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The history of climate services in IMD

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सार – IMD को देश में मौसम और जलवायु मामलों पर नोडल एजेंसी के रूप में कार्य करने के लिए बनाया गया था। यह लेख जलवायु सेवाओं के क्षेत्रीय अनुप्रयोगों से सीधे जुड़ाव के साथ एक अलग शाखा बनने की यात्रा को व्यापक रूप से कवर करता है और यह एक संपूर्ण दस्तावेज नहीं है। सैद्धांतिक रूप से, मौसम और जलवायु में अंतर होता है क्योंकि मौसम एक समय निर्दिष्ट जानकारी है और दूसरा एक निश्चित अवधि के लिए वैध सांख्यिकीय विवरण है। हालाँकि, दोनों भूभौतिकीय घटनाओं को संदर्भित करते हैं जो व्यक्तिगत और सामूहिक रूप से जीवन को प्रभावित करते हैं। जलवायु संबंधी अनुभव हमेशा से मानवीय गतिविधियों को प्रभावित करने वाली स्मृतियों के माध्यम से जीवित रहे हैं, लेकिन आधुनिक समय में भौतिक प्रेक्षणों को गणितीय और सांख्यिकीय तरीकों से व्यवस्थित और व्यापक रूप से दर्ज किया गया है। इसने सामाजिक अनुप्रयोगों को वस्तुनिष्ठ तरीके से करने की अनुमति दी। जलवायु खतरों के संबंध में कृषि, जल संसाधन, स्वास्थ्य, ऊर्जा उत्पादन और सुरक्षा पर जलवायु प्रभाव विशेष रूप से दिलचस्प हैं। जलवायु सेवाएँ मानवजनित प्रभावों के कारण होने वाले परिवर्तनों सहित विभिन्न समय अवधि में जलवायु की परिवर्तनशीलता से संबंधित हैं। इसने जलवायु ज्ञान के अनुप्रयोगों को बहुत महत्वपूर्ण बना दिया था। एक रूपरेखा जिसके भीतर इन सेवाओं को कार्य करने की आवश्यकता है, उसका भी यहाँ संकेत दिया गया है।

ABSTRACT. IMD was created to act as the nodal agency in the country on weather and climate matters. This article broadly covers the journey of Climate Services becoming a separate branch with direct linkages to sectoral applications and is not an exhaustive documentation. Notionally, weather and climate differ in the former being a time specified information and the latter a statistical description valid for a certain duration of time. Both, however, refer to geophysical phenomena which impact life as individuals and collective societies. Climatic experiences have for ever lived through memories influencing human activities but in modern times physical observations have been recorded systematically and extensively subjected to mathematical and statistical treatment. This allowed societal applications to be done in objective manner. Of particular interest are the climate effects on agriculture, water resources, health, energy production and safety with respect to climate hazards. Climate services pertain to variability of climate over different periods of time including the changes due to anthropogenic effects. This had made applications of climate knowledge very critical. A framework within which these services need to function are also indicated here.

Key words – Weather, Climate, Climate change, Climate observations, Prediction techniques, Societal sectors, Agriculture, Water resources, Health, Energy generation, Weather hazards, GFCS, NFCS.

1. Introduction

1.1. *Basic notions of Climate*

It is perhaps trivial to state that weather is the state of atmosphere at a given location and a specified point in time, whereas climate is its pattern over a certain span of time. Thus, weather is described by a set of physical quantities and climate is denoted by a process of abstraction using statistical attributes like say the Mean, Probability distribution *etc*. In a *posteriori* sense the climate is constructed from the time series of observations (climatology) while in *a priori* sense the statistical attributes are predicted by models.

It is entirely incidental to our consideration that predictions can be specified by time (deterministic) with reasonable accuracy, only up to a certain point in future. Beyond this time, we expect that, at least, statistical attributes of the predicted outcome will hold good. By definition then, all such predictions are to be called as climate predictions. It can easily be appreciated that in a practical sense the net impacts evaluated from statistical attributes will always be a poor substitute for what we could have got from the actual time series of outcomes, if that were to be available. Despite this shortcoming climate information is useful because it can yield accumulated impacts on real systems over a specified period of time, which in turn can tell whether tolerance limits of such systems (*viz*. holding capacity of dams, wilting point of crops, point of dehydration *etc*) are likely to be breached or not.

Even ancient societies have used the diurnal and seasonal cycles, the most elementary weather patterns, for phasing their activities. The word 'climate' itself originates in the Greek word 'klima', meaning solar altitude and the ancient Indian text of *Manusmriti*[1] holds the sun responsible for the season of rains and ultimate wellbeing of society. But losses due to anomalous conditions appearing within the seasonal cycles have been considered inescapable till recent times. Modern societies seek prior information about these very anomalous conditions, because in many situations they have the technological means to[1] overcome the adversities.

1.2. *The nature of Climate information*

All societal applications of climate information have respective lead times and durations. As for example a crop sensitive information must be notified in advance and be relevant for an entire phenological phase of the crop. On the other hand, a reservoir Dam design needs to know the outcome possibilities for its life time of centuries. The deterministic predictions can only go thus far and climate predictions somewhat more. For the rest of the period the *posteriori* approach of climatology will have to be used in the faith that the future will behave like the past. That too is suspect in the face of climate change. Challenges faced in providing climate information are indeed profound.

Climate studies have come to include physical, chemical and biological climate processes in a very major way. Knowledge of these is needed to predict climatic impacts and hence forms a part of Climate information in its totality. Moreover, boundaries of climate studies have considerably widened with our ability to handle the entire Earth System through numerical models. It is now becoming possible to determine climatic impacts in far more areas of applications. To give examples, the impact of extreme heat on crop growth can be refined via additional considerations like say, affected insect pollination, or the effect of deforestation can be estimated from various angles *viz*. water resource, agricultural productivity, climate change *etc*.

1.3. *Climate Services*

The scope of applications of climate information is truly growing exponentially. From its humble beginnings a century and half ago, it has grown in a major way in terms of demand for information, analysis, prediction, user engagement and policy input. The unification of all these functions under the common head of Climate Services has become necessary.

The Climate services (CS) are essentially scientifically based information that help users understand the different aspects of climate, such as its variability in space and time, deterministic and probabilistic statistics *etc* which can be used to appropriately formulate actions and policies. Climate services can be diverse and include climate forecasts and projections, current and past climate monitoring, archival of climate data and generation of statistical information. The climate information is also combined with sectoral information *viz*. economic conditions, census statistics, population distribution, crop distribution, hydrological information *etc*., that is/are relevant for assessing vulnerability. Climate services may include weather statistics (especially hazardous weather) in order to highlight their generic features. These may include atlases of storm tracks, catalogue of disastrous phenomena *etc.*

2. Background of climate services

2.1. *Early developments in India*

India has more than two centuries of modern meteorological observations and approximately 150 years of systematic observations taken at fixed hours of the day so that the effect of diurnal cycle gets filtered out and data is rendered amenable to climate analyses. Aided by the advent of telegraphy the data was primarily used for synoptic diagnostics of severe weather events, but equally significantly, for foreshadowing an ensuing monsoon as well. Evidently, as more and more global data began to be exchanged new strategies to find seasonal climate precursors emerged. First the Himalayan (later Eurasian) snow cover and then the Pacific region atmospheric pressures entered the regression equations for monsoon rainfall. Applications for agriculture were the next logical step which indeed happened by way of early delineations of agro-climatic zones by the middle of last century[2].

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[1] Manusmriti :

[2] Planning Commission in 1966 for the first time tried to regionalize India in terms of physical conditions, rainfall, orography, forest *etc*. In the 1988 Planning Commission designated 15 agroclimatic zones in India.

The earliest compilation of Rainfall statistics for the region by Henry Blanford (1886) also examines the causative factors and raises the spectre of rainfall alterations due to large scale deforestation which were underway in Central India at that time. The history of climate services, with its early beginnings, runs pretty long in India.

2.2. *Organizational growth*

From the end of 18th century to the middle of 19th century several provincial observatories were set up across India, which initially retained data at their ends but later began to send it in a delayed mode to the Alipore Office in Kolkata (then Calcutta), for record keeping. All provincial establishments were merged into one entity when the India Meteorological Department (IMD) came up in 1875 with its headquarters in Alipore. All early work related to data compilation were carried out there. The IMD became the national Meteorological Service and repository of all Climate data. In course of time the headquarters of IMD shifted to Shimla in 1912, where Sir Gilbert Walker carried out his researches on long range forecasting of Indian summer monsoon and thereafter to Pune in 1927. The data archive and Climatological division remained in Pune even after the headquarters were shifted to Delhi in 1947. The Pune office began to issue climatological publications including those in agrometeorology as routine practice as well as research.

The Climatology division, redesignated as the Research office of IMD for climate and hydrometeorological studies in 1980, worked in conjunction with the Agro-meteorology division to produce a vast array of research output on spatial patterns of rainfall, crop weather relationships, river basin climatology and operational climate diagnostic bulletins to name a few that found direct application in the Government as well as with private stakeholders. The first World Climate Conference of 1979 had highlighted the issue of Global Warming. Its ramifications were felt worldwide. In India a revision of climatology, reworking of Climate Normals and a vigorous search for Trends in climate records *etc*. gained priority.

The National Climate Centre was created within this office in 2005 which gained international responsibilities of a Regional Climate Centre for RA II (region South Asia) in 2010. Yet, the formal establishment of a specialized climate service by IMD was to wait till 2017, when the Pune office was again re-designated as the Office of Climate Research and Services. As a recent development this centre has become the Global Production Centre in 2023 sharing its climate model out-put with all National Meteorological and Hydrological services of the world.

3. Advancement of climate services

3.1. *Climate monitoring, information and publication services*

The National Data Centre (NDC) in Pune, which started with a second-generation electronic computer (EC 1040) in 1977, went through a series of upgradations, as modern Data Centres constantly need to do, in order to handle higher and complex dissemination needs. In addition to station data, gridded rainfall and surface temperature data onwards of 1901 and 1951 respectively are routinely made available to users, especially the NWP and GIS communities. The climate variables on record are the standard surface and upper air parameters, agrometeorological parameters, soil moisture, atmospheric radiation and environmental parameters *viz*. surface and upper air ozone, UV radiation, precipitation chemistry and aerosol concentrations. Satellite meteorological data on radiances as well as derived parameters are available from the Delhi archives of IMD.

3.1.1. *Rainfall observations and hydrometeorology*

Recognizing the inevitability of multiple agencies making efforts to record Rainfall and also the vital need for their centralised collation, a Rainfall Resolution was passed by the then Government in 1890 making IMD the nodal agency (pp98 (IMD 1975) for all rainfall records and procedural matters.

3.1.2. *Climate monitoring*

Monitoring of time and space variations of atmospheric observables or indices formed out of them that are indicative of prevailing circulation patterns or exceedance of certain threshold values, anomalous patterns *etc.*, on a periodic basis (weekly, monthly *etc*) are basic tools of climate diagnosis. Climate diagnostic bulletins of India are being published since 1996 and in recent years state-specific bulletins are being provided for management decision making. Simplified annual summaries (since 2004) and monthly summaries (since

2021) are also being supplied for easy comprehension. Climatological Normals, decadal means and other long-term patterns, that help in viability assessments, are prepared and published.

Several other products *viz*. Atlases of Rainfall. Marine climatology, Cyclone tracks for Indian seas, Solar Radiation, Climate Hazard and vulnerability Disaster and Reports for Disaster weather events and Damage assessment are prepared. WMO had initiated Marine climatological services in 1963 following which Marine Climatology Atlas for North Indian Ocean have been prepared and updated with Decadal Climate summaries.

3.2. *Drought research*

During 1965 and 1966, major parts of India were under prolonged and severe drought conditions due to deficient monsoon rainfall. On the recommendations of the Planning commission, Drought Research Unit started functioning from the Pune Office in 1967 conducting studies on different aspects of drought. The primary activity of this Unit is to detect the occurrence of a meteorological drought and its intensity and monitor agricultural drought conditions during the SW and NE monsoon seasons. It developed an index of water availability in soils related to agricultural needs. It issues weekly aridity outlook. Its other functions are to delineate and identify drought prone areas of the country, study past droughts and conduct research on different aspects of droughts (Chowdhury *et al*., 1976; RAO 1985; RAO and BHIDE 1980).

3.3. *Climate forecasting services*

3.3.1. *Seasonal forecasting services*

Seasonal forecasting can be recognized as the oldest form of climate service delivered by IMD. It has a fascinating history as well as a journey studded with numerous challenges and rewards. After Sir Henry Blanford was appointed as the Imperial Meteorological Reporter of India in 1875, systematic observation started evolving paving the way for developing climate statistics. The development of climate service in India was based on practical necessities. The 1877 countrywide famine, for example, was a deciding factor of developing seasonal forecasting in India. The seasonal forecast, thus, is an instance of dissemination of first climate service in India. Blanford, issued tentative climate forecast during 1882-1885 based on snowfall estimates over Himalayas (Blanford 1884). Based on the success of his approach, the first seasonal forecast is issued in 4th June 1886. The same strategy is followed even today, following the same approach. After him, John Eliot used predictors outside India for the first time, *viz*., pressure of Mauritus, Zanzibar and Seychelles in the monsoon forecast of 1896. The most systematic approach was taken by Sir Gilbert Walker, who laid the basis for a forecast on a statistical association. He was the first meteorologist who systematically examined the relationship between Indian monsoon rainfall and global circulation parameters using correlation-based method and selected 28 predictors to issue forecast based on regression equation during the year 1906 (IMD 2001). [also refer: https://www.tropmet.res.in/monsoon/files/ seasonal_ prediction.php]. Walker realized that India being more or less continent cannot be considered as one homogenous area as regards the distribution of rainfall so in 1922 started to issue forecast for three homogeneous regions (Peninsula, North East India and North west India. In 1988 a major change made in the operational model and adopted the 16-parameter power regression and parametric models. IMD introduced a new two stage forecast strategy for Long Range Forecast in 2003, according to which the first stage forecast for the seasonal (June to September) rainfall over the country as a whole is issued in April and the update for the April forecasts is issued in June along with forecast for the homogeneous regions of India including monthly forecast for July. IMD started generating dynamical Seasonal forecast based on atmospheric General Circulation models (AGCM) in 2005 and Coupled Ocean Atmosphere model developed under Monsoon Mission in the year 2012 (Sreejith *et al*., 2023). In 2007, IMD introduced statistical ensemble forecasting system (SEFS) (Rajeevan *et al*., 2007) for the south-west monsoon season (June – September) rainfall over the country as a whole. Recently in 2021, IMD adopted new strategy a Multi-Model Ensemble (MME) forecasting system based on coupled global climate models (CGCMs) output from different global climate prediction and research centers and started to issue spatial rainfall probability forecast for Indian region. Since 2023, IMD started to issue outlook for Heatwave over Indian region during hot weather (March to May) season.

In the last thirty-forty years, operational seasonal forecasts have seen a sea-change. The regression-based model continues to be in forefront for seasonal forecasting. However, with the introduction of highperformance computing systems, dynamical seasonal forecasting has now become a major tool for operational seasonal forecasts. As a part of *National Monsoon Mission* initiative *(Rao et al*., 2019), after a rigorous evaluation IMD introduced dynamical seasonal forecast initially in experimental mode and then finally adopted the model for operational forecast. A multi-ensemble seasonal forecast with 38 km horizontal spatial resolution is the basis of current generation operational forecasts. IMD is also leading in developing operational seasonal forecasts with regional updates for different homogeneous regions of India. For the last three years, IMD has adopted a new multi-model multi ensemble probabilistic forecast system.

3.3.2. *Subseasonal forecasting services*

Existence or a low frequency forty-day mode over Indian region started getting recognized since the early 1970's. Some indications were there that these modes could give medium range predictability over Indian region was given by some studies in IMD and can be operationally used in operational services. Studies during early 1980s show such medium range forecast can be used for agromet advisory services based on weekly or pentad average (Ramasastry *et al*., 1986; DE 1982). Forecasting Indian Monsoon subseasonal variability is difficult but essential for stakeholders. Studies suggest that sub-seasonal modes show complex spatial features and temporal evolution during boreal summer over monsoon regions are linked to extreme events *e.g*. cyclogenesis. The intraseasonal "*active spell*" of the South Asian monsoon produces more low-pressure systems than the "*break spell*" (Goswami *et al*., 2003). Some studies (Rohini *et al*., 2016; Lekshmi and Chattopadhyay, 2022) found that Extratropical Rossby waves modes intrude over India, generating dominant sub-seasonally changing temperature patterns, with some of those intrusion results in heatwaves. Many studies report similar findings. Thus, subseasonal background can promote extreme events. Predicting such variabilities in the medium range (~10 days) and in the extended range (2-3weeks range) can help large number of stakeholders. The extended range forecast (ERF) service of IMD, is a recent one and cater to the need of people. The ERF is attempted in both using statistical and dynamical prediction system. Many institutions worldwide have developed empirical models to predict subseasonal modes such as Madden-Julian Oscillation in recent decades. These models may track and predict intra-seasonal rainfall in India and the tropical region. Other worldwide modelling facilities include the European Centre for Medium Range Weather Forecasting (ECMWF), National Centre for Environment Prediction (NCEP) and Japan Meteorological Agency (JMA). At these centres, GCMs and coupled atmosphere-ocean models generate real-time operational forecasts. Recent coupled models provide excellent guidance for long-range projections (Saha *et al*., 2014).

Although the initial effort to have some understanding of the predictive behaviour was attempted in the 1980s and 1990s (Ramasastry *et al*., 1986; DE 1990), the tropical intraseasonal prediction was still not well understood so that the operational medium to extended range prediction was not formally attempted in India. IMD formally began issuing ERF in 2008 using statistical and dynamical model outputs from multiple Indian and international institutes. Statistical models first provided the basis of forecast (Chattopadhyay *et al*., 2008) which was then extended in future dynamical models. IMD recently adopted a fully coupled model as a part of extended range forecasting initiatives based on a version of NCEP CFS and GFS models which were adopted as a part of National Monsoon Mission initiative. Currently operational extended range forecast is generated once every week and is extremely successful in several sector specific applications (Sahai *et al*., 2019; Pattanaik *et al*., 2023)

3.4. *Environmental meteorology services*

IMD set up India's first observational network for environmental monitoring in 1973 as a part of global network called BAPMoN. It intends to study the likelihood of acid rain and to document atmospheric attenuation of solar radiation for India. It was upgraded for inclusion in Global Atmosphere Watch programme of WMO in the year 2000 with an additional objective of studying radiative effects of aerosols including the absorbing Black Carbon aerosols. Radiation as acclimate process involving atmospheric constituents, mainly aerosols is considered important for climate simulation. IMD established the Environmental Monitoring and Research Centre, EMRC in Delhi in 2004 as a nodal centre for environmental services.

The *System For Air Quality Warning and Research* (SAFAR (Beig *et al*., 2021) was developed by IITM and operated in collaboration with IMD in 2010 for the Commonwealth games in Delhi. It was later extended to Mumbai and Ahmedabad in 2015 and 2017 respectively. Even though the forecasting is done in a weather service time frame the modelling itself employs methods of climate – chemistry processes. There is an air chemistry observational network on an urban scale in these projects which is a climate resource by itself. In later years an Air Quality Early Warning System jointly developed by IITM, IMD and NCMRWF was put to operation, since 2018 and covers 46 cities as on date. This is extendable to climate lead times in future.

3.5. *Climate application services*

In the history of IMD, the development of operational services for weather and climate is strongly embedded with stakeholder requirements. The evolution of seasonal forecasting system is a glorious example on how it has driven the research and services in India. The application of climate information in allied fields have evolved parallelly.

3.5.1. *Agroclimatic services*

The application of climate information on agriculture is perhaps the oldest. Forced by debilitating impacts of severe droughts the Royal Commission on Agriculture recommended setting up of an Agricultural Meteorology Division within IMD in 1932. It was set up in Pune under the leadership of Dr. L.A. Ramados and to make a modest beginning, began to issue regular Farmer Bulletins from 1945. Rainfall based agroclimatic mapping were used (Kelkar, 1981), which paved the way for proper agrometeorological advisories intended for respective State authorities began in 1977 in the short-range category of a few days and was progressively enhanced by 1991 to medium range of a week with specificity at the level agro-climatic zones (using NWP predictions from the National Centre for Medium Range Forecast, Delhi and collaboration between Indian Council for Agricultural Research and State Agricultural Universities). It was in due course converted to a single window service of IMD at a smaller scale of Districts in 2008, finally reaching Block level specificity in 2018 under the scheme of *Gramin Krishi Mausam Sewa* (GKMS). A robust user-provider linkage had come into being by this time that leveraged Media and IT advantages in a big way and set up inter-Ministerial mechanisms of delivery.

The farmers, understandably, have a bigger role to play at their levels in response to these weather forecasts but when the climate information in the form of extended range forecasts of weekly values started to flow in, with a lead time of fortnight to month, did the era of agroclimatic services truly begin. Needless to say, that the triple involvement of provider-Government-farmer, that is already in place, will remain the delivery mechanism. Slow moving responses from markets, technical service providers and financing agencies can now be mobilised better. The underlying strategy of the project which was undertaken to generate monthly to seasonal forecasts and interpret them in terms of various risks (Mohanty *et al*., 2013; Ghosh *et al*., 2015) will be as much specific to agriculture as to other areas of generic application.

3.5.2. *Hydrometeorological services*

Another example is that of hydrometeorological services. The hydrometeorology section is established in Poona in 1946 to coordinate receiving rainfall from IMDs own as well as State rainguage observations and act as an office for rainfall registration and generating rainfall statistics as well as climatology on various spatial scales (*e.g*. state district or block level). In addition to regular monitoring of rainfall and calculating statistics over different regions, hydrometeorological services were set up to cater to the need of rainfall information for flood monitoring purposes in ten different river basins across India. For example, a special hydrometeorological observatory service is established at Alipore to advise the Damodar Valley reservoir complex to regulate reservoir water storage.

IMD has set up a flash flood guidance service for major cities in India and neighbouring countries of Bangladesh, Nepal and Bhutan. Two daily bulletins by names of National Flash Flood Guidance Bulletin and South Asia Flash Flood Guidance Bulletin are issued (https://mausam.imd.gov.in/imd_latest/contents/flash_flood.php).

The hydrometeorological service has evolved a lot in the past 30 years. The hydrology and drought monitoring unit at Pune supplies real-time weekly updates on water stress and computes extreme event statistics, trend of rainfall *etc* (https://imdpune.gov.in/caui.php).

3.5.3. *Climate and health*

There are several potential areas for providing climate services to the health-sector with sufficient lead times for preventive action. In the case of communicable diseases, the life cycle of the vectors that communicate the pathogens are dependent on weather. Prior knowledge of favourable climate windows for vectors is a sought-after information by the medical community. IMD presently provides information for mosquito borne diseases through its bulletins, but it is certain to extend to other diseases.

Heat waves based on Maximum Temperature considerations are one of the major climate advisories since long. But, with Heat waves on the rise, heat induced sicknesses became widespread for which various indices of heat stress are provided in regular bulletins of IMD.

3.5.4. *Energy sector services*

The first assessment of the potential for solar energy and wind over India were published by Anna Mani and Rangarajan (1980, 1981) and Mani 1992 respectively. They are continuing to be extensively used for renewable energy generation in the country.

IMD has been providing meteorological forecasts for power load demand prediction and near real time operations of the National Power Corporation and to the renewable energy sector for several years now.

3.5.5. *Gridded climate data sets*

Gridded Climate Data sets Climate research and services gridded precipitation and Temperature data sets are valuable for a wide range of applications such as environmental decision-making, risk assessment, climate model verification, climatic and hydrological modelling, and water resource planning, all of which require an understanding of the spatial distribution of the data. IMD brought out many gridded rainfall products include the one degree spatial resolution dataset for 1951 to 2003 (Rajeevan *et al*., 2006), one degree spatial resolution dataset for 1901 to 2004 (Rajeevan *et al*., 2008), 25km spatial resolution dataset for 1901 to 2010 (Pai *et al*., 2014). Similarly gridded daily temperature data sets also prepared since 1951 onwards (Srivastava *et al.*, 2009).

4. Future course of climate services

Society has always been clear about seeking climate information for choosing options upfront of a commitment and weather information for mid-course corrections. As societal production systems become more and more competitive, they need to be made more resilient by way of technology or exercise of proper options, both of which require climate information. This is where the value of climate services come in. Undoubtedly, demands will become diverse and more critical in future – more so because climate change will narrow down viable options even further. Society is beginning to factor in climate reality into their planning and preparedness.

As noted by Brasseur and Gallardo (2016), the US National Academy of Sciences [National Research Council, 2001] mentions that the "*climate information is becoming a progressively important element of the public and private decision-making process" and that "the timely delivery of useful products through direct and accessible user interface*" could limit national risks. It is pertinent to recognize here that climate services cannot be entirely a unidirectional flow. Growing awareness in different sectors of our economy would throw more questions at multiple service providers, thus necessitating a network mode of interactions. Indeed, a comprehensive frame work needs to be put in place.

4.1. *Global framework for climate services*

The World Climate Conference-3, 2009 in Geneva, decided to establish a Global Framework for Climate Services (GFCS) to strengthen production, availability, delivery and application of science-based climate monitoring and prediction services.

The World Meteorological Organization (WMO) fosters collaboration among members of the UN system and with other international organizations in observations, climate research and application of climate information in various sectors. WMO cosponsors the World Climate Research Programme (WCRP), the Global Climate Observing System (GCOS), and, the Inter-governmental Panel on Climate Change (IPCC). The GFCS integrates these collective efforts to promote cooperation in scientific, technological and socioeconomic research, in taking systematic observations and in development of climate related data archives.

The GFCS identifies the following major sectors for primary attention-Water resources, Agricultural production, Health, Energy production and Natural hazards. It is but obvious that all other areas of societal concern like say Urban development, Eco-system management, Mining and Industries, Transportation, Tourism *etc* would be addressed through a suitable combination of the said primary sector considerations.

4.3. *Indian initiatives*

While the international efforts have objectives of furthering scientific knowledge, global facilitation and finding basis for negotiations within the paradigm of common but differentiated responsibilities, it becomes the national responsibility to asses the national aspirations, capabilities and declarable goals. As a first step towards the latter are the periodic National Communication from India (to the IPCC), prepared by IITM. They contain status of emission and sequestration of GHGs in India and future regional scenarios of climate - consequent to adapting different economic growth paths. This is meant to fulfil India's commitment to the UNFCCC in the first place and also to take a national position in the global negotiations.

The complexity of the climate change issue has been realized and after an extended period of ground work, a need is felt for a national framework for climate services in India because all the areas of societal concern under governance of different ministries and authorities need to act in a unified way to achieve a balanced growth of economy.

4.3.1. *Implementation of national framework for climate services for India*

The climate service has been broadening its horizon by engaging different stakeholders including government agencies, research institutions, NGOs, private sector, and local communities to ensure a coordinated approach towards National Framework for climate services. It would create linkages for interaction and cross sectoral working principles. It would also identify existing as well future players.

4.3.2. *Advanced climate modelling and machine learning based climate forecast*

To give a basis of our climate understanding different MoES institutes need to take leadership in developing and deploying high-resolution regional climate models tailored to Indian sub-continental conditions to improve accuracy of the findings. The climate forecast at a city scale or a village scale requires advanced downscaled models. Often data driven machine learning models are quite useful. The recent machine learning models like Google GraphCast *(Lam et al*., 2023), Pangu-Weather model (Bi *et al*., 2023) in the medium to extended range shows great potential. These models are generating experimental subseasonal forecasts over different parts of the globe (*e.g*. ECMWF PANGU https://charts.ecmwf.int/products/pangu_medium-t-z).

India is experimenting with downscaling and short-range forecasting using AIML techniques. In near future this modelling initiative is expected to grow in the same pace as international services (Narkhede *et al*., 2022; Kumar *et a*l., 2023).

4.3.3. *Public-Private Partnerships*

Climate service needs to foster collaborations with private sector entities for innovative climate solutions, such as climate-resilient technologies, insurance products, and sustainable infrastructure. The partnerships can be public to public, private to private, creating a networked mode of functioning.

5. Conclusions

The climate service has undergone a sea change in the last ten years. Current climate services in IMD are now modern, technology based and tailored to stakeholders from various user sectors. Some major achievements are:

(*i*) The service now primarily depends on state-of-the-art climate monitoring and prediction systems.

(*ii*) Development of climate statistics on various spatio-temporal scales with a focus on extreme events,

(*iii*) Development of district level vulnerability assessments related to meteorological disasters,

(*iv*) As a regional climate centre (RCC) recognized by WMO, IMD Pune is providing state of art seasonal outlook to neighbouring countries under the SASCOF framework.

(v) Monthly El-Nino related updates in the form of bulletin. The climate services are now targeted to be integrated in the National Framework for Climate services (NFCS) which will continue to improve applications of several priority sectors. As IMD marches ahead towards a climate-challenged future, with global warming potentially threatening mankind and all living creatures, it is constantly adapting to new challenges and formulating new strategies, upgrading to latest state-of-art technology and assuring the best service and outreach to stakeholders.

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