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Climate services in Brazil: Past, present, and future perspectives

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ABSTRACT

From the devastating effects of the 1877–1879 Great Drought in the Northeast region to the creation of the Center for Weather Forecast and Climate Studies (CPTEC) at the National Institute for Space Research (INPE) in the early 1990 s, Brazil went from a total absence of meteorological expertise to becoming a member of a select group of nations with the infrastructure and technical expertise to build and run a global general circulation model. This article reviews the most critical moments in the development of climate services in Brazil, addressing the evolution of its infrastructure for observation, monitoring, modeling, and prediction, the still incipient efforts in systematically understanding users' perspectives and needs, and the work required to incorporate the usable science and co-production paradigms into the main centers of production of climate information. Advances and challenges are analyzed, and actions for strengthening the climate services framework are proposed.

Practical implications

Climate services are considered to be fundamental for planning the activities of several Brazilian economic sectors (e.g., water management, energy and agricultural production, and health protection). This paper documents, from a historical perspective, the activities that boosted the development of climate services in Brazil, including climate studies, monitoring, and prediction initiatives, as well as initial efforts for systematically understanding users' perspectives and needs, and the work needed for incorporating the usable science and co-production paradigms into the climate information production process. To further develop these services in Brazil, the following recommendations are put forward:

Investment in synergistic forms of cooperation that contribute to the popularization of climate services in strategic settings – such as university undergraduate courses, agricultural extension organizations, academic conferences, etc. – contributing to capacity building in key sectors of the Brazilian technical and economic landscape.

Creation of a forum and an associated research network integrated with representatives of private users, third sector organizations, public

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institutions, and social, climate, and applied scientists, from various areas, for coordinating and operationalizing climate services activities in Brazil. The climate services forum would promote and organize a permanent agenda of discussion and popularization of climate services initiatives. The associated research network would coordinate and perform climate services research targeting societal demands of specific sectors (agriculture, water management, energy production, health, among others) through, for example, previously designed and agreed upon case studies. The defined case studies would involve social, climate and applied scientists, and end users working together towards the development of a set of climate service solutions, while addressing the requirements and expectations of the latter, and taking into consideration the current scientific knowledge and limitations.

Application of the co-production principles to all phases of research (from research design, to the setting of its goals, products, and criteria for evaluation of success – including the possibility of forms of research that are not academic) for collaboratively constructing the usability of climate knowledge and information.

These recommendations are envisioned to contribute to changes in the way climate science is produced for supporting climate services from the "demand-pull" to the "end-to-end" paradigm. This new paradigm involves interaction from the research project design stage and during all research stages with all interested actors – scientists and stakeholders, mainly users – in the knowledge co-production processes and the science and services to be produced.

1. Climate services development in Brazil

Brazil has suffered the negative impacts of extreme weather events throughout its entire history (Cavalcanti, 2012, Marengo et al., 2013, Espinoza et al., 2014, Marengo et al., 2016, Marengo et al., 2017, Lima and Magalhães, 2018, Pontes Filho et al., 2020). Government action and concerted scientific attention to the patterns of climate variability in the country and their adverse effects date to the Great Drought of 1877–1879 (Davis, 2017). Over a century later, the country acquired competence for producing climate forecasts and established a center of excellence for training South American climate scientists. It joins the small number of countries that have developed a global general circulation model building on expertise acquired through collaboration with scientists from developed countries. The cooperation with end-users and important stakeholders has increased steadily in the last three decades. This article reviews the evolution of climate services in Brazil, highlighting the most important historical developments, including current efforts and suggests paths for future progress.

The concept of *climate services* can be traced back to the late 1970 s and the US National Climate Program Act of 1978 (Henderson, 2016). The nomenclature became mainstream in the field of Meteorology after the establishment of the Global Framework for Climate Services (GFCS) concept during the third World Climate Conference in 2009 (Hewitt et al., 2012). An implementation plan was drafted and discussed at an Extraordinary Session of the World Meteorological Congress and implemented by the World Meteorological Organization (WMO) in October 2012 (Hewitt et al., 2012, Vaughan and Dessai, 2014). According to the WMO, the main goal of the adoption of the GFCS was transitioning the world of meteorology from the paradigm of *products* to that of *service*, making the perspective, decision context, and information needs of user communities (WMO, 2020) the central elements in the development and dissemination of climate information.

In practical terms, the implementation of the climate services across the planet faced three important challenges: 1) lack of or unequal infrastructure and capacity for observation, monitoring, modeling, and prediction; 2) absence of systematic research on users' perspectives, needs, and decision processes; and 3) resistance to forms of evaluation of the quality of climate information not based on scientific/technical parameters, but on societal needs instead.

This article will address these challenges, focusing on the Brazilian case. First, the development of the infrastructure and capacity for producing high-quality climate information will be summarized. Next, the efforts to understand users' needs and perspectives and to partner with key stakeholders in the country will be discussed. Finally, the article will briefly discuss the gradual integration of the ideas of usable science and co-production into climate research in the country and propose actions to strengthen it.

2. The development of infrastructure and capacity for the production of climate services in Brazil

In 1886, the Rio de Janeiro Observatory initiated the creation of the first meteorological observational network in Brazil (Barboza, 2006). The Observatory was incorporated in 1909 into the Directorate of Meteorology and Astronomy, a Division of the Agriculture Ministry (Marques, 1997). The Directorate, which later became the Brazilian National Institute of Meteorology (INMET - Instituto Nacional de Meteorologia, in Portuguese), started developing research and alert services and a weather forecast infrastructure at the beginning of the last century. The research included studies on the causes of droughts in Northeast Brazil (Ferraz, 1955) and, as in the United States of America (USA), was motivated by the desire to protect and optimize crop production and promote economic growth (Henderson, 2016).

A new movement towards the modernization of meteorological services in Brazil occurred in the late seventies. Leading scientists of the National Institute for Space Research (INPE – Instituto Nacional de Pesquisas Espaciais) envisioned the possibility of implementing an operational numerical weather and climate forecasting system with an infrastructure equivalent to that already implemented in European countries and the USA. Therefore, there was the need to create adequate conditions to make weather and climate services feasible in the country. The first important step was the creation of a national operational center for numerical weather and climate predictions. At that stage, it was necessary to convince the Brazilian government to invest in modernizing the forecasting infrastructure, including investments for acquiring a supercomputer and in training personnel in numerical modeling for weather and climate forecasting and high-performance computing (SBMET, 1985).

INPE developed climate studies based on observations and atmospheric physics modeling. Marco Maringolo Lemes, a Brazilian scientist working at INPE, developed the first numerical weather modeling studies (Lemes, 1973), envisaging operational weather forecasts for the next few days. The observational weather studies were led by Vernon E. Kousky, a USA scientist who worked at INPE. Vadlamudi Brahmananda Rao, one of the first researchers at INPE in the Meteorology Department, and an expert in climate dynamics, supervised many students who later worked in the Atmospheric Model development. At that time, several scientists returning to Brazil after completing doctoral studies abroad, particularly in the USA, helped structure the graduate program in Meteorology at the Institute. Additionally, their modeling experience acquired abroad further stimulated the desire for creating a center for weather and climate forecasting in Brazil (Miguel et al., 2016).

At the state level, an important event was the creation of the Ceará Meteorology and Artificial Rain Foundation (FUNCEME) on September 18th, 1972. The state agency started its activities motivated by the need to ease the severe droughts that impacted the state of Ceará. After 15 years dedicated to the studies of artificial weather modification through cloud seeding techniques, the agency's structure was modified in 1987, and its name changed to Ceará Meteorology and Water Resources Foundation (FUNCEME). The focus shifted to the use of scientific information, which has become more robust as of the early 2000s. The institution started to structure its products, projects, and programs with a strategy based upon having the user's needs in mind. Despite being a state institution, this effort favored the strengthening of partnerships at the national level and with other states in the country and the improvement of the network of international partnerships. Its mission is to inform decisions and public policy on climate, water, and the environment. Nowadays, FUNCEME contributes strongly, at the national level, to the drought monitoring and seasonal climate forecast systems, and at the global level, to drought preparedness programs all over the world, through a collaboration with the World Bank (Bretan and Engle, 2017).

At the same time, the Semi-Arid Tropics Program (PTSA - Programa Trópico Semi-Árido), created in 1974 by the National Council for Scientific and Technological Development (CNPq - Conselho Nacional de Desenvolvimento Científico e Tecnológico), was supporting INPE's graduate research program. One of the objectives of this program was to produce scientific knowledge to understand the physical and dynamical atmospheric mechanisms leading to droughts in Northeast Brazil. A study of this program (Sugahara, 1982) reviewed Walker's (1928) regression equation developed for producing rainfall climate prediction for the state of Ceará, which established relationships between observed rainfall in two locations (the cities of Fortaleza and Quixeramobim), sea level pressure, and precipitation in distant regions.

Brazilian climate research was still embryonic in the early eighties. Still, the interest in developing additional studies, particularly those related to Northeast droughts, attracted the attention of several national and international climate scientists. Visits by foreign scientists, such as Stefan Hastenrath, from the University of Wisconsin in the USA, to INPE, stimulated various studies by highlighting the influence of the Atlantic Ocean surface temperatures on rainfall regimes and on the Brazilian climate, particularly over the Northeast region (Hastenrath and Heller, 1977).

The importance of the Atlantic Ocean for the Brazilian climate was also highlighted by Moura and Shukla (1981), who associated a tropical Atlantic dipole pattern with rainfall anomalies over Northeast Brazil. Still, during the eighties, INPE's meteorology activities were expanded and it started to train personnel in climate modeling. In 1982, the Atmospheric Modeling Center (CEMA - Centro de Modelagem Atmosférica), a research laboratory at INPE for processing experimental numerical weather forecasts (Moura, 2014), was founded.

The 1982–83 El Niño event boosted worldwide interest in climate research. This El Niño and its global and regional climate impacts, including those over Brazil, were discussed at the First International Conference on Southern Hemisphere Meteorology, hosted by INPE in 1983. That year, the USA National Meteorological Center (NMC)[1] launched a global climate monitoring bulletin, including maps and climate diagnostic analyses. In 1986, INPE launched the Climanálise Bulletin containing diagnostic climate analyses, and, in partnership with INMET, started producing climate predictions for Brazil.

In the mid-eighties, leading INPE scientists sought support for the creation of a meteorological forecasting center using numerical dynamic and physical models. They were supported by the Brazilian Society for the Advancement of Science (SBPC - Sociedade Brasileira para o Progresso da Ciência) and the Brazilian Meteorological Society (SBMET - Sociedade Brasileira de Meteorologia) (SBMET, 1985). In the late seventies, they had already highlighted the need to modernize Brazilian meteorology by criticizing a drought forecast for Northeast Brazil produced by the Institute of Space Activities[2] (IAE - Instituto de Atividades Espaciais) using a statistical model. The INPE scientists' pronouncements were covered widely in the media (O Globo, 1980, O Globo, 1982a, O Globo, 1982b, Revista Isto É, 1983) and reached the National Congress (BRASIL, 1983a, BRASIL, 1983b, BRASIL, 1983c, BRASIL, 1983d).

In 1987, the Center for Weather Forecast and Climate Studies (CPTEC - Centro de Previsão de Tempo e Estudos Climáticos) was approved by the Brazilian government to be created and implemented at INPE. Luiz Gylvan Meira Filho, an INPE scientist, was one of the main instigators in the creation of this center, initially conceived by him and Joseph Smagorisky[3] as a Latin American and Caribbean center for weather and climate forecasting (Meira Filho, 2012). In that same year, the International Conference on Geophysical Fluid Dynamics with Special Emphasis on El Niño was held at INPE (Kayano and Nobre, 1987), as this phenomenon gained remarkable visibility in the media and in society. In 1991, the then Science and Technology Department (SCT - Secretaria da Ciência e Tecnologia) established a Program for Weather, Climate and Water Resources Monitoring, originally known as the "Northeast Project" (Fé and Nobre, 1996), aiming to organize and structure Regional Meteorological Centers in Brazil. INPE coordinated this program, conducting climate monitoring activities and providing support for establishing regional centers in Brazilian states. In the state of Ceará, FUNCEME had already reorganized its activities and started, at that time, monitoring drought conditions and disseminating climate forecasts in the media. There were strong interactions between INPE and FUNCEME scientists. A statistical model, the Oceanic Statistical Modelling System (SIMOC – Sistema de Modelagem Estatística dos Oceanos), was developed in a collaboration between INPE and FUNCEME to provide climate predictions to Northeast and Southern Brazil (Repelli and Nobre, 1998, Pezzi et al., 1998).

CPTEC started producing weather forecasts using a Numerical Weather Prediction System (NWP) in 1994, with a global atmospheric physical model provided by the USA Center for Ocean-Land-Atmosphere Studies (COLA), which was adapted to Brazilian conditions for running on a recently acquired supercomputer. At that moment, Carlos Nobre was the head of CPTEC, and José Paulo Bonatti was INPE's scientist who was responsible for implementing this global modeling capability at the institution. In 1995 CPTEC started routinely producing seasonal climate forecasts for the next three months using the same model (Miguel, 2017a). There were several contributions of seasonal predictions for South America using the CPTEC/COLA Atmospheric Global Circulation Model to the Experimental Long-lead Forecast Bulletin (e.g., Cavalcanti et al., 1998). The description and performance assessment of the global model used at CPTEC for producing these forecasts was later documented by Cavalcanti et al. (2002), Marengo et al. (2003), Coelho et al. (2012), and Coelho (2013).

Between 1994 and 2007, CPTEC consolidated its research, monitoring and climate forecast activities and was able to follow the advancements of meteorological centers in developed countries. This was possible despite challenges in hiring specialized personnel and budget

[1] The National Meteorological Center became part of the National Centers for Environmental Predictions (NCEP), which was created in 1995, linked to the National Weather Service (NWS), and is part of NOAA (National Oceanic Atmospheric Administration).

[2] The name of IAE changed in 1991 to the Institute of Aeronautics and Space.

[3] Joseph Smagorinsky (1924–2005) was a meteorologist and founding director of NOAA's Geophysical Fluid Dynamics Laboratory. He was a pioneer in the 50s in combining computers and mathematical models to make extended predictions of the weather and trends in the global climate.

shortages, particularly for maintaining and updating the computational infrastructure. Since its creation, CPTEC has devoted attention not only to improving the quality of the disseminated forecasts but also to increasing the center's visibility in the media and to meeting government and society's demands by offering observational and satellite-based monitoring services and weather and climate forecast information, among other products, for decision making and public policy. This strategy guaranteed the required resources for computational infrastructure updates (Nobre, 2012).

In the late nineties, CPTEC started organizing monthly meetings with other Brazilian meteorological institutions to produce and disseminate seasonal climate forecasts for the country through participant consensus, following the Regional Climate Outlook Forum (RCOF) initiative stimulated by the WMO. This process involves the evaluation of the current climatic conditions and climate forecasts for the following months using national and international climate models.

In 2007, CPTEC started producing hybrid (empirical-dynamic) seasonal precipitation forecasts for South America through a research project entitled "Euro-Brazilian Initiative for Improving South American Seasonal Forecasts (EUROBRISA)," involving partners from Brazil and Europe. These predictions were produced by combining and calibrating the predictions of a set of European coupled ocean–atmosphere dynamic climate models and of an empirical (statistical) model constructed using historical observations of sea surface temperature and precipitation over South America (Coelho et al., 2006). During the same year, INMET started producing seasonal climate forecasts for Brazil employing statistical models constructed using historical observations (Lucio et al., 2010).

In 2010, with INMET support, CPTEC was designated by the WMO as a Global Producing Centre of Long-Range Forecasts (GPC-LRF) and joined a group of 12 international centers which were recognized for their capabilities in producing operational global seasonal climate forecasts, at that time. With this designation, CPTEC started to contribute to one of the GFCS components (Hewitt et al., 2012) through the cascading of climate information from the global to the regional and to local scales.

In 2013, the national multi-model seasonal climate forecast system was implemented, consisting of a joint effort of CPTEC, INMET, and FUNCEME, with the aim of elaborating a seasonal climate forecast for Brazil using a methodology that objectively aggregates the forecasts produced by each of the three institutions (Coelho, 2014).

Between 2012 and 2016, the Northeast Brazil region experienced a remarkable hydrometeorological drought, which had its risk, due to anthropogenic activity, investigated by scientists from FUNCEME and CPTEC in collaboration with colleagues from international institutions (Martins et al., 2017). In 2015, CPTEC, in collaboration with scientists from other national and international institutions, diagnosed the drivers of a major drought over southeast Brazil during the summer of 2014 (Coelho et al., 2016a, Coelho et al., 2016b, Otto et al., 2015). This event led to a great water shortage in São Paulo, which was later further investigated by Pattnayak et al. (2018).

In 2016, in collaboration with scientists from national and international institutions, CPTEC developed a new global model version for NWP, known as the Brazilian global Atmospheric Model (BAM, Figueroa et al., 2016). This model is currently used at CPTEC for producing operational NWP. Saulo Rabello Maciel de Barros, Paulo Yoshio Kubota, and Silvio Nilo Figueroa were the leading Brazilian scientists in the development of this model. In 2020, an updated version of this model was configured and evaluated, in collaboration with UK scientists, for climate studies (Coelho et al., 2021a; Coelho et al., 2021b) and sub-seasonal predictions (Guimarães et al., 2020). Two inter-comparison assessment studies revealed the CPTEC model (BAM) presenting sub-seasonal prediction performance similar to other international models (Guimarães et al., 2021, Klingaman et al., 2021). Another study compared climate simulation produced by CPTEC (BAM) and UK Met Office Hadley Center model version 3 (HadGEM3) and reported that the two models were consistent with nine models participating in the Sixth Coupled Model Intercomparison Project (CMIP6) in capturing essential features of South American land–atmosphere interactions at the annual scale (Baker et al., 2021). This new model version (BAM) is currently also used at CPTEC to produce operational seasonal climate forecasts.

At the regional level, FUNCEME's performance in Ceará has been prominent in the production of climate monitoring and forecasting information to support decision-makers. FUNCEME, in partnerships with regional public entities in water resources and agriculture, has been providing relevant climate data and forecast information for decision-making to help mitigate drought impacts. The objective has been to minimize the effects, adopting mitigation actions to reduce economic loss and social damage. In recognition of the work carried out by FUNCEME, public sectors that benefited from these climate services have been contributing by providing financial resources for improving climate monitoring and forecasting systems for Ceará.

This brief climate sciences trajectory reveals a remarkable evolution of this scientific field since the 1980s, with the creation and expansion of meteorology undergraduate and graduate programs in Brazil, the improvement of numerical weather and climate prediction and monitoring infrastructures, and enhanced connections between national and international meteorological research centers. Federal government actions provided institutional support for advancing climate and weather sciences, which instrumentalized the scientific institutions to meet specific political demands, for example, for defining strategies to deal with climate crises such as droughts, whose impacts usually affect several economic sectors and poor populations. The expansion of weather and climate sciences in the country over the past decades was accompanied by important advances in the development of climate services at national and regional levels. Regional climate impacts in some states of Brazil motivated the development of these services. However, there is still a clear need to make further progress in various aspects of climate science and services at both national and regional levels to effectively help socially relevant policymaking.

3. Research on users' perspectives, needs, and decision processes

Research on climate services is relatively new in various parts of the world (Brasseur and Gallardo, 2016). In Brazil, as elsewhere, the meteorological community first interpreted the concept of climate services and the novel agenda brought about by the WMO GFCS as the need to improve systems for monitoring, forecasting, and climate risk warnings.

In that which concerns the historical efforts in approximating the work of climate forecasters and users, two trends are identified and will be developed in this section. The first is related to the attempts at incorporating climate information into strategic governmental decision making at different levels and in different parts of the country; the second, much more recent trend, is related to the work of Brazilian social scientists, in collaboration with North American colleagues, on the research of the conditions for the creation of usable climate sciences, mainly in the Northeast region.

The incorporation of climate information in decision-making has historically required the contribution of the applied sciences (e.g. hydrology, agriculture, health, energy, and disaster). In Brazil, agriculture and water management, and later, disaster monitoring and warning, were the fields in which such contribution developed more robustly. With the gradual increase of the monitoring of meteorological stations across the country and the development of forecasting capabilities at INMET in Brasília, at CPTEC in São José dos Campos, at FUNCEME in Fortaleza, and also at the state of Paraná Meteorological System (SIMEPAR - Sistema de Tecnologia e Monitoramento Ambiental do Paraná) in Curitiba, strategic governmental agencies started to use meteorological information more systematically in the country. This narrowing of the distance between stakeholders and meteorological organizations was centered around weather information at first and has been slowly moving towards incorporating climate information. We refer here to the use of information that involves some degree of inter-institutional communication and adjustment and not to the use of information available on websites or disseminated by media outlets.

Due to its placement under the auspices of the Ministry of Agriculture in Brazil, INMET has provided weather and climate information to the National Supply Company (CONAB - Companhia Nacional de Abastecimento) since the early 1990s. CONAB is a public organization created in 1991 to manage Brazil's grain stocks and agricultural market prices. INMET has also supplied information to the National Center for Risk and Disaster Management (CENAD - Centro Nacional de Gerenciamento de Risco e Desastres), which issues warnings to Civil Defense bodies across Brazil. During the same period, CPTEC has developed partnerships with both the National Water Agency (ANA - Agência Nacional de Águas) and the National Operator of the Integrated Electric System (ONS - Operador Nacional do Sistema Elétrico), providing these high-level agencies with weather and climate information. These INMET and CPTEC collaborations, despite the non-mediated relation between these agencies and the users, followed the historical pattern of delivery of meteorological products crafted and evaluated according to endogenous criteria of the field of meteorology that are non-adjusted to the specific needs of users.

State level institutions that evolved, from applied sciences in the fields of agronomy and water management, into meteorological agencies had the advantage of a historically closer bond with users. This is the case of SIMEPAR in Paraná, which was formed in 2000 from a group of institutions originally dedicated to agricultural research, hydrology, and environmental monitoring. Yet the oldest experience of a close connection between producers and users of climate information in Brazil was developed in the State of Ceará and relates to the history of FUNCEME in acting in the field of drought forecasting. Perhaps the most relevant experience of the use of climate forecasts in this fashion is the program called "Sowing Time" ("Hora de Plantar"), put in place in the late 1980s. In this program, the Agricultural Secretariat at the state government adjusted the calendar of distribution of drought-resistant seeds to farmers according to the climate prediction produced and disseminated by FUNCEME (Lemos et al., 2002). Given the politically charged nature of agricultural policy in the state, and the difficulties in forecasting the onset of the rainy season, the management of the program demanded a close connection and coordination between the actions of FUNCEME and the Agricultural Secretariat.

There were also experiments linking the availability of agricultural credit in the Northeast Region to climate forecasts. The Bank of the Northeast announced, in the late 1990s, that the expansion or contraction of the total amount of credit available to farmers was based on, among other things, climate forecasts. The association between credit and climate forecasts was perceived as a politically sensitive issue and was constantly attacked by politicians and the media.

Around the same time, in 1996, the National Ministry for Agriculture implemented a new system for Agricultural Zoning of Climate Risk, developed by the Brazilian Company for Agricultural Research (Embrapa - Empresa Brasileira de Pesquisa Agropecuária). A few years later, this system became a decisive factor for the concession of credit for farmers across Brazil; differently from what took place in the Northeast Region, the Embrapa climate risk zoning affected small scale, family-based agriculture, and also large agribusiness enterprises. Despite criticism springing from the usual differences between peoples' perceptions of climate patterns and the observational databases, the Agricultural Zoning of Climate Risk is well established as a key pillar of the agricultural credit mechanisms in Brazil.

Also, in the 1990s, new actors appeared in the meteorological scene in Brazil: private companies specialized in crafting the weather and climate information, produced by the large national and international climate centers, for specific users in the corporate world. This had been done in the past by independent meteorologists working as private consultants. With the creation and growth of the activities of the companies dedicated to that goal, this market gained visibility and grew considerably. The two most active and visible enterprises in this sector are Somar, created in 1995, and ClimaTempo, in 1999. In 2019, StormGeo, a Norwegian multinational weather services company, acquired 51% of Climatempo, and in 2021, this new company acquired Somar, forming the largest private meteorology company in the Southern Hemisphere. Another recent development in the private sector is the growing emergence of Brazilian startups dedicated to providing information related to climate services.

In the last two decades, new developments in the interinstitutional collaboration related to droughts moved this scenario closer to some of GFCS standards regarding user needs. FUNCEME and CPTEC collaborated in drought monitoring in the past, but since then different states have developed their own independent drought monitoring system. More articulated state response to droughts was evidently needed, involving all of the state's administrative spheres, not only in the form of emergency response but also with a long-term perspective (De Nys et al., 2016, Martins and Reis Junior, 2021, Martins et al., 2016a). Initially, the Ministry of National Integration decided to concentrate efforts on drought monitoring, as well as on three drought preparation plans for manageable systems to establish proof of concept (pilots for urban supply, water resources, and rainfed agriculture). The monitoring model brings together information from federal and state institutions to produce a single map, initially monthly, of drought conditions for the region and was inspired by both the Mexican and the United States' drought monitors (Martins et al., 2016b, Martins et al., 2016c). This model requires intense participation and collaboration between institutions of different administrative spheres (more than 50 institutions), which represents a significant challenge to a country not used to such concerted initiatives, and the integration of all the relevant regional databases (Martins and Reis Junior, 2021).

The Drought Monitor went operational in July of 2014 with a focus in the Northeast Region, having, at the time, FUNCEME as the central institution. In February of 2017, the leadership process was transferred to ANA with the support of FUNCEME and the Federal University of Ceará (UFC - Universidade Federal do Ceará). The Monitor, under ANA leadership, started to expand and other states have already joined the network (11/2018: Minas Gerais; 04/2019: Espírito Santo; 12/2019: Tocantins; 05/2020: Rio de Janeiro; 06/2020: Goiás; 07/2020: Mato Grosso do Sul; 08/2020: Paraná, Santa Catarina, and Rio Grande do Sul; 11/2020: São Paulo; 06/2021: Mato Grosso). Today the process counts on more than 45 contributing state and federal institutions.

In parallel with that, the National Center for Monitoring and Early Warning of Natural Disasters (CEMADEN - Centro Nacional de Monitoramento e Alertas de Desastres Naturais), an offspring of CPTEC, founded in the early 2010s, also created a drought monitor focused mainly on small scale subsistence farming in the Northeast region. The CEMADEN agricultural drought monitor is fed, not only by data from climate modeling, but also, from information collected from hundreds of municipal agricultural secretariats spread over the Northeast region. The large network of organizations that compose the ANA coordinated drought monitor, and the interaction with decision-makers at the municipal level, in the case of the CEMADEN agricultural monitor, provides both initiatives a degree of capillarity and articulation with users not seen previously, on this scale, in the country.

The second trend, mentioned at the beginning of this section, refers to research on users' needs and perspectives and how they can be connected to the production of climate information (Victor, 2015, Jorgenson et al., 2019). Typically, this type of research is developed by the social and behavioral sciences, broadly defined[4]. The importance of social sciences in contributing to the development of climate services is increasingly becoming more evident as funding agencies, such as the

[4] In disciplinary fields such as sociology, anthropology, political science, economics, psychology, and geography.

Belmont Forum and the Inter-American Institute for Global Change Research, list the participation of social scientists as a requirement for research funding. The activities in this second trend can be divided into two moments: research done before the creation of the WMO GFCS, and efforts that took place after, and under the influence of the global framework.

The output of the Brazilian social sciences throughout the 20th century on issues related to drought has been prolific but largely disconnected from decision making and the climate sciences. Two efforts in the State of Ceará, in the late 1990s and early 2000s, have an important role in the transformation of this scenario. Perhaps as an effect of the success of the book *Good Government in the Tropic*, published in 1997 by political scientist Judith Tendler and the praise of the use of science – mainly hydrology and the climate sciences - in the actions of the government of the state, Ceará gained international attention. At that time, a group of social scientists from the Bureau of Applied Research in Anthropology (BARA) of the University of Arizona started a large multi-site research project with scholars from the UFC to understand the effects of the drought on the local society, economy, and political relations. The effort had as one of its goals the construction and proposition of public policy actions based on its findings. The leading researchers in that project would later contribute to the development of the sociological conceptual basis for the idea that there can be no proper climate services development without a detailed understanding of how different social groups relate to the local environment and to the scientific information that they eventually receive (e.g. Dilling and Lemos, 2011, Lemos et al., 2002, Lemos et al., 2013).

In parallel with this, the International Research Institute for Climate and Society (IRI) started a series of collaborations with FUNCEME. The IRI is an organization created in the United States in 1996, in the wake of the El Niño of 1993 and its global negative effects, and is hosted inside Columbia University, in New York. It was conceived to develop research under the paradigm of the "end-to-end approach" – therefore taking the users' perspectives and needs as an integral dimension of the work of producing climate information. Antonio Divino Moura, a Brazilian scientist who had previously occupied leading roles at INPE and INMET, was one of the founders and the first director of the IRI. As part of the cooperation between IRI and FUNCEME, a group of social scientists, associated with Columbia University, carried out field research in Ceará, with the *explicit* goal of understanding how climate information was received, interpreted, and used (or not) in different social settings. The difference between the BARA-UFC research and the IRI-Columbia-FUNCEME research, despite convergent results, is the fact that the latter was developed under the auspices of two climate institutions (IRI and FUNCEME) and with the mandate to explore difficulties and challenges in communication and the use of climate information, particularly the probabilistic nature of climate predictions used to express uncertainties. Also, in this case, some of the researchers associated with the research effort would later push forward the agenda of usable science and co-production (Broad et al., 2007, Orlove et al., 2011, Peterson et al., 2010, Taddei, 2008, Taddei, 2013, Taddei, 2019).

At INPE, during the first two decades of the 21st century, a few social scientists, working within the field of Science and Technology Studies (STS), developed research that plays a role in the development of climate services in Brazil, even if indirectly, as it is not directly focused on the usage of climate information (Lahsen, 2009, Lahsen, 2017, Lahsen et al. 2020, Monteiro et al., 2014, Monteiro and Rajão, 2017, Miguel, 2017a, Miguel et al., 2019).

Many other research groups were doing similar research and arriving at similar conclusions in other parts of the globe. And yet, the results were largely scattered across disciplines and academic groups dedicated to different geographic areas. In Brazil, research on issues related to the users' perspectives and needs did not become institutionalized in academic programs nor did it become an area of study that attracted young students. Most research done in this area was, and still is, induced by international funding and collaborations.

After the creation of the GFCS in 2009, in tandem with the development and popularization of the concepts of usable science (Dilling and Lemos, 2011, Tang and Dessai, 2012) and co-production (Jasanoff, 2004, Meadow et al., 2015, Bremer and Meisch, 2017), the strengthening of the collaboration and dialogue between the social sciences, the climate sciences and the applied environmental sciences became an explicit mission of some of the most important funding bodies for climate and environmental research across the planet. For that which concerns Brazil, the two funding organizations that brought this effort to research done in the country were the Inter-American Institute for Global Change Research (IAI) and the Belmont Forum.

IAI funded the project *Towards usable climate science: Informing decisions and provision of climate services to the agriculture and water sectors of southeastern South America*[5], led by Argentine anthropologist Cecilia Hidalgo, and with the participation of climate scientists, hydrologists, agronomists, and social scientists from Argentina, Brazil, Paraguay, and the United States. The project ran from 2012 and 2017, and it is relevant to the history of climate services in Brazil, as it provided the context for dialogue between several organizations, including INMET, CPTEC, EMBRAPA, and researchers from three Brazilian federal universities, specifically on the issue of what makes climate information usable in situations of use (Hidalgo, 2020).

A second relevant research effort is the project *Climate Services Through Knowledge Co-Production: A Euro-South American Initiative for Strengthening Societal Adaptation Response to Extreme Events* - CLIMAX[6], led by Argentine climate scientist Carolina Vera from 2016 to 2021 and composed by researchers from the climate, applied environmental, and social sciences from Argentina, Brazil, France, Netherlands, and Germany. On the Brazilian team, researchers from CPTEC and INMET were accompanied by others from EMBRAPA, the ONS, and social scientists from the Federal University of São Paulo (UNIFESP - Universidade Federal de São Paulo). This effort is relevant because it is the first in which the notion of co-production of climate services was part of the methodological design of the research, as a starting point rather than an end goal. However, actual co-production was found to be challenging to perform during this project, suggesting the need to rethink research strategies and partner commitments for producing actionable climate information in future similar efforts.

An additional effort that deserves mention is the fact that, as this text is being written, the Regional Climate Center for the South of South America (CRC-SAS) is in the process of constructing an online platform that is a Drought Information System for the South of South America (SISSA)[7]. One of the activities of SISSA is the comprehensive documentation of the institutions, policies, and practices associated with droughts in six countries in South America, carried out by a team of anthropologists, geographers, and agronomists, intending to propose drought mitigation and adaptation plans that are designed with the direct participation of local stakeholders and relevant organizations.

Finally, while all these activities and efforts demonstrate that it has been several decades since the seeds of climate services appeared in the country, and that decisive steps were taken for their development, the climate services agenda is still not widely disseminated in the climate sciences, in the applied environmental sciences, and in the social sciences.

4. Future perspectives on climate services

Throughout the development of climate services in Brazil, some trends are identifiable. First, the development of meteorological infrastructures was accompanied by a growing process of articulation with agronomic sciences, hydrology, atmospheric chemistry, soil studies,

[5] For more information, see http://serviciosclimaticos.blogspot.com.
[6] See http://www.climax-sa.org.
[7] See https://sissa.crc-sas.org

environmental modeling, geosciences, and other applied sciences. This did not occur to the same extent with the social sciences. However, this path towards interdisciplinarity already allows for a more comprehensive view of practical issues involving climate and weather in the form of applied research. It also demonstrates that climate services in Brazil are not solely provided by meteorological institutions; nor should they be, given the important role of agronomic and hydrological research centers in the country.

Second, the ways in which climate information informs decision-making have more layers than that which the most intuitive understanding of providing services to users conveys. Historical examples demonstrate that, often, there are more than two agents involved in the process – a meteorological agency, a state agricultural secretariat or a public bank, and a larger group of users, for instance. Sociologically speaking, a pattern that can be noted is that of cooperation between a scientific and a governmental institution that builds the "end-user" in the form of "a population" that can be served through public policies (Miguel, 2017b), often in the form of a "command line," as is the case with civil defense. This historical pattern does not reflect the main goals of the GFCS and problematizes them simultaneously, showing that the practical contexts of decision-making are more complex than what is portrayed at the GFCS. This demonstrates that more research on the social science aspects of climate services is needed (Lemos et al., 2020), not only for identifying the conditions for their full application but also for the very refinement of the conceptual base upon which the GFCS is built.

With that being said, the fact is that the panorama of climatic services in Brazil is constituted by a dispersed network of agencies and efforts, and most of these services are not even identified and understood as climate services. This lack of coordination is a barrier to the construction of synergistic forms of cooperation.

One potentially positive element of the current scenario is that the increasing visibility of the climate change agenda may spill over into the climate services research. Research on climate change has been growing rapidly in the last two decades, and research networks such as the Climate Network (Rede Clima), set up in 2007, and the National Science and Technology Institute for Climate Change (INCT - Instituto Nacional de Ciência e Tecnologia para Mudanças Climáticas), created in 2008, brought the issue of "impacted populations" into the climate change agenda. The growth of concern and work on the correlated international agenda, such as the SDGs and the 2030 Agenda, may increase national academic attention to the issues linked to climate services. This, nevertheless, has not yet materialized.

The recommendation which we would like to propose, based on the analysis of the current state of the climate services in Brazil, is the investment in synergistic forms of cooperation that contribute to the popularization of the topic in strategic settings – such as university undergraduate courses, agricultural extension organizations, academic conferences, etc. – thus contributing to capacity building in key sectors of the Brazilian technical and economic landscapes. To coordinate and operationalize activities with this goal, we suggest the creation of a climate services forum and an associated research network integrated by representatives of private users, third sector organizations, public institutions, and social, climate, and applied scientists from various areas. The climate services forum would promote and organize a permanent agenda of discussion and popularization of climate services initiatives. The associated research network would coordinate and perform climate services research targeting societal demands of specific sectors (agriculture, water management, energy production, health, among others) through, for example, previously designed and agreed upon case studies.

The organization of this initiative in the form of a forum and an associated research network would ensure a horizontal structure in which end-users, intermediaries, and researchers would be able to design and implement research protocols that embody the principles of co-production, applying it to all phases of collaboration (from research design to the setting of goals, products, and criteria for evaluation of success – including the possibility of forms of research that are not academic) and collaboratively constructing the usability of climate knowledge and information.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have influenced the work reported in this paper.

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