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Equatorward North Atlantic jet biases in CMIP models and implications for simulated regional atmosphere-ocean linkages

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EGU General Assembly 2022

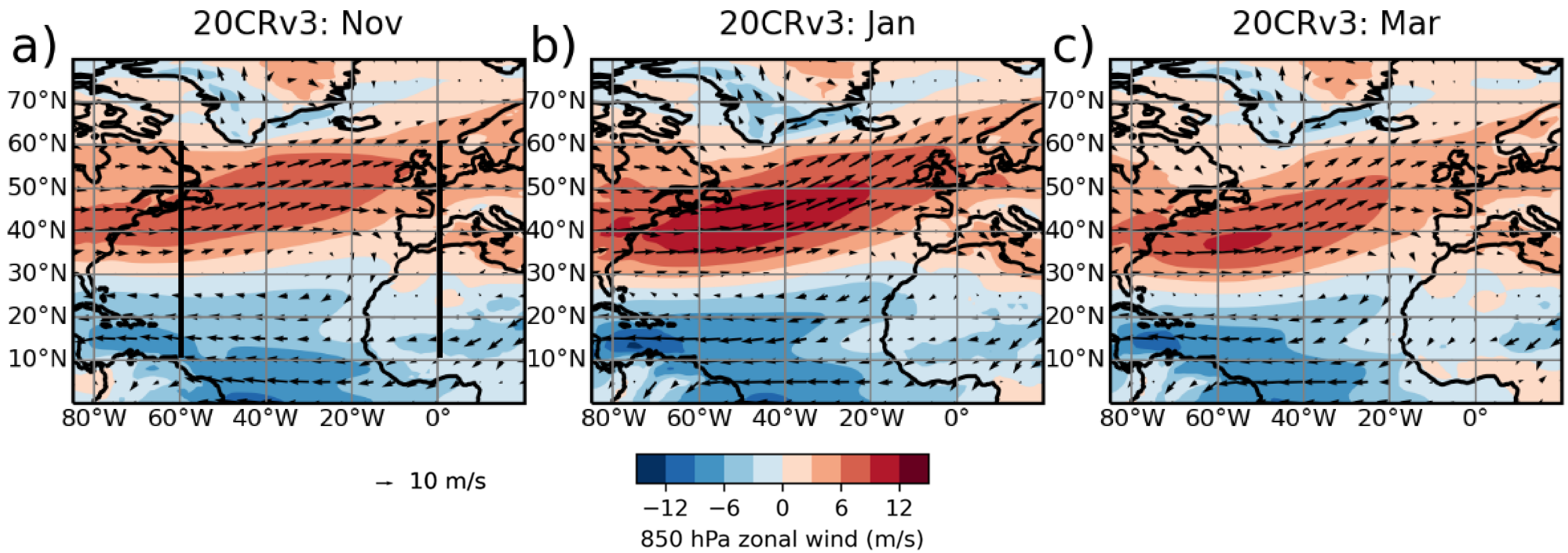
Additional display material

See Bracegirdle et al. (2022), ERL, https://doi.org/10.1088/1748-9326/ac417f

Overview

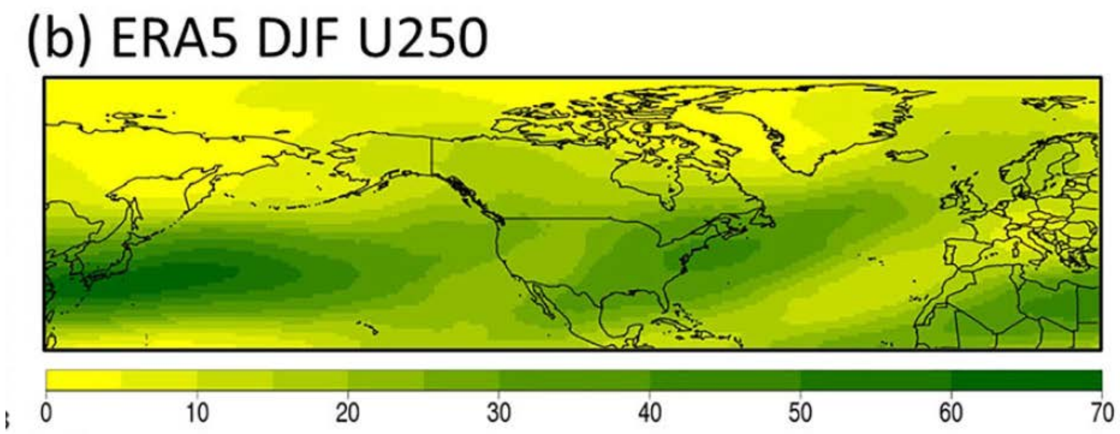
- Introduction and motivation
- Part 1 – An update on North Atlantic (NA) jet biases in the latest climate models
- Part2 – Implications for model representation of NA atmosphere-ocean linkages

Introduction: NA low-level jet structure



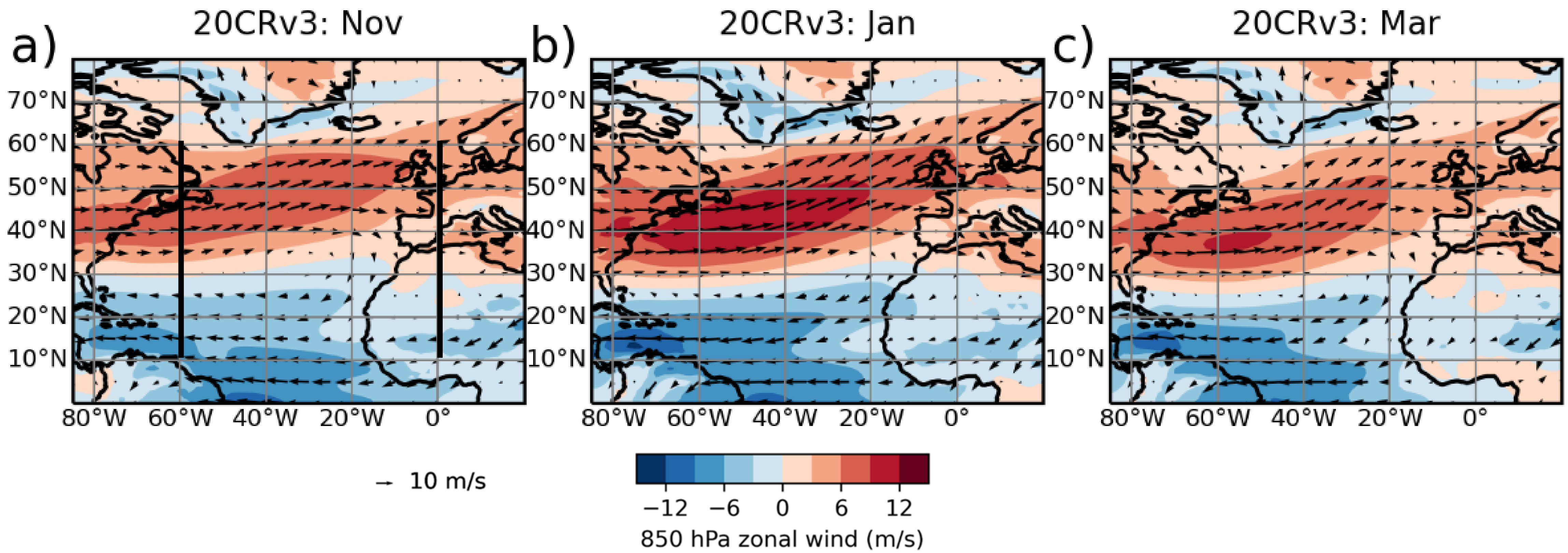
- Early, mid and late-winter climatologies of time mean 850 hPa (~1.5 km) winds over the NA. Derived from reanalysis data (20CRv3) over the period 1861-2005.
- Note the changes in structure over the season, including an equatorward shift of the western part of the jet.

- The low-level tropospheric jet extends to the upper troposphere

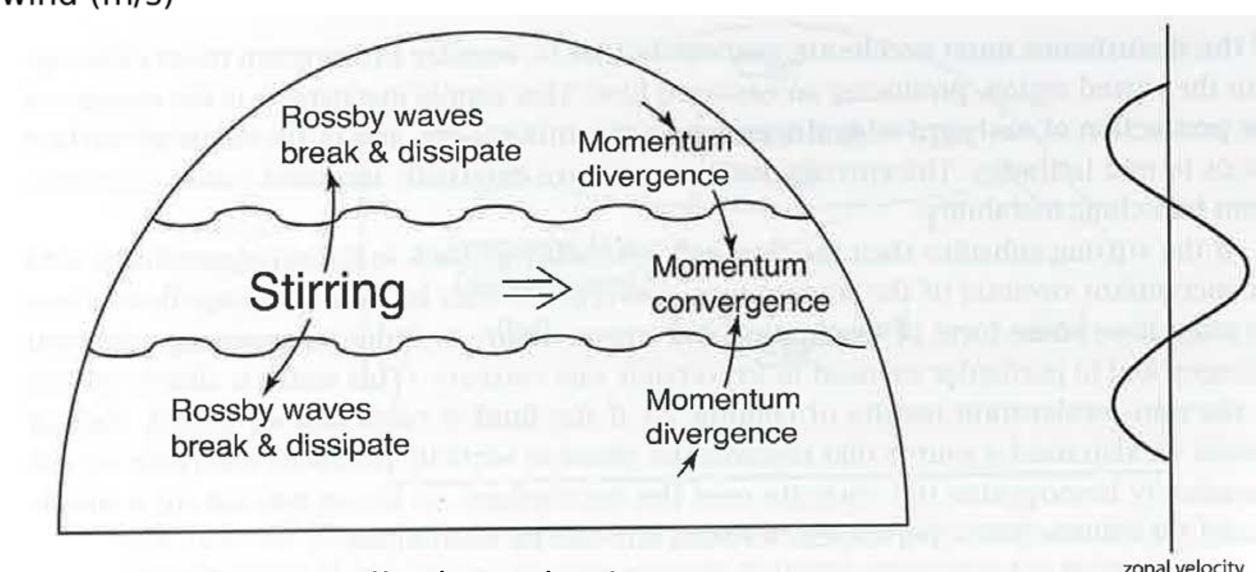


Harvey et al. (2020)

Introduction: what drives the jet?



- Planetary-scale time mean jets emerge from stirring by eddies (baroclinic cyclones in this case).
- This results in momentum convergence in the jet core and divergence on its northern and southern flanks.
- Meridional temperature gradients are a key factor in the location and strength of baroclinic eddies.



Vallis (2006), Chapter 12, page 490.

Introduction: Impacts of jet variability

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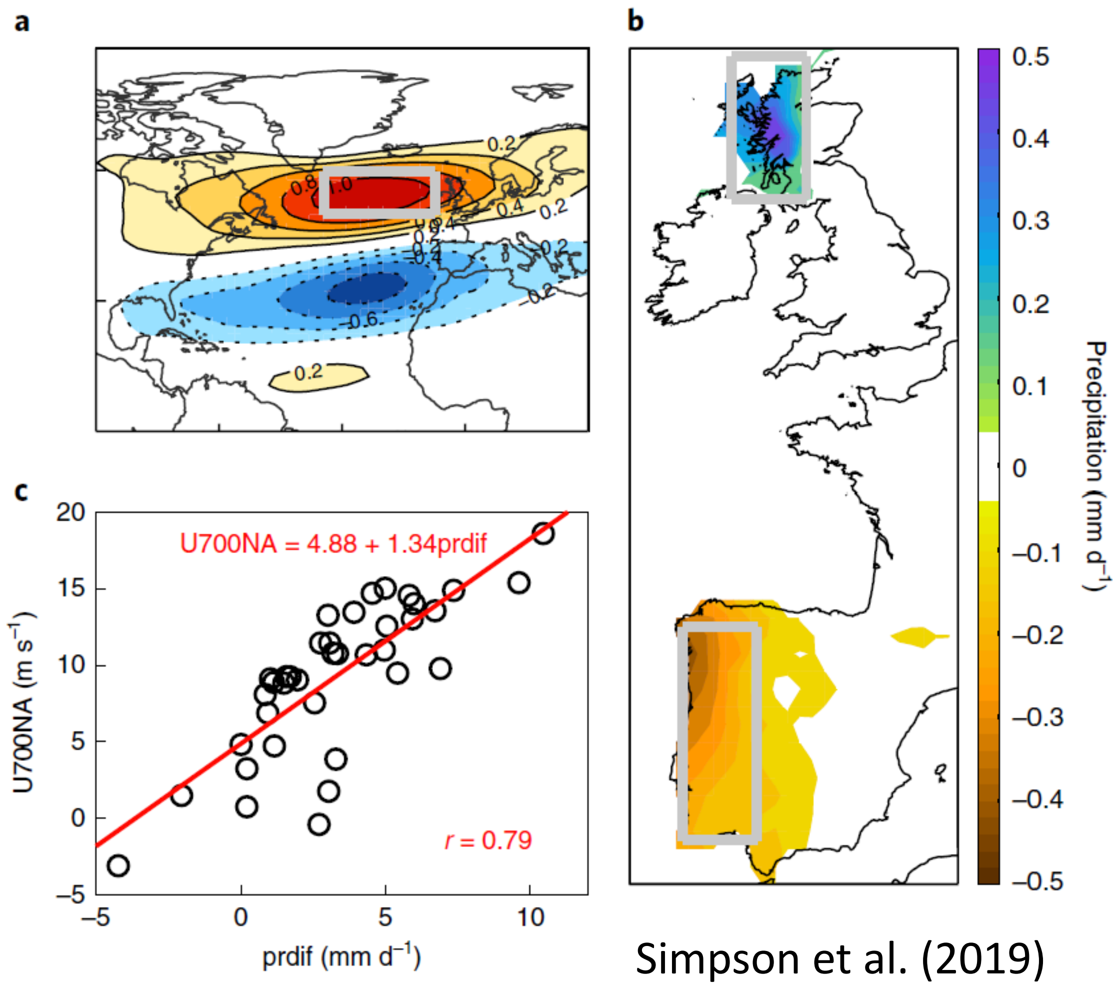
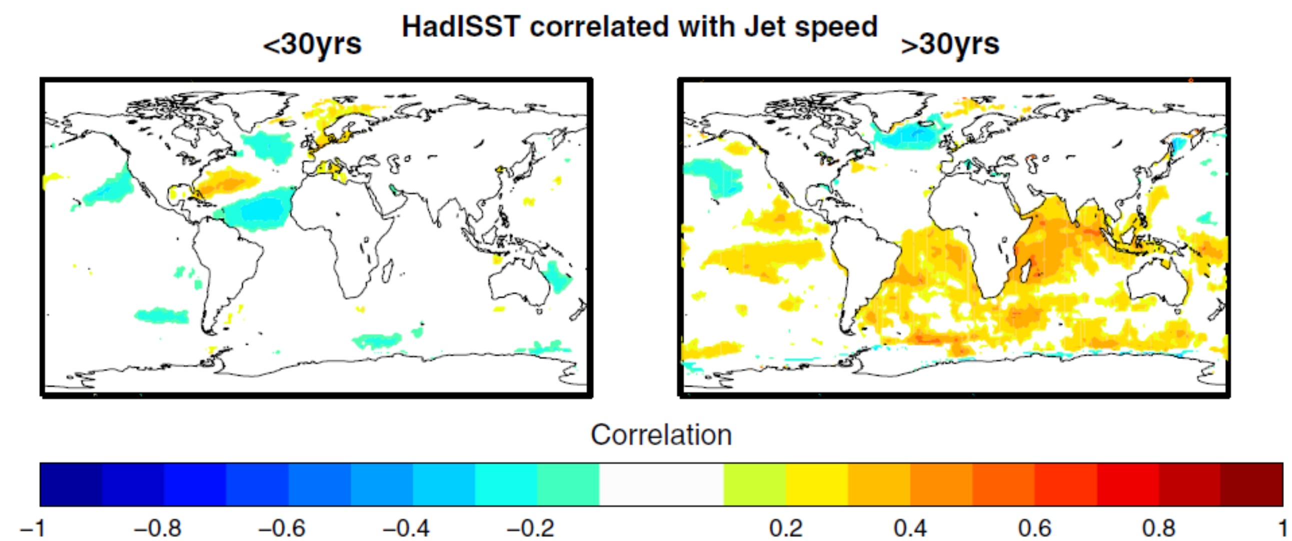


Simpson et al. (2019)

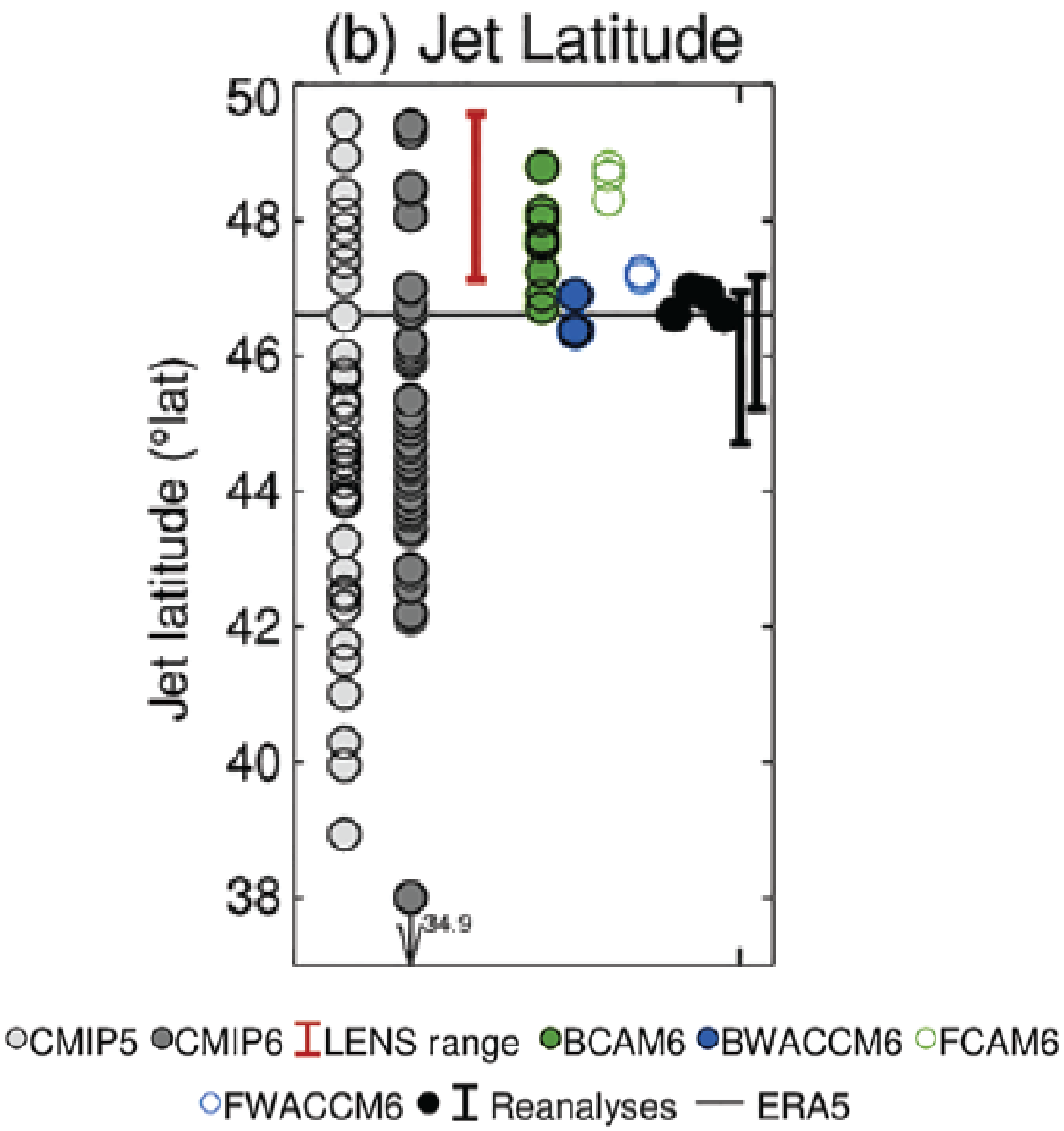


Woollings et al. (2015)

- Jet variability affects conditions over western Europe
- For example significant impacts on winter precipitation over the northwest of the UK and Portugal/Spain.

- Jet speed variability exhibits strong links with key regions of the NA ocean, in particular the sub-polar gyre (SPG).
- The SPG is key for deep water formation and is a important for seasonal-decadal predictability of the NA climate system.

Introduction: Climate model jet biases

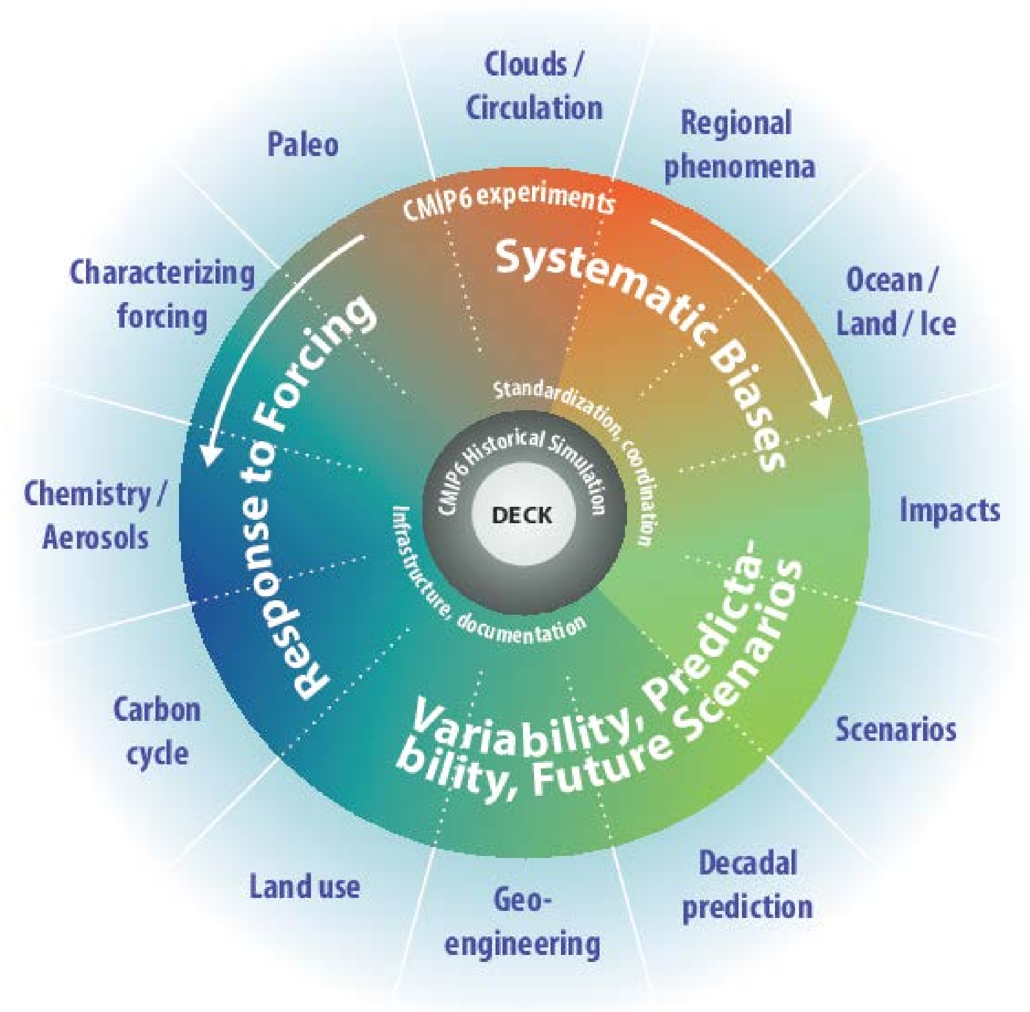


Simpson et al., (2020)

- Previous generations of climate models (CMIP5 and before) exhibit an equatorward bias in simulated location of winter NA eddy driven jet.
- This is most prominent in early winter (Iqbal et al., 2018).
- Recent research shows that the canonical winter (DJF) bias is slightly reduced in the latest generation of climate models (CMIP6).
- **Is the prominent early-winter equatorward bias seen in previous model generations still evident in CMIP6?**

Climate models: CMIP5 and CMIP6

- World Climate Research Programme (WCRP) Coupled Model Inter-comparison Project (CMIP).
- Closely aligned with the IPCC process.
- Previous generation: CMIP5, major part of IPCC AR5.
- Current generation: CMIP6, major part of IPCC AR6.
- A huge range of climate model experiments and configurations.
- Focus here is on *historical* simulations. These are free-running full-complexity climate models with historical evolutions of natural and anthropogenic climate forcings (such as volcanic eruptions and greenhouse gas changes).



Eyring et al. (2016)

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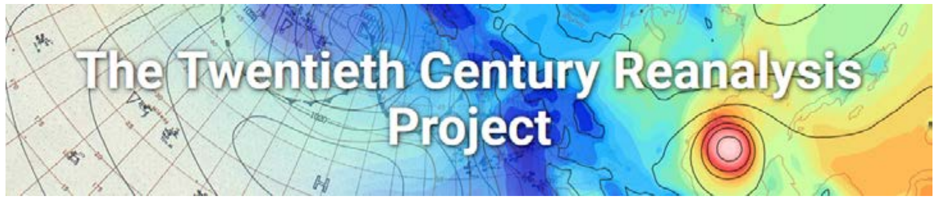
Reanalysis datasets



ECMWF

- Reanalysis datasets provide an estimate of the observed state of the atmosphere in the past.
- Provide a model-based interpolation between available observations (both in space and time).
- Most draw from a wide range of data sources.
- Changing input data (e.g. introduction of satellite remote sensing in the late 1970s) can introduce inconsistencies.
- Longer-term reanalyses based just on limited data types (e.g. sea level pressure) can provide more consistent reconstructions further back in time.
  - One such dataset is the main reanalysis used here: the **NOAA-CIRES-DOE 20th Century Reanalysis (20CRv3)**. This is based on surface pressure observations. It is available from 1836, although we used data from 1861 due to uncertainty over early corrections of biased ship observations.
  - To sample uncertainty associated with model interpolation between observations, **80 ensemble members** are available.
- To check consistency with other datasets, two ECMWF datasets are also used.
  - **ERA20C**. Like 20CRv3 this is a longer-term dataset (from 1900) with reduced observational data input (sea-level pressure and surface winds).
  - **ERA5**. A full complexity reanalysis available from 1950 to present day.

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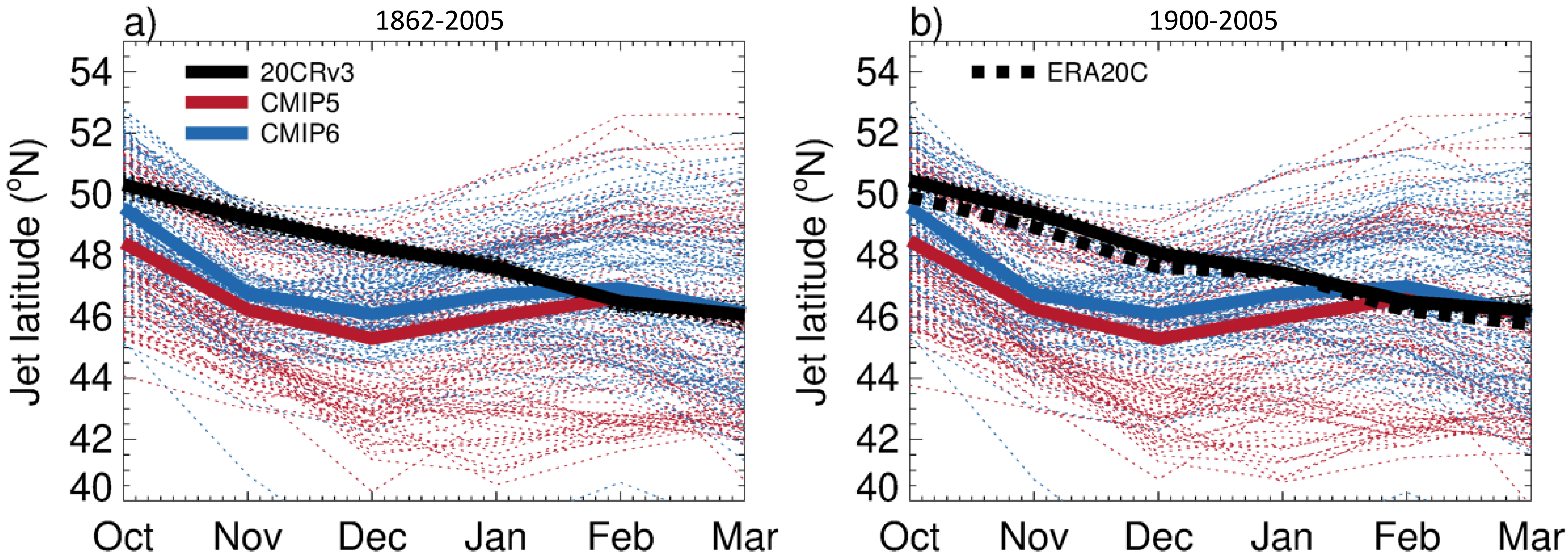
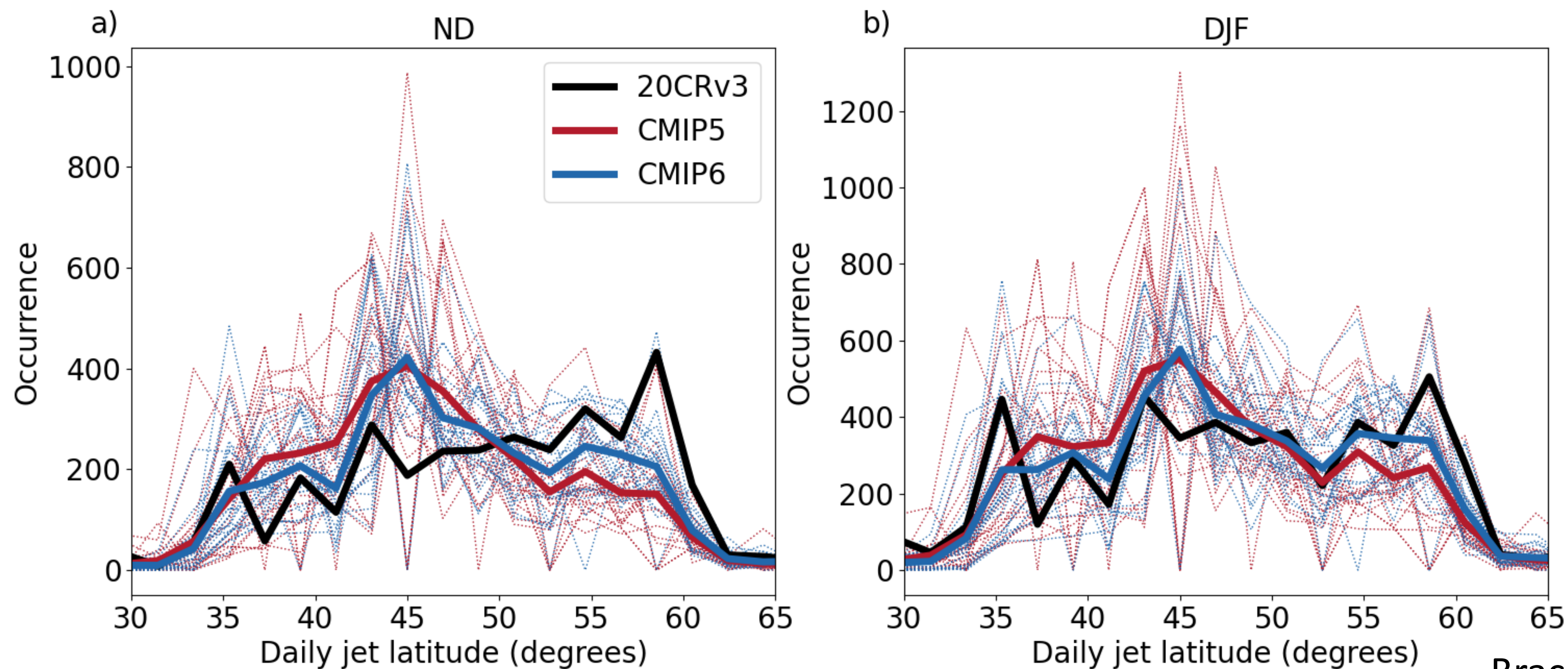
Observed and simulated NA low-level jet latitude month by month



Bracegirdle et al. (2022)

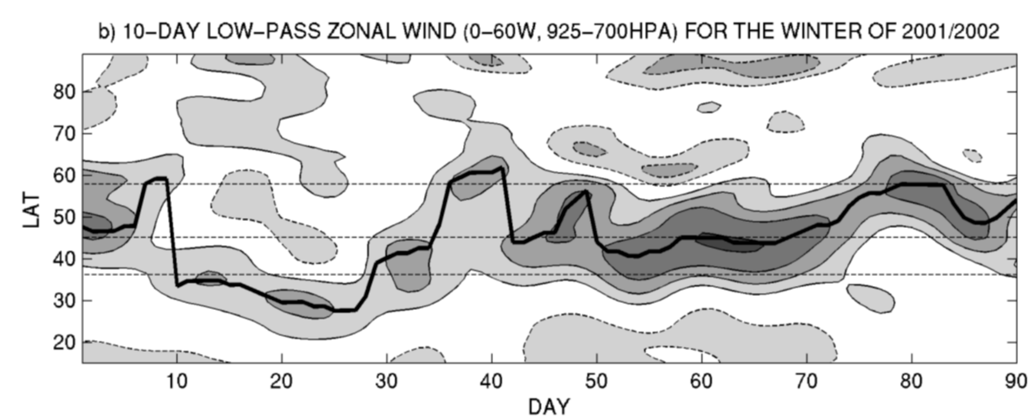
- The reanalysis-derived climatological jet latitude exhibits an overall equatorward shift from ∼50◦ N in October to ∼46◦ N in March
- A clear Equatorward bias persists in the early winter (November – December)
  - 35 CMIP5 models; 37 CMIP6 models

Daily jet latitude variability



Bracegirdle et al. (2022)

- In Nov-Dec there is a clear northern preferred jet location.
- CMIP models general fail to capture this.
- Less apparent for canonical winter (DJF).



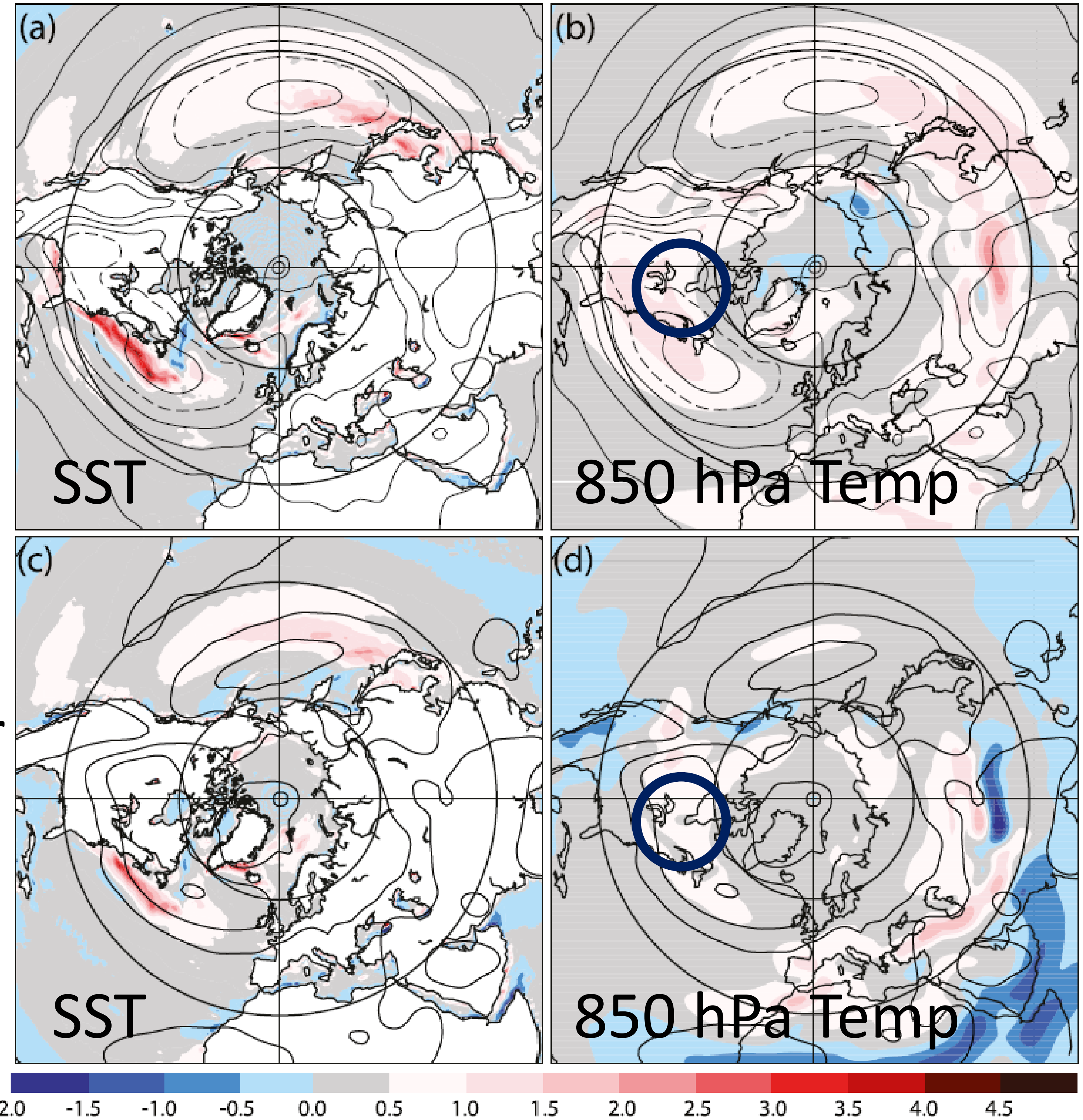
Woollings et al. (2010)

Why does the jet shift equatorward from early to late winter?

Meridional temperature gradients and storm tracks

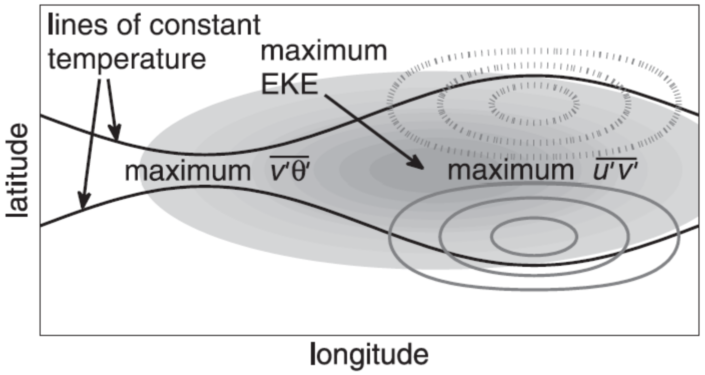
Winter (DJF)

Summer (JJA)



"the upstream portion of the Atlantic storm track and the lower tropospheric baroclinicity over North America remain coincident throughout the year, moving together in latitude."

Hoskins and Hodges (2019, pt1)

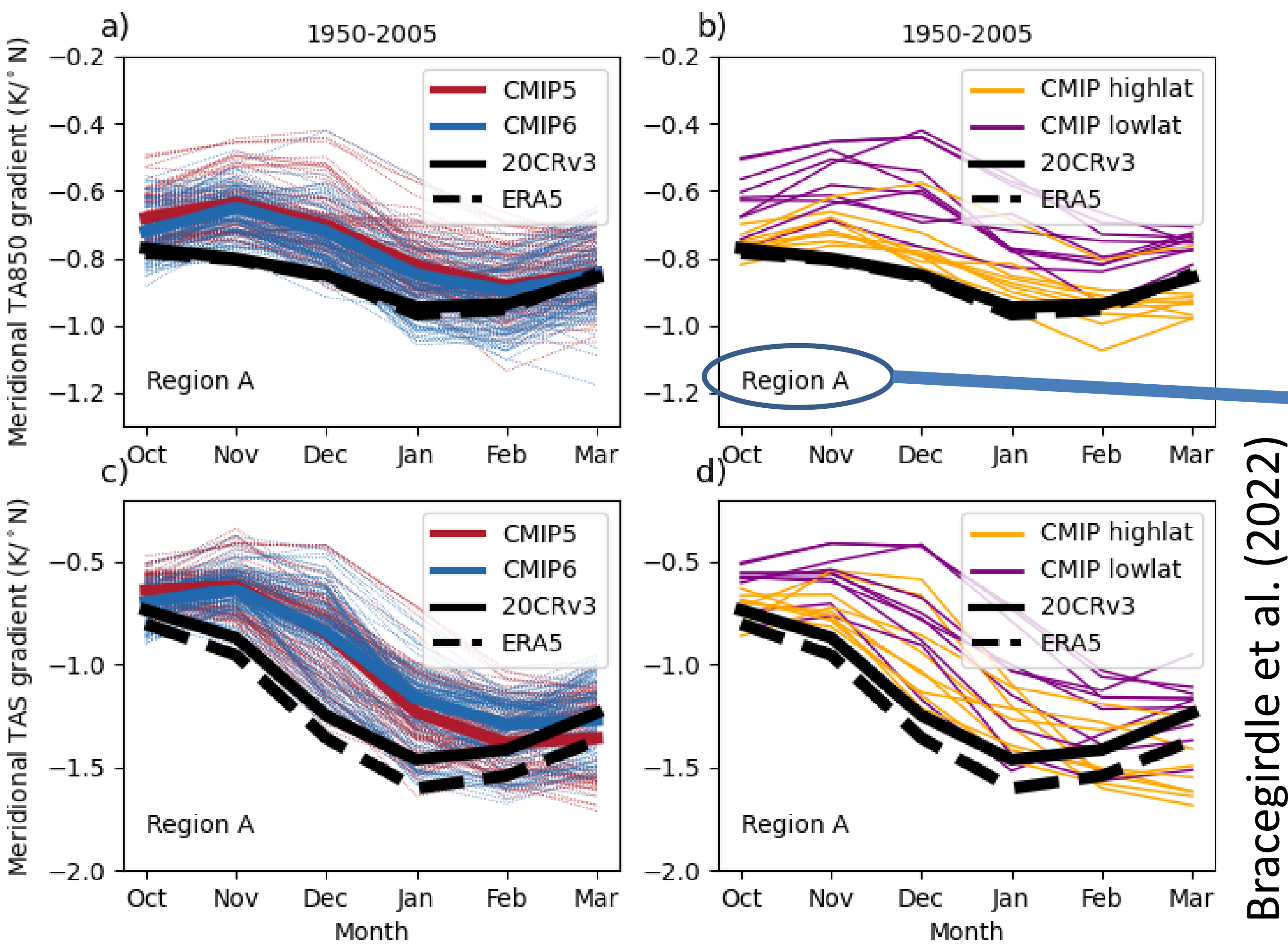


Eddies continue to grow as they leave the most unstable region (Gerber and Vallis, 2009).

Why is the latitude bias more pronounced in early winter?

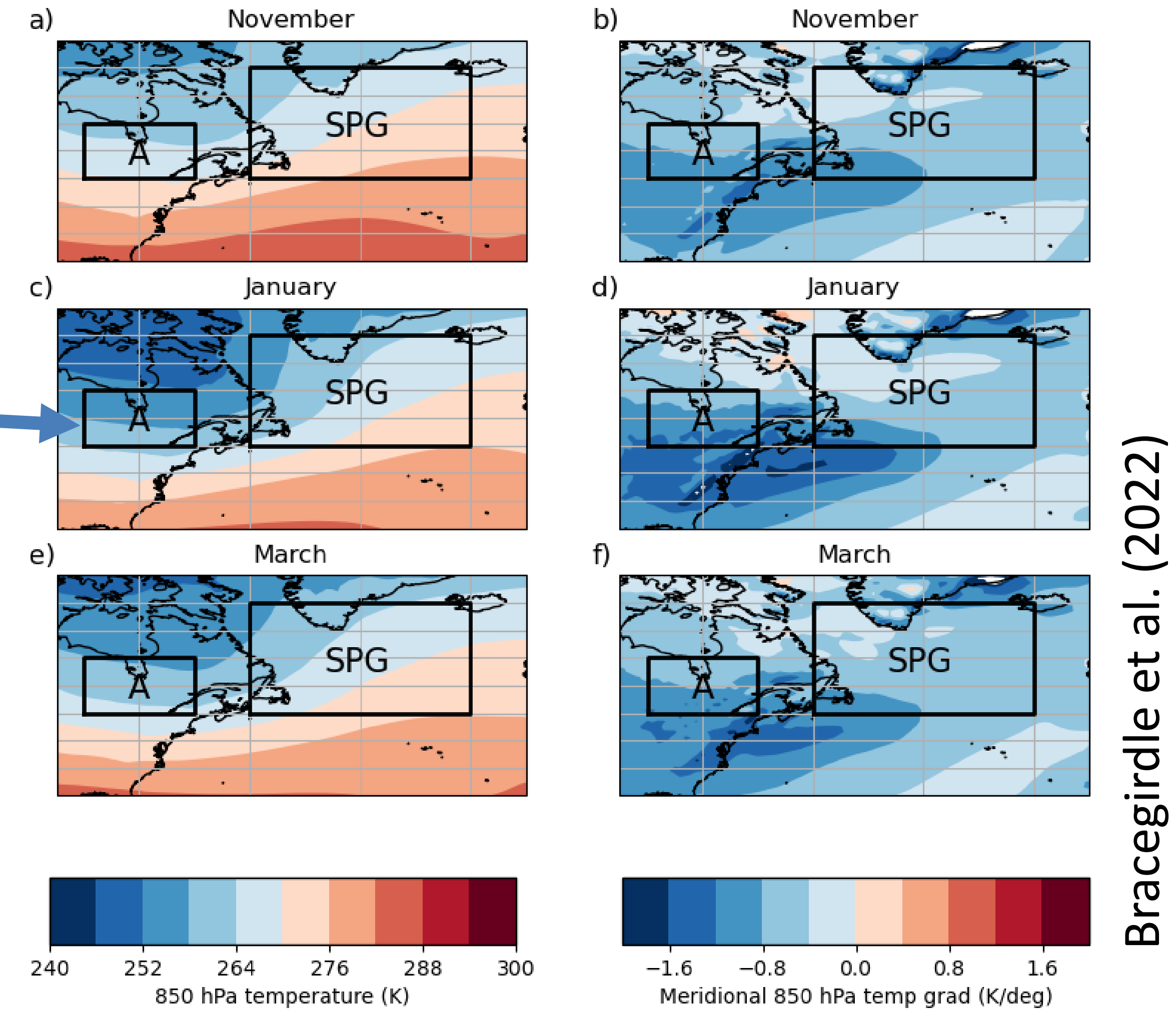
a link to eastern N. American temperature gradients

Eastern N. America meridional temperature gradient



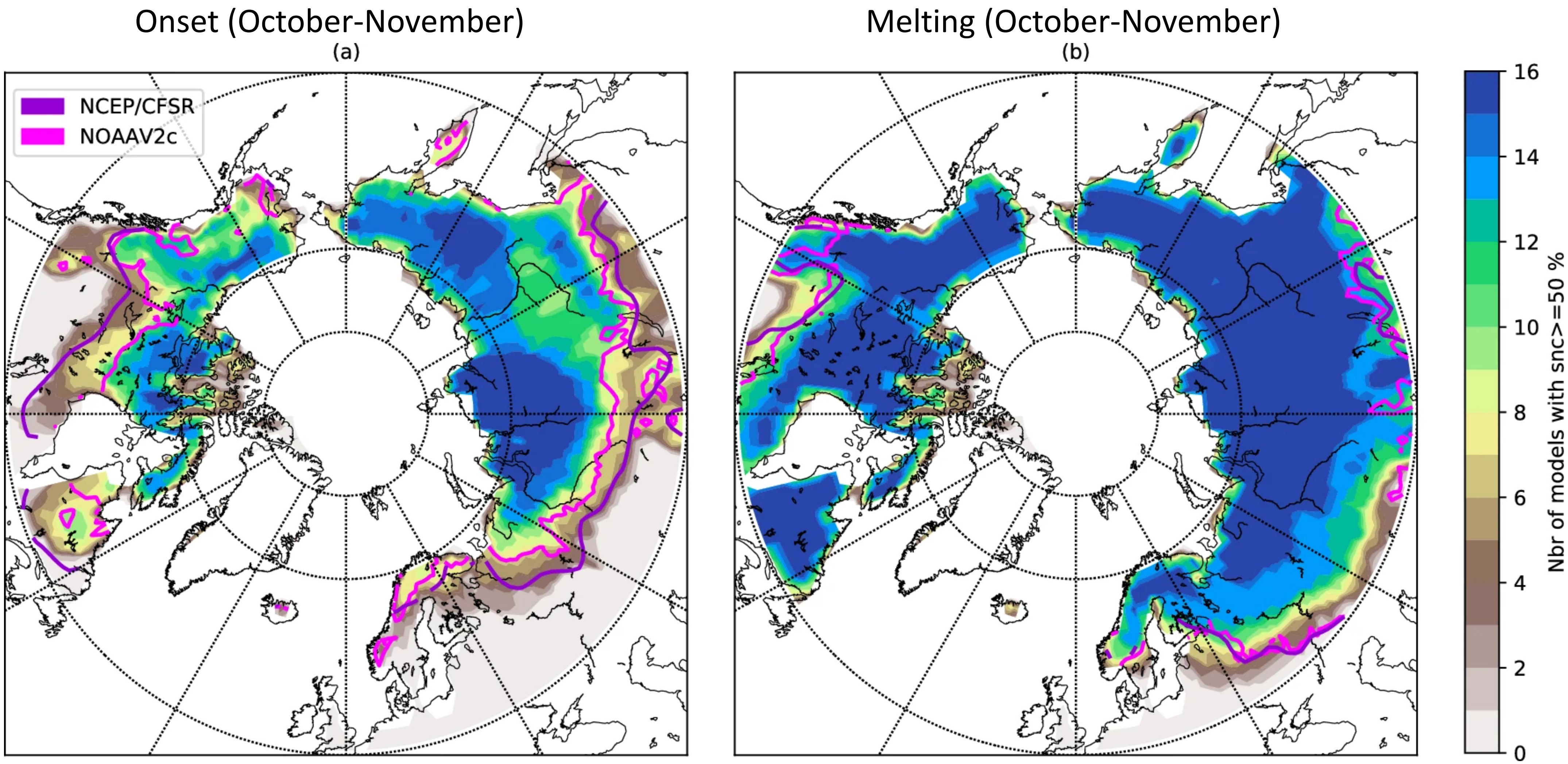
850 hPa temperature (20CRv3 climatology)

Meridional 850 hPa temperature gradient (20CRv3 climatology)



- Early winter meridional temperature gradients systematically too weak in CMIP models.
- Those models with weaker gradients also exhibit larger equatorward jet biases (purple lines in b and d of left plot).

N. America snow cover biases in early winter in CMIP5



Santolaria-Otin and Zolina (2020)

- The snow margin position (SMP) in the CMIP5 historical simulations is in better agreement with observations in spring than in autumn, when close agreement across the CMIP5 models is only found in central Siberia.
- Many CMIP5 models do not capture the onset season over eastern N. America, with the snow margin too far north.

N. America snow cover biases in early winter in CMIP5

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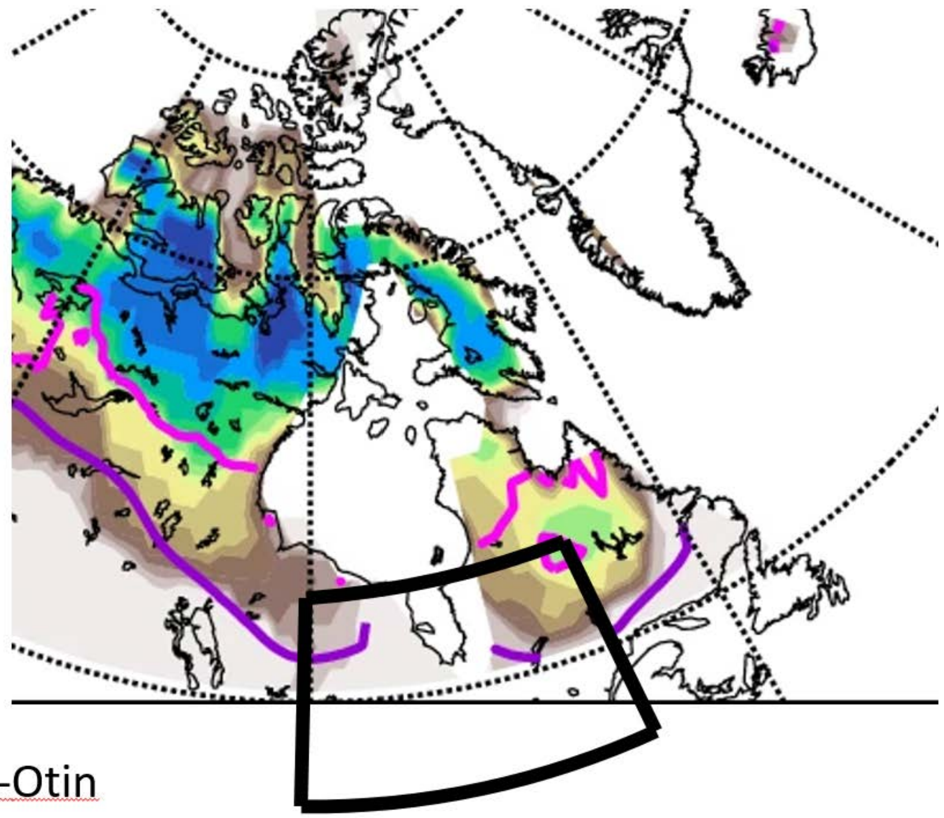
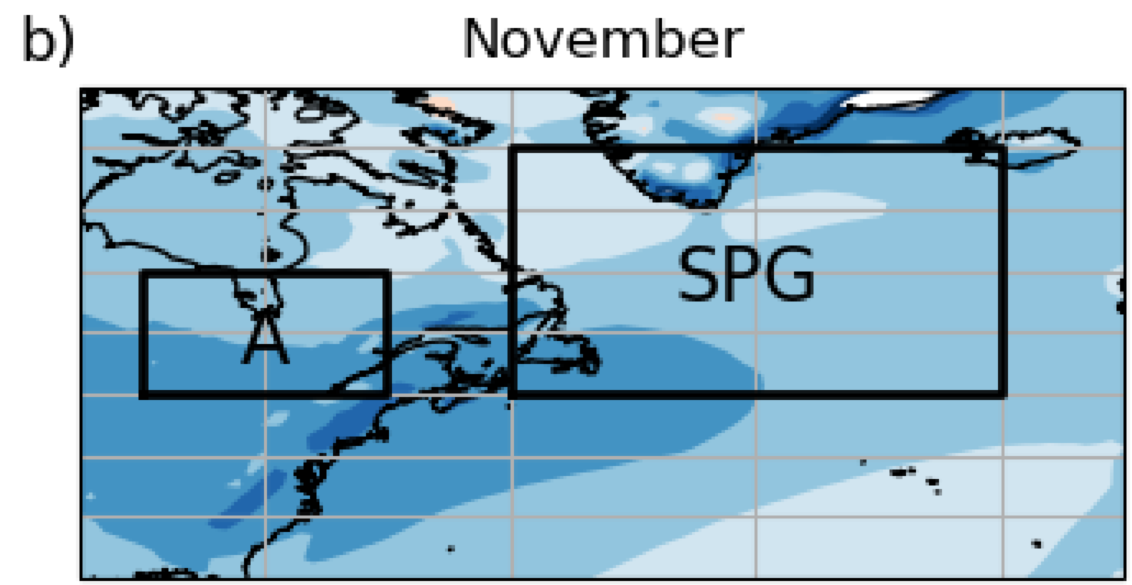
Onset (October-November)



Santolaria-Otin and Zolina (2020)



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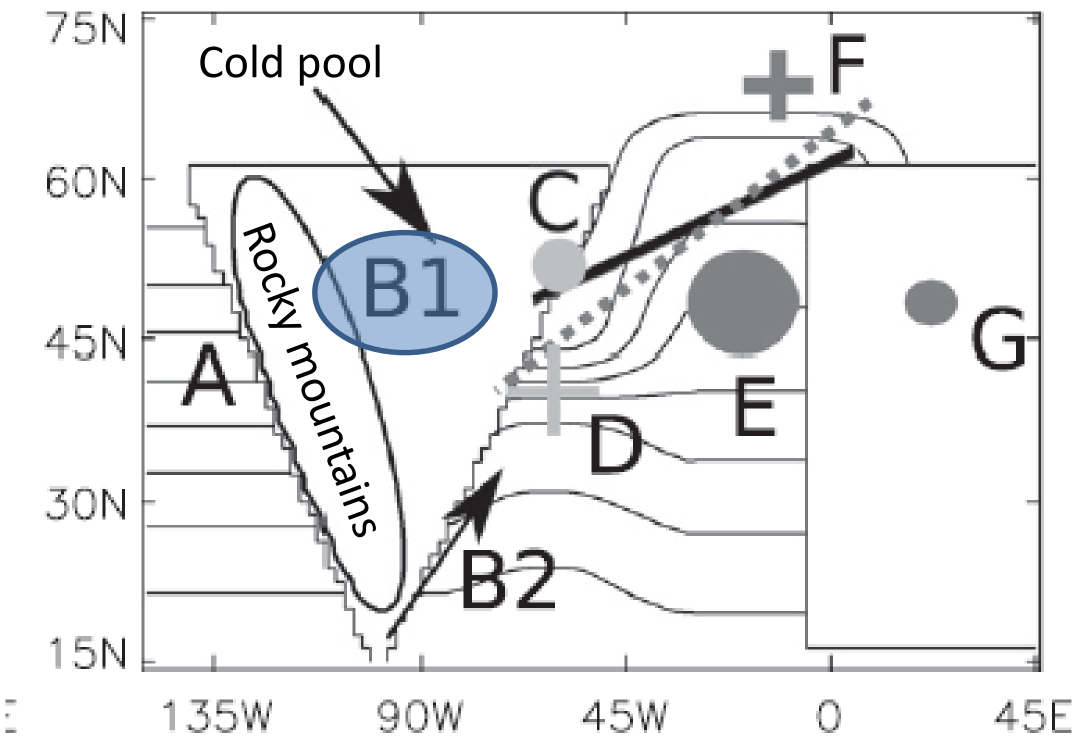
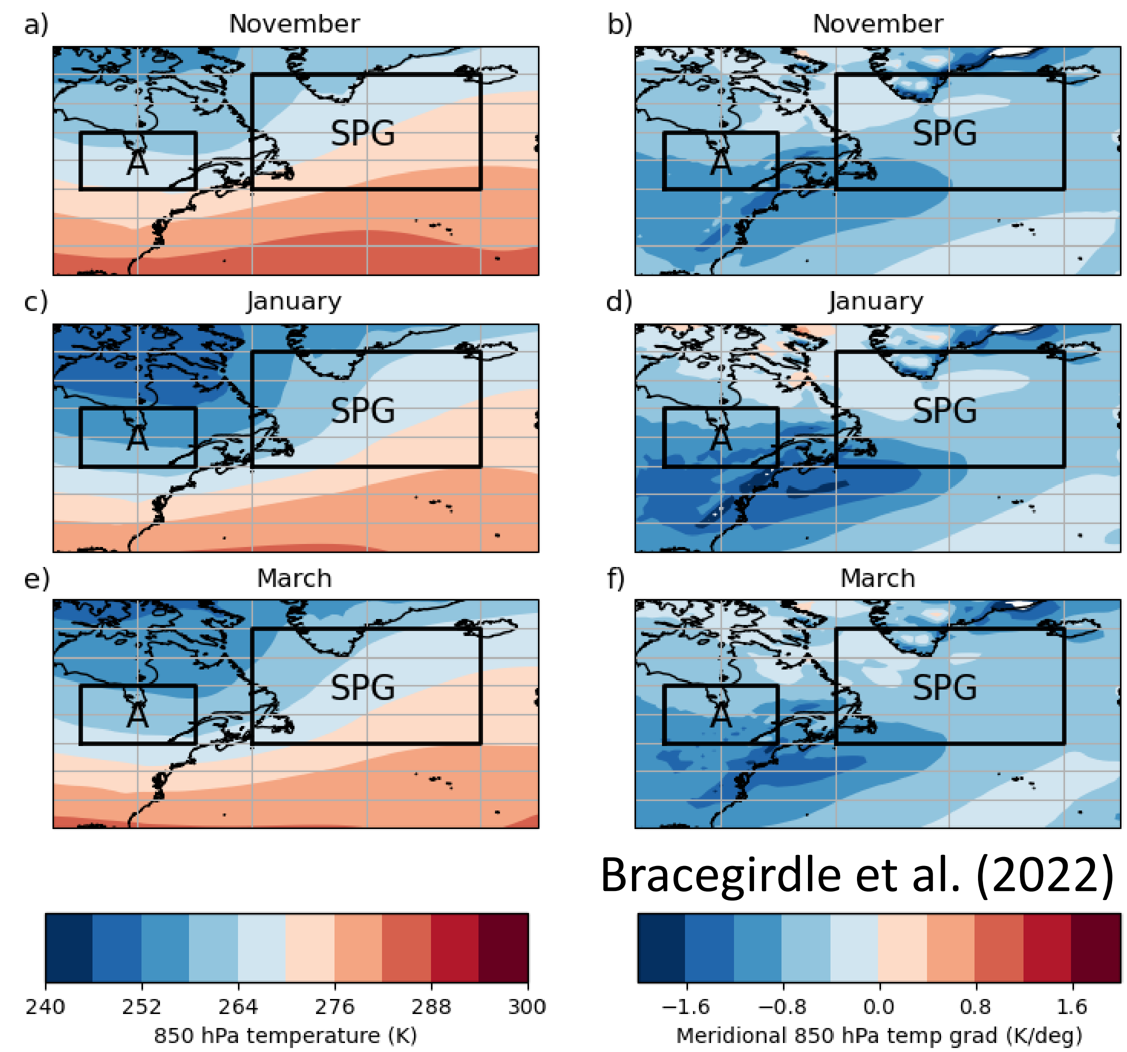
Model representation of the Rocky mountains

Schematic of the ingredients of the NA storm track
Brayshaw et al. (2011)





Bracegirdle et al. (2022)

- The inbound flow at point A is deflected by the Rocky Mountains producing a cold pool at point B1. See Brayshaw et al. (2011) for a full explanation.
- Is the cold pool effect too weak in climate models? Could deficient gravity wave drag play a role (e.g. Pithan et al., 2016)
- Is there a way in which model deficiencies would be more pronounced in early winter? Snow onset?

Summary of part 1

- Early winter equatorward jet latitude biases still exist in the CMIP6 ensemble, but are slightly reduced compared to CMIP5.

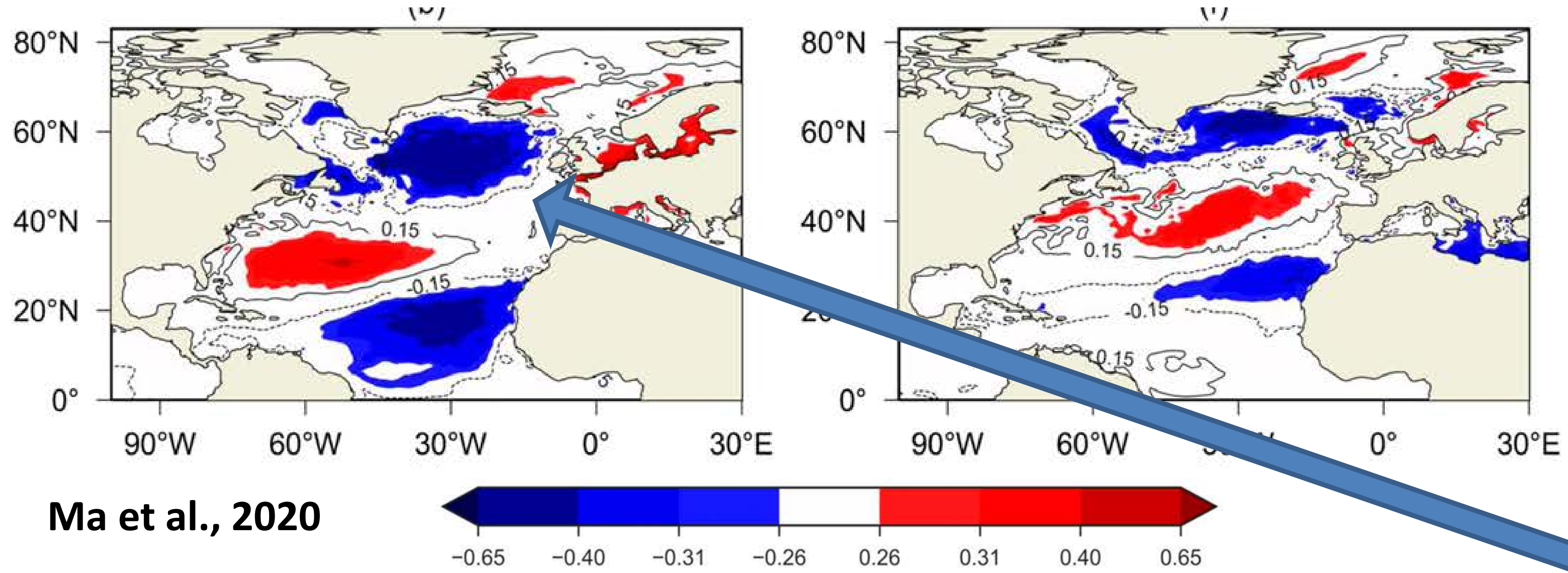
- A potential explanation is provided through the identification of a strong link between NA jet latitude bias and systematically too-weak model-simulated low-level temperature gradients over eastern North America in early-winter.

Overview

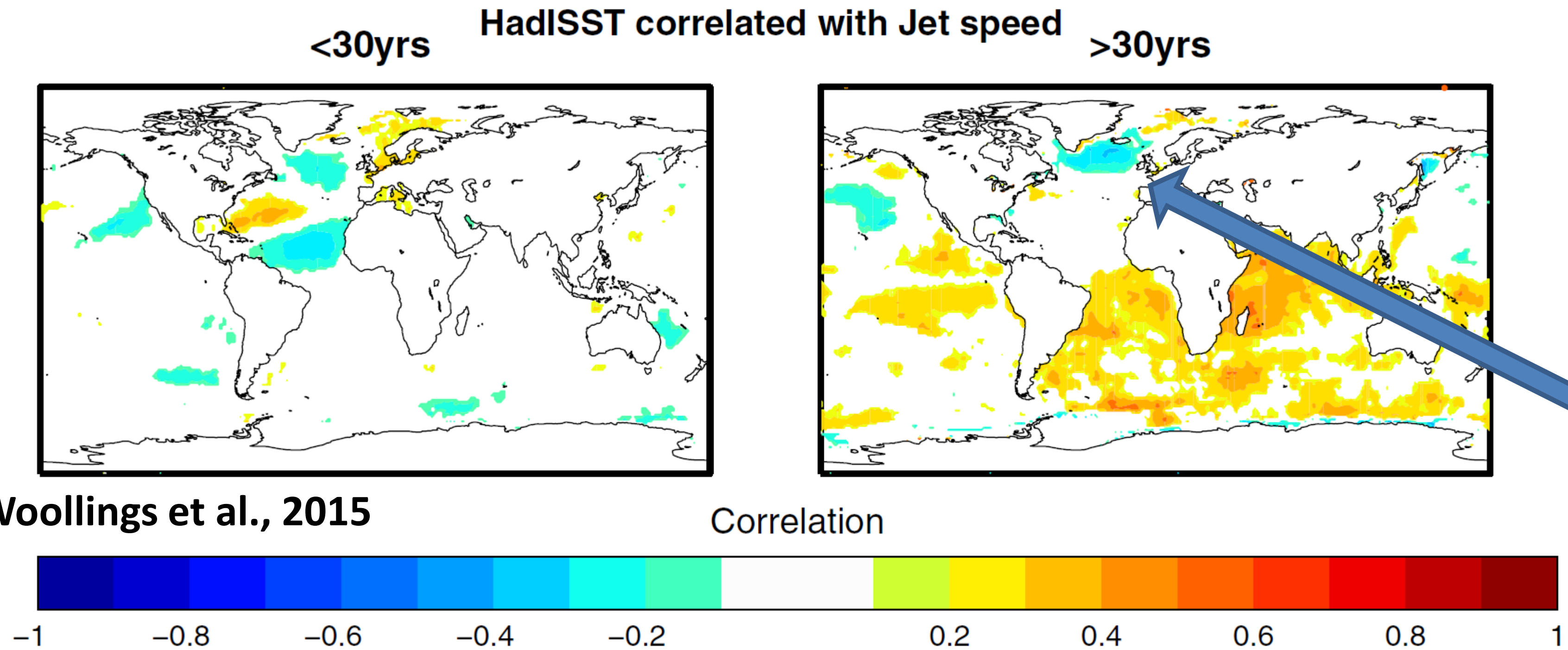
- Introduction – setting the scene
- Part 1 – An update on NA jet biases in the latest climate models
- Part2 – Implications for North Atlantic atmosphere-ocean linkages

The NA tropospheric jet and the SPG

Correlation between Jan jet speed (left) and latitude (right) and Feb surface temp



Ma et al., 2020



Woollings et al., 2015

- The eddy driven jet can be characterised by it's speed and latitude.
- Jet diagnostics based on lower-tropospheric westerly wind between 60W and 0W.
- On seasonal timescales jet speed variability induces more persistent SST anomalies than jet latitude variability (Ma et al., 2020) (seasonal hindcast simulations).
- The main region of persistence is the SPG.
- Decadal jet speed variability in a climate model is consistent with driving from subpolar gyre SST anomalies (Woollings et al., 2015).

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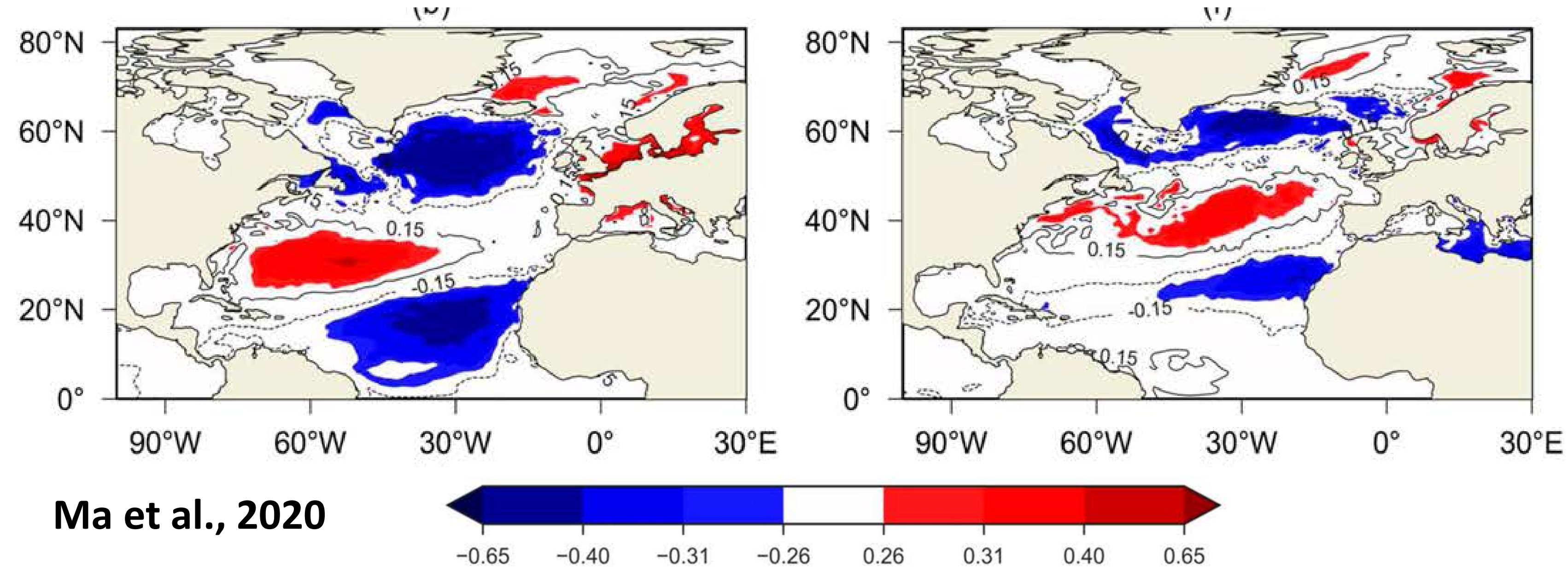
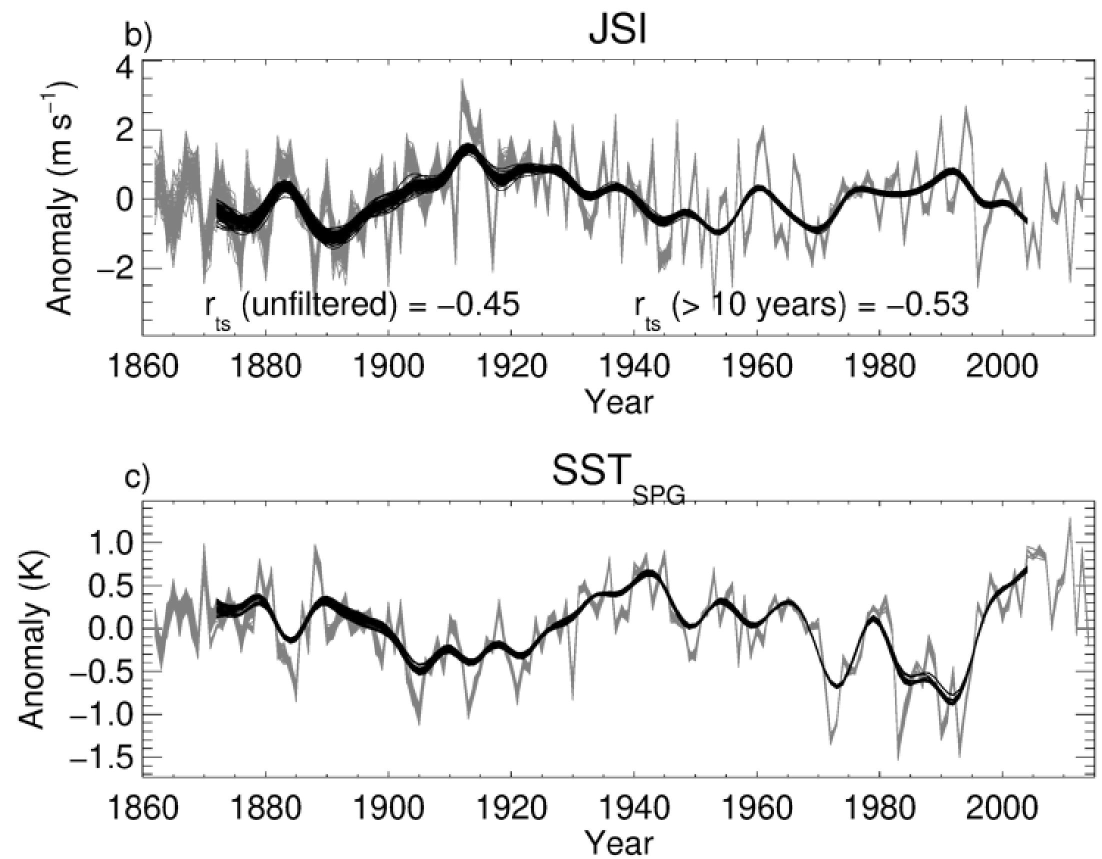


Ma et al., 2020

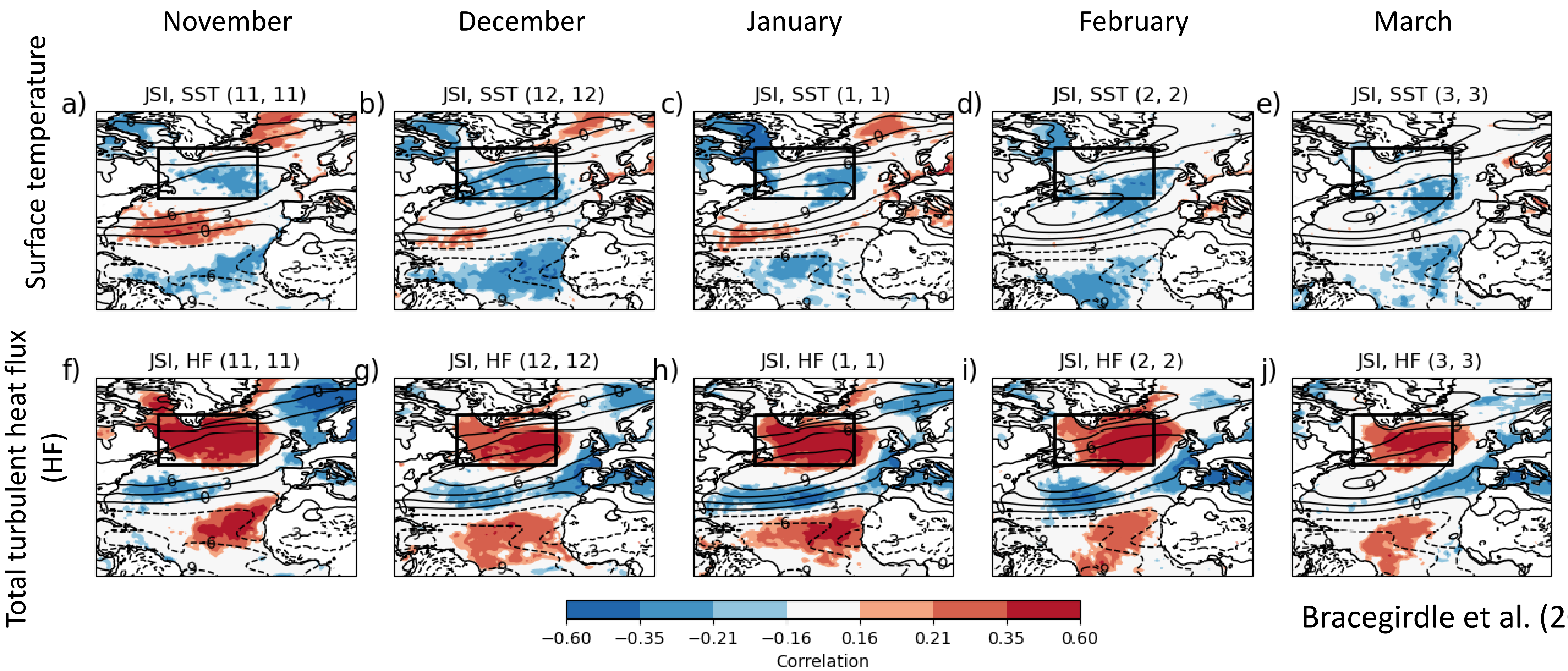


Key question:

- Do climatological equatorward jet biases reduce the strength of simulated interactions between jet speed and the SPG?

Linearly detrended time series of winter mean (DJFM) diagnostics from 20CRv3. For jet speed, correlations with SST_{SPG} are shown..

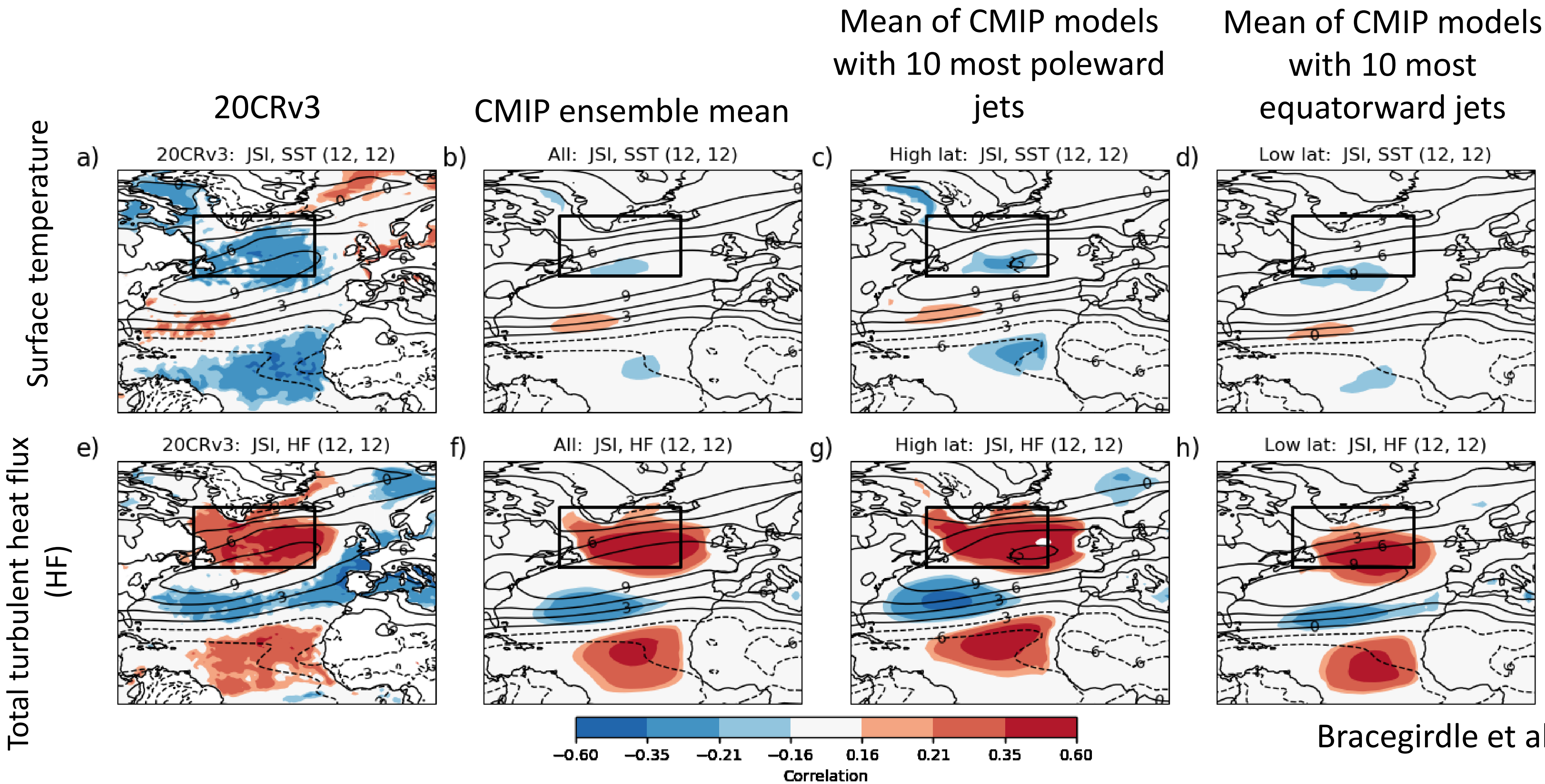
Jet and surface temperature variability in reanalysis data



Bracegirdle et al. (2022)

- Spatial maps of time series correlations between jet speed (JSI) and gridded surface temperature. From 20CRv3 for 1862-2005.
- JSI – SST_SPG correlations stronger over the SPG region in early winter.

Jet and surface temperature variability in reanalysis and CMIP (December)



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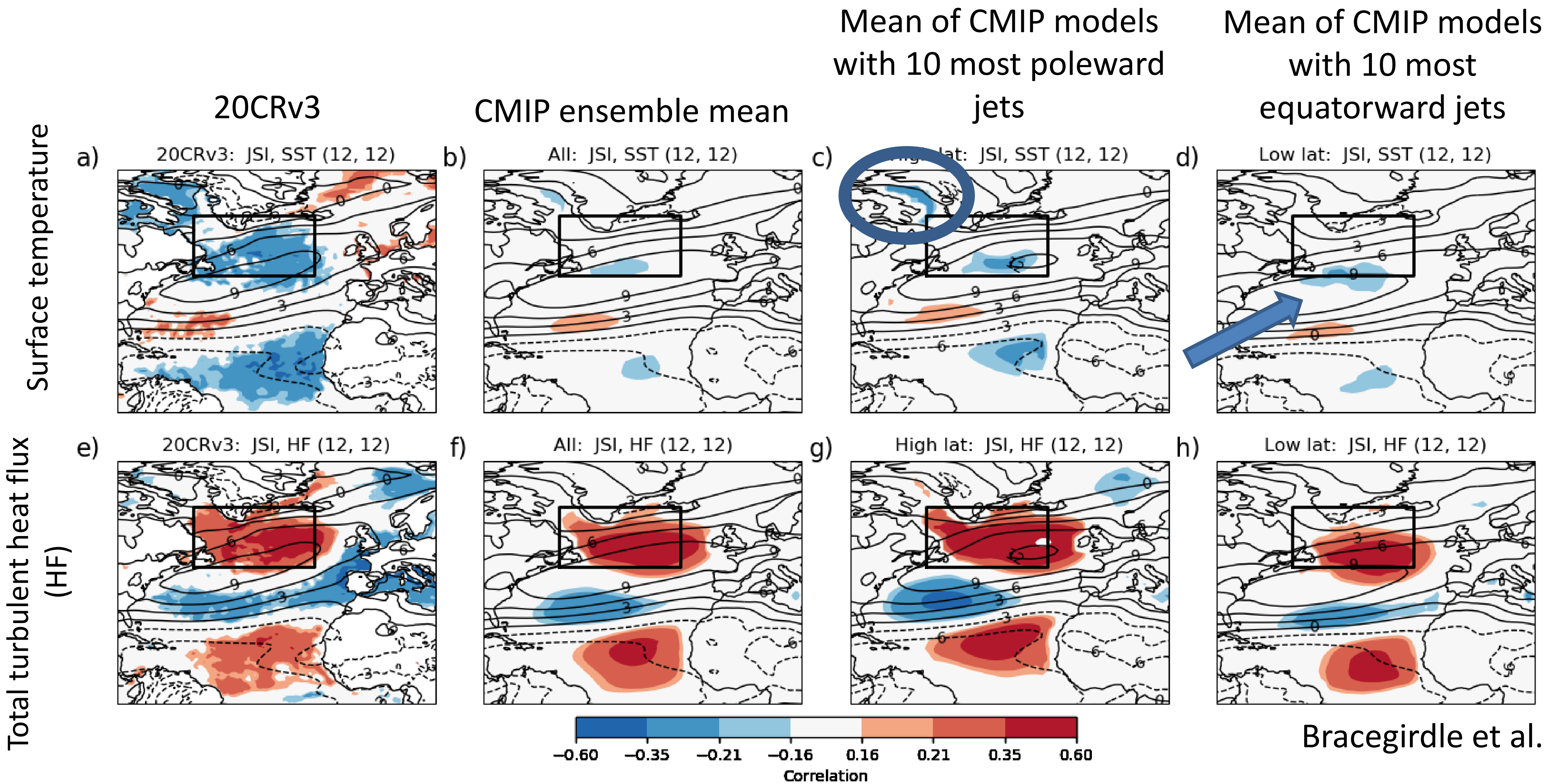

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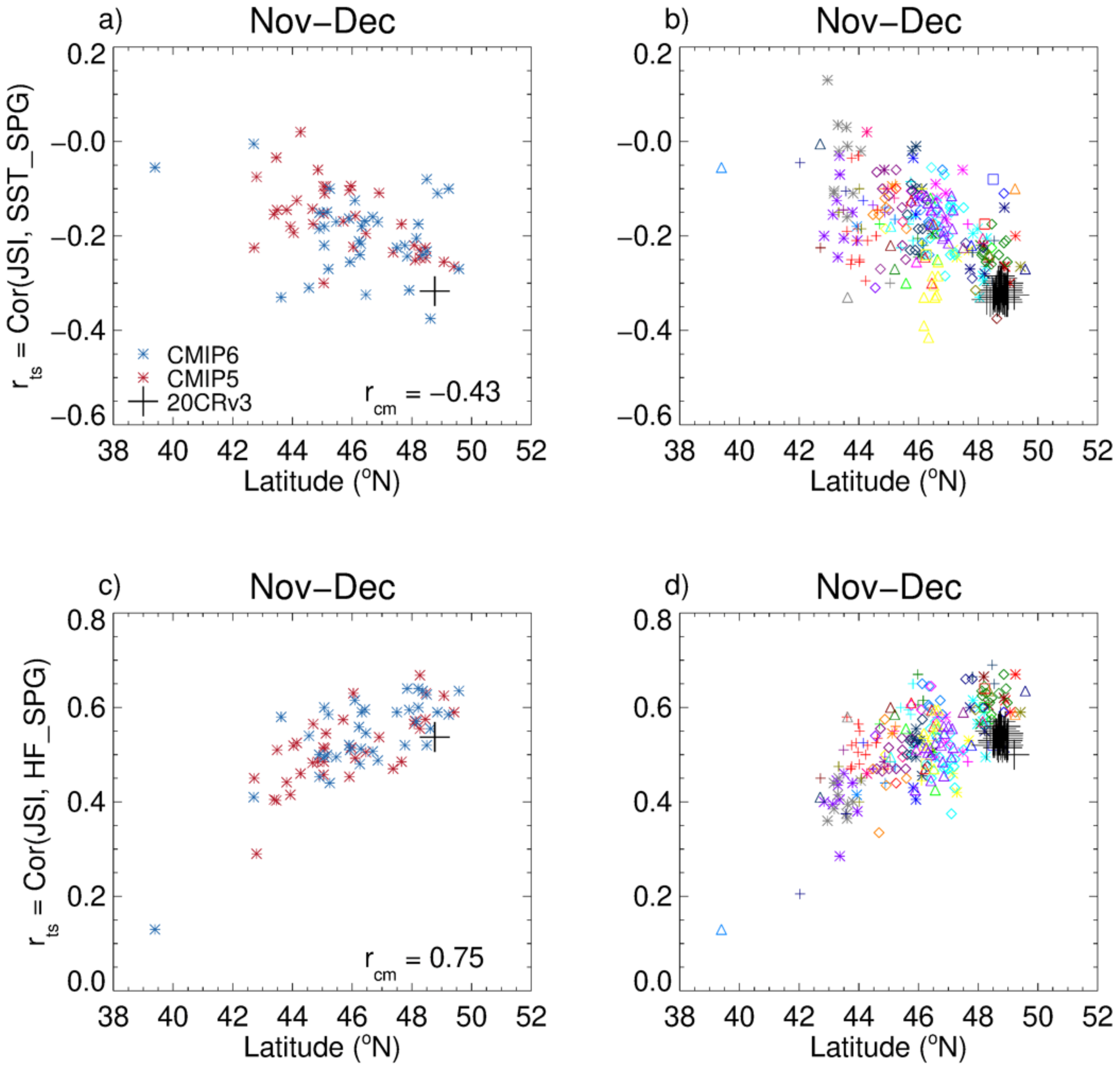
Inter- and intra-model ensemble spread (early winter)

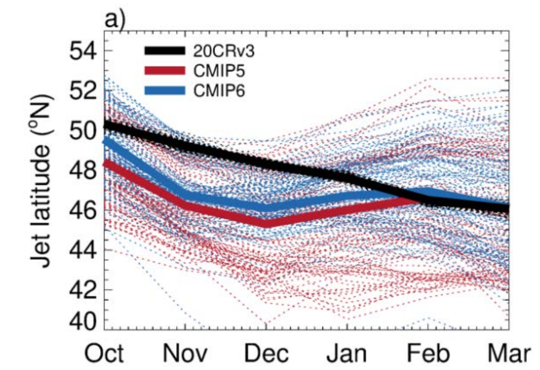


- Models with small biases in jet latitude also exhibit jet speed / SPG linkages that better match reanalysis data (note that re-analysis heat fluxes are a highly derived quantity and may have significant model-related biases).
- The largest biases are generally associated with CMIP5 models, with an indication of improvements in CMIP6.
- Intra-ensemble variability (caused by model-generated internal climate variability) suggested some sampling uncertainty in real-world r_{ts}, but less so for climatological jet latitude.

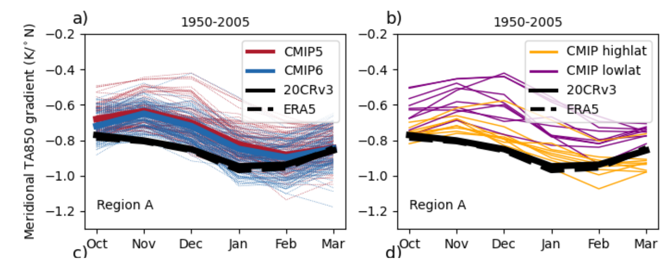
Scatter plots between climatological jet latitude (x-axis) and atmosphere-ocean time series correlations (y-axis) for early winter (November - December). In a and c each asterisk represents the realization mean from each CMIP model (red showing CMIP5; blue CMIP6) and the black cross shows the 20CRv3 ensemble mean. In b, c all ensemble members are shown, for which each symbol/colour combination represents an individual model. From Bracegirdle et al. (2022).

Overall Conclusions (parts 1 and 2)

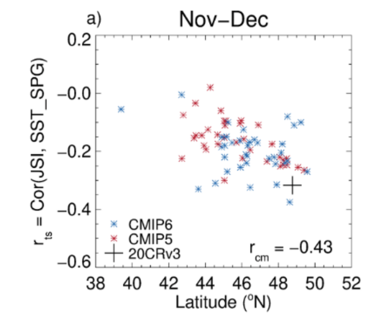
- Early winter equatorward jet latitude biases still exist in the CMIP6 ensemble, but are slightly reduced compared to CMIP5.

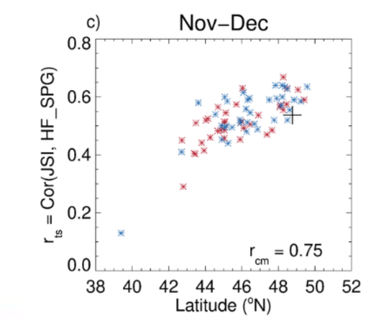


- A potential explanation is provided through the identification of a strong link between NA jet latitude bias and systematically too-weak model-simulated low-level temperature gradients over eastern North America in early-winter.



- The CMIP early-winter latitude biases are large enough to significantly alter the patterns of jet speed – SST correlations. They weaken the link between high latitude surface temperature and jet speed variability (in particular the SPG region, but also regions of sea ice cover around Greenland).





Possible implications

- Potential systematic underestimation of SPG region responses to jet speed variability associated with teleconnections to drivers in other parts of the globe or climate forcing.

- Potential systematic under-estimation of early-winter SPG SST anomalies on jet speed in seasonal forecasts.

Remaining questions

- What are the causal drivers behind the link to meridional temperature gradients over eastern N. America? The direction of causality is not clear. Is the link to snow cover significant? Could the representation of orographic influences induce larger early-winter biases?

- How prominent are early winter biases at upper levels in the atmosphere and to what extent could processes there be driving the lower-troposphere.

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Methods

Atmospheric circulation indices

The NAO index used here is an EOF-based definition derived from mean sea level pressure over the NA region (20-80°N, 90°W-40°E; following (Hurrell, 1995)). It is defined as the principal component time series of the leading EOF of year-to-year anomalies in seasonal (e.g. DJF) or monthly-mean MSLP.

The jet speed diagnostic follows Bracegirdle et al. (2018). It is based on the definition of (Woollings et al., 2015), whereby the maximum in the latitudinal profile of zonally-averaged zonal wind at 850 hPa is identified. The zonal averaging is conducted for the longitude range 60°W – 0° and the value of the maximum defines the jet speed index (JSI). Seasonal means are assembled from jet diagnostics calculated from monthly mean fields. The use of monthly mean fields, rather than the more standard daily mean, was motivated by the desire to maximise the number of models and ensemble members available for inclusion. A comparison with results based on daily fields in Bracegirdle et al. (2018) showed that annual to multi-decadal variability in the monthly-derived index is a close analogue to the daily-derived version.

2.4 Ocean surface diagnostics over the sub-polar gyre

Area-weighted spatial means of sea surface parameters SST and HF are defined over the SPG region 45°N – 65°N, 60°W – 20°W, denoted SST_{SPG} and HF_{SPG}. This box broadly spans the spatial extent of the SPG as identified by Biri Klein (2019). Grid boxes with more than 10% land were masked out.

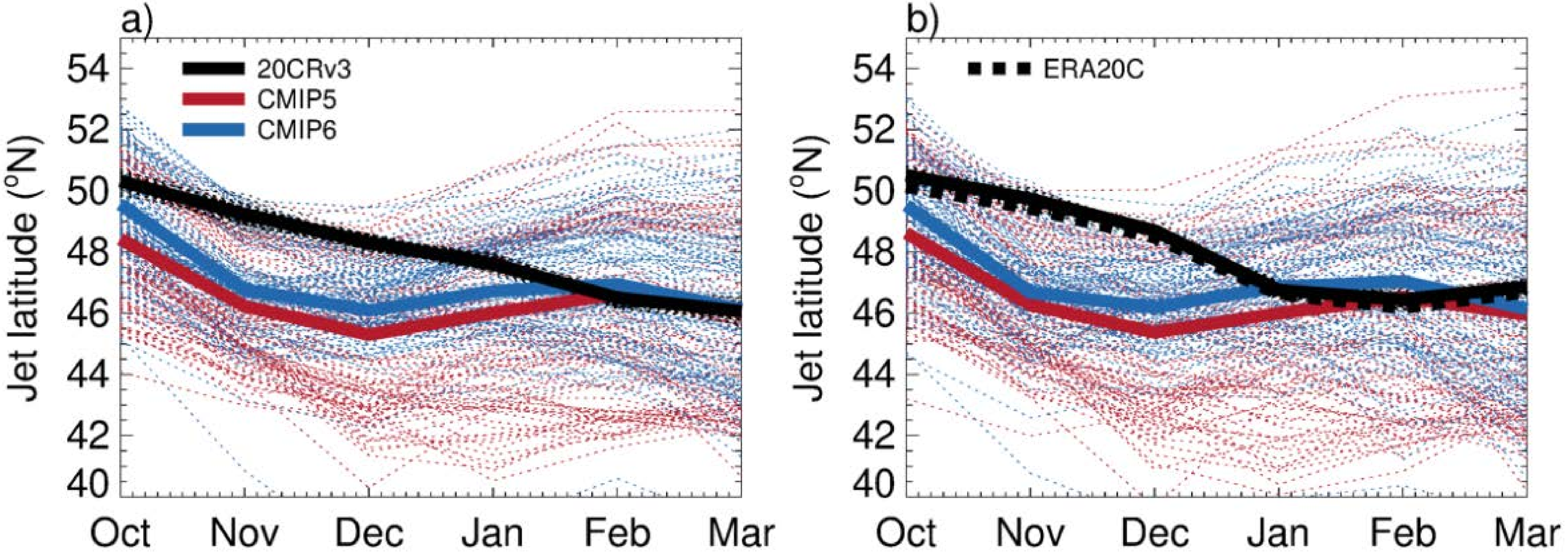

Fig. S2. As in Fig 1, but for 1950-2005 in panel b.

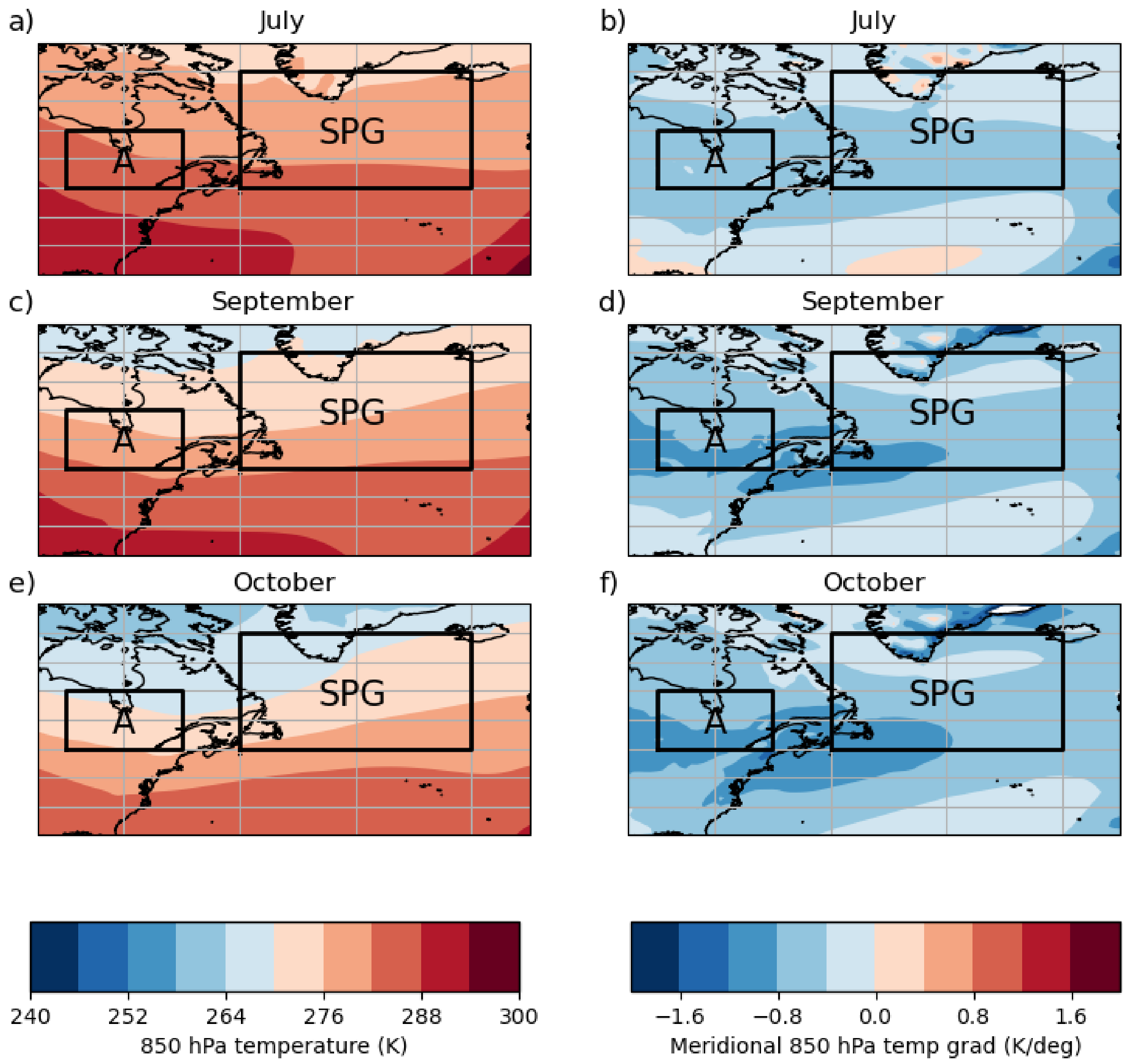

Fig. S3. As in Fig. 3, but for July (a, b), September (c, d) and October (e, f).

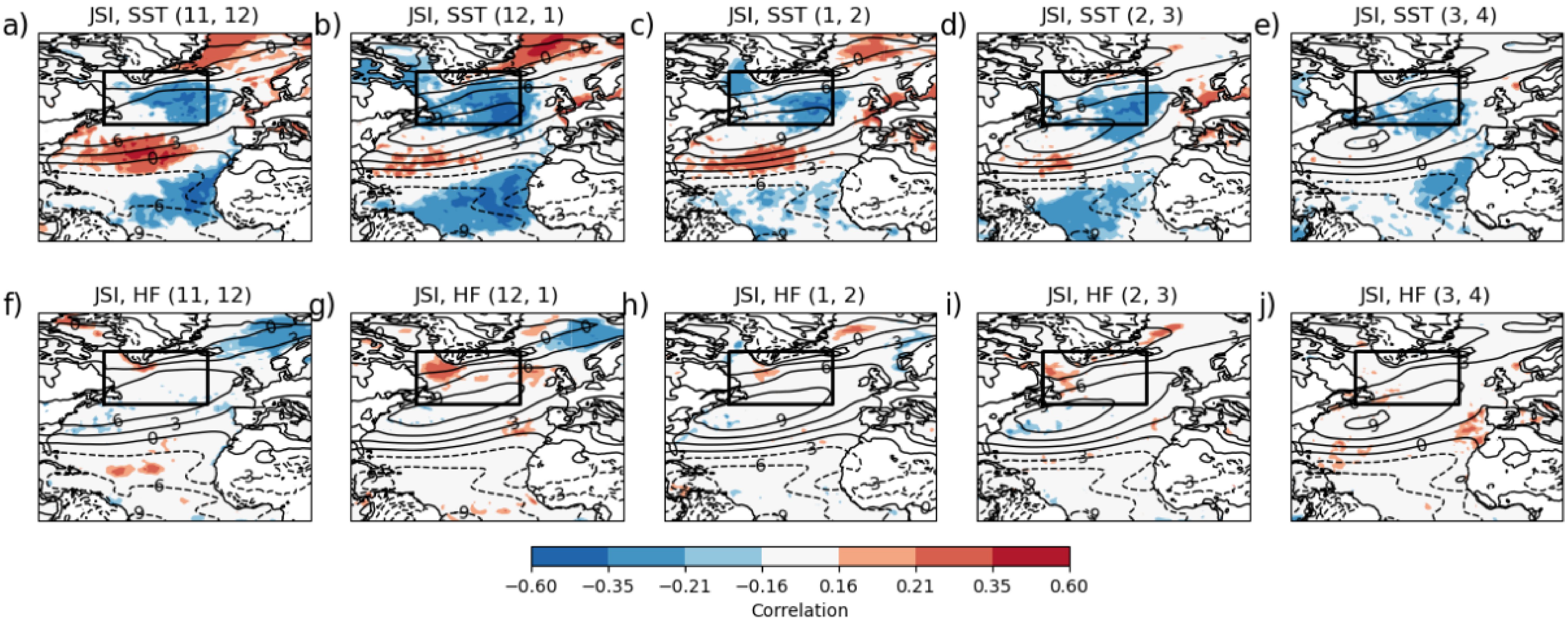

Fig. S4. As in Fig. 5, but with a one-month lag between atmosphere and ocean variables whereby jet speed (November) leads surface variables (December). For example, in panel a) year-to-year variability in November JSI is correlated with year-to-year variability in December surface temperature.

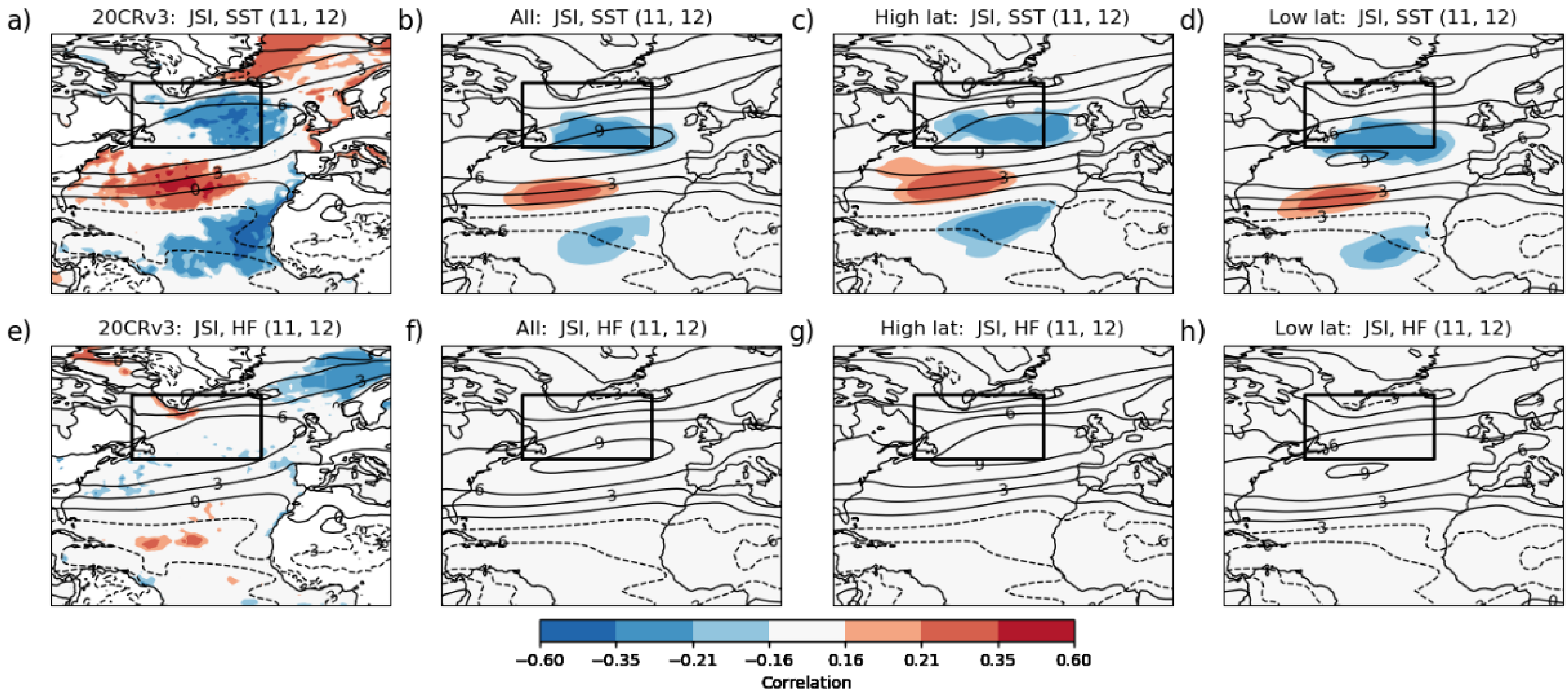

Fig. S5. As in Fig. 6, but for November JSI and December surface variables (i.e. a 1-month lag between JSI and ocean surface variables).

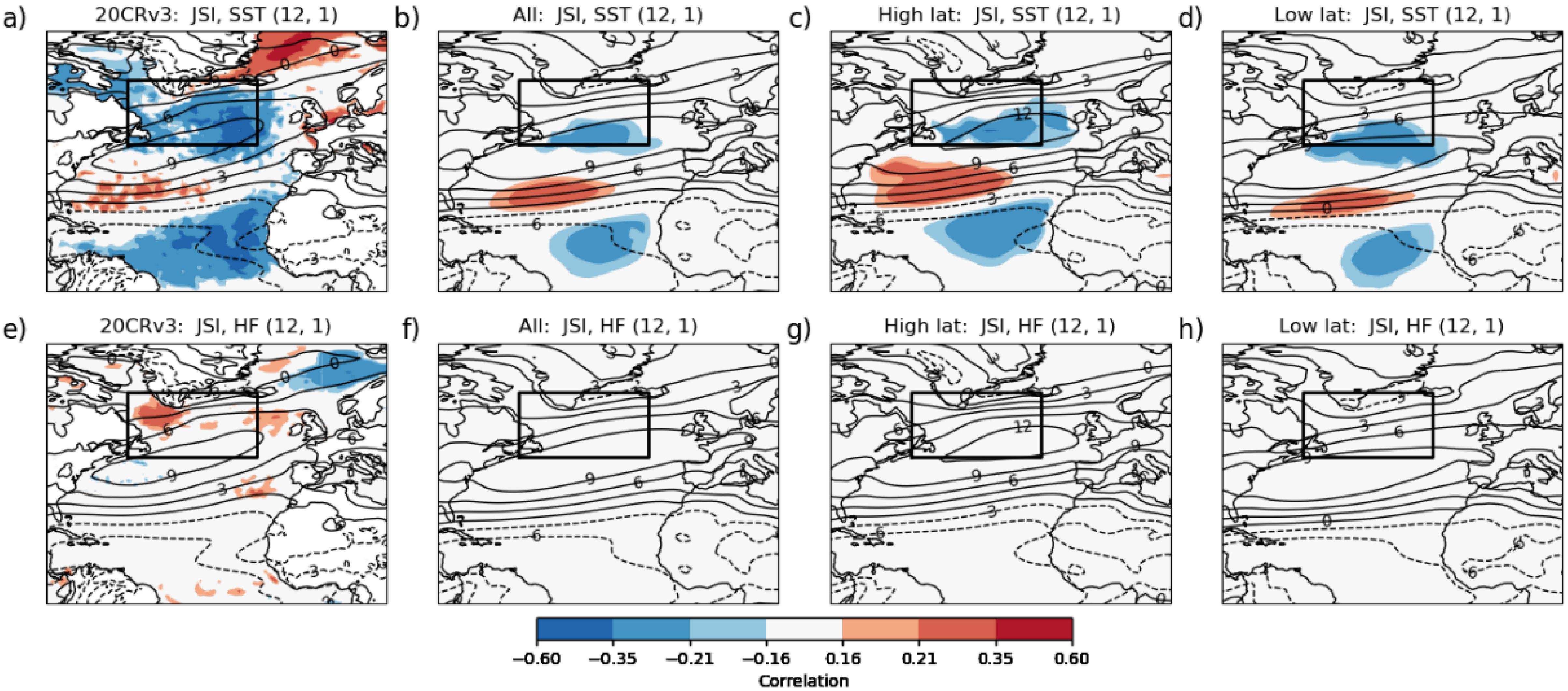

Fig. S6. As in Fig. S5, but for December JSI and January surface variables.

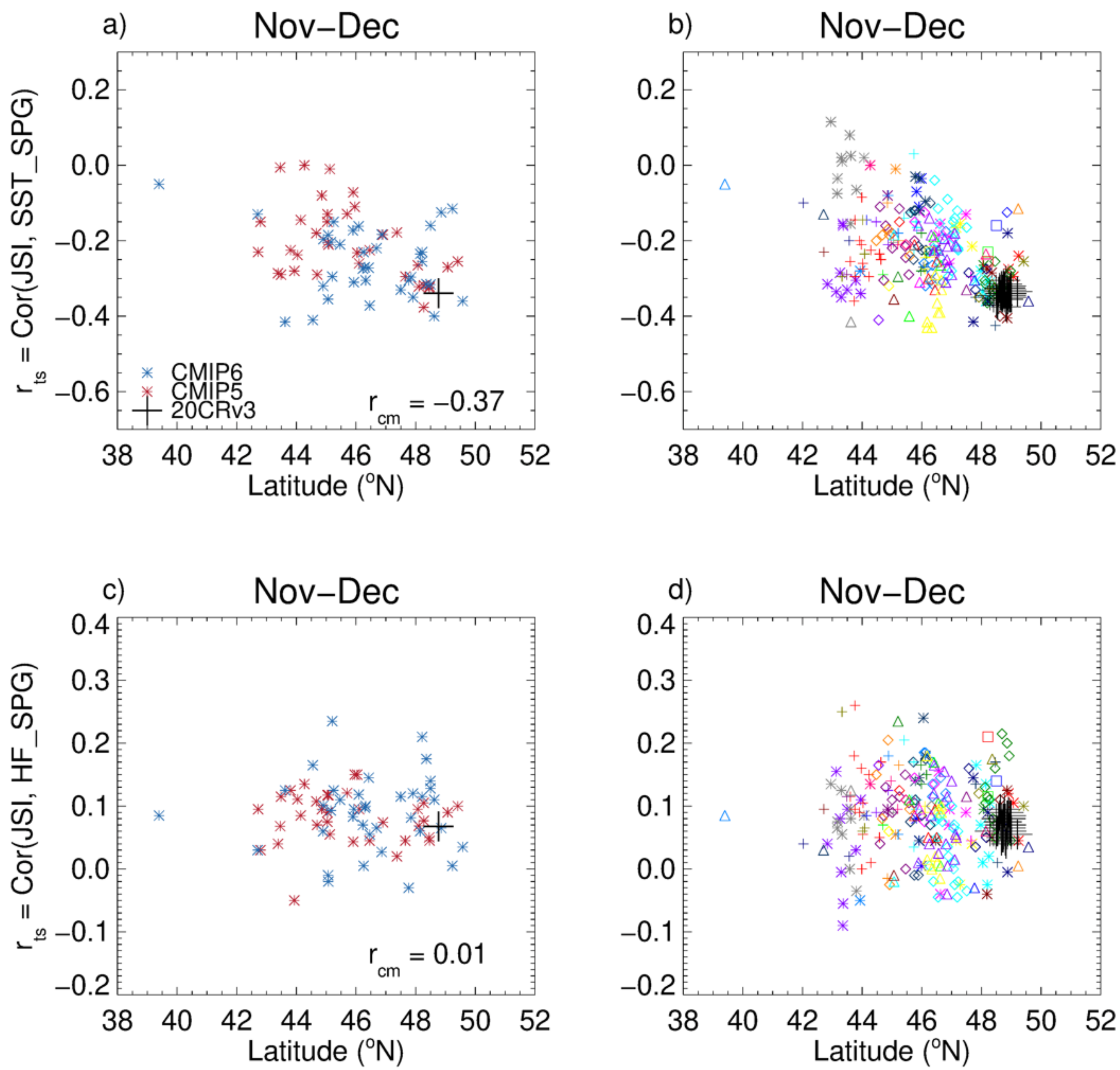

Fig. S7. As in Fig. 8, but with surface variables lagging by 1 month (i.e. Dec-Jan).

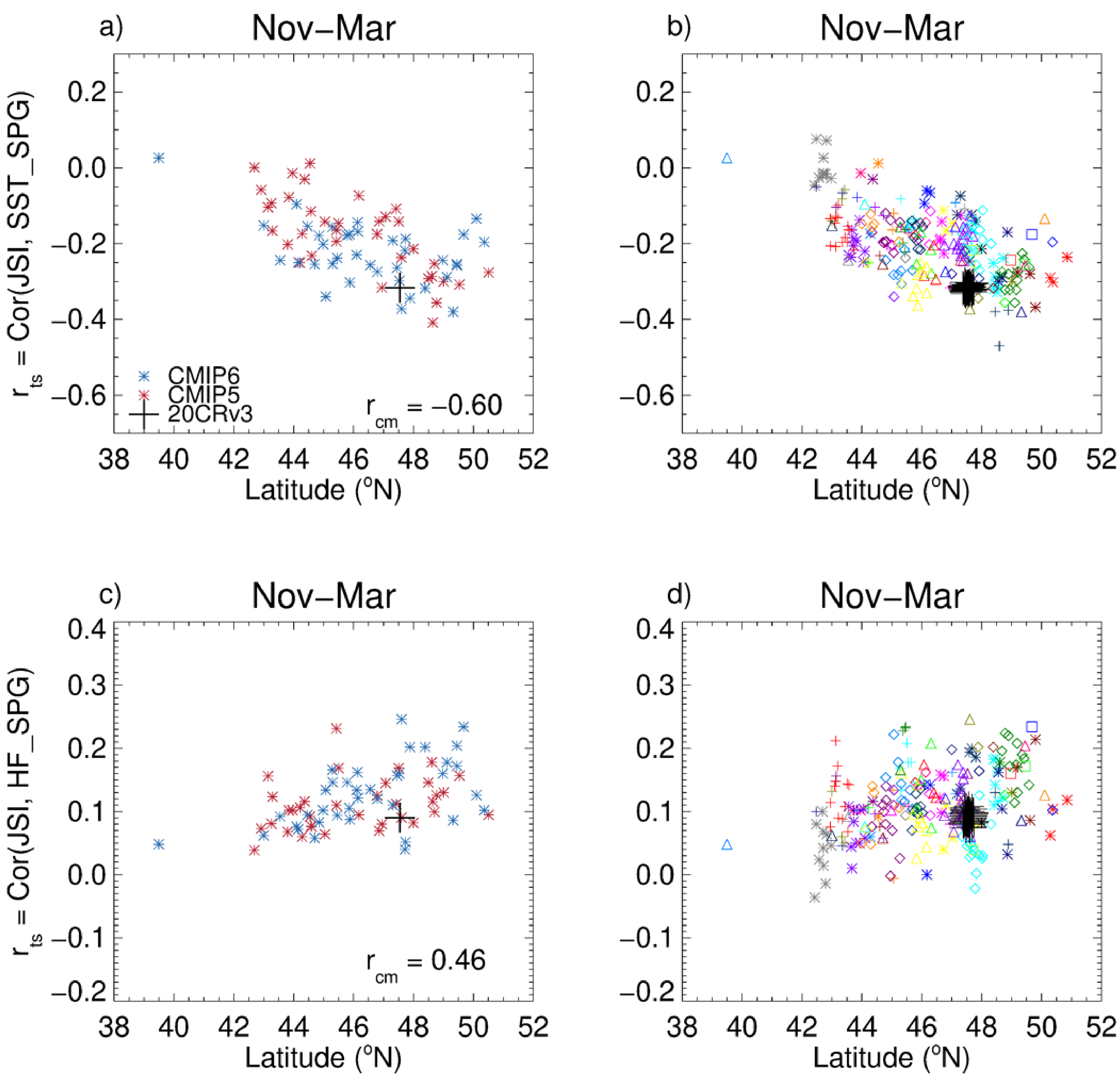

Fig. S8. As in Fig. 9, but with surface variables lagging by 1 month (i.e. Dec-Apr).