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Potential applications for climate services originated from the CLIMAX project

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CLIMAX (*Climate Services Through Knowledge Co-Production: A Euro-South American Initiative For Strengthening Societal Adaptation Response to Extreme Events*) was an international project funded by FAPESP-Belmont forum developed during the 2016–2021 period. Germany, France, Netherlands, Argentina/France and Brazil were the international partners who worked in common objectives and tasks. The project was composed of four main Work Packages (WP), which interacted to achieve the final goal of developing potential applications to climate services. Here, some of the researches and results conducted by the team in Brazil, aiming at the application by climate services in several sectors, mainly in the energy sector are presented, some including international partners collaborations. The *WP0—Co-design and Co-Production of Knowledge*, was developed in collaboration with the energy sector, the National Operator of Electric System (ONS). Climate research activities were conducted through interactions between climate researchers, energy sector personnel and social scientists, focusing on applications. *WP1—Physical processes explaining climate variability in South America*, aimed to study the remote and regional features associated with precipitation extremes over South America, with emphasis on regions where the main hydrographic basins are located. *WP2—Predictability and Prediction tools* developed several studies, mainly at the sub-seasonal timescale, which was a timescale identified to be useful for ONS. WP3—*Social processes explaining climate information appropriation* was composed of social scientists and had the mission of producing a characterization of the electric sector. Here, some of the WP1 and WP2 results are summarized, illustrating the potential applications. WP0 and WP3 results are presented in other papers.

KEYWORDS

CLIMAX, physical processes, climate variability, prediction, climate services, South America, subseasonal prediction, Amazon

Introduction

This paper aims to show some of the results obtained during the CLIMAX-FAPESP project (2015/50687-8), in Brazil, with the collaboration of the international partners, as a contribution for the general CLIMAX-FAPESP-Belmont project, in the context of climate services. The participant institutions of CLIMAX-FAPESP-Belmont general project were: National Institute for Space Research-INPE (Brazil), National Centre for Scientific Research -CNRS (France), National Research Institute for Sustainable Development—IRD (France), Climate and Environmental Science Laboratory -LSCE (France), Wageningen University and Research, Wageningen Environmental Research-ALTERRA (Netherlands), Technical University Munich-TUM (Germany) and Potsdam Institute for Climate Impact Research -PIK (Germany). The general project comprises five Work Packages (WPs): WP0: Co-design and Co-Production of Knowledge; WP1: Physical processes explaining climate variability in South America; WP2: Predictability and Prediction tools; WP3: Social processes explaining climate information appropriation, and WP4 manages the general interaction within and among WPs with all international partners, under the guidance of the general coordinator.

In the present document, the WP1 and WP2 results are discussed in the light of the development of potential applications in Climate Services. The objectives of WP1 were to better understand the role of remote and regional features on South America climate variability, and its impacts on the occurrence and intensity of extreme events, using historical data and model simulations. One of the studies focused on effects of land cover changes in tropical South America, mainly in the Amazon. WP2 evaluated precipitation and temperature prediction performance studies focused mainly at subseasonal to seasonal timescales. The subseasonal prediction has been identified as an important ingredient to guide climate services in several sectors, including energy and agricultural production.

WP1—Physical processes explaining climate variability in SA

Precipitation variability and teleconnections in model climate simulations

Several studies were developed, in the project, to better understand the influences of teleconnections on South America climate variability, and to verify the ability of global models in representing the associated spatial patterns. The main mode of precipitation variability at the peak of austral summer (January), displays three regions of variability, with the Southeast region (SE) in opposite phase to the South (S) and the Northwest (NW) regions. The Brazilian Global Atmospheric Model (BAM-v0), (Figueroa et al., 2016) and the Regional Eta Model (Chou et al., 2014) simulate these observed characteristics. This mode of variability was obtained from Empirical Orthogonal Function (EOF) analyses for the 1981–2010 period. This configuration is also obtained in cases of extreme precipitation in each of the above-mentioned regions (Cavalcanti et al., 2017). The Southeast-South dipole is related to the occurrence of the South Atlantic Convergence Zone (SACZ) variability, which produces excessive precipitation over Southeast Brazil and drought in South Brazil, Uruguay and Argentina, or opposite conditions between the two regions. The ability of these two models in representing these conditions contributes to the interpretation of subseasonal to seasonal climate predictions. This dipole pattern was discussed in several studies, such as Mo and Paegle (2001), Cunningham and Cavalcanti (2006), Carvalho et al. (2011), (Gonzalez and Vera, 2014) and Vera et al. (2018). These studies show the influence of atmospheric wavetrains propagating over the Pacific Ocean toward South America on the convective activity manifested over the SACZ. Cavalcanti et al. (2020) showed the representation of the Pacific South America (PSA) wavetrain, as well as the Southern Annular Mode (SAM) in climate simulations of the BAM-v-0. Therefore, the ability of the BAM-v0 model in representing these teleconnections is important to the subseasonal to seasonal predictions of rainfall in the Southeastern South America. The knowledge of the mechanisms linked to climate variability over South America and their representation in models used for producing climate predictions is important for adequately delivering Climate Services. The occurrence of favorable wavetrains in the Pacific and teleconnections, linked to changes in the atmospheric circulation over South America, produce precipitation anomalies that can be predicted and monitored.

Influences of large scale and regional features on the precipitation intensity of frontal systems in Southeast Brazil

It is known that frontal systems contribute to precipitation increase in the summer season in several areas of South America. The main characteristics of the atmosphere in observations and model results were analyzed in Andrade and Cavalcanti (2018), associated with precipitation intensity over Southeast Brazil during the passage of frontal systems. The intensity was classified using the ranking of total precipitation in 3 days. The cases with percentile below 5% were called dry and percentile above 95%, wet. Regional atmospheric features were associated with the position and intensity of low pressure, the post-frontal high, humidity flux and humidity convergence over the region. At high levels, the position and intensity of the frontal trough were important, being close to the region when there is excess of precipitation, and displaced to the ocean in the dry cases. The kinetic energy and wave activity over South Pacific were higher in the wet cases, and could be linked to the trough intensification. The BAM-v0 represented the main characteristics associated with frontal systems, such as the temperature gradient, the wind confluence and the ridge-trough pair associated with the frontal system. However, the model underestimated the moisture convergence, eddy kinetic energy and wave activity, in the wet cases. As circulation features have higher skill than precipitation, they can be analyzed when a frontal system is displacing from South to Southeast. Therefore, the knowledge of these features associated with the occurrence of precipitation intensity during the passage of a frontal system can be useful as a monitoring tool in weather forecasting over Southeast Brazil.

The South American monsoon system in global and regional models

The South America Monsoon System (SAMS) is the main driver of the rainy season in large areas of South America. Its variability affects several regions where droughts or floods have impacts in sectors like agriculture, hydropower and the economy. Therefore, the production of rainfall prediction for the SAMS region is a highly important task. To increase the confidence in model predictions, it is necessary to verify, first, how models simulate this system. The Regional Eta model and BAM-v0 were able to reproduce the main characteristics of the SAMS, such as the summer- winter precipitation pattern, differences of atmospheric circulation features, humidity flux, wind flow at low and high levels, including the Bolivian High and the Atlantic Trough. The SAMS domain is well reproduced by the global and regional models. The onset and demise dates are reasonably well simulated, as well as the transition features in the beginning of the onset and beginning of demise (Cavalcanti and Raia, 2017). The onset is characterized by a reduction of Sea Level Pressure (SLP) over the continent and increase of humidity flux from Northwest to Southeast. During demise, there is SLP increase over the continent and a reduction of humidity flux southwards. These characteristics that occur previous to the onset and after the demise, which are well represented by the global and regional models, could be applied in SAMS monitoring and model predictions, contributing to Climate Services actions.

Coelho et al. (2021a) assessed the ability of a Brazilian (BAM-1.2, Coelho et al., 2021b) and a UK (HadGEM3, Williams et al., 2018; Ridley et al., 2019) climate model in representing the main features of the South American Monsoon system. Climatological ensemble means of AMIP-type climate simulations computed over the period 1981–2010 for both models were evaluated for selected variables. The assessment started by examining how well the models represented the precipitation contrast between the dry austral winter (JJA) and the wet summer (DJF) seasons. Particular attention was devoted to characterizing the climatological annual precipitation cycle over key South American regions. Despite the identified precipitation underestimation for the Brazilian model and slight overestimation for the UK model, both models adequately simulated the precipitation contrast between winter and summer and the associated circulation features. Monsoon strength was evaluated by computing the monsoon precipitation intensity index, which allowed identifying the region over South America where the precipitation annual range (difference between summer and winter mean precipitation) represents the annual mean value plus 50%. Both models depicted the South American monsoon region as identified by this index. In contrast to other monsoon regions (e.g., Asia) where reversal of wind direction between the ocean and the continent is observed during the wet (summer) and dry (winter) seasons, the South American monsoon lacks this feature. However, following a similar approach to Zhou and Lau (1998), by computing summer (DJF) and winter (JJA) wind differences with respect to the annual mean circulation, an apparent circulation reversal in the core monsoon region was revealed, with a cyclonic feature during the summer and an anticyclonic feature during the winter, which were adequately represented by both models.

Next Coelho et al. (2021a) assessed how well the two models represented some of the key elements of the South American monsoon system during the austral spring (SON) and summer (DJF), which are considered as the pre-monsoon and peak monsoon seasons, respectively. Both models were able to represent the key elements including the northwest-southeast precipitation band and associated ascending vertical motion over central South America, the Bolivian High pressure and the northeast South America trough at upper levels (200 hPa) during the summer, the subtropical anticyclones at lower levels (850 hPa) over the Atlantic and Pacific Oceans, and the low level jet east of the Andes, the latter having an important role in transporting humidity from the tropical South America to southern parts of the continent. Both models identified a consistency between regions of excessive precipitation and enhanced ascending vertical motion, or deficient precipitation and reduced ascending vertical motion. The subtropical anticyclone and associated high pressure system over the South Atlantic was found to be overestimated by the two models. In BAM-1.2 this overestimation feature manifested near the southeast South America region, which consistently showed a precipitation deficit. HadGEM3 predominantly underestimated pressure over the continent, leading to excess precipitation over southeastern South America.

The ability of the two models to represent the upper (200 hPa) and lower (850 hPa) levels divergent circulation and the regional Walker circulation during the austral spring (SON) and summer (DJF) seasons were investigated as these are also recognized as key features of the South American monsoon system. Both models adequately represented the upper-level divergence and lower-level convergence over the South American monsoon core region, and the upper-level convergence and the lower-level divergence over the subtropical anticyclones in the Pacific and Atlantic. The associated monsoon convection over South America was found to be weaker in BAM-1.2 than observed, consistent with the identified precipitation deficit over the continent. This model deficiency was reported in Coelho et al. (2021b) and was associated with BAM-1.2's atmosphere being more transparent than the real world's atmosphere, leading to misrepresentation of cloud-radiation interactions. Despite some identified deficiencies, humidity and precipitable water representation in both models resembled the observations. BAM-1.2 underestimated humidity over the core monsoon region at around 925 hPa and HadGEM3 showed a similar underestimation feature at around 700 hPa. The Walker circulation with ascending motion over the South American monsoon core region and descending motion (subsidence) over the subtropical anticyclones in the Pacific and Atlantic was well simulated by both models, including the strengthening of this circulation from the pre-monsoon (SON) to the peak monsoon (DJF) season.

To further diagnose the spatial precipitation structure of the South American monsoon system as represented in both observations and model simulations, a year-to-year seasonal precipitation variability analysis was performed for both the austral spring (SON) and summer (DJF). This analysis consisted of computing the correlation between the 1981 and 2010 time series of seasonal mean precipitation anomalies averaged over part of southeast Brazil (15–25°S, 40–50°W, at the continental end of the northwest-southeast precipitation band earlier described), and the corresponding 1981–2010 time series of seasonal mean precipitation anomalies at each grid point over the study domain. This linear association assessment revealed that during the austral spring (SON) both models reproduced the northwest-southeast oriented correlation pattern identified in the observations, which is aligned with the northwest-southeast oriented precipitation band described earlier. However, both models overestimated the spatial extent of this pattern. During the austral summer (DJF) a similar feature was identified in the observations, together with an area of negative correlation over southeastern South America, highlighting a dipole-like pattern previously documented in the literature (Nogues-Paegle and Mo, 1997; Vera et al., 2006; Gonzalez and Vera, 2014). This pattern represents excess precipitation over southeast Brazil and deficient precipitation over southeastern South America and is usually manifested when the South Atlantic Convergence Zone is active. The opposite precipitation conditions over these two regions are usually manifested when the convergence zone is inactive. Both of the investigated models reproduced this dipole-like correlation pattern, despite overestimating the spatial extent of these patterns, particularly over the South Atlantic Ocean.

In addition, Coelho et al. (2021a) assessed how well the two investigated models represented the 1997/1998 to 2013/2014 climatological distribution of rainy season onset and demise dates over southeast Brazil (15–25°S, 40–50°W) and the South America monsoon core region (10–20°S, 45–55°W) when compared to the observations. Onset and demise dates are important aspects of the South America monsoon system in terms of both scientific and societal interest and therefore worth advancing knowledge about our current capability in simulating these features. The historical mean onset dates for both regions were estimated to occur around mid-October. BAM-1.2 simulated onset dates close to the observed dates, while HadGEM3 simulated slightly earlier onset dates than observed. BAM-1.2 also represented interannual variability in onset dates closer to the observations than HadGEM3. The two models represented similar interannual variability in demise dates to the observations. Despite the identified deficiencies, particularly in representing the interannual variability in onset dates, both models adequately simulated the main observed climatological features of both rainy season onset and demise dates for the two investigated regions.

The climatological and year to year variability analysis revealed both model deficiencies and strengths. Overall, both investigated models satisfactorily represented the main features of the South American monsoon system evaluated here. This assessment motivates and provides confidence on the use of these models or improved versions of these models in future research to further advance the scientific capability in producing prediction information to help society deal with South American monsoon climate variability and its associated impacts. These results could be used as relevant contributions to Climate Services in predictions of SAMS features. For example, onset and demise data predictions of this system can contribute to help improve management actions in the agriculture and energy sectors, which depend on the information about the beginning and duration of the rainy season for various decisions.

Influences of Madden and Julian Oscillation (MJO) on South America

The Madden-Julian Oscillation (MJO) is the main mode of intraseasonal variability in the tropical atmosphere. It is identified in several variables, but using Outgoing Longwave Radiation (OLR), which is a proxy for convection, it can be easily noticed, mainly over tropical Indian and Western Pacific Oceans. The typical pattern is a pair of positive and negative OLR anomalies that displaces eastward (Madden and Julian, 1972). A review of this oscillation is described in Zhang (2015) and the impacts over South America meteorological conditions is provided in several papers, such as Kayano and Kousky (1999), Liebmann et al. (1999), Carvalho et al. (2004), Alvarez et al. (2016), Shimizu and Ambrizzi (2016), Shimizu et al. (2016), Barreto et al. (2019) among others.

The real-time multivariated index monitoring of MJO phases, created by Wheeler and Hendon (2004) uses OLR and zonal winds to detect the oscillation. Barreto et al. (2019) applied a new multivariate index (MRI.SA) using OLR, zonal wind and precipitation. In this way, each phase of MJO was linked to precipitation anomalies over South America. Phases (8 + 1) and (4 + 5) present strong convection anomalies over the maritime continent and South America, but with opposite signs. These patterns represent the dominant mode of precipitation over South America. When there is lack of convection over the Maritime continent, there is excess rainfall over parts of North, Northeast, Central-West (CW) and Southeast regions of Brazil, and reduced rainfall over Southern Brazil and Northwest South America. The opposite occurs when there is strong anomalous convection over the Maritime continent. Phases (2 + 3) and (6 + 7) show a west-east dipole pattern of convection over tropical Indian-West Pacific Oceans. When there is anomalous strong convection over the Indian Ocean, excess of precipitation occurs over Northeast Brazil and lack of precipitation over NW and Western tropical-subtropical South America. Opposite conditions of the west-east tropical dipole imply a reduction of precipitation over NE Brazil and excess over NW and CW South America. Besides the use of precipitation linked to OLR and zonal winds, this approach allowed the development of a space-phase diagram with the MRI.SA index at different lags, represents the positive precipitation locations over South America and over the Equatorial Pacific. The construction of this diagram in near real time could be used for monitoring precipitation extremes over different areas of South America. The near real time predictions performed by centers, such as ECMWF, within the subseasonal to seasonal project, that can be used to predict the MJO and its influence on South America precipitation is an ongoing activity. This application can be transferred to Climate Services and it will be useful to sectors that need intraseasonal precipitation information. In the CLIMAX project, the subseasonal to seasonal timescales were identified as an important source of information for planning activities of ONS.

Droughts in South America and associated processes

The atmospheric and oceanic features that contributed to the extended dry period during 2019/2020 drought in Brazil, Argentina, Paraguay and Uruguay were analyzed and reported in Gomes et al. (2021). The 2019/2020 drought in South America caused many impacts on several sectors, as agriculture, water resources, and environment. A regional feature was the reduction of humidity flux over the continent, and the occurrence of different processes in a large scale contributed to the dry conditions. Steady conditions observed over South America (positive geopotential anomalies) and southeast South Atlantic (negative geopotential anomalies) from September 2019 to March 2020 were associated with a persistent pattern of west-east convection anomalies in the tropical Pacific. During 2019 austral spring there were occurrence of two events that could have contributed to the drought. One was the positive phase of the Indian Ocean Dipole, which triggered a wavetrain from the Indian Ocean to the South American, influencing temperature and precipitation in the continent. Another one was the Sudden Stratospheric Warming (SSW), which induced the negative phase of the Southern Annular Mode in December, and generated subsidence over the subtropics, affecting the precipitation over South America. The heating observed in the stratosphere propagated to the troposphere over South America from September 2019 to March 2020. Positive SST anomalies were detected during the whole period in all oceans, mainly in the North Atlantic Ocean, which could generate a meridional circulation, and subsidence over South America, as seen in other cases. The development of a La Niña episode at the end of the studied period contributed to the reduced precipitation in South Brazil. The monitoring of these features that contributed to this drought is important to management of the water resources and hydropower energy, and could be used in Climate Services. Droughts in Central, Southeast and South regions can also be associated with lack of humidity from the Amazon region (Arraut et al., 2012; Drumond et al., 2014; Cavalcanti et al., 2017). In the next section, we discuss the results of experiments with vegetation models in which we analyze the probable impacts of deforestation in the Amazon and the increase of CO2 in the atmosphere on the climate, with the decrease in evaporation and precipitation; and the increase in temperature in the region.

Impacts of deforestation and the elevated concentration of CO_2 in the atmosphere on gross primary productivity (GPP), evaporation and climate in Southern Amazonia

The southern region of the Amazon has suffered great anthropogenic influence and this has intensified since 1990, due to government infrastructure investment programs, such as the expansion of roads. Recurrent patterns of deforestation within a distance of up to 100 km from the roads have been observed. The supply of electricity with low price policies also stimulated the expansion of agriculture and cattle raising, which is often done illegally, converting large forests into pastures. In order to analyze the likely impacts on evaporation and Land Use Change (LUC) in this region, an experiment with four Dynamic Global Vegetation Models (DGVMs) was conducted in which each of the CLIMAX partner institutions was responsible for one of the models: LPJ–GUESS (Technical University of Munich—Germany), LPJmL (Potsdam Institute for Climate Impact Research—Germany), ORCHIDEE (Climate and Environmental Science Laboratory—France) and INLAND (National Institute for Space Research—Brazil).

Three different datasets as climate forcings (GLDAS 2.0, GSWP3 and WATCH+WFDEI) were applied. These same climate forcings were used, considering them as "observed data" to analyze evidence of climate change in temperature and precipitation in this study region. The outputs of DGVMs were compared with data that were obtained by flux towers, remote sensing and meteorological data (FLUXCOM, Global Land Evaporation Amsterdam Global Land Evaporation Amsterdam Model v3.5a). Land Use Change (LUC) data were based on a composition of PRODES Amazon information. The period of this study was 1981–2010.

Although the simulations were performed for the whole South America, the study area was delimited in the Southern Amazon between 7 and 14°S of latitude and 66 and 51°W of longitude, which comprises the states of Rondônia, Southern Amazonia, Northern Mato Grosso and Southern Pará, in Brazil; and the northern part of Bolivia's territory. This region has been one of the most affected by Land Use Change (LUC) in the last 30 years. Two sets of simulation experiments were conducted in relation to CO2: 1) increasing CO2 from the pre-industrial period until 2010 named **historic CO_2**; 2) applying a constant value of 278 ppm (pre-industrial) of atmospheric CO2 named **constant CO_2**, hereafter. We run both CO_2 experiments under Land Use Change (LUC) and Potential Natural Vegetation (PNV) conditions, respectively. In the PNV simulation experiments, vegetation dynamics results from climate conditions without anthropogenic influence. All combination options of CO_2 and land cover change lead to four sets of simulation experiments per climate input: 1. **LUC historic CO_2**; 2. **LUC constant CO_2**; 3. **PNV historic CO_2**; 4. **PNV constant CO_2**.

Results published in Rezende et al. (2022) showed that elevated CO_2 fertilization contributed to a GPP increase of around 15% and compensated for deforested regions compared to PNV regions. Also, in the regions with the highest LUC there was a reduction of evaporation around 10 %, of precipitation around 15 mm and a temperature increase of 1°C in the dry season. In the rainy season, the increase in temperature was 0.6° C and the decrease in precipitation was around 30 mm. The uncertainties found in the DGVMs were also analyzed and discussed, and most of them originated from issues of plant physiology, such as how the models allocate carbon and estimate the Leaf Area Index (LAI). These experiments, showing the reduction of evaporation with the land use, are relevant for the Amazon region but also to other regions, as the Amazon humidity is transported to South and Southeast Brazil and contribute to the precipitation in these regions. With less evaporation, less humidity can be transported, which reduce precipitation over agriculture and hydropower energy areas. The continuous monitoring of the deforestation and humidity transport is another issue to be considered in Climate Services. Furthermore, the quantification of deforestation can contribute to predictive models to estimate evaporation, as well as the regional precipitation that occurs in moisture recycling processes (Seneviratne et al., 2010).

WP2—Predictability and prediction

Global models—Climate features and subseasonal to seasonal predictions

BAM is the Brazilian Atmospheric Global Model developed at CPTEC/INPE and derived from earlier versions, including CPTEC/COLA AGCM. It is a spectral model and for climate purposes has the horizontal resolution within 100–200 km and 36 or 42 vertical layers. As it is an atmospheric model, the global Sea Surface Temperature (SST) is the bottom boundary forcing. A description of the model is documented in Figueroa et al. (2016) and Coelho et al. (2021b).

The Global Atmospheric Brazilian model BAM-v1.2 was used by Baker et al. (2021) and Coelho et al. (2021b) for evaluating the model ability in representing the global climate features, including key atmospheric patterns and surface atmosphere interactions of relevance for producing an adequate representation of precipitation conditions over South America. Predictions of the expected climate conditions for the next 3 to 6 months, which are known as seasonal predictions, are relevant for planning activities of a number of sectors, including agricultural and energy production. In order to advance the current practices for the production of seasonal predictions in South America, a number of studies have been conducted including (a) the investigation of procedures for combining and calibrating predictions produced with different climate models including rainy seasonal onset predictions (Coelho et al., 2017; Rodrigues et al., 2019; Osman et al., 2021), (b) the assessment of prediction quality produced by dynamical and empirical (statistical) climate models (Gubler et al., 2020), and (c) the investigation of the importance of considering biomass burning aerosols for improving the representation of the observed seasonal climate conditions (Freire et al., 2020).

Another time scale of great relevance for a number of application sectors is the sub-seasonal time scale. Predictions at this time scale provide information for the expected atmospheric conditions for the next four weeks. A number of studies were conducted for advancing the knowledge about the virtues and limitations of the present capability of global models in predicting the meteorological conditions over South America on this time scale, as well as for advancing our current capacity for producing these predictions.

The current global climate models (De Andrade et al., 2019), including the Brazilian model (Guimarães et al., 2020, 2021) revealed adequate predictive ability for anticipating precipitation and temperature conditions 2 weeks in advance particularly over the tropical region, which includes a large part of Brazil. For predictions produced 3–4 weeks in advance, prediction ability was reduced, maintaining moderate levels for the third week for some parts of Brazil and also moderate performance for the fourth week over the tropical Pacific and northern South America. A particular topic of research interest was prediction quality assessment through the application of methods designed to evaluate the performance of both probabilistic and deterministic sub-seasonal predictions of precipitation and temperature over South America (Coelho et al., 2018; Alvarez et al., 2020).

The ability of global sub-seasonal prediction models in representing the spatial precipitation and associated atmospheric circulation patterns was also investigated (Cavalcanti et al., 2021; Klingaman et al., 2021). The two main Southern Hemisphere teleconnection patterns (SAM and PSA) were well represented in subseasonal hindcasts of the Subseasonal to Seasonal (S2S) project, and predictions by ECMWF and NCEP models 2 weeks in advance were able to identify precipitation anomalies over South America associated with those teleconnections. This is a very important result that can contribute to improving predictions in subseasonal timescale. All these evaluation studies provided a comprehensive assessment of the current capability of global models in predicting atmospheric conditions over South America and therefore helped build confidence among scientists for starting the production of routinely sub-seasonal predictions for the continent.

A research highlight of this project was the configuration and evaluation of the Brazilian global model for producing sub-seasonal predictions (Guimarães et al., 2020), which showed competitive performance compared to international models participating in the international S2S prediction project (Guimarães et al., 2021). By developing the capability of producing predictions on this time scale, Brazilian sectors such as agriculture and energy production and distribution, tourism, among others, which require anticipated information for planning their activities weeks in advance, can be benefited.

These evaluation studies provided support for the use of the Brazilian model (BAM) for routinely producing seasonal predictions for Brazil, a procedure that has been conducted every month at INPE. This project therefore contributed to advancing Brazil's capability in producing operational seasonal climate predictions with an improved model version. The availability of results from subseasonal and seasonal predictions to users is important to allow management actions in several economical sectors. In the case of energy sector, actions to use hydroelectricity or thermoelectric energy depend on the knowledge of the precipitation variability from weeks and months ahead.

Regional model

The Regional Eta Model is a state-of-the-art atmospheric model used for research and operational purposes. The name of the model derives from the Greek letter η (eta) which denotes the vertical coordinate. The model was originally developed in the University of Belgrade and the former Yugoslav Hydrometeorological Service (Messinger et al., 1988). The model was operational at the National Centers for Environmental Prediction (Black, 1994) and became operational at the end of 1996 at the Center for Weather Forecasts and Climate Studies (CPTEC) of the Brazilian National Institute for Space Research (INPE) (Chou, 1996). The model has produced operationally seasonal forecasts since 2001 over the South American domain with 40 km horizontal resolution.

Seasonal precipitation forecasts are needed for planning in the energy and agriculture sectors. Global climate models can provide the large-scale patterns of these forecasts. However, climate impacts may differ at regional scale; therefore, the downscaling of global climate forecasts using a Regional Climate Model (RCM) should add value to the coarse global climate forecasts. The forecasts for South America reproduced the seasonal variability of precipitation and showed significant improvement over the driver global model forecasts. A 10-year reforecasts of the Eta RCM over South America at 40-km resolution was evaluated (Chou et al., 2020a), using an updated finite volume version of the model (Mesinger et al., 2016). These reforecasts were driven by the INPE's global atmospheric climate model at about 200-km horizontal resolution and consisted of a 5-member ensemble built from initial conditions of 5 different consecutive days. The three-month averages of precipitation showed spatial and temporal variability reproduced by these forecasts, although over the central part of the continent, systematic underestimation of precipitation during the rainy seasons occurred, although the precipitation in the Intertropical Convergence Zone was often overestimated throughout the year. The 2m temperature was underestimated by these reforecasts in most parts of the continent. The 1-month lead forecast produced higher precipitation forecast skill than the 2-month lead forecasts. The northern part of the continent, in the North and Northeast Brazil, the skills are higher especially during NDJ (November-December-January) and through the trimesters until JJA (June-July-August) of the following year. However, in southeast South America, the SESA region, the precipitation skill is low. The comparison of the areas of skill score above 0.3, between the global model driver forecasts and the Eta RCM forecasts showed that the RCM has more areas of skill than the global model.

The Regional Eta Model is under continuous development. The RCM version is the same applied to produce weather forecasts and for projections of climate change and at different horizontal resolutions (Lyra et al., 2017; Chou et al., 2020b). Therefore, the current version of the Eta model is a unified

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version for all applications, and produces forecasts in a seamless manner. Seasonal predictions of precipitation and temperature from a regional model with resolution greater than the global models are useful to regionalize the applications in Climate Services.

Conclusion

CLIMAX was a transdisciplinary project with participation of climate and social scientists and collaborators from the energy sector, the national operator of electricity, in Brazil and the agriculture sector, in Argentina. This paper summarized the results of some studies conducted in WP1 and WP2 as part of the Brazilian component of the project, which were conducted in collaboration with international project partners, and that could be used for delivering improved Climate Services. In Figure 1 the main features that can be monitored and predicted, related to precipitation over South America are summarized. They could be applied in sectors such as agriculture, energy, civil defense, tourism, sectors that affect the economy and society. In the CLIMAX project, the emphasis was on the energy sector of the National Operator of Electric System (ONS), but the results can be applied to other sectors mentioned above. Some results can be coupled with hydrological and agricultural models at subseasonal to seasonal timescales. We propose the set of features as potential applications in Climate Services, aiming to provide a contribution to the development of products, which can be used in specific sectors that rely on precipitation variability.

Results confirm the influences of Pacific and Atlantic SST, MJO, SAM and PSA, as remote features, on climate variability over South America. Regional features were identified associated with the SAMS and wet and dry extremes over South America. The extreme precipitation over several areas of South America is linked to remote and regional features. The intensity of precipitation associated with frontal systems over Southeast Brazil is related to large scale and synoptic features. Results also show that global and regional models represent reasonably well many of these features.

Several aspects of climate were represented by BAM, such as teleconnections, the main mode of precipitation variability over South America, the precipitation dipole between Southeast Brazil and Southeastern South America, atmospheric characteristics associated with frontal systems, and the South America Monsoon features. The regional Eta model also represented the SAMS features and the observed characteristics of extreme wet and dry cases in the monsoon region. The MJO influence on South America precipitation was analyzed using the MRI.SA index, which contributed to identifying precipitation anomaly patterns connected to eight phases of the MJO.

By comparing the simulations of four Dynamic Global Vegetation Models (DGVMs) with observable data (satellites and flow towers), the effects of Land Change Use (LUC) and atmospheric elevated CO_2 (eCO_2 on evapotranspiration (ET) and vegetation productivity in the southern Amazon were analyzed. This is the region with the highest deforestation in the last 30 years. LUC had a negative effect on ET in most simulations, and within our region, in the sub-region (61°-63°W, 10°-13°S; 51°-52° W, 10°-14°S), where deforestation was more intense, we observed that the decrease in evapotranspiration was around 10% (9.98%), in the dry season. In the mean for the entire study region, the decrease in ET was ~4% and 1.2% (dry and rainy seasons, respectively), and in the northwest region there was no significant decrease in ET, as well as there was no loss of native forest cover. The difference between the experiments **LUC historic CO_2** and **PNV constant CO_2**, indicated that in a scenario of eCO2, there was an increase of GPP that may have compensated deforestation, in relation to productivity of vegetation. On the other hand, the effect of eCO2 on evapotranspiration was not clear, due uncertainties in model results and on vegetation productivity there was an increase of around 18% in the remaining vegetation. LUC changes in São Francisco Basin also produced hydrological changes between 2010 and 2012.

The prediction studies indicated that the current global models, including the BAM, have a suitable performance in anticipating precipitation and temperature conditions for the first 2 weeks of prediction, particularly over the tropical region that covers a large portion of Brazil. For the third and fourth weeks prediction, performance is reduced, but still provides information that can be beneficial for applied sectors in need of anticipated meteorological conditions. The CLIMAX project enabled the analyses of predictions produced with several models from the Subseasonal to Seasonal Project (S2S), in addition to predictions produced with the BAM for the subseasonal timescale, which were found to be competitive to similar international model predictions. These predictions are important for several societal sectors, such as agriculture, electricity production and distribution, tourism, among others that need information weeks ahead for activities planning.

Other results obtained during the project that could be used in Climate Services include influences of extratropical Pacific and Atlantic SST on Southern Brazil meteorological conditions; aspects of soil moisture in South America associated with precipitation variability; the assessment of the representation of extreme precipitation over São Francisco Basin and Parana Basin in hindcasts of ECMWF and NCEP S2S project models; the representation of rainy and dry cases over São Francisco basin by the regional Eta model, including the associated atmospheric conditions; the analyses of the MRI.SA index in Subseasonal to Seasonal Project (S2S) models and the development of climate indices to monitor climate variability in South America.

The results of the research conducted in WP1 and WP2 of the CLIMAX project by the Brazilian team, produced in

FIGURE 1
Features that could be monitored and predicted as a contribution to actions of Climate Services applied to Agriculture, Energy, Tourism, Civil Defense and Society.

collaboration with international partners, are contributions for potential applications and improvements in climate services. The conducted research contributed to advance the understanding of some aspects of the observed South American precipitation variability, and provided confidence for the use of model predictions over South America, particularly in the subseasonal to seasonal timescales Regional. The transdisciplinary characteristic of the project allowed interactions among scientific and social scientists and members of the energy and agriculture sectors. Several studies were developed based on the application needs. This approach was a paradigm shift, changing the usual direction from the research results to the users, to a new direction from the collaborators users to the development of research.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author/s.

Author contributions

All authors listed have made a substantial, direct, and intellectual contribution to the work and approved it for publication.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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