# SPECIAL PROJECT FINAL REPORT

All the following mandatory information needs to be provided.

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| **Project Title:** | Attributing predictable signals at subseasonal timescales |
| **Computer Project Account:** | spgbnort |
| **Start Year - End Year :** | 2019 - 2019 |
| **Principal Investigator(s)** | Warwick Norton |
| **Affiliation/Address:** | Citadel LLC<br>120 London Wall<br>London EC2Y 5ET |
| **Other Researchers (Name/Affiliation):** | Jason Beech-Brandt (Citadel)<br>Ann Shelly (Citadel)<br>Dan Rowlands (Citadel) |

The following should cover the entire project duration.

## Summary of project objectives

(10 lines max)

- Examine the interannual predictability of the NAO & PNA at week 3+
- Was the strong positive NAO period 1988-1994 forced from the tropics?
- Are years with poor skill over Europe directly linked to skill of predicting the NAO, are there linkages to teleconnection patterns in the Pacific?
- How much skill of the NAO comes from the tropics v initial conditions?
- What is the role of the tropics and initial conditions in the NAO under prediction conundrum?

## Summary of problems encountered

(If you encountered any problems of a more technical nature, please describe them here.)

The slowness of downloading the data from the experiments out of MARS meant we were delayed in analysing the results.

## Experience with the Special Project framework

(Please let us know about your experience with administrative aspects like the application procedure, progress reporting etc.)

Staff at ECMWF (as normal) were helpful in assisting with any problems.

## Summary of results

(This section should comprise up to 10 pages, reflecting the complexity and duration of the project, and can be replaced by a short summary plus an existing scientific report on the project.)

See below.

## List of publications/reports from the project with complete references

This was only a one year project and we have only just analysed the results so we have yet to disseminate the results to a wider audience.

## Future plans

(Please let us know of any imminent plans regarding a continuation of this research activity, in particular if they are linked to another/new Special Project.)

We expect to do more analysis of the results as this is a very rich dataset. Once ERA5 is extended back to 1950 we will consider applying for a further special project where we can examine predictability over an even greater number of years.

## Summary of results

### 1. Model experiments

We ran an extension of our previous Special Project (Norton et al., 2017) to perform hindcast experiments for winters 1979-2018 (40 years) using a 39 member ensemble (in the previous Special Project we just analysed the winters of 2015/16 and 2016/17).

We performed 3 sets of experiments:

1. Control runs initialized from ERA5 with observed SSTs (SP experiments).
2. As in 1 with the addition that the 15N-15S band is relaxed to ERA5 tropical fields (SPR experiments). See previous Special Project for details.
3. As in 2 except the initial conditions to form the ensemble are taken from the other 39 years of ERA5 while the tropical relaxation is taken from the correct year (tropics only SPM experiments). In these experiments the SSTs are taken from the year of the initial conditions.

Hence experiment 2 includes the role of the initial conditions and perfect knowledge of the deep tropics, while experiment 3 has no knowledge of the initial conditions and skill comes only from the tropics.

The results of experiment 3 can be reordered to determine the role of the initial conditions (which includes the stratosphere) with no knowledge of the tropics i.e. a 39 member ensemble with the tropics relaxed to the 39 years of ERA5 from years different to the initial conditions. These initial conditions only experiments are labelled SPI.

For each year, the experiments are initialised every 2 weeks from 20 October to 9 February (so 9 start dates per year). The runs were for a duration of 4 weeks (28 days) at TL255L137 using model cycle 45r1. Even though the horizontal resolution is significantly lower than the operational monthly forecast, we have not noticed a significant difference in skill at day 20+ between the control experiment in the previous Special Project (at TL255L60) and the operational extended forecast, also here the key objective for this project is to understand the relative skill between different years.

Our initial aim was to analyse interannual variability in weeks 3-4 forecast skill (i.e. subseasonal skill). However with only 9 experiments per year, the sampling noise is too large to obtain meaningful results. Hence we analysed instead the skill of the mean week 4 forecasts for the December-February period (i.e. seasonal skill) where we take the mean of the 7 (17 Nov to 9 Feb) start dates. We have also analysed the mean week 3 & 4 signals and results are similar. The original proposal included twice as many start dates which would have allowed more analysis of the subseasonal skill but we only received half of the requested computer allocation.

We ran out of computer resources at the late stages in the project and didn’t complete the final start date (9 February) for the SPM experiments but this does not impact our results.

## 2. Example results

Figures 1,3,4 below show results from the experiments for 3 representative years.

The winter of 1989/90 (Figure 1) was strong +ve NAO with also strong +ve WPO & EPO (West and East Pacific Oscillations, see Linkin & Nigam, 2008, with the high heights stretching across the central Pacific and low heights over Alaska). This was a very warm winter for Europe and the US. The models under represented the strength of the NAO and WPO/EPO by at least a factor of 2. With a corrected tropical forcing, SPR has a stronger NAO signal than SP. Comparison of SPM and SPI shows the NAO signal is coming from both the tropical forcing (SPM) and initial conditions (SPI). The sum of SPM and SPI is similar to SPR suggesting here no significant nonlinearity to the tropical forcing and initial conditions.

This year has remarkable resemblance to the winter we have just had (2019/20), see Figure 2. The very strong +ve NAO/WPO/EPO is very evident. Like in the control experiment (SP), the week 4 operational extended forecast significantly under represented the strength of the +ve NAO and +ve EPO (heights not low enough over Greenland and Alaska).

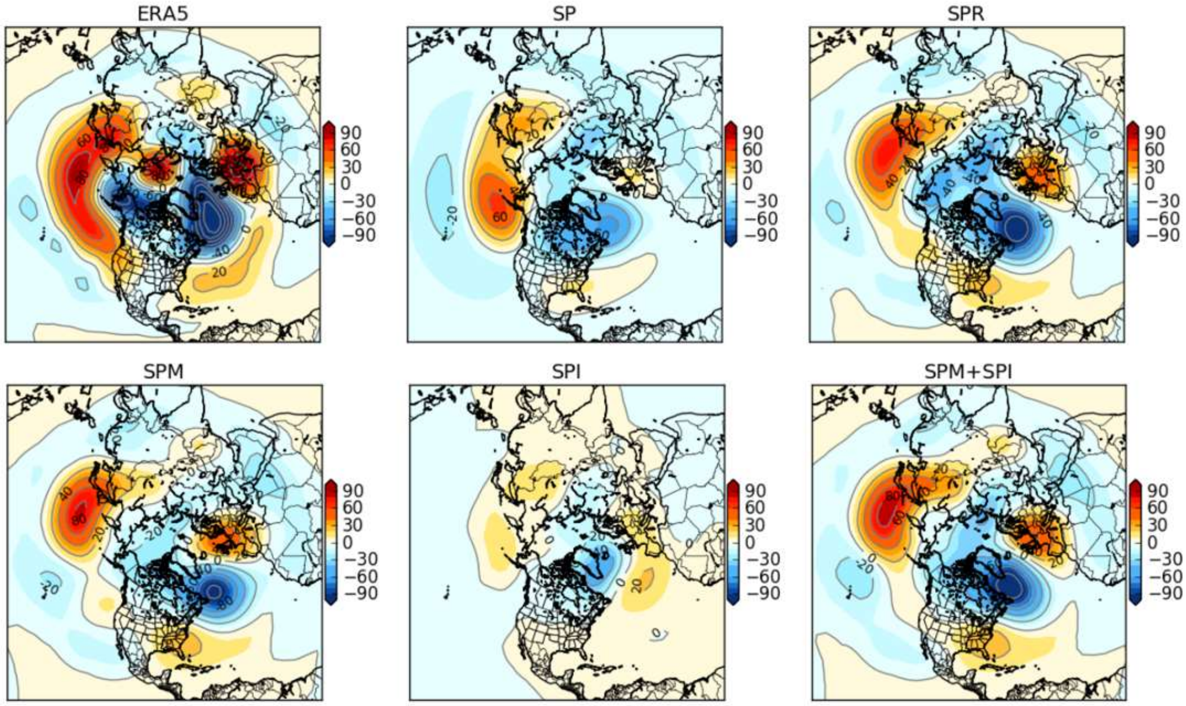

**Figure 1.** 500 hPa height anomalies for the winter of 1989/90 averaged over 7 weeks throughout December-February. ERA5 and week 4 forecasts: control (SP), relaxed tropics (SPR), tropics only (SPM), initial conditions only (SPI), sum of SPM+SPI.

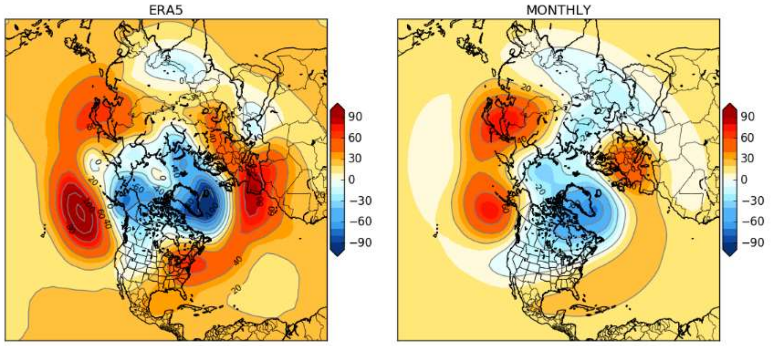

**Figure 2.** 500 hPa height anomalies for winter of 2019/20 (December-February). ERA5 (left) and week 4 forecasts from operational ECMWF extended system.

The winter of 2009/10 (Figure 3) was strong -ve NAO with also strong -ve EPO. This was a cold winter for Europe and the US. As we found for 1989/90 all the experiments captured the essence of the pattern with SPR showing the best correspondence with the observed pattern though SPR still under represented the strength of the –ve NAO by at least a factor of 2. Both the tropics and the initial conditions contributed to the –ve NAO pattern but here SPM+SPI has a weaker signal than SPR showing some role of nonlinear interactions between the initial conditions and tropical forcing.

The winter of 2000/1 (Figure 4) was weak –ve NAO and had mixed signals in the Pacific. This winter was cold for Northern Europe and the eastern US but warm for southern Europe. The relaxed tropics experiment (SPM) showed a moderately strong +ve NAO signal while the initial conditions only experiment (SPI) showed something of –ve NAO pattern. SPR was closer to –NAO than SPM+SPI (with higher heights over Greenland) but still did a poor job in forecasting the cold pattern on both sides of the Atlantic.

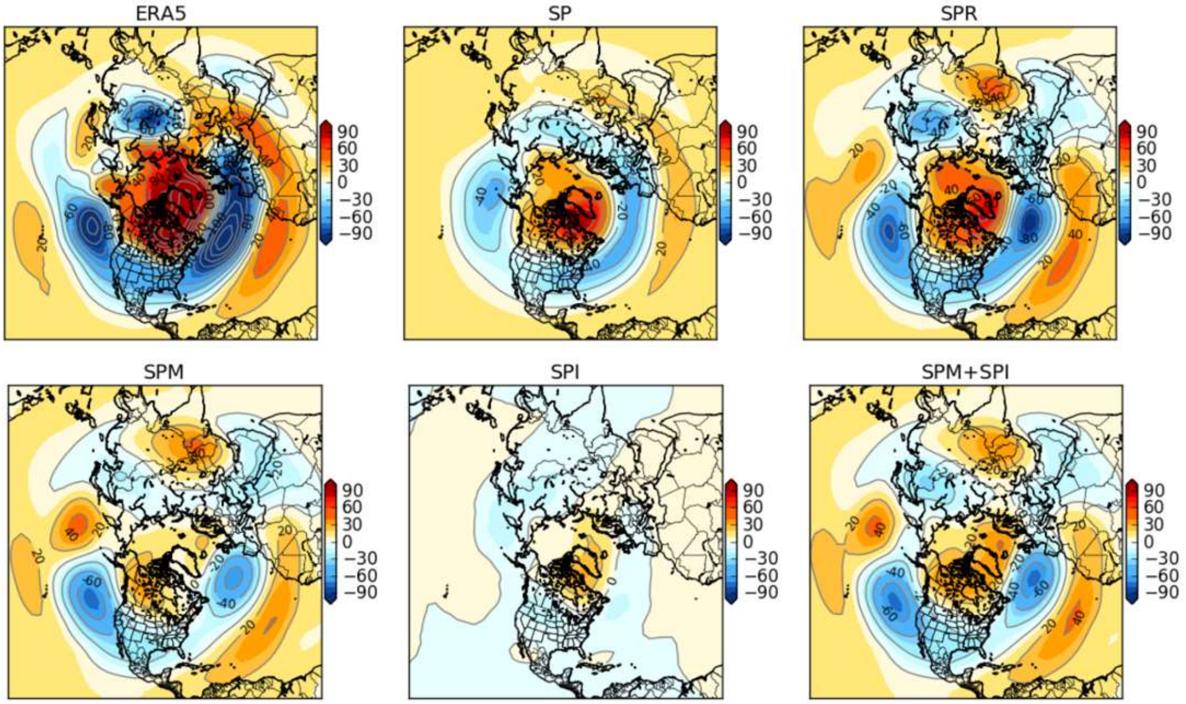

**Figure 3.** 500 hPa height anomalies for the winter of 2009/10 averaged over 7 weeks throughout December-February. ERA5 and week 4 forecasts - control (SP), relaxed tropics (SPR), tropics only (SPM), initial conditions only (SPI), sum of SPM+SPI.

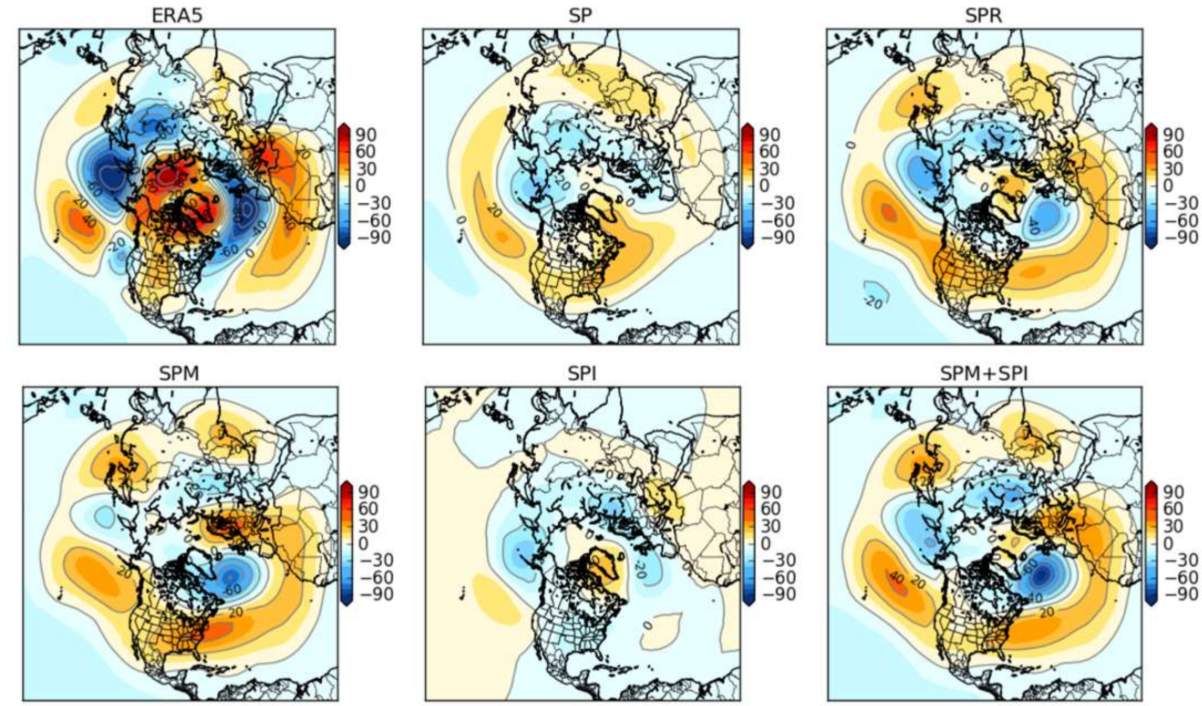

**Figure 4.** 500 hPa height anomalies for the winter of 2000/1 averaged over 7 weeks throughout December-February. ERA5 and week 4 forecasts - control (SP), relaxed tropics (SPR), tropics only (SPM), initial conditions only (SPI), sum of SPM+SPI.

## 3. Interannual variability in Northern Hemisphere Skill

Figure 4 shows the northern hemisphere skill for the mean week 4 forecast as a function of year. The most skilful forecast is the relaxed tropics (SPR) with mean ACC=0.39 followed by tropics only (SPM) and the combined tropics only (SPM) with initial conditions only (SPI) with mean ACC=0.33. Generally the SPR experiment follows the skill of the tropics only experiment but there are a few notable exceptions particularly the years 2011/12 to 2014/15 where skill of SPR (and the control experiment SP) is significantly above SPM.

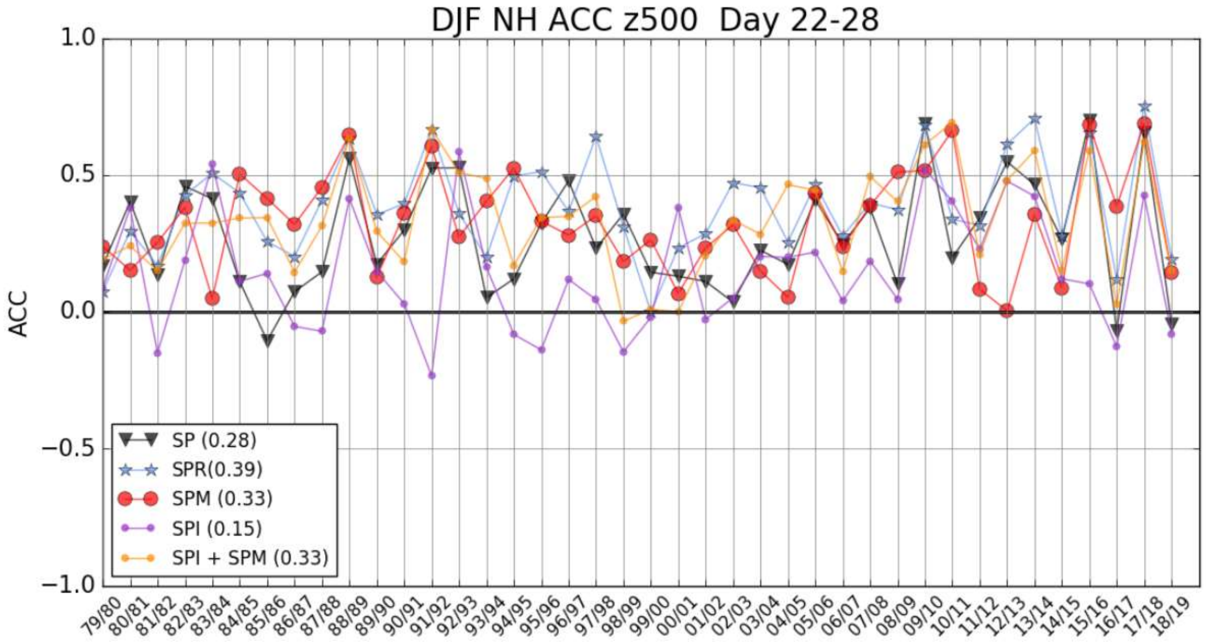

**Figure 5.** Northern hemisphere 500 hPa anomaly correlation for mean week 4 DJF pattern. Control (SP), relaxed tropics (SPR), mixed initial conditions with relaxed tropics (SPM), initial conditions only (SPI), sum of SPM+SPI. Number in parenthesis in legend is mean skill over the 40 years.

## 4. Interannual variability in Atlantic and Pacific teleconnection indices

All the model experiments have some skill in predicting the NAO (see Figure 5). The control experiment (SP) has the same correlation 0.73 to the observed NAO as the relaxed tropics experiment (SPR). The tropics only (SPM) and initial conditions only (SPI) are similar in overall skill. However the sum of SPM+SPI has correlation of only 0.55 compared to the full relaxed experiment of 0.73 suggesting some nonlinearity in predicting the NAO. Very notable in Figure 5 is how the observed NAO has excursions much larger than the mean model response particularly for the periods 1988/89 to 1994/5 and 2007/8 to 2013/14. We will discuss this more in the next section.

Figure 6 shows the corresponding plot for the PNA index. The El Nino years of 1982/3, 1986/87, 1991/92, 1997/8, 2009/10, 2015/16 stand out clearly having a very predictable +ve PNA response. Here the relaxed tropics run (SPR) is more skilful than the control run (SP) showing the direct impact of exactly knowing the tropical forcing. The combined tropics only and initial conditions only (SPM+SPI) is nearly as skilful as SPR showing PNA is nearly linear in predicting from initial conditions and tropical forcing.

Figure 7 shows the corresponding plot for the WPO index. Here the relaxed tropics is the most skilful forecast but the combined tropics only (SPM) and initial conditions only (SPI) are less skilful indicating some role for nonlinearity. Note again here how the observed WPO index has much larger excursions compared to the model forecasts.

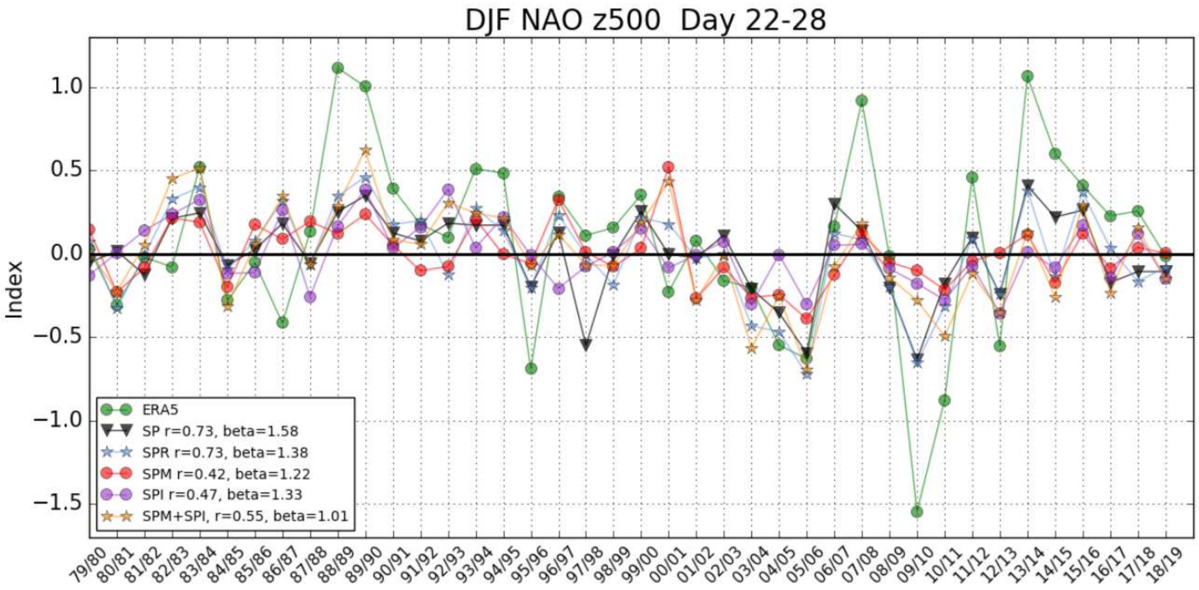

**Figure 6.** DJF NAO ERA v mean week 4 forecasts. Control (SP), relaxed tropics (SPR), mixed initial conditions with relaxed tropics (SPM), initial conditions only (SPI), sum of SPM+SPI. The legend gives the correlation between forecasts and ERA (r), and the under prediction factor (beta, see section 5).

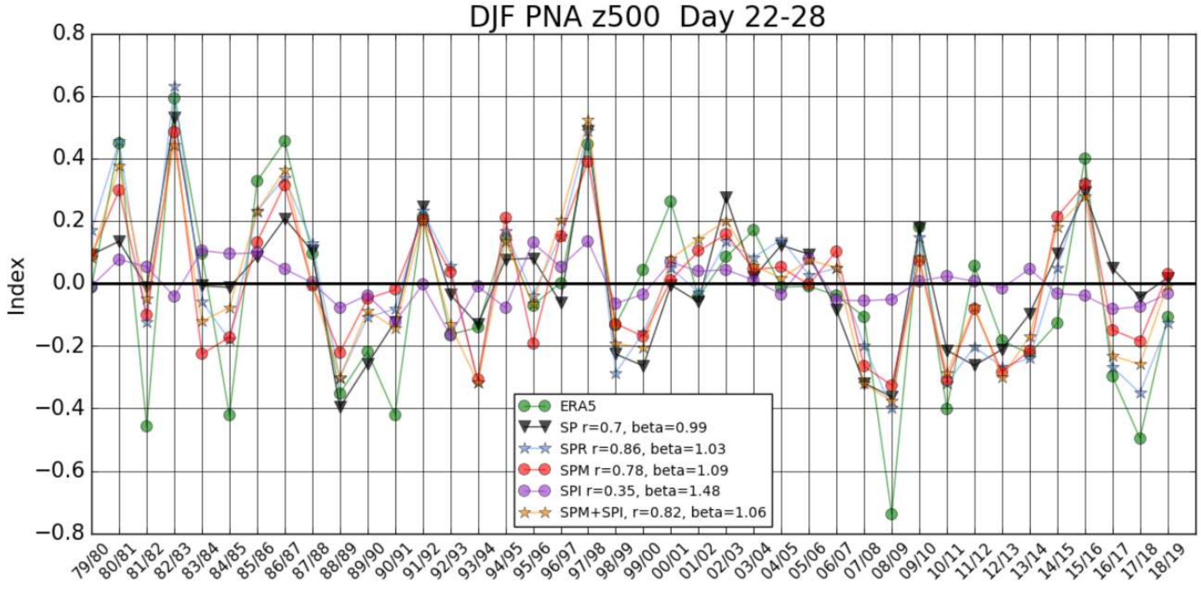

**Figure 7.** DJF PNA ERA v mean week 4 forecasts. Control (SP), relaxed tropics (SPR), mixed initial conditions with relaxed tropics (SPM), initial conditions only (SPI), sum of SPM+SPI. The legend gives the correlation between forecasts and ERA (r), and the under prediction factor (beta, see section 5).

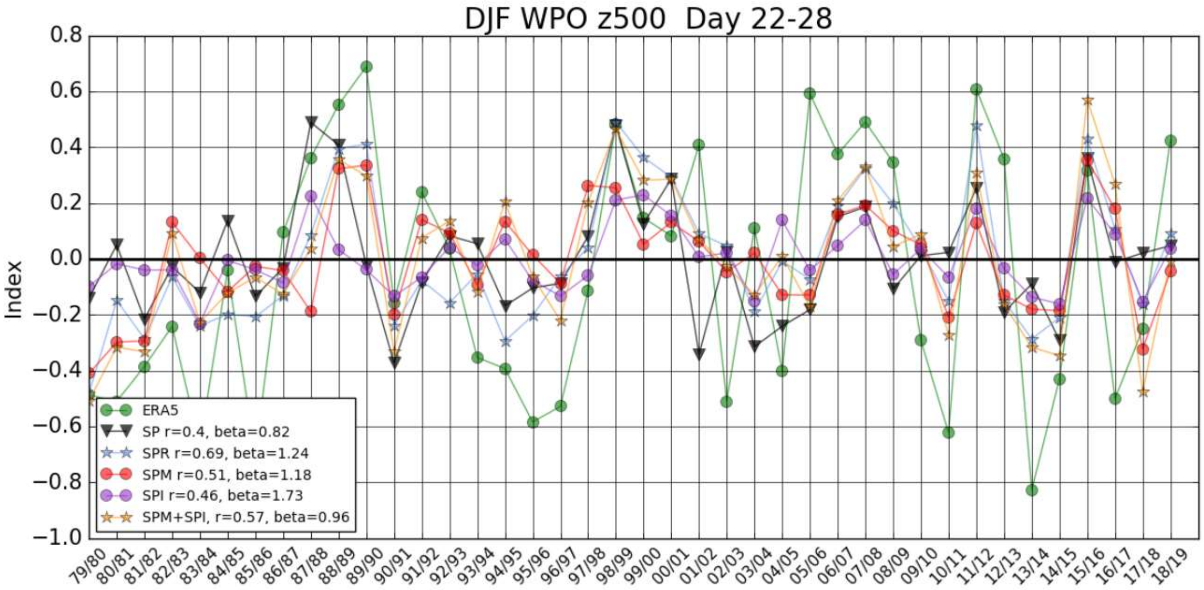

**Figure 8.** DJF WPO ERA v mean week 4 forecasts. Control (SP), relaxed tropics (SPR), mixed initial conditions with relaxed tropics (SPM), initial conditions only (SPI), sum of SPM+SPI. The legend gives the correlation between forecasts and ERA (r), and the under prediction factor (beta, see section 5).

## 5. Under prediction of the NAO

The under prediction of the NAO is an important scientific question as to why it arises and has practical implications for users (like Citadel) as it suggests current operational systems are underestimating the amount of real world predictability. The under prediction of the NAO was first found in seasonal hindcasts of GLOSEA5 by Scaife et al (2014) where correlation skill is higher than would be expected from the model signal-to-noise ratio (see also Eade et al, 2014), but it appears to be a ubiquitous feature across a range of models and timescales (from week 2 to decadal).

The beta parameter shown in the legend of Figures 6,7,8 indicates the under prediction factor for the different teleconnection indices and experiments where beta > 1 indicates the best fit to the observations is to scale up the ensemble mean forecast, while beta < 1 is to scale down the ensemble mean forecasts. Figure 9 shows a scatter plot of the ensemble mean NAO in the relaxed tropics (SPR) experiment v the observed NAO where the regression gives beta=1.37 indicating the model forecast for the NAO should be scaled up. This is less than for the control forecast (SP) which has beta=1.58. The tropics only (SPM) and initial conditions only (SPI) also someone under predict the NAO, but the combined SPM+SPI (Figure 10) remarkably has beta very close to 1. Note SPM+SPI is a worse forecast than SPR in terms of skill.

In contrast, apart from the initial conditions only experiment (SPI), the PNA has beta close to 1 for all experiments (see legend in Figure 7).

For the WPO, the control forecast (SP) has beta < 1, while the relaxed tropics experiment (SPR) has beta > 1 (see legend in Figure 8). The SPR (r=0.69) is significantly more skilful then SP (r=0.4) so some aspect of the tropical forcing in the free running model is degrading the simulation of the WPO and hence its forecast of the WPO needs to be damped. In contrast, with the correct tropical forcing, SPR forecasts the WPO with similar accuracy to the NAO (r~0.7) but again under predicts it (beta=1.24). The combined SPM+SPI experiments have beta close to 1 (again similar to the NAO).

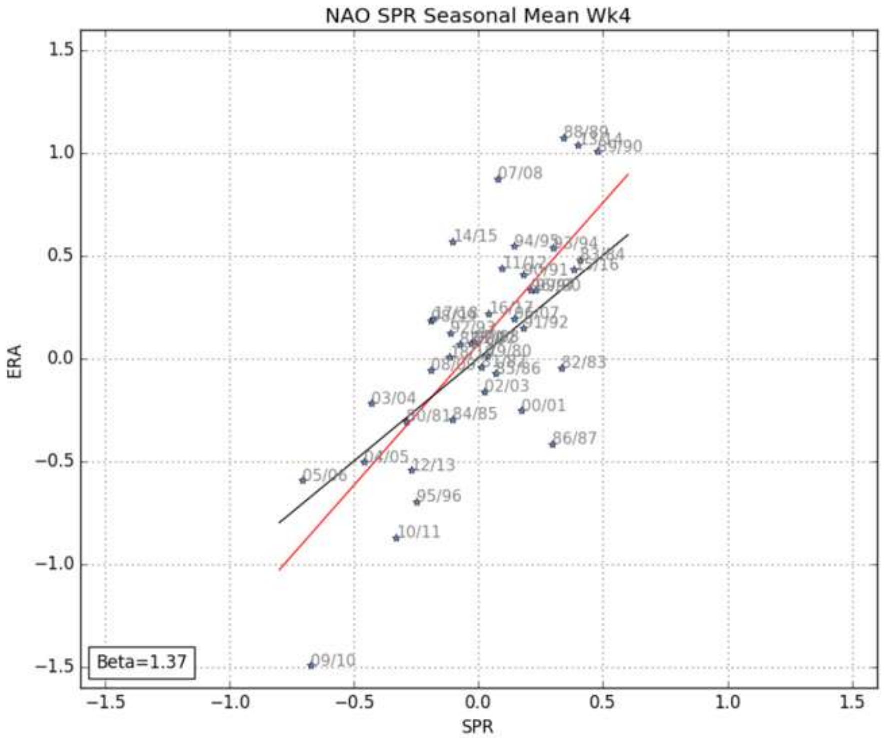

**Figure 9.** DJF NAO mean week 4 forecast from relaxed experiment (SPR) v ERA. Red is regression line, black line is slope=1.

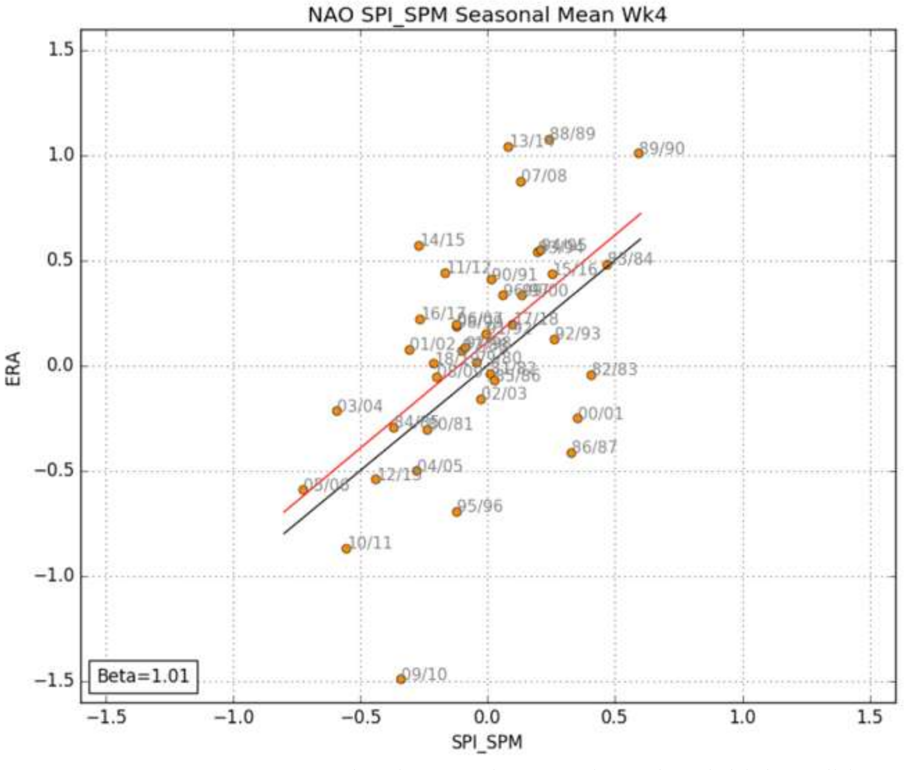

**Figure 10.** DJF NAO mean week 4 forecast from tropics only + initial conditions only experiments (SPR+SPI) v ERA. Red is regression line, black line is slope=1.

## 6. Relationship between skill and teleconnection indices

Perhaps not surprisingly, the skill of the Atlantic/European sector has some relationship to the magnitude of NAO forecast, see Figure 11 (left) from experiment SPR, with years with strong NAO signals being more predictable. The two extreme years of 1995/6 and 2009/10 both had strong –ve NAO signals. In contrast years with weak NAO signals have low or even negative skill. The two years with significantly negative skill are 1979/80 where the forecasts completely missed the –ve NAO signal, and 2018/19 where the forecasts somewhat over predicted –ve NAO.

We don't find any relationship between the PNA and the skill of the Atlantic/European sector but there is a weak negative relationship between Atlantic/European skill and the forecast of the WPO and EPO, see Figure 11 (right). The poorly predicted winter of 1979/80 had a strong WPO signal but not 2018/19.

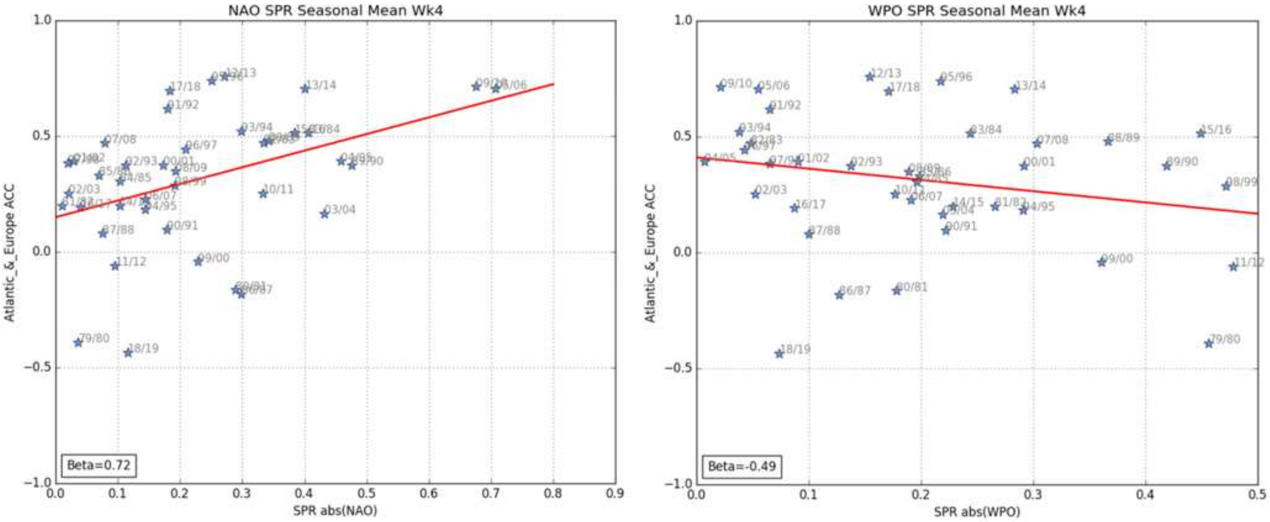

**Figure 11.** Skill of Atlantic/European sector (500 hPa heights anomaly correlation for domain 60W-30E, 20-90N) for week 4 mean DJF forecast from relaxed experiment (SPR) v magnitude of NAO forecast (left) and magnitude of WPO forecast (right). Red are regression lines.

## 7. Discussion

The most interesting result (so far) from the analysis of this Special Project is the nonlinearity of the predictability of the NAO & WPO (skill of SPR > SPM + SPI) and possible connection to the under prediction of the NAO & WPO (beta > 1 for SPR, but beta ~1 for SPM + SPI). While for the PNA predictability is approximately linear (SPR ~ SPM + SPI), and all experiments have beta ~1. It is also noteworthy that the NAO has stronger amplitude in the relaxed tropics experiments (SPR) in the strong NAO years compared to the control experiment (SP) (e,g. Figure 1 & 3) yet the overall skill of SP & SPR is the same (ACC=0.73). This means SP has greater under prediction of the NAO (beta=1.58) than SPR (beta=1.38).

The nonlinearity of the NAO v the linearity of the PNA has been discussed in the literature e,g, Benedict et al. (2004). The WPO is the Pacific basin analogue of the NAO (Linkin and Nigam, 2008) so it is not surprising to find a similar result for the WPO. Both the NAO & WPO can viewed as essentially the signal of combined variations in the strength and orientation of the storm track and the associated eddy-driven jet (Woollings et al., 2010). The feedback from eddies and indeed wave breaking are sensitive to the initial jet state. So we should expect some nonlinear coupling between the tropically forced teleconnection and the initial state. The models with initial conditions and tropical forcing (SP & SPR) appear to know something about this coupling but the under prediction indicates it is too weak.

In our previous Special Project, we discussed the possible role of mean state jet errors and this is also a feature here – all the model experiments have jets in week 4 which are too weak and shifted slightly poleward. Furthermore the Pacific jet does not extend far enough east. It still seems (to us) that this is the most likely cause of the too weak nonlinear coupling in predicting the NAO and WPO.

However we need to investigate mechanisms further and also the role of the stratosphere. The winter of 1989/90 (Figure 1) had a similar forecast between SPR and the combined SPM+SPI even though the NAO and WPO/EPO were weaker than observed. All the models this year under predicted the strength of stratospheric polar vortex and this could have been an important factor.

Results from the project indicate that the strong +ve NAO years 1988-1994 were largely predictable and in particular having hindcast set going back longer than the operational extended hindcast set (which is 20 years) allows analysis of a year (1989/90) which had very similar predictability to last winter (2019/20).

Figure 5 shows that generally the skill of predicting the wintertime week 4 pattern follows the skill of the tropics only model (SPM) but this is not always the case. The years 2011/12 to 2014/15 had skill of SPR significantly above SPM. The overall skill of the winter 2000/1 (see Figure 4) and the following years in the early 2000s was poor. It is not obvious looking at the strength of tropical forcing why these years should behave differently – this is something we will investigate further.

## References

Benedict, J. J., *et al.* (2004), Synoptic View of the North Atlantic Oscillation*, J. Atmos. Sci*., 61, 121-144.

Eade, R., *et al* (2014), Do seasonal-to-decadal climate predictions underestimate the predictability of the real world? *Geophys. Res. Letts*, 41, 5620-5628.

Linkin, M. E., Nigam, S. (2008), The North Pacific Oscillation – West Pacific Teleconnection Pattern: Mature-phase structure and winter impacts, *J. Climate*, 21, 1979-1997.

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Scaife, A. A., *et al.* (2014), Skilful long range prediction of European and North American winters, *Geophys. Res. Letts.*, 41, 2514–1519.

Woollings, W, et al. (2010), A regime view of the North Atlantic Oscillation and its response to anthropogenic forcing, J. Climate, 23, 1291-1307.