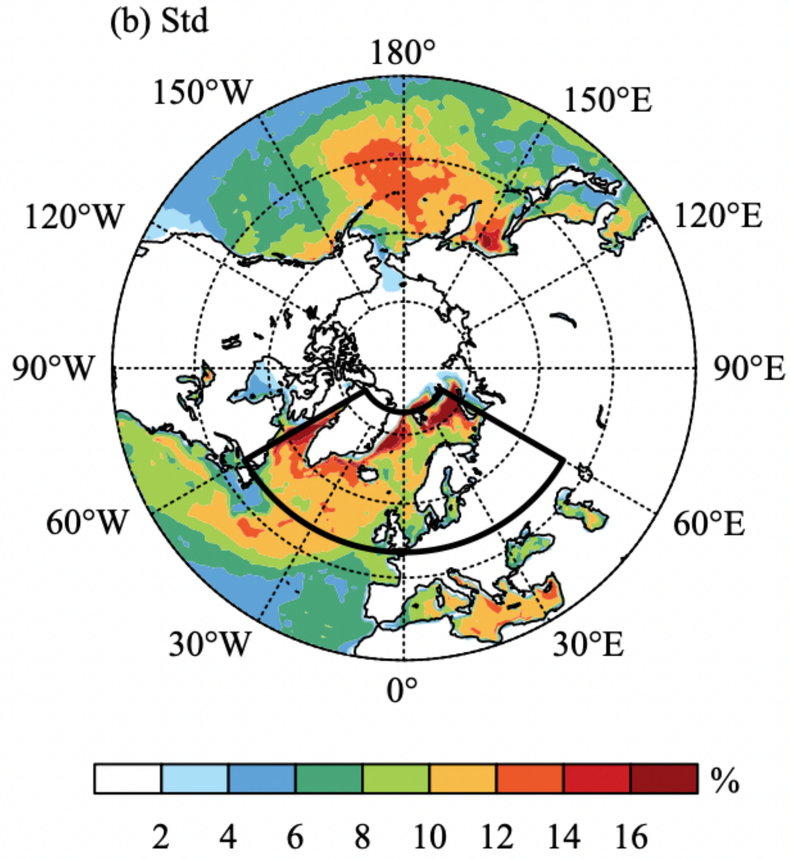
Leading modes of N. Atlantic MCAO frequency

- Mean & variability of winter MCAO frequency is large over N. Atlantic
- EOF is performed to extract the leading modes

Climatology



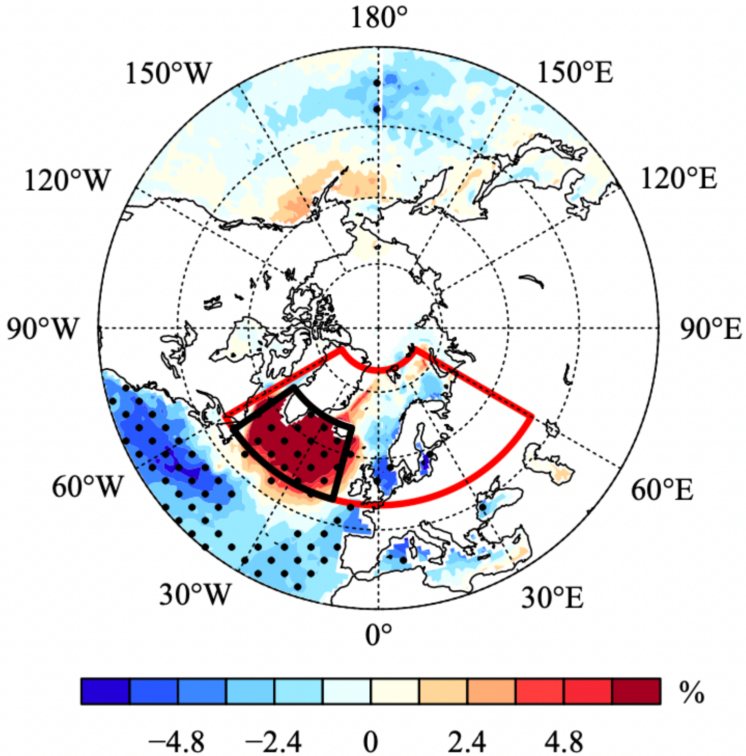
Standard deviation



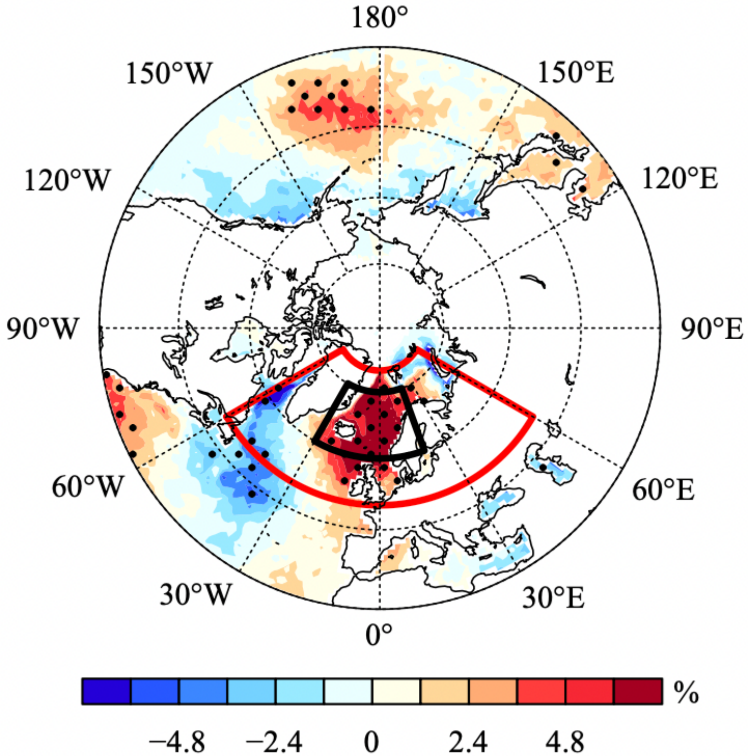
Leading modes of N. Atlantic MCAO frequency

- EOF1: North-south dipole
- EOF2: east-west dipole

EOF1 (24.1%)



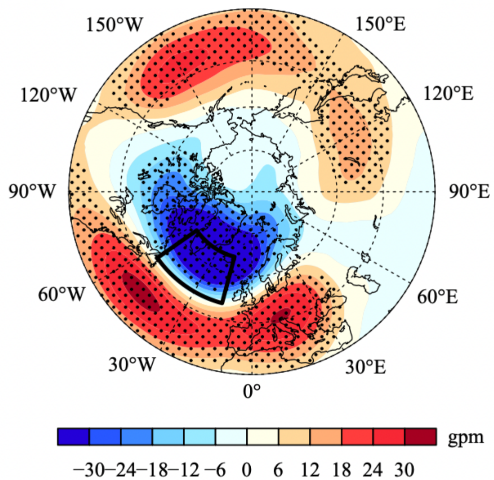
EOF2 (15.5%)



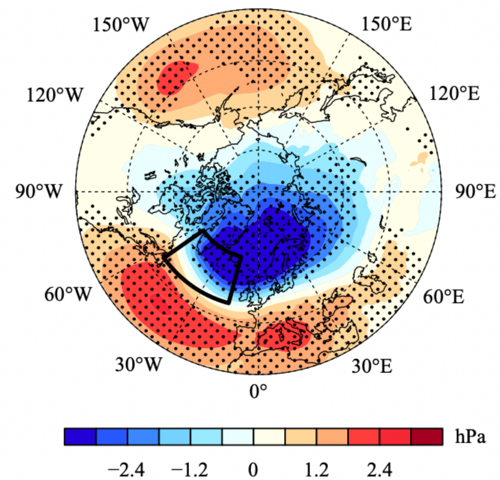
EOF1 is driven by NAO

- +NAO → Enhanced westerly → More continent cold air intrusion

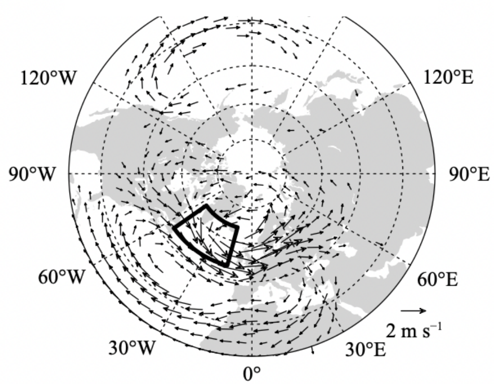
Z500



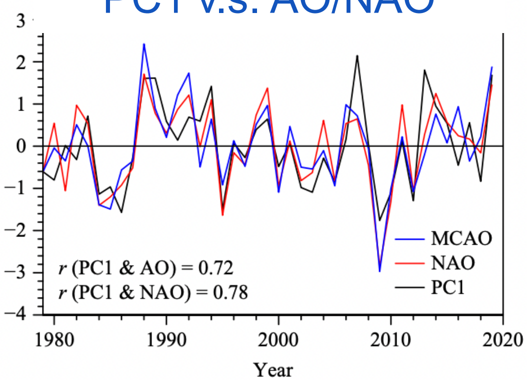
SLP



850hPa wind



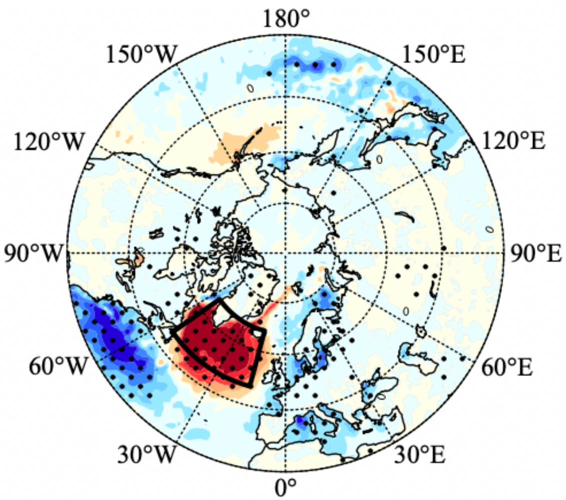
PC1 v.s. AO/NAO



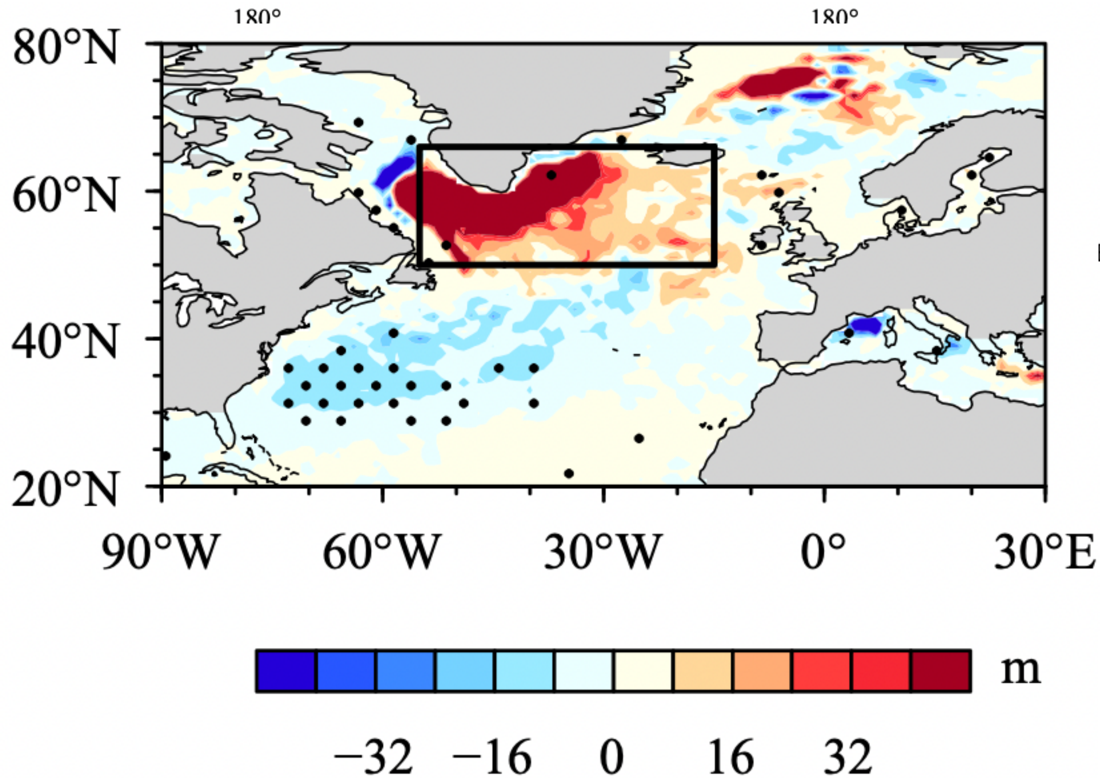
EOF1’s influence on the ocean

- It increases ocean’s heat loss via increasing SHF & LHF
- The resultant changes in mixed layer depth is ~40 meters

Turbulent heat flux



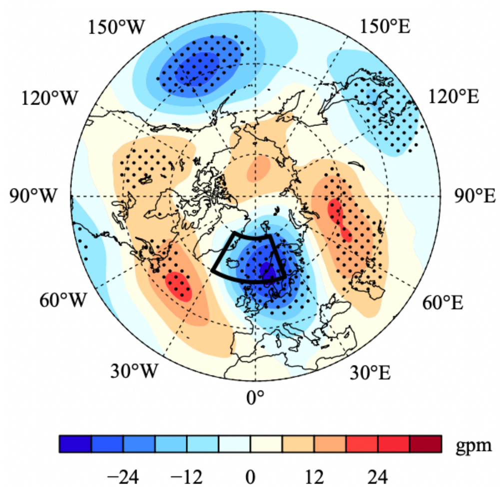
Mixed layer depth



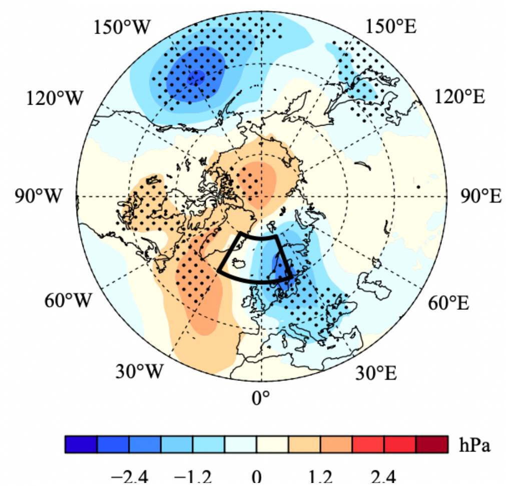
EOF2 is driven by Scandinavian pattern

- -SCAN → Enhanced northerly → More polar cold air intrusion

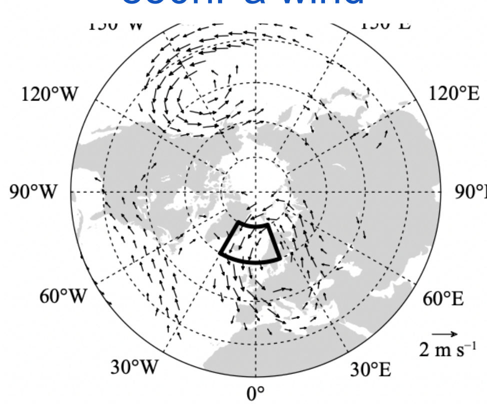
Z500



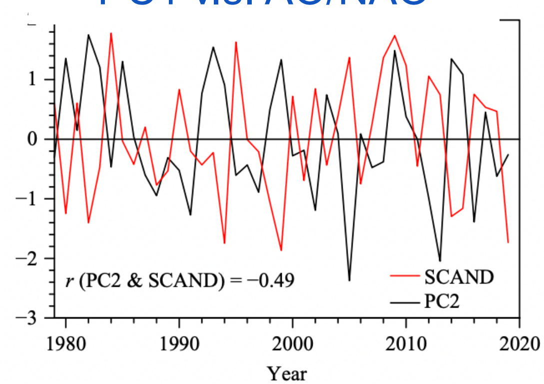
SLP



850hPa wind

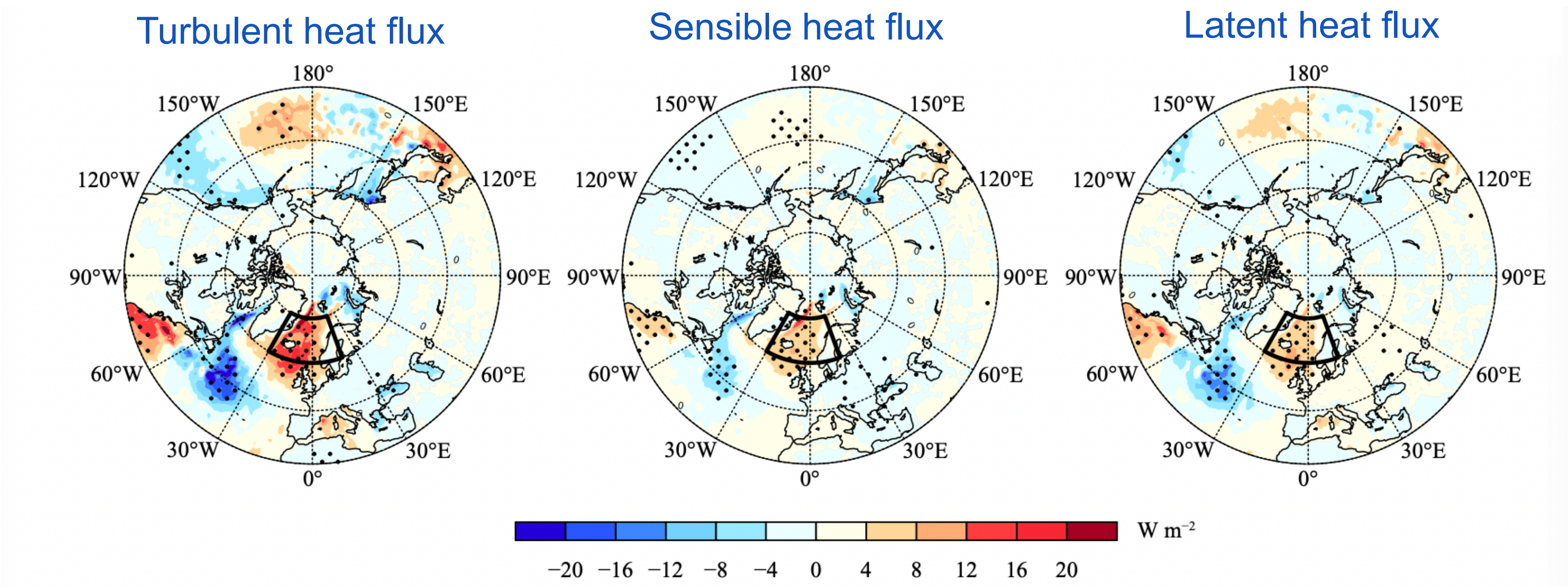


PC1 v.s. AO/NAO



EOF2’s influence on the ocean

- It increases ocean’s heat loss via increasing SHF & LHF



Summary

- Winter MCAOs experience significant trend in the past decades
- Regions surrounding the Arctic
  - More frequent but weaker
  - Declining Arctic sea ice creates more open water
- Mid-latitude N. Pacific & Atlantic
  - Less frequent
  - Midlatitude atmos. circulation driven by the ocean
- Two leading modes of MCAO frequency over N. Atlantic
  - Meridional & zonal dipoles, driven by NAO & Scandinavian pattern
  - Induce strong turbulent heat flux & changes in mixed layer depth
- For details, please see
  - Ran, Wang*, et al. (2025) J Meteor Res, doi:10.1007/s13351-025-5030-4
  - Ran, Wang*, et al. (2026) J Climate, doi:10.1175/JCLI-D-24-0658.1

Thanks!


Long-standing Friendship
Decades of Cooperation
IAP RUS
IAP CAS
IAP RUS
IAP CAS
COLLABORATION • EXCHANGE • INNOVATION