# Seasonal and Subseasonal Forecasts: Overview and applications for Economics

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# Contents

## Background & Scope

Per the Weather Research and Forecasting Innovation Act of 2017, NOAA's National Weather Service is required to collect and utilize information to make reliable and timely foundational forecasts of subseasonal and seasonal temperature and precipitation. As weather technology progresses, it becomes easier to create seasonal and subseasonal forecasts. What are the potential uses for these forecasts? In what fields would they be of especially high value? This bibliography explores research primarily from the last twenty years on these longer term forecasts and their applications, especially their potential and existing economic impacts. It is organized into five sections: a general overview of seasonal and subseasonal forecasts, their applications for agriculture, their applications for aquaculture and fisheries, their applications for water resource management, and their applications for health and safety.

### Section I – Overview of Seasonal and Subseasonal Forecasts

Section one is intended to provide an overview of the current and potential value of seasonal and subseasonal forecasts. It covers value assessments and projections for future use and research.

### Section II – Applications for Agriculture

Section two is intended to provide an overview of research applying seasonal and subseasonal forecasts to agricultural issues. It covers potential benefits, models for integrating seasonal forecasting into current agricultural practice, economic valuations, and assessments of their current or future use by farmers around the world.

### Section III – Applications for Aquaculture and Fisheries

Section two is intended to provide an overview of research applying seasonal and subseasonal forecasts to aquaculture and fisheries management. It covers sustainability, risk management, and fishery management.

### Section IV – Applications for Water Resource Management

Section two is intended to provide an overview of research applying seasonal and subseasonal forecasts to water resource management. It covers forecast models, decision making frameworks, and valuations of long term forecasts for water management.

### Section V – Applications for Health and Safety

Section two is intended to provide an overview of research applying seasonal and subseasonal forecasts to health and safety issues. It covers forecast guidance, risk management, and warning systems as they relate to human health especially in terms of heat waves.

## Sources Reviewed

Along with a web search for relevant materials the following databases were used to identify sources: Clarivate's Web of Science: Science Citation Index Expanded, Elsevier's Science Direct, ProQuest's Science and Technology including ASFA and MGA, EconLit Full-Text, and Lexis Advance. Only English language materials were included and there was no date range specification.

## Section I: Overview of Seasonal and Subseasonal Forecasts

Alessandri, A., De Felice, M., Catalano, F., Lee, J. Y., Wang, B., Lee, D. Y., et al. (2018). Grand European and Asian-Pacific multi-model seasonal forecasts: maximization of skill and of potential economical value to end-users. Climate Dynamics, 50(7-8), 2719-2738. https://doi.org/10.1007/s00382-017-3766-y

Multi-model ensembles (MMEs) are powerful tools in dynamical climate prediction as they account for the overconfidence and the uncertainties related to single-model ensembles. Previous works suggested that the potential benefit that can be expected by using a MME amplifies with the increase of the independence of the contributing Seasonal Prediction Systems. In this work we combine the two MME Seasonal Prediction Systems (SPSs) independently developed by the European (ENSEMBLES) and by the Asian-Pacific (APCC/CliPAS) communities. To this aim, all the possible multi-model combinations obtained by putting together the 5 models from ENSEMBLES and the 11 models from APCC/CliPAS have been evaluated. The results demonstrate the useful application of MME seasonal predictions for energy demand forecasting over Italy. It is shown a significant enhancement of the potential economic value of forecasting energy demand when using the better combinations from the Grand MME by comparison to the maximum value obtained from the better combinations of each of the two contributing MMEs. The above results demonstrate for the first time the potential of the Grand MME to significantly contribute in obtaining useful predictions at the seasonal time-scale.

Marta, B. S., Meaghan, D., & Suraje, D. (2018). Assessing the value of seasonal climate forecasts for decision-making. Wiley Interdisciplinary Reviews: Climate Change, 9(4), e523. https://doi.org/10.1002/wcc.523

Seasonal climate forecasts (SCF) can support decision-making and thus help society cope with and prepare for climate variability and change. The demand for understanding the value and benefits of using SCF in decision-making processes can be associated with different logics. Two of these would be the need to justify public and private investment in the provision of SCF and demonstrating the gains and benefits of using SCF in specific decision-making contexts. This paper reviews the main factors influencing how SCF is (or can be) valued in supporting decision-making and the main methods and metrics currently used to perform such valuations. Our review results in four key findings: (a) there is a current emphasis on economic ex ante studies and the quantification of SCF value; (b) there are fundamental differences in how the value of SCF is defined and estimated across methods and approaches; (c) most valuation methods are unable to capture the differential benefits and risks of using SCF across spatiotemporal scales and groups; and (d) there is limited involvement of the decision-makers in the valuation process. The paper concludes by providing some guiding principles towards more effective valuations of SCF, notably the need for a wider diversity and integration of methodological approaches. These should particularly embrace ex-post, qualitative, and participatory approaches which allow co-evaluation with decision-makers so that more comprehensive and equitable SCF valuations can be developed in future.

White, C.J. et al. (2017). Potential applications of subseasonal-to-seasonal (S2S) predictions. Meteorological Applications. https://doi.org/10.1002/met.1654

While seasonal outlooks have been operational for many years, until recently the extended-range timescale referred to as subseasonal-to-seasonal (S2S) has received little attention. S2S prediction

fills the gap between short-range weather prediction and long-range seasonal outlooks. Decisions in a range of sectors are made in this extended-range lead time; therefore, there is a strong demand for this new generation of forecasts. International efforts are under way to identify key sources of predictability, improve forecast skill and operationalize aspects of S2S forecasts; however, challenges remain in advancing this new frontier. If S2S predictions are to be used effectively, it is important that, along with science advances, an effort is made to develop, communicate and apply these forecasts appropriately. In this study, the emerging operational S2S forecasts are presented to the wider weather and climate applications community by undertaking the first comprehensive review of sectoral applications of S2S predictions, including public health, disaster preparedness, water management, energy and agriculture. The value of applications-relevant S2S predictions is explored, and the opportunities and challenges facing their uptake are highlighted. It is shown how social sciences can be integrated with S2S development, from communication to decision-making and valuation of forecasts, to enhance the benefits of 'climate services' approaches for extended-range forecasting. While S2S forecasting is at a relatively early stage of development, it is concluded that it presents a significant new window of opportunity that can be explored for application-ready capabilities that could allow many sectors the opportunity to systematically plan on a new time horizon.

Crean, J., Parton, K., Mullen, J., & Hayman, P. (2015). Valuing Seasonal Climate Forecasts in a State-Contingent Manner. Australian Journal of Agricultural and Resource Economics, 59(1), 61-77. https://onlinelibrary.wiley.com/journal/10.1111/%28ISSN%291467-8489/issues

We applied state-contingent theory to climate uncertainty at a farm level to assess the value of seasonal climate forecasts in the Central West region of NSW. We find that modelling uncertainty in a state-contingent manner results in a lower estimate of forecast value than the typical expected value approach. We attribute this finding to a more conservative long-term farm plan in the discrete stochastic programming (DSP) model, which is better balanced for climate uncertainty. Hence, a climate forecast, even though it still revises probabilities held by farmers, does not call forth such large changes in farm plans and associated farm incomes. We then use the DSP model to assess how attributes of a hypothetical forecasting system, particularly its skill and timeliness, as well as attributes of the decision environment, influence its value. Lastly, we assess the value of current operational forecast systems and show that the value derived from seasonal climate forecasts is relatively limited in the case study region largely because of low skill embodied in forecasts at the time when major farm decisions are being made.

Robertson, A. W., Kumar, A., Peña, M., & Vitart, F. (2014). Improving and Promoting Subseasonal to Seasonal Prediction. Bulletin of the American Meteorological Society, 96(3), ES49-ES53. https://doi.org/10.1175/BAMS-D-14-00139.1

There is growing interest in the scientific, operational, and applications communities in developing forecasts that fill the gap between medium-range weather forecasts (up to 2 weeks) and long-range or seasonal ones (3–6 months). A new World Weather Research Programme/World Climate Research Programme (WWRP/WCRP initiative on subseasonal to seasonal (S2S) prediction has recently been launched to foster collaboration and research in the weather and climate communities, with the goals of improving forecast skill and physical understanding, promoting forecast uptake by operational centers, and exploitation by the applications community. A key component of the project is to create an archive of S2S operational forecasts from EPSs (see Table 1 for project and model acronyms) that will become available in 2015. The meeting was the first scientific conference organized by the World Meteorological Organization (WMO)'s S2S steering

group and U.S. THORPEX members, and it aimed to bring together the research and applications communities with operational centers interested in S2S prediction.

Doblas-Reyes, F. J., Garcia-Serrano, J., Lienert, F., Biescas, A. P., & Rodrigues, L. R. L. (2013). Seasonal climate predictability and forecasting: status and prospects. Wiley Interdisciplinary Reviews-Climate Change, 4(4), 245-268. https://doi.org/10.1002/wcc.217

Seasonal climate forecasts occupy an intermediate zone between weather forecasting and climate projections. They share with the numerical weather prediction the difficulty of initializing the simulations with a realistic state of the atmosphere and the need to periodically verify different aspects of their quality, while additionally are burdened by uncertainties in feedback processes that also play a central role in constraining climate projections. Seasonal predictions have to deal also with the challenge of initializing all the components of the climate system (ocean, sea ice, and land surface). The value of skilful seasonal forecasts is obvious for many societal sectors and is currently being included in the framework of developing climate services. Seasonal forecasts will in addition be valuable by increasing the acceptance of climate projections among the general public. This advanced-review article presents an overview of the state-of-the-art in global seasonal predictability and forecasting for climate researchers and discusses fundamental advances to increase forecast quality in the near future. The article concludes with a list of challenges where seasonal forecasting is expected to focus on in the near future.

Millner, A., & Washington, R. (2011). What determines perceived value of seasonal climate forecasts? A theoretical analysis. Global Environmental Change, 21(1), 209-218. https://doi.org/10.1016/j.gloenvcha.2010.08.001

Seasonal forecasts have potential value as tools for the management of risks due to inter-annual climate variability and iterative adaptation to climate change. Despite their potential, forecasts are not widely used, in part due to poor performance and lack of relevance to specific users' decision problems, and in part due to a variety of economic and behavioural factors. In this paper a theoretical model of perceived forecast value is proposed and applied to a stylized portfolio-type decision problem with wide applicability to actual forecast users, with a view to obtaining a more complete picture of the determinants of perceived value. The effects of user wealth, risk aversion, and perceived forecast trustworthiness, and presentational parameters, such as the position of forecast parameter categories, and the size of probability categories, on perceived value is investigated. Analysis of the model provides several strong qualitative predictions of how perceived forecast value depends on these factors. These predictions may be used to generate empirical hypotheses which offer the chance of evaluating the model's assumptions, and suggest several means of improving understanding of perceived value based on qualitative features of the results.

Arun, K. (2010). On the assessment of the value of the seasonal forecast information. Meteorological Applications, 17(4), 385-392. https://doi.org/10.1002/met.167

Seasonal climate forecasts are now routinely produced at many operational and research centres. With the availability of the emerging technology of seasonal climate predictions for managing risks, however, it has proven difficult to quantify the value of seasonal climate forecasts in various applications. The definition of the value in the context of the use of the Seasonal Forecast Information (SFI) is the net benefit a user (or society) incurs as a result of change in management

practices in response to the availability of the SFI. A review of the difficulties associated with the value assessment of the SFI is presented. The paper includes a broad overview of pathways how the SFI is used by the various users and applications. The discussion then summarizes difficulties associated with isolating the benefits of the use of the SFI leading to the current paradigm where the value assessments from the use of the SFI are hard to quantify.

Lemos Maria, C., & Rood Richard, B. (2010). Climate projections and their impact on policy and practice. Wiley Interdisciplinary Reviews: Climate Change, 1(5), 670-682. https://doi.org/10.1002/wcc.71

This article examines the relationship between projections of climate change and the responses to those projections. First, it discusses uncertainty and its role in shaping not only the production of climate projections but also the use of these projections by decision makers. We find that uncertainty critically affects the way climate projections move from useful to usable, where usefulness is defined by scientists' perception of users' needs, and usability is defined by users' perception of what knowledge can be readily applied to their decision. From the point of view of the natural scientist, we pose that there is an uncertainty fallacy, that is, a belief that the systematic reduction of uncertainty in climate projections is required in order for the projections to be used by decision makers. Second, we explore the implications of climate projections for policy and decision making, using examples from the seasonal climate forecast applications literature as an analog. We examine constraints and opportunities for their application in policy and practice and find that over reliance on science and technical solutions might crowd out the moral imperative to do what is needed to improve livelihoods and to guarantee ecosystems' long term sustainability. We conclude that, in the context of high uncertainty, decision makers should not look for perfect forecasts, but seek to implement knowledge systems that integrate climate projections with other kinds of knowledge and that consider the multiple stressors that shape their decision environment.

## Section II: Agriculture

Ceglar, A., Toreti, A., Prodhomme, C., Zampieri, M., Turco, M., & Doblas-Reyes, F. J. (2018). Land-surface initialisation improves seasonal climate prediction skill for maize yield forecast. *Scientific Reports, 8*. https://doi.org/10.1038/s41598-018-19586-6

Seasonal crop yield forecasting represents an important source of information to maintain market stability, minimise socio-economic impacts of crop losses and guarantee humanitarian food assistance, while it fosters the use of climate information favouring adaptation strategies. As climate variability and extremes have significant influence on agricultural production, the early prediction of severe weather events and unfavourable conditions can contribute to the mitigation of adverse effects. Seasonal climate forecasts provide additional value for agricultural applications in several regions of the world. However, they currently play a very limited role in supporting agricultural decisions in Europe, mainly due to the poor skill of relevant surface variables. Here we show how a combined stress index (CSI), considering both drought and heat stress in summer, can predict maize yield in Europe and how land-surface initialised seasonal climate forecasts can be used to predict it. The CSI explains on average nearly 53% of the inter-annual maize yield variability under observed climate conditions and shows how concurrent heat stress and drought events have influenced recent yield anomalies. Seasonal climate forecast initialised with realistic land-surface achieves better (and marginally useful) skill in predicting the CSI than with

climatological land-surface initialisation in south-eastern Europe, part of central Europe, France and Italy.

Hardegree, S. P., Abatzoglou, J. T., Brunson, M. W., Germino, M. J., Hegewisch, K. C., Moffet, C. A., . . . Meredith, G. R. (2018). Weather-Centric Rangeland Revegetation Planning. *Rangeland Ecology & Management, 71*(1), 1-11. https://doi.org10.1016/j.rama.2017.07.003

Invasive annual weeds negatively impact ecosystem services and pose a major conservation threat on semiarid rangelands throughout the western United States. Rehabilitation of these rangelands is challenging due to interannual climate and subseasonal weather variability that impacts seed germination, seedling survival and establishment, annual weed dynamics, wildfire frequency, and soil stability. Rehabilitation and restoration outcomes could be improved by adopting a weather-centric approach that uses the full spectrum of available site-specific weather information from historical observations, seasonal climate forecasts, and climate-change projections. Climate data can be used retrospectively to interpret success or failure of past seedings by describing seasonal and longer-term patterns of environmental variability subsequent to planting. A more detailed evaluation of weather impacts on site conditions may yield more flexible adaptive-management strategies for rangeland restoration and rehabilitation, as well as provide estimates of transition probabilities between desirable and undesirable vegetation states. Skillful seasonal climate forecasts could greatly improve the cost efficiency of management treatments by limiting revegetation activities to time periods where forecasts suggest higher probabilities of successful seedling establishment.

Nidumolu, U., Lim-Camacho, L., Gaillard, E., Hayman, P., & Howden, M. (2018). Linking climate forecasts to rural livelihoods: Mapping decisions, information networks and value chains. *Weather and Climate Extremes*. https://doi.org/10.1016/j.wace.2018.06.001

Climate variability is a key source of livelihood risks faced by smallholder farmers in drier environments in many developing countries. Climate information provided on seasonal time-scales can sometimes improve agricultural decision-making. However, there are many barriers to the effective dissemination, communication and use of such information on farm and across the value chain. We used a case study in southern India to explore ways of overcoming some of these barriers such as those limiting access to information and effective communication of probabilistic forecast information. Firstly, we used social network analysis at the village level to identify particular individuals, groups or/and institutions who are central in information networks so as to be able to support them to increase the efficiency, effectiveness, equity and robustness of information transfers. This allowed us to identify potential opportunities and challenges around access, communication and forecast use. Close linking of formal and informal networks appeared to be a common, positive influencing factor. Secondly, we used value chain analysis to assess how pre-and post-farm decision-makers could use seasonal climate forecasts (SCF) in their own businesses and how this may propagate up and down the value chain. We found that the motivation for using SCF varied across the value chain and was likely of limited use to smaller, off-farm value chain players who take a short-term adaptive management approach to planning. However, it was seen as having significant potential for larger businesses who take a more strategic approach. This identified a possible risk of increased competitive inequality between businesses of different sizes. Thirdly, we addressed the challenge of translating probabilistic climate forecast information into support for decision making by using decision analysis with intermediaries enabling them to structure clearly problems with embedded climate probabilities. The construction of decision-trees enabled farm advisers and local researchers to explore the potential value of SCF by using the decision trees as a

"boundary object" around which farmers and other decision makers, agricultural scientists, climate scientists, economists, social scientists and policy-makers could have thoughtful discussion leading to useful strategies to better manage climate risk.

Ogutu, G. E. O., Franssen, W. H. P., Supit, I., Omondi, P., & Hutjes, R. W. A. (2018). Probabilistic maize yield prediction over East Africa using dynamic ensemble seasonal climate forecasts. *Agricultural and Forest Meteorology, 250*, 243-261. https://doi.org/10.1016/j.agrformet.2017.12.256

We tested the usefulness of seasonal climate predictions for impacts prediction in eastern Africa. In regions where these seasonal predictions showed skill we tested if the skill also translated into maize yield forecasting skills. Using European Centre for Medium-Range Weather Forecasts (ECMWF) system-4 ensemble seasonal climate hindcasts for the period 1981-2010 at different initialization dates before sowing, we generated a 15 member ensemble of yield predictions using the World Food Studies (WOFOST) crop model implemented for water-limited maize production and single season simulation. Maize yield predictions are validated against reference yield simulations using the WATCH Forcing Data ERA-Interim (WFDEI), focusing on the dominant sowing dates in the northern region (July), equatorial region (March-April) and in the southern region (December). These reference yields show good anomaly correlations compared to the official FAO and national reported statistics, but the average reference yield values are lower than those reported in Kenya and Ethiopia, but slightly higher in Tanzania. We use the ensemble mean, interannual variability, mean errors, Ranked Probability Skill Score (RPSS) and Relative Operating Curve skill Score (ROCSS) to assess regions of useful probabilistic prediction. Annual yield anomalies are predictable 2-months before sowing in most of the regions. Difference in interannual variability between the reference and predicted yields range from +/- 40%, but higher interannual variability in predicted yield dominates. Anomaly correlations between the reference and predicted yields are largely positive and range from + 0.3 to + 0.6. The ROCSS illustrate good pre-season probabilistic prediction of above-normal and below normal yields with at least 2-months lead time. From the sample sowing dates considered, we concluded that, there is potential to use dynamical seasonal climate forecasts with a process based crop simulation model WOFOST to predict anomalous water-limited maize yields.

Ouédraogo, M., Barry, S., Zougmoré, R., Partey, S., Somé, L., & Baki, G. (2018). Farmers' Willingness to Pay for Climate Information Services: Evidence from Cowpea and Sesame Producers in Northern Burkina Faso. *Sustainability, 10*(3), 611. https://doi.org/10.3390/su10030611

Climate information is recognized as a powerful tool to reduce the effect of climate risk and uncertainty on crop production and increase the resilience and the adaptive capacity of farmers in semi-arid zones. This paper estimates farmers' willingness to pay (WTP) for climate information within cowpea and sesame value chains in Northern Burkina Faso. The study used the contingent valuation method for a monetary valuation of farmers' preferences for climate information. Data were collected using a structured questionnaire from 170 farmers. The study found that 63% of respondents were willing to pay for climate information services (CIS) such as seasonal climate forecast (SCF), decadal climate information (10-DCI), daily climate information (1-DCI) and agro-advisories. The predicted value for the WTP was XOF 3496 for SCF, XOF 1066 for 10-DCI, XOF 1985 for 1-DCI and XOF 1628 for agro-advisories. The study also showed that several socioeconomic and motivation factors have greater influence on farmers' WTP for CIS. These included the gender, age, education of the farm head and the awareness of farm head to climate

information. The outcomes of this paper should support policy makers to better design an efficient mechanism for the dissemination of climate information to improve the adaptive capacity of farmers to climate risks in Burkina Faso.

Rodriguez, D., de Voil, P., Hudson, D., Brown, J. N., Hayman, P., Marrou, H., & Meinke, H. (2018). Predicting optimum crop designs using crop models and seasonal climate forecasts. *Scientific Reports, 8*(1), 2231. https://doi.org/10.1038/s41598-018-20628-2

Expected increases in food demand and the need to limit the incorporation of new lands into agriculture to curtail emissions, highlight the urgency to bridge productivity gaps, increase farmers profits and manage risks in dryland cropping. A way to bridge those gaps is to identify optimum combination of genetics (G), and agronomic managements (M) i.e. crop designs (GxM), for the prevailing and expected growing environment (E). Our understanding of crop stress physiology indicates that in hindsight, those optimum crop designs should be known, while the main problem is to predict relevant attributes of the E, at the time of sowing, so that optimum GxM combinations could be informed. Here we test our capacity to inform that "hindsight", by linking a tested crop model (APSIM) with a skillful seasonal climate forecasting system, to answer "What is the value of the skill in seasonal climate forecasting, to inform crop designs?" Results showed that the GCM POAMA-2 was reliable and skillful, and that when linked with APSIM, optimum crop designs could be informed. We conclude that reliable and skillful GCMs that are easily interfaced with crop simulation models can be used to inform optimum crop designs, increase farmers profits and reduce risks.

Templeton, S. R., Hooper, A. A., Aldridge, H. D., & Breuer, N. (2018). Farmer Interest in and Uses of Climate Forecasts for Florida and the Carolinas: Conditional Perspectives of Extension Personnel. *Weather, Climate, and Society, 10*(1), 103-120. https://doi.org/10.1175/wcas-d-16-0057.1

In baseline surveys that were conducted in Florida, North Carolina, and South Carolina, extension personnel were asked whether, how, and which farmers would use climate forecasts to manage production and other aspects of their agribusinesses. In making such assessments extensionists use their expertise to account for, the authors assume, net benefits to farmers of the forecasts, given any help that they also expect to provide their clients. Models of conditional probabilities are estimated to show how the assessments depend on the expertise and other characteristics of the extensionist and her clientele. For example, if a person has worked at least 7 years in extension, she is more likely to agree or strongly agree that farmers are interested in using climate forecasts. An extensionist who works with field crop producers is more likely than one who does not to think that a farmer can use climate forecasts to improve planting schedules, harvest planning, crop selection, nutrient management, and land allocation. An extensionist is more likely to assess that farmers who produce particular crops can use climate forecasts to be more successful if she works with them. An extensionist whose clientele's average farm size exceeds 200 acres is more likely to indicate that a farmer can use climate forecasts to improve irrigation management, harvest planning, and crop selection. In addition to serving as references for future work, these conditional assessments almost always provide more nuanced and useful information than unconditional ones about potential farmer interest in and uses of climate forecasts for the three-state region.

Amegnaglo, C. J., Anaman, K. A., Mensah-Bonsu, A., Onumah, E. E., & Amoussouga Gero, F. (2017). Contingent valuation study of the benefits of seasonal climate forecasts for maize farmers in the Republic of Benin, West Africa. *Climate Services, 6*, 1-11. https://doi.org/10.1016/j.cliser.2017.06.007

This study aims to assess the economic benefits of seasonal climate forecasts in West Africa based on a random survey of 354 maize farmers and to use the contingent valuation method. Results indicate that farmers need accurate seasonal climate forecasts between 1 and 2months before the onset of rains. The most desirable dissemination channels are radio, local elders, local farmer meetings and extension agents. The most likely used farming strategies are change of: planting date, crop acreage, crop variety, and production intensification. The vast majority of farmers are willing to pay for seasonal climate forecasts, and the average annual economic value of seasonal climate forecasts are about USD 5492 for the 354 sampled farmers and USD 66.5million dollar at the national level. Furthermore, benefits of seasonal climate forecasts are likely to increase with better access to farmer based organisation, to extension services, to financial services, to modern communication tools, intensity of use of fertilizer and with larger farm sizes. Seasonal climate forecasts are a source of improvement of farmers' performance and the service should be integrated in extension programmes and in national agricultural development agenda.

Canal, N., Deudon, O., Le Bris, X., Gate, P., Pigeon, G., Regimbeau, M., & Calvet, J. C. (2017). Anticipation of the winter wheat growth based on seasonal weather forecasts over France. *Meteorological Applications, 24*(3), 432-443. https://doi.org/10.1002/met.1642

The aim of this study was to examine the ability of a crop model forced by seasonal weather forecasts to anticipate correctly the agrometeorological variables affecting the growth of winter wheat in France. The method is based on wheat growth simulations over 199 sites in France for the period 1981-2005 driven by seasonal weather forecasts, consisting of 6 month long, 45 member hindcasts starting on 1 February. These simulations were challenging a climatologically based wheat growth forecasting system currently used by ARVALIS - Institut du vegetal. Both simulations were evaluated against a reference dataset. The simulations using the seasonal weather forecast present good skills for the dates of occurrence of the main growth stages: the leaf sheaths strongly erect' stage (also referenced as Zadoks scale Z30), the head visible' stage (Zadoks scale Z50) and the kernel hard' stage (Zadoks scale Z91). The simulations forced by the seasonal weather forecasts have lower bias than those forced by the climatological data: respectively -0.2 against 1.4 days for the Z30 stage, 1.1 against 3.2 days for the Z50 stage, 1.3 against 4.2 days for the Z91 stage. It is shown that the seasonal forecasting system provides more hit rates than the climatologically based method does. Thus, for the different events forecasted here, better predictability is found using the seasonal forecasting system. Despite shortcomings highlighted in this study, it is shown that a method based on seasonal weather forecasts could be applied in an operational context over France, in order to improve the method currently used in the agricultural sector.

Han, E., & Ines, A. V. M. (2017). Downscaling probabilistic seasonal climate forecasts for decision support in agriculture: A comparison of parametric and non-parametric approach. *Climate Risk Management, 18*, 51-65. https://doi.org/10.1016/j.crm.2017.09.003

Seasonal climate forecasts (SCF) are produced operationally in tercile-probabilities of the most likely categories, e.g., below-, near- and above-normal rainfall. Inherently, these are difficult to translate into information useful for decision support in agriculture. For example, probabilistic SCF

must first be downscaled to daily weather realizations to link with process-based crop models, a tedious process, especially for non-technical users. Here, we present two approaches for downscaling probabilistic seasonal climate forecasts – a parametric method, predictWTD, and a non-parametric method, FResampler1, and compare their performance. The predictWTD, which is based on a conditional stochastic weather generator, was found to be not very sensitive to types of rainfall information (amount, frequency or intensity) in constraining or conditioning the stochastic weather generator, but conditioning the stochastic weather generator on both rainfall frequency and rainfall intensity had distorted the distribution of the downscaled seasonal rainfall total. Both predictWTD and FResampler1 are sensitive to the length of climate data, especially for a wet SCF; climate data longer than 30years was found suitable for reproducing the theoretical distribution of SCF. FResampler1 performed well as predictWTD in downscaling probabilistic SCF, however, it requires the generation of more realizations to ensure stable simulations of the seasonal rainfall total distributions.

Jönsson, A. M., & Lagergren, F. (2017). Potential use of seasonal forecasts for operational planning of north European forest management. *Agricultural and Forest Meteorology, 244-245*, 122-135. https://doi.org/10.1016/j.agrformet.2017.06.001

Weather and climate conditions can have large impacts on the outcome of forest management operations: Suboptimal conditions can increase the amount of driving damage to forest ground caused by the heavy machines used for harvesting, forwarding and soil scarification. Planting of tree seedlings is commonly practised after clear cutting, and drought in summer or soil frost uplifting in autumn reduces the likelihood of successful plant establishment. Weather and climate also influence the risk of forest fires and the occurrence and development of pest and pathogens, and thereby the timing suitable for surveillance and countermeasures. In this study, the potential use of seasonal forecasts to support the operational planning of forest management in northern Europe was assessed. The analysis was based on temperature and precipitation data from WFDEI System 4 with 15 ensemble members representing seasonal hindcasts (retrospective predictions) for the period of 1981–2010. The data was used directly and as input to a soil model from which monthly indices of frozen soil and plant water stress were calculated. Relatively low skills were found for most months, and in particular for longer lead times. Highest skill was found for bias corrected temperature of January to March, with one month lead time. The skill was higher for the soil model indices, in particular those related to soil frost, as they are influenced by cumulative processes and the initial model conditions contribute to the skill. Probabilistic forecasts on frozen soil can thus be valuable for planning of which areas to harvest, taking the risk of driving damage to forest soils and forest roads into account.

Klemm, T., & McPherson, R. A. (2017). The development of seasonal climate forecasting for agricultural producers. *Agricultural and Forest Meteorology, 232*, 384-399. https://doi.org/10.1016/j.agrformet.2016.09.005

This review summarizes advances in seasonal climate forecasting with a focus on agriculture, predominantly since the year 2000. The main research methods used were keyword searches in publisher unaffiliated databases such as Web of Knowledge and in publication libraries of institutions known for their interdisciplinary work in climate forecasting and agriculture. Crop and livestock producers use seasonal climate forecasts for management decisions such as planting and harvest timing, field fertilization, or grazing. Agricultural users have often criticized lack of forecast skill and usability as well as a lack of understanding of user needs among forecast developers.

Recently, interdisciplinary studies started exploring agricultural decision-making and integrating social science and climate science in order to improve the value of seasonal forecasts. Producer requests include direct and derived forecast products, such as total rainfall and consecutive dry days, information on uncertainty, and comparisons to previous years. The review explores single-model and ensemble forecasts, describes different measures of forecast value, and highlights economic and other agricultural decision factors besides weather and climate. It also examines seasonal climate forecasts from an agricultural perspective, explores communication challenges and how to overcome them, and delves into end-to-end forecast concepts that span forecast production to forecast application by end users.

Togliatti, K., Archontoulis, S. V., Dietzel, R., Puntel, L., & VanLoocke, A. (2017). How does inclusion of weather forecasting impact in-season crop model predictions? *Field Crops Research, 214*, 261-272. https://doi.org/10.1016/j.fcr.2017.09.008

Accurately forecasting crop yield in advance of harvest could greatly benefit decision makers when making management decisions. However, few evaluations have been conducted to determine the impact of including weather forecasts, as opposed to using historical weather data (commonly used) in crop models. We tested a combination of short-term weather forecasts from the Weather Research and Forecasting Model (WRF) to predict in season weather variables, such as, maximum and minimum temperature, precipitation, and radiation at four different forecast lengths (14 days, 7 days, 3 days, and 0 days). This forecasted weather data along with the current and historic (previous 35 years) data were combined to drive Agricultural Production Systems sIMulator (APSIM) in-season corn [Zea mays L] and soybean [Glycine max] grain yield and phenology forecasts for 16 field trials in Iowa, USA. The overall goal was to determine how the inclusion of weather forecasting impacts in season crop model predictions. We had two objectives 1) determine the impact of weather forecast length on WRF accuracy, and 2) quantify the impact of weather forecasts accuracy on APSIM prediction accuracy. We found that the most accurate weather forecast length varied greatly among the 16 treatments (2 years x 2 sites x 2 crops x 2 management practices), but that the 0 day and 3 day forecasts were, on average, the most accurate when compared to the other forecast lengths. Overall, the accuracy of the in-season crop yield forecast was inversely proportional to forecast length ($p = 0.026$), but there was variation among treatments. The accuracy of the in-season flowering and maturity forecasts were not significantly affected by inclusion of weather forecast length ($p = 0.065$). The 14 day forecast provided enough lead time to improve flowering prediction in 8 out of the 16 treatments. The fact that maximum temperature was the most accurate predicted variable by WRF was the reason for improvements in flowering predictions. Our results suggest that a weather forecast from WRF was not better than historical weather for yield prediction.

Capa-Morocho, M., Ines, A. V. M., Baethgen, W. E., Rodriguez-Fonseca, B., Han, E., & Ruiz-Ramos, M. (2016). Crop yield outlooks in the Iberian Peninsula: Connecting seasonal climate forecasts with crop simulation models. *Agricultural Systems, 149*, 75-87. https://doi.org/10.1016/j.agsy.2016.08.008

Seasonal climate prediction can potentially contribute to achieving a more resilient cropping system management. This can help alleviate food insecurity and the economical sustainability of farming at large. For this purpose, seasonal climate forecasts are used to generate crop forecasts. This study assesses two methods for linking seasonal climate forecasts with crop models to improve crop yield predictability in the Iberian Peninsula (IP). Crop models usually require daily

weather data and therefore, we tested two methods to disaggregate seasonal climate forecasts into daily weather realizations: (1) a conditional stochastic weather generator (predictWTD) and (2) a simple forecast probability resampler (FResampler1). These methods were evaluated under three seasonal rainfall forecasts by analyzing the impacts on rainfed wheat yield and on irrigation requirements and yields of maize crop. In addition, we estimated the gross margins ((sic) ha (-1)) and the production risks associated with contrasting scenarios of seasonal rainfall forecasts (dry and wet). Both methods provided comparable predictability and therefore, both seem feasible options for using seasonal forecasts to establish yield forecasts and irrigation requirements. The large impact of crop prices and of irrigation cost on gross margins for both crops suggests that using a combination of information on expected market prices and crop forecast based on seasonal climate forecasts can be an effective tool for farmer's decision-making, especially under dry forecast situation and/or in locations with low annual precipitation. These methods can help to quantify the benefits and risks from the seasonal weather forecasts to farmers in the IP. The anticipation of risks and the opportunity that skillful climate and crop forecast provide allows for windows of opportunity to prepare and preempt mitigating actions. 

Nidumolu, U. B., Lubbers, M., Kanellopoulos, A., van Ittersum, M. K., Kadiyala, D. M., & Sreenivas, G. (2016). Engaging farmers on climate risk through targeted integration of bio-economic modelling and seasonal climate forecasts. *Agricultural Systems, 149*, 175-184. https://doi.org/10.1016/j.agsy.2016.09.011

Seasonal climate forecasts (SCFs) can be used to identify appropriate risk management strategies and to reduce the sensitivity of rural industries and communities to climate risk. However, these forecasts have low utility among farmers in agricultural decision making, unless translated into a more understood portfolio of farm management options. Towards achieving this translation, we developed a mathematical programming model that integrates seasonal climate forecasts to assess 'what-if?' crop choice scenarios for famers. We used the Rayapalli village in southern India as a case study. The model maximises expected profitability at village level subject to available resource constraints. The main outputs of the model are the optimal cropping patterns and corresponding agricultural management decisions such as fertiliser, biocide, labour and machinery use. The model is set up to run in two steps. In the first step the initial climate forecast is used to calculate the optimal farm plan and corresponding agricultural management decisions at a village scale. The second step uses a 'revised forecast' that is given six weeks later during the growing season. In scenarios where the forecast provides no clear expectation for a dry or wet season the model utilises the total agricultural land available. A significant area is allocated to redgram (pigeon pea) and the rest to maize and paddy rice. In a forecast where a dry season is more probable, cotton is the predominant crop selected. In scenarios where a 'normal' season is expected, the model chooses predominantly cotton and maize in addition to paddy rice and redgram. As part of the stakeholder engagement process, we operated the model in an iterative way with participating farmers. For 'deficient' rainfall season, farmers were in agreement with the model choice of leaving a large portion of the agriculture land as fallow with only 40ha (total area 136ha) of cotton and subsistence paddy rice area. While the model crop choice was redgram in 'above normal and wet seasons, only a few farmers in the village favoured redgram mainly because of high labour requirements, and the farmers perceptions about risks related to pests and diseases. This highlighted the discrepancy between the optimal cropping pattern, calculated with the model and the farmer's actual decisions which provided useful insights into factors affecting farmer decision making that are not always captured by models. We found that planning for a 'normal' season alone is likely to result in losses and opportunity costs and an adaptive climate risk management approach is prudent. In an interactive feedback workshop, majority of participating farmers agreed that their knowledge on

the utility and challenges of SCF have highly improved through the participation in this research and most agreed that exposure to the model improved their understanding of the role of SCF in crop choice decisions and that the modelling tool was useful to discuss climate risk in agriculture.

Ramírez-Rodrigues, M. A., Alderman, P. D., Stefanova, L., Cossani, C. M., Flores, D., & Asseng, S. (2016). The value of seasonal forecasts for irrigated, supplementary irrigated, and rainfed wheat cropping systems in northwest Mexico. *Agricultural Systems, 147*, 76-86. https://doi.org/10.1016/j.agsy.2016.05.005

Half of global wheat production occurs in irrigated cropping regions that face increasing water shortages. In these regions, seasonal forecasts could provide information about in-season climate conditions that could improve resource management, helping to save water and other inputs. However, seasonal forecasts have not been tested in irrigated systems. In this study, we show that seasonal forecasts have the potential to guide crop management decisions in fully irrigated systems (FIS), reduced irrigation systems (supplementary irrigation; SIS), and systems without irrigation (rainfed; RFS) in an arid environment. We found that farmers could gain an additional 2USDha−1season−1 in net returns and save up to 26USDha−1season−1 in N fertilizer costs with a hypothetical always-correct-season-type-forecast (ACF) in a fully irrigated system compared to simulated optimized N fertilizer applications. In supplementary irrigated systems, an ACF had value when deciding on sowing a crop (plus supplementary irrigation) of up to 65USDha−1season−1. In rainfed systems, this value was up to 123USDha−1 when deciding whether or not to sow a crop. In supplementary irrigated and rainfed systems, such value depended on initial soil water conditions. Seasonal forecasts have the potential to assist farmers in irrigated, supplementary irrigated, and rainfed cropping systems to maximize crop profitability. However, forecasts currently available based on Global Circulation Models (GCM) and the El Niño Southern Oscillation (ENSO) need higher forecast skill before such benefits can be fully realized.

Roudier, P., Alhassane, A., Baron, C., Louvet, S., & Sultan, B. (2016). Assessing the benefits of weather and seasonal forecasts to millet growers in Niger. *Agricultural and Forest Meteorology, 223*, 168-180. https://doi.org/10.1016/j.agrformet.2016.04.010

West African farmers need to take every year crucial decisions based on some characteristics of the rainy season such as the onset, the offset, the cumulated rainfall or the occurrence of dry spells. Knowing these parameters in advance may therefore be of interest for them. This paper aims at assessing the impacts of 10-days and seasonal forecasts on Niger millet growers' cropping practices and their income. To do so, we apply an ex-ante approach based on the crop model SARRA-H coupled with an economic model that simulates the choice of cropping strategies among 24 available. The approach takes explicitly risk aversion into account and focuses on two different kinds of typical farmers with restricted and large adaptation capacities, in reference to the availability of viable decision options sensitive to forecast information. Results show (i) that 10-days forecasts alone or a combination of 10-days and seasonal forecasts could be quite beneficial for all types of farmers (e.g. median income change with 10-days forecast ranges from +1.8% to +13% according to adaptation possibilities), (ii) that in most of the cases farmers with access to fertilizers and larger arable land benefit more from forecasts and (iii) that even if seasonal forecasts are not really beneficial alone, they are when used in combination with 10-days forecasts. Despite these positive results, one has to underline that income losses may occur in about 20% of cases when using these forecasts, which may be a limiting factor to their effective adoption.

Ferrise, R., Toscano, P., Pasqui, M., Moriondo, M., Primicerio, J., Semenov, M. A., & Bindi, M. (2015). Monthly-to-seasonal predictions of durum wheat yield over the Mediterranean Basin. *Climate Research, 65*, 7-21. https://doi.org/10.3354/cr01325

Uncertainty in weather conditions for the forthcoming growing season influences farmers' decisions, based on their experience of the past climate, regarding the reduction of agricultural risk. Early within-season predictions of grain yield can represent a great opportunity for farmers to improve their management decisions and potentially increase yield and reduce potential risk. This study assessed 3 methods of within-season predictions of durum wheat yield at 10 sites across the Mediterranean Basin. To assess the value of within-season predictions, the model SiriusQuality2 was used to calculate wheat yields over a 9 yr period. Initially, the model was run with observed daily weather to obtain the reference yields. Then, yield predictions were calculated at a monthly time step, starting from 6 mo before harvest, by feeding the model with observed weather from the beginning of the growing season until a specific date and then with synthetic weather constructed using the 3 methods, historical, analogue or empirical, until the end of the growing season. The results showed that it is possible to predict durum wheat yield over the Mediterranean Basin with an accuracy of normalized root means squared error of <20%, from 5 to 6 mo earlier for the historical and empirical methods and 3 mo earlier for the analogue method. Overall, the historical method performed better than the others. Nonetheless, the analogue and empirical methods provided better estimations for low-yielding and high-yielding years, thus indicating great potential to provide more accurate predictions for years that deviate from average conditions.

Haigh, T., Takle, E., Andresen, J., Widhalm, M., Carlton, J. S., & Angel, J. (2015). Mapping the decision points and climate information use of agricultural producers across the U.S. Corn Belt. *Climate Risk Management, 7*, 20-30. https://doi.org/10.1016/j.crm.2015.01.004

The usefulness of climate information for agricultural risk management hinges on its availability and relevance to the producer when climate-sensitive decisions are being made. Climate information providers are challenged with the task of balancing forecast availability and lead time with acceptable forecast skill, which requires an improved understanding of the timing of agricultural decision making. Achieving a useful balance may also require an expansion of inquiry to include use of non-forecast climate information (i.e. historical climate information) in agricultural decision making. Decision calendars have proven valuable for identifying opportunities for using different types of climate information. The extent to which decision-making time periods are localized versus generalized across major commodity-producing regions is yet unknown, though, which has limited their use in climate product development. Based on a 2012 survey of more than 4770 agricultural producers across the U.S. Corn Belt region, we found variation in the timing of decision-making points in the crop year based on geographic variation as well as crop management differences. Many key decisions in the cropping year take place during the preceding fall and winter, months before planting, raising questions about types of climate information that might be best inserted into risk management decisions at that time. We found that historical climate information and long term climate outlooks are less influential in agricultural risk management than current weather, short term forecasts, or monthly climate projections, even though they may, in fact, be more useful to certain types of decision making.

Kgakatsi, I. B., & Rautenbach, C. J. (2014). The contribution of seasonal climate forecasts to the management of agricultural disaster-risk in South Africa. *International Journal of Disaster Risk Reduction, 8*, 100-113. https://doi.org/10.1016/j.ijdrr.2014.01.002

This study examined the use of Seasonal Climate Forecast (SCF) information in the agricultural sector in South Africa following the compilation and dissemination of early warning information aiming to reduce risks faced by farming communities. SCF information received from the scientific community is disseminated to the agricultural sector through intermediaries. The study assessed the channels through which SCF information is disseminated to end users by intermediaries. To achieve this, ethnographic interviews took place with 110 intermediaries covering national, provincial, agricultural union's structures. In these interviews the status of the preparation of early warning information, the effectiveness of the dissemination of information and the success in capacitating end users to understand the SCF information, were assessed in order to create a more functional system. The findings highlighted that improved channels and structures, through which reliable and timely SCF information that could serve as early warning should be developed. In addition, it was found that end user SCF information feedback programmes should improve, which will assist intermediaries to improve the dissemination of information. Governing bodies, intermediaries and end-users should collectively identify institutional, social and infrastructural barriers in the channels of early warning information dissemination, and should jointly devise action plans to overcome these.

Makaudze, E. M. (2014). Assessing the economic value of El Nino-based seasonal climate forecasts for smallholder farmers in Zimbabwe. *Meteorological Applications, 21*(3), 535-544. https://doi.org/10.1002/met.1366

This study demonstrates the potential value of forecasts to smallholder farmers in Zimbabwe, the majority of whom often suffer severely from the impact of drought. Using crop simulation models to compare yield performances of farmers with and without forecasts, results indicate that, for a drought year, farmers with forecasts (WF) record higher yield gains (28%) compared to those without forecasts (WOF): in particular, farmers located in the most arid regions (NR V) recorded the highest yield gains (42%). A similar trend is observed during a neutral/average year, as farmers WF obtain predominantly higher yield gains (20%) than those WOF. However, during a good year, results show a different pattern as no yield gains are observed. In fact, farmers WOF perform better; suggesting forecasts in this case may not make much difference. Using gross margin analysis, results show farmers WF obtaining higher returns during a drought (US$ 0.14 ha (-1)) and neutral year (US$ 0.43 ha (-1)) but again not for a good year as farmers WOF outperform those WF. To summarize, forecasts can play an important role as loss-minimization instruments especially if the underlying year is an El Nino (drought) year. In conclusion, to attain full economic value of forecasts, complementary policies (currently missing) such as effective communication, improvement in forecast extension skills and promotion of farmer participatory and outreach activities could prove vital in enhancing the value of forecasts to smallholder farmers in general.

Solís, D., & Letson, D. (2013). Assessing the value of climate information and forecasts for the agricultural sector in the Southeastern United States: multi-output stochastic frontier approach. *Regional Environmental Change, 13*(1), 5-14. https://doi.org/10.1007/s10113-012-0354-x

A multi-output/input stochastic distance frontier model is used to analyze the effect of interannual climatic variability on agricultural production and to assess the impact of climate forecasts on the economic performance of this sector in the Southeastern United States. The results show that the omission of climatic conditions when estimating regional agricultural production models could lead to biased technical efficiency (TE) estimates. This climate bias may significantly affect the effectiveness of rural development policies based on regional economic performance comparisons. We also found that seasonal rainfall and temperature forecasts have a positive effect on economic performance of agriculture. However, the effectiveness of climate forecasts on improving TE is sensitive to the type of climate index used. Policy implications stemming from the results are also presented.

Crane, T. A., Roncoli, C., Paz, J., Breuer, N., Broad, K., Ingram, K. T., & Hoogenboom, G. (2010). Forecast Skill and Farmers' Skills: Seasonal Climate Forecasts and Agricultural Risk Management in the Southeastern United States. *Weather, Climate, and Society, 2*(1), 44-59. https://doi.org/10.1175/2009WCAS1006.1

During the last 10 yr, research on seasonal climate forecasts as an agricultural risk management tool has pursued three directions: modeling potential impacts and responses, identifying opportunities and constraints, and analyzing risk communication aspects. Most of these approaches tend to frame seasonal climate forecasts as a discrete product with direct and linear effects. In contrast, the authors propose that agricultural management is a performative process, constituted by a combination of planning, experimentation, and improvisation and drawing on a mix of technical expertise, situated knowledge, cumulative experience, and intuitive skill as farmers navigate a myriad of risks in the pursuit of livelihood goals and economic opportunities. This study draws on ethnographic interviews conducted with 38 family farmers in southern Georgia, examining their livelihood goals and social values, strategies for managing risk, and interactions with weather and climate information, specifically their responses to seasonal climate forecasts. Findings highlight the social nature of information processing and risk management, indicating that both material conditions and value-based attitudes bear upon the ways farmers may integrate climate predictions into their agricultural management practices. These insights translate into specific recommendations that will enhance the salience, credibility, and legitimacy of seasonal climate forecasts among farmers and will promote the incorporation of such information into a skillful performance in the face of climate uncertainty.

Meza, F. J., Hansen, J. W., & Osgood, D. (2008). Economic Value of Seasonal Climate Forecasts for Agriculture: Review of Ex-Ante Assessments and Recommendations for Future Research. *Journal of Applied Meteorology and Climatology, 47*(5), 1269-1286. https://doi.org/10.1175/2007jamc1540.1

Advanced information in the form of seasonal climate forecasts has the potential to improve farmers' decision making, leading to increases in farm profits. Interdisciplinary initiatives seeking to understand and exploit the potential benefits of seasonal forecasts for agriculture have produced a number of quantitative ex-ante assessments of the economic value of seasonal climate forecasts.

The realism, robustness, and credibility of such assessments become increasingly important as efforts shift from basic research toward applied research and implementation. This paper surveys published evidence about the economic value of seasonal climate forecasts for agriculture, characterizing the agricultural systems, approaches followed, and scales of analysis. The climate forecast valuation literature has contributed insights into the influence of forecast characteristics, risk attitudes, insurance, policy, and the scale of adoption on the value of forecasts. Key innovations in the more recent literature include explicit treatment of the uncertainty of forecast value estimates, incorporation of elicited management responses into bioeconomic modeling, and treatment of environmental impacts, in addition to financial outcomes of forecast response. It is argued that the picture of the value of seasonal forecasts for agriculture is still incomplete and often biased, in part because of significant gaps in published valuation research. Key gaps include sampling of a narrow range of farming systems and locations, incorporation of an overly restricted set of potential management responses, failure to consider forecast responses that could lead to "regime shifts," and failure to incorporate state-of-the-art developments in seasonal forecasting. This paper concludes with six recommendations to enhance the realism, robustness, and credibility of ex-ante valuation of seasonal climate forecasts. associated with these three activities as a way of exploring effective application of seasonal climate information and identifies additional research to enhance applicability.

Semenov, M. A., & Doblas-Reyes, F. (2007). Utility of dynamical seasonal forecasts in predicting crop yield. *Climate Research, 34*(1). https://doi.org/10.3354/cr034071

Advance predictions of crop yield using crop simulation models require daily weather input for the whole growing season. Seasonal forecasts, based on coupled ocean-atmosphere climate models, are now available up to 6 mo in advance from a number of operational meteorological centres around the world. Seasonal forecasts are not directly suitable for crop simulations, because of model biases and mismatch of spatial and temporal scales. However, it is possible to utilise seasonal forecasts for yield predictions by constructing site-specific daily weather using a stochastic weather generator linked to seasonal forecasts. In our study, we use the LARS-WG weather generator and a subset of predictions by DEMETER (Development of a European Multimodel Ensemble system for seasonal to inTERannual climate prediction), i.e. seasonal ensemble hindcasts from the general circulation model (GCM) of ECMWF (European Centre for Medium-range Weather Forecasting) for 1980-2001. To assess the value of seasonal forecasts, 2 sets of scenarios were created, one based on seasonal forecasts and the other on historical climatology. The Sirius wheat simulation model was used to compute distributions of wheat yield at 2 locations in Europe and New Zealand. The main conclusion is that the use of dynamical seasonal forecasts at selected sites has not improved yield predictions compared with the approach based on historical climatology. The likely reason is that for dynamic seasonal forecasts, the skill score for temperature and precipitation is generally low for latitudes.

Hansen, J. W. (2005). Integrating Seasonal Climate Prediction and Agricultural Models for Insights into Agricultural Practice. *Philosophical Transactions: Biological Sciences, 360*(1463), 2037-2047. http://www.jstor.org/stable/30041393

Interest in integrating crop simulation models with dynamic seasonal climate forecast models is expanding in response to a perceived opportunity to add value to seasonal climate forecasts for agriculture. Integrated modelling may help to address some obstacles to effective agricultural use of climate information. First, modelling can address the mismatch between farmers' needs and

available operational forecasts. Probabilistic crop yield forecasts are directly relevant to farmers' livelihood decisions and, at a different scale, to early warning and market applications. Second, credible ex ante evidence of livelihood benefits, using integrated climate-crop-economic modelling in a value-of information framework, may assist in the challenge of obtaining institutional, financial and political support; and inform targeting for greatest benefit. Third, integrated modelling can reduce the risk and learning time associated with adaptation and adoption, and related uncertainty on the part of advisors and advocates. It can provide insights to advisors, and enhance site-specific interpretation of recommendations when driven by spatial data. Model-based 'discussion support systems' contribute to learning and farmer-researcher dialogue. Integrated climate-crop modelling may play a genuine, but limited role in efforts to support climate risk management in agriculture, but only if they are used appropriately, with understanding of their capabilities and limitations, and with cautious evaluation of model predictions and of the insights that arises from model-based decision analysis.

McCrea, R., Dalgleish, L., & Coventry, W. (2005). Encouraging use of seasonal climate forecasts by farmers. *International Journal of Climatology, 25*(8). http://dx.doi.org/10.1002/joc.1164

What encourages use of seasonal climate forecasts? Considerable effort is being applied in developing seasonal climate forecasts and demonstrating the potential benefits available to farmers from using seasonal climate forecasts. This study examines three factors underlying the use of seasonal climate forecasts by farmers: the level of forecast understanding by farmers, the format presentation of the forecasts, and the attitude of farmers towards the usefulness of forecasts as indicators of future rainfall. Using judgement analysis, the use of forecasts in cropping decisions was determined for 73 Australian farmers. Then a moderated regression analysis was used to predict forecast use from the three underlying factors. The study found that a good understanding of the forecast was more important than the forecast format in predicting its use. However, this main effect of good understanding on higher use was qualified by a three-way interaction, such that good understanding was only associated with higher use when farmers had a favourable attitude toward the usefulness of seasonal climate forecasts and the forecasts were presented in a frequency format. Thus, the study found all three factors were important in predicting the use of seasonal climate forecasts by farmers. However, relatively little is known about farmer attitudes toward the usefulness of seasonal climate forecasts and how these attitudes arise, and further research is recommended in these areas.

Ingram, K. T., Roncoli, M. C., & Kirshen, P. H. (2002). Opportunities and constraints for farmers of west Africa to use seasonal precipitation forecasts with Burkina Faso as a case study. *Agricultural Systems, 74*(3), 331-349. https://doi.org/10.1016/s0308-521x(02)00044-6

Skill of seasonal precipitation forecasts for west Africa has improved to the point that forecasts may be of value to agricultural users, especially farmers. We studied agricultural production systems in three agro-ecozones of Burkina Faso to establish: (1) farmer interest in and ability to use forecasts; (2) forecast information farmers request; (3) lead-time required for greatest forecast value; (4) needs for forecast dissemination, interpretation, and application; and (5) possible strategies for using climate forecasts to improve crop production and resource management. The three agro-ecozones studied were a cotton-based system in the relatively high rainfall Sudan area of southwest Burkina Faso; a sorghum and millet based system in the low rainfall central plateau; and a cattle-based system in the very low rainfall Sahel area in the north. Potential value of forecasts to farmers differed among the three zones, with greatest apparent value to farmers of the central plateau and

least apparent value to cattle herders of the Sahel. While farmers in all three agro-ecozones expressed a strong interest in receiving seasonal precipitation forecasts, they were much more interested in receiving forecasts of when the rains would start and end, and whether there would be interruptions in rains. Our results suggest that if seasonal precipitation forecasts are disseminated, they should be a part of an extension package that includes discussion of the probabilistic nature of the forecasts, potential response strategies, and risk management. Furthermore, farmers may need greater access to basic agricultural technologies, such as plows, new crop varieties, and fertilizers, before they can benefit fully from precipitation forecasts.

Jones, J. W., Hansen, J. W., Royce, F. S., & Messina, C. D. (2000). Potential benefits of climate forecasting to agriculture. *Agriculture Ecosystems & Environment, 82*(1-3), 169-184. https://doi.org/10.1016/s0167-8809(00)00225-5

Climate variability leads to economic and food security risks throughout the world because of its major influences on agriculture. Accurate forecasts of climate 3-6 months ahead of time can potentially allow farmers and others in agriculture to make decisions to reduce unwanted impacts or take advantage of expected favorable climate. However, potential benefits of climate forecasts vary considerably because of many physical, biological, economic, social, and political factors. The purpose of this study was to estimate the potential economic value of climate forecasts for farm scale management decisions in one location in the Southeast USA (Tifton, GA; 31 degrees 23'N; 83 degrees 31'W) for comparison with previously-derived results for the Pampas region of Argentina, The same crops are grown in both regions but at different times of the year. First, the expected value of tailoring crop mix to El Nino-Southern Oscillation (ENSO) phases for a typical farm in Tifton was estimated using crop models and historical daily weather data. Secondly, the potential values for adjusting management of maize (Zea maize L.) to different types of climate forecasts (perfect knowledge of (a) ENSO phase, (b) growing season rainfall categories, and (c) daily weather) were estimated for Tifton and Pergamino, Argentina (33 degrees 55'S; 60 degrees 33'W). Predicted benefits to the farm of adjusting crop mix to ENSO phase averaged from US$ 3 to 6 ha(-1) over all years, depending on the farmer's initial wealth and aversion to risk. Values calculated for Argentina were US$ 9-15 for Pergamino and up to US$ 35 for other locations in the Pampas. Varying maize management by ENSO phase resulted in predicted forecast values of US$ 13 and 15 for Tifton and Pergamino, respectively The potential value of perfect seasonal forecasts of rainfall tercile on maize profit was higher than for ENSO-based forecasts in both regions (by 28% in Tifton and 70% in Pergamino). Perfect knowledge of daily weather over the next season provided an upper limit on expected value of about US$ 190 ha (-1) for both regions. Considering the large areas of field crop production in these regions, the estimated economic potential is very high. However, there are a number of challenges to realize these benefits. These challenges are generally related to the uncertainty of climate forecasts and to the complexities of agricultural systems.

Hammer, G. L., Holzworth, D. P., & Stone, R. (1996). The value of skill in seasonal climate forecasting to wheat crop management in a region with high climatic variability. *Australian Journal of Agricultural Research, 47*(5), 717-737. https://doi.org10.1071/ar9960717

In Australia, and particularly in the northern part of the grain belt, wheat is grown in an extremely variable climate. The wheat crop manager in this region is faced with complex decisions on choice of planting time, varietal development pattern, and fertiliser strategy. A skillful seasonal forecast would provide an opportunity for the manager to tailor crop management decisions more appropriately to the season. Recent developments in climate research have led to the development of a number of seasonal climate forecasting systems. The objectives of this study were to determine

the value of the capability in seasonal forecasting to wheat crop management, to compare the value of the existing forecast methodologies, and to consider the potential value of improved forecast quality. We examined decisions on nitrogen (N) fertiliser and cultivar maturity using simulation analyses of specific production scenarios at a representative location (Goondiwindi) using long-term daily weather data (1894-1989). The average profit and risk of making a loss were calculated for the possible range of fixed (i.e. the same every year) and tactical (i.e. varying depending on seasonal forecast) strategies. Significant increase in profit (up to 20%) and/or reduction in risk (up to 35%) were associated with tactical adjustment of crop management of N fertiliser or cultivar maturity. The forecasting system giving greatest value was the Southern Oscillation Index (SOI) phase system of Stone and Auliciems (1992), which classifies seasons into 5 phases depending on the value and rate of change in the SOI. The significant skill in this system for forecasting both seasonal rainfall and frost timing generated the value found in tactical management of N fertiliser and cultivar maturity. Possible impediments to adoption of tactical management, associated with uncertainties in forecasting individual years, are discussed. The scope for improving forecast quality and the means to achieve it are considered by comparing the value of tactical management based on SOI phases with the outcome given perfect prior knowledge of the season. While the analyses presented considered only one decision at a time, used specific scenarios, and made a number of simplifying assumptions, they have demonstrated that the current skill in seasonal forecasting is sufficient to justify use in tactical management of crops. More comprehensive studies to examine sensitivities to location, antecedent conditions, and price structure, and to assumptions made in this analysis, are now warranted. We have examined decisions related only to management of wheat. It would be appropriate to pursue similar analyses in relation to management decisions for other crops, cropping sequences, and the whole farm enterprise mix.

Kingwell, R. S. (1994). Risk attitude and dryland farm management. *Agricultural Systems, 45*(2), 191-202. https://doi.org/10.1016/0308-521x(94)90178-i

A model of the dryland farming system in the eastern wheatbelt of Western Australia is briefly described The model named MUDAS, explicitly accounts for climatic and price risk, and dryland farm management responses to such risk, assuming certain risk attitudes of the farmer. The management decisions associated with various risk attitudes, ranging from risk neutrality to extreme risk aversion, are presented. These decisions are compared and contrasted assuming two price scenarios. Results show that in both price scenarios the effect of increased risk aversion was to shift resources away from cropping toward the livestock enterprise and to change the tactical management of the farming system. In particular, increased risk aversion reduced the area of crop in the favourable weather-years and enabled pastures to be more productive thereby supporting more sheep at higher stocking rates.

Kingwell, R. S., Pannell, D. J., & Robinson, S. D. (1993). Tactical responses to seasonal conditions in whole-farm planning in Western Australia. *Agricultural Economics, 8*(3), 211-226. https://doi.org/10.1016/0169-5150(93)90015-5

In dryland agricultural systems, efficient farm management requires a degree of flexibility according to variations in climate from year to year. Tactical adjustments to the mix of farm enterprises can capitalize on good growing conditions and minimise losses under poor growing conditions. In this paper, a -discrete stochastic programming model of dryland wheat-sheep farms in Western Australia is used to identify optimal tactical adjustments to climate and to calculate the value of these tactical adjustments. The model, MUDAS, includes nine discrete season types with a

wide range of options for tactical adjustments in each. In the standard model, optimal tactical responses increase expected net cash surplus by approximately 22% relative to a fixed or inflexible strategy. In most season types, changes to the long term farm strategy are made on less than 10% of the farm area, although in some seasons over 25% of the farm can require adjustments to the enterprise selected. The benefits of flexibility are not evenly distributed across different season types but occur predominantly in the best and worst seasons. The magnitude of benefits is affected differently by different commodity prices. Benefits of flexibility are due to capitalizing on knowledge about the greater volatility of profits from cropping than from livestock production. Deterministic models and even stochastic models which don't include activities for tactical adjustments miss this key feature of the system.

Easterling, W. E., & Mjelde, J. W. (1987). The importance of seasonal climate prediction lead time in agricultural decision making. *Agricultural and Forest Meteorology, 40*(1), 37-50. https://doi.org/10.1016/0168-1923(87)90053-0

Monthly and seasonal climate predictions are of potential value in agricultural decision making. Most studies evaluating the usefulness of climate predictions to various economic sectors have focused primarily on accuracy levels as the primary impediment to wider use of the predictions in decision making. It is argued here, however, that prediction lead time is also an important factor in the usefulness of the predictions. It is shown that lead time (or lack thereof) is the most important variable distinguishing between subscribers to a National Oceanic and Atmospheric Administration (NOAA) prediction who use the prediction in decision making from those who do not. Indeed, the lack of lead time is a major deterrent to the use of the prediction. Detailed decision analysis of east-central Illinois corn production reveals that a prediction of early summer conditions available in early spring has significantly more value than the same prediction available in late spring. The increased value of the early summer prediction that is available in early spring stems primarily from added flexibility in nitrogen application. Further, economic trade-offs are found between lead time and predictive accuracy. These findings are likely to have relevance beyond agriculture to other dynamic decision-making activities.

## Section III: Aquaculture and Fisheries

Dunstan, P. K., Moore, B. R., Bell, J. D., Holbrook, N. J., Oliver, E. C. J., Risbey, J., et al (2018). How can climate predictions improve sustainability of coastal fisheries in Pacific Small-Island Developing States? Marine Policy, 88, 295-302. https://doi.org/10.1016/j.marpol.2017.09.033

Climate and weather have profound effects on economies, the food security and livelihoods of communities throughout the Pacific Island region. These effects are particularly important for small-scale fisheries and occur, for example, through changes in sea surface temperature, primary productivity, ocean currents, rainfall patterns, and through cyclones. This variability has impacts over both short and long time scales. We differentiate climate predictions (the actual state of climate at a particular point in time) from climate projections (the average state of climate over long time scales). The ability to predict environmental conditions over the time scale of months to decades will assist governments and coastal communities to reduce the impacts of climatic variability and take advantage of opportunities. We explore the potential to make reliable climate predictions over time scales of six months to 10 years for use by policy makers, managers and

communities. We also describe how climate predictions can be used to make decisions on short time scales that should be of direct benefit to sustainable management of small-scale fisheries, and to disaster risk reduction, in Small-Island Developing States in the Pacific

Hobday, A. J., Spillman, C. M., Eveson, J. P., Hartog, J. R., Zhang, X., & Brodie, S. (2018). A Framework for Combining Seasonal Forecasts and Climate Projections to Aid Risk Management for Fisheries and Aquaculture. Frontiers in Marine Science, 5(137). https://doi.org/10.3389/fmars.2018.00137

A changing climate, in particular a warming ocean, is likely to impact marine industries in a variety of ways. For example, aquaculture businesses may not be able to maintain production in their current location into the future, or area-restricted fisheries may need to follow the fish as they change distribution. Preparation for these potential climate impacts can be improved with information about the future. Such information can support a risk-based management strategy for industries exposed to both short-term environmental variability and long-term change. In southern Australia, adverse climate impacts on valuable seafood industries have occurred, and they are now seeking advice about future environmental conditions. We introduce a decision tree to explain the potential use of long-term climate projections and seasonal forecasts by these industries. Climate projections provide insight into the likely time in the future when current locations will no longer be suitable for growing or catching particular species. Until this time, seasonal forecasting is beneficial in helping industries plan ahead to reduce impacts in poor years and maximise opportunities in good years. Use of seasonal forecasting can extend the period of time in which industries can cope in a location as environmental suitability declines due to climate change. While a range of short-term forecasting approaches exist, including persistence and climatological forecasts, only dynamic model forecasts provide a viable option for managing environmental risk for marine industries in regions where climate change is reducing environmental suitability and creating novel conditions.

Hobday, A. J., Spillman, C. M., Paige Eveson, J., & Hartog, J. R. (2016). Seasonal forecasting for decision support in marine fisheries and aquaculture. Fisheries Oceanography, 2016 v.25 Suppl S1, pp. 45-56. https://doi.org/10.1111/fog.12083

The production of marine protein from fishing and aquaculture is influenced by environmental conditions. Ocean temperature, for example, can change the growth rate of cultured animals, or the distribution of wild stocks. In turn these impacts may require changes in fishing or farming practices. In addition to short-term environmental fluctuations, long-term climate-related trends are also resulting in new conditions, necessitating adjustment in fishing, farming and management approaches. Longer-term climate forecasts, however, are seen as less relevant by many in the seafood sector owing to more immediate concerns. Seasonal forecasts provide insight into upcoming environmental conditions, and thus allow improved decision making. Forecasts based on dynamic ocean models are now possible and offer improved performance relative to statistical forecasts, particularly given baseline shifts in the environment as a result of climate change. Seasonal forecasting is being used in marine farming and fishing operations in Australia, including wild tuna and farmed salmon and prawns, to reduce uncertainty and manage business risks. Forecast variables include water temperature, rainfall and air temperature, and are considered useful up to approximately 4 months into the future, depending on the region and season of interest. Species-specific habitat forecasts can also be made by combining these environment forecasts with biological habitat preference data. Seasonal forecasts are useful when a range of

options are available for implementation in response to the forecasts. The use of seasonal forecasts in supporting effective marine management may also represent a useful stepping stone to improved decision making and industry resilience at longer timescales.

Tommasi, D., Stock, C. A., Hobday, A. J., Methot, R., Kaplan, I. C., Eveson, J. P., et al. (2017). Managing living marine resources in a dynamic environment: The role of seasonal to decadal climate forecasts. Progress in Oceanography, 152, 15-49. https://doi.org/10.1016/j.pocean.2016.12.011

Recent developments in global dynamical climate prediction systems have allowed for skillful predictions of climate variables relevant to living marine resources (LMRs) at a scale useful to understanding and managing LMRs. Such predictions present opportunities for improved LMR management and industry operations, as well as new research avenues in fisheries science. LMRs respond to climate variability via changes in physiology and behavior. For species and systems where climate-fisheries links are well established, forecasted LMR responses can lead to anticipatory and more effective decisions, benefitting both managers and stakeholders. Here, we provide an overview of climate prediction systems and advances in seasonal to decadal prediction of marine-resource relevant environmental variables. We then describe a range of climate-sensitive LMR decisions that can be taken at lead-times of months to decades, before highlighting a range of pioneering case studies using climate predictions to inform LMR decisions. The success of these case studies suggests that many additional applications are possible. Progress, however, is limited by observational and modeling challenges. Priority developments include strengthening of the mechanistic linkages between climate and marine resource responses, development of LMR models able to explicitly represent such responses, integration of climate driven LMR dynamics in the multi-driver context within which marine resources exist, and improved prediction of ecosystem relevant variables at the fine regional scales at which most marine resource decisions are made. While there are fundamental limits to predictability, continued advances in these areas have considerable potential to make LMR managers and industry decision more resilient to climate variability and help sustain valuable resources. Concerted dialog between scientists, LMR managers and industry is essential to realizing this potential.

## Section IV: Water Resource Management

Arnal, L., Cloke, H. L., Stephens, E., Wetterhall, F., Prudhomme, C., Neumann, J., Krzeminski, B., Pappenberger, F. (2018). Skilful seasonal forecasts of streamflow over Europe? Hydrology and Earth System Sciences, 22(4). https://doi.org/10.5194/hess-22-2057-2018

This paper considers whether there is any added value in using seasonal climate forecasts instead of historical meteorological observations for forecasting streamflow on seasonal timescales over Europe. A Europe-wide analysis of the skill of the newly operational EFAS (European Flood Awareness System) seasonal streamflow forecasts (produced by forcing the Lisflood model with the ECMWF System 4 seasonal climate forecasts), benchmarked against the ensemble streamflow prediction (ESP) forecasting approach (produced by forcing the Lisflood model with historical meteorological observations), is undertaken. The results suggest that, on average, the System 4 seasonal climate forecasts improve the streamflow predictability over historical meteorological observations for the first month of lead time only (in terms of hindcast accuracy, sharpness and overall performance). However, the predictability varies in space and time and is greater in winter

and autumn. Parts of Europe additionally exhibit a longer predictability, up to 7 months of lead time,for certain months within a season. In terms of hindcast reliability, the EFAS seasonal streamflow hindcasts are on average less skilful than the ESP for all lead times. The results also highlight the potential usefulness of the EFAS seasonal streamflow forecasts for decision-making (measured in terms of the hindcast discrimination for the lower and upper terciles of the simulated streamflow). Although the ESP is the most potentially useful forecasting approach in Europe, the EFAS seasonal streamflow forecasts appear more potentially useful than the ESP in some regions and for certain seasons, especially in winter for almost 40% of Europe. Patterns in the EFAS seasonal streamflow hindcast skill are however not mirrored in the System 4 seasonal climate hindcasts, hinting at the need for a better understanding of the link between hydrological and meteorological variables on seasonal timescales, with the aim of improving climate-model-based seasonal streamflow forecasting.

Jamal, A., Linker, R., & Housh, M. (2018). Comparison of Various Stochastic Approaches for Irrigation Scheduling Using Seasonal Climate Forecasts. Journal of Water Resources Planning and Management, 144(7). https://doi.org/10.1061/(asce)wr.1943-5452.0000951

This paper presents a modeling framework for real-time decision support for irrigation scheduling using probabilistic seasonal weather forecasts which are incorporated into simulation-optimization framework. The simulation of the field processes is performed by the Soil Water Atmosphere Plant (SWAP) model, whereas the optimization is performed by three different stochastic programming methods: implicit approach, explicit single-stage approach and explicit two-stage approach. To evaluate the benefit of the probabilistic forecasts, the irrigation schedules from the different stochastic methods are compared with the best benchmark of perfect forecasts as well as with the real field and the Agriculture Extension Service of Israel schedules. The analysis is performed on a real case study of irrigated chickpeas field in Kibbutz Hazorea, Northern Israel. The results show that incorporating stochastic weather forecasts could lead to substantial improvements compared with current irrigation practices.

Meissner, D., Klein, B., & Ionita, M. (2017). Development of a monthly to seasonal forecast framework tailored to inland waterway transport in central Europe. Hydrology and Earth System Sciences, 21(12), 6401-6423. https://doi.org/10.5194/hess-21-6401-2017

Traditionally, navigation-related forecasts in central Europe cover short-to medium-range lead times linked to the travel times of vessels to pass the main waterway bottlenecks leaving the loading ports. Without doubt, this aspect is still essential for navigational users, but in light of the growing political intention to use the free capacity of the inland waterway transport in Europe, additional lead time supporting strategic decisions is more and more in demand. However, no such predictions offering extended lead times of several weeks up to several months currently exist for considerable parts of the European waterway network. This paper describes the set-up of a monthly to seasonal forecasting system for the German stretches of the international waterways of the Rhine, Danube and Elbe rivers. Besides focusing on improving the forecast methodology, especially by combining the individual approaches, the focus is on developing useful forecast products on monthly to seasonal timescales for waterway transport and to operationalize the related forecasting service.

Shamir, E. (2017). The value and skill of seasonal forecasts for water resources management in the Upper Santa Cruz River basin, southern Arizona. Journal of Arid Environments, 137, 35-45. https://doi.org/10.1016/j.jaridenv.2016.10.011

The potential for adaptive water resources management based on seasonal forecasts in the arid Upper Santa Cruz River, southern Arizona was examined. We demonstrated that seasonal forecasts can be used to optimize water resources management and increase supply. Using El Nino Southern Oscillation (ENSO) to forecast the wet seasons (winter and summer) can provide information during extreme ENSO. We found that ENSO is a better indicator for dryer than normal winters during La Nina and dryer than normal summers during El Nino. As in indicator of wetter than normal seasons (i.e. El Nino and La Nina in the winter and summer, respectively) ENSO is often not a consistent predictor and moreover, on several occasions the wetter than normal rainfall did not yield above normal seasonal flows. We also examined the seasonal precipitation forecasts for the region from the Climate Forecast System (CFS). The CFS showed reasonable predictive skill for the winter that extends up to four months lead-time. The only CFS skill for forecasting summer rainfall was observed for predicting above normal rainfall in July with one-month lead-time. Seasonal forecasts can substantially improve water resources management but currently requires considerations of large uncertainties in the operationally available forecasts.

Viel, C., Beaulant, A. L., Soubeyroux, J. M., & Ceron, J. P. (2016). How seasonal forecast could help a decision maker: an example of climate service for water resource management. Advances in Science and Research, 13, 51-55. https://doi.org/10.5194/asr-13-51-2016

The FP7 project EUPORIAS was a great opportunity for the climate community to co-design with stakeholders some original and innovative climate services at seasonal time scales. In this framework, Meteo-France proposed a prototype that aimed to provide to water resource managers some tailored information to better anticipate the coming season. It is based on a forecasting system, built on a refined hydrological suite, forced by a coupled seasonal forecast model. It particularly delivers probabilistic river flow prediction on river basins all over the French territory. This paper presents the work we have done with "EPTB Seine Grands Lacs" (EPTB SGL), an institutional stakeholder in charge of the management of 4 great reservoirs on the upper Seine Basin. First, we present the co-design phase, which means the translation of classical climate outputs into several indices, relevant to influence the stakeholder's decision making process (DMP). And second, we detail the evaluation of the impact of the forecast on the DMP. This evaluation is based on an experiment realised in collaboration with the stakeholder. Concretely EPTB SGL has replayed some past decisions, in three different contexts: without any forecast, with a forecast A and with a forecast B. One of forecast A and B really contained seasonal forecast, the other only contained random forecasts taken from past climate. This placebo experiment, realised in a blind test, allowed us to calculate promising skill scores of the DMP based on seasonal forecast in comparison to a classical approach based on climatology, and to EPTG SGL current practice.

## Section V: Health and Safety

Ardilouze, C., Batte, L., & Deque, M. (2017). Subseasonal-to-seasonal (S2S) forecasts with CNRM-CM: a case study on the July 2015 West-European heat wave. *Advances in Science and Research, 10*, 115-121. https://doi.org/10.5194/asr-14-115-2017

An intense heat wave struck West Europe in early July 2015. The degree of anticipation of that event is assessed through the new CNRM near-real time subseasonal to seasonal forecast system. A warm anomaly over France was detected for the first week of July in all the successive forecasts issued in June, even up to one month ahead. On the other hand, the positive 500 hPa geopotential anomaly observed during that period was little anticipated. Despite the limited skill of the forecast system beyond twelve days, the relatively successful anticipation of that event pleads for a predictability study based on a multi-system assessment.

Batte, L., Ardilouze, C., & Deque, M. (2018). Forecasting West African Heat Waves at Subseasonal and Seasonal Time Scales. *Monthly Weather Review, 146*(3), 889-907. https://doi.org/10.1175/mwr-d-17-0211.1

Early indication of an increased risk of extremely warm conditions could help alleviate some of the consequences of severe heat waves on human health. This study focuses on boreal spring heat wave events over West Africa and the Sahel and examines the long-range predictability and forecast quality of these events with two coupled forecasting systems designed at Meteo-France, both based on the CNRM-CM coupled global climate model: the operational seasonal forecasting System 5 and the experimental contribution to the World Weather Research Programme/World Climate Research Programme (WWRP/WCRP) subseasonal-to-seasonal (S2S) project. Evaluation is based on past reforecasts spanning 22 years, from 1993 to 2014, compared to reference data from reanalyses. On the seasonal time scale, skill in reproducing interannual anomalies of heat wave duration is limited at a gridpoint level but is significant for regional averages. Subseasonal predictability of daily humidity-corrected apparent temperature drops sharply beyond the deterministic range. In addition to reforecast skill measures, the analysis of real-time forecasts for 2016, both in terms of anomalies with respect to the reforecast climatology and using a weather-type approach, provides additional insight on the systems' performance in giving relevant information on the possible occurrence of such events.

Hudson, D., Marshall, A. G., Alves, O., Young, G., Jones, D., & Watkins, A. (2015). Forewarned is Forearmed: Extended-Range Forecast Guidance of Recent Extreme Heat Events in Australia. *Weather and Forecasting, 31*(3), 697-711. https://doi.org/10.1175/WAF-D-15-0079.1

There has been increasing demand in Australia for extended-range forecasts of extreme heat events. An assessment is made of the subseasonal experimental guidance provided by the Bureau of Meteorology's seasonal prediction system, Predictive Ocean Atmosphere Model for Australia (POAMA, version 2), for the three most extreme heat events over Australia in 2013, which occurred in January, March, and September. The impacts of these events included devastating bushfires and damage to crops. The outlooks performed well for January and September, with forecasts indicating increased odds of top-decile maximum temperature over most affected areas at least one week in advance for the fortnightly averaged periods at the start of the heat waves and for forecasts of the months of January and September. The March event was more localized, affecting southern Australia. Although the anomalously high sea surface temperature around southern Australia in March (a potential source of predictability) was correctly forecast, the forecast of high temperatures over the mainland was restricted to the coastline. September was associated with

strong forcing from some large-scale atmospheric climate drivers known to increase the chance of having more extreme temperatures over parts of Australia. POAMA-2 was able to forecast the sense of these drivers at least one week in advance, but their magnitude was weaker than observed. The reasonably good temperature forecasts for September are likely due to the model being able to forecast the important climate drivers and their teleconnection to Australian climate. This study adds to the growing evidence that there is significant potential to extend and augment traditional weather forecast guidance for extreme events to include longer-lead probabilistic information.

Lazenby, M. J., Landman, W. A., Garland, R. M., & DeWitt, D. G. (2014). Seasonal temperature prediction skill over Southern Africa and human health. *Meteorological Applications, 21*(4), 963-974. https://doi.org/10.1002/met.1449

An assessment of probabilistic prediction skill of seasonal temperature extremes over Southern Africa is presented. Verification results are presented for six run-on seasons; September to November, October to December, November to January, December to February, January to March, and February to April over a 15-year retroactive period. Comparisons are drawn between downscaled seasonal 850hPa geopotential height field forecasts of a two-tiered system versus downscaled height forecasts from a coupled ocean-atmosphere system. The ECHAM4.5 atmospheric general circulation model (GCM) is used for both systems; in the one-tiered system the ECHAM4.5 is directly coupled to the ocean model Modular Ocean Model version three (MOM3), and in the two-tiered system the ECHAM4.5 is coupled with Van den Dool sea surface temperature (SST) hindcasts. Model output statistical equations are developed using canonical correlation analysis (CCA) to reduce system deficiencies. Probabilistic verification is conducted using the relative operating characteristic (ROC) and reliability diagram. The coupled model performs best in capturing seasonal maximum temperature extremes. Seasons demonstrating the highest ROC scores coincide with the period of highest seasonal temperatures found over Southern Africa. The above-normal category of the one-tiered system indicates the highest skill in predicting maximum temperature extremes, implying the coupled model predicts skilfully when there is a high likelihood of experiencing extremely high seasonal maximum temperatures during mid to late summer. The downscaled coupled maximum temperature hindcasts are evaluated additionally in terms of their monetary value and quality to the general public. The seasonal forecast system presented in this study should be able to reduce risks in decision making by the health industry in Southern Africa.

Lowe, R., Garcia-Diez, M., Ballester, J., Creswick, J., Robine, J. M., Herrmann, F. R., & Rodo, X. (2016). Evaluation of an Early-Warning System for Heat Wave-Related Mortality in Europe: Implications for Sub-seasonal to Seasonal Forecasting and Climate Services. *International Journal of Environmental Research and Public Health, 13*(2). https://doi.org/10.3390/ijerph13020206

Heat waves have been responsible for more fatalities in Europe over the past decades than any other extreme weather event. However, temperature-related illnesses and deaths are largely preventable. Reliable sub-seasonal-to-seasonal (S2S) climate forecasts of extreme temperatures could allow for better short-to-medium-term resource management within heat-health action plans, to protect vulnerable populations and ensure access to preventive measures well in advance. The objective of this study is to assess the extent to which S2S climate forecasts could be

incorporated into heat-health action plans, to support timely public health decision-making ahead of imminent heat wave events in Europe. Forecasts of apparent temperature at different lead times (e.g., 1 day, 4 days, 8 days, up to 3 months) were used in a mortality model to produce probabilistic mortality forecasts up to several months ahead of the 2003 heat wave event in Europe. Results were compared to mortality predictions, inferred using observed apparent temperature data in the mortality model. In general, we found a decreasing transition in skill between excellent predictions when using observed temperature, to predictions with no skill when using forecast temperature with lead times greater than one week. However, even at lead-times up to three months, there were some regions in Spain and the United Kingdom where excess mortality was detected with some certainty. This suggests that in some areas of Europe, there is potential for S2S climate forecasts to be incorporated in localized heat–health action plans. In general, these results show that the performance of this climate service framework is not limited by the mortality model itself, but rather by the predictability of the climate variables, at S2S time scales, over Europe.

McGregor, G. (2015). Climatology in support of climate risk management: A progress report. *Progress in Physical Geography: Earth and Environment, 39*(4), 536-553. https://doi.org/10.1177/0309133315578941

Climate risk management has emerged over the last decade as a distinct area of activity within the wider field of climatology. Its focus is on integrating climate and non-climate information in order to enhance the decision-making process in a wide range of climate-sensitive sectors of society, the economy and the environment. Given the burgeoning pure and applied climate science literature that addresses a range of climate risks, the purpose of this progress report is to provide an overview of recent developments in the field of climatology that may contribute to the risk assessment component of climate risk management. Data rescue and climate database construction, hurricanes and droughts as examples of extreme climate events and seasonal climate forecasting are focused on in this report and are privileged over other topics because of either their fundamental importance for establishing event probability or scale of societal impact. The review of the literature finds that historical data rescue, climate reconstruction and the compilation of climate data bases has assisted immensely in understanding past climate events and increasing the information base for managing climate risk. Advances in the scientific understanding of the causes and the characterization of hurricanes and droughts stand to benefit the management of these two extreme events while work focused on unravelling the nature of ocean–atmosphere interactions and associated climate anomalies at the seasonal timescale has provided the basis for the possible seasonal forecasting of a range of climate events. The report also acknowledges that despite the potential of climate information to assist with managing climate risk, its uptake by decision makers should not be automatically assumed by the climatological community.

White, C. J., Franks, S. W., & McEvoy, D. (2015). Using subseasonal-to-seasonal (S2S) extreme rainfall forecasts for extended-range flood prediction in Australia. In M. Rogger, H. Aksoy, M. Kooy, A. Schumann, E. Toth, Y. Chen, V. B. Estupina, & G. Bloschl (Eds.), *Changes in Flood Risk and Perception in Catchments and Cities* (Vol. 370, pp. 229-234). https://doi.org/10.5194/piahs-370-229-2015

Meteorological and hydrological centres around the world are looking at ways to improve their capacity to be able to produce and deliver skillful and reliable forecasts of high-impact extreme rainfall and flooding events on a range of prediction timescales (e.g. sub-daily, daily, multi-week, seasonal). Making improvements to extended-range rainfall and flood forecast models, assessing

forecast skill and uncertainty, and exploring how to apply flood forecasts and communicate their benefits to decision-makers are significant challenges facing the forecasting and water resources management communities. This paper presents some of the latest science and initiatives from Australia on the development, application and communication of extreme rainfall and flood forecasts on the extended-range "subseasonal-to-seasonal" (S2S) forecasting timescale, with a focus on risk-based decision-making, increasing flood risk awareness and preparedness, capturing uncertainty, understanding human responses to flood forecasts and warnings, and the growing adoption of "climate services". The paper also demonstrates how forecasts of flood events across a range of prediction timescales could be beneficial to a range of sectors and society, most notably for disaster risk reduction (DRR) activities, emergency management and response, and strengthening community resilience. Extended-range S2S extreme flood forecasts, if presented as easily accessible, timely and relevant information are a valuable resource to help society better prepare for, and subsequently cope with, extreme flood events.