Winter North Atlantic jet variability under global warming: Past trends and future projections

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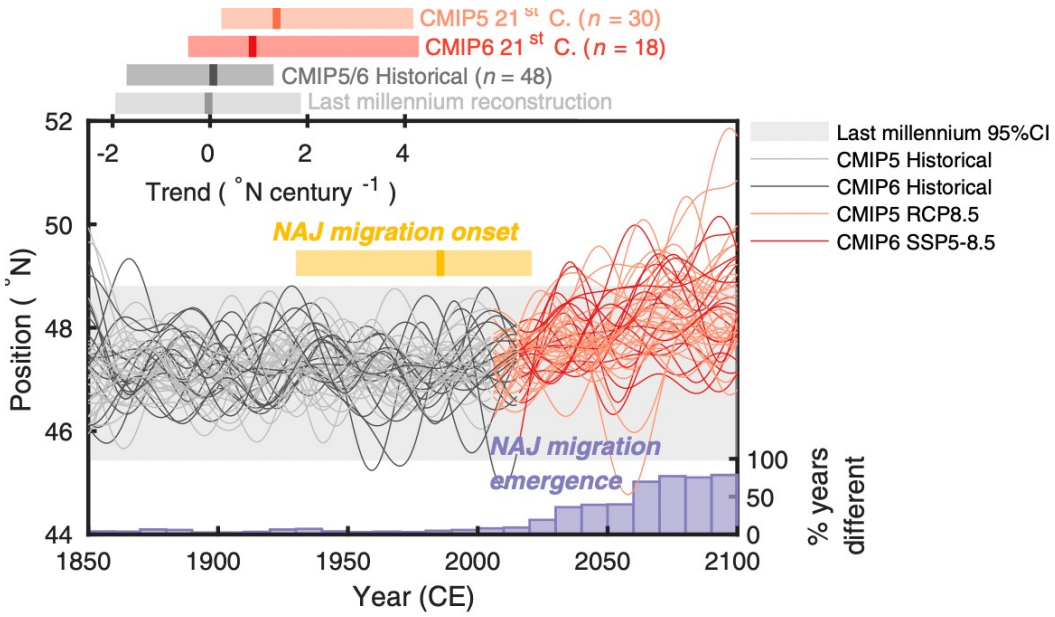
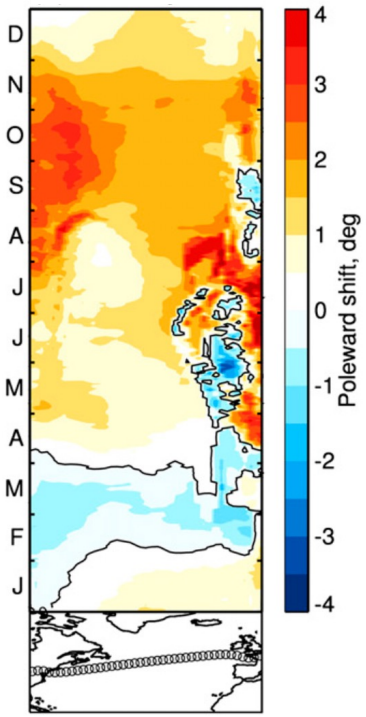
Introduction

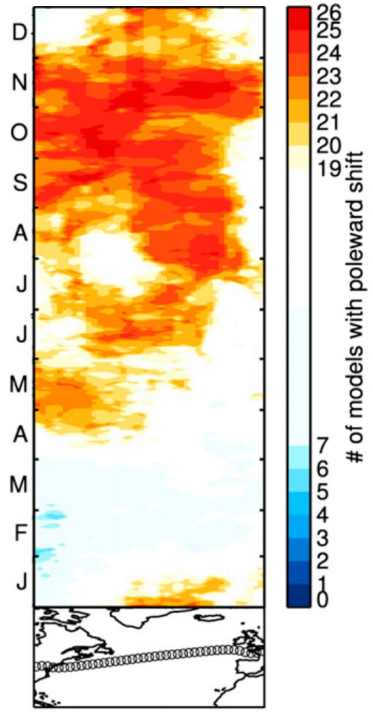
Jet trends in previous studies



General trend: Projected **poleward displacement** in climate models[1] (Osman et al. 2021)



North Atlantic jet shift trend



North Atlatic model agreeement

Different trends **depending on the season, low agreement** among models in winter[2] (Simpson et al. 2014)

[1]Osman, B. M., Coats, S., Das, S. B. & Chellman, N. North Atlantic jet stream projections in the context of the past 1,250 years. PNAS 118, e2104105118 (2021).
[2]Simpson, I. R., Shaw, T. A. & Seager, R. A diagnosis of the seasonally and longitudinally varying midlatitude circulation response to global warming. J. Atmos. Sci. 71, 2489-2515 (2014).

Objectives

- Analysis of **jet stream trends** (observed and projected) in winter (DJF) over the **North Atlantic**

- Understanding the **physical mechanism** leading to the observed trends

Data and methods

Data hierarchy

The analysis of winter jet stream trends is based on the following data hierarchy

Reanalysis	ERA5
Fully-coupled climate simulations	CESM2
Idealized aquaplanet experiments	ICON 2.6.4

ERA5

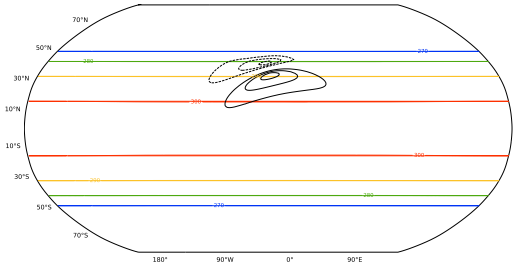
- Reanalysis for the period 1979-2022
- Global data, 0.5° spatial resolution
- Data interpolated to 11 pressure levels between 100 and 900 hPa

CESM2 simualtions

- 5 ensemble members
- Approximately 1° horizontal resolution
- Simulation period from 1980 until 2100
  - Prescribed forcing between 1980 and 2014
  - SSP370 scenario from 2015

ICON aquaplanet experiments

- 5-year simulations in perpetual winter configuration
- Horizontal resolution of approximately 80 km and 70 vertical levels
- SST baseline distribution with a superimposed SST front with an amplitude of 10 K and located at 30°W and different latitudinal positions
- Two simulations:
  - Control: baseline SST and front
  - Warming: baseline SST uniformly warmed by 4 K and front



Aquaplanet setup

Analysis

- The North Atlantic jet stream is driven by eddy momentum flux convergence associated with the propagation of large-scale Rossby wave that originate from regions of enhanced baroclinicity[1]
- Baroclinicity is inspected through the slope of isentropic surfaces

$$slope = \frac{d\theta/dy}{d\theta/dp}$$

- Eddy momentum convergence is inspected by means of E vector, whose direction is opposite to eddy momentum transfer

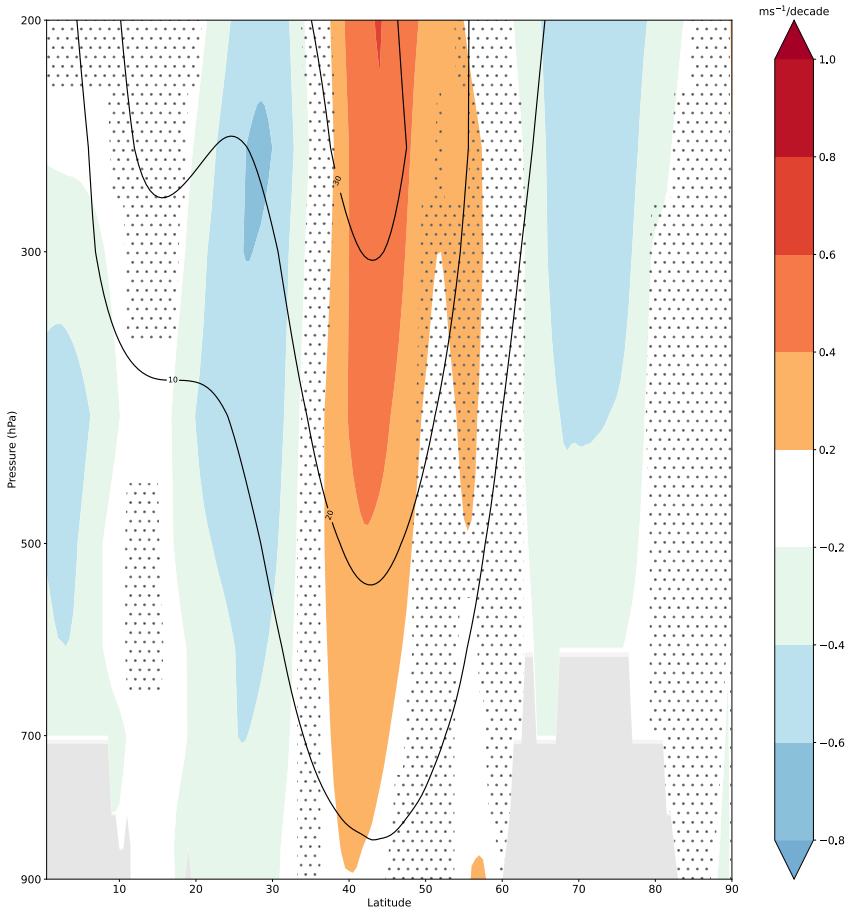
$$\boldsymbol{E} = \left(0.5\overline{(v'^2 - u'^2)}, \overline{-u'v'}, \frac{f}{d\theta/dp}\overline{v'\theta'}\right)$$

- Diabatic heating (temperature tendencies due to parameterized processes) and advection trends are also analyzed as they affect trends in potential temperature and thus, the isentropic slope

[1] Vallis, G. K. Atmospheric and Oceanic Fluid Dynamics: Fundamentals and Large-Scale Circulation (Cambridge University Press, 2017), 2 edn

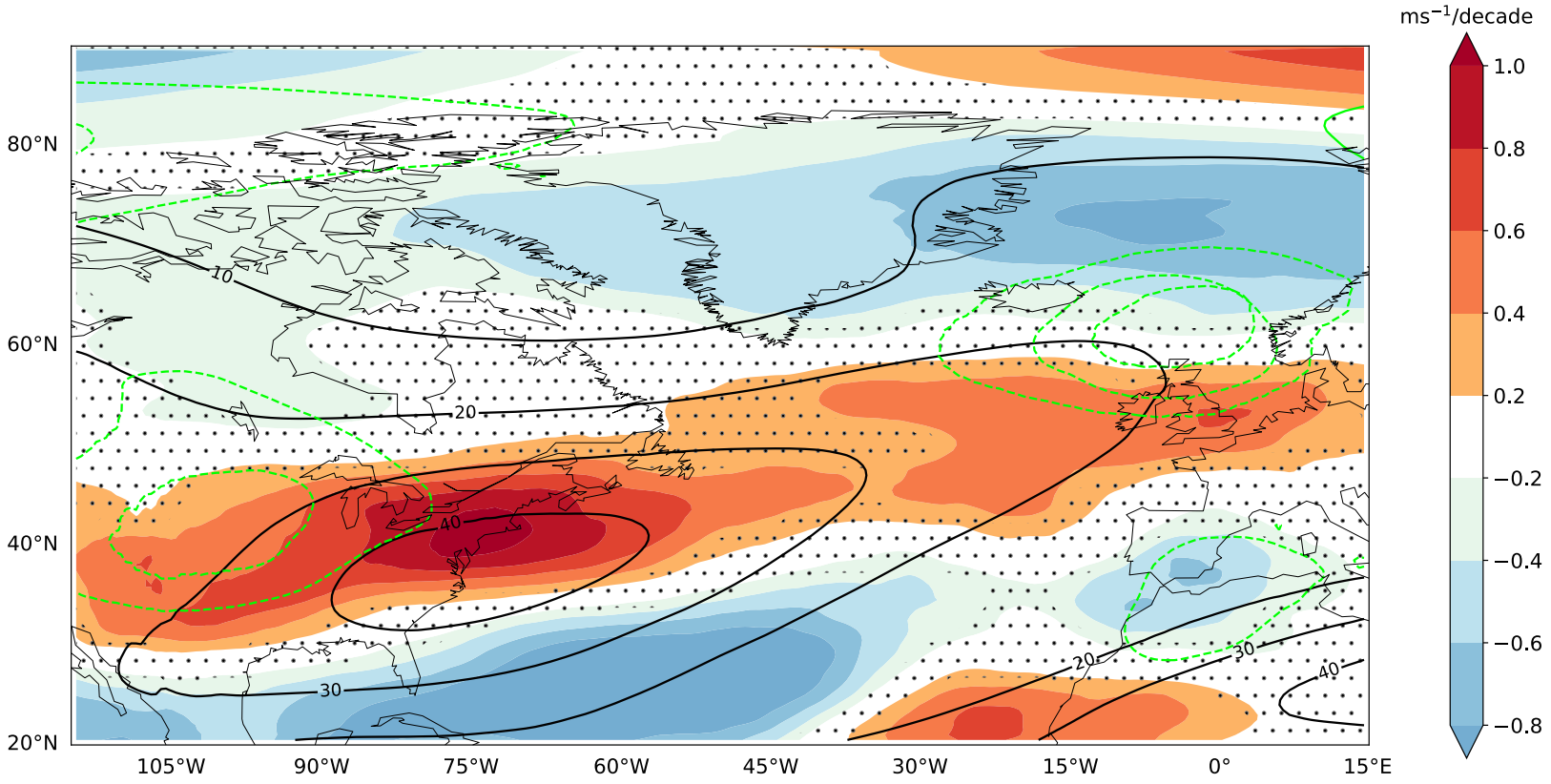
Results

Jet trends (ERA5)



Zonal mean 80 – 15°W

Shading	Trend (per decade)
Black contours	Climatological mean
Green contours	500-hPa geopotential trend
Stippling	non-significant trends

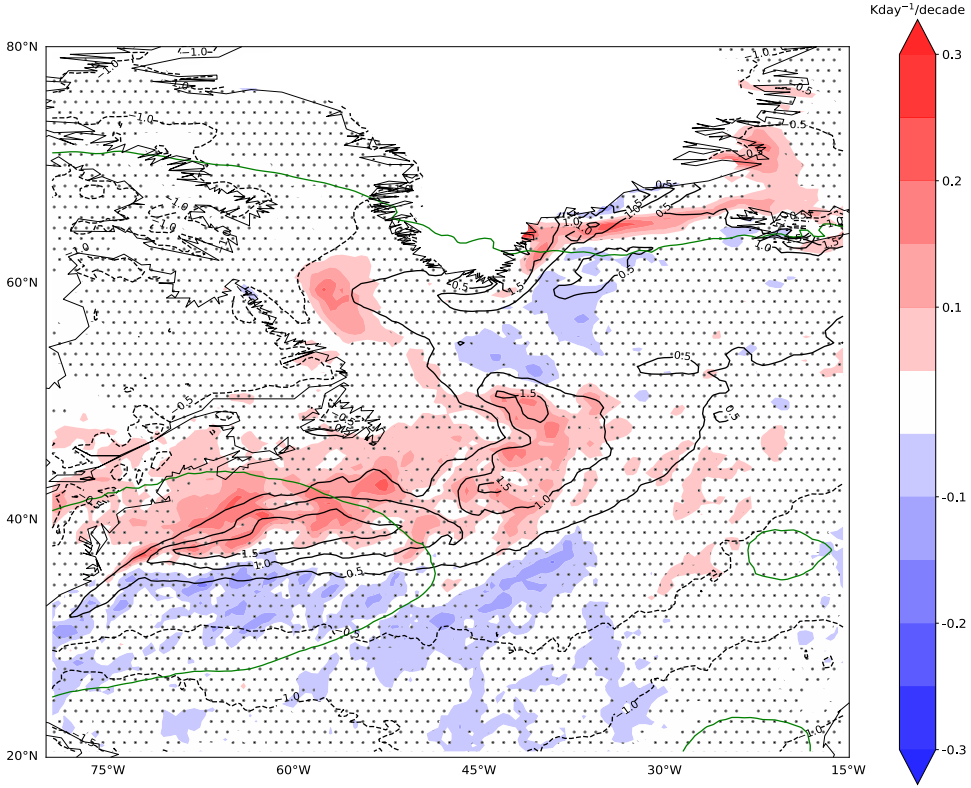


Trends at 250 hPa

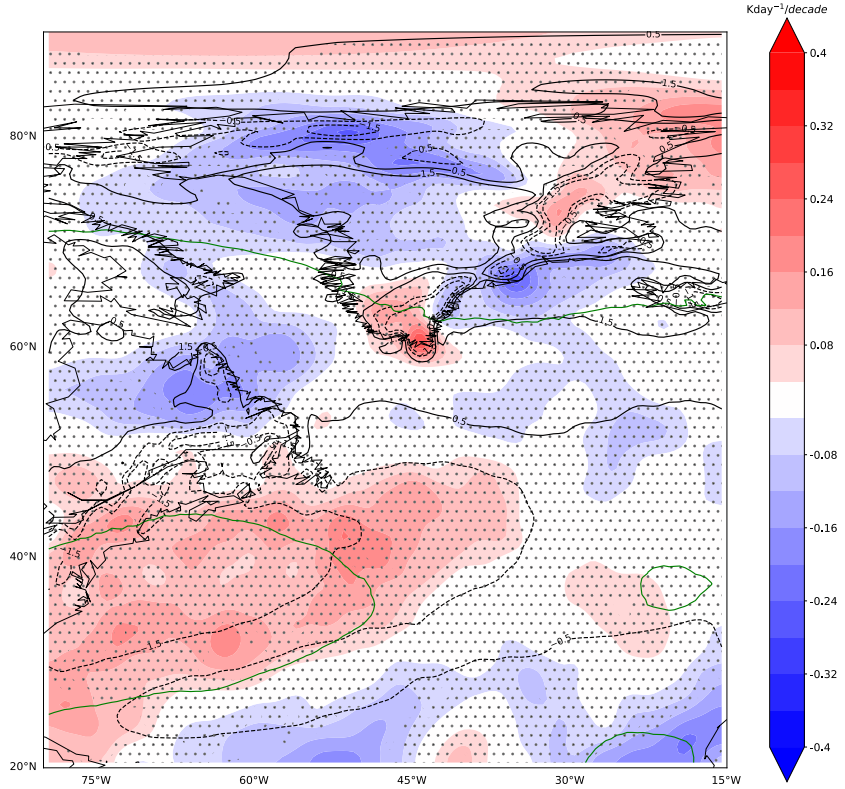
Strengthening of the jet, especially over the entrance region and extension over Europe

Intensification of the climatological trough over North America

Diabatic heating and advection trends



Shading	Trends (per decade)
Black contours	Climatological mean
Green contour	Region of strongest potential temperature trend (0.35 K/dec)
Stippling	non-significant trends

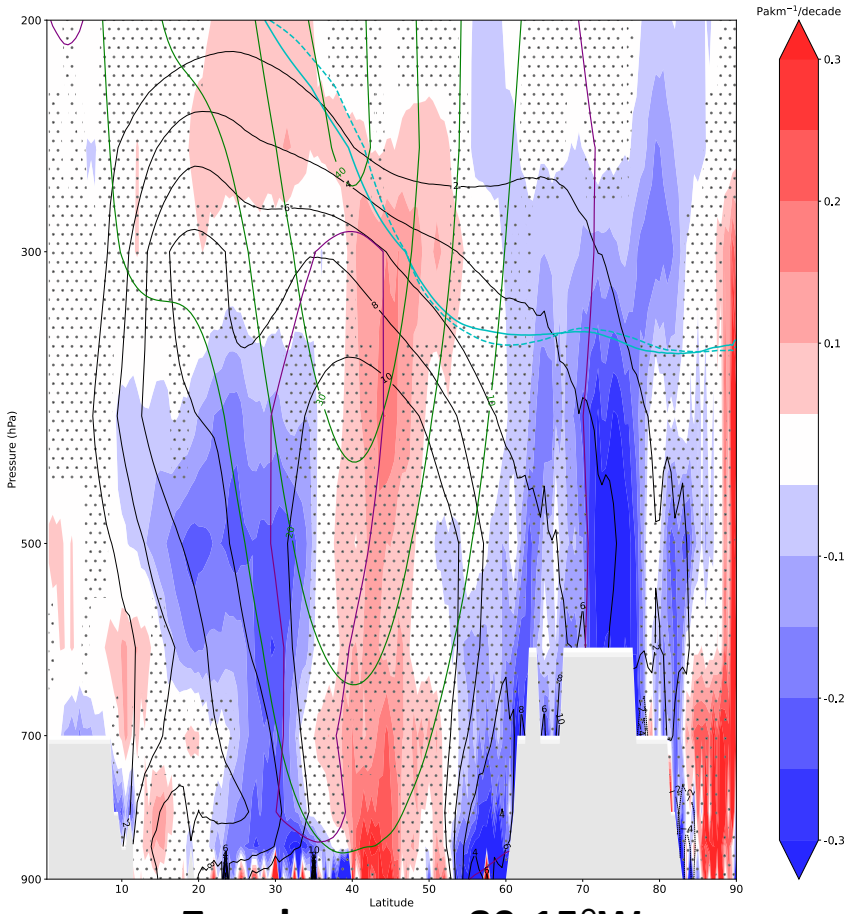


Diabatic heating trend (300 – 850 hPa)
Increase over the Gulf Stream
North of area of strongest potential temperature trend
as a consequence of the increase in heating, a westward tilted trough is formed[1], which is located upstream at upper levels (see previous slide)

Advection trend (300 – 850 hPa)
Reduced cold advection over western NA -> reduced land-sea contrast
Coincident with area of strongest potential temperature trend

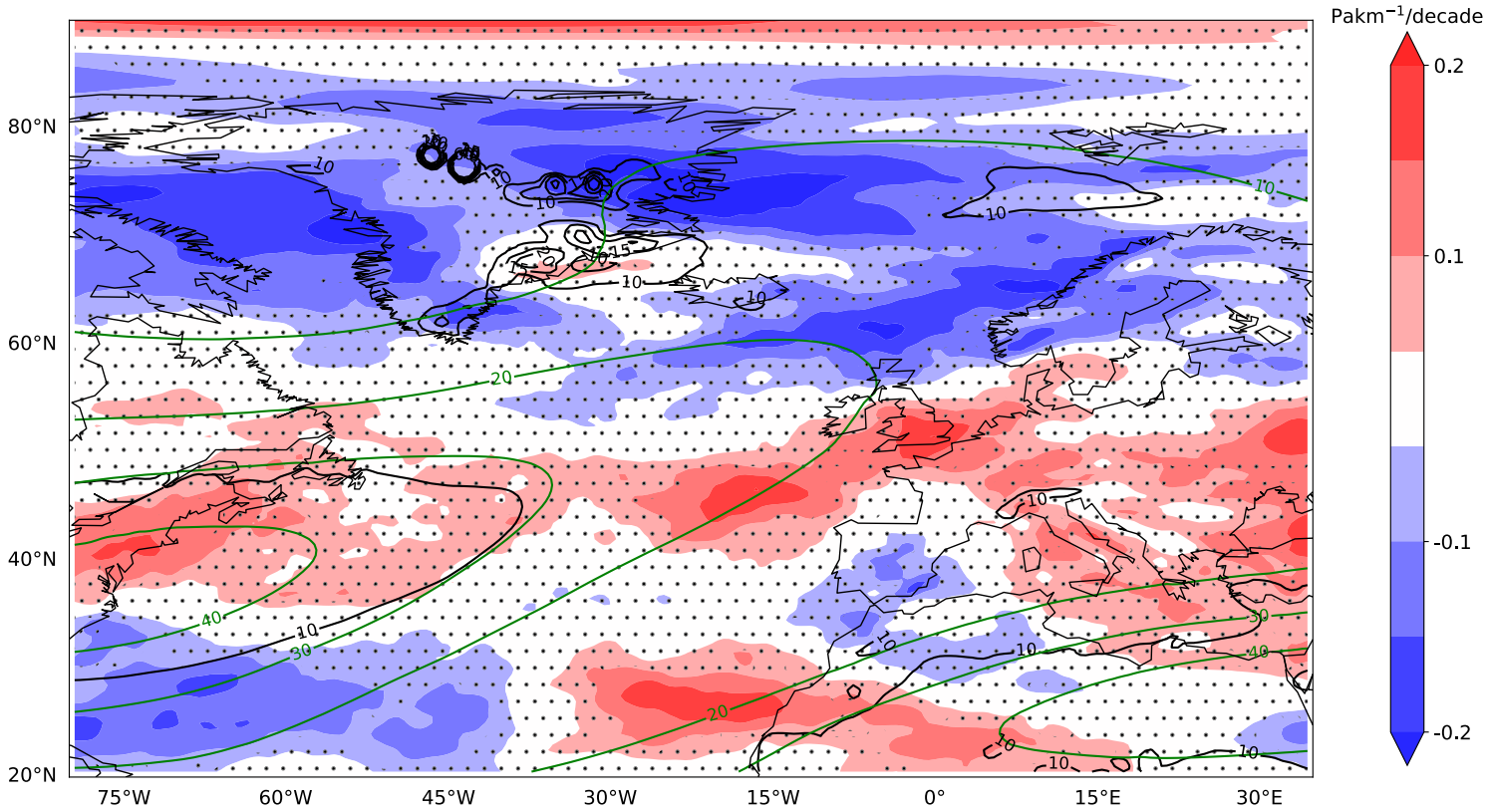
[1] Hoskins, B. J. & Karoly, D. J. The steady linear response of a spherical atmosphere to thermal and orographic forcing. J. Atmos. Sci. 38, 1179–1196 (1981).

Slope trends



Zonal average 80-15°W

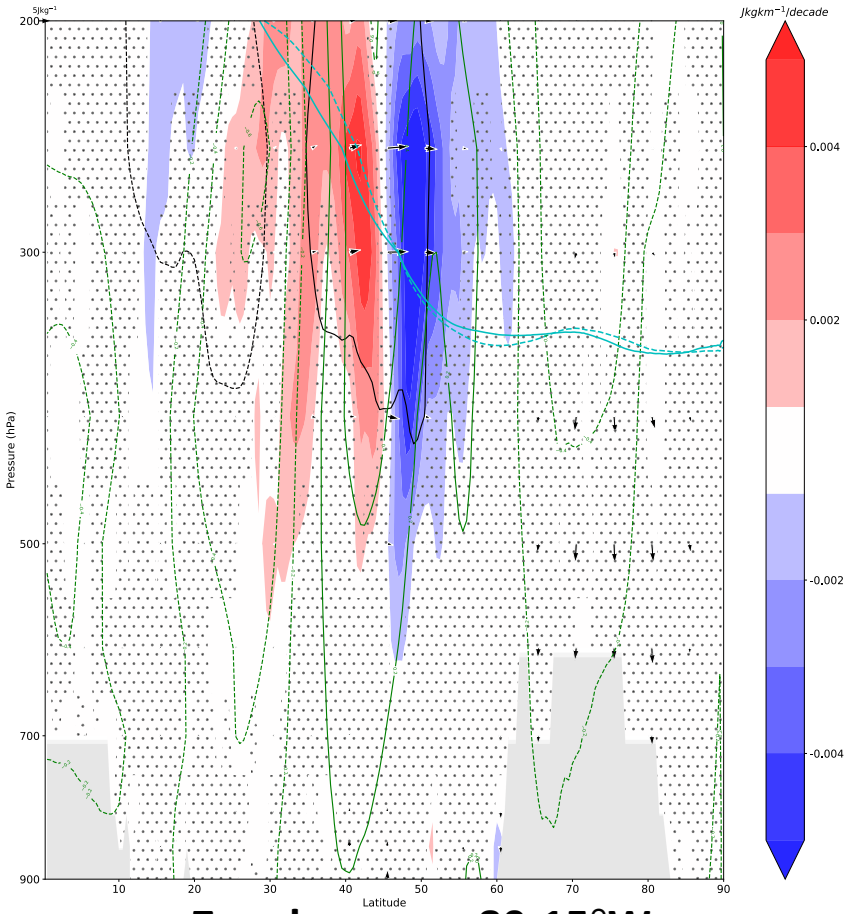
Shading	Trend (per decade)
Black contours	Climatological mean
Green contours	Zonal wind speed climatology
Purple contour	Region of strongest potential temperature trend
Blue contours	Tropopause level in first and last decade



Average 200-500 hPa

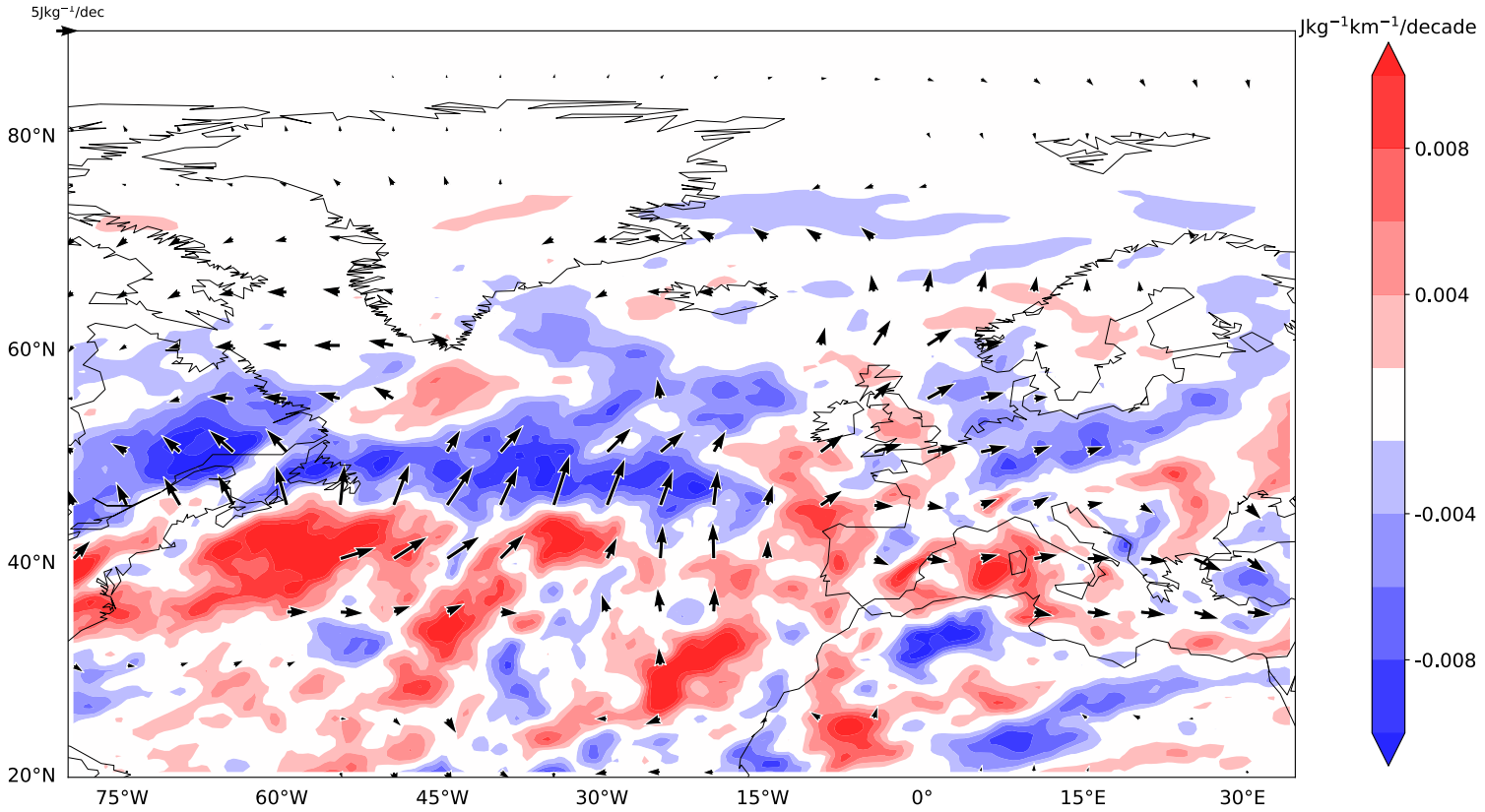
Slope increases around the climatological jet position
Alligned with the positive trend in diabatic heating

E vector trends



Zonal average 80-15°W

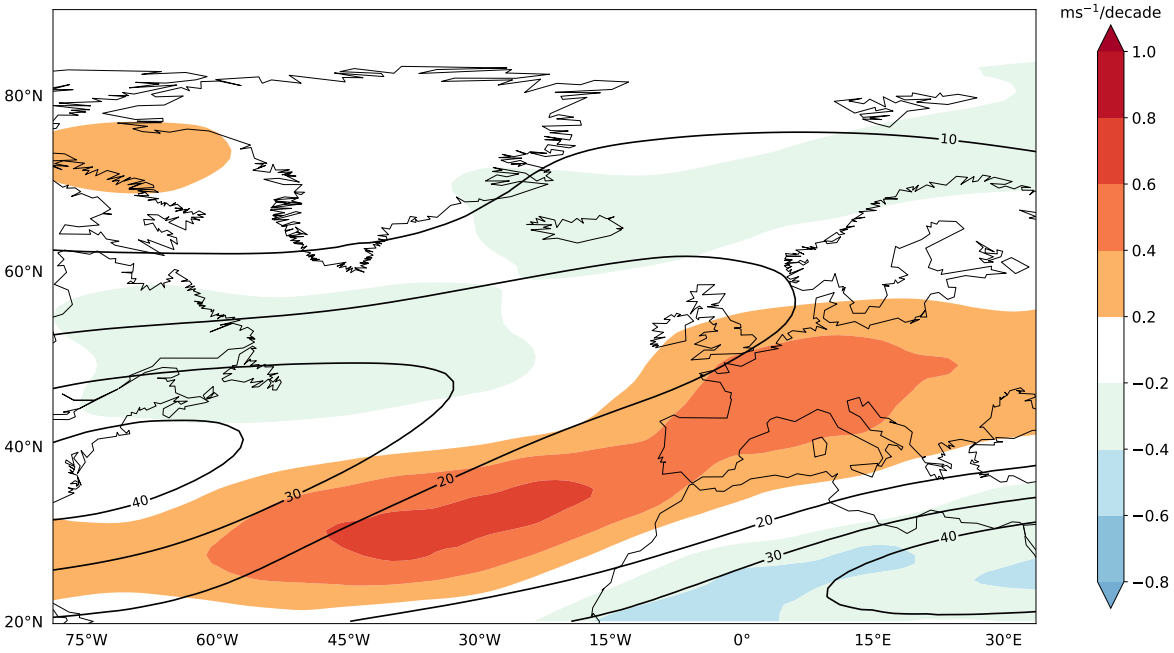
Shading	E vector divergence trend (per decade)
Black contours	CE vector divergence limatological mean
Green contours	Zonal wind speed climatology
Arrows	E vector trend



Trends at 250 hPa

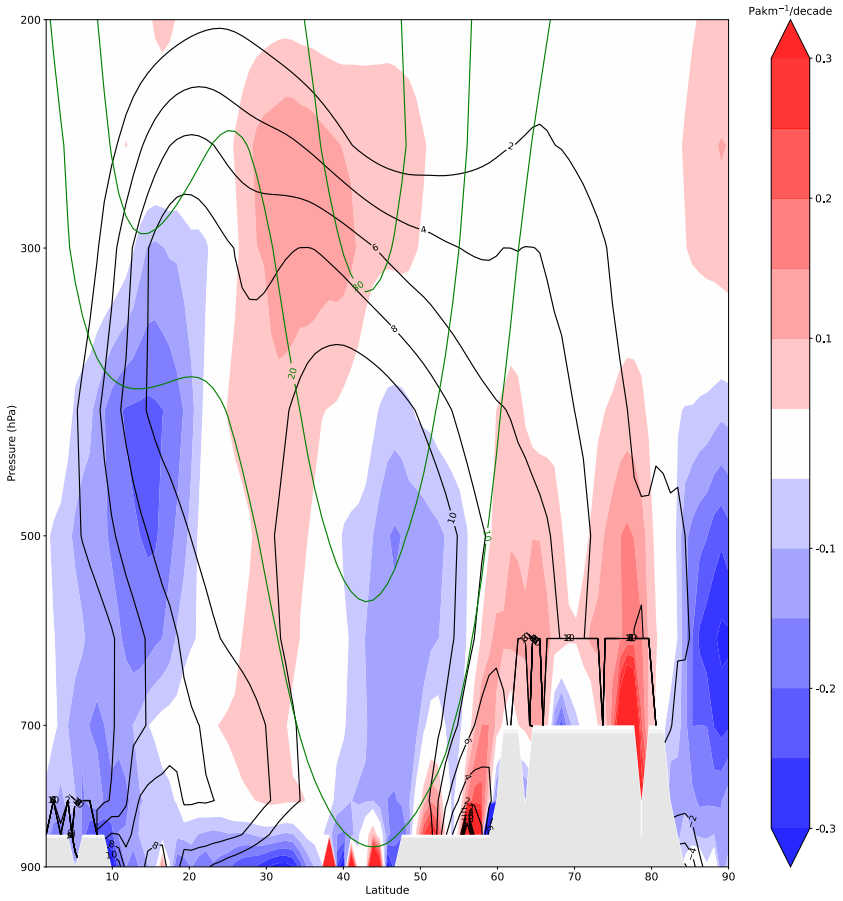
Increase of eddy momemtum convergence around the jet core
Poleward pointing E vector trend away from area of increased slope
The asymmetry in E vector trend (only poleward E vectors) could be explained by enhanced cyclonic eddies downstream of the trough anomaly

CESM trends (ensemble mean 1980-2022)



Zonal wind trend at 250 hPa (ensemble mean)

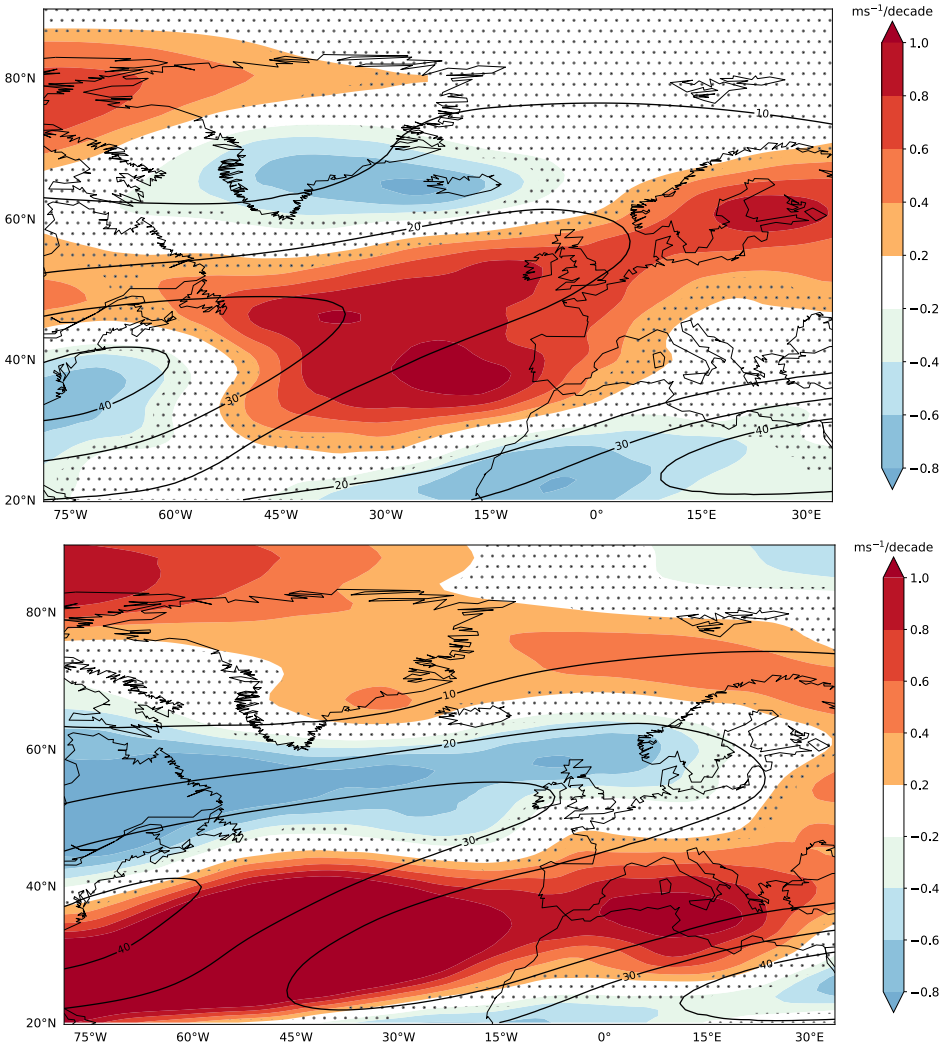
Positive wind speed trend is located more equatorward than in ERA5



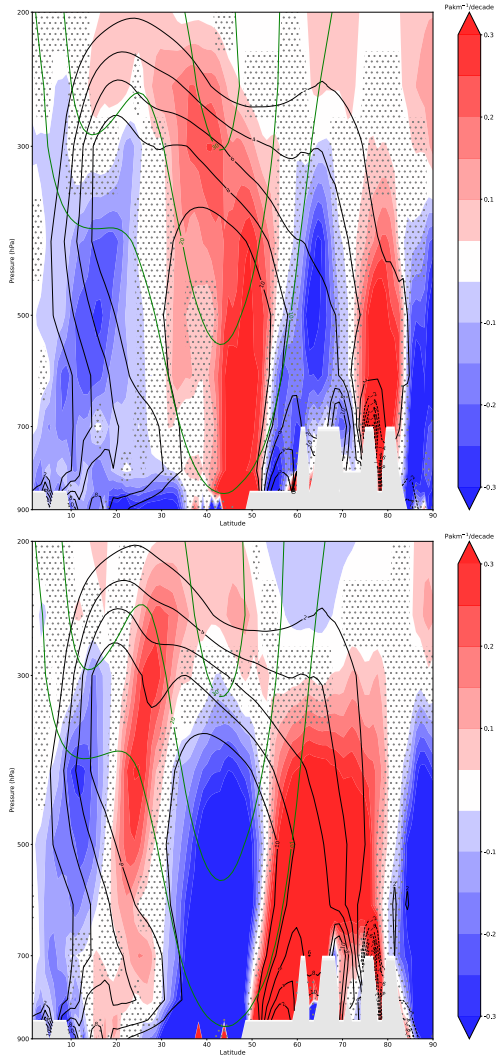
Zonal average of the slope

Similar tripple pattern as in observations, but shifted to the equator
This agrees well with the equatorward jet shift

Some individual members (1980-2022)



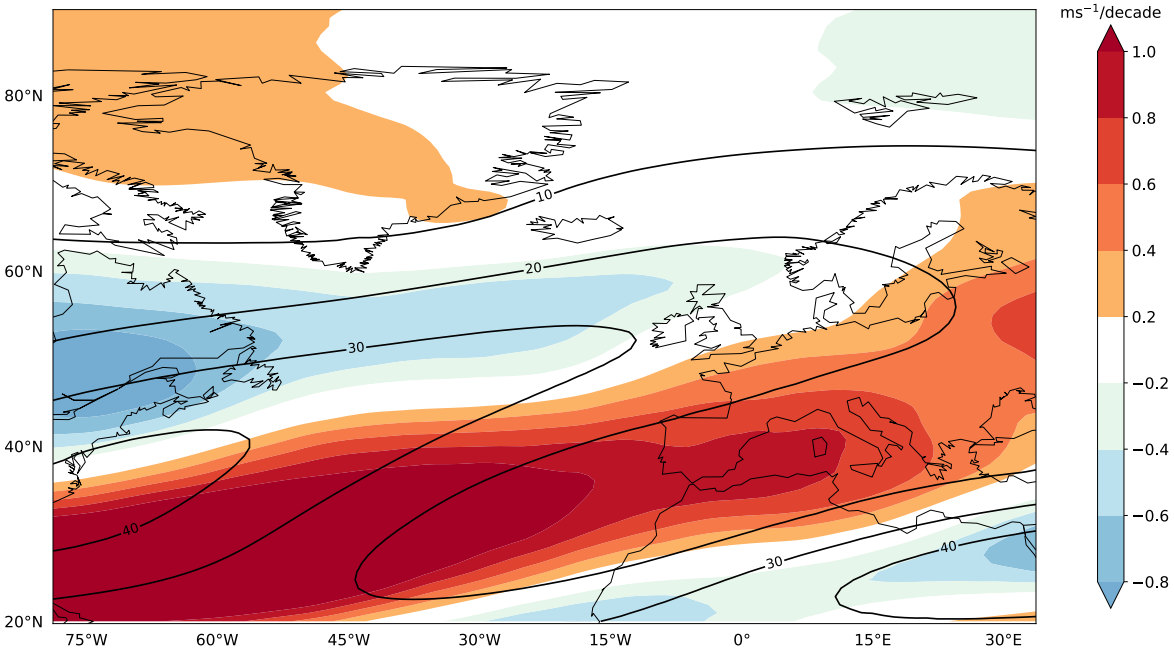
Zonal wind trend (250 hPa)



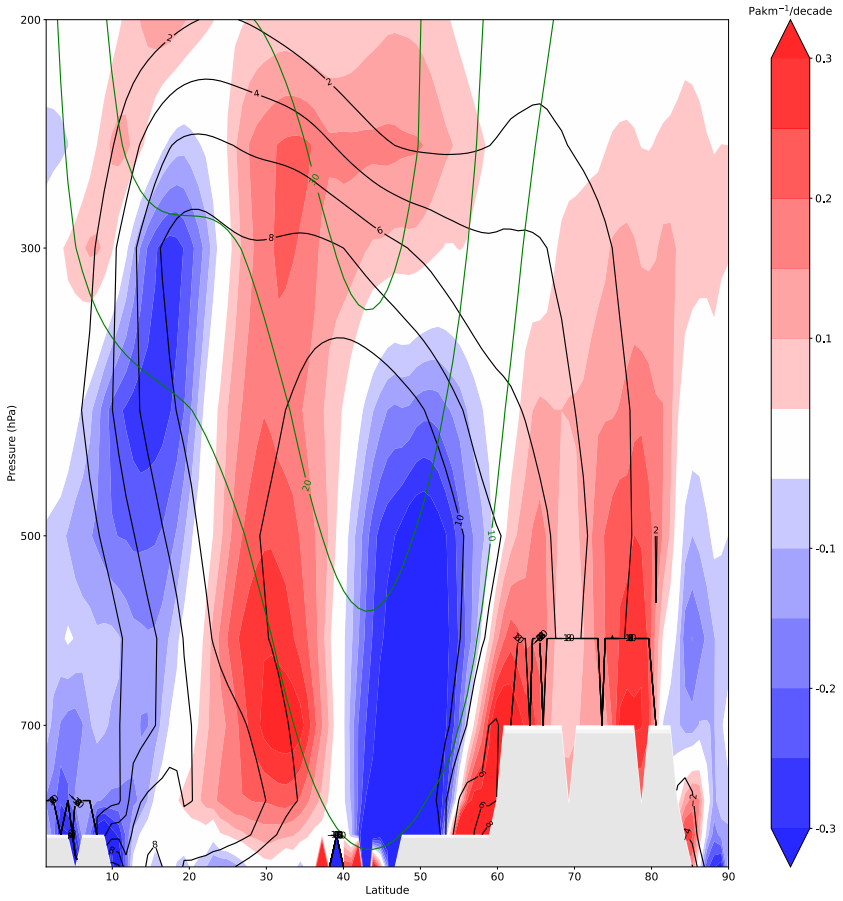
Slope trend (zonal mean 80 – 15°W)

- Large spread in wind trends for this period
- Positive wind trends alligned with positive slope trends

CESM trends (ensemble mean 2057-2100)



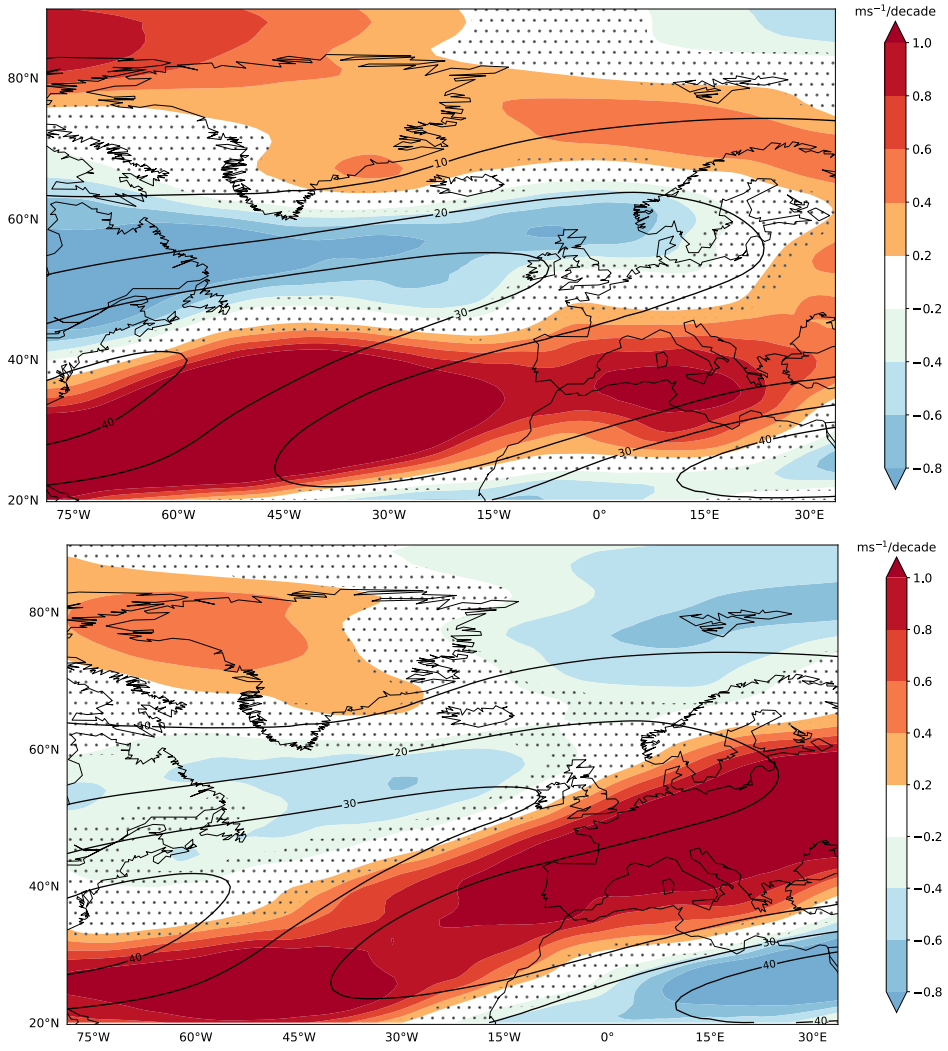
Zonal wind trend at 250 hPa (ensemble mean)



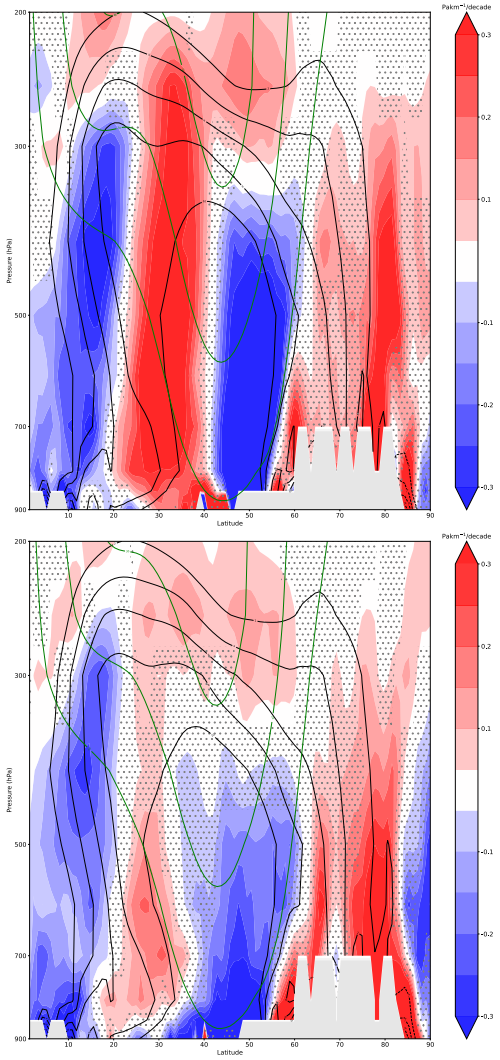
Zonal average of the slope

Similar ensemble mean patterns to what
is obtained for the historical period, but more intense

Some individual members (2057-2100)



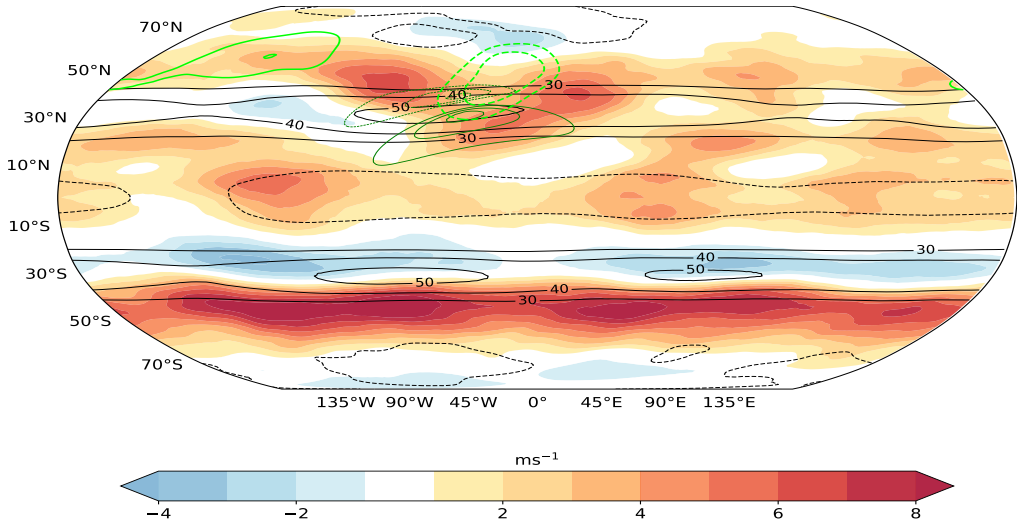
Zonal wind trend (250 hPa)



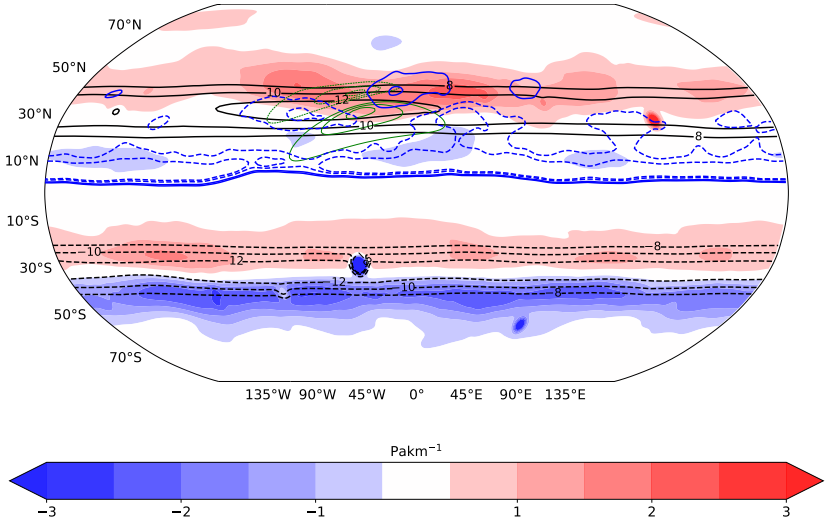
Slope trend (zonal mean 80 – 15°W)

- Reduced spread at the end of the century
- More intense trends in this period
- This could incdicate a delay in the response of some ensemble members

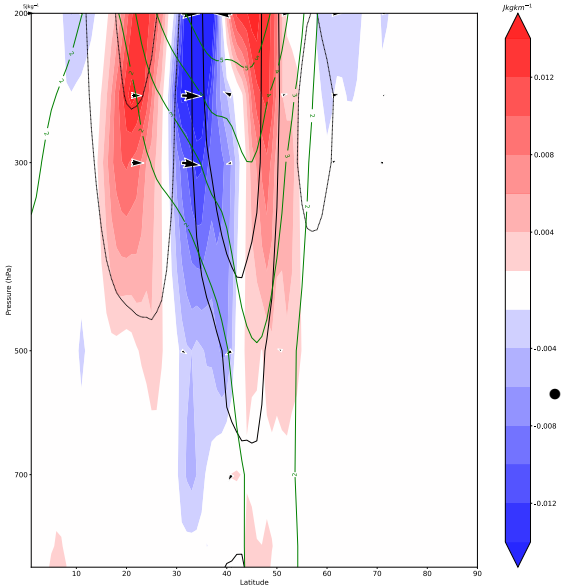
Aquaplanet simulations



250-hPa zonal wind / 500-hPa geopotential difference

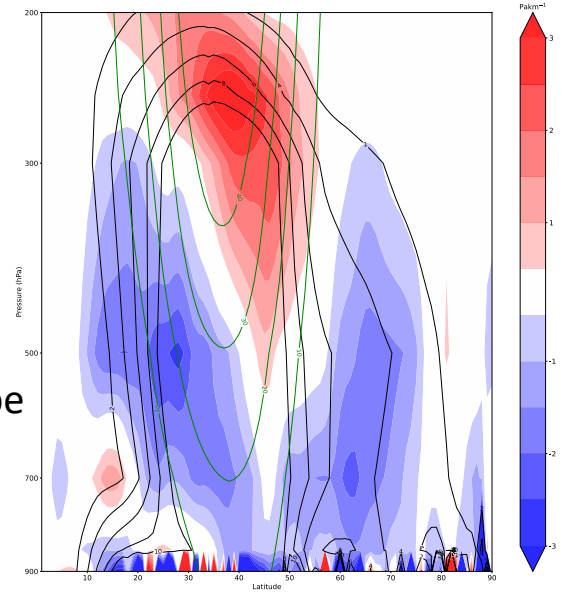


Slope (200-500 hPa) / diabaic heating (300-850 hPa)



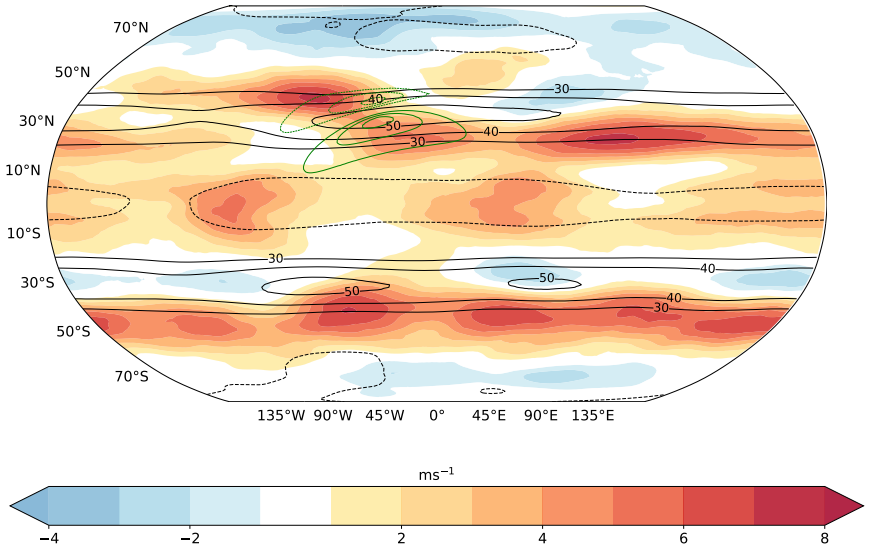
E vector divergence / zonal wind speed difference

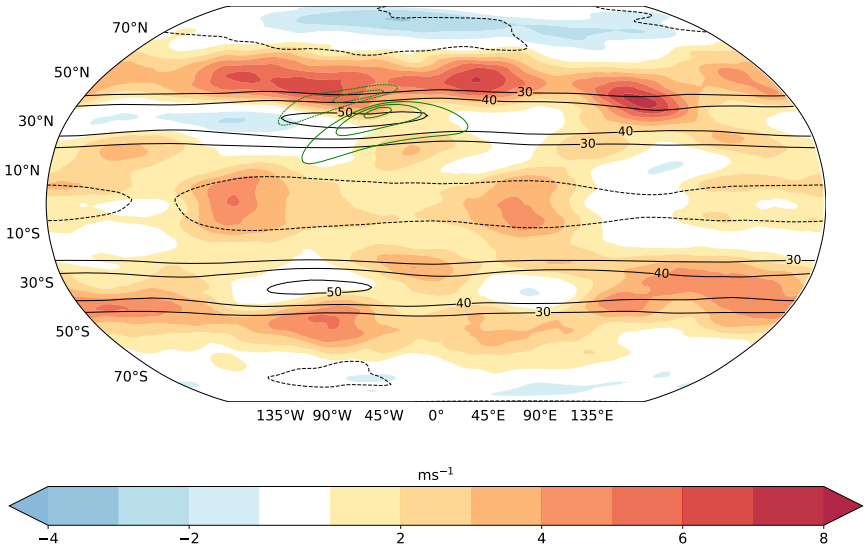
- Similar features to what is observed in ERA5
- Not a clear poleward shift of the jet in the NH
- Upper-level trough intensified upstream
- Similar tripple pattern in the slope and enhanced eddy momentum convergence

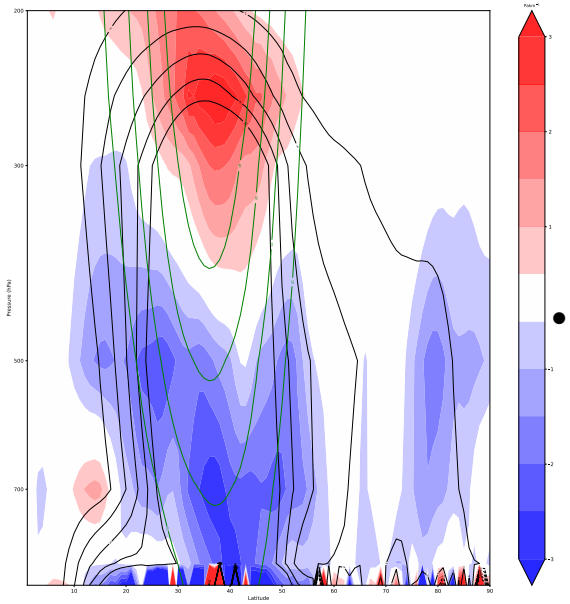


Slope difference/ zonal wind climatology (cntl)

Sensitivity to SST position

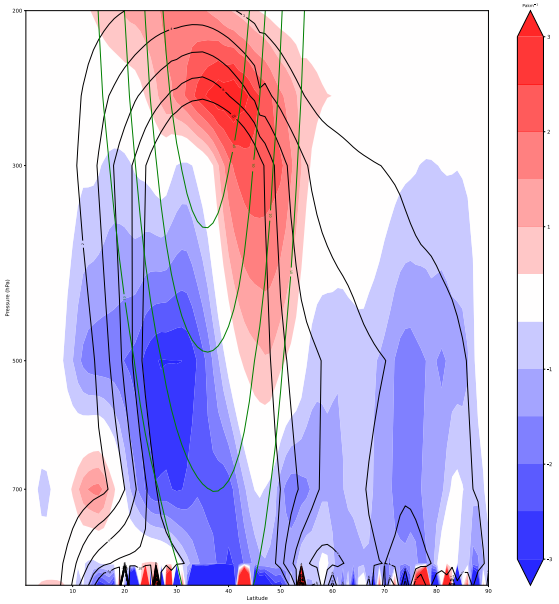






Front at 38N

- Strong sensitivity of the jet shift to the location of the SST front
- The jet shift is again related to the baroclinicity response pattern
- Equatorward shift downstream of the front when it is located more southward
- Reduced influence of the front when it is located at higher latitudes



Front at 42N

Conclusions

Conclusions

- The North Atlantic jet stream has intensified in winter and roughly remained in place during the last decades
- Diabatic heating has intensified over the Gulf Stream. As a result, baroclinicity and eddy momentum convergence have increased around the jet core
- The analyzed climate simulations fail to reproduce the observed behavior. There is a large ensemble spread, especially over the historical period. The adequate simulation of the positive baroclinicity trend is crucial for the jet trends
- The main physical mechanisms can be reproduced with idealized aquaplanet experiments. However, the jet response exhibits a large sensitivity to the position of the SST anomaly