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# Weather Forecasting in Brazil: A Concise Historical Review

*Previsão de Tempo no Brasil: Uma Breve Revisão Histórica*

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**Abstract**

The main objective of this article is to describe the factors and issues responsible for the evolution of the weather forecast in Brazil. This is done based on a historical review of the formation and evolution of the national meteorological services in the last 170 years and on the development of weather forecasting methods. Changes in the routines of weather forecasting services in two centenary Brazilian institutions, the National Institute of Meteorology and the Brazilian Navy, since the creation of the first subjective forecasts to the present day, are highlighted. Information about the 14 undergraduate courses in Meteorology in Brazil is given, which support the technological development of this science, through scientific research and training of human resources. The introduction of meteorological radar in the 1970s, and its current networks, as well as the elaboration of the first numerical weather predictions (NWP) by the Center for Weather Forecasting and Climate Studies (Centro de Previsão do Tempo e Estudos Climáticos do Instituto Nacional de Pesquisas Espaciais – CPTEC/INPE), in 1995, are also described. To complement, a survey is presented, showing the current working conditions of weather forecasters. The survey results reveal that 45% of the 102 meteorologists interviewed use the Czech Republic Windy application to prepare their weather forecasts operationally and almost 60% use the Wyoming University website to obtain data from radiosondes launched in Brazil. It is important to highlight that, since the introduction of NWP by CPTEC/INPE, at the end of the 1990s, there has been a great advance in the field of weather forecasting. Moreover, observational networks have undergone a great expansion, with a significant increase in the number of weather stations in recent decades. Despite all the progress achieved, there is still a need for the integration of observational networks and databases of various institutions. Finally, the development of applications that meet the demand of young meteorologists in the operational centers is advisable.

**Keywords:** Synoptic Meteorology; Meteorology Services; Numerical Weather Prediction

**Resumo**

O objetivo principal deste artigo é descrever os fatores e as questões que determinaram a evolução da previsão de tempo no Brasil. Isso é feito com base numa revisão histórica da formação e evolução dos serviços meteorológicos nacionais nos últimos 170 anos e o desenvolvimento dos métodos de previsão de tempo. As mudanças nas rotinas dos serviços de previsão de tempo nas duas instituições centenárias brasileiras, o Instituto Nacional de Meteorologia e a Marinha do Brasil, desde a elaboração das primeiras previsões subjetivas até os dias atuais, são destacadas. Acrescentam-se informações sobre os 14 cursos de graduação em Meteorologia no Brasil, que apoiam o desenvolvimento tecnológico dessa ciência, por meio de pesquisas científicas e formação de recursos humanos. A introdução do radar meteorológico na década de 1970, e suas atuais redes, assim como a elaboração das primeiras previsões numéricas de tempo (PNTs) pelo Centro de Previsão do Tempo e Estudos Climáticos do Instituto Nacional de Pesquisas Espaciais (CPTEC/INPE) em 1995, também são descritas. Para complementar, apresenta-se uma enquete que retrata as atuais condições de trabalho dos previsores de tempo. Os resultados dessa enquete revelam que 45% dos 102 meteorologistas entrevistados utilizam o aplicativo Windy da República Tcheca para elaborar a previsão do tempo operacionalmente e quase 60% recorrem ao sítio da *Wyoming University* para obter dados de radiossondas lançados no Brasil. É importante ressaltar que a partir da introdução da PNT pelo CPTEC/INPE, no final da década de 1990, houve um grande avanço na previsão do tempo. Ademais, as redes observacionais sofreram grande ampliação, com aumento expressivo do número de estações meteorológicas nas últimas décadas. Apesar de todo o progresso alcançado, ainda existe a necessidade de investimentos na integração das redes observacionais e dos bancos de dados de várias instituições e na elaboração de aplicativos que atendam a demanda dos jovens meteorologistas nos centros operacionais.

**Palavras-chave:** Meteorologia Sinótica; Serviços de Meteorologia; Previsão Numérica de Tempo

## 1 Introduction

The word "synoptic" comes from the Greek "synoptkós" which means to present an overview of the whole, to elaborate a synopsis. Synoptic Meteorology is a branch of Meteorology that deals with the diagnosis and forecast of meteorological systems with spatial and temporal scales around 1000 km and 2 weeks respectively (Gerrity et al. 2020). The history of Weather Forecasting is intertwined with the history of Meteorology and meteorological institutions, since the first activities of this science were dedicated to weather forecasting. In Brazil, the first activities of the Central Meteorological Department of the Navy (Repartição Central Meteorológica da Marinha), the current Navy Hydrography Center (Centro de Hidrografia da Marinha - CHM) in 1888, and the current National Institute of Meteorology (Instituto Nacional de Meteorologia - INMET) in 1909, were also aimed at providing weather warnings respectively to sailors and farmers (Oliveira 2009). Such warnings would later develop into weather forecasts for these users. Thus, comprehensive histories of Meteorology in Brazil can be found in commemorative texts of both institutions, associated with their centenaries: i) the CHM (Neiva 1988) and ii) the INMET (Oliveira 2009). In addition, Sampaio Ferraz in his article "A Meteorologia no Brasil" (The Meteorology in Brazil) published in the book "As Ciências no Brasil" (The Sciences in Brazil), organized by Fernando de Azevedo in 1955, and republished by the Federal University of Rio de Janeiro (Universidade Federal do Rio de Janeiro - UFRJ) in 1994, describes in details the Meteorology in Brazil from the stage of embryonic Meteorology, in the 16th century until the middle of the 20th century (Sampaio-Ferraz 1994).

The main objective of this article is to describe the factors and issues responsible for the evolution of the weather forecast in Brazil. This is done based on a historical review of the formation and evolution of the national meteorological services in the last 170 years, and on the development of the weather forecasting methods. We also highlight the factors that led to this evolution, including the new methods of observation and communication, in addition to the extraordinary advance of information technology. The first subjective predictions elaborated at the beginning of the 20th century until the current numerical weather predictions (NWPs) are highlighted. Thus, this historical summary is divided into 3 phases: The first phase (described in Section 2), "The Earliest Times of Meteorology", covers from the founding of the Astronomical Observatory to the elaboration of the first systematic weather forecast. The second phase (in Section 3), "The Era of the Subjective Weather Forecasting", extends from the first weather forecasts until the beginning of the NWP, produced by the Center for Weather Forecasting and Climate Studies of the National Institute for Space Research (Centro de Previsão do Tempo e Estudos Climáticos do Instituto Nacional de Pesquisas Espaciais - CPTEC/INPE). Finally, the third phase (described in Section 5) is referred to as "The Era of the Numerical Weather Prediction". In Section 4 we present a brief history of weather radar. The current organization of meteorological services is presented in Section 6 and the main weather sites available for weather forecasting are presented in Section 7. Finally, the conclusions and final considerations are presented in Section 8.

## 2 The Earliest Times of Meteorology

The evolution of Brazilian Meteorology and its recognition as a physical science only began to strengthen after the first regular meteorological observations carried out by the Imperial Observatory of Rio de Janeiro. After the independence of Brazil on September 7, 1822, the port of Rio de Janeiro became very often visited by several vessels, whose captains needed to know the magnetic declination, as well as the average time and longitude to regulate their stopwatches. Thus, the Imperial Government decided to create in the city of Rio de Janeiro, like in all "cultured countries", the Astronomical Observatory, a fact that began with the decree of October 15, 1827 (Morize 1987).

The Astronomical Observatory, although founded in 1827, only started operating twenty years later, in 1846, when it began to be managed by the Ministry of War under a new name of Imperial Observatory of Rio de Janeiro (Liais 1881). According to the German scientist Frederico Maurício Draenert, one of the first to describe the climate of Brazil, meteorological activities at the Observatory only started in 1851 (Draenert 1886). In 1871, the Observatory was taken from the military administration and reorganized by its new director, the French astronomer Emmanuel Liais, who in 1881 was succeeded by the Belgian astronomer Luís Cruls, who was succeeded, after his death in 1908, by the French astronomer Henrique Charles Morize (Oliveira 2009; Sampaio-Ferraz 1994).

Considering the history of a country that became independent in 1822, meteorological activities started only 30 years later (in 1851), it seems a rapid evolution. However, in the 16th century in Europe, Meteorology had already given its first scientific signs thanks to the invention of the first meteorological instruments: the thermoscope, by Galileo Galilei in 1593 and the mercury barometer, by Evangelista Torricelli in 1644, both in Italy, and the hygrometer of human hair by Johann Heinrich Lambert and Horace Benedict de Saussure in Switzerland in 1783 (Nebeker 1995; Sorbjan 1996). In Italy, the first meteorological observation network, consisting of seven stations located in that country, and involving measurements of air temperature, atmospheric pressure, relative air humidity and the sky condition, was created by Ferdinand II de' Medici in 1654 (Sorbjan 1996). In the United Kingdom, Admiral Fitz Roy, founder of the Meteorological Office (Met Office), in 1854, produced synoptic forecasts (a term created by himself) for the general public since 1861 (https://www.metoffice.gov.uk/about-us/who/our-history). Fitz Roy was also known for being the commander of the HMS (Her/His Majesty's Ship) Beagle, when Charles Darwin made his voyage around the world between 1831 and 1836 (Bergeron 1981).

According to Neiva (1988), hydrographic ships on campaign off the Brazilian coast had already been carrying out meteorological observations since 1862. However, it was only on April 4, 1888, that the Central Meteorological Department was created, subordinated to the Secretary of State for Navy Affairs and headed by the Lieutenant Commander Américo Brasílio Silvado. Neiva (1988) comments that from 1886 onwards, the General Telegraph Department, under the direction of engineer Guilherme Schüch, known as Barão de Capanema, also began installing meteorological observation stations in the national territory.

Barboza (2006) reports that on the night of July 11, 1887, a storm caused the sinking of the steamship Rio-Apa off the coast of Rio Grande, in Rio Grande do Sul state, causing the death of about 160 passengers. At that time in Brazil, there was no weather forecasting whatsoever, just an incipient meteorological network maintained by the Rio de Janeiro Observatory. Even so, Henrique Morize, at the time an engineering student and an employee of the Rio de Janeiro Observatory, took the initiative to report to society the event. The commotion caused by the sinking of the Rio-Apa forced, in a way, the organization of a weather forecasting service.

Thus, at the end of the 19th century, as described in Sampaio-Ferraz (1994), the need for integration and organization of meteorological services was evident, which incidentally continues to be pursued to this day. In that way, it begins a dispute for the leadership of the national entity in charge of gathering and consolidating the meteorological services. Silvado defended the idea that this division should be under the aegis of the Ministry of Navy, while Morize defended that the National Observatory should be in charge of such a mission. This controversy lasted for some years and it was finally decided by the government authorities to create the Directorate of Meteorology and Astronomy at the National Observatory under the responsibility of the Ministry of Agriculture, Industry and Commerce, on November 18, 1909, under the headship of Morize. By the way, the year of 1909 is considered by the current INMET as the starting point of this institute (Oliveira 2009). With this decision, the national meteorological network was unified, including the state networks, the Telegraph network and the Navy network. Thus, it can be said that this first institutional arrangement was successful aiming at the unification of meteorological activities at the national level.

Sampaio Ferraz, who graduated in Civil Engineering in England in 1900, was Morize's assistant and became the Head of the Meteorology Section of the National Observatory. This section was in charge, by internal regulations, of developing activities related to weather forecasting, climatology, studies of droughts, drought regimes and river floods. In 1913, Sampaio Ferraz was appointed to perform advanced internships in the main European meteorological institutes and took the opportunity to print in Brussels his manual called "Meteorological Instructions" aimed at standardizing meteorological observation processes and guaranteeing the use of established rules in the most developed countries in this sector. Back in Brazil, Sampaio Ferraz receives Morize's mission to organize the first synoptic charts and perform the weather forecasting, covering a large part of Brazil, Chile, Uruguay, Paraguay and Argentina. With great effort, in 1917 Sampaio Ferraz performed systematic weather forecasting and started to disclose the referred forecasts for the Federal District and the State of Rio de Janeiro (Sampaio-Ferraz 1994).

At the beginning of the 20th century in Europe, Meteorology already stood out as an independent science and operational service, with autonomy and without the natural obstacles of Astronomy. Therefore, the situation of the mixed Board with two sections was naturally uncomfortable: Astronomy and Meteorology. Aiming at a greater autonomy, in 1921 the government of Epitácio Pessoa promoted the separation of the two institutes and created the Directorate of Meteorology (Diretoria de Meteorologia), with Joaquim de Sampaio Ferraz being its first director, remaining in the position until 1930.

In the period between 1855 and 1890, most of the world meteorological services were already organized and had as their main task the elaboration of the weather forecasting (Bergeron 1981). In the 1850s, Joseph Henry, first director of the Smithsonian Institution in Washington (USA) and also considered the father of the National Weather Service, produced a daily synoptic map indicating the weather conditions from the first network of meteorological stations linked by telegraph, which had already been invented by Samuel Morse and patented in 1838 (https://siarchives.si.edu/history/joseph-henry). At that time, with the amount of data available, scientists made new discoveries and developed new theories about the weather. Henry identified that local storms were part of larger weather systems and Lapham used these data to show that storms moved across the country from west to east and that their trajectories could be traced on maps https://www.smithsonianmag.com/history/joseph-henrys-legacy-147074473/).

## 3 The Era of the Subjective Weather Forecasting

According to Neiva (1988) the period between 1933 and 1948 represented a phase of obscurity in national Meteorology, mainly, with the temporary disappearance of the Directorate of Meteorology. Only by acts of 1941 and 1942, which took effect in the following years, the Meteorology regained momentum with the unification of services and the nominal extinction of state agencies. Also in 1943 the Aeronautical Meteorological Service, under the Ministry of Aeronautics, was created.

During World War II (1939-1945), Meteorology took on a new breath, because the belligerents realized that the weather forecasting was extremely necessary for war operations. Thus, steps were taken for a new outbreak of meteorological development, in Europe and in the United States of America (USA), based on reliable observations and the application of methods, albeit rudimentary, of short-term weather forecasting, based on manually elaborated synoptic analyses. This fact also influenced Brazil, causing an increase in meteorological activities. At the same time, during the end of World War II, until the 1950s, there was an extraordinary dedication to advanced studies on weather forecasting, treated as an important branch of physics and with advanced mathematical applications.

Moura (1996) highlights that this post-war movement led to the establishment of the NWP, mainly in the USA, with the participation of German, Norwegian and Japanese scientists, including Carl Gustav Rossby, John von Neumann, Jule Gregory Charney, Norman Phillips, Joseph Smagorinsky, Ragnar Fjortoft, Sikuro Manabe, Kikuro Niakoba, among others. This group took back the pioneering studies of Bjerknes (1904) and Richardson (1922), trying to show that the primitive equations of motion could be solved numerically using fast computers. At the same time, in the mid-1940s, the first digital computer was developed, the ENIAC (Electronic Numerical Integrator and Calculator), with a design by Von Neumann. However, this period of high physical-mathematical studies that culminated in the dominance of the NWP in the following decades was not immediately followed by the countries of Europe and South America.

In Brazil, in the 1940s, the meteorologists Adalberto Serra, Leandro Ratisbona and Salomão Serebrenick stood out, among others, with in-depth studies on Synoptic Meteorology and Climatology and the publication of important pioneering works in this area in our country. It is important to mention the works of Serra (1948), specifically on weather forecasting techniques; Serra & Ratisbona (1942a) with the famous work “Air Masses in South America”; Serra & Ratisbona (1942b), with the work “The rain regimes in South America”; Serebrenick (1942) with the work “Meteorological classification of climates in Brazil”. Thus, in the 1950s, Brazil continued to use Synoptic Meteorology techniques for subjective weather forecasting, with applications mainly in Aeronautics, Navy and Agriculture.

In 1958, a group of Meteorologists founded the Brazilian Society of Meteorology (Sociedade Brasileira de Meteorologia - SBMET). Among the objectives of SBMET, in addition to bringing meteorologists together, was to create an undergraduate course in Meteorology in Brazil. The creation of the first undergraduate course, in 1964, was preceded by several negotiations in the late 1950s and early 1960s (Oliveira 2009; Pereira & Spinardi 2003). It is worth mentioning that the first steps were the creation, of the Campaign for the Training of Meteorologists (Campanha de Formação de Meteorologistas - CAME), by the Ministry of Education and Culture, in analogy with the creation of the Campaign for the Training of Geologists (CAGE, Barroso 1996). The next step was the signature of an agreement between CAME and the National Faculty of Philosophy of the University of Brazil (current Federal University of Rio de Janeiro -UFRJ). The role of CAME was to promote the training of meteorologists, reserving federal resources for paying professors, buying bibliographic material, improving the infrastructure and paying students scholarships.

It is also important to emphasize that even before the creation of the first undergraduate course in Meteorology at UFRJ, the first non-military institution to teach the technical course in Meteorology was the National Technical School, named today as Federal Center for Technological Education Celso Suckow da Fonseca, in the year of 1959 (Neiva Filho, Vasconcellos & Souza 2015). Currently, there are 14 universities in the country offering undergraduate courses in Meteorology (Table 1), most of them also with graduate courses, in addition to the INPE. The INPE’s Graduate Studies Program in Meteorology (Programa de Pós-graduação em Meteorologia - PGMet), the oldest in Brazil, began in 1968 (http://www.inpe.br/posgraduacao/met/sobre-curso.php). These 14 Meteorology undergraduate courses, most of them created after 2000, provide technical and scientific support to the development of the Meteorology in the country.

**Table 1** Brazilian universities offering an undergraduate course in Meteorology and its years of creation.

| University and website link | Acronym | Year of creation of the undergraduate course in Meteorology |
|---|---|---|
| Universidade Federal do Rio de Janeiro<br>(Federal University of Rio de Janeiro)<br>https://meteorologia.igeo.ufrj.br/ | UFRJ | 1964 |
| Universidade Federal de Campina Grande<br>(Federal University of Campina Grande)<br>http://www.dca.ufcg.edu.br/ | UFCG | 1973 |
| Universidade Federal do Pará<br>(Federal University of Pará)<br>https://www.famet.ufpa.br/ | UFPA | 1975 |
| Universidade de São Paulo<br>(University of São Paulo)<br>https://www.iag.usp.br/atmosfericas/bacharelado | USP | 1976 |
| Universidade Federal de Pelotas<br>(Federal University of Pelotas)<br>https://institucional.ufpel.edu.br/unidades/id/335 | UFPEL | 1978 |
| Universidade Federal de Alagoas<br>(Federal University of Alagoas)<br>https://icat.ufal.br/pt-br/graduacao/meteorologia | UFAL | 1979 |
| Universidade Federal de Santa Maria<br>(Federal University of Santa Maria)<br>https://www.ufsm.br/cursos/graduacao/santa-maria/meteorologia/ | UFSM | 2008 |
| Universidade Federal de Itajubá<br>(Federal University of Itajubá)<br>https://meteorologia.unifei.edu.br/ | UNIFEI | 2010 |
| Universidade Federal de Santa Catarina<br>(Federal University of Santa Catarina)<br>https://meteorologia.grad.ufsc.br/ | UFSC | 2012 |
| Universidade Estadual Paulista "Júlio de Mesquista Filho"<br>(State University of São Paulo "Júlio de Mesquita Filho)<br>https://www.fc.unesp.br/#!/departamentos/fisica/cursos/meteorologia/pagina-inicial/ | UNESP | 2013 |
| Universidade Federal do Oeste do Pará<br>(Federal University of Western Pará)<br>https://sigaa.ufopa.edu.br/sigaa/public/curso/portal.jsf?id=284585&lc=pt_BR | UFOPA | 2013 |
| Universidade do Estado do Amazonas<br>(State University of Amazonas)<br>https://sites.google.com/a/uea.edu.br/coordenacao-meteorologia/ | UEA | 2014 |
| Universidade Federal do Rio Grande do Norte<br>(Federal University of Rio Grande do Norte)<br>https://www1.ccet.ufrn.br/meteorologia-bacharelado/ | UFRN | 2014 |
| * Universidade Estadual do Norte Fluminense Darcy Ribeiro<br>North Fluminense State University<br>https://uenf.br/cct/lamet/ | UENF | 2020 |

* In the accreditation phase

In the period from the 1960s until the operational implementation of the NWP in Brazil in the 1990s, the world witnessed an extraordinary advance in the field of meteorological observations, information technology and communication processes. Thus, this period can be described as a preparation for the development of modern activities in current Meteorology, with a leap in quality and consistent with the scientific and technological effort involving various branches of science. In the field of meteorological observation for operational purposes, the Radiosonde, the Meteorological Radar, the Meteorological Satellite and the Automatic Weather Stations stand out. In the field of computer science, the development of hardware and software stands out, with supercomputers and numerical models and algorithms. Finally, in the field of communications, the improvement of data and image transmissions stands out, overcoming the old teletypes and telegrams. Because of its importance in short-term weather forecasting, we present in Section 4 a historical summary of the evolution of weather radar, not exhausting the subject, but providing a generic view for an indispensable understanding of the current stage of weather forecasting.

## 4 A Brief History of Weather Radar

The Radar (Radio Detection and Ranging) was invented in 1904 by the German Engineer Christian Hulsmeyer, who showed that it is possible to identify the presence of ships through the reflection of radio waves. During the 1930s, British, German, French and American researchers developed the so-called pulsed radar, aiming at using the instrument to identify objects at a distance, with no physical presence other than radio waves (Sauvageot 1982).

Until World War II, radars were used only for war activities. However, in 1941, experiments using a radar with a wavelength of 10 cm (S-band) showed that it was possible to track rain clouds. This opened the perspective of using this instrument in Meteorology. Research continued into the post-war period, and by 1950 a reflection radar capable of measuring the position and intensity of precipitation was available, which was then incorporated into meteorological services in short-term weather forecasting (Sauvageot 1982).

According to Ligda (1951), meteorological phenomena with spatial scale from 10 to 100 km could not be detected by ordinary synoptic charts because they appear on these charts as “noises”. On the other hand, the microscale could not even identify these phenomena because they are very small. Thus, Ligda (1951) showed that the only way to overcome these difficulties would be using meteorological radar images, which produce useful information about the structure and behavior of portions of the atmosphere that were not covered by traditional meteorological information. Furthermore, Ligda (1951) suggested that these phenomena occur on a “meso-meteorological” scale.

Between 1950 and 1980, reflection radars, which measure the position and intensity of precipitation, were incorporated by meteorological services around the world. But it was not until the 1970s that radars began to be standardized and organized into networks. One of the main innovations in radar was the introduction of dual polarization, using the Doppler effect. This made it possible to track the relative speed of air particles, as well as the position and intensity of rain clouds (Sauvageot 1982). Thus, from 1980 to 2000, radar networks in the USA, Japan and Europe became common and conventional radars were replaced by Doppler radars. The development of radars was highly benefited by the fast advances in computer technology with the formulation of algorithms to detect, for example, severe weather signals, improving operational meteorological applications and scientific research.

In Canada, a 5 cm research Doppler radar was developed in 1985, which incorporated the Doppler technology in 1993. European countries, led by France, set up their Doppler radar networks in early 2000.

The experience of installing and operating meteorological radars in Brazil shows a set of initiatives performed by different institutions at different times. Today, there are three national radar networks, accounting for 26 instruments in operation, with little interaction between them (Table 2):

**Table 2** Information on the weather radars installed in Brazil by federal institutions.

| Region | Body | Location |
|---|---|---|
| Distrito Federal | DECEA | Gama (Brasília) |
| Acre | SIPAM | Cruzeiro do Sul |
| Alagoas | CEMADEN | Maceió |
| Amapá | SIPAM | Macapá |
| Amazonas | SIPAM | Manaus<br>São Gabriel da Palha<br>Tabatinga<br>Tefé |
| Bahia | CEMADEN | Salvador |
| Espírito Santo | CEMADEN | Santa Tereza |
| Maranhão | SIPAM | São Luiz |
| Mato Grosso do Sul | CEMADEN | Jaraguari |
| Minas Gerais | CEMADEN | Almenara<br>São Francisco<br>Três Marias |
| Pará | SIPAM | Belém<br>Santarém |
| Pernambuco | CEMADEN | Petrolina |
| Rio de Janeiro | DECEA | Pico do Couto (Petrópolis) |
| Rio Grande do Norte | CEMADEN | Natal |
| Rio Grande do Sul | DECEA | Canguçu<br>Santiago |
| Rondônia | SIPAM | Porto Velho |
| Roraima | SIPAM | Boa Vista |
| Santa Catarina | DECEA | Morro da Igreja |
| São Paulo | DECEA | São Roque |

(i) Department of Airspace Control (Departamento de Controle do Espaço Aéreo - DECEA) of the Brazilian Air Force (Força Aérea Brasileira – FAB). From the 1990s onwards, DECEA developed and installed a network composed of 6 S Band Doppler radars, installed in the following locations: Gama (Distrito Federal - DF), Pico do Couto (Rio de Janeiro - RJ), Canguçu and Santiago (Rio Grande do Sul - RS), Morro da Igreja (Santa Catarina - SC) and São Roque (São Paulo - SP);

(ii) Amazon Protection System (Sistema de Proteção da Amazônia - SIPAM). In the 2000s, SIPAM installed a network of 11 S Band Doppler meteorological radars in the Legal Amazon: Manaus, São Gabriel da Cachoeira, Tabatinga and Tefé (Amazonas - AM), Cruzeiro do Sul (Acre - AC), Macapá (Amapá - AP), São Luiz (Maranhão - MA), Belém and Santarém (Pará - PA), Porto Velho (Rondônia - RO), Boa Vista (Roraima - RR)

(iii) National Center for Monitoring and Early Warning of Natural Disasters (Centro Nacional de Monitoramento e Alertas de Desastres Naturais - CEMADEN). CEMADEN, in partnership with DECEA, installed a network of 9 S-band Doppler radars in the following locations: Maceió (Alagoas - AL), Salvador (Bahia - BA), Santa Tereza (Espírito Santo - ES), Almenara, São Francisco and Três Marias (Minas Gerais - MG), Jaraguari (Mato Grosso do Sul - MS), Petrolina (Pernambuco - PE) and Natal (Rio Grande do Norte - RN).

In addition to these three national networks, several radars were installed by state initiatives and municipal institutions (Table 3), comprising a set of networks of considerable value for monitoring rainfall and short-term weather forecasting.

The Institute of Meteorological Research (Instituto de Pesquisas Meteorológicas - IPMET) was the pioneer in Brazil in terms of installation and operation of meteorological radars, with the installation in 1974 of the first C-band radar, in the city of Bauru, operating until 1992 and being replaced by an S-Band Doppler radar, which remains in operation to the present day (ipmetradar.com.br/2historico.php). The three radars in the State of São Paulo (two from IPMET and one from the Department of Water and Electric Energy of São Paulo - DAEE) have not been used in a network with image integration between them. This initiative is being carried out by a team from USP.

The state of Rio de Janeiro has four meteorological radars: the DECEA's S-band radar (Table 2); one from the City Hall of Rio de Janeiro (Rio Early Warning System – Alerta Rio), located on the top of Serra da Carioca, in the Tijuca National Park; and two from the State Institute for the Environment (Instituto Estadual do Ambiente - INEA): one at UENF campus, in Macaé, and another located in

**Table 3** Information on the weather radars installed in Brazil by state and municipal institutions.

| State | Institution | Location | Start Operation | Final Operation | Radar type |
|---|---|---|---|---|---|
| São Paulo | IPMET (Meteorological Research Institute) | Bauru | 1974 | 1992 | C Band |
| | | | 1992 | current | S Band Doppler |
| | | Presidente Prudente | 1990 | current | S Band Doppler |
| | DAEE | Salesópolis | 1989 | 2014 | S Band |
| | | | 2014 | current | Double polarization S Band |
| Rio de Janeiro | Alerta Rio | Rio de Janeiro (Parque Nacional da Tijuca) National Park of Tijuca | 2010 | current | C Band |
| | INEA | Macaé (UENF) | 2014 | current | Double polarization S Band |
| | | Mangaratiba | 2014 | current | Double polarization S Band |
| Ceará | FUNCEME | Fortaleza | 1993 | current | Doppler X Band |
| | | Quixeramobim | 2011 | current | Doppler S Band |
| Paraná | SIMEPAR | Teixeira Soares | 1998 | current | Doppler S Band |
| | | Cascavel | 2014 | current | Circular polarization S Band Doppler |
| Minas Gerais | CEMIG | Matheus Leme | 2012 | current | Double polarization C Band Doppler |
| Espírito Santo | CCMH | Aracruz | 2013 | current | Double polarization S Band Doppler |
| Santa Catarina | EPAGRI/CIRAM | Lontras | 2014 | current | Double polarization S Band Doppler |

Mangaratiba, which operate together. Such radars provide a complete coverage over the state of Rio de Janeiro, but only INEA radars produce integrated images for their entire coverage area. The integration of these four radars produces a single mosaic for the entire coverage area. These equipments have been used intensively to help in regional weather forecasting, with a wide advantage especially in the weather analysis, allowing the elaboration of meteorological early warnings, predicting adverse weather situations in Rio de Janeiro.

In addition to the radars installed in São Paulo and Rio de Janeiro, the Meteorology Foundation of Ceará (Fundação Cearense de Meteorologia - FUNCEME), the Paraná Environmental Monitoring and Technology System (Sistema de Tecnologia e Monitoramento Ambiental do Paraná - SIMEPAR), the Minas Gerais Energy Company (Companhia Energética de Minas Gerais - CEMIG), the Capixaba Hydrological Monitoring Center (Centro Capixaba de Monitoramento Hidrológico - CCMH) and the Agricultural Research and Rural Extension Company of Santa Catarina/Santa Catarina Environmental Resources and Hydrometeorology Information Center (Empresa de Pesquisa Agropecuária e Extensão Rural de Santa Catarina/Centro de Informações de Recursos Ambientais e Hidrometeorologia de Santa Catarina - EPAGRI/CIRAM), maintains seven more radars in operation in their states.

Despite the 39 existing meteorological radars, there are still uncovered areas, such as the Midwest Region of Brazil. Moreover, the integration of these radars and the elaboration of complete maps of images are necessary in many parts of Brazil. Another issue is the integration of radar images with satellite images, to comprise a complete picture of images that can effectively help in the weather forecasting.

## 5 The Era of Numerical Weather Prediction

Before the operational implementation of the NWP in Brazil, several scientific papers on the subject were published, mainly by INPE researchers. Therefore, the scientific bases were already sufficiently known for that time, but the indispensable elements for the elaboration of the operational NWP were missing: A numerical model and a supercomputer to run that model, in addition to an institution to accommodate all NWP operations in Brazil. According to Miguel, Escada & Monteiro (2016), the first supercomputer was purchased (NEC-SX-3, of 3.2 billion operations of floating point per second, 3.2 gigaflops, of processing capacity) in 1994, being accommodated in CPTEC/INPE. The CPTEC had been recommended since 1987, but implemented only in 1993, and the appropriate numerical model for that time (atmospheric general circulation model (AGCM) of the "Center for Ocean-Land Atmosphere Studies" (COLA) - USA) was chosen. Therefore, conditions were created for the implementation of numerical forecasting in Brazil, starting in 1995, with CPTEC/INPE as the precursor institution of the new stage of development of Brazilian Meteorology. Since then, Brazilian weather forecasting has undergone a leap in quality, associating itself with the NWP and the dissemination of observational systems, including automatic weather stations, satellite and radar images, in addition to the improvement of systems of data communication. Currently (2021) the CRAY XT-6 Supercomputer is in operation at CPTEC/INPE, executing 244 trillion floating point operations per second (244 teraflops).

The AGCM developed by COLA and used by CPTEC received increasing improvements over time and researchers named it CPTEC/COLA from 2002 onwards. The changes continued in the following years and in 2004 already completely modified in its dynamic and physical part, it was renamed CPTEC/INPE AGCM. In 2016, the AGCM CPTEC/INPE was replaced by the BAM (Brazilian Global Atmospheric Model) which works today with a 20 x 20 km horizontal resolution, 96 vertical layers, covering the entire globe and producing forecasts for up to 264 hours (11 days).

In addition to the AGCMs, there are also regional atmospheric models (RAMs), such as Eta model (Mesinger et al. 1988) which was implemented at CPTEC in 1995 (Chou 1996). This category of model takes into account orography, land-sea interactions, among others, and is intended to forecast meteorological phenomena at a mesoscale in greater detail. This model was the first operational RAM at CPTEC and greatly aided Brazilian meteorologists in their daily task of weather analysis and forecasting. The Eta model was also the pioneering model over South America focusing on monthly to seasonal-scale simulations. This dynamical downscaling technique over South America was carried out by Chou, Nunes & Cavalcanti (2000) who performed a couple of 1-month long simulations with the aim of exploring the quality of extended range forecasts nesting the Eta into the CPTEC/COLA GCM (Solman 2013). Unfortunately, in 2019, the Eta model was replaced, for operational purposes, by the Weather Research and Forecasting - WRF (Iriart et al. 2011), with a horizontal resolution of 5 km. The Brazilian Regional Atmospheric Modeling System (BRAMS) had the same fate. BRAMS was an adaptation of the American Regional Atmospheric Modeling System (RAMS), implemented in 2003, but currently no longer operational at CPTEC/INPE.

In addition to CPTEC/INPE, two more important national centers that execute NWP operationally should be mentioned. These are INMET and CHM. In 2000, INMET started to operate the Brazilian High Resolution Model (Modelo Brasileiro de Alta Resolução - MBAR), with a horizontal resolution of 25 km, developed in cooperation with the German government (Oliveira 2009). To implement the MBAR, INMET created its High Performance Meteorological Computing Center (Centro de Computação Meteorológica de Alto Desempenho - CCMD). Currently, INMET runs the Consortium for Small-scale Modeling (COSMO), a limited-area hydrostatic model developed with the support of the German meteorological center Deutscher Wetterdienst (DWD) and the Swiss meteorological center MeteoSchweiz (MCH). COSMO is nested into the German Icosahedral Non hydrostatic Model (ICON), producing medium range forecasts (up to 15 days) over South America at 7-km horizontal resolution (https://vime.inmet.gov.br/).

The CHM Navy Weather Service operates two regional numerical models: COSMO and WRF, both described above. The Navy's COSMO follows the same criteria as the model operated by INMET, that is, a consortium of European countries and Brazil. The COSMO operated by CHM is also initialized by the data produced by ICON, with the same horizontal resolution (7 km). On the other hand, WRF is used in contingency moments, as a technical backup to COSMO, that is, it comes into operation in cases where, due to some technical problem, it ceases to operate normally.

## 6 The Current Meteorological Services Organization

To understand the organization of Brazilian meteorological services, it should be considered first that in Brazil, Meteorology is not an activity of the exclusive competence of the Union. Without an arrangement or public responsibility for the sector, there is a huge space for the creation of several public institutions: federal, state, and municipal. Sometimes the overlaps of activities cause waste of financial and human resources, besides hindering the rational use of modern technologies in computer science, meteorological observations and communication systems. However, it should be noted the existence of indispensable institutions for important sectoral services, such as aeronautics, navy, agriculture, civil defense, among others.

In the field of Aeronautical Meteorology, we highlight the Integrated Center for Aeronautical Meteorology (Centro Integrado de Meteorologia Aeronáutica - CIMAER), a unit of DECEA, under the Ministry of Defense (https://www.decea.mil.br/). CIMAER aims to provide the service of Aeronautical Meteorology, under the Brazilian Airspace Control System (Sistema de Controle do Espaço Aéreo Brasileiro - SISCEAB), to guarantee safety standards and the economy and efficiency of flights. The centralization of the aeronautical meteorological service under CIMAER, created in 2019, was intended to avoid the redundancy of personnel and functions to perform the surveillance and weather forecasting activities previously carried out by the SISCEAB Network of Meteorological Centers and the sparse interaction between these Centers. To integrate the meteorological products for civil and military aviation and to make access to this information faster, more efficient and safe, DECEA created a website called Aeronautical Command Meteorology Network (Rede de Meteorologia do Comando da Aeronáutica - REDEMET). At the REDEMET website (https://www.redemet.aer.mil.br/), besides the hourly Meteorological Aerodrome Reports (METARs) collected from around 100 meteorological stations, and satellite and radar images, also meteorological charts produced using WRF are available. Unfortunately, so far, the limited number (34) of upper air soundings (TEMPs) are not available at REDEMET.

The Management and Operational Center of the Amazon Protection System (Centro Gestor e Operacional do Sistema de Proteção da Amazônica - CENSIPAM - https://www.gov.br/defesa/pt-br/assuntos/censipam), a civil body created in 2002 and still subordinate to the Ministry of Defense, works in meteorological surveillance in the Amazon, maintaining a network of 11 weather radars in the region (see Table 2).

The CHM, from the Brazilian Navy Command, under the Ministry of Defense, aims to support the application of the Naval Power through activities related to Meteorology, hydrography, oceanography, cartography, navigation and nautical signaling, ensuring the quality of navigation safety activities. At the CHM Navy Weather Service website (https://www.marinha.mil.br/dhn/), besides the forecasts produced by COSMO regional model, it is possible to access real-time data from 13 coastal sites meteorological stations and some moored buoys. Moreover, CHM maintains, since 1994, the National Oceanographic Database (Banco de Dados Oceanográfico – BNDO) to support the Intergovernmental Oceanographic Commission (Comissão Oceanográfica Internacional – COI).

The CPTEC/INPE, under the Ministry of Science, Technology and Innovations (Ministério da Ciência, Tecnologia e Inovações - MCTI), aims to provide the country with the state-of-the-art technologies in numerical weather and climate prediction and to be able to continuously improve them. Thus, the implementation of the NWP by CPTEC/INPE should have given support to other Brazilian institutions in their weather forecasting tasks. But, in fact, as pointed out in Section 5, this is not what happened, as CHM and INMET's RAMs are running nested to the German ICON model.

On May 3, 2021, the creation of the National Meteorology System (Sistema Nacional de Meteorologia - SNM) was announced. It was formed by INMET, INPE and CENSIPAM. The purpose of the SNM was to eliminate any type of overlapping of activities between these three institutions, in order to make National Meteorology more efficient. Then, CPTEC/INPE stopped disclosing to the general public the weather forecasts and meteorological warnings, an activity that started to be performed by INMET. However, it is clear that, in order to avoid overlaps, INMET should use INPE's models, which in fact has never occurred. Anyway, after just five months, in October 2021, the SNM was extinguished.

The CEMADEN, also subordinated to the MCTI, has been dedicated to monitoring natural threats in risk areas in Brazilian municipalities susceptible to the occurrence of natural disasters. CEMADEN's ultimate goal is to reduce the number of fatalities and material damage throughout the country. CEMADEN was created in 2011, after the Rio de Janeiro Mountain Region megadisaster, which killed more than 900 people between January 11 and 12, 2011. At CEMADEN website (https://www.gov.br/mcti/pt-br/rede-mcti/cemaden/), it is possible to access data from its network of automatic rain gauges, more than 3,000, as well as data from hydrological stations.

In addition to CEMADEN, the National System of Protection and Civil Defense (Sistema Nacional de Proteção e Defesa Civil - SINPDEC), of the Ministry of Regional Development, aims to reduce the risks of disasters, including prevention, mitigation, preparation, response and recovery actions, acting at the three levels of federal, state and municipal government. All Brazilian states have a body responsible for developing civil protection and defense activities in their respective territories, including the meteorological, hydrological and geological monitoring of risk areas, performed in conjunction with the Union and municipalities. We highlight here the Amazonas (http://www.defesacivil.am.gov.br/cemoa/), Espírito Santo (https://alerta.es.gov.br/), Rio de Janeiro (http://www.contingenciaverao.rj.gov.br/index.php), Santa Catarina (https://www.defesacivil.sc.gov.br/avisos-meteorologicos/), and São Paulo (http://www.defesacivil.sp.gov.br/previsao-do-tempo/) services. The first Brazilian state Civil Defense (Civil Defense of the State of Guanabara) was created in December 1966 after the great flood of January 11 and 12, 1966, when 117 people died.

In terms of agrometeorology, INMET is officially the Brazilian institution responsible for developing the meteorological activities applied to agriculture, being subordinate to the Ministry of Agriculture, Livestock and Supply (Ministério da Agricultura, Pecuária e Abastecimento - MAPA). INMET is also Brazil's representative at the World Meteorological Organization (WMO). Currently, INMET operates 570 (170) automatic (conventional) meteorological stations and they also store the longest series of meteorological data in BDMEP Database (Banco de Dados Meteorológicos do INMET).

In addition, a joint initiative of the Brazilian Agricultural Research Company Agricultural Informatics (Empresa Brasileira de Pesquisa Agropecuária - EMBRAPA Informática Agropecuária), the Center for Meteorological and Climate Research Applied to Agriculture (Centro de Pesquisas Meteorológicas e Climáticas Aplicadas à Agricultura - CEPAGRI) of the University of Campinas (UNICAMP) and CPTEC/INPE resulted in the website "Agritempo". The website Agritempo provides data and meteorological products free of charge, aiming to serve the different actors of the agricultural sector such as producers, cooperatives, private companies, government agencies and public agricultural research institutes. Also noteworthy in the agrometeorology area is the EPAGRI/CIRAM of Santa Catarina, with meteorological, hydrological and even maritime warnings on its website (https://ciram.epagri.sc.gov.br/).

With regard to the Brazilian electricity sector, the performance of Meteorology is of fundamental importance and has grown in recent years to support the generation, transmission and distribution of energy. According to Lima (2005), the insertion of Meteorology within the activities of companies in the electricity sector occurred only after the accident with the power plants of the Rio Pardo in the state of São Paulo, in January 1977, when the dams of Euclides da Cunha and Armando de Salles Oliveira broke. Some companies in the sector began to structure themselves, implementing meteorological centers, as it was the case of the São Paulo Energetic Company (Companhia Energética de São Paulo - CESP), Minas Gerais Energetic Company (Companhia Energética de Minas Gerais - CEMIG) and Furnas Centrais Elétricas. In the case of the Paraná Energetic Company (Companhia Paranaense de Energia - COPEL), Meteorology activities are supported by the SIMEPAR through an agreement between the two companies. With the restructuring of the electricity sector in the late 1990s, the National Electric System Operator (Operador Nacional do Sistema Elétrico - ONS) began to coordinate and control the operation of electricity generation and transmission facilities in the National Interconnected System (Sistema

Interligado Nacional - SIN). Among the ONS attributions stands out the monitoring and meteorological forecast for the hydrographic basins and transmission lines of SIN interest, for the centers of energy consumption (Machado et al. 2007).

Some of the Brazilian states have established state meteorological services to meet the demands of their own states and in some cases covering broader regions. Thus, the following institutions can be cited: (i) FUNCEME (http://www.funceme.br/), today integrating the Department of Water Resources of Ceará (Secretaria de Recursos Hídricos do Ceará), which produces weather forecast for the state of Ceará and also for several states in the Northeast Region of Brazil; (ii) SIMEPAR (http://www.simepar.br/), a state entity linked to the Secretariat of State and Sustainable Development and Tourism of the state of Paraná, created in 1993, and which carries out weather and climate monitoring activities in the state of Paraná. SIMEPAR maintains a good weather observation network through data collection platforms, as well as a lightning detection network, weather radar, and satellite image reception.

An example of a municipal organization that carries out weather forecasting and monitoring activities is the Alerta Rio (alertario.rj.gov.br), created in 1996. The Alerta Rio uses a network of rainfall and meteorological stations, all equipped with telemetry systems, as well as a weather radar, with real-time images (Table 3). It is important to note that the Alerta Rio was created in September 1996, after the disaster caused by a heavy rainfall in the municipality of Rio de Janeiro on February 13, 1996 (Pinguelli, Rosa & Lacerda 1997). During this disaster, 200 people died and 30,000 became homeless (Dereczynski, Calado & Barros 2017).

In addition to all these services, it is important to mention the attempt of the MCTI to create a network of official state services dedicated to regional activities in the areas of Meteorology and Hydrology, called "Program for Monitoring Weather, Climate and Water Resources" (Programa de Monitoramento de Tempo, Clima e Recursos Hídricos – PMTCRH, PMTCRH 1991). The PMTCRH survived for more than ten years, but it was discontinued in the early 2000s. The Rio de Janeiro State Meteorology System (Sistema de Meteorologia do Estado do Rio de Janeiro - SIMERJ), linked to PMTCRH, had a good performance from 1997 until 2011 and served as the basis for the creation of the current CEMADEN Rio de Janeiro, subordinated to the State Civil Defense. It is important to note that CEMADEN and CEMADEN Rio de Janeiro have the same name, but are distinct institutions, being the former subordinate to the MCTI.

Regarding the important data generated by these various federal, state and municipal institutions, it would be very helpful if they could be made available in a single database. Nowadays it is necessary to access separately the BDMEP, BNDO, HIDROWEB Database from the National Agency for Water and Basic Sanitation (Agência Nacional de Águas e Saneamento Básico - ANA), and the CEMADEN Observational Network.

## 7 Main Weather Sites Available for Weather Forecasting

Currently, the meteorologists use websites and applications (apps) to prepare the weather forecast. Among Brazilian websites, the most accessed are those maintained by CPTEC/INPE (https://www.cptec.inpe.br), INMET (https://portal.inmet.gov.br/) and CIMAER/DECEA (REDEMET - https://www.redemet.aer.mil.br/). In addition to these, there are applications from private companies that are accessed by laymen and meteorologists, such as Windy developed in the Czech Republic (https://www.windy.com).

Figure 1 shows the results of a survey on meteorological sites used for weather forecasting, performed in March 2021 using Google Forms. A total of 102 meteorologists working operationally in national weather forecasting services answered the questionnaire, being all fields mandatory and all responses unique. The results show the three preferred sites where meteorologists access each type of information: For satellite images (Figure 1A), Windy was the most voted (30.4% of meteorologists) and in second place was CPTEC/INPE (29.4%), followed by INMET (18.6%). Radar images (Figure 1B) are preferably obtained from REDEMET (58.8%), then from Windy (16.7%) and third from CEMADEN (7.8%). Almost 60% of meteorologists prefer to consult atmospheric soundings (Figure 1C) through the website of the University of Wyoming (http://weather.uwyo.edu/), in second place (19.6%) in the website Meteorology Applied to Regional Weather Systems (Meteorologia Aplicada a Sistemas de Tempo Regionais - MASTER) of the Astronomy and Geophysics Institute from USP - IAG/USP (http://www.master.iag.usp.br/) and finally 5.1% prefer INMET. Observational data (Figure 1D) and forecasts in the form of meteograms (Figure 1E) are preferably accessed in INMET website (39.2% and 30.4% respectively). One last question asked: "If you had to choose only one of the websites/apps below to prepare your weather forecast, which one would it be? The answer of 45.1% of meteorologists was Windy (Figure 1F).

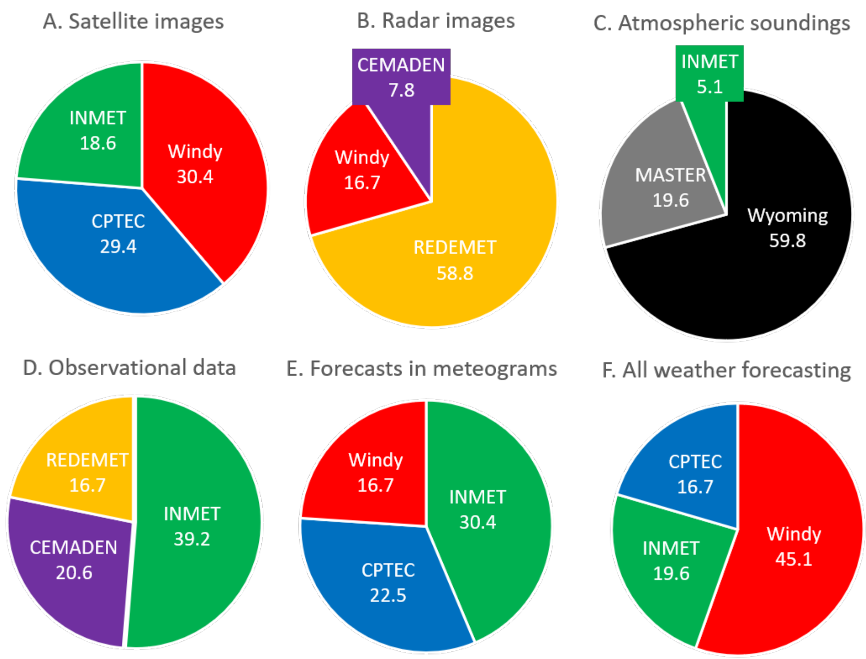


**Figure 1** Preferred sites for obtaining: A. Satellite images; B. Radar images; C. Atmospheric soundings; D. Observational data; E. Forecasts in meteograms and F. All weather forecasts.

It is important to emphasize that this survey with operational meteorologists was carried out in a period of social isolation caused by the Coronavirus pandemic (COVID-19). As of mid-March 2020, most weather services have been performed remotely, and the usual daily face-to-face briefings from weather forecasting centers have been replaced by short online meetings. Thus, the forecasters had to quickly adapt to a new work routine, preferring light applications and quick access via their home internet. Furthermore, the new generation of meteorologists is used to social media (Instagram, Facebook, Tweeter…), where communication occurs in a summarized and often superficial way. On the other hand, weather forecasting became popular through the access to several apps via cell phone, increasing the demand for information to meet the needs of outdoor sports practices, tourism and leisure in general. Due to all these facts it is understandable why the Windy app has become so popular.

## 8 Conclusions and Final Considerations

This article presents a concise historical review of weather forecasting in Brazil, dividing it into three main phases: i) The Earliest Times of Meteorology; ii) The Era of the Subjective Weather Forecasting, and iii) The Era of the Numerical Weather Prediction. In addition, we present a brief history of weather radar, the current organization of meteorological services and the results of a survey on websites, involving 102 meteorologists working operationally in weather forecasting services.

Firstly, it is clear that the great advance achieved in the field of weather forecasting occurred after the introduction of the NWP by CPTEC/INPE at the end of the 1990s. Moreover, observational networks have undergone a great expansion, with a significant increase in the number of weather stations in recent decades. Also, the current 14 undergraduate courses in Meteorology, most of them created after 2000, meet the increase in demand for specialists.

Regarding the organization of the current meteorological services it is evident that it was not designed in a way to bring institutions together, either at the federal, state and municipal levels or even considering the civil and military areas. Many services were created to meet a certain demand, without connection with other existing institutions. Thus, there is a huge duplication of efforts, shading of activities, additional expenses and in some cases some gaps. Moreover, throughout the history of Meteorology institutions are formed from a governmental response to the occurrence of some adverse event.

A broad and complete overview of surface observations over the continent and offshore could be obtained by considering the integration of INMET, INPE, CEMADEN, CIMAER and CHM networks. Moreover, the current framework of 39 meteorological radars in Brazil is not negligible, however, it needs to be completed, as there are still areas without coverage, as the Midwest Region of Brazil. Another issue is the integration of radar images with satellite images to comprise a complete picture of images that can effectively help in the weather forecasting.

Finally, the result of the survey on the meteorological websites accessed for obtaining the products for the preparation of weather forecasts indicates that changes need to be implemented, ensuring easy access to data. A fast and well-developed application like Windy, however with more details for a good meteorological analysis, should be created to mainly serve the new generation of meteorologists.

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