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Exploring the landscape of seasonal forecast provision by Global Producing Centres

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Abstract
Despite the growing demand for seasonal climate forecasts, there is limited understanding of the landscape of organisations providing this critically important climate information. This study attempts to fill this gap by presenting results from an in-depth dialogue with the organisations entrusted with the provision of seasonal forecasts by the World Meteorological Organisation, known as the Global Producing Centres for Long-Range Forecasts (GPCs-LRF). The results provide an overview and detailed description of the organisational setup, mandate, target audience of GPCs-LRF and their interactions with other centres. Looking beyond the GPCs-LRF to other centres providing seasonal forecasts, some of which have been rapidly taking prominent places in this landscape, revealed a heterogeneous and still maturing community of practice, with an increasing number of players and emerging efforts to produce multi-model ensemble forecasts. The dialogues pointed at the need to not only improve climate models and produce more skilful climate forecasts, but also to improve the transformation of the forecasts into useful and usable products. Finally, using the lenses of credibility, salience and legitimacy, we explore ways to bridge the fragmentation of the information offered across the organisations considered and the people involved in the delivery and use of seasonal forecasts. The paper concludes by suggesting ways to address the boundary crossing between science, policy and society in the context of seasonal climate prediction.

Keywords GPC · Long-range forecast · Best practices · Science-policy-society

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1 Introduction

Long-range forecasts (LRFs), more commonly known as seasonal forecasts, are fundamental pieces of climate information. These forecasts predict monthly and seasonal anomalies or deviations from the expected climatological conditions, rather than providing specific information on the daily weather patterns over those periods of time (Doblas-Reyes et al. 2013). Seasonal forecasts can be an important element for strengthening resilience as they permit anticipating risks within timeframes common for decision making (Bruno Soares et al. 2018; Hewitt et al. 2020). By informing and improving decision-making processes, seasonal forecasts bring value and advantages to weather-dependent sectors. Thus, the demand and use of seasonal forecasts have been increasing in sectors such as agriculture, health, energy, transport, tourism, or water and land management (Palin et al. 2016; Bruno Soares 2017; Lowe et al. 2017; Haines 2019; Lledó et al. 2019; Gerlak et al. 2020; Köberl et al. 2021).

The World Meteorological Organisation (WMO) has established different frameworks for monitoring and predicting the state of the atmosphere. Amongst these, the Global Data-processing and Forecasting System (GDPFS) has a central role in providing standardised weather and climate products and services globally (WMO 2019a). The GDPFS is a complex system involving a number of organisations with diverse mandates and functions. As part of this system, WMO has designated 14 centres that provide global seasonal forecasts on a monthly basis, known as the Global Producing Centres for LRFs (GPCs-LRF). After the first GPCs-LRF were designated in 2006, the Lead Centre for LRF Multi-Model Ensemble (LC-LRFMME) was established a few years later to support the GPC-LRF operations, and collect and display single-model and multi-model ensemble (MME) seasonal forecasts in a single platform (Graham et al. 2011). This global network of centres provides seasonal products and services to all WMO members and other organisations.

The requirements for a centre to be designated as a GPC-LRF and the functions it is expected to perform, such as providing forecasts for specific variables and forecast times, are described in WMO's GDPFS manual (WMO 2019a) and dedicated WMO webpages.[1]An effort to improve the clarity of this complex infrastructure, produced in parallel to the preparation of this paper, is the Guidance on Operational Practices for Objective Seasonal Forecasting (WMO 2020).

The WMO infrastructure for seasonal forecasts, its operational standards and purpose, along with recommendations for improvement of this framework, were first described by Graham et al. (2011). Besides, research conducted as part of the European SPECS project investigated the presentation and visualisation of seasonal forecasts provided by different GPCs-LRF, with the aim to identify and recommend ways to improve the communication, and users' understanding and interpretation of these products (Davis et al. 2016). However, to date, only a limited number of studies have discussed this framework as part of the existing seasonal forecast capabilities (Stockdale et al. 2010; Rapp et al. 2011; Kryjov 2012; Kushnir et al. 2019), whilst others assessed the MME forecasts issued by the LC-LRFMME (Kim et al. 2020). Earlier work evaluating the seasonal forecasts provided by some GPCs-LRF found that the communication and visualisation of forecasts differ at each centre (Davis et al. 2016). However, there is limited research assessing the varying quality of climate information offered in websites in terms of visualisation and accessibility, or

[1] https://public.wmo.int/en/programmes/global-data-processing-and-forecasting-system

assessing the often complicated and diverse user interfaces employed in the online provision of seasonal forecasts (Hewitson et al. 2017; Padilla et al. 2021). Concerns on how publicly accessible climate information is communicated were also expressed by Robbins et al. (2019), who highlighted that many seasonal forecasts remain under-utilised, primarily because this knowledge is poorly communicated.

To the best of our knowledge, an in-depth analysis emerging from dialogue with GPCs-LRF and the LC-LRFMME has not been previously conducted to thoroughly address how these centres operate, their interactions with other seasonal forecast providers, their target audience and what information is available to specific users or freely accessible by the general public. This gap in the literature might stem from the poor understanding and awareness of this network beyond the actors directly involved. The present study attempts to fill this gap and shed a light on this complex network of organisations providing seasonal forecasts, not only focusing on the established WMO framework, but also by exploring the wider picture of seasonal forecast providers. Thus, the study looks beyond the GPCs-LRF and explores the increasingly global role of Copernicus Climate Change Service (C3S) and other institutions providing seasonal forecasts to the wider public. By delivering clarity regarding the organisational architecture of seasonal forecast provision, the paper unpacks and discusses some enablers of the effective and efficient provision of this critical climate information for strengthening resilience and managing climate risks from the perspectives of credibility, salience and legitimacy (Cash et al. 2002) of the actors and information provided.

2 Methodology

To obtain a better understanding of the GPC-LRF network for seasonal forecast provision, we conducted in-depth interviews with the 14 GPCs-LRF, the LC-LRFMME and other key institutions providing seasonal forecasts (Table 1). Semi-structured interviews in the form of 1-h video calls were set up with one or more representatives from each centre or institution. In addition, WMO representatives responsible for the GPC activities participated in an interview to provide their insights into the organisation, mission and ambitions of this framework. The interviews were conducted by science communication and social science specialists, mainly using the online software platform Zoom.[2]

An interview guide with a list of questions was prepared to direct interviews with the GPCs-LRF (provided in the Supplementary Material). The questions were clustered into three sections, focusing on the specific centre/institution, their seasonal forecast products and finally their challenges and ambitions. First, the interviewees were questioned on their centre and operations, the motivation of their centre in becoming a GPC-LRF, their mandate as a GPC-LRF (key duties and responsibilities), the perceived target audience of their forecasts and interactions with other institutions and the LC-LRFMME. The second part of the interview discussed the seasonal forecasts presented on the centre's website, including the variables shown, the forecast visualisation, whether they were provided with certain visualisation criteria by WMO and if all data are openly accessible, only available to specific users or tailored to certain sectors upon request. Finally, the interviewees were questioned on the challenges (technical or operational) faced when providing seasonal

[2] www.zoom.us

Table 1 GPCs-LRF and other seasonal forecast providers interviewed in this study

No	Interviewee	Full name(s) of centres	Location (WMO region)	Website[a]
1	GPC Beijing	China Meteorological Administration (CMA), Beijing Climate Center (BCC)	Beijing, China (Region II)	bcc.ncc-cma.net/
2	GPC CPTEC (Brazil)	Center for Weather Forecast and Climate Studies (CPTEC), National Institute for Space Research (INPE)	Cachoeira Paulista, Brazil (Region III)	clima1.cptec.inpe.br/gpc/pt
3	GPC ECMWF	European Centre for Medium-Range Weather Forecasts	Reading, UK (Region VI)	www.ecmwf.in
4	GPC Exeter	Met Office	Exeter, UK (Region VI)	www.metoffice.gov.uk/research/climate/seasonal-to-decadal/gpc-outlooks
5	GPC Melbourne	Bureau of Meteorology (BOM)	Melbourne, Australia (Region V)	http://www.bom.gov.au/climate/ahead/
6	GPC Montreal	Meteorological Service of Canada (MSC)	Montreal, Canada (Region IV)	weather.gc.ca/saisons
7	GPC Moscow	North EurAsia Climate Centre (NEACC)	Moscow, Russia (Regions II and VI)	neacc.meteoinfo.ru/
8	GPC Offenbach	Deutscher Wetterdienst (DWD)—German Meteorological Service	Offenbach, Germany (Region VI)	www.dwd.de/seasonalforecasts
9	GPC Pretoria	South African Weather Services (SAWS)	Pretoria, South Africa (Region I)	https://www.weathersa.co.za/home/longrangeforecast
10	GPC Seoul	Korea Meteorological Administration (KMA)	Seoul, South Korea (Region II)	https://web.kma.go.kr/eng/index.jsp
11	GPC Tokyo	Japan Meteorological Agency (JMA), Tokyo Climate Centre (TCC)	Tokyo, Japan (Region II)	http://ds.data.jma.go.jp/tcc/tcc/products/model/index.html
12	GPC Toulouse	Météo-France	Toulouse, France (Region VI)	seasonal.meteo.fr
13	GPC Washington	Climate Prediction Center (CPC), National Oceanic and Atmospheric Administration (NOAA)	WA, USA (Region IV)	www.cpc.ncep.noaa.gov/
14	CMCC (GPC applicant)	Euro-Mediterranean Centre on Climate Change	Italy (Region VI)	www.cmcc.it/

Table 1 (continued)

No	Interviewee	Full name(s) of centres	Location (WMO region)	Website[a]
15	WMO Lead Center for Long-Range Forecast Multi-Model Ensemble (LC-LRFMME)	Jointly coordinated by KMA (GPC Seoul) and CPC/NOAA (GPC Washington)	South Korea and USA	www.wmolc.org/
16	IRI	International Research Institute for Climate and Society	USA	iri.columbia.edu/
17	APCC	Asia–Pacific Economic Cooperation (APEC) Climate Center	South Korea	https://www.apcc21.org/
18	BSC	Barcelona Supercomputing Center	Spain	www.bsc.es
19	C3S	Copernicus Climate Change Service	Europe	climate.copernicus.eu
20	WMO	World Meteorological Organisation	Global	public.wmo.int

[a]Website links were correct at the time of publication. The WMO Regions are defined as follows: I—Africa; II—Asia; III—South America; IV— North America, Central America and the Caribbean; V—South-west Pacific; VI—Europe. GPC: Global Producing Centre; WMO: World Meteorological Organisation

forecasts, plans for improvement of their products or website, their ambitions for the future and the availability of any financial or technical support for their activities. The interview guide facilitated an in-depth discussion, as the questions were open-ended and the wording used was aimed at soliciting details from the interviewees. This semi-structured type of qualitative interview thus allowed for followed-up comments to each question, sometimes prompting further questions, broadening the topics that were initially listed in the interview guide (Newing 2011).

As GPC Seoul and GPC Washington jointly coordinate the LC-LRFMME, the interviews with these GPCs-LRF included some additional questions exploring this role. In addition, at the time of conducting the interviews, CMCC was a prospective GPC-LRF officially assigned in September 2021; hence, some questions (e.g. GPC mandate) were skipped in their interview.

Interviews with the centres and other institutions that are not part of the GPC-LRF network (IRI, APCC, BSC, C3S and WMO) also had a semi-structured format. However, a tailored interview guide was prepared before each interview. Despite minor differences, the questions covered the same topics as the GPC-LRF interviews in an attempt to learn more about the institution and its seasonal forecasting activities, the seasonal forecast products, and perceived challenges and ambitions related to seasonal forecasting (as an example, the IRI interview guide is provided in the Supplementary Material).

The qualitative analysis software MAXQDA was used to analyse the transcripts of the recorded interviews (Kuckartz and Radiker 2019). We applied the coding technique to label and organise the information in the interviews, and identify different themes (Gibbs 2007). Labelling was conducted by systematically marking sections of the interview transcripts with a different "code" (e.g. "demand for LFR" or "LRF products"). Codes were created for each emerging theme, and the list of codes was expanded as we advanced through the documents, until there were no more new themes. This indexing of the data facilitated easily searching for a particular code through all the documents and extracting all the material that concerned a particular theme (Newing 2011). Some codes naturally came from questions predefined in the interview guide (e.g. "GPC mandate" or "challenges"), whilst others emerged from the discussions (e.g. "sharing experience" or "open climate data"). Points and comments that were recurring in several interviews (i.e. marked with the same code) were summarised into general findings. Less frequently mentioned themes (i.e. the related code appeared only in one or few interviews) are presented in the results as individual inputs if they brought particular new or alternative insights. Most findings presented in the next sections are supported by quotes taken from the interviews.

3 WMO architecture for seasonal forecast production

Within the GDPFS, established by WMO, GPCs-LRF form a network of centres responsible for seasonal forecast provision. Most of the GPCs-LRF also function as National Meteorological and Hydrological Services (NMHSs) and typically have more than one designation within the GDPFS mechanism, e.g. Regional Climate Centres (RCCs).

The WMO manual on GDPFS (WMO 2019a) is the single source of technical regulations for all meteorological centres designated by WMO. Its function is to ensure the consistency and standardisation of the data, information and production practices of centres. The manual lists a number of requirements that centres must fulfil in terms of the products (e.g. the minimum variables to display) and activities provided (e.g. presenting the forecasts on a website). However, the manual does not discuss any procedures in place to ensure that these standards are met in the long run to maintain the forecast quality, and does not specify any visualisation requirements that centres must meet. In addition, the GPC-LRF network can be unclear for those unfamiliar with the GDPFS mechanism. Nevertheless, a recently published WMO report (2020) is a positive undertaking towards increasing the transparency of the WMO architecture for seasonal forecasts.

This section provides a detailed description of the architecture of seasonal forecast provision by GPCs-LRF, based on background information from the literature and findings from the interviews conducted in our study. Whilst the results are presented anonymously, direct quotes from interview participants are clearly indicated.

3.1 Global Producing Centres for Long-Range Forecasts and the Lead Centre

3.1.1 A network of seasonal forecast producers

In the last decades, the number of institutions producing and providing seasonal forecasts and the use of this type of climate information have been increasing. This served as motivation to establish a network of accredited centres that regularly provide global predictions for seasonal timescales. Since 2006, WMO has designated a total of 14 GPCs-LRF across the globe (Beijing, CMCC, CPTEC Brazil, ECMWF, Exeter, Melbourne, Montreal, Moscow, Offenbach, Pretoria, Seoul, Tokyo, Toulouse and Washington), with the task of producing global seasonal forecasts that are available to all WMO member states (Table 1).

GPCs-LRF develop and run their own climate models, producing global seasonal forecasts in the form of data and graphical products according to the mandatory requirements set in the GDPFS manual (WMO 2019a). The minimum requirements that must be fulfilled include producing ensemble forecasts for 2-m (surface) temperature, total precipitation and sea surface temperature, with further recommended variables of 500-hPa height, 850-hPa temperature, 850-hPa wind and mean sea-level pressure. These forecasts must be issued monthly and have a global coverage and lead time of 0–4 months. Furthermore, GPCs-LRF are required to perform skill assessments, according to the standard verification measures defined in the GDPFS manual, and present the forecast products on a dedicated webpage.

Within the GDPFS framework, the LC-LRFMME was also designated to support the GPC-LRF activities and widely disseminate the forecasts produced by GPCs-LRF, ensuring a consistent and uniform visualisation of the results. The LC-LRFMME's responsibilities include collecting the global seasonal forecasts from all GPCs-LRF, presenting them in a common format and developing MME forecasts. Whilst each GPC-LRF is responsible for the verification of its produced forecasts, the LC-LRFMME is responsible for the standardised verification of the forecast systems, and for maintaining an archive of the GPC-LRF and MME forecasts. The forecast products displayed on the LC-LRFMME website include monthly and seasonal mean anomalies from individual GPCs-LRF, and a range of deterministic and probabilistic MME forecasts produced using different methods (e.g. regular multiple regression).

3.1.2 Interview results: insights into the centres' role

Most centres mentioned that they had already been producing seasonal forecasts for several years prior to their GPC-LRF designation, thus becoming a GPC-LRF "was not a big step, […] but the driving motivation was putting together data to improve forecasts" (GPC-LRF interviewee). Another important motivation for organisations to become GPCs-LRF was the possibility to be part of a wider community, the GPC-LRF network. Being part of this network was seen by some participants as an accreditation for following good practices and an opportunity to increase the visibility of their organisation. Some participants argued that the WMO affiliation also helped them establish regional collaborations, since their activities and products are often centred on their corresponding region despite offering global forecasts.

The central role of LC-LRFMME within this network was evidenced from the interviews. By providing all the forecasts in a uniform way on its website, the LC-LRFMME provides centralised access to forecast products that allows for easy comparison of the forecasts. Some interviewees considered that "there's not a strong drive to actually produce better graphics and improve [their] own web output", and that the role of the LC-LRFMME is "a good alternative for having a standardisation, and that's the main purpose of the Lead Centre: to collect all the data and put all the information out in the same format" (GPC-LRF interviewee). By contrast, other centres endeavoured to improve the interface and visualisation of these forecasts based on user feedback, as they saw the need to also provide this information directly to their users, rather than only through the LC-LRFMME route. This appears to be highly dependent on the individual centre's requirements and perception of their users' needs.

The interviewees specified that GPCs-LRF have a formal monthly interaction with the LC-LRFMME, although in many cases this is an automated job of data transfer. When it comes to interactions between GPCs-LRF, some formal channels are established, such as through WMO's Expert Team on Operational Climate Prediction Systems, although one interviewee suggested that collaboration "is more based on personal initiative and contacts". Other occasional collaborative opportunities include joint research projects involving various GPCs-LRF.

In brief, GPCs-LRF see this network as "an opportunity to collaborate with other institutions that work at the same level on developing seasonal forecasts and also opening up the data to WMO users" (GPC-LRF interviewee). The LC-LRFMME appears to act as a substitute for the lack of widely shared standards on the visualisation and presentation of seasonal forecasts.

3.2 Seasonal forecast products

When discussing the value of global seasonal forecasts, the interviewees suggested that users from different parts of the world have different interests in certain climate conditions depending on their region. A default regional interest thus emerges naturally in all GPCs-LRF, with some centres mentioning that they develop customised products for their region, considering regional needs or characteristic climatological phenomena (e.g. Asian summer monsoon). Some GPC-LRF representatives went further than this to suggest that they lacked the necessary knowledge and experience for providing forecast information to users in other regions, since this information is region-specific. Thus, information provided by RCCs and Regional Climate Outlook Forums (RCOFs) to their local region may be more useful or relevant in some cases. Many interviewees saw the tailoring and provision of information for users in other countries or regions as the responsibility of the corresponding NMHSs.

Even though seasonal forecast provision is fundamentally driven by the need to provide salient regional information, the interviewees highlighted their global value and pointed to a recently developed WMO product, namely the Global Seasonal Climate Update (GSCU).[3]The operational GSCU product was created through collaboration of a WMO task team, the LC-LRFMME, the GPCs-LRF and IRI (WMO 2020), and is available on the LC-LRFMME website.[4]It provides a summary of the current climate conditions and global forecasts for temperature, precipitation and other indices for the upcoming season, based on the MME forecast of LC-LRFMME. The report is sent to all the GPCs-LRF for their feedback before its monthly issue.

The regional and global aspects of seasonal forecasts are not necessarily seen as detached but rather as complementary by some interviewees. An interesting suggestion by an interviewee was to produce a global forecast for the rainy season onset. Although most of the users would be interested in the regional forecast, such a map could be used for global food emergency planning and security, amongst other purposes.

The conversation in the interviews further addressed the climate variables provided by the GPC-LRF forecasts, considering also variables other than those required by guidance. In this respect, a few participants emphasised the importance of focusing on variables that might optimise the skill. For example, large-scale atmospheric variables, such as geopotential height at 500 hPa, may provide a good indication of large-scale circulation patterns, which are generally associated with higher skill (Lledó et al. 2020); however, those are not necessarily the variables typically requested by users. There were suggestions by the interviewees for using these global circulation patterns as a proxy for the local precipitation and temperature. Indeed, some users downscale information on regional temperature and precipitation from the global circulation data (e.g. as suggested in Ramon et al. 2021). In addition, the issue of forecast quality has been central in scientific discussions and, hence, the forecast quality measures always accompany the GPC-LRF forecast maps.

The visual representation of the seasonal forecasts was also discussed in our interviews. Although guidelines for visual representation are not provided by WMO, some of the participants stated that visual standardisation could promote consistency within the GPC-LRF infrastructure. A suggestion was to follow the good practices applied by some centres, such as the visual communication approach of the Australian Bureau of Meteorology,[5]suggested by one participant as a good practice. On the other hand, other interview participants thought that any standardisation of the visual presentation would be difficult or unnecessary for a global product, since some aspects (e.g. how maps are centred) can vary depending on the region of origin of the key audience.

However, the visualisation and other aspects of these seasonal forecast products are not constant, but are continuously evolving and improving, according to the interviewees. GPCs-LRF are going through frequent redesign processes to improve their websites, visual representation of their products or their climate models. In some cases, product redesign is guided by user feedback, in an attempt to make these products more user-friendly. The available resources, and financial or technical support for making such improvements vary significantly from country to country, and depend mainly on national and institutional contributions, as revealed in the interviews. This means that, in some cases, GPCs-LRF can only focus on the most urgent needs when it comes to product or model improvements.

Finally, some participants had interesting perspectives about the future of seasonal forecast products. As stated by a GPC-LRF interviewee, “the future is true Web Map Service,

[3] https://public.wmo.int/en/our-mandate/climate/global-seasonal-climate-update

[4] https://wmolc.org/gscuBoard/list

[5] http://www.bom.gov.au/climate/outlooks/#/overview/summary

like GIS [geographic information system] data. So in a sense, we will probably move away from the graphical products and be more data providers […], providing data in a format that many apps on a cellphone or computer can easily display".

In brief, a climate information product has a broad meaning in the context of seasonal forecasts, from customised regional information to a global seasonal outlook. Similarly, the visual presentation of these products has been receiving different attention. We recognised an interesting tension between providing the mandatory variables, those that users indeed need and those that show high skill: "The idea is basically to construct products that are sensible and meet the needs of the users, but also have some skill" (GPC-LRF interviewee).

3.3 Audience and increasing demand for seasonal forecasts

3.3.1 Main audience

The main audience of the GPC-LRF products are NMHSs of the 187 WMO members in six regions, covering the entire globe. Besides NMHSs, GPCs-LRF provide information to their respective country's governmental authorities, for example, to the ministries of agriculture and energy, or to the environmental department. Often, the forecasts enable NMHSs to produce information about regional seasonal prospects. Other target audiences of the climate data and forecasts produced by the GPCs-LRF include RCCs, which are responsible for providing regional products (such as seasonal forecasts) to support regional and national climate activities and needs, although their mandate and role often overlap those of GPCs-LRF (Rapp et al. 2011; WMO 2011), and RCOFs, which are platforms bringing together climate experts and stakeholders.

3.3.2 Interview results: increasing demand from new audiences

When discussing the profile of their users, the interviewees identified specific sectors interested in seasonal forecasts, such as the water, energy (including power companies), transport and insurance sectors. Participants also reported their interaction with contingency planners and emergency responders. There is an evident link between the type of sectors engaged and the nature of climate emergency in certain regions or countries. For example, GPCs-LRF interact with water supply bodies and reservoir managers, or agricultural community experts and farmers' associations in regions that have recently suffered from droughts, such as South Africa. In the UK and other regions affected by European windstorms, seasonal forecasts can provide support to transportation planners during winter. Another example is the 2019–2020 bushfires in Australia, which led to a significant increase in requests for monthly and seasonal briefings, and tailoring of the services they provide, according to one interviewee. "I think the [2019–2020] fires were quite a game changer. If [users] came to the Bureau in the past, 10 years ago, and said: 'how can you help me?', we would probably just point them at the website, but we do a lot more now" (interviewee from GPC-LRF Melbourne). Besides, other governmental institutions and departments dealing with topics not typically connected with weather and climate issues (e.g. trade) have also shown an interest in global seasonal forecasts. As stated during several interviews, some GPCs-LRF are directly "called by [their national] government to participate in meetings for specific sectors" (GPC-LRF interviewee). We could not expect, however, the survey participants to always clearly distinguish their role as a GPC-LRF or NMHS.

Most GPCs-LRF have some interaction with the users of their forecasts through a support service, bulletins, newsletters or media briefings. Some centres also organise occasional training sessions. These trainings sometimes involve intermediaries, and as a GPC-LRF interviewee specified, they do not tend to train users directly, but rather provide training to advisers who then interact with users.

Some GPCs-LRF also collaborate with commercial users who purchase seasonal forecast products, such as airports or renewable energy companies. These collaborations often include training on the use of seasonal forecasts. However, some participants pointed out that the nature of the forecast is the limiting factor for its broader use, noticing a "mismatch between user expectations and what the seasonal forecast can provide. People might want to know when to have their party in the garden or something, […] on a particular day" (GPC-LRF interviewee), which is something that a seasonal forecast cannot provide with skill beyond what a naïve climatological estimate can do. Finally, whilst some participants stressed that they were continuously trying to reach more potential users, others pointed out limitations: "we also have limited resources, we can not consult every single user" (GPC-LRF interviewee).

In brief, although NMHSs present the key audience of the GPC-LRFs, most of the interviewees observed an increasing interest in seasonal forecasts and tailored information, particularly from sectors strongly dependent on climate, such as agriculture, water management and energy, but also from other sectors. However, managing the users' expectations was mentioned as an issue, as they can have high expectations on the accuracy, whilst the forecast skill may be too low to be considered useful: "forecasts with limited or modest skill can be only used with success by sophisticated users" (GPC-LRF interviewee).

3.4 Opportunities for interaction

3.4.1 Interaction through RCOFs

RCOFs serve as an important platform for providing seasonal forecasts. These forums bring together national, regional and international climate experts, policymakers and other stakeholders within a region to provide consensus-based, user-relevant climate predictions (Ogallo et al. 2008; WMO 2016). Since their launch in 1997, they have spread to 19 regions of the world (Gerlak et al. 2018). Prior to each meeting, the key participants (including GPCs-LRF, NMHSs, RCC and other regional/climate prediction centres) conduct the preparatory work to contribute to the provision of the seasonal outlook, aiming to reach a consensus on the message that is going to be provided for the next season for a specific region.

3.4.2 Interview results: more opportunities for interaction

Most of the interview participants recognised RCOFs as important venues for interaction amongst regional experts, such as staff members of meteorological services, but also for interactions between seasonal forecast providers and users. These regional events also provide an opportunity for collaboration between GPCs-LRF, since representatives of GPCs-LRF from other regions are sometimes invited, according to some interviewees. These events may host training sessions on the application of climate prediction products, providing added value to all participants and promoting learning. Often, RCOFs consult different sources of information and different models.

Another important opportunity for collaboration and face-to-face interaction for GPCs-LRF is the WMO Expert Team meetings, which take place every 2 years and where GPC-LRF representatives participate. These meetings discuss the work of the GPC-LRF network, the latest developments and challenges related to seasonal forecasts, applications from new GPC-LRF candidates and future activities.

In brief, the collaboration between GPCs-LRF has a strong regional character, with RCOFs and similar events providing an important opportunity for networking, joint learning, but also consensus-building for regional seasonal outlooks. A more global collaboration is achieved through the WMO Expert Team.

3.5 Identified challenges

One of the topics covered in the interviews was the key challenges related to the production and provision of seasonal forecasts. Most of the interviewees pointed at the forecast skill as the key issue: "It's really down to basic predictability, more than thinking about how we package the forecasts and how we get them out. If you have more skill, all those downstream aspects would improve." (GPC-LRF interviewee). The lack of skill issue was present when discussing individual climate model prediction, but it also seems to affect MME forecasts. The key challenges described in the interviews could be grouped under the following three topics:

(1) **Improving climate models and forecast provision.** Climate models are continuously improved to include a better representation of physical climate processes. Model improvements also involve increasing resolution, which would require increased computational power and data storage; however, many institutions face a lack of resources for these improvements. When it comes to forecast provision, there is an evident interest in the community for moving towards cloud computing solutions, which poses new challenges. Another challenge mentioned was the provision of seamless predictions consistently over multiple temporal scales. "I think it would generate a lot more interest just simply being able to provide information at all timescales" (GPC-LRF interviewee).

(2) **Producing more skilful ensemble forecasts.** The majority of the institutions interviewed expressed a strong interest in participating in MME forecasts. The provision of these forecasts by the LC-LRFMME was seen as an important motivation for some institutions to seek a GPC-LRF designation. However, producing MME forecasts requires certain consistencies in how the models are run; for example, the contributing models should have a common hindcast period. In addition, producing an MME requires coordination between the participating institutions. An earlier monthly distribution of the Lead Centre's MME forecast was suggested by some participants, but that would need to accommodate the operational schedule of the 14 GPCs-LRF. Furthermore, participating in multiple MME initiatives at the same time poses a further challenge for centres, since they are required to format their data according to the specifications of each initiative.

(3) **Providing useful and usable products**. Generating products that are useful and usable would require more substantive interaction between providers and users, as well as building local competencies. However, the provision of local data from global models

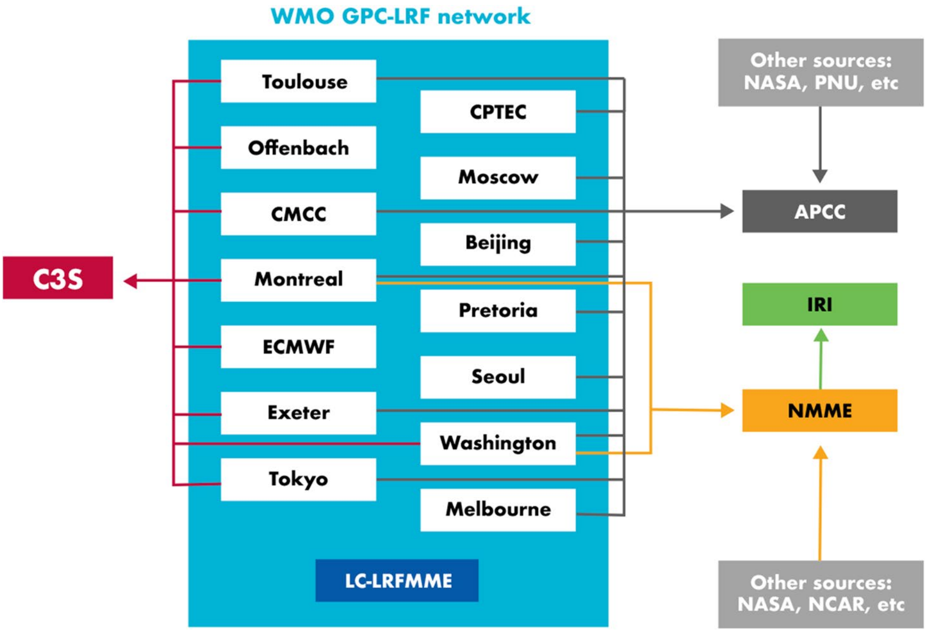

Fig. 1 Key providers of seasonal forecast included in our study and the interactions between them

is challenging, since precise information for the entire globe at the seasonal timescale using a single model is "scientifically not possible", as explained by a participant. "For each region, [the model] will have different behaviour; a model which works fine over Europe might not work fine over South America and vice versa" (GPC-LRF interviewee). Another challenge is developing sectoral applications, as this requires consideration and combination of different types of information to produce useful indicators and information for the sector. Some GPCs-LRF went a step forward, and their team includes experts who have direct conversations with various sectors and stakeholders. Finally, some participants suggested that, to build user capacity, the users need to be provided with sufficient data so that they can calculate their own forecast product. This would increase the independence of users, and hence enhance local capacities. Freeing climate data is a topic of an ongoing discussion and change within the seasonal forecasting community, as discussed in the next section.

In brief, insufficient forecast skill often appears as an inherent aspect of seasonal forecasting. Suggestions for moving the forecasting practice forward included blending timescales and providing seamless information in a single product, from several weeks to decades ahead. Finally, the interviewees recognised that providing usable seasonal forecasts requires closer interaction and a coproduction process with users.

4 The changing landscape of seasonal climate data provision

The organisational landscape for producing seasonal forecasts is formed by a wider set of institutions outside the WMO network of GPCs-LRF described in the present study, including some emerging players and networks. These institutions are committed to providing seasonal single-model or MME forecasts based on data obtained from the GPCs-LRF and other centres. Seasonal forecast providers interviewed and included in our analysis include APEC Climate Centre (APCC; Busan, South Korea), the Copernicus Climate Change Service (C3S) and International Research Institute for Climate and Society (IRI) at Columbia University (Palisades, NY, USA) (Fig. 1). In addition, further insights were provided by interviewing experts in seasonal forecast provision at the Barcelona Supercomputing Centre (Barcelona, Spain). The rest of this section presents results obtained from literature reviews, complemented with results from the interviews with the aforementioned institutions and GPCs-LRF.

Some of these seasonal forecast producers have a working mode similar to the LC-LRFMME in terms of providing seasonal MME forecasts. For example, APCC collects the seasonal forecast data from 14 forecasting centres (including GPCs-LRF) from 10 Asia–Pacific Economic Cooperation countries and provides an MME (Min et al. 2009). APCC's primary audience are NMHSs and governments of these countries.

C3S,[6] one of the six thematic services set up by the European Commission's Copernicus Programme, has been implemented by ECMWF to deliver information about the current and past state of the climate. C3S provides open access to seasonal forecasts on their website, with seven prediction systems from centres worldwide currently included, most of which also act as GPCs-LRF. In addition, they provide their own MME forecasts based on these systems. According to insights obtained during our interviews, C3S appears to have established a demanding and well-defined protocol for the production of seasonal forecasts and data it collects, as well as for data quality control. For instance, all contributors are required to use the same calibration period, that is, to run their models over the same hindcast period. In this manner, all C3S products are created in the same way and relative to the same baseline, making them directly comparable. C3S provides financial support to centres for allowing their seasonal prediction data to be freely accessed on the C3S infrastructure. "What we pay for is freeing that data to the public", as noted by a C3S representative. In some cases, the payment assures availability of a broader range of outputs than what those centres produce as GPCs-LRF. In addition, an advantage that some participants in the C3S MME have is the possibility to apply for funding to support developing their capabilities, and moving from research to operational mode.

In the case of IRI, the institution aims to generate new climate data, but also to provide their users with the best climate services, according to an interviewed representative. IRI is further interested in other aspects of information provision and acknowledges that "the best way to do that is to have local translators, transfers and users" (an interviewee from IRI). In addition, IRI provides different platforms, such as the Climate Predictability Tool,[7] and training to build local capacities for developing tailored regional forecasts in different parts of the world.

6 https://cds.climate.copernicus.eu/about-c3s

7 https://iri.columbia.edu/our-expertise/climate/tools/cpt/

Many GPCs-LRF confirmed sending their seasonal forecast data to some of these and other institutions, thus contributing to different MME forecasts. Other than the C3S and APCC MMEs, another widely mentioned MME was the North American MME (NMME), developed by the National Oceanic and Atmospheric Administration (NOAA, USA), which combines forecasts of coupled models from North American centres (Kirtman et al. 2014). Participation in the different MME approaches was acknowledged for increasing the visibility of seasonal forecast producers, according to several interviewees.

The main difference amongst these seasonal forecast provision players was noted to be the different target audience or users. Nevertheless, some interviewees saw an increasing overlap between the MME products of LC-LRFMME and other seasonal forecast providers, which may appear to function in parallel in some cases. Since the cost to produce an ensemble product is exceptionally high, an interviewee suggested developing a wider multi-model initiative, or “a global multi-model ensemble centre”, beyond the existing networks.

Some interviewees considered that the C3S MME and NMME have changed the landscape of forecast provision by bringing in the open-data policy, inspiring other institutions to consider moving towards this direction. Looking at the past, an important landmark for the international cooperation in meteorology and climatology was the adoption of WMO Resolution 40 in 1995 (Bautista Pérez 1996), which provided a distinction between essential and additional data, i.e. the data that had to be made public and the data for which the country could decide whether to make public, respectively. Seasonal forecasts pertain to the latter category. Hence, if a GPC-LRF comes from a country that has a data restriction policy, the public can only see the graphical presentation of forecasts on the LC-LRFMME website, whilst WMO members can also download the related digital climate data when the centre’s data policy allows it. Providing free data is not an easy decision, since selling data presents “one of the main income sources [for NMHSs] in certain countries. So, when we think of open data policy, for a developed country it may be welcome, but in some developing or underdeveloped countries, it’s going to be quite a challenge” (interviewee from WMO). It should be noted that a new WMO data policy (namely, the WMO Unified Data Policy Resolution) is currently under preparation, which is expected to cover some aspects of seasonal forecasts.[8]

In brief, the appearance of C3S and other initiatives that produce MMEs is changing the ecosystem of seasonal forecast provision. Being part of an MME was seen as an important ambition for most GPC-LRF interviewees. However, the interaction of seasonal data producers with this wider set of organisations is not uniform, and the practice of simultaneously participating in many different MME efforts does not seem sufficiently efficient. “The big thing now is to participate in all these exchanges… And most of the time these exchanges have different formats or files or different lists of variables. So this for us is a big burden” (GPC-LRF interviewee). With all the emerging players, the unequal availability of resources becomes even more tangible. However, the increasing number of players with free data policies stimulates the liberation of climate data. Still, “everybody is in favour of [open data], but in practice things are a bit more complicated” (GPC-LRF interviewee). The issue has been slowly transforming within the WMO member states, although WMO’s position remains that “the data sharing policy of a country or member has to be respected, this cannot be forced”.

[8] public.wmo.int/en/our-mandate/what-we-do/observations/Unified-WMO-Data-Policy-Resolution.

5 New demand, old architecture: towards standardising climate services

The results from the interviews conducted with key staff of the GPCs-LRF and other relevant institutions show that the landscape of seasonal forecast provision is continuously transforming. Nevertheless, there is substantive room for improvement, and a need for more transparent data provision processes, better management of the interactions across relevant institutions and enhancing the interactions with users. The increased demand for seasonal forecasts translates into a wider variety of users, with diverse needs (ranging from a need for just data to very elaborated and sophisticated services), expectations and capabilities to understand the underlying science. The utility of climate services is often determined by their demand-driven nature, which is again linked to the level of engagement, coproduction and evaluation by stakeholders (Findlater et al. 2021). Framing of climate services as a process, and not only a product, better corresponds to the demand-driven approach and could help better contextualise climate information, hence more easily inform and improve decisions (Findlater et al. 2021). The importance of interacting with users is clearly noted in WMO's 2021 State of Climate Services report (WMO 2021). Further research should explore the interactions between GPCs-LRF and users, in order to provide insights into how to advance the seasonal climate services process and improve decision making.

The interaction between the GPCs-LRF and the LC-LRFMME often involves an automated handling of data, which is efficient, but does not encourage regular direct interaction between centres. It has previously been argued that this supply-driven approach is more likely to improve climate data, but not necessarily to contribute to better informed decisions (Findlater et al. 2021). Direct interaction would allow for sharing knowledge, or identifying improvement areas and emerging user needs. Still, occasional interactions between centres enabled through other mechanisms of the WMO framework for seasonal forecasts, such as RCOFs, as well as the WMO Expert Team, are important opportunities for improving the provision of climate services.

The worlds of climate science and climate data users—whether these are policymakers, intermediaries or private sector stakeholders—have different understandings and prerequisites for trustworthiness of the forecasts. To ease up those boundaries, several authors have suggested the use of the framework put forward by Cash et al. (2002), assessing the characteristics of *credibility*, *salience* and *legitimacy* of the architecture that provides seasonal forecasts in a manner that facilitates interactions amongst what today remains a fragmented set of institutional and administrative mechanisms (Bruno Soares and Dessai 2016).

The framework based on the concepts of credibility, salience and legitimacy as criteria for enhancing the science-policy-society interface has been applied in the past to explore how to ease up the difficult boundary-crossing conditions required by climate change science (e.g. Dilling and Lemos 2011; Bauer et al. 2016; Leitch et al. 2019; van Voorn et al. 2016). In a recent publication, Cash and Belloy (2020) explored how these concepts can be used to explore novel challenges, such as the increased cross-scale nature of most science-to-action processes or the challenges and opportunities presented by the digital transformation.

Examining the results of our empirical exploration of the GPCs-LRF through the lenses of the credibility, salience and legitimacy framework suggests that these three characteristics are not mutually exclusive; thus, an optimal balance is required between them. This will lead towards a more cohesive and efficient interaction amongst the organisations involved, the users and audiences, the processes and products, as well as society at large. A proper understanding of how to reach such ambition requires new research; thus, this section also reflects on potential research areas that emerge from our empirical investigation.

5.1 Enhancing credibility

The credibility of GPCs-LRF and seasonal forecasts can be enhanced with a more transparent approach to the production of forecasts and by implementing quality assurance principles that address issues beyond climate data and encompass quality assurance of climate services. Our interviews demonstrated that the GPCs-LRF see being part of the network as an opportunity to collaborate on developing the forecasts and opening their data to WMO users, thus enhancing the transparency of the overall process. Scientific literature reflects on the importance of good communication with users as a driver of transparency, credibility and quality of seasonal forecasts (Vaughan and Dessai 2014). Endorsement by a prominent institution such as WMO also increases visibility and the possibility to be regarded as a trusted source, according to the study participants. Further enhancing the transparency of seasonal forecast provision would require in-depth exploration of the whole WMO infrastructure, including components such as RCOFs. In addition, further research of the increasingly relevant role of C3S and the drivers of explicit data quality control is recommended.

Forecast quality is another important aspect of credibility, since it is perceived as the reliability or usefulness of the forecasts for decision making. Although often related to skill, quality is actually a complex concept that encompasses other aspects, such as reliability and precision (Weisheimer and Palmer 2014; Lang et al. 2021). The interviewees perceived low forecast skill as the key challenge and limitation for providing useful information. The level of skill significantly differs between models or MMEs, but also amongst regions and seasons (Hemri et al. 2020). The forecast skill assessment, however, depends on the evaluation process, which might even lead to artificial skill and, hence, distort the estimated forecast utility (Risbey et al. 2021). Collaboration between scientists and forecast users is fundamental to understand and address this complex challenge and to broaden the discussion about forecast quality beyond the issue of skill.

The increasing role of MME forecasts is evident, perhaps suggesting a diminishing role of single-model forecasts. However, the seasonal forecast MME landscape is changing rapidly, and there is no clear overview of who participates in each ensemble, or how we can treat different outcomes (MME forecasts) that sometimes consider the same inputs (model data). Collaboration between all these players and coordination across multiple sources of data and information is needed to improve the credibility of seasonal climate data.

Collaboration and coordination at regional level are more obvious through RCOFs or similar events serving as an opportunity for joint learning and reaching consensus. The recently published WMO guidance provides a set of principles and recommendations on good practices for producing objective seasonal forecasts at regional and national levels based on global seasonal forecasts (WMO 2020). By establishing a testable and reproducible approach with transparent forecast quality assessment, WMO aims to support the shift from consensus-based to objective forecast practice. This could substantially improve the overall credibility and legitimacy of the seasonal forecast provision at the regional scale. The GSCU is an interesting attempt to shift this collaborative practice to the global scale. It will be, however, important to develop other types of standardised documents that are co-designed with other actors to ensure progress and integration of the views of users and other stakeholders.

5.2 Enhancing salience

The salience of the information provided by GPCs-LRF could be enhanced by improving the forecasts in terms of skill, user interface, visualisation and communication. In their analysis of the existing organisational structure of seasonal forecasts, Graham et al. (2011) argued that attention to visualisation is fundamental, including the balance of text and graphical visualisation employed, given the potential for misinterpretation of text-based translations of probability information. However, some participants in our study felt that there was no need for further effort by individual GPCs-LRF to improve their forecast visualisation, since the LC-LRFMME, C3S and other MME forecast providers each follow their own preferred visualisations. Another topic that deserves careful attention might be exploring how to conduct model data analysis directly on the cloud, as is currently available in the C3S infrastructure, to give users independence and build capacities within the user community.

Furthermore, the interviewees in our study recognised that the improvement of various aspects of the forecast products is fundamental for enhancing communication, which would require closer collaboration and product co-development with the users. The increasing demand for climate information further emphasises that production of salient data would require an iterative process of knowledge sharing and new knowledge coproduction, building new partnerships and trust across the science-policy-society boundary (Bruno Soares and Dessai 2016; Bojovic et al. 2021).

Besides improving the product, the salience of the GPCs-LRF can be enhanced by adjusting the timeliness of seasonal forecast provision. However, coordinating such an effort is not an easy step in this complex network. Moreover, improving the seamless and cross-timescale characteristics of the forecasts could enhance salience. The recent ambitions of WMO are precisely aimed at achieving a seamless GDPFS collaborative framework that integrates societally critical operational functions of the Climate Services Information System[9] into the existing GDPFS (WMO 2019b, 2020). This includes the recently established network of the Lead Centre for Annual-to-Decadal Climate Prediction and its corresponding GPCs, as well as plans to expand the overall GPC portfolio to cover subseasonal forecasts, with further designation of centres for each timescale. For these ambitions to be effective, the resulting architecture must bridge the gaps and fragmentation that exist across climate services stakeholders, and address the rapidly increasing demand for climate information in the form of fully matured climate services. The lessons from seasonal forecasting might prove the key for success in this endeavour.

The tension between efforts to enhance credibility and salience is evident. When discussing the common compromises made in the provision of seasonal forecasts, one of the interviewees highlighted that the skill of some variables can be quite low in seasonal forecasts, and recognised the need to optimise it by finding a balance between variables that users are interested in (e.g. precipitation) and those that can be predicted with higher skill. The same GPC-LRF interviewee noted the importance of “large-scale atmospheric

[9] https://gfcs.wmo.int/CSIS

variables that give a good indication of large-scale circulation patterns [and] are generally associated with a higher skill".

5.3 Enhancing legitimacy

Lastly, the legitimacy of the GPCs-LRF and the emerging seamless GDPFS collaborative framework could be improved by furthering standardisation, creating independent quality control and certification systems that emerge from a consensus-building process amongst the different stakeholders involved in the value chain of climate services. Nevertheless, building consensus in the field of climate forecasting is challenging. Climate science is rapidly advancing, with developments of larger and faster climate models, and improved resolution aiming towards global simulations at kilometre scale. In addition, the accelerating role of MMEs is shifting the perception of single-model outputs, which is the priority for the GPCs-LRF.

At the same time, providers of seasonal forecasts need to deal with high uncertainty, and insufficient skill for some regions and seasons. The plethora of co-existing networks of seasonal forecast providers, lack of comparability between different forecasts or clarity on how models contribute to different MMEs create challenges in reaching a consensus forecast, which further postpones the needed debate with different forecast users, public administrations and other actors about operationalising climate information into fully mature climate services. However, this lack of consensus in information sources is not a new issue at the climate change science-policy-society boundary. Rather than postponing the engagement with the broader user community, scientists should acknowledge that uncertainty and the lack of consensus are inherent aspects of the fast-evolving landscape of seasonal forecast provision (Pearce et al. 2015).

Several steps can be taken to build legitimate and standardised processes with relevance for users. For example, careful recommendations could be provided for the selection of credible and salient information for different regions, thereby facilitating applications and decision-making processes. Although this aspiration clearly resonates with the recent WMO guidance (WMO 2020), there is a need for further guidance documents that would kick-start wider operationalisation and open discussions beyond the scientific community. Working towards creating guidance documents will also build a community of best practices (Born 2021) and move closer to standardisation processes (St.Clair and Aalbu 2016).

Overall, the most important way to enhance the legitimacy of the GPCs-LRF might be by ensuring the auditability of their processes and products, and the eventual creation of an independent verification system for the wider elements that create the full value chain of climate services. Long-term experience of application of quality assurance principles from the field of technology qualification in engineering and emerging efforts in the climate science community (Pacchetti et al. 2021; Nightingale et al. 2019) could pave the way for enhancing the auditability of climate forecasts. For example, generic standards for the creation of assurance cases for software-related systems, e.g. ISO/IEC 15,026–1,[10] can shed light on how to best select an optimal framework for enhancing the legitimacy of the architecture that provides seasonal forecasts, ensuring its auditability even in the absence of a fully matured standardised field. These are just examples of processes created to provide

[10] https://www.iso.org/standard/80625.html

trust in complex technologies deployed in society that would need to be explored as the standardisation of climate information moves forward.

6 Concluding remarks

This study attempts to provide clarity on the organisational structure of centres that provide LRFs, a fundamental element for climate risk decision making. In-depth dialogues with representatives from the GPCs-LRF and other actors revealed that seasonal forecast provision is a heterogeneous and still maturing community of practice. In addition, the need for moving towards demand-driven, process-focused and quality-assured climate services at the seasonal timescale is evolving. Although the results presented are subject to common limitations associated with qualitative research and tend to have a subjective nature, our dialogues provide important general conclusions. Applying the coding technique enables the robust identification of key themes and achieving saturation, i.e. finding insights that were repeatedly mentioned by informants. The dialogues with centres identified key challenges that the community faces: on one side, the need to improve climate forecast systems and produce more skilful climate forecasts, and on the other, the quest to improve the forecast provision to achieve more useful and usable products.

One way to enhance this knowledge infrastructure is by further exploring and maturing the standardisation of climate service provision to improve credibility and enhance trust amongst the organisations and people involved in the delivery, operationalisation and use of seasonal forecasts. The communities involved in the development and provision of climate services are fragmented, often unaware of each other, and tend to follow practices that do not fully integrate interdisciplinary and transdisciplinary knowledge required for bridging the usability gap of seasonal forecasts. Providing salient and usable seasonal forecasts would hence require leaving scientific silos and starting a coproduction process with the ever-increasing community of forecast users. Standardisation requires building consensus across multiple actors engaged in both the production of climate and non-climate data needed for climate risk decision making. Further advancing legitimacy would require developing quality assurance and best practices that are particularly aimed at audiences beyond the scientific community. Best practices could help users select credible and salient information for different regions and decision-making processes, as well as build a community of practice.

Finally, it is important to balance the demands between credibility, salience and legitimacy to achieve boundary-crossing improvements and consensus between science, policy and society. This can only be achieved if all the actors with a stake in climate services are involved and their interests considered, resulting in a balancing act that is inclusive, embraces all knowledge and integrates experiences and know-how.

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