REQUEST FOR A SPECIAL PROJECT 2023–2025

MEMBER STATE:	United Kingdom
Principal Investigator[1]**:**	Mr. Matthew Wright
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Other researchers:	Dr. Antje Weisheimer (ECMWF; University of Oxford) Prof. Tim Woollings (University of Oxford) Dr. Tim Stockdale (ECMWF)
Project Title:	Investigating multi-decadal climate variations in seasonal forecasts: the role of aerosol and greenhouse gas forcings

If this is a continuation of an existing project, please state the computer project account assigned previously.	**SP** ________________	
Starting year: (A project can have a duration of up to 3 years, agreed at the beginning of the project.)	2023	
Would you accept support for 1 year only, if necessary?	YES ☒	NO ☐

Computer resources required for 2023-2025: (To make changes to an existing project please submit an amended version of the original form.)		**2023**	**2024**	**2025**
High Performance Computing Facility	(SBU)	23,600,000	29,600,000	29,600,000
Accumulated data storage (total archive volume)[2]	(GB)	83,840	189,130	294,410

Continue overleaf

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[1] The Principal Investigator will act as contact person for this Special Project and, in particular, will be asked to register the project, provide annual progress reports of the project's activities, etc.

[2] These figures refer to data archived in ECFS and MARS. If e.g. you archive x GB in year one and y GB in year two and don't delete anything you need to request x + y GB for the second project year etc.

Principal Investigator: Mr. Matthew Wright

Project Title: Investigating multi-decadal climate variations in seasonal forecasts: the role of aerosol and greenhouse gas forcings

Abstract

Seasonal forecasts provide information on monthly mean weather-statistics a season or more in advance. Seasonal predictive skill depends on many factors, including the geographical forecast region and the specific events being predicted. It has recently been found by (Weisheimer et al., 2021) and (Weisheimer et al., 2022) that seasonal predictive skill for key indices (ENSO, PNA, NAO) undergoes substantial multi-decadal variations between 1901 and 2010. The physical mechanisms for these variations are still unclear. Simultaneously, the CONFESS project is developing a higher resolution aerosol dataset to be used in the IFS.

This three-year project aims to collaborate with CONFESS and Dr. Tim Stockdale from ECMWF to investigate the role of aerosol and greenhouse gas forcings on the multi-decadal variations in seasonal forecast skill. Firstly, the 1930s 'Dust Bowl' over North America will be used as a case study to test aerosol sensitivities. Secondly, aerosol and greenhouse gas sensitivities over the boreal winter for the whole 20th century will be tested, allowing comparison to Weisheimer et al.'s previous work. Finally, the spatial variation in aerosol load will be investigated.

The outcomes of this project are consistent with the aims of the World Climate Research Programme and wider research community and complement the work that CONFESS is doing to improve aerosol representation in the ECMWF seasonal forecasting system. This will ultimately help improve ECMWF's seasonal forecasts.

Project Description

The completed form should be submitted/uploaded at https://www.ecmwf.int/en/research/special-projects/special-project-application/special-project-request-submission.

All Special Project requests should provide an abstract/project description including a scientific plan, a justification of the computer resources requested and the technical characteristics of the code to be used.

Following submission by the relevant Member State the Special Project requests will be published on the ECMWF website and evaluated by ECMWF as well as the Scientific Advisory Committee. The evaluation of the requests is based on the following criteria: Relevance to ECMWF's objectives, scientific and technical quality, and justification of the resources requested. Previous Special Project reports and the use of ECMWF software and data infrastructure will also be considered in the evaluation process.

Requests asking for 3,000,000 SBUs or more should be more detailed (3-5 pages). Large requests asking for 10,000,000 SBUs or more might receive a detailed review by members of the Scientific Advisory Committee.

Motivation and background

The ability to forecast weather and climate reliably on a seasonal timescale is of great societal and scientific interest. If floods, droughts, and rainfall onset can be reliably predicted a season or more in advance, the economic and social costs of these events can be significantly reduced (Shukla et al., 2000; Weisheimer & Palmer, 2014). Examples include being able to better predict tropical droughts in northern South America, India, parts of southern Africa and Australia, and earlier warnings of tropical cyclones in the Philippines and other parts of southeast Asia. This is particularly topical as some extreme weather events increase in frequency and severity due to climate change (IPCC, 2021).

Seasonal predictions provide estimates of seasonal-mean weather statistics, typically up to four months ahead. Physically, this prediction is achievable because some elements of the coupled climate system have an intrinsic predictability time greater than that of individual synoptic weather systems. This includes ocean dynamics and hydrology of land masses, which force the atmosphere's lower boundary, and large-scale atmospheric circulation patterns, including the stratosphere. El-Niño Southern Oscillation (ENSO) is the strongest mode of multi-annual atmospheric variability. ENSO provides a significant source of predictability around the world (Barnston et al., 2019; L'Heureux et al., 2020; Tippett et al., 2019; Weisheimer et al., 2009), through atmospheric and oceanic teleconnections (Yeh et al., 2018).

Seasonal predictive skill has improved markedly over the past century, with successive generations of operational meteorological forecast systems improving on the accuracy and length of forecasts that are possible (Johnson et al., 2019). However, there is still generally lower predictive skill in the extra-tropics compared to the tropics, notably in the North Atlantic (Müller et al., 2005; Shi et al., 2015), where there is a complex, seasonally dependent relationship between ENSO, the North Atlantic Oscillation (NAO) and the strength and position of the jet stream (O'Reilly, 2018; Parker et al., 2019; Woollings et al., 2010).

Recently, there has been interest in finding out how seasonal predictive skill changed over the 20th century, by initialising state-of-the-art models on past start dates. These hindcasts can be compared to reanalysis datasets to conclude how skilfully the model predicts seasonal-mean statistics. (Weisheimer et al., 2021) and (Weisheimer et al., 2022) used ECMWF's SEAS5 system to produce hindcasts for the whole 20th century and investigate multi-decadal variations in seasonal predictive skill. They found that seasonal predictive skill, for ENSO and for the PNA and NAO indices, undergoes substantial multi-decadal variations between 1901 and 2010. Figure 1 shows how the PNA, and NAO prediction skill varies in time. Predictive skill is best in recent periods (as expected, given the models are tuned to current conditions), and comparable between 1900 and 1950. It is, however, much reduced between approximately 1950 and 1975. Since this variation does not correlate with the quality of available observations and is seen in both atmosphere-only and coupled hindcast runs, it is concluded that this is not just a feature of the model but a robust atmospheric and/or oceanic dynamics phenomenon. The exact details of this are the subject of open research, and this work hopes to contribute to that effort.

Aerosols are known to have a significant impact on radiative forcing and thus on climate. Aerosols are small particles suspended in the air. They can be produced naturally (Satheesh & Krishna Moorthy, 2005), e.g. desert dust, sea salt, or anthropogenically (Charlson et al., 1992), e.g. sulfate, nitrate. Anthropogenic-driven land use changes are also important for determining how many natural aerosols are produced (Artaxo et al., 2013), e.g. increased desert dust due to desertification, increased black carbon due to human-induced biomass burning, decreased biogenic aerosols due to deforestation. Their direct effect on the climate system is scattering and reflecting incoming short-wave radiation and absorbing outgoing long-wave radiation. Most aerosols scatter and reflect more radiation than they absorb, so they have a cooling effect on the earth's atmosphere. Aerosols also have indirect effects on the climate system, which are mainly due to their interactions with clouds. Most anthropogenic aerosols are found in the troposphere, with mainly volcanic aerosols in the stratosphere. The largest uncertainties are in the troposphere, so we will focus on tropospheric aerosols in this Special Project.

Despite their known importance, representations in models still lack spatial and temporal resolution (Ban-Weiss et al., 2014), and there are uncertainties in individual aerosols' radiative properties. Feedbacks between aerosols and clouds, which are sub-grid scale processes, are also badly represented: this is the largest source of uncertainty in global weather and climate models (Wang et al., 2021). Sensitivity studies have been conducted, e.g. (Dittus et al., 2021). This study investigated the role of aerosol forcing in Pacific multi-decadal variability in the period 1981-2012, but did so in a climate context, not a seasonal forecasting one. Thus, aerosol forcing is poorly constrained, even in state-of-the-art forecast models and there is a gap in understanding seasonal forecasts' sensitivity to aerosol forcing. Improving the representation of aerosols has the potential to greatly improve our understanding of how predictive skill has changed.

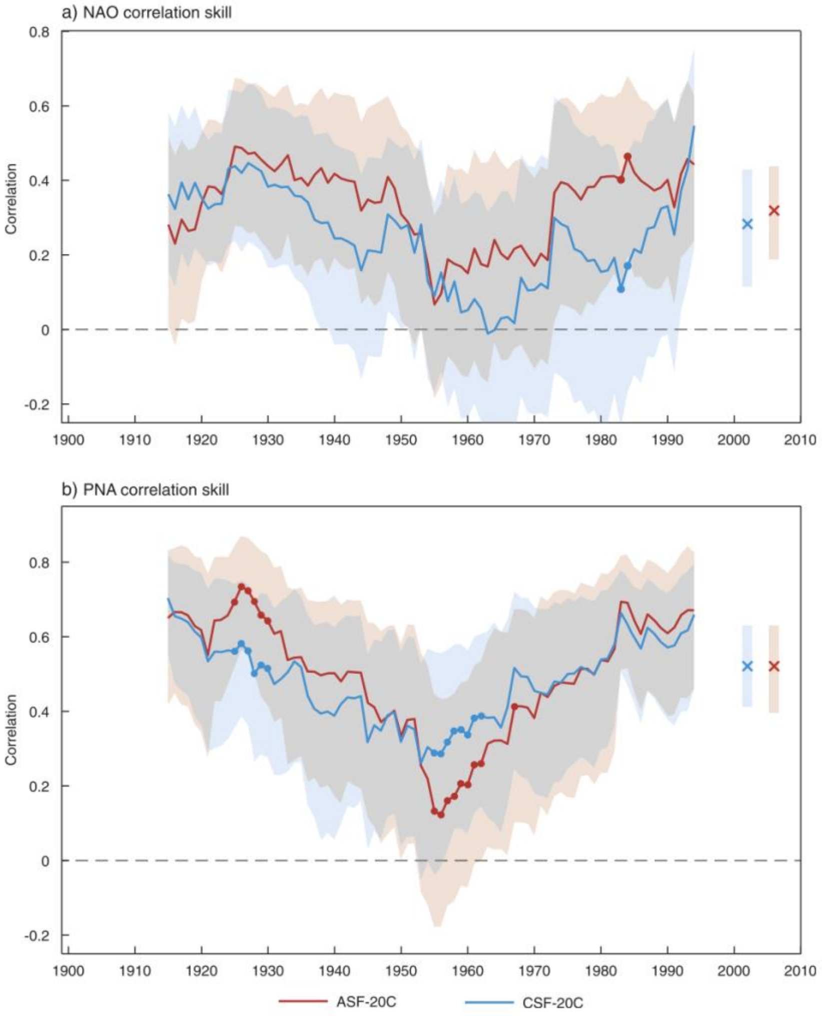

***Figure 1**: Taken from (Weisheimer et al., 2021). Decadal variability of extratropical forecast skill of the (a) NAO and (b) PNA in DJF from forecasts initialized in November with 30-year moving-window correlation coefficients of the hindcast ensemble mean with CERA-20C. Atmosphere-only seasonal forecasts ASF-20C are in red, and coupled seasonal forecasts CSF-20C are in blue. Shading indicates the 5%–95% confidence intervals. Correlations for each 30-year window are plotted at the central year. Bars on the right show correlations and confidence intervals over the full hindcast period 1901–2009. The circles on the lines show where the difference in skill between ASF-20C and CSF-20C is significant at the 95% level. The significance was calculated using a Monte Carlo significance test in which the two ensembles are shuffled and split into two random ensembles; the difference in the correlation of these two random ensembles is then calculated and this is repeated 10,000 times to give the final significance levels.*

The North American ‘Dust Bowl’ of the 1930s provides a good case study to test aerosol and land use sensitivity. The ‘Dust Bowl’ was a long drought and associated severe dust storms in American and Canadian prairies between 1932 and 1939, peaking in intensity in 1934 (Worster, 2004). Natural variation in the climate system caused a severe drought and recent agriculturally driven land use changes had increased the soil’s susceptibility to wind erosion. These factors combined to give a very dry period characterised by dust storms. The dust storms contained a large aerosol load, potentially leading to a feedback effect which made the drought last longer (Cook et al., 2008). Some models are able to predict the drought fairly well (Miller et al., 2008) using prescribed SSTs, but predict a drought centred too far south and without strong cross-continental warming. The ‘Dust Bowl’ is well studied, but not from the perspective of seasonal predictive skill in the context of the whole 20th century. It thus provides an interesting event to test the sensitivity of atmospheric dynamics and predictive skill to aerosol load and land use changes.

The CONsistent representation of temporal variations of boundary Forcings in reanalyses and Seasonal forecasts project (CONFESS) project is funded by the EU’s Horizon 2020 research and innovation programme and coordinated by ECMWF. It aims to improve representations of land cover and vegetation, and tropospheric aerosols, in C3S models (CONFESS Project, n.d.). The spatial and temporal resolution of land cover and aerosol datasets used in models is being improved by harmonising CMIP6 and CAMS datasets. This new dataset, and the insights it will provide, offers a good opportunity to explore aerosol forcing's impact on seasonal forecasts in ECMWF's model.

The World Climate Research Programme's (WRCP) Explaining and Predicting Earth System Change Lighthouse Activity (World Climate Research Programme, n.d.) outlines the need for the scientific community to attribute and predict multi-annual to decadal changes in the climate system. For example, they suggest large ensemble single forcing experiments over historical periods, which do not currently exist but will be very useful in meeting their objectives. Incomplete forcing experiments are similar to this, but they remove one forcing component and leave the rest unchanged. Like single forcing experiments, these enable the impact and sensitivity of each element to be assessed but are closer to the real world than single forcing experiments, which are extremely idealised. Running incomplete forcing experiments with the newest aerosol and land use datasets will be a valuable asset to the scientific community and contribute to worldwide efforts in this field.

This Special Project aims to investigate the role of different forcing mechanisms on seasonal predictive skill, working with CONFESS's new aerosol to test sensitivity to aerosol load, greenhouse gas concentrations. We will focus on the 1930s 'Dust Bowl' as a case study, and then extend our analysis to the period of reduced predictive skill for large-scale circulation indices as identified by Weisheimer et al. in the middle of the century. This project will collaborate with CONFESS and other ECMWF researchers to help improve future seasonal forecasting systems at ECMWF.

Scientific plan

This project will collaborate with ECMWF's seasonal forecasting team and the CONFESS programme to investigate sensitivities of seasonal forecast skill to aerosol forcing and greenhouse gas forcing. We have developed this scientific plan in consultation with Dr. Tim Stockdale (ECMWF), who is a supporting researcher for this Special Project. CONFESS has developed a new time-varying aerosol climatology for 1971-2019, with additional aerosol data going back to 1951. This data can inform our choices for the sensitivity runs. CONFESS will also run three low-resolution experiments to look at sensitivity of aerosol variations over the period 1981-2020, which we will be able to use as a comparison point for our model runs. If the CONFESS dataset is not ready by the time we run our situations, we would consider other datasets of historical aerosol forcing, including the CMIP6 dataset.

Incomplete, modified forcing experiments will be used to test the sensitivity of atmospheric and oceanic teleconnections, and predictive skill, to the aerosol load, spatial distribution and temporal trend, and greenhouse gas concentrations. These experiments complement the scientific community's ongoing work to attribute changes to the climate system to specific forcing components (see WRCP's projects, outlined above). We are aiming to test sensitivities to these forcings, rather than replicate exactly the observed trends.

The experiments that we propose running are outlined in Table 1. Coupled runs will be used, as ocean dynamics may play an important role in circulation and teleconnection changes that influence the 'Dust Bowl' and seasonal predictive skill. The initial conditions for the coupled model will be taken from CERA-20C (Laloyaux et al., 2018), as in previous work from (Weisheimer et al., 2021, 2022).

In the first phase, we will use the 'Dust Bowl' as a case study to investigate the sensitivities of teleconnections and predictive skill to aerosols. For these experiments we will use a shorter time period of 30 years, 1920-1949. The 'Dust Bowl' period of 1932-1939 is completely covered, with about 10 years of hindcasts before the event to give us baseline predictive skill for the relevant locations and signals. The model will be initialised in April and run for five months, to enable study of the end of boreal spring and all of boreal summer, when the 'Dust Bowl' had maximum intensity.

Experiment 1A acts as a control with default aerosol forcing, and 1B and 1C modify the natural aerosol forcing considerably, by at least a factor of 5. Natural aerosols will be modified because dust – a natural aerosol – was the predominant contributor to aerosol effects in the 'Dust Bowl'. These experiments will enable conclusions to be drawn about the sensitivity of teleconnections that caused the 'Dust Bowl' and predictive skill in the early-mid 20th century to aerosol loading.

The second phase will expand the time period to 81 years, 1930-2010, and focus on aerosols, running a set of experiments with varying aerosol and greenhouse gas forcings. For these experiments, the time period we will run is 1930-2010. This gives 81 years of seasonal hindcasts, a large enough dataset to identify trends in teleconnections and in predictive skill from the early 20th century to the present day. We will have full coverage of the low skill mid-century period (approximately 1950-1975), plus periods before and after to compare the skill and circulation to. Runs will be initialised in November to capture the boreal winter, which is when there is the strongest ENSO signal. Again, 2A acts as a control for the whole period, with default aerosol forcing used. 2B will remove the anthropogenic greenhouse gas forcing in the atmosphere, whilst 2C and 2D will increase and decrease aerosol forcing, respectively. The exact method and scaling that will be used to change the forcings will be decided using evidence from the literature and the results of the first phase experiments.

Finally, in phase three, we will run three specific sensitivity analyses, focusing on the spatial distribution of aerosols. Again, the time period 1930-2010 will be used, and the model will be initialised in November. The current plan is to enhance aerosol forcing over three regions (North America, south-east Asia and Europe) in three separate experiments, giving a comparison of each region's sensitivity to aerosol forcing. However, these experiments are currently not concrete and will be refined based on the results of the first two phases.

Table 1: Outline of the experiments proposed for this Special Project.

Phase	**Year**	**Experiment name**	**Details**
1: 'Dust Bowl' case study	2023	1A: control	1920-1949, April starts, five months
	2023	1B: increased natural aerosol	
	2023	1C: decreased natural aerosol	
2: multi-decadal variations in predictive skill across the whole 20th century	2023	2A: control	1930-2010, November starts, four months
	2024	2B: decreased greenhouse gas forcing	
	2024	2C: decreased aerosols	
	2024	2D: increased aerosols	
3: regional sensitivity analysis	2025	3A, 3B, 3C: sensitivity analyses of aerosols' spatial distribution	
	2025		
	2025		

Technical characteristics of code to be used

We propose to use the coupled ECMWF model for the seasonal hindcasts. The atmospheric part of IFS will be run in Cycle 48r1 at resolution TCo199, with 91 vertical levels (L91). The horizontal resolution is similar to the model version of the long seasonal hindcasts generated previously (Weisheimer et al., 2021, 2022), and thus allows a fair comparison. The NEMO version that will be used is the default version 3.4, run with 1° horizontal resolution and 42 vertical levels. Both the atmosphere and the ocean will be initialised using the CERA-20C reanalysis. We will run all simulations with 25 ensemble members.

Justification of computer resources requested

Whilst the exact details of the forcings to be used are to be finalised, the computer resources required are independent of the forcings, so we are confident the numbers below are accurate. These numbers rely on initial testing from the seasonal forecast team at ECMWF on the ATOS machine.

For the proposed model configuration, the anticipated costs in terms of SBUs are shown below, based on 1 forecast month with 1 ensemble member and 1 start year costing 1,216 SBU. We multiply this figure by the number of forecast months, ensemble members and start years to get the total number of SBUs required:
Experiments 1A, 1B, 1C: 1,216 * 5 * 25 * 30 = 4,560,000 SBUs
Experiments 2A, 2B, 2C, 2D, 3A, 3B, 3C: 1,216 * 4 * 25 * 81 = 9,849,600 SBUs

This leads to the following costs:
2023: 3 x 4,560,000 + 9,849,600 = 23,529,600 SBUs
2024: 3 x 9,849,600 = 29,548,800 SBUs
2025: 3 x 9,849,600 = 29,548,800 SBUs

These numbers are rounded up to the nearest hundred thousand in the units requested to allow some units for testing.

In agreement with the reduced archiving settings of standard seasonal forecast research experiments at ECMWF, a total of 1,354 spatial fields per months will be archived. This includes a selection of 6-hourly and daily data together with monthly mean fields at the surface and selected pressure levels. With one field being of size 3.2 MB, this corresponds to 4.3 GB per month of simulations. We multiply this figure by the number of forecast months, ensemble members and start years to get the total number of GB required:
Experiments 1A, 1B, 1C: 4.3 * 5 * 25 * 30 = 16,248 GB
Experiments 2A, 2B, 2C, 2D, 3A, 3B, 3C: 4.3 * 4 * 25 * 81 = 35,095 GB

This leads to the following storage requirements:
2023: 3 x 16,248 + 35,095 = 83,840 GB
2024: 3 x 35,095 = 105,290 GB
2025: 3 x 35,095 = 105,290 GB

We require data to be accessible for the remainder of the project, so these storage amounts are cumulative. We therefore require 83,840 GB in year 1, 189,130 GB in year 2 and 294,410 GB in year 3.

References

Artaxo, P., Rizzo, L. v., Brito, J. F., Barbosa, H. M. J., Arana, A., Sena, E. T., et al. (2013). Atmospheric aerosols in Amazonia and land use change: From natural biogenic to biomass burning conditions. *Faraday Discussions*, *165*(0), 203–235. https://doi.org/10.1039/c3fd00052d

Ban-Weiss, G. A., Jin, L., Bauer, S. E., Bennartz, R., Liu, X., Zhang, K., et al. (2014). Evaluating clouds, aerosols, and their interactions in three global climate models using satellite simulators and observations. *Journal of Geophysical Research: Atmospheres*, *119*(18), 10,876-10,901. https://doi.org/10.1002/2014JD021722

Barnston, A. G., Tippett, M. K., Ranganathan, M., & L'Heureux, M. L. (2019). Deterministic skill of ENSO predictions from the North American Multimodel Ensemble. *Climate Dynamics*, *53*(12), 7215–7234. https://doi.org/10.1007/s00382-017-3603-3

Charlson, R. J., Schwartz, S. E., Hales, J. M., Cess, R. D., Coakley, J. A., Hansen, J. E., & Hofmann, D. J. (1992). Climate forcing by anthropogenic aerosols. *Science*, *255*(5043), 423–430. https://doi.org/10.1126/science.255.5043.423

CONFESS Project. (n.d.). CONFESS H2020 Project – CONsistent representation of temporal variations of boundary Forcings in reanalysES and Seasonal forecasts. Retrieved June 15, 2022, from https://confess-h2020.eu/

Cook, B. I., Miller, R. L., & Seager, R. (2008). Dust and sea surface temperature forcing of the 1930s "Dust Bowl" drought. *Geophysical Research Letters*, *35*(8). https://doi.org/10.1029/2008GL033486

Dittus, A. J., Hawkins, E., Robson, J. I., Smith, D. M., & Wilcox, L. J. (2021). Drivers of Recent North Pacific Decadal Variability: The Role of Aerosol Forcing. *Earth's Future*, *9*(12), e2021EF002249. https://doi.org/10.1029/2021EF002249

IPCC. (2021). *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*.

Johnson, S. J., Stockdale, T. N., Ferranti, L., Balmaseda, M. A., Molteni, F., Magnusson, L., et al. (2019). SEAS5: The new ECMWF seasonal forecast system. *Geoscientific Model Development*, *12*(3), 1087–1117. https://doi.org/10.5194/gmd-12-1087-2019

Laloyaux, P., de Boisseson, E., Balmaseda, M., Bidlot, J. R., Broennimann, S., Buizza, R., et al. (2018). CERA-20C: A Coupled Reanalysis of the Twentieth Century. *Journal of Advances in Modeling Earth Systems*, *10*(5), 1172–1195. https://doi.org/10.1029/2018MS001273

L'Heureux, M. L., Levine, A. F. Z., Newman, M., Ganter, C., Luo, J., Tippett, M. K., & Stockdale, T. N. (2020). ENSO Prediction. In M. J. McPhaden, A. Santoso, & W. Cai (Eds.), *Geophysical Monograph 253* (First Edit, pp. 227–246). John Wiley & Sons, Ltd. https://doi.org/10.1002/9781119548164.ch10

Miller, J., Naik, N., Cane, M., Ting, M., Kushnir, Y., & Seager, R. (2008). Would Advance Knowledge of 1930s SSTs Have Allowed Prediction of the Dust Bowl Drought?*. *Journal of Climate*, *21*(13), 3261–3281. https://doi.org/10.1175/2007JCLI2134.1

Müller, W. A., Appenzeller, C., & Schär, C. (2005). Probabilistic seasonal prediction of the winter North Atlantic Oscillation and its impact on near surface temperature. *Climate Dynamics*, *24*(2–3), 213–226. https://doi.org/10.1007/s00382-004-0492-z

O'Reilly, C. H. (2018). Interdecadal variability of the ENSO teleconnection to the wintertime North Pacific. *Climate Dynamics*, *51*(9–10), 3333–3350. https://doi.org/10.1007/S00382-018-4081-Y/FIGURES/15

Parker, T., Woollings, T., Weisheimer, A., O'Reilly, C., Baker, L., & Shaffrey, L. (2019). Seasonal Predictability of the Winter North Atlantic Oscillation From a Jet Stream Perspective. *Geophysical Research Letters*, *46*(16), 10159–10167. https://doi.org/10.1029/2019GL084402

Satheesh, S. K., & Krishna Moorthy, K. (2005). Radiative effects of natural aerosols: A review. *Atmospheric Environment*, *39*(11), 2089–2110. https://doi.org/10.1016/j.atmosenv.2004.12.029

Shi, W., Schaller, N., Macleod, D., Palmer, T. N., & Weisheimer, A. (2015). Impact of hindcast length on estimates of seasonal climate predictability. *Geophysical Research Letters*, *42*(5), 1554–1559. https://doi.org/10.1002/2014GL062829

Shukla, J., Anderson, J., Baumhefner, D., Brankovic, C., Chang, Y., Kalnay, E., et al. (2000). Dynamical Seasonal Prediction. *Bulletin of the American Meteorological Society*, *81*(11), 2593–2606. https://doi.org/10.1175/1520-0477(2000)081<2593:DSP>2.3.CO;2

Tippett, M. K., Ranganathan, M., L'Heureux, M., Barnston, A. G., & DelSole, T. (2019). Assessing probabilistic predictions of ENSO phase and intensity from the North American Multimodel Ensemble. *Climate Dynamics*, *53*(12), 7497–7518. https://doi.org/10.1007/s00382-017-3721-y

Wang, C., Soden, B. J., Yang, W., & Vecchi, G. A. (2021). Compensation Between Cloud Feedback and Aerosol-Cloud Interaction in CMIP6 Models. *Geophysical Research Letters*, *48*(4), e2020GL091024. https://doi.org/10.1029/2020GL091024

Weisheimer, A., & Palmer, T. N. (2014). On the reliability of seasonal climate forecasts. *Journal of the Royal Society Interface*, *11*(96). https://doi.org/10.1098/rsif.2013.1162

Weisheimer, A., Doblas-Reyes, F. J., Palmer, T. N., Alessandri, A., Arribas, A., Déqué, M., et al. (2009). ENSEMBLES: A new multi-model ensemble for seasonal-to-annual predictions - Skill and progress beyond DEMETER in forecasting tropical Pacific SSTs. *Geophysical Research Letters*, *36*(21). https://doi.org/10.1029/2009GL040896

Weisheimer, A., Befort, D. J., MacLeod, D., Palmer, T., O'Reilly, C., & Strømmen, K. (2021). Seasonal forecasts of the twentieth century. *Bulletin of the American Meteorological Society*, *101*(8), E1413–E1426. https://doi.org/10.1175/BAMS-D-19-0019.1

Weisheimer, A., Balmaseda, M. A., Stockdale, T. N., Mayer, M., Sharmila, S., Hendon, H., & Alves, O. (2022). Variability of ENSO Forecast Skill in 2-Year Global Reforecasts Over the 20th Century. *Geophysical Research Letters*, *49*(10), e2022GL097885. https://doi.org/10.1029/2022GL097885

Woollings, T., Hannachi, A., & Hoskins, B. (2010). Variability of the North Atlantic eddy-driven jet stream. *Quarterly Journal of the Royal Meteorological Society*, *136*(649), 856–868. https://doi.org/10.1002/qj.625

World Climate Research Programme. (n.d.). Explaining and Predicting Earth System Change. Retrieved June 15, 2022, from https://www.wcrp-climate.org/epesc

Worster, D. (2004). *Dust Bowl : the southern Plains in the 1930s*. Oxford University Press.

Yeh, S. W., Cai, W., Min, S. K., McPhaden, M. J., Dommenget, D., Dewitte, B., et al. (2018). ENSO Atmospheric Teleconnections and Their Response to Greenhouse Gas Forcing. *Reviews of Geophysics*, *56*(1), 185–206. https://doi.org/10.1002/2017RG000568