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Advances in application of sub-seasonal weather forecast in Indian agriculture

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ABSTRACT

Under the climatic variability and climate change, skilful weather forecast in different spatial and temporal scale encourages the farmers to organize and activate their own resources in the best possible way to increase the crop production. Though medium range weather forecast is used extensively in operational agromet advisory services, sub-seasonal forecast provides additional decision-relevant information to support the timing of crop planting, irrigation scheduling, and harvesting, particularly in water-stressed regions. In view of that, dynamical and statistical and sub-seasonal seasonal forecast is generated and delivered to the farmers as climate information services in number of countries in the world. Under the Gramin Krishi Mausam Sewa (GKMS) Project, Agricultural Meteorology Division, India Meteorological Department (IMD) in collaboration with Indian Institute of Tropical Meteorology (IITM), Pune, All India Coordinated Research Project on Agrometeorology (AICRPAM), CRIDA, Indian Council of Agricultural Research, Hyderabad prepares Agromet Advisory fortnightly taking into consideration realized rainfall during previous fortnight and extended range rainfall forecast for next fortnight and crop information i.e., state and stage of the crops. In the present article agricultural applications of sub-seasonal forecasts on agricultural management in India has been explored. It has been showed how the extended range weather forecast i.e., sub-seasonal forecast has been developed and translated into agromet advisories for the farming communities to increase crop production in India and whether the present state of accuracy could be used for generating advisory under contingent crop planning conditions and other advisories by citing different case studies and ultimately helping the farming communities to improve their economic conditions. It has been demonstrated here that sub-seasonal forecasts are increasingly being used across agriculture in the country. The sub-seasonal forecasting time scale is therefore a new concept for many users. Because of the additional value of sub-seasonal forecasts for decision-making, it is increasingly gaining interest among users. Present case studies clearly suggest the forecast at sub-seasonal time scale is need of the hour.

Keywords: Gramin Krishi Mausam Sewa, medium range weather forecast, sub-seasonal weather forecast, extended range weather forecast, agricultural management

Uncertainties of weather and climate pose a major threat to food security in number of countries in the world. The diversity and uncertainties present both an opportunity and a challenge on crop production. Every aspect of agriculture from long term planning to tactical decisions in day-to-day agricultural operations is dependent on climate and weather. Exciting opportunities exist today to help the agricultural community through improved weather forecast and agrometeorological advisory services. An effective information flow system from forecasters to agricultural organisations and farmers is feasible today for providing effective weather-based agromet advisories within the evolved institutional system in each country. Crop and location specific agromet advisories along with early warnings of impending risks based on different spatial and temporal weather forecasts and prevailing crop situation are increasingly being provided to farmers to enable them to take the necessary measures to mitigate the envisaged setbacks to crops by weather. Numerous efforts have been carried out so that the scientific products can be transferred to users by extension institutions effectively and efficiently, with increased opportunities for feedback from users to iteratively improve products (Hewitt *et al.*, 2013). Despite the advances in the seasonal forecasting of extreme events, the development of operational tools and services remains a challenge. There is also a need to further improve the models to enhance the skill in predicting smaller fluctuations, which

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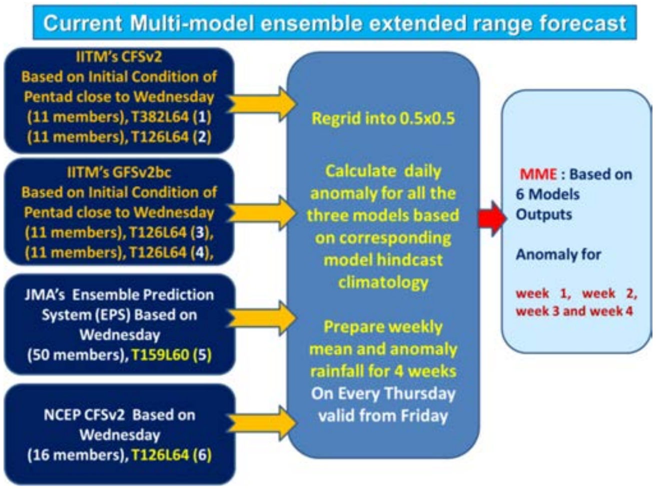

Fig. 1: Schematic flow of extended range weather forecast

often concern the users at the field level.

The agriculture sector is already one of the most advanced in terms of using weather forecasts and seasonal outlooks to support operational decisions (Clements *et al.* 2013). Sub-seasonal forecasts are starting to provide additional decision-relevant information to support the timing of crop planting, irrigation scheduling, and harvesting, particularly in water-stressed regions. In this way, dynamical and statistical sub-seasonal seasonal forecasting have been implemented and delivered to agriculture including aquaculture farmers as climate information services in number of countries in the world.

The sub-seasonal-to-seasonal predictive time scale, encompassing forecast ranges from 2 weeks to a season, is a rapidly maturing discipline. Climate Research Programme (WCRP), collaborate to jointly tackle the challenge of providing skilful and useable sub-seasonal forecasts. Significant advancements have been made in this line, including the joint WWRP–WCRP sub-seasonal to seasonal prediction project (Robertson *et al.* 2018), which is advancing the science in identifying and simulating key sources of sub-seasonal predictability and identifying "windows of opportunity" (Vitart 2014; Mariotti *et al.* 2020), quantifying and reducing inherent uncertainties, and working toward their future operationalization (Robertson *et al.* 2014; Vitart *et al.* 2017; Lang *et al.* 2020). As sub-seasonal prediction science continues to mature, the availability of extended-range forecasts provides opportunities for enhanced application-focused capabilities.

In the present article agricultural applications of sub-seasonal forecasts on agricultural management in India has been explored. It has been showed how the extended range i.e., sub-seasonal forecast has been developed and translated into agromet advisories for the farming communities to increase crop production in India and whether the present state of accuracy could be used for generating advisory under contingent crop planning conditions and other advisories by citing different case studies and ultimately helping the farming communities to improve their economic conditions.

With the onset of monsoon and as per the medium range weather forecast, sowing of rainfed soybean & cotton were started in districts in Marathwada region of Maharashtra from second week of June, 2017. In subsequent weeks, farmers in Maharashtra are worried because they fear their kharif crop would be destroyed due to lack of rains. Though dry spell was captured through experimental sub-seasonal forecast, the same was not communicated and as a result crops started wilting. Almost 85% sowing is complete in Latur district, and crops were drying due to a long dry spell. Thus, it was decided to use Sub-Seasonal to Seasonal (S2S) Weather Forecast by the India Meteorological Department and Indian Institute of Tropical Meteorology in issuing advisories from 2018.

OPERATIONAL OF SUB-SEASONAL WEATHER FORECAST IN INDIA

Under the Gramin Krishi Mausam Sewa (GKMS) Project, Agricultural Meteorology Division, India Meteorological Department (IMD) in collaboration with Indian Institute of Tropical Meteorology (IITM), Pune, All India Coordinated Research Project on Agrometeorology (AICRPAM), CRIDA, Indian Council of Agricultural Research, Hyderabad prepared Agromet Advisory fortnightly taking into consideration realized rainfall during previous fortnight and extended range rainfall forecast for next fortnight and crop information i.e., state and stage of the crops. This information was used from 2014 to 2016 experimentally. Meteorological data were collected from the Data Centre, India Meteorological Department and crop production data, information on pest and disease incidences and different farm managements practices were also obtained from the State Department of Agriculture in the country. India.

For this purpose, the group of Indian Institute of Tropical Meteorology (IITM) has indigenously developed Ensemble Prediction system (EPS) based on the state-of-the-art Climate Forecast System Model Version (CFSv2). The EPS generates many forecasts from different initial conditions so that the expected forecast and the expected spreads or uncertainties in terms of probability from this forecast. Comparison is shown elsewhere between CFSv2 skill and the atmosphere only GFSv2 model forced with bias corrected SST forecasted from CFSv2. This system uses suite of models at different resolutions viz., (I) CFSv2 at T382 (≈ 38 km), (ii) CFSv2 at T126 (≈ 100 km), (iii) GFSbc (bias corrected SST from CFSv2) at T382 and (iv) GFSbc at T126. This dynamical prediction system developed at IITM has been transferred to IMD and the same has been implemented by IMD for generating operational ERWF products to different sectors including agriculture.

Under GKMS, needs of farming community were defined through ascertaining information requirement of diverse groups of end-users. It emerged that the prime need of the farmer is location specific weather forecast in quantitative terms. Hence, the same was developed and made operational in 2008. Thereafter, a mechanism was developed to district level weather forecast (DLWF) and climatic information along with agrometeorological information to prepare district level agromet-advisories outlining the farm management actions to harness favourable weather and mitigate impacts of adverse weather.

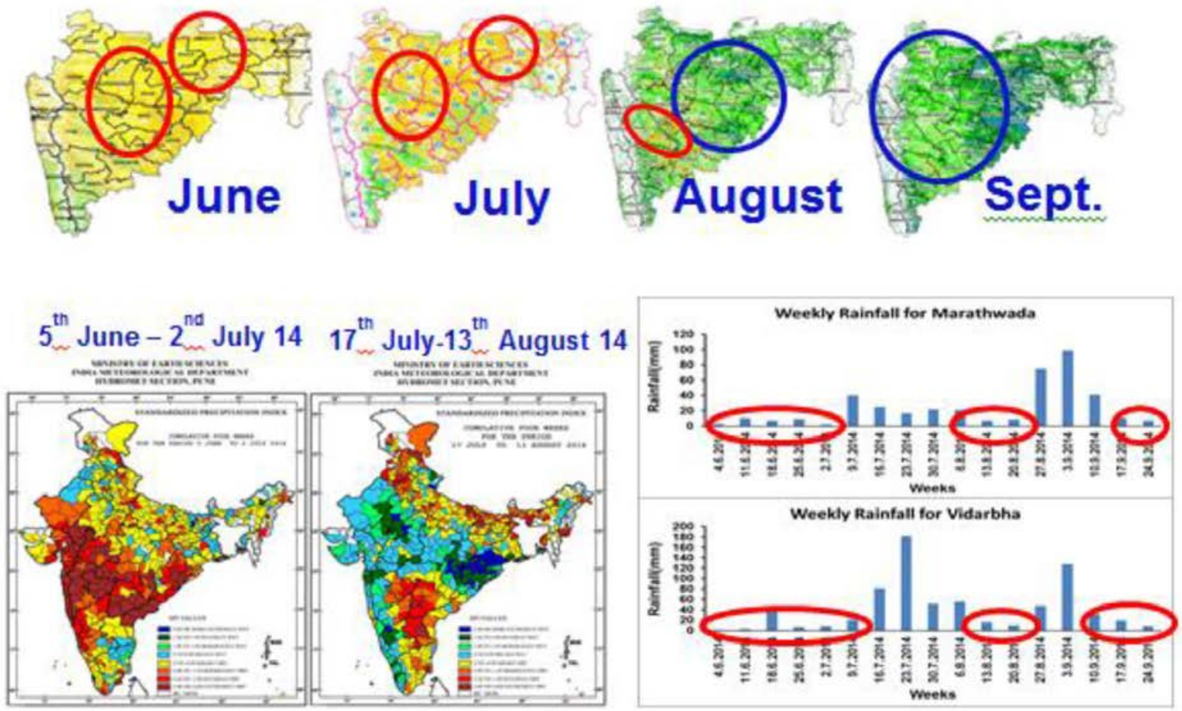

Fig. 2: Poor rainfall situation in June and July 2014 for Marathwada and Vidarbha

CASE STUDIES IN APPLICATION OF EXPERIMENTAL SUB-SEASONAL WEATHER FORECAST

Advisories for cultivation of contingent crop during drought condition

During the experimental period in the monsoon season from June to September 2014, it has been noticed that drought like situation was prevailed in Madhya Maharashtra, Marathwada and Vidarbha regions of Maharashtra. This was captured well in the extended range weather forecast and contingency crop planning was given for Marathwada and Vidarbha as follows:

For Madhya Maharashtra instead of normal crops like sunflower, soybean, cotton, hybrid jowar, hybrid pearl millet, red gram and sesame, it was advised to adopt contingency plan i.e., intercropping of pearl millet+redgram, sunflower+ red gram, soybean+ red gram, guar + red gram. For Marathwada the districts affected were Aurangabad, Beed, Jalna, Osnamabad, Parbhani, Hingoli, Nanded, Latur. The normal crops grown in this region are cotton, soybean, red/black gram, sorghum, sunflower, sugarcane. Contingency given for intercropping of cotton+pigeon pea, pigeon pea+ sunflower or bajra and for short duration varieties of soybean. In Vidarbha, the districts to be affected were Buldhana, Chandrapur, Yeotmal. The normal crops grown in this region are Bt. Cotton and in eastern parts of Vidarbha, it is rice. Contingency were given for American cotton/Desi cotton and intercropping in western Vidarbha region. For intercropping cotton: sorghum: cotton: sorghum, short duration pigeon pea and intercropping of sorghum with pigeonpea were advised. In eastern Vidarbha, contingency for direct sowing of early maturing and mid late maturing rice varieties by wet seeding method were given. The farmers in this region follow the same and benefited by the agromet advisories provided to them. This has been shown schematically below in Fig. 2.

Similarly in 2015, using the ERWF based contingency was given for dry regions of North Interior Karnataka, Rayalaseema and Telangana. In North Interior Karnataka, number of contingency plans were advised like sowing of fodder crops on preference sowing of niger, foxtail millet (PSC-1, RS-118), mataki , horse gram (PHG-9, KBH-1), castor as well as intercropping of pearl millet + pigeon pea (2:1), pigeon pea + sesame (1:2 or 2:4), bajra + castor (2:1) in light and medium black soils and bajra, pigeon pea, castor, chilli, sesame, foxtail millet, onion, bajra + castor (2:1), fodder crops in medium black soils after receipt of sufficient rain. In Telangana, instead of cotton, red gram, jowar, sowing of sole red gram (Maruti, Lakshmi, PRG 158 etc.) adopting closer spacing of 90 x 30 cm. And in Rayalaseema sowing of red gram (PRG-158, Asha, LRG-41), castor (PCH-111, PCH-222, Kranti, GCH-4, Haritha) and rainfed groundnut (Kadiri-6, Kadiri-9, Narayani and dharani) in Anantapur district after receipt of sufficient rain, sowing of contingent crops like pearl millet, cowpea, green gram, sunflower (Morden) was also advised. Feedback from different users on the use of alternate crops was found to be very encouraging.

Though the agromet advisories based on the ERWF were issued to the different parts of the country, verification of the same has been made in Assam state particularly on sowing of rice on pre-monsoon season and pest and diseases incidences on rice. Two case studies on verification of ERWF are illustrated as follows.

Advisories for control of rice hispa in Sali Rice

In August 2016, deficit of rainfall was forecasted over Assam region. The expected weather condition was favourable for building up insect rice hispa population in Sali rice after the continuous rainfall during July/ (early August) followed by sunny days with high temperature and high humidity during August. Insect infestation is usually found maximum in the early tillering stage of Sali rice. Due to occurrence of flood during July, transplanting was delayed and paddy in those floods affected areas was in the early tillering stage during August/September. Under the situation of occurrence of dry spells during August/September (after long wet spell), delayed transplanted crops are to be affected more as compared to the July transplanted paddy. Therefore, following advisories were issued on 2nd August, 2016.View of rice field at Narayanpur, Lakhimpur during 2016.

Advisories for pest

Sunny days/high temperature after continuous and heavy rainfall for long period (1 to 2 weeks) during August is very conductive for heavy infestation of rice (which is at tillering stage) with Rice Hispa. Therefore, farmers are advices to be ready for tackling the situation. Rice hispa can be controlled by spraying with Chloropyriphos 20 EC or Monocrotophos 40 EC @1.5 ml per liter of water. It is advised to spray recommended insecticides when there is one damage leaf per hill due to attack of leaf folder or appearance of one adult hispa per hill is observed.

Based on ERWF normal to above normal rainfall forecast (Fig. 3) were issued over Assam region during July and early August followed by deficient rainfall in the next half of August. As per the realized rainfall maps of July and August 2016 (Fig. 4), it is seen that good rainfall occurred in July to the early part of August followed by dry spells. Thus, the forecast is well in agreement with the realized rainfall. The realized weather condition was favourable for attack of pest on Sali rice. Based on the weather forecast farmers were advised for taking prophylactive measures for controlling the pest. (Advisories for pest are shown above). Farmers those followed the agromet advisories were benefited by avoiding the loss due to rice hispa infestation on Sali rice.

Advisories for sowing of rice during pre-monsoon season

In Ganokdoloni village of Lakhimpur district of Assam during 2014-15, the yield of all bao varieties grown in the village was reduced substantially as compared to the earlier season (2013-14), which was due to exposure of the crop to severe moisture stress at the seedling stage (March to May), as the village was experienced with long dry spell from 24th November, 2014 to the first week of May, 2015.

Thus, the farmers in this village had lot of confusion to start sowing of bao rice in 2016. Up to 30thMarch, 2016, farmers of the village did not start sowing of bao varieties of rice. Based on the forecast of continuous rainfall during April, 2016 received from IMD, farmers were advised to complete the sowing as early as possible (within first/second week of April). Though, the situation of the village was worse than the previous year, due to more rainfall during April and May farmers were able to complete the sowing. Thus, the advisory given based on extended weather forecast was proved to very useful for the farmers of the village. In this village during 2016-17, extended rainfall forecast of IMD was well utilized for issuing useful advisories to the farmers of the village. Fig. 5 and 6: MME mean rainfall and anomaly; IC 30 MAR 2016, (01-28 April 2016) respectively and Fig. 7 shows realised rainfall in April 2016.

Climatic conditions and seasonal forecasts can help the farmers in planning for the upcoming season to maximize productivity based on expected weather patterns. Seasonal forecast can also be used to decide which crops to grow, seed varieties for planting, purchase seed and inputs and prepare their land accordingly.

Though there has been considerable skill in medium range weather forecast which has already been demonstrated, there was mixed feeling in the skill of sub-seasonal to seasonal forecast in the country. The seasonal drought as well as the unprecedented deficiency of July (» -51%) rainfall over India during 2002 was not able to forecast by any operational centre. Like 2002, 2009 monsoon season also witnessed large deficiency in seasonal rainfall (» -22% of long period average). The drought year of 2009 was associated with many dry spells of monsoon and some transition phases of monsoon from weak phases to active phases and vice versa. It was noticed that various climate research centres in India and abroad using statistical and dynamical models could not predict the extent of deficiency of 2009 seasonal monsoon rainfall during JJAS. However, a proper real time monitoring of intra-seasonal fluctuation of monsoon rainfall during 2009 monsoon season by IMD was quite useful in assessing the extent and gravity of drought situation of the country. Long dry spell of June was very much predicted by the model from the beginning of June (initial condition of 4th June). They have also demonstrated that the dry spells of monsoon during almost the entire June, 1st half of August and 2nd half of September 2009 were well anticipated in the model forecasts, thus, was very useful in the real time forecasting of these dry spells of monsoon 2009.It is not only the agricultural sector which is benefited from the proper outlook of extended range weather forecast (Tyagi and Pattanaik, 2012), a skilful extended range forecast can also be very useful for reservoir operation in reducing floods (Pattanaik and Das, 2015). A number of studies (Calanca *et al.* 2011; Stone and Meinke, 2005; Harrison *et al.*, 2007; Hirschi *et al.*, 2012; Yan *et al.*, 2017) were made in Europe, America, Australia, Africa on the use of monthly forecast on pest forecasting, soil moisture availability, drought forecasting etc. and ultimately the crop performance and it has been inferred from these studies that both these forecasts have substantial potential to increase the crop production by adopting strategically decision well in time.

The forecast skill of the seasonal monsoon rainfall over India during JJAS in the previous (CFS version1; CFSv1) and new version (CFS version 2; CFSv2) of the NCEP operational systems have been analysed by Pattanaik and Kumar, 2014, which shows useful skill of monsoon prediction in this time scale. As the large-scale features are better predicted in both CFSv1 and CFSv2 coupled models the hybrid (dynamical–empirical) models for seasonal forecast of monsoon based on the forecast variables of CFSv1 and CFSv2 shows improved skill compared to the actual skill of the model forecasts. As there has been considerable improvement of the skill of sub seasonal to seasonal forecast in recent years, efforts

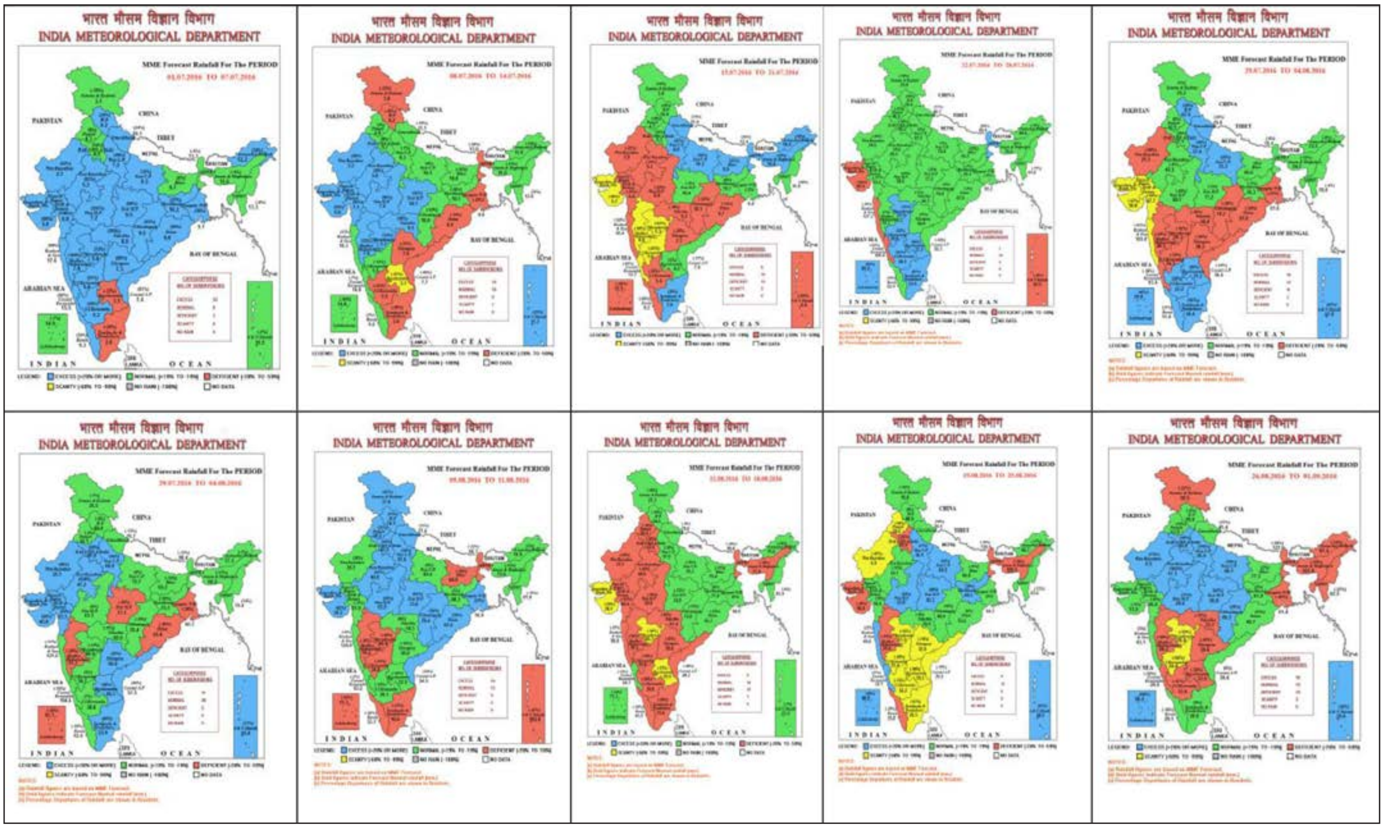

Fig. 3: ERWF for rainfall for July and August 2016

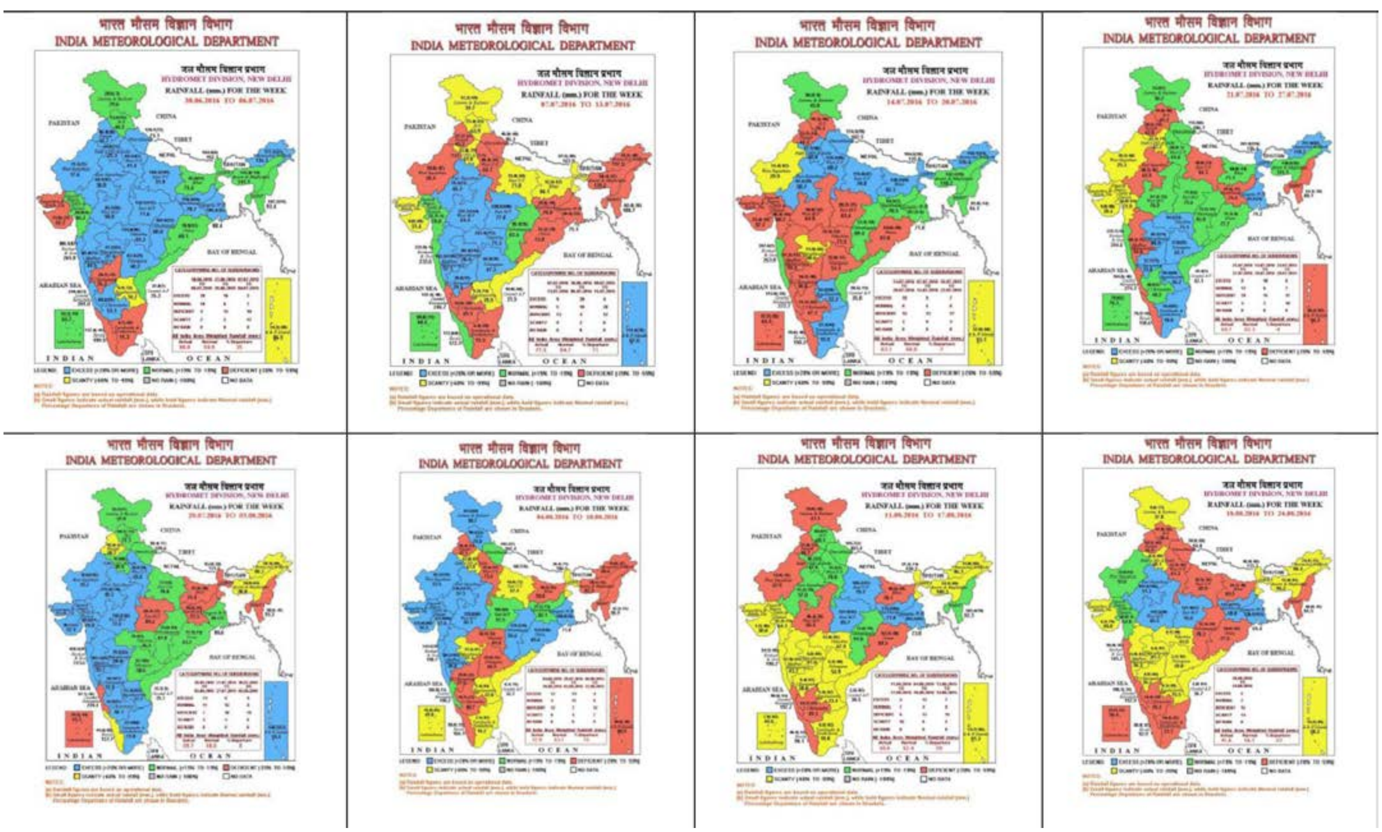

Fig. 4: Realised rainfall for July and August 2016

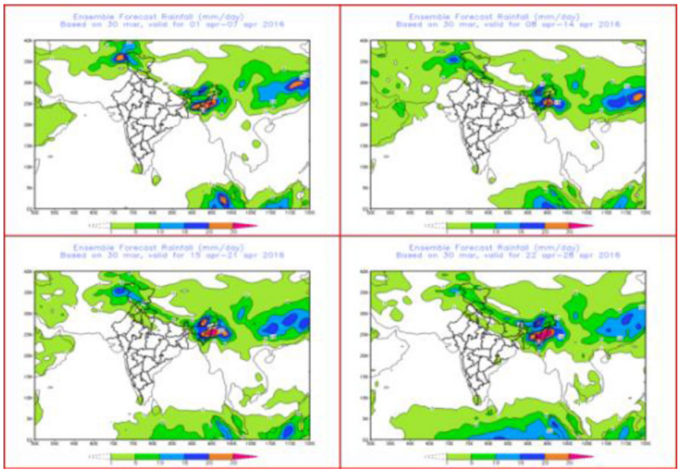

Fig. 5: ERWF rainfall forecast; IC 30 MAR 2016, (01-28 April 2016)

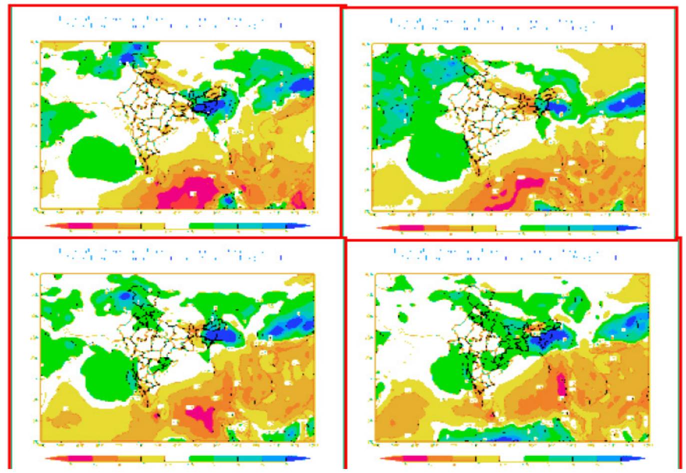

Fig. 6: ERWF Rainfall Anomaly; IC 30 MAR 2016, (01-28 April 2016)

have been made in application of this forecast in agriculture for more crop productivity.

Special weather forecast in relation to extreme weather like cyclone, cold wave, heat wave, frost, hailstorms etc. is also issued to the farmers. These forecasts are normally issued for planting, applying agricultural, chemical crop protection, forestry operations as well as for serving other weather-related agricultural elements associated with the crop and its location. As an example, the forecast strategy of cyclone and the corresponding advisories are mentioned below.

Agricultural management in Bihar, India

A probabilistic sub-seasonal forecast system was developed for the state of Bihar, one of the most climate-sensitive states in India. Precipitation forecasts were issued in real time during the June–September 2018 monsoon to explore the potential value of the sub-seasonal forecasts for small-holder farmers who operate farms of less than 5 acres. Four districts were selected—two in the northern plains (flood prone) and two in the southern plains (drought prone). The project was a collaboration between IRI, The University of Arizona, Indian Meteorological Department (IMD), Regional Integrated Multi-Hazard Early Warning System for Africa and Asia (RIMES), and the government of Bihar (Robertson *et al.*, 2019). Real-time National Centers for Environmental Prediction (NCEP) CFSv2 (Saha *et al.* 2014) SUB-SEASONAL forecasts, calibrated against observed gridded rainfall fields from the IMD using canonical correlation analysis, were generated each month during June–September 2018.

The forecasts were limited to 2 weeks in advance as the calibrated probabilistic forecasts for weeks 3–4 was concentrated around climatological probabilities (0.33), which was a limitation of the forecast's potential utility. The 2018 monsoon recorded a large rainfall deficit over Bihar (~25% below its long-term average) with 11 of the 18 weeks registering deficits. The real-time SUB-SEASONAL forecast captured the signal of the weaker monsoon in 2018 over Bihar, including the delayed monsoon onset and the observed break phase in August at the week 2 lead time. The quantitative verification of the district-level hindcasts and real-time forecasts over the monsoon season in 2018. To assess the usability and utility of the real-time SUB-SEASONAL forecasts to the user community, "field schools" involving ~300 farmers were conducted prior to the monsoon in May 2018. The curriculum extended beyond the presentation of climate forecasts to include contextual information on climate systems and variability, the technology of forecasting, and the range of adaptations available under specific forecast conditions. During the monsoon season, real time forecasts were displayed through a virtual "map room. Text summaries based on the forecast maps were sent to two of Bihar's state agricultural universities (SAUs)—one for the flood districts and the other for the drought districts—who translated the forecast summary into the local language (Hindi). These were disseminated through a nongovernmental organization (NGO) directly to farmers via text message A user survey was conducted at the end of the 2018 monsoon season across the four districts to find out how farmers used the SUB-SEASONAL forecasts for farm-level planning and decisions (October 2018). The survey found that almost half of the farmers that participated in the field school used the forecasts to change their farming practices and irrigation schedules compared to previous years. Farmers used the late arrival of the 2018 monsoon (~16 days), which was well captured across Bihar by the SUB-SEASONAL forecast, to delay the sowing of rice and other crops until closer to the monsoon onset. They also changed to a less water demanding variety of paddy rice in response to expectations of a weaker monsoon. Water resource management. Forecast information on SUB-SEASONAL time scales is crucial for managing water resources, especially in times of flood or drought.

CONCLUSION

Like medium range weather forecast, usefulness of extended and seasonal weather forecast enables farmers to organize and carry out appropriate cultural operations to cope with or take advantage of the forecasted weather is warranted. Also, it is useful for strategic planning of farm operations. Weather forecast at higher spatial resolution with reasonable accuracy is important to enhance adoption level. Monthly forecasts with possible weekly distribution are more helpful for crop stage specific management. Though in the

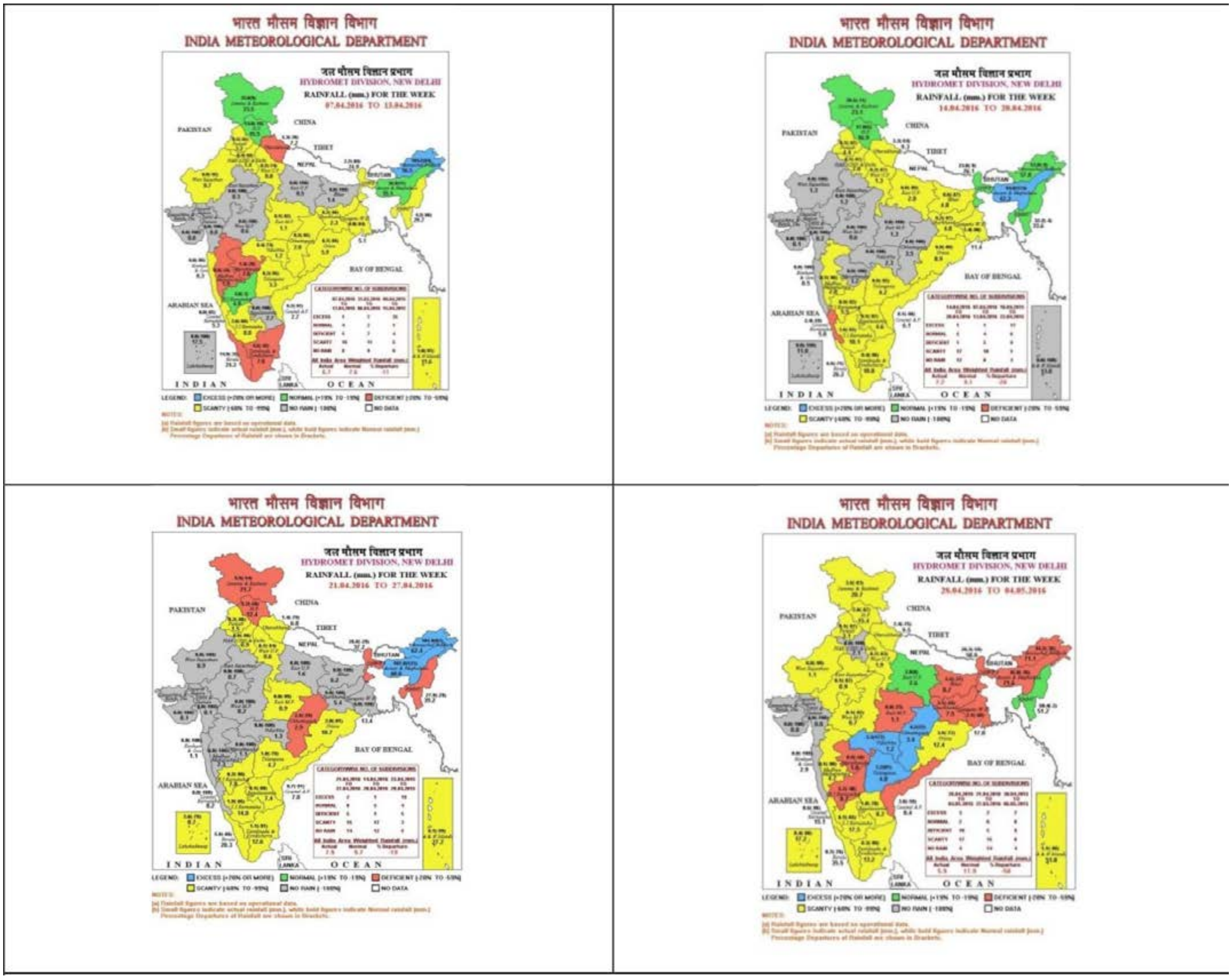

Fig. 7: Realised rainfall in April 2016

present study usefulness of extended range and seasonal forecast could be demonstrated with some case studies, more studies are required in these areas in different agroclimatic zones in the country to assess the skill of these forecast as well as usability of the same in agriculture in the country.

It has been demonstrated here that sub-seasonal forecasts are increasingly being used across agriculture in the country. The sub-seasonal forecasting time scale is therefore a new concept for many users. Because of the additional value of sub-seasonal forecasts for decision-making, it is increasingly gaining interest among users. Present case studies clearly suggest, the forecast at sub-seasonal time scale is need of the hour. Some of the most effective real-time/operational applications presented here are where sub-seasonal forecasts have been communicated to end users and contributed to "situational awareness". This is true in the case of farmers determining the planting and management of crops, informed by the timing of the monsoon in Bihar, sowing of crop and pest incidences in Assam in India.

Increasing the ability of users to engage simply and transparently with sub-seasonal forecasts, and to employ new technologies such as machine learning and artificial intelligence tools to build and augment impact models, would help to further accelerate this process. Crucially, this study provides a platform toward the creation of a national community of researchers and users with a shared aim of exploring and promoting applications of this new generation of forecasts. Sub-seasonal forecasting represents a significant opportunity to generate useful, usable, and actionable forecast information and services for and with users for a range of sectoral applications on previously untapped predictive time scales.

Conflict of Interest Statement: The author(s) declare(s) that there is no conflict of interest.

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REFERENCES

Calanca, P., Bolius, D., Weigel, A. P. and Liniger, M. A., (2011). Application of long-range weather forecasts to agricultural decision problems in Europe. *J. Agric. Sci.*, 149(1):15-22.

Clements, J., A. Ray, and G. Anderson, (2013). The value of climate services across economic and public sectors: A review of relevant literature. USAID Rep., 54 pp., www.climate-services.org/wp-content/uploads/2015/09/CCRD-ClimateServices-Value Report_FINAL.pdf.

Harrison, M., Kanga, A., Magrin, G.O., Hugo, G., Tarakidzwa, I., Mullen, C. and Meinke, H., (2007). "Use of seasonal forecasts and climate prediction in operational agriculture", Report of the Working Group on the Use of Seasonal Forecasts and Climate Prediction in Operational Agriculture, WMO/TD No. 1344 March Geneva, Switzerland.

Hewitt, C., C. Buontempo, P. Newton. (2013). Using climate predictions to better serve society's needs. 639 *Eos Trans. Am. Geophys. Union*. 11:05-107

Hirschi, M., Spirig C. and Weigel, A. P., (2012). Monthly Weather Forecasts in a Pest Forecasting Context: Downscaling, Recalibration and Skill Improvement, *J. Applied Meteorol. Climatol.*, 56(9): 1633-1638.

Lang, A. L., K. Pegion, and E. A. Barnes, (2020). Introduction to special collection: Bridging weather and climate: Subseasonal-to-seasonal (S2S) prediction. *J. Geophys. Res. Atmos*., 125: e2019JD031833, https://doi.org/10.1029/2019JD031833.

Mariotti, A., Cory Baggett, Elizabeth A. Barnes, Emily Becker, Amy Butler, Dan C. Collins, Paul A. Dirmeyer, Laura Ferranti, Nathaniel C. Johnson, Jeanine Jones, Ben P. Kirtman, Andrea L. Lang, Andrea Molod, Matthew Newman, Andrew W. Robertson, Siegfried Schubert, Duane E. Waliser, and John Albers (2020). Windows of opportunity for skillful forecasts subseasonal to seasonal and beyond. *Bull. Amer. Meteor. Soc*., 101: E608–E625, https://doi.org/10.1175/BAMS-D-18-0326.1.

Pattanaik, D. R. and Kumar, A., (2014). A hybrid model based on latest version of NCEP CFS coupled model for Indian monsoon rainfall forecast, *Atmosph. Sci. Letter*, 16(1): 10-21.

Pattanaik, D. R. and Das, Ashok Kumar, (2015). Prospect of application of extended range forecast in water resource management: a case study over the Mahanadi River basin, *Natural Hazards*, 77(2): 575-595.

Robertson, A. W., A. Kumar, M. Peña, and F. Vitart, (2014): Improving and promoting sub seasonal to seasonal prediction. *Bull. Amer. Meteor. Soc*., 96: ES49–ES53, https://doi.org/10.1175/BAMS-D-14-00139.1.

Robertson, A. W., S. J. Camargo, A. Sobel, F. Vitart, and S. Wang, (2018). Summary of workshop on sub-seasonal to seasonal predictability of extreme weather and climate. npj *Climate Atmos. Sci.*, 1, 20178, https://doi.org/10.1038/s41612-017-0009- 1.

Robertson, A.W, Acharya, Nachiketa, Goddard, Lisa , Pattanaik, D. R. , Sahai, ,A. K. Singh K. K., Ghosh, Kripan , Agarwal, Anshul , and Buizer, James L. (2019). Sub seasonal Forecasts of the 2018 Indian Summer Monsoon Over Bihar. JGR Atmosph., 124(24): 13861-13875. https://doi.org/10.1029/2019JD031374

Saha, S., and Coauthors, (2014). The NCEP Climate Forecast System version 2. *J. Climate*, 27, 2185–2208, https://doi.org/10.1175/JCLI-D-12-00823.1

Stone, R. C. and Meinke, H., (2005). Operational seasonal forecasting of crop performance, *Philos. Trans. R. Soc. Lond. B. Biol. Sci*., 360: 1463, 2109-2124.

Tyagi, Ajit and Pattanaik, D. R., (2012). Real time extended range forecast activities in IMD - Performance Assessments and Future Prospects. IMD Met. Monograph No. ERF 01/2012, 1-132.

Vitart, F.: (2014). Evolution of ECMWF sub-seasonal forecast skill scores. *Quart. J. Roy. Meteor. Soc.*, 140:1889–1899, https://doi.org/10.1002/qj.2256

Vitart, F., and Coauthors, (2017). The Subseasonal to Seasonal (S2S) Prediction Project database. *Bull. Amer. Meteor. Soc.*, 98:163–173, https://doi.org/10.1175/ BAMS-D-16-0017.1.

Yan, H., Moradkhani, H. and Zarekarizi, M., (2017). A probabilistic drought forecasting framework: A combined dynamical and statistical approach, *J. Hydrol*., 548(5): 291-304.