Part B-1

1. Excellence

1.1. Quality, credibility and innovative aspects of the research

Introduction: The Mediterranean region (MED) is a hotspot of anthropogenic climate change and impacts are probably already felt today; recent heatwaves and persistent droughts have led to crop failures, wild fires and water shortages, causing large economic losses[1,2]. Climate models robustly project further warming and drying of the region, putting it at risk of desertification[3]. The particular vulnerability of this water-limited region to climatic changes has created an urgent need for reliable forecasts of rainfall on subseasonal to seasonal (S2S) timescales, i.e. 2 weeks up to a season ahead. This S2S time-range is particularly crucial, as the prediction lead time is long enough to implement adaptation measures, and short enough to be of immediate relevance for decision makers. However, predictions on lead-times beyond approximately 10 days fall into the so-called "weather-climate prediction gap", with operational forecast models only providing marginal skill[4]. The reasons for this are a range of fundamental challenges, including a limited causal understanding of the underlying sources of predictability[5-7].

The proposed research effort aims to improve S2S forecasts of MED rainfall by taking an innovative, interdisciplinary approach that combines novel causal discovery algorithms from complex system science with operational forecast models. This will overcome current limitations of conventional statistical methods to identify relevant sources of predictability and to evaluate modelled teleconnection processes. The outcomes of this project will (i) identify key S2S drivers of MED rainfall, (ii) systematically evaluate them in forecast models, (iii) derive process-based bias corrections to (iv) boost forecast skill. My strong background in both causal inference techniques and atmospheric dynamics puts me in a unique position to lead this innovative effort and to achieve real progress in reducing the "weather-climate prediction gap" for the MED region.

State-of-the-art: Forecasts of weather (up to 2 weeks) and climate (seasonal and beyond) differ in their respective sources of predictability[6]. Numerical weather prediction systems include complex high resolution representations of atmospheric processes with the prediction strongly depending on the atmosphere's initial state. In contrast, climate predictions are usually based on coupled atmosphere-ocean processes and are performed on coarser grids due to higher computational costs, with the skill arising from the large-scale oceanic boundary conditions on the atmospheric state. In between, i.e. on the S2S timescale, many high-impact events such as droughts and heat waves take place[6,7], which are, however, not well captured either by weather or by climate models[8]. Forecasts on this timescale are extremely challenging since the memory of the atmospheric initial conditions is mostly already lost, but large-scale oceanic boundary conditions only play a small role[5,6]. Recent studies indicated potential for skilful S2S predictions by considering relatively slow moving components of the climate system that interact with the atmosphere, like sea-surface temperatures, sea-ice or soil-moisture[5-8]. However, the signal of these processes is small compared to internal atmospheric variability and the exact causal pathways and physical mechanisms are poorly understood and not accurately captured by climate models[7].

In the MED region, precipitation occurs mainly in winter, making this season particularly critical for reliable S2S predictions for water-dependent sectors like agriculture[9]. Winter rainfall in this region, particularly in the western part, is linked to the phase of the North Atlantic Oscillation (NAO), a well-known atmospheric circulation pattern over the Atlantic, historically defined as the sea level pressure difference between Iceland and the Azores. Operational ensemble forecasts have skill in predicting the NAO[10,11], indicating that there indeed exist sources for long-lead predictability, but these forecasts also raise questions[11,12]:

First, the exact sources of predictability of the NAO are not well understood, thus it is not clear where the models' skill comes from. Previous studies proposed different mechanisms to impact NAO variability and MED rainfall

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[1] Hoerling, M., *et al.* (2012), On the increased frequency of Mediterranean drought. *J. Clim.*
[2] Kelley, C. P., *et al.* (2015), Climate change in the Fertile Crescent and implications of the recent Syrian drought. *Proc. Natl. Acad. Sci.*
[3] Guiot, J. & Cramer, W. (2016), Climate change: The 2015 Paris Agreement thresholds and Mediterranean basin ecosystems. *Science.*
[4] Weisheimer, A. & Palmer, T. N. (2014), On the reliability of seasonal climate forecasts. *J. R. Soc. Interface*
[5] Mariotti, A., *et al.* (2018), Progress in subseasonal to seasonal prediction through a joint weather and climate community effort. *npj Clim.& Atm. Sci.*
[6] Vitart, F., *et al.* (2018), The sub-seasonal to seasonal prediction project (S2S) and the prediction of extreme events. *npj Clim.& Atm. Sci.*
[7] Sillmann, J. *et al.* (2017) Understanding, modeling and predicting weather and climate extremes: Challenges and opportunities. *Weather and Clim. Extremes.*
[8] Robertson, A. W., *et al.* (2018), Summary of workshop on sub-seasonal to seasonal predictability of extreme weather and climate. *npj Clim.& Atm. Sci.*
[9] Kelley, C., *et al.* (2012), Mediterranean precipitation climatology, seasonal cycle, and trend as simulated by CMIP5, *Geophys. Res. Lett.*
[10] Scaife, A. A., *et al.* (2014), Skillful long-range prediction of European and North American winters. *Geophys. Res. Lett.*
[11] Weisheimer, A., *et al.* (2017). Atmospheric seasonal forecasts of the twentieth century: multi-decadal variability in predictive skill of the winter North Atlantic Oscillation (NAO) and their potential value for extreme event attribution. *Q. J. Royal Meteorol. Soc.*
[12] Siegert, S., *et al.* (2016), A Bayesian Framework for Verification and Recalibration of Ensemble Forecasts: How Uncertain is NAO Predictability? *J. Clim.*

including the stratospheric polar vortex[13,14], the Madden-Julian-Oscillation (MJO)[15], the Quasi-Biennial Oscillation (QBO)[16], Barents and Kara sea ice[17] and Eurasian snow cover[18]. However, some of the hypothesised processes operate and interact on vastly different time-scales, making it extremely challenging to identify the underlying causal pathways. *Second*, it is not clear to what extent models are biased in representing the mechanisms causing NAO and MED rainfall variability. Even when capturing the relevant teleconnection pathway, models typically underestimate the response to a certain forcing[19]. For example, they might respond too weakly to Arctic sea ice loss, likely having negative implications for forecast skill. In theory, bias corrections and post-processing of certain climate indices could account for such problems, but as the exact underlying processes are not understood, there is no physics-guided approach to do this[20]. *Third*, the above challenges are compounded by the lack of suitable established statistical methods to address these issues. A key task is separating the signal (i.e. the teleconnection pattern) from the noise (i.e. chaotic atmospheric variability)[21]. In contrast to numerical weather predictions (where many daily forecasts provide huge verification data sets), and long-term climate projections (where one can to limit oneself to summary statistics), evaluating S2S forecast models requires more sophisticated tools. Currently such evaluations are mainly based on the correlation between model output and observations. However, as correlation does not mean causation, this approach is strongly limited in interpretability: indirect links, common drivers and autocorrelation effects can lead to spurious, non-causal correlations, often leading to false conclusions regarding the strength and direction of a signal[22].

In recent years, rapid methodological progress has been made in computer science and statistics to identify and quantify causal dependencies from time series data alone, by estimating their joint probability distribution under certain assumptions[22,23], suggesting also enormous potential to overcome some of the methodological shortcomings frequently faced in climate science. Such causal discovery algorithms have only recently been applied to climate science to understand teleconnection pathways[24,25] and to improve predictions of climate indices[26,27]. In particular, Kretschmer et al. (2016)[24] introduced the concept of causal effect networks (CEN), in which nodes represent different processes and the links represent the strength of the causal relationship. It was shown that, when guided by physical theory, CENs can complement model experiments to infer causal relationships in the climate system.

Research objectives: Motivated by the previous discussion, the overarching research questions are

RQ1. What are the remote and local sources of S2S predictability of MED winter rainfall variability and extreme events and how do these processes interact with each other?
RQ2. How well are these processes captured in operational forecast models?
RQ3. How far can statistical post-processing be applied to boost skill of MED rainfall forecasts?

Although these objectives are very challenging, their realization is realistic given my experience in applying causal discovery techniques to climate science. Moreover, the project will profit from the outstanding expertise of the partners covering the topics of climate dynamics (T. G. Shepherd, UREAD) and seasonal forecasting (A. Weisheimer, ECMWF; F. J. Doblas-Reyes, BSC), which will assure that the proposed research goals are achieved.

Research methodology and approach: The main idea of this proposal is to achieve higher S2S forecast skill of MED rainfall via an improved physical understanding of the dynamical drivers. In contrast to conventional statistical methods (based on correlation), this project takes an innovative approach which will help to overcome the above-mentioned challenges: I will apply recently developed causal discovery algorithms from complex system science to

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13 Baldwin, M. P., *et al.* (2003), Stratospheric Memory and Skill of Extended-Range Weather Forecasts. *Science*
14 Kretschmer, M. et al. (2018), More-persistent weak stratospheric polar vortex states linked to cold extremes. *Bull. Amer. Meteor. Soc.*
15 Schwartz, C. & Garfinkel, C. S. (2017), Relative roles of the MJO and stratospheric variability in North Atlantic and European winter climate. *J. Geophys. Res.*
16 Garfinkel, C. I., *et al.* (2018), Extratropical Atmospheric Predictability from the QBO in Subseasonal Forecast Models. *J. Geophys. Res.*
17 Wang, L., *et al.* (2017), A robust empirical seasonal prediction of winter NAO and surface climate. *Scientific Reports*
18 Brands, S., *et al.* (2012), Seasonal predictability of wintertime precipitation in Europe using the snow advance index. *J. Clim.*
19 Scaife, A. A., & Smith, D., (2018), A signal-to-noise paradox in climate science. *npj Clim.& Atm. Sci.*
20 Maraun, D. *et al.* (2017), Towards process-informed bias correction of climate change simulations. *Nature Climate Change*
21 Shepherd, T. G. (2014), Atmospheric circulation as a source of uncertainty in climate change projections, *Nat. Geosci.*
22 Runge, J., *et al.* (2014), Quantifying the strength and delay of climatic interactions: The ambiguities of cross correlation and a novel measure based on graphical models. *J. Clim.*
23 Runge, J. (2018), Causal network reconstruction from time series: From theoretical assumptions to practical estimation. *Chaos*
24 Kretschmer, M., *et al.* (2016), Using Causal Effect Networks to analyze different Arctic drivers of mid-latitude winter circulation, *J. Clim.*
25 Ebert-Uphoff, I. & Deng, Y. (2012), Causal Discovery for Climate Research Using Graphical Models, *J. Clim.*
26 Kretschmer, M., et al. (2017), Early prediction of extreme stratospheric polar vortex states based on causal precursors. *J. Geophys. Res.*
27 Kolstad, E. W. (2017), Causal Pathways for Temperature Predictability from Snow Depth. *J. Clim.*

identify, quantify and evaluate the key teleconnection pathways influencing MED rainfall in operational forecast models, which will give concrete guidance for statistical post-processing to boost forecast skill.

More precisely, causal effect networks (CENs) of different S2S processes potentially influencing MED rainfall will be created using the *PCMCI* algorithm[28]. This is a multi-variate statistical approach which is advantageous over other techniques, as it has been particularly designed to infer causal relationships in high-dimensional, strongly auto-correlated time-series data like those characteristic of the climate system. Most importantly, it has high detection power of causal relationships even if the transferred signal between processes is weak. The algorithm iteratively tests for conditionally independent relationships amongst the considered processes at different lags. For the linear case, for example, to identify spurious correlations (i.e., those which arise from autocorrelation effects or by the presence of indirect links or common drivers), it step-wisely calculates partial correlations of two time series and regresses out the potential influence of (a combination of) other processes[24,28]. CENs thus allow for more causal interpretations with respect to the input data and time-scale. It is based on a rigorous mathematical framework[29], is flexible in handling linear and non-linear relationships[28], and has been systematically tested on generic data[23,24].

As described below in more detail, this proposal is organized around four work packages (see Fig. 1).

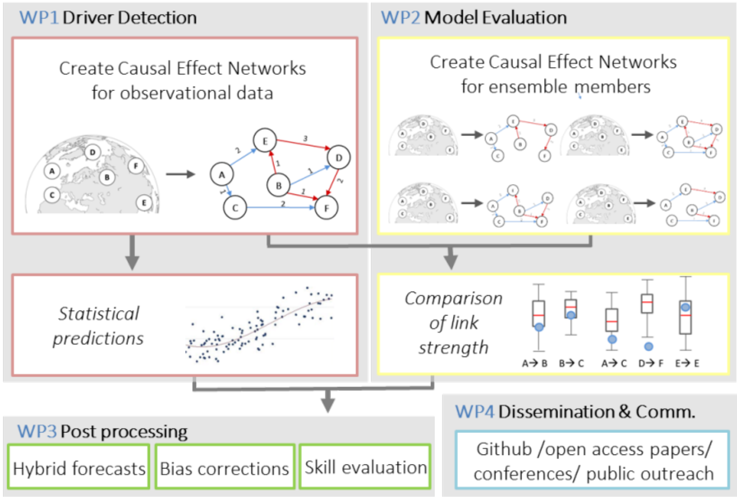

Figure 1: Schematic overview of work packages

<u>**WP1 - Driver Detection in Observations:**</u> To address RQ1, different hypothesized drivers of S2S MED rainfall will be systematically re-evaluated in WP1 by creating CENs of observation/reanalysis data. I will focus on processes that have been suggested to influence the MED rainfall variability in previous studies[13-18] (e.g. the stratospheric polar vortex, the QBO, the MJO, sea ice concentrations). This will give different time-series as input data, the *actors*, each representing a relevant component of the suggested teleconnection mechanisms. The actor time-series will be created by calculating spatial averages based on the existing literature, using Empirical Orthogonal Functions (EOFs), or when necessary, using recently developed machine learning techniques[26]. Next, CENs will be created to detect the causal, i.e. conditionally dependent, relationships amongst the considered actors by using both linear (partial correlations) and non-linear (transfer entropy) metrics. As some of the proposed drivers act on different temporal scales, CENs will be created for different S2S time-scales and lead-times. Moreover, to evaluate the robustness of causal linkages given different atmospheric and oceanic background states, CENs will be created for subsampled data sets (e.g. conditioned on the phases of the QBO). Further, the Fast Causal Inference (FCI) algorithm[30] will be applied to also assess the existence of potential not-considered, latent confounders which might affect the network structure. Overall, this will reveal the key S2S teleconnection processes influencing MED rainfall/NAO. Based on these causal drivers, optimal statistical prediction models will then be derived using multivariate linear regression or random forest regression and their performance will be compared.

<u>**WP2 - Process-based model evaluation:**</u> To address RQ2, the representation of the relevant teleconnection processes as identified in WP1 will be evaluated in operational forecast models using CENs. In contrast to conventional approaches using correlation-based analyses, this will permit much stronger conclusions on model biases. Input data will mainly come from the world-leading, newly available high-resolution ECMWF model system 5 (SEAS5) and from the European community Earth-System Model (EC-Earth). Moreover, if available, data from the S2S prediction project[6], and if necessary, data from the ECMWF 20th century hindcast will be evaluated. To assess the role of initial conditions and of forecast drift with forecast lead time, data with different initialization dates (e.g. 1st of November vs. 1st of December) will be used. To obtain larger data sets, time-series of the prospective actors will be created by following a bootstrapping approach, randomly choosing an ensemble member for each winter. Next, a CEN will be constructed for each set of actors, yielding a distribution of the individual link strengths of the

[28] Runge, J. et al. (2018), Detecting causal associations in large nonlinear time series datasets. *Science Advances (in revision)*
[29] Pearl, J. (2000), *Causality: Models, Reasoning and Inference* , Cambridge University Press New York, NY, USA.
[30] Spirtes P., *et al.* (1993): *Causation, Prediction and Search*. Lecture Notes in Statistics 81, Springer-Verlag

networks. This allows a comparison of the model spread with the observations. If, for example, the detected link strength between some observed processes (at some lag) is outside the distribution of the same link obtained from the different ensemble members, this indicates a systematic misrepresentation of this linkage in the forecast model. In contrast, if the uncertainty range of the observational value contains the model´s median, this gives confidence for a similar causal structure between model and real world.

WP3 - Statistical post-processing: To address RQ3, WP3 will capitalize on the results from WP1 and WP2 to boost skill of S2S forecasts of MED rainfall. For this purpose, (i) process-based bias corrections of the ensemble members will be created and their performance will be evaluated in combination with (ii) hybrid forecasts. For (i), it is suggested to bias-correct the over/underestimated influences of individual teleconnection processes as identified in WP2. For instance, if the causal influence of a driver was found to be systematically underrepresented in the forecast model, a correction factor is applied to account for this quantified bias. For (ii), an approach similar to that in Dobrynin *et al.* (2018)[31] will be followed. Thus, subsampled ensemble members based on "first-guess" criteria from the empirical prediction model (WP1) will be selected to increase the model´s signal. However, in contrast to their approach, the empirical predictions are here based on *causal* precursors which are not only expected to increase forecast skill but will also result in higher physical confidence and interpretability. Both (i) and (ii) thus intend to increase forecast skill based on an improved physical understanding of the underlying processes, and are furthermore computationally cheap and do not require changes of model-parameters. The performance of both post-processing steps will be evaluated by performing leave-k-out cross-validation (hindcasting), by splitting the data into training and test periods (forecasting) and other standard metrics to assess skill.

WP4 – Dissemination and Communication: This WP is established to ensure that the developed approach is generic in nature and can also be applied to study other regions, time-scales and models (scaling effects). For this purpose, Python code including a *jupyter* notebook tutorial will be made publicly available on github. The generated knowledge will further be disseminated into different relevant networks of S2S research, MED climate research, causal discovery research, and regional stakeholder. Moreover, results will be published in high-quality, journals and I will also engage in non-scientific, public outreach (see 2.2, 2.3 and section 3).

Originality and innovative aspects of the research, interdisciplinary & advancements within the research field:
Proposed here is a physics-guided application of causal inference techniques to systematically evaluate dynamical processes relevant for MED rainfall. Several recent studies called for such a process-based evaluation of atmospheric dynamics to understand systematic model biases[7,20,32], and this work would be the first to do so by introducing a new, multi-variate statistical method. Existing approaches mostly use bivariate statistics based on correlations and linear regression to compare modelled and real world processes. However, as correlation does not imply causation, these studies are strongly limited in interpretability and can further not reliably quantify causal relationships. The research project is further highly interdisciplinary as it combines (i) causal inference from complex system science with (ii) atmospheric dynamics research and (iii) S2S ensemble forecasts. This research proposal focuses on improving predictions for the MED region only but it will provide a methodological blueprint to apply causal inference tools to study relevant processes for other regions, variables, and models. Thus, this project aims to promote and establish this new approach in the climate research community, from which I, as well as the hosting and partner institutes, will profit in both the short and long term.

1.2. Quality and appropriateness of training and of two-way transfer of knowledge between researcher and host

Transfer of knowledge from the host/partners to the researcher: The excellence of the *Department of Meteorology at UREAD* and of my supervisor, Ted Shepherd, will provide me with the essential background and expertise to go on to a leadership position in climate research. I expect to complement my experience in analysing teleconnections with my supervisor`s profound expertise and theoretical knowledge of the dynamics of atmospheric circulation. Besides the interactions with my academic advisor, I will benefit from interactions with fellow group members during weekly group meetings, as well as from the many seminars and discussions offered at Reading in the area of atmospheric dynamics and S2S research. Moreover, I will acquire a set of transferrable skills which will improve my career prospects both within and outside academia. By managing this program of research, I will gain project, time, and financial management skills. People Development at the University of Reading further offers a wide range of learning and development opportunities including open sessions, online resources, locally delivered training, coaching and mentoring, and I plan to take their courses in "Research Impact", "Inclusive Teaching" and "Proposal

[31] Dobrynin, M., *et al.* (2018), Improved teleconnection-based dynamical seasonal predictions of boreal winter. *J. Geophys. Res.*
[32] Overland, J., *et al.* (2016), Nonlinear response of mid-latitude weather to the changing Arctic. *Nature Climate Change.*

Writing". At *ECMWF*, I will learn about practical and theoretical challenges of S2S operational ensemble forecasts. I will get access to their data and will learn about the different model particularities and differences. I will work closely together with my mentor Antje Weisheimer, who has published widely on the topic of S2S research, which will particularly help me to better understand the role of model biases. Moreover, I will profit from the lively research environment at ECMWF and will attend the regular seminars on S2S forecasting both from ECMWF staff and the many external visitors. During my research stays at *BSC*, I will have weekly meetings with the other mentor, *Francisco J. Doblas-Reyes*, a leading expert in the field. Moreover, I will learn about the use of EC-Earth for S2S predictions. The BSC will also offer the opportunity to learn about the efficiency of python codes through the parallelisation of the functions and the use of workflow solutions. At BSC, I will also have regular meetings and exchanges with the members of the Climate Prediction group, heavily involved in many of the aspects considered in this proposal, and the researchers of the Earth System Services group involved in "MED-GOLD", a pioneering project on climate services for the Mediterranean agricultural sector, as well as other climate services initiatives. In this way I will profit from their knowledge about MED climate but also learn about the particular stake-holder needs that are serviced by S2S forecasts.

Transfer of knowledge from the researcher to the host/partners: To the *Department of Meteorology at UREAD* I will bring my theoretical and practical skills in the newly evolving field of using causal inference techniques in climate science, gained during my PhD and current postdoctoral fellowship at the Potsdam Institute of Climate Impact research (PIK). This includes existing collaborations with Dr. Jakob Runge, a leading expert in causal inference from the DLR for Climate Informatics in Jena, Germany. To further promote this novel approach, I will give regular presentations at the Department and I plan to organize workshops on the use of the python package *tigramite* to train fellow researchers in the application of causal discovery algorithms, as I did already for colleagues at PIK. At PIK, I was strongly involved in co-supervising the PhD project of Giorgia Di Capua (on the use of causal inference to improve predictions of the Indian Summer Monsoon) and other group members. At Reading, I plan to expand these mentoring and supervision skills by supporting Elena Saggioro in her PhD project (on causal stratosphere-troposphere interactions in the Southern Hemisphere) with my expertise in this field. Furthermore, I will bring my experiences and research network on the topic of linkages between Arctic Amplification and mid-latitude weather (in particular via a stratospheric pathway), as well as on extreme weather research, gained at PIK under the supervision of Dr. Dim Coumou (now at VU Amsterdam). Both topics are fairly new but quickly evolving research fields and I can bring my knowledge, conections and overview of the relevant literature into the research group. The partner institutes *ECMWF/BSC* will directly profit from my dedication to evaluate the representation of teleconnections in their models. My dedication and experience in using machine learning and new statistical techniques in weather and climate research are particularly of interest for other local researchers. I will give regular presentations introducing the approach and updating the researchers of these institutes on my findings, which will help them to understand systematic model errors and give concrete guidance for model development.

1.3. Quality of the supervision and of the integration in the team/institution

The supervisor, *T. G. Shepherd*, obtained a PhD in Meteorology from the Massachusetts Institute of Technology in 1984. After a postdoctoral fellowship at the University of Cambridge and a faculty position at the University of Toronto, he moved to the Department of Meteorology at the University of Reading in 2012 where he currently holds a €2.5M ERC Advanced Grant (until Feb. 2020). His research ranges from theoretical geophysical fluid dynamics to climate modelling and data analysis, with a focus on atmospheric circulation. He has over 200 peer-reviewed publications which have had a very high impact (>9000 citations, h=51 on Web of Science). He has graduated 20 PhD students and supervised over 30 post-doctoral fellows and Research Associates. He has held leadership roles in scientific assessments of the IPCC and in the World Climate Research Programme, and is a Fellow of the American Geophysical Union and the Royal Society (of London). He was also part of the ECMWF's "Stratosphere Task force" aiming to improve S2S predictions based on better representations of stratospheric processes. The mentor, *A. Weisheimer* holds a senior scientist position in the Earth System Predictability Section of ECMWF's Research Department. Moreover, she leads a research group on Predictability of Weather and Climate in the Physics Department of Oxford University. She had leading roles in the research projects SPECS (Seasonal-to-decadal climate Predictions for the improvements of European Climate Services, FP7), IMPETUS (Improving Predictions of Drought for User Decision-Making, NERC) and SummerTIME (Summer: Testing Influences and Mechanisms for Europe, NERC) and is currently leading a work package in the EUCP (European Climate Predictions, H2020) project. With her outstanding expertise and best available infrastructure at ECMWF she will provide essential knowledge for the success of this fellowship. The other mentor, *F. J. Doblas-Reyes*, director of the Earth

Sciences Department at the national supercomputing centre in Spain, BSC, is a research professor at ICREA (Institució Catalana de Recerca i Estudis Avançats). He has extensive experience in modelling and forecasting, with a focus on atmospheric and coupled processes, and climate services. He has a leading role in the projects EUCP (European Climate Prediction system), PRIMAVERA (Process-based climate simulation: Advances in high-resolution modelling and European climate Risk Assessment), APPLICATE (Links between the polar regions and the low latitudes) and leads the QA4SEAS (Quality Assessment Strategies for Multi-model Seasonal Forecast) contract for the Copernicus Climate Change Service, all of immediate relevance for this research proposal. He is currently the supervisor of two IF MSC grantees. He has authored 150 peer-reviewed papers with an h-index of 40 in WoS.

Integration in the Department/Partner Institutes: During the fellowship, I will mainly be hosted within the supervisor's research group at the *Department of Meteorology at UREAD* (currently 3 PhD students and 4 Post-Docs). Individual meetings with my supervisor will be held every other week to provide scientific guidance, feedback and mentoring. Moreover, I will attend the weekly group seminars as well as the other climate seminars regularly provided at the Department. The Department is world renowned as a leading centre for weather and climate research and offers an outstanding environment for an early-career scientist to develop their career, with approximately 80 post-doctoral fellows. It is committed to postdoctoral career development and follows the European Charter for Researchers. I will take part fully in the Reading Researcher Development Programme (RRDP) which has been specially designed to support the planning and promotion of personal and professional development among researchers throughout various stages of their career and adheres to the Local Concordat for Research Staff and the University's Code of Good Practice in Research. I will be provided an appropriate working space (office, library and necessary facilities) and computing facilities will be dealt with a specifically designed IT support team of the University. Further I will be provided annual Performance and Development Reviews (PDRs) to discuss and advise me on my past and future research and career plans. One day per week, I will be seconded to *ECMWF*, the world-leading S2S forecast centre, located in Reading only 2 miles away from the Meteorology Department. Every second week, I will have meetings with my co-supervisor, A. Weisheimer and I will also attend the regular seminars here. Moreover, I plan extended research stays at *BSC* where I will be integrated in the department of my other mentor F. J. Doblas-Reyes with whom I will have weekly individual meetings during my stays and a number of regular joint meetings with other members of the department working on climate prediction, climate services and machine learning. Next to the individual meetings, to assure a smooth project flow, there will be joint meetings with Weisheimer and Shepherd once a month, and quarterly teleconferences including also Doblas-Reyes. Overall, the outstanding quality and international faculty of the Department of Meteorology, ECMWF and BSC, together with my supervisor's and mentors' expertise will provide a rich intellectual environment for me to expand my knowledge as well as my scientific network, but at the same time an opportunity for me to bring my own unique contribution and to build a research niche for myself.

1.4. Potential of the researcher to reach or re-enforce professional maturity/independence during the fellowship

The following attributes will enable me, during this Fellowship, to gain the ability to go on to a leadership position in climate research with a focus on S2S predictability by securing a permanent academic position.

Strong publication record and outreach: Despite having only been awarded a PhD in April 2018, I already have 3 accepted, peer-reviewed lead-author papers in high impact factor journals (*BAMS*, *Journal of Climate, GRL*), with another lead-author and further 4 co-author papers in review and 4 in preparation (see CV). My publications have had significant impact. In particular, my paper introducing causal effect networks[24] (currently 27 citations in WoS) has gained attention from both a methodological perspective, as well as from the research community analysing the influence of Arctic Amplification on mid-latitude weather[33], a strongly debated topic. My paper in *BAMS*[14] has also contributed significantly to this debate, showing the importance of stratospheric variability, and received broad coverage in international print media and twitter. With currently 7968 reads, it is the most read *BAMS* article of the last 12 months. Three additional papers in high-impact journals are planned to directly result from this fellowship (see 2.2). Moreover, I am engaged and trained in presenting new results to scientific and non-scientific audiences as well as to journalists (e.g. NYT, FT), and I will continue doing this during my fellowship (see section 2).

Independent, innovative research and expertise: Already during my PhD, I have been given a large degree of independence to follow my research interests. Being a mathematician by training, I was particularly keen on applying novel statistical methods to climate science-related problems, yet without ignoring the underlying physical properties. This has made me a pioneer in applying causal discovery algorithms to study climate dynamics. By

[33] Shepherd, T. G. (2016), Effects of a warming Arctic, *Science*

allowing me to complement and broaden my experiences, as well as design and control my own research program to develop a proof-of-concept for the use of causal techniques to evaluate teleconnection in climate models and improve S2S forecast skill, this fellowship would further greatly develop my independence as a researcher.

Mentoring and supervision: Methods which I developed during my PhD are now applied by Coumou's group members G. Di Capua, S. Vijverberg, and P. Pfleiderer. By helping them use these methods, I am strongly involved in their PhD projects from which I have gained mentoring and supervision skills. Also, I have taught an undergrad class in Mathematics at the University of Potsdam. These experiences provide an optimal basis for me to deepen my supervision skills by also co-supervising members of Shepherd's research group during this fellowship.

International scientific reputation and network: I am well-connected to both the complex system science community and the climate research community. Currently I am involved in a review paper on the linkage of Arctic Amplification on mid-latitude weather (for Nature Climate Change) and a perspective paper on the use of causal inference tools in the Earth System (for Nature Communications), both with renowned, international author lists (amongst others: Dr. J. Overland, Dr. T. Vihma; Prof. M. Scheffer, Prof. M. Reichstein). I gave talks at the Geoscience conferences EGU (2016, 2018) and AGU (2016, 2017) and was given one of the few prestigious oral presentations at this year's SPARC meeting in Japan. I am a member of the program committee of the 8^{th} international workshop on Climate Informatics (Boulder, USA) and was an invited speaker at the Causality in Complex Systems workshop 2017 in the Netherlands. The quality of my work has further been recognized through invitations to give seminars at several world-leading research centres including DAMTP at the University of Cambridge, the MPI in Hamburg, and Imperial College London. Moreover, I am acquainted with working at other international institutes. During my PhD, I spent three months at Harvard University and AER (Atmospheric and Environmental Research) to work with Prof. E. Tziperman and Dr. J. Cohen, which resulted in my *BAMS* paper. Moreover, I was invited to the Department of Meteorology in Reading by T. Shepherd, where I stayed for three months at the end of my PhD, starting collaborations with him and his research group members G. Zappa and I. Polichtchouk as well as with A. Weisheimer at ECMWF. Thus, I am already familiar with the scientific infrastructure at Reading, which will facilitate a smooth project start of this fellowship and will further allow me to quickly expand my network.

2. Impact

2.1. Enhancing the future career prospects of the researcher after the fellowship

My goal is to establish a unique impact-oriented, stake-holder relevant research program in atmospheric dynamics based on causal discovery statistics, by securing a permanent position at a leading European research institute. As such, I wish to become an expert in S2S forecasting, a relatively young research field with enormous potential for the application of novel methodological approaches, which is considered particularly relevant for political and economic decision makers (e.g. in water and crop management). The program of research proposed here will act as a stepping stone to achieve my goal by allowing me to develop a methodological proof-of-concept to use causal inference techniques for model evaluation of (S2S) teleconnection processes. Moreover, it will substantially broaden my knowledge on atmospheric dynamics (by working with T. Shepherd) and train me in operational S2S forecasting, (by working with A. Weisheimer and F. J. Doblas-Reyes), both necessary qualifications for my goal. In particular, I will become experienced in using SEAS5 and EC-Earth, two state-of-the art forecast models. By being integrated in three world-leading research institutes and by publishing in high-impact journals and attending international conferences, this fellowship will equip me with the ability to promote my research and network with other scientists, and therefore will allow me to stay at the forefront of European climate research. Closing the "weather-climate prediction gap" is a cross-community effort and this fellowship will further give me the opportunity to create synergies between different research communities (operational forecasting, climate dynamics, complex system science). This will also enable several new collaborations and follow-on studies and provide motivation for future grant proposals, which will enhance my career opportunities following this fellowship. For instance, the proposed methodological approach can easily be adapted to improve S2S forecasts for other regions, seasons and models. Furthermore, it is advantageous to evaluate teleconnection processes in multi-model ensembles (e.g. CMIP5/CMIP6) to identify the effects of model biases for regional climate projections. As a fellowship holder, I will be eligible to submit research proposals at Reading, and my proposal writing will benefit from the skills and experience of my supervisors and other colleagues to gain wider feedback. Working at ECMWF and BSC will give me valuable insights into stake holder-driven research, something I plan to address more in my own research but where I am currently relatively unexperienced. Especially the climate services activities of the Earth Science Services group at the BSC will be useful in this context. I will capitalize on the broad networks of my supervisor and mentors in this regard, which will help me to design research programs relevant for societal decision makers. This fellowship will further equip me with new skills on project management, including financial aspects. By attending different training modules at the University of Reading (e.g., on "Inclusive Teaching" and "Proposal Writing") I will significantly expand my scientific soft skills, which will be very helpful for future positions. Furthermore, by being involved in my supervisor's research group, I will gain additional supervision and teaching experiences.

2.2. Quality of the proposed measures to exploit and disseminate the project results

Dissemination of results: To ensure maximum impact, I will share my research results in multiple ways, aiming to reach diverse audiences. Three first-author papers will be published, targeted towards relevant peer-reviewed, high-impact journals such as Nature Geoscience, Environmental Research Letters and Journal of Climate; *(1)* on the S2S processes driving MED rainfall including an empirical prediction model, *(2)* on the representation of these teleconnection processes in different operational forecast models, and *(3)* on boosting forecast skill by applying statistical post-processing on the model-ensemble including hybrid forecasts. I will use the self-archiving open access option, available within the University of Reading throughout the CentAUR institutional repository. To present and discuss my findings and to be exposed to questions and ideas on a regular basis, I will attend different conferences and workshops; I will present results at the EGU General Assembly in the S2S forecasting sessions to promote the novel methodological approach to a larger scientific audience. To address the MED climate research community, I will attend the Med-CLIVAR conference (a scientific network to promote better communication of the evolution of the Mediterranean climate), where I will focus on presenting results of driving processes of MED rainfall. To address a more impact-oriented audience, I will reach out to MedECC (Mediterranean Experts on Environmental and Climate Change, a scientist-stakeholder network working towards an assessment of risks and vulnerabilities), who I will predominantly inform about forecast opportunities at different forecast times. Further, I will use my connections to the complex system science community (e.g. by organising meetings with the Climate Informatics research group in Jena) to give them feedback on the practical challenges which I encountered, to help them further improving the methods.

Exploitation of results: By providing a methodological blueprint, this fellowship will become the stepping-stone for further scientific advances; I will make my code publically available on github, including a jupyter notebook tutorial. This will ensure that my analyses can be reproduced and further allow other researchers to apply the methods to study different data sets and regions, likely leading to new collaborations with researchers worldwide. I will further upload the causal network input data based on open access data sources on the *Causeme.net* homepage, an online platform to benchmark causal inference methods, which will help advance progress on method development. Moreover, next to regularly presenting and discussing results at UREAD, ECMWF and BSC, I will particularly make sure that my findings from the model evaluation (WP2) are fed back to the model developers at ECMWF and BSC, which will give them concrete targets for model improvement. Moreover, I will use my good connections to the impacts research community at PIK to ensure that new stake-holder driven research possibilities based on my results, especially for the agriculture and climate service sector can be assessed. IP issues are not anticipated from this project. However, in the unlikely event that IPR issues shall arise, UREAD has specifically dedicated Research Enterprise Services with legal contract teams who will be assisting in dealing with these.

2.3. Quality of the proposed measures to communicate the project activities to different target audiences

The primary goal of the public engagement strategy of his proposal will be to create awareness among the general public of challenges and opportunities of S2S forecasting, as it provides a potential source of information on diverse socio-economic aspects of human life. It will also disseminate more widely knowledge of (MED) climate change and the distinction between weather and climate, which is often a source of confusion in the public. The outreach will be designed in a way that can be understood by the general public and will contain multiple forms: **(1)** To engage with a broad, non-scientific public audience I will contribute three posts on the above papers in the "Weather and Climate" blog maintained by the Department of Meteorology at Reading. **(2)** To increase the general visibility of my research, I will sign up at "Request a Woman Scientist", a resource platform for journalists, educators and policy makers to facilitate contacting female experts. **(3)** I will take part in the annual "British Science Festival", and the "European Researcher Night", to connect with interested laypeople. **(4)** I will regularly attend the "Café Scientifique" hosted by the Reading Branch of the British Science Association, which takes place once a month where everyone is welcome to ask a question on scientific issues. **(5)** As a member of the Lise Meitner Society, a non-profit organization with the aim to improve equal opportunities for women in STEM, I will engage in the monthly "500 Women Scientists" science pod at London. I will further assess the potential with others to start a science pod in Reading directly. **(6)** At PIK, I gave regular talks to student groups on climate change and at the "Girls´ day", an annual day of action to motivate girls and women to take up scientific careers. During this fellowship I will reach out to local schools and will offer to give similar lectures. Moreover, I will continue my activity as a "Cyber mentor", an online platform to mentor girls and support their interest in STEM. **(7)** I will participate in one of the regular DataBeers events, aiming to discuss and promote Big Data related research to the interested public, both in Barcelona and London.

3. Quality and Efficiency of the Implementation

3.1. Coherence and effectiveness of the work plan, appropriateness of the allocation of tasks and resources

Work Packages Month	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
WP1: Driver detection																								
Literature search																								
CENs based on observation data																								
Statistical prediction model																								
WP2: Model evaluation																								
Process evaluation in SeaS5																								
Process evaluation in EC Earth										(B)	(B)													
WP3: Post processing																								
Hybrid forecast SeaS5/EC Earth																								
Bias Corrected Forecasts SeaS5																								
Bias Corrected Forecasts EC Earth																				(B)			(B)	
WP4: Dissemination & Communication																								
Paper Writing							D4.1								D4.2						D4.3			
Python Tutorial on github																			D4.4					
Upload data on *Causeme.net*																	D4.5							
Workshops and conferences								D4.6					D4.7			D4.8		D4.9			D4.10		D4.11	
Public engagement																								
Milestones				M1												M2								

Table1: Work packages (WP) with expected deliverables (D) and milestones (M). WPs are described in detail in 1.1 (WP1-3) and 2.2-2.3 (WP4). Planned research stays in Barcelona at BSC are marked by a (B).

The work plan will be executed over two years, organized to achieve the project goals in an efficient manner. It consists of four work packages (see 1.1 and 2.2-2.3 for detailed descriptions) with staged deliverables and milestones summarized in Table 1. The first months are mainly reserved to address the driver detection in observation data (**WP1**), including literature search and data downloading. The results will then be used to systematically evaluate the processes in forecast models (**WP2**), starting with SEAS5 and later EC-Earth. The last months of the fellowship will mainly be used for statistical post processing to boost forecast skill (**WP3**). Outreach activities (**WP4**) will occur throughout the fellowship. Next to the weekly visits at ECMWF, research stays in Barcelona at BSC are planned for the end of the first year, aiming to learn about EC-Earth including downloading and analysing the data (first stay: 2 months), and towards the end of the fellowship to discuss (second stay: 1 week) and present (third stay: 1 week) respective findings. Several deliverables will result from the work plan including three first author papers (**D4.1-4.3**, see 2.2), the release of a python tutorial on github (**D4.4**), uploading data on *Causeme.net* (**D4.5**), presentations at the yearly EGU meeting (**D4.6**, **D4.9**) at the MEDclivar meeting (**D4.7**), at a MED stake-holder meeting (**D4.8**), at a meeting with the DLR climate informatics group (**D4.10**) and final report meetings at ECMWF and BSC (**D4.11**). There are two milestones: **M1**, the selection of the hypotheses in WP1, which will inform the direction of the CEN calculation using observations (WP1) and using model data (WP2). The second milestone, **M2**, will emerge with the completion of WP2, yielding a quantification of the represented teleconnection processes in forecast models, which will pave the way for WP3.

Appropriateness of the allocation of tasks and resources: To ensure feasibility, the work plan was designed based on my previous experiences using CENs. I reserved sufficient time for an extensive literature search at the beginning of the project, as broad expert knowledge of the involved processes and timescales is indispensable for a physics-based application of CEN. The required computational power is relatively low and calculations of CENs can be performed on a laptop such that most of the allocated time for WP1-WP3 is planned to be used for different, comprehensive data analyses. Necessary equipment (desktops, laptops, super-computing facilities, storage) to conduct the research will be provided by the host institutions and is more than sufficient for attaining the project objectives. At ECMWF and BSC I will get full access to download SEAS5 and EC-Earth data and all resources for my training in the areas of S2S forecast and model assessment will be available. The EC-Earth data will be available from the Department's gitlab system and I will be able to use these resources during the periods I am not at the BSC. Moreover, based on my experience in previous, analogous projects, I have allocated three months for creating figures and the writing of each publication. Travel activities will be completed using the fellowship funding. The experience and expertise of my host and partner institutes and my supervisors in project planning and resource management will be fully available to assist me during the implementation of the action.

3.2. Appropriateness of the management structure and procedures, including risk management

Project organisation and management structure: The Human Resource Department of the University of Reading will provide all the necessary administrative support (employment contract, registration for National Insurance, finding housing) to facilitate my move to Reading. Moreover, through the "Financial Services" and the "Research & Enterprise teams" the University will further support me administratively throughout the fellowship. I will receive monthly financial reports for scrutiny, which I will also share and discuss with my main supervisor, who is very experienced in project management and will also supervise me in this regard. Throughout the fellowship, two individual meetings per months with my supervisor T. Shepherd and mentor A. Weisheimer as well as joint monthly meetings and quarterly teleconferences including also F. J. Doblas-Reyes will help to monitor the project progress and guide the research. This will allow an evaluation of progress against the work plan, so that I can seek assistance in a timely and periodic manner if the necessity arises. The regular meetings, the scientific integration within the departments, and publishing in peer-review journals will ensure the quality of research. Output obtained within the project will be systematically archived, and development of code and data analysis scripts will be carried out using versioning software to ensure traceability and replicability of results at all stages. Departmental Outreach resources (Blackboard Organisation) will be used for dissemination and outreach activities. At ECMWF I will be fully supported (administration, technical requirements) to most efficiently use the local research infrastructure. My research stays at BSC will be planned in advance and the Project Management Office at BSC will support me in all legal, financial and administrative arrangements needed.

Risks that might endanger reaching project objectives: Overall, the scientific and administrative risks of the project can be considered low; I am already experienced in using causal discovery algorithms including the use of the python package *tigramite* and I am also well connected to the developer, Dr. Jakob Runge, who will advise me in case I encounter methodological issues. Through my previous stay at UREAD, I am already familiar with the local infrastructure and I have access to their computer servers and therefore I do not anticipate any major delays due to technical or administrative tasks. I already have experiences in analysing SEAS5 data and although working with EC-Earth will be mostly new for me, I do not expect any major obstacles here, given my mentor's expertise and the provided technical support at the BSC. Moreover, for the very unlikely case of server problems to access SEAS5 or EC-Earth data, I can easily switch my work plan and start with the model for which data is available. Once the *actor* time-series are calculated, the required computational power is very low and can be performed on a personal computer, such that I will mostly be independent from the Reading high-performance cluster. For the unlikely event that boosting forecast skill (WP3) is not achieved in time, the results from WP1 and WP2 alone will already provide important new insights for the S2S research community and the modeller's at ECMWF and BSC.

3.3. Appropriateness of the institutional environment (infrastructure)

<u>The Department of Meteorology at UREAD</u> is the largest of its kind and world-renowned for its pioneering work in weather and climate research. In the 2017 Center for World University Rankings, it was ranked 2nd in the world for research in Meteorology and Atmospheric Sciences. The department hosts over 200 academic and research scientists, enabling a wide range of collaboration and feedback opportunities. The infrastructure requirements for this proposal consist of access to computing facilities and the advice and support to use these effectively. I will benefit from the Department of Meteorology's dedicated computing clusters and support staff with the highest quality technical support. <u>ECMWF</u> research is world-leading in numerical weather prediction. They work collaboratively with scientists across the world on all aspects of prediction systems as well as the many areas that support forecast production. They operate a large-scale data handling system where I can store and retrieve the data I need, and further provide full-extent software support. At <u>BSC,</u> the combination of outstanding high performance computing facilities and high-quality user support constitutes an excellent infrastructural basis. I will get access to all key research facilities, infrastructure, and equipment. All three institutes have extensive experience in hosting fellows and providing them with project management support, which will provide the perfect environment to guarantee a successful completion of the proposed research. Furthermore, they have extensive subscriptions to all relevant online journals, allowing immediate access to a comprehensive range of scientific literature.