# Stratospheric impact on uncertainty in NAO driven by tropical heating

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## Key Points

- ✓ Large ensemble seasonal reforecasts reveal a predictable link between tropical Indian Ocean heating and the NAO via a flow-dependent stratospheric pathway.
- ✓ The impact of Indian Ocean heating on the NAO can be stronger than that of El Niño in the presence of an anomalously strong stratospheric pathway.
- ✓ Competition between basins, flow-dependent response, and intrinsic variability contribute to the uncertainty in seasonal forecasts of NAO.

## 1. Tropical heating and the NAO

- The boreal winter of 2019/20 was notable for the accuracy of many operational seasonal forecasting systems, including the ECMWF seasonal forecasting system (SEAS5), which consistently predicted the positive phase of the NAO, particularly for the late winter period.
- There was no significant El Niño in 2019/20, but anomalously warm conditions occurred over the Indian Ocean (Figure 1).
- In comparison, the winters of 1997/98 and 2015/16 also had strong warm SST anomalies in the Indian Ocean, and with extreme El Niño conditions in the Pacific, but with different NAO responses (Figure 2g-i).
- Here we investigate the role of tropical heating as a predictability driver for the wintertime NAO, with an emphasis on forecast uncertainty linked to intrinsic variability in the stratosphere.

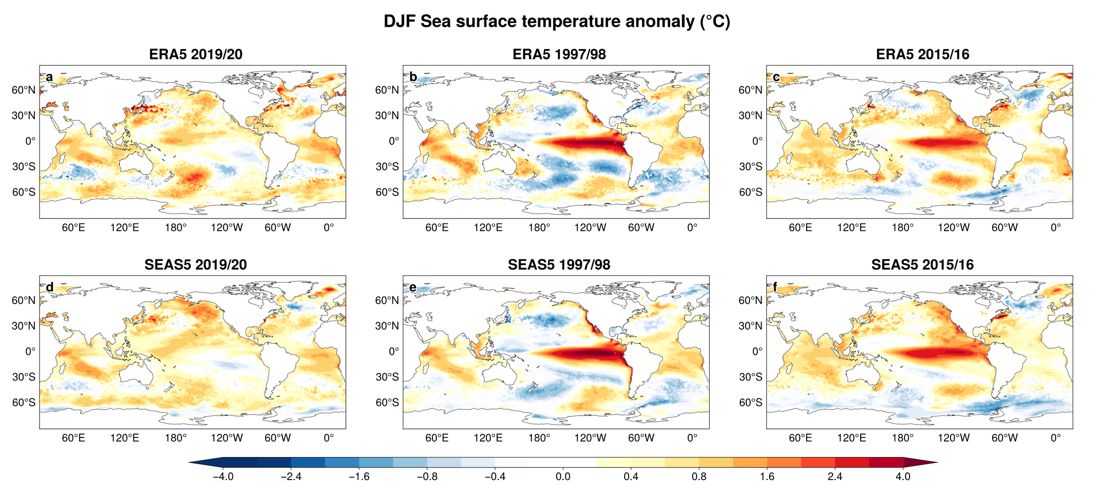
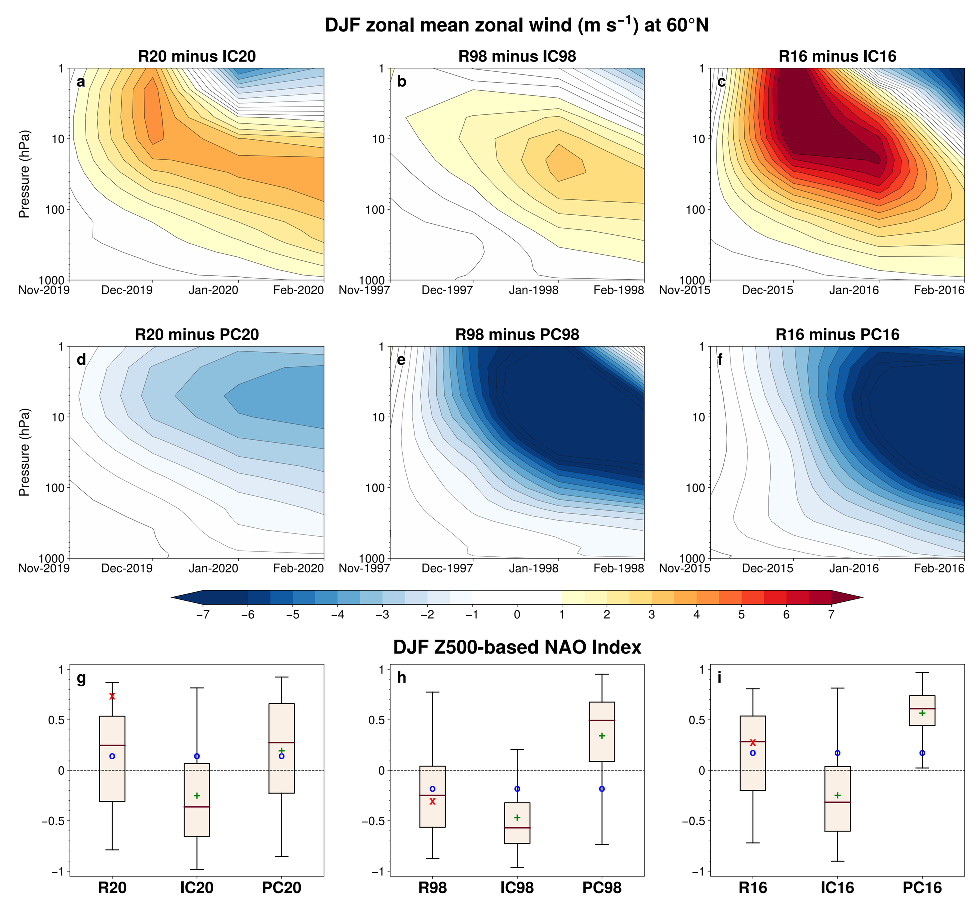



*Figure 1: December to February (DJF) seasonal mean sea surface temperature anomaly (ºC) from ERA5 (a-c) and ensemble mean of SEAS5 (d-f) for 2019/20 (left column), 1997/98 (middle column) and 2015/16 (right column).*

## 2. Experiments and methodology

- We use the atmosphere-only version of SEAS5 and perform a suite of seasonal reforecast case studies with a large ensemble size of 101 members:
  - **R20/R98/R16:** Reference experiments forced by daily ERA5 SST initialized on 01-Nov-2019/1997/2015
  - **IC20/IC98/IC16:** same as R but with climatological SST over the Indian Ocean
  - **PC20/PC98/PC16:** same as R but with climatological SST over the Pacific Ocean
- NAO index is calculated as the projection of model DJF mean 500 hPa Geopotential height (Z500) anomaly onto the first EOF of ERA5 Z500 over the North Atlantic domain (90°W-40°E, 20°N-80°N) normalized by its standard deviation.
- Stratospheric polar vortex (SPV) is represented by the DJF mean zonal mean zonal wind anomaly (m s$^{-1}$) at 60°N.
- Anomalies are based on a 1981-2016 climatology.

## 3. Competing effects of Indian and Pacific heating on NAO




- Warm Indian Ocean favours a strong stratospheric polar vortex (SPV+), while a warm Pacific Ocean favours a weak stratospheric polar vortex (SPV-).
- In 1997/98, the constructive impact of Indian Ocean is overcome by the canonical negative NAO response related to ENSO heating in the Pacific.
- In 2015/16, there is a very strong stratospheric impact that overcomes the impact of ENSO in the Pacific leading to a positive NAO.

*Figure 2: DJF seasonal mean zonal mean zonal wind (m s$^{-1}$) at 60°N plotted as the difference between ensemble means of the R and IC/PC experiments for (a)-(d) 2019/20, (b)-(e) 1997/98 and (c)-(f) 2015/2016. Also plotted in (g)-(i) are the box-and-whisker plots of the DJF mean NAO index for the R, IC, and PC experiments. NAO indices from ERA5 (Red cross) and the ensemble means from the R (Blue circles) and the IC/PC (Green plus signs) experiments are overlaid.*

- Destructive interference between teleconnections from Indian and Pacific SST anomalies contribute to the uncertainty in seasonal NAO predictions

## 4. Uncertainty in NAO mediated by the Stratosphere

- While the phase of the ensemble mean NAO in the reference experiments is correct, there is a large spread across the ensemble members (Figure 2g-i). To gain insight into the reasons for this spread, intra-ensemble diagnostics are performed: we estimate the probabilities of the phases of NAO & SPV as well as the NAO conditioned on the SPV.

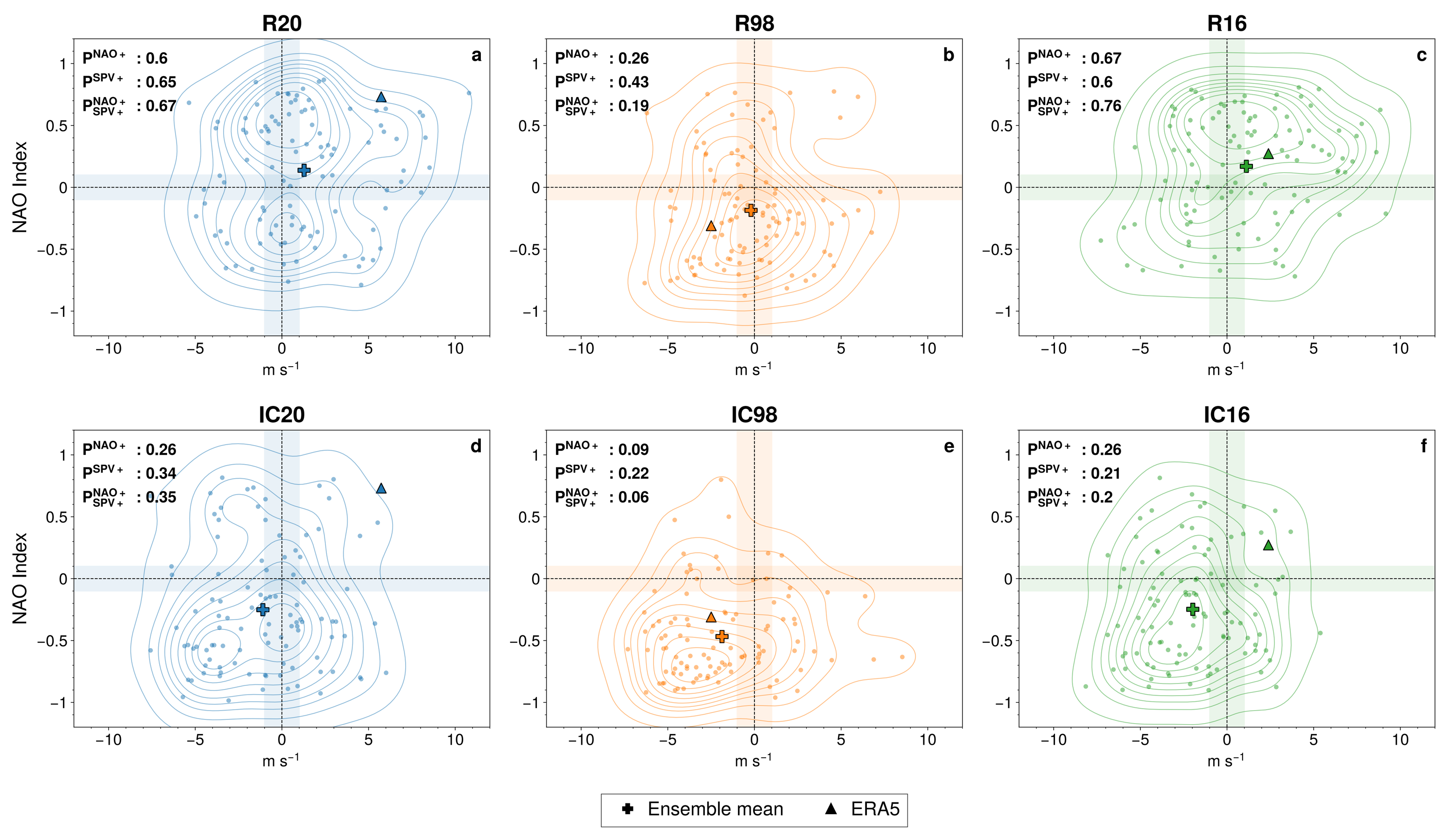



*Figure 3: DJF mean 100 hPa zonal mean zonal wind anomaly at 60ºN (m s$^{-1}$) plotted as scatter diagram against the DJF mean NAO Index for the R (top panels) and IC (bottom panels) experiments. The associated kernel density estimation contours are overlaid. Also plotted are the ensemble mean (plus sign) and ERA5 (triangle sign). The probability estimates for the occurrence of positive phase of NAO ($P^{NAO+}$), strong SPV ($P^{SPV+}$) and of positive NAO conditioned on strong SPV ($P^{NAO+}_{SPV+}$) are listed.*

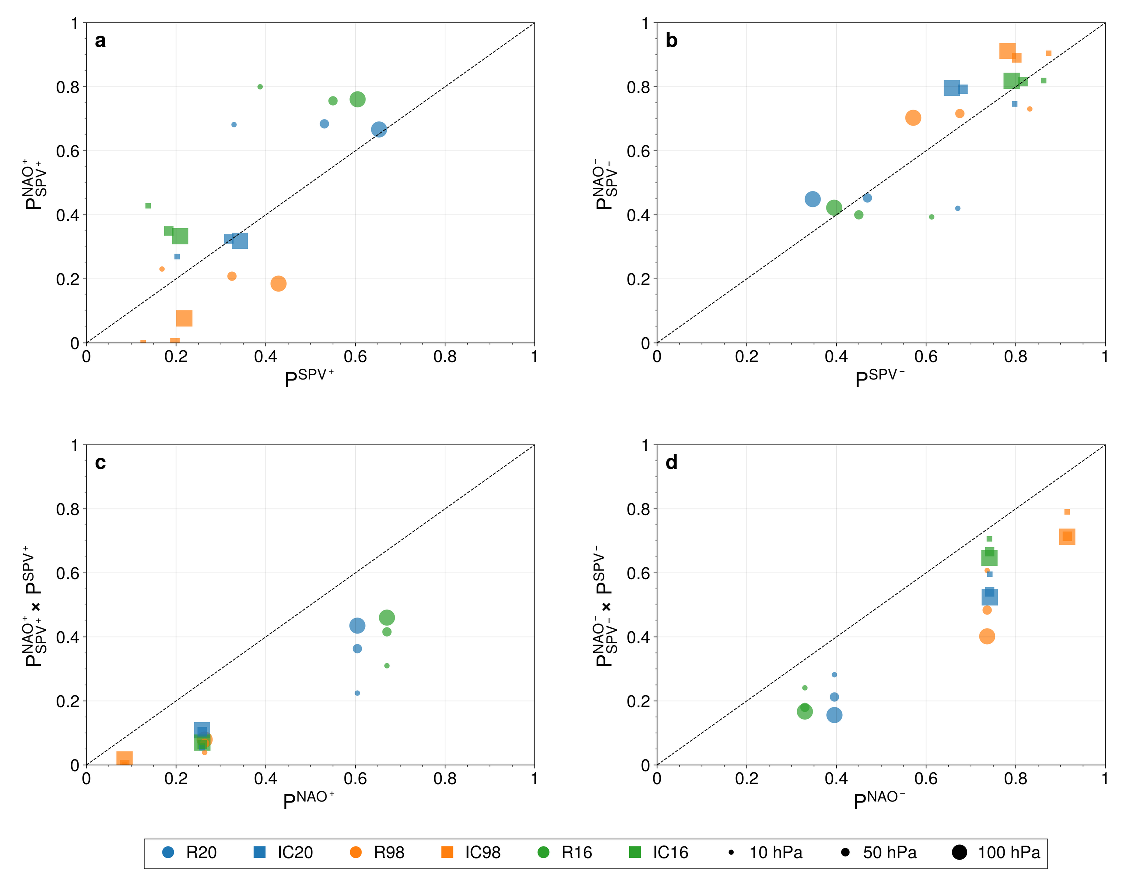



*Figure 4: Scatter diagram of probabilities (a) $P^{SPV+}$ against $P^{NAO+}_{SPV+}$ (b) $P^{SPV-}$ against $P^{NAO-}_{SPV-}$ (c) $P^{NAO+}_{SPV+} \times P^{SPV+}$ against $P^{NAO+}$ and (d) $P^{NAO-}_{SPV-} \times P^{SPV-}$ against $P^{NAO-}$, for the R (filled circle) and IC (filled square) experiments for 10 hPa (small-size circle/square), 50 hPa (medium-size circle/square and 100 hPa (large-size circle/square).*

- Removing the Indian Ocean SST anomalies: (i) decreases the probability of SPV+ and the probability of NAO+ conditioned to SPV+ (ii) increases the probability of SPV- and the probability of NAO- conditioned to SPV-.
- The probability of NAO+ conditioned to SPV+ was the highest in R16 even in the presence of El Niño as well as consistently high in the vertical.
- R98 shows the lowest probability of SPV+ and weak conditioning on NAO+ by the SPV consistent with the El Niño in the Pacific favouring a weak SPV.
- In summary, there is a clear year-to-year variation in the probabilities of SPV and its association with the NAO. The Indian Ocean state plays an important role for these variations, although it is not always the dominant factor. It is the strongest factor in R16 and the weakest in R98.

## Further reading

Senan, R., Balmaseda, M., Molteni, F., Stockdale,* T. N., Weisheimer, A., Johnson, S. & Roberts, C. D. (2024): The relative role of Indian and Pacific tropical heating as seasonal predictability drivers for the North Atlantic Oscillation, *JGR-Atmospheres (accepted).*