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1. AGRICULTURAL METEOROLOGY

Satellite-Based Crop Monitoring Systems

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Introduction

Agriculture accounts for approximately 40% of overall economic activity in many countries in Southern Africa, and a predominant share of this activity depends critically on rainfall. Consequently, agricultural production is highly vulnerable to adverse climatic events, including droughts, floods, and tropical cyclones. Recent growing pressure on regional food systems has renewed interest in making food supply chains more resilient to such events. A prerequisite for effective monitoring and management of supply chain risk is real-time knowledge of changing conditions on the ground.

Satellite-based crop monitoring systems can provide stakeholders with timely information on crop status, emerging production shortfalls, and likely implications for food security, thereby facilitating appropriate management responses. A flood early warning system using optical weather satellite data has been operational for the past 25 years, demonstrating the feasibility and value of satellite-based risk assessment schemes. Space-based monitoring of crop conditions is particularly relevant in the context of precision agriculture and variable-rate application, where improved knowledge of the spatiotemporal dynamics of crop state can support more precise and targeted management interventions.

A comprehensive description of current methodologies for estimating crop physiological, phenological, and growth metrics from optical images is coupled with a review of approaches for predicting agricultural yields, detecting stress, assessing soil moisture availability, and tracking irrigation requirements. Examples are provided of how these techniques can be exploited to meet the changing demands for information from farmers, food producers, and governments alike, with a particular emphasis on the application of satellite-based monitoring in Southern Africa.

Theoretical Foundations of Satellite-Based Crop Monitoring

The scientific rigor of crop condition monitoring is ensured by a model-driven approach grounded in available research. At its core is the formal relationship between observable signals in optical data, their radiometric correction, and the biophysical concepts expressed in crop remote sensing literature. Monitoring methodologies are defined for transforming radiometrically and geometrically corrected time series of optical images into simulation-ready time series. The performance of these simulation-ready time series, relative to ground truth data, determines the agricultural value of the methods. Three aspects of satellite-based crop monitoring are examined: spectral indices and vegetation monitoring, radiometric/geometric correction, and data fusion and temporal analysis two foundational elements that support the estimation of physiological and phenological metrics.

The use of spectral indices in vegetation monitoring is now widespread and supported by an extensive body of literature. Different indices have different strengths and weaknesses; they are sensitive to different characteristics of vegetation and to different environmental conditions. A detailed treatment of available vegetation monitoring indices and their relative strengths is beyond the present scope, but it is important to emphasize that careful selection of a small number of indices, each focused on a specific aspect of the underlying biophysics of the land surface, will yield the best monitoring results. Key considerations in index selection include sensitivity to crop biomass accumulation, insensitivity to soil brightness effects, and relative immunity to atmospheric effects.

Indices that incorporate temporal information, such as those deriving from phenological models, offer additional robustness.

Spectral Indices and Vegetation Monitoring

Vegetation spectral indices are instrumental for crop monitoring. The most common one is the Normalized Difference Vegetation Index (NDVI), which utilizes spectral information recorded in visible and near-infrared bands. NDVI correlates positively with vegetation biochemical variables but saturates at high biomass. Other indices, such as the Enhanced Vegetation Index (EVI) and Soil-Adjusted Vegetation Index (SAVI), were devised to speed up saturation. However, crop monitoring requires a flexible index that can evolve with growth and is sensitive to growth stage: NDVI cannot drop below zero. Negative NDVI values indicate variable soil brightness, which can hinder crop monitoring. Following these specifications, a new NDVI variant was created. Different indices provide complementary vegetation information, and triad analysis allows selection of the most informative index combination for a specific application.

Monitoring phenological signals through satellite imagery is crucial for informing farming management. Reliable estimates of crop growth stages assist with irrigation scheduling, fertilizer management, and timely scouting for pests and diseases. Temporal trajectories of NDVI and associated vegetation indices can indicate plant vigor and underline problematic areas at risk of water stress during repro-duction. Increased biomass during grain filling suggests greater yield potential but may also indicate greater susceptibility to lodging or disease. Variable-rate yield applications can improve management, but the added cost must be justified by commensurate returns. Early indications of crop failure or reduced yield potential are critical for timely calamity assistance, food relief, or alternative supply sourcing. Plotting NDVI temporal profiles against crop type-specific reference curves helps identify key stages and abnormal signatures.

Radiometric and Geometric Correction

Radiometric normalization, atmospheric correction, and geometric rectification are fundamental pre-processing stages in the development of consistent satellite imagery time series. Radiometric normalization reduces differences in surface reflectance induced by variation in illumination geometry and atmospheric conditions. Atmospheric correction removes the effects of atmospheric gases and aerosols, particularly water vapour, which are known to absorb and scatter shortwave radiation and introduce spectral distortions which hinder the interpretation of surface reflectance. Geometric rectification removes displacements between images from different acquisitions, enabling pixel-wise comparisons of surface reflectance across space and time. Together, radiometric normalization, atmospheric correction, and geometric rectification are considered essential preparatory steps in the production of ready-to-use satellite imagery time series for the analysis of dynamic land surface phenomena.

The need for radiometric normalization in time-series analyses of optical satellite imagery arises primarily from differences in solar illumination angle and atmospheric scattering at the time of image acquisition. Such differences induce systematic, non-surface-related spectral variability in the images, degrading the confidence of subsequent analyses. The need for atmospheric correction arises from the presence of gases and aerosols in the atmosphere, whose properties change in time and space, adding noise-like components to the imagery which mask the spectral information provided by the surface.

Data Fusion and Temporal Analysis

Data fusion, spatiotemporal harmonization, gap-filling, and trend extraction are critical to optical time-series analysis. Spaceborne optical data are typically collected by many different sensors with different revisit frequencies and viewing angles. Although multi-data fusion with different optical systems improves dataset completeness, the sensitivity of optical sensors to atmospheric conditions often leads to data gaps over cloudy pixels. Such limits can be mitigated through the combination of imagery with synthetic aperture radar (SAR) systems that operate in all weather.

Multi-sensor optical data fusion is performed through a simple weighted least

square method, combining Dengan infrared optical imagery with Sentinel optical imagery and SCATSAT scatterometer-derived wind data, to identify the potential of low-cost Indian Kaveri microwave satellite observations for weather prediction. Spatiotemporal harmonization over a 90-day growing season is performed using unweighted linear interpolation. Data gaps caused by cloud contamination during crop growth are filled with spatial (geographically weighted) information. Remaining data gaps due to persistent cloud cover conditions around harvest are finally filled by polynomial fitting with respect to time.

3. Sensor Platforms and Data Sources

Satellite monitoring of crop, soil, and weather characteristics relies on a range of sensor platforms and the corresponding data sources. Optical imaging satellites such as Sentinel-2, Landsat, and MODIS represent the primary category, offering multispectral data for vegetation surveillance at resolutions explicitly suited to agriculture. Synthetic Aperture Radar (SAR) sensors represent a second category; by virtue of having different sensitivity characteristics, they provide complementary rather than duplicative information and have different limitations, most notably susceptibility to surface moisture and vegetation structure. At the other end of the spatiotemporal resolution spectrum, Unmanned Aerial Vehicles (UAVs) carry cameras for high-resolution surface imaging at much higher frequencies than orbiting satellites, helping to generate ground-truth information or solve specific problems, together with aircraft and balloons.

Broadly available optical data have primarily been generated by free and open crowdsourced data policies, although new data sources from more recent private satellites have attracted commercial operations. SAR data remain limited in individual coverage and have yet to support operational large-scale monitoring, although data from external sources, at least in Europe, can be provided through spatial data infrastructures. These different data sources and platforms therefore occupy distinct but complementary operational niches. Users must link data to underlying principles (geophysical and biophysical models) and to information-content and observation-error determinants, as well as emotional and data-governance issues.

Optical Imaging Satellites

A wide variety of optical imaging satellites are now operational, with differing spectral bands, spatial resolution, revisit frequency, and the limitation of cloud cover. Many Lcasing satellites are available to users, and some have been explicitly designed for observing agricultural production systems. In terms of access to platform data, conditions differ: Landsat-5, -7, and -8, as well as the Sentinel family of satellites, are equipped with open data policies; no licensing restrictions apply to the use of these data. Others, however, are only available to selected users or subject to proprietary constraints. Additional issues are also worth considering, such as data provenance, the interface with commercial products, and the juxtaposition of societal needs with the business models that govern the provision of satellite sensors.

Optical sensors deliver consistent surface reflectance over long periods; their data can be used to detect and quantify change or to analyze relationships with other variables. However, optical imagers are limited by cloud cover, and water vapor and atmospheric aerosols may also influence the signal. The use of optical radar combined with optical products should also be discussed; the correlation between the vegetation indices derived from These products justifies this approach.

Synthetic Aperture Radar

Synthetic Aperture Radar (SAR) sensors exploit the interaction of microwave radiation (EM waves with wavelengths of millimeters to centimeters) with the surface of the Earth. Unlike optical sensors that measure surface reflectance in the visible, near-infrared, and thermal infrared, SAR measures the backscatter reflected by the surface soil and vegetation. This backscatter is a function of the surface's geometric, physical, and moisture characteristics, making SAR capable of detecting soil moisture and surface structure. Given the capability to penetrate clouds, SAR is particularly useful for monitoring temperate and moist regions, where cloud cover reduces the frequency of optical data capture. These data can complement the information obtained

from optical imagery.

At the level of a SAR resolution cell, radar backscatter depends on both the roughness and moisture contained in the soil and the geometric structure of the backscatter of plants. In regions with a very sparse vegetation cover throughout the year, radar backscatter mainly depends on the moisture content of the soil. As vegetative cover increases, the influence of soil moisture decreases, and backscatter becomes more dependent on the geometric structure of the vegetation canopy (e.g., leaf area index [LAI]). Hence, the SAR response is expected to be sensitive to vegetation moisture (indirectly through its influence on the backscatter of the snow-covered ground) and to the geometric structure of the vegetation canopy (sensitive to the growing season stage).

Unmanned Aerial Vehicle Corroboration

High-resolution data collected from unmanned aerial vehicles (UAVs) are valuable for corroborating satellite-based monitoring systems across different scales. UAV datasets provide accurate information on critical crop parameters but lack sufficient temporal density to estimate growth dynamics. Flight plans should follow the phenological cycle of the target crops, while the integration of UAV and satellite data requires a precise mathematical model and calibration. For close-range applications, such as irrigation monitoring, dedicated flights can be planned to overlap with the existent field conditions, while spectral–temporal data fusion will allow airborne and spaceborne observations acquired at different times to be combined.

UAVs are flexible, cost-effective platforms capable of carrying multiple sensors, offering a new approach to crop monitoring and precision agriculture. The UAV-enabled selection of spectral bands, wavelengths, or classes, as well as a high spatial resolution, help reduce the uncertainty in the decision-making process. UAV datasets can supplement continuous observations of changes in vegetation reflectance owing to crop growth, and association with lower-resolution satellite data can yield consistent spectral-temporal information for decision support. The combination of UAVs and optical imaging satellites provides an operational solution capable of overcoming the specific constraints of UAV and optical satellite data. While the former can provide cloud-free data at a high spatial resolution, the latter enables multitemporal observations across the entire growing season.

Data Accessibility and Governance

Recent years have seen a strong emphasis on open access and data sharing, driven in part by global crises, but also by underlying technological advancements. It has become increasingly easy and cheap to acquire a large number of data often at no cost for a broad range of applications that hold great potential for facilitating the advancement of society. These data may therefore be viewed as a common good for humankind. However, data are not free of cost and responsibility; the diligence invested in producing these data must be recognized and governed. Open access by itself cannot and should not be regarded as a universal good. Access without control may incur undesirable consequences, and ethics must guide these emerging practices. Similar considerations generally apply to the exploitation of remotely sensed data for agriculture.

The concept of open data transcends geographical boundaries; it is not limited to developed regions but equally applies to developing and underdeveloped countries. Open access to satellite data has stimulated agricultural research among scholars in these areas. The availability of Sentinel-1 and Sentinel-2 data, and the foreseen operation of Sentinel-3, Sentinel-5P, and Sentinel-HR, offer unprecedented opportunities for any country with sufficient human resources and a well-defined research roadmap. These free data can complement ASTER, Landsat, MODIS, and other archives. As hyperspectral optical satellites operated by private agencies may be low-cost alternatives in the future, updates of bottom-up open-access policies may broaden usage.

Methodologies for Crop State Estimation

A variety of biophysical and phenological metrics can be derived from optical satellite time-series data for monitoring plant vigor and

stress levels during the growing season and for inferring critical growth stages. Yield forecasting models use optical satellite observations in combination with eco-geophysical predictors such as weather, soil, and terrain characteristics to estimate crop yields in near real time, and these forecasts are frequently validated at multiple temporal and spatial scales. Soil moisture dynamics can also be estimated from optical Earth observations and linked to satellite-based estimates of crop evapotranspiration, thereby providing irrigation scheduling support.

Optical satellite data can also play an important role in crop type mapping. Either supervised or unsupervised classification methods can be used, with training data obtained from ground campaigns or secondary data sources. Feature selection is critical for optimizing classification accuracy, especially when distinguishing similar-looking crop types. An accuracy assessment using representative validation data is essential to determine the reliability of both individual classifications and multi-annual maps produced by aggregating the results over multiple years.

Physiological and Phenological Metrics

Physiological metrics of crop vigor and physiological stress are required to support management decisions. Although not always well correlated with crop yield, they can explain major influences on field productivity and the need for variable-rate application. Typical predictors of early and late-season stress try to synthesize key properties of many crops and are also linked to water-stressed conditions. Time of flowering and harvest are essential for irrigation scheduling and planning post-harvest operations. Segmented trends in optical images at a typical growth pattern provide indications of crop type and input requirement. Crop growth stage classification focuses on five stages common for the rice-wheat system, which may also apply to maize in the region. More detailed monitoring of crop stress and of the crop-fallow-wheat-fallow pattern is necessary to identify especially vulnerable farms and regions. Monitoring provides a platform for the timely assessment of crop water requirements, prepares stakeholders at different planning levels for possible problems, and serves as an early warning for action.

There is an increasing need in policy formulation and response at both local and national scales to establish the relationship of satellite- and model-based monitoring of temperature and precipitation with food security variables. The possibility of detecting food shortages early through monitoring and the quality of such alerts may influence contingency planning at national and state levels during drought-prone years.

Yield Forecasting and Stress Detection

Recent local and global agricultural production declines highlight the need for improved crop monitoring. Crop conditions such as yield and moisture function on different scales and are affected by water management. Yield is affected by multiple factors, while severity of pest and disease stress is often difficult to detect. Addressing these considerations supports earlier and more accurate decisions by providing forecast graphics and modeled inputs. For yield, short-range forecasting employs crop, weather, and meteorological extremes; medium-range forecasting incorporates drought projection using sea surface temperature monitoring; and long-range forecasting evaluates climatic indices, El Niño events, and smuggling. Beyond agriculture, the monitoring system supports applications in precision farming, food security planning, and climate-resilient development.

On-farm yield predictions are derived using crop growth stage information, NDVI, temperature, and precipitation data. Temperature outside optimum growing conditions negatively influences yield, while precipitation and NDVI positively influence yield. When local-scale outputs are integrated with climate forecasts, these predictions can serve as potential inputs for agro-meteorological early warning systems that benefit the agricultural sector, policymakers, and food supply systems. Periods of water stress also impact yield and can potentially be monitored with just NDVI data. Monitoring vegetation health supports detecting moisture stress in groundnut and impact forecasting for mustard and rainfed rice. Time-series NDVI data for sugarcane have successfully been used for quality assessment, while limits on extraction remain for tropical crops grown

mainly in dry-season months.

Soil Moisture and Water Availability

Soil moisture is a critical vegetation parameter affecting both photosynthesis and stomatal conductance, while also controlling plant water stress and, therefore, crop yield. Empirical methods for estimating regional soil moisture status based on optical satellite data take advantage of the strong correlation of land surface moisture with vegetation indices or, in some cases, normalized difference wetness indices derived from the visible and NIR spectral bands. Biophysical approaches supported by radiative transfer theory have the potential to estimate a variety of land surface parameters, including soil moisture, from canopy reflectance under well-posed inversion conditions. The Kappa-fuzzy model was designed to retrieve soil moisture, and its performance was enhanced by multivariate spatialized sensitivity analysis.

Evapotranspiration measures the amount of water lost from an area and can be estimated by combining remotely sensed surface temperature with surface energy balance algorithms. Surface latent heat flux models based on crops and meteorological parameters are capable of estimating potential evapotranspiration and describing crop water consumption. The above processes are necessary for irrigation scheduling.

Crop Type Classification and Mapping

Crop type classification and mapping play a key role in informing precision farming and food security actions whose foundation relies on the assessment of crop type distribution. Image classifiers are built either using reference samples or unsupervised techniques to use the power of machine learning to separate the classes. The key features selected are then used to classify each pixel to its most probable category. Finally, the classification accuracy is assessed, and the trained model is applied to generate a map of the spatiotemporal dynamics of crop types.

Two approaches exist to classify crop types: supervised and unsupervised. In the supervised approach, the spectral reflectance profiles of different crop types are first obtained from a training dataset. Based on the characteristics of these signature profiles, different machine-learning or statistical classifiers are trained. The trained classifiers are validated using an independent set of reference data and used to classify all other pixels over the study area. In unsupervised classification, a training dataset is not required. The algorithm mines the data for clusters of similar spectral values and associates them with crop types that land cover expert's label. The accuracy assessment is equally important, as the ability to correctly classify both specific and unique classes quantifies performance for the end user.

Typically, these methods use a small number of spectral bands, while the nonlinear iterative partial least squares method uses the entire hyper-spectral range (near infrared, visible, and shortwave infrared) though this requires a hyperspectral satellite. A critical step often omitted by users is the selection of relevant bands and features. The choice has an important effect on classification accuracy because most data contain irrelevant and redundant features that reduce performance. Consequently, remote sensing applications based on classification have often produced low accuracy.

Applications in Agriculture and Policy

The monitoring capacities of satellite-based systems support various applications at different scales. At the farm level, they provide essential decision support, such as detecting temporal deviations in crop growth, estimating yield potential, mapping nutrient/vigor stress, indicating harvest time, and quantifying agriculture-related greenhouse gas emissions. These products are relevant for precision agriculture approaches involving variable-rate applications. Several studies also demonstrate the capacity of satellite data to support regional- to continental-scale food supply chain analyses, offering early warnings of reduced food supply and related risks. Food security indicators generated from the monitoring systems, such as crop area, growth stage, and yield, can help assess climate-induced risks, support policy actions, and evaluate resilience.

Crop monitoring systems capable of detecting occurrence and impacts of climate-induced hazards in real time play a crucial role in information dissemination and feed-back mechanisms within broader monitoring–early warning–response systems. Drought impact

monitoring, based on those systems, has been recognized as a key component of resilience assessments and adaptation plans across Africa and is also an important theme across the broader Global Framework for Climate Services. Drought indices developed from satellite observations of several agricultural phenology parameters have proven to correlate well with reported drought impacts and are utilized for impact assessment in various sectors. Drought hazards and their impacts consequently inform decision makers on agricultural adaptation strategy implementation and support other development activities.

Farm Management and Precision Agriculture

The potential of satellite-based crop monitoring for farm-level management remains largely unfulfilled. In several experimental applications it has also been used in an operational decision-support capacity at the farm level. Despite the high spatial resolution provided by UAV flights, direct in situ intervention in case of abnormal crop growth vigilance remains advantageous, especially when temporal changes in crop condition can be interpreted and anticipated with satellite data. Examples are variable-rate nitrogen-fertilizer application or the timely planning of developmental crop-rotation changes. Be it optimized use of agrochemical inputs or field-management decisions,

Many of these applications nevertheless share a lacuna in empirical testing due to the lack of time-series archives that correlate crops with yield-varying parameters for a given area. Prediction tools, therefore, only become decision-support options once validated against observational data from multiple sites over multiple years. At that level they not only afford gain to the individual farmer but also act as a coarser-scale regional component of precision farming. Satellite data enhance monitoring on multiple scales within the food-supply system from farm to country and beyond. Monitoring products at these scales are indispensable for effective management of food supply, security, and risk.

Food Security and Supply Chain Resilience

Effective monitoring of agricultural areas improves food security and supply chain resilience by providing near-real-time information on crop growth and stress. Such information supports food supply and security risk assessments and early warnings by monitoring crop growth anomalies, interpreting food supply fluctuations, and activating emergency response policies. For example, an ongoing drought in South America can influence soybean and maize production. Phytosanitary problems, such as the recent fall armyworm infestation in Africa and Asia, can also negatively affect crop yields. In Europe, heat waves in the summer of 2019 have raised concerns about food shortages, due to reduced yields of summer crops.

Users can compare current or forecasted crop conditions with phenological signals to assess potential yield and food supply fluctuations. Risk of below-normal production can be assessed by monitoring in-season crop vigor. In South America, for example, below-normal NDVI values in January contributed to recent forecasts of below-normal soybean production. Risk of above-normal production can be assessed by monitoring in-season crop stress. In June 2019, below-normal NDVI values in Europe indicated heightened risk of poor yields for summer crops. For traders and speculators, monitoring crop conditions aids market decisions by indicating unusual growing conditions, anticipated production fluctuations or shortages, and changes in supply-and-demand balances.

Climate Change Adaptation and Risk Assessment

Among the impacts of climate change, increased frequency and intensity of extreme weather events particularly threaten food production systems, especially in the world's tropical and sub-tropical zones. Droughts and floods can have major short-term impacts on crop production and threaten food security at all scales, from the single household to regional or national levels. Satellite sensors covering many parts of the world with sensors capable of producing measurements sensitive to the effects of dry or wet conditions enable cost-effective independent monitoring of crop conditions, yield forecasts, and ultimately the food supply situation. Such monitoring can be used to assess the risks of production failures

due to climatic hazards, anticipate crisis situations, and generate these early warnings with an appropriate lead time for decision-makers and the general public. Satellite-based monitoring of crop conditions vulnerable to stresses commonly associated with climate change adaption also contribute to climate change risk assessments in the agricultural sector.

Observation of crop growth offers opportunities to assess short-term yield-relevant climatic hazards. Combining crop condition signals with empirical crop-yield production functions or more complex models makes it possible to assess and quantify crop yield responses of a production area. In many cases, climatic conditions such as air temperature and rainfall are added to the models as additional predicting variables. However, the use of such approaches requires the application of statistical methods specifically designed for relationships in which one variable of the relationship is uncertain. Resulting assessments provide important information for early warning systems, food supply crisis assessment and management, risk assessment in food security, and support for timely responses. Information on drought impacts is indispensable for food security analysis and for timely risk management to mitigate adverse effects on rural economies and populations.

Validation, Uncertainty, and Limitations

The accuracy of satellite-based crop monitoring systems depends on the reliability of ground truth reference data and uncertainty quantification, as well as consideration of systems' limitations and ethical implications.

Ground truth and reference data: Validation efforts require seasonal field campaigns for network sampling of selected observer-dominant points, using inconsistent data sampling schemes on representative spatio-temporal scales. The robustness of derived products relies on openly available reference data sets with low geometric and radiometric uncertainties compared against in situ-flux measurements. Such validation bank shares unconsumed parcels, spatio-temporally upscaled, sampling target carbon, water, and energy fluxes of surface-atmosphere interactions for unsaturated land surfaces. External and independent accuracy assessments ensure that validation bank suffices on these sites, yielding scienced-based analysis and comparison of growing season, year, and global EVI-based VSP shortwave (SW) fluxes with in situ-flux tower measurements.

Uncertainty quantification: Results uncertainty under satellite-based modelling stems from data gaps, cloud cover, external factors, and product-related sources, germinating in data retrieval and modulation assumptions for quantity and quality estimation process. This uncertainty can be propagated when composite gridded maps are constructed, applying accredited error models specific to the data sources of interest. Hence, quantification can concern all quantities of interest including maps, products, and error estimates. Careful uncertainty evaluation and reporting with results aids proper interpretation of analyses. It is useful to follow model-data comparison in assessing response shapes and model efficiency of carbon, water, and energy fluxes predictive functions with uncertainty bounds on sums.

Limitations and ethical considerations: Major challenges are common cloud cover and the consequent limited availability of optical imaging satellite data. Composite approaches combining multi-sensor data over long seasons are essential for overcoming cloud cover limitations. Models and algorithms are location-specific, declaring the need for tester personnel capacitating knowledge co-production. Emphasis is placed on enabling local experts with indigenous knowledge for successful implementation and on-site engagement of models.

Ground Truth and Reference Data

Ground truth data are essential for validating any type of remote sensing products. In agriculture, reference measurements often consist of crop type, growth stage and management information, yield statistics, meteorological station data, and ancillary data that characterize topography, soil, and location. Despite satellites being adept at detecting surface features and dynamics, ground-reference sampling must utilize an adequately designed statistical sampling scheme

(including stratification and randomization), and the location and timing of data collection must adequately represent the employed spectral data. Such ground-reference information is surveyed through dedicated field campaigns or by compiling published and archived data from governmental agencies and research institutions.

The groundwork of a reference dataset must generally be standardized, and structured sampling protocols with clearly defined measurement practices are mandatory. For the evaluation of vegetation indices, crop or vegetation growth stages (anthesis and harvest) are most useful, and these data should be collected at sufficiently low frequencies (e.g., every 1 or 2 weeks) to reflect yearly variations and constraints imposed by management practices (fertilizing, sowing, irrigating, harvesting). These timings can also be related to phenological phase temperatures, which are monitored at the station and aggregated to the period used for computing, for example, the NDVI.

Uncertainty Quantification

Errors in remotely sensed estimates can have major impact on subsequent applications. Therefore, an Uncertainty Quantification (UQ) process allows identification of potential sources of uncertainty, a systematic analysis of their effects in the product and, consequently, their communication to final users.

Uncertainty quantification requires an understanding of error propagation frameworks, an estimation of the real fitness of a model to a problem and the development of sampling designs that allow obtaining reliable benchmarks of what a model is being built for. Consequently, the UQ procedure is divided into three main components: a quantitative assessment of the input data, an uncertainty attribution analysis based on simulation techniques, and an uncertainty propagation using any of the widely known methods, such as the Monte Carlo approach.

Measurement protocols aim to build uncertainty estimates for remote-sensed products, including assessment of the obtained validation benchmarks and their integration in the products pipeline. The construction of dedicated datasets usually allows identifying and minimizing the biases introduced by uncertainty in remote sensing products. Uncertainty quantification techniques can be applied to products that require a continuous monitoring, combining both the uncertainty attributed to the remote-sensed estimates with that obtained from simulations that determine the applied model fit to the real dynamic of the monitored process.

Operationalizing Satellite-Based Monitoring Systems

The architecture of satellite-based crop monitoring systems is outlined in terms of their processing and data-usage aspects. Key requirements for data pipelines and user interfaces to support operational deployment and enhance management decisions are discussed. Development of processing pipelines, user interfaces, and decision-support tools is crucial to operationalize any research activity. Monitoring systems need to routinely ingest and process large volumes of data to deliver outputs with legal or policy implications. Therefore, attention must be given to the architecture at early stages of development to ensure all relevant elements are suitably addressed.

Satellite-based crop monitoring products have been largely inaccessible to those needing early warnings for food security-related issues. Services such as periodic monitoring, alert generation, and risk assessment require information to be provided regularly and on time. Therefore, it must be presented in an easy-to-understand manner to facilitate use by nonspecialists and guide policy decisions. Reliable potential-management suggestions would foster user interest and trust in the product. Resilience to climate extremes such as droughts can be built by using timely alerts for damage assessment and recovery planning, incorporating crop yield forecasts in early warning bulletins, and creating crop-condition dashboards for aid planning.

System Architecture and Data Pipelines

Remote sensing research often deploys multiple data processing steps to derive seamless time series of spectral-temporal and spectral-temporal-phenological products that support downstream yield estimation or validation tasks. While satellite image time series can be ingested or processed in bulk, all

sources share a common architecture that follows a modular approach with data extraction, processing, and application steps.

First, different image sources are imported to examine the spectral temporal behavior of a given region of interest. Data can be analyzed using dedicated images such as Sentinel-2 optical clouds or NASA MODIS data. Processing steps can include time series radiometric normalization using cross-calibration models developed for a specific study area, attempted atmospheric correction to radiometrically represent surface signals, geometric rectification, and cloud masking. Time series are spatiotemporally harmonized from different sources and sensors to minimize discrepancies arising from the combined use of multiple satellite sources with varying spectral and spatial resolution. Consequently, data gaps are filled using data fusion or empirical temporal extrapolation methods such as Savitzky–Golay filtering, Bayesian additive regression trees, or continuous wavelet transform. Finally, robust long-term spectral signal behavior can be analyzed by decomposing time series into additive nondeterministic components using functional regression techniques.

User Interfaces and Decision Support Tools

Data accessibility and usability represent key prerequisites for maximizing the benefits of satellite-based crop monitoring. Multiple hurdles have to be overcome for effective user-focused implementation. Visualization interfaces need to fulfil fundamental criteria for syntactically and semantically meaningful data interpretation. Although map products visually convey a concise and robust overview of crop dynamics, their polychotomous nature usually precludes unequivocal interpretation. Variability over time and space frequently causes alarm signals for indicators with limited observation time, such as crop stress alerts, that would benefit from a more explicit alerting mechanism. Furthermore, interpretation guides represent invaluable complements to the final products, as they enhance qualitative user engagement and aid in the formulation of specific management recommendations.

Beyond providing easily interpretable maps, users demand decision-support tools that allow the integration of satellite data into diverse applications. The illustrated yield forecast revealing expected harvest volumes over the agricultural region is a typical example. An early-warning application detecting likely periodical crop stress has also been successfully translated into a web-based tool. These models currently operate in standalone mode, ignoring sensed yields that could be exploited as predictors for stress or early-warning assessments. Users increasingly engage with precision agriculture and their main focus is improving productivity while concomitantly minimizing costs. Such principles can be experimentally supported by decision tools utilizing sensor-derived information or images, such as moisture maps that would provide the optimum moment for irrigation, thus economizing water and energy.

Capacity Building and Stakeholder Engagement

A good level of in-country expertise in remote sensing applications and the ability to interpret the resulting outputs is critical for operational implementation. Knowledge transfer may take the form of dedicated training activities or on-the-job capacity building facilitated by more experienced users. Such transfer requires a small number of highly experienced operators with a good grasp of the potential for and limitations of satellite-based applications. The operational use of remotely sensed data by external users with training supplied by these few experts needs to remain minimal in order to maximize the opportunities for an effective knowledge transfer. Investing in the education and training of new students represents the best way to minimize long-term external support. Platforms for formal education in remote sensing applications should continue, alongside targeted training courses tailored to the specific needs of managers and users.

The composition of these training programs should incorporate remote sensing theory and expertise but, most importantly, also place emphasis on applied long-term projects and case studies for end users. The effective governance of applications is a further production constraint. The involvement of a number of users through initial participative workshops helps define a framework for

coordination of activities across groups. The realization of the system becomes the first step toward addressing use and governance. A proper product definition coupled with an understanding of all user needs remains essential to ensure the establishment and sound operationalization of an effective product service. Formal institutional mechanisms can help structure the generation and use of the underlying data products and services.

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2. AGRICULTURAL METEOROLOGY

Monsoon Dynamics and Agricultural Production

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Introduction

Comprehensive understanding of the South Asian monsoon system provides crucial insights into climate-ecosystem interactions and their possible futures. Research demonstrates varying climatic influences on agricultural production in different indian regions. Farmers' sensitivity to climatic risk has driven widespread adoption of protective strategies, but changing climatic dynamics may render these insufficient. These factors should influence policy for prudent management of india's agricultural water resources. Monsoon dynamics are visually represented in a set of multiple-source maps showing an interrelated series of underlying climatic factors, their spatial distinctness, dependence on rainfall quantity and distribution, and connections to risk-reducing adaptation.

Overview of the South Asian Monsoon System

The South Asian monsoon system is a dynamic weather system affect-ing the economic and societal aspects of many countries due to changes in the processes of local monsoon variability. It has attracted the attention of many scientists from numerous perspectives, including monsoon breaks, intraseasonal oscillation- and northward jumps over the Bay of Bengal. Therefore, a deeper understanding of the effects of internal and external forcing on monsoon variability based on many historical records is required to extract climate information at various time-scales.

The South Asian monsoon is primarily driven by the atmospheric pressure difference between the Asian landmass and the Indian Ocean. Though, Baiu is particularly strong on the northwest edge of the Pacific Ocean, the effect of the heat distribution on Baiu is not as general compared to that of the Indian monsoon. The asymmetric surface heating of the Asian land region during summer creates a remarkable thermal depression over the Tibetan Plateau that also must be considered. The seasonality of the Indian monsoon has an important interplay with extratropical circulation and the southern hemisphere off-equatorial trough. Much more moisture converges into the Bay of Bengal than discharge. The moisture balance in the Bay of Bengal for the summer monsoon is helpful for understanding the vapour source of the rainfall over the Indian subcontinent.

Key Climatic Parameters Governing Monsoon Variability

Three of the key climatic parameters governing the variability of the summer monsoon over the Indian subcontinent are the Indian Ocean sea surface temperature (SST), the tropical easterly jet stream (TEJ) in the upper troposphere and the distribution of autumn-winter-spring land-precipitation over the Eurasian continent. Regardless of the seasons, centered around 12.5°N, the Indian Ocean SST acts on the atmosphere through differential heating. A positive (negative) differential heat source in the equatorial Indian Ocean is shown to increase (decrease) the moisture availability over the central and northwestern part of the subcontinent and thus strengthen (weaken) the monsoon rains. This, in turn, influences the occurrence of droughts and floods. During summer, the TEJ serves as a barrier between tropical convective and mid-

latitude eddy weather systems. An upstream enhancement of the TEJ near the eastern Tibetan Plateau causes an El Niño-like response in the tropical Pacific Ocean and is correlated with a concurrent rainfall dip in central India.

The response of monsoon rainfall to the Eurasian land-precipitation and the influence of autumn-winter-spring land-precipitation are found to be the opposite of that to the equatorial Indian Ocean SST. Large (small) land-precipitation during the cooling phases of the Eurasian region enhances (reduces) the summer monsoon rainfall over central India while shifting the centre of the summer monsoon from central India towards northwestern India during the predominant phases. Such realisations quantitatively explain the established relations between land-precipitation and the Indian summer monsoon.

Intra-seasonal and Inter-annual Variability

Both intra-seasonal and inter-annual variability of rainfall during the growing season play a crucial role in agriculture production of crops grown under rainfed conditions. Fifty per cent of the total annual rainfall over the entire country is received during the month of July and August. However, the distribution of rainfall within the monsoon season is not uniform. At times, July is characteristically dry (or dry spell), while there may be excess rainfall in August, or vice versa. Intra-seasonal distribution of rainfall during the monsoon season is largely determined by the passage of synoptic systems such as cyclonic disturbances in the central trough and tropical cyclones over the Bay of Bengal. Cyclonic systems act as efficient rain-generating mechanisms. Disturbances between the active and weak phases of the monsoon may lead to dry spells during July/August period and may be detrimental to paddy crop at the critical phonological stage. A prolonged dry spell of about eight weeks from the end of June to the end of August may displace the crop from its physiological maturity stage in a high rainfall area in the north-Eastern region, despite normal contribution of rainfall during June and September. Monsoon droughts have also been observed because of the combined effect of anomalously dry July and August, while surplus rainfall during these months might lead to floods.

The inter-annual variability is very high and is evident from the fluctuations in the overall agriculture production in india, with years of surplus, drought, and flood conditions. In recent decades some very deficient monsoon seasons have occurred such as 1972 falls in 1976, 1987, 2002, and 2004, with considerable affect on agriculture production. Years of surplus rainfall such as in 1971, 1976, 1988, 1993, and 1996 have also been observed, causing affect on crop production and economy, due to excess rainfall at critical periods associated with flooding. Primarily due to the deficiency of rainfall during the monsoon season, droughts are more frequents than floods in the country. However, during the La Niña phase of the ocean-atmospheric phenomenon, El Niño Southern Oscillation (ENSO), generally excess rains have been received.

Seasonal Rainfall Onset and Withdrawal Dates

An alternative rain-window length index can be constructed by using absolute (instead of normalized) seasonal rainfall and defining its limit using onset and withdrawal dates of the seasonal rains. The duration of the window is defined as the difference between the seasonal rainfall onset and withdrawal dates, taken from India Meteorological Department data. A second estimate of onset and withdrawal dates is based on the seasonal rainfall at each grid point being at least 10 mm. For northern India before the mid-1960s, a longer rain window duration leads to a longer growing season. After the El Niño-induced drought of 1966–67, production in North-South India is affected differently by window duration, possibly owing to the increased importance of transport by the southwestern monsoon.

In India, wheat and rice are grown during the winter and summer seasons, respectively, when environmental conditions are least conducive for a crop-growing season. Maize is cultivated in both the winter and summer seasons. Early (before March) sown wheat is reported to have higher yields. Higher than normal rainfall during the winter season is likely to adversely affect wheat production,

mainly in northern India. In the western part of Andhra Pradesh, where a sizeable area is under maize crop during the summer, heavy rainfall is reported to be detrimental for maize production. An increase in summer rainfall is favourable for larger production of summer groundnut, summer sunflower, summer bajra and summer jowar.

Humidity, Atmospheric Moisture Transport, and Convective Processes

About agriculture, the most important humidity parameter is relative humidity, which is defined as the ratio of water vapour pressure to saturation vapour pressure. Water vapour pressure is an actual measure of the vapour content in the air and influences the rate of evaporation from open water bodies, soil surfaces, and vegetation. The growth and development of crops are greatly influenced by the atmospheric moisture content during their life cycle, especially during the flowering, fruit formation, and grain-ripening stages. Agriculture within the humid tropics is especially sensitive to variation in humidity as there are large variations in the moisture available for plant growth. During the monsoon season, when 80-90% of the annual precipitation occurs, agricultural operations are entirely dependent on the rainfall received. In contrast, relative humidities in the pre-monsoon and post-monsoon periods often approach values below 40%.

Humidity influences agriculture mainly through its effects on evaporation and the rate of convective processes in the atmosphere. High humidity generates a drop in the rate of evaporation, which in turn slows soil moisture replenishment used by the crops. At high relative humidities, the convective systems become less active and cloud height decreases, with a resultant fall in rainfall intensity. Hence, the summer growth of crops is sensitive to changes in humidity when vapour pressure is above 12 hPa. The most significant negative correlation between crop yield and humidity is identified for rice in West Bengal. Normal Humidity, Atmospheric Moisture Transport, and Convective Processes. Regarding agriculture, the most important humidity parameter is relative humidity, which is defined as the ratio of water vapour pressure to saturation vapour pressure. Water vapour pressure is an actual measure of the vapour content in the air and influences the rate of evaporation from open water bodies, soil surfaces, and vegetation. The growth and development of crops are greatly influenced by the atmospheric moisture content during their life cycle, especially during the flowering, fruit formation, and grain-ripening stages. Agriculture within the humid tropics is especially sensitive to variation in humidity as there are large variations in the moisture available for plant growth. During the monsoon season, when 80-90% of the annual precipitation occurs, agricultural operations are entirely dependent on the rainfall received. In contrast, relative humidities in the pre-monsoon and post-monsoon periods often approach values below 40%.

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Pressure Fields, Circulation Indices, and Teleconnections

Pressure cells and circulation indices play a significant role in modulating the southwest monsoon. Teleconnections are another important set of links among long-term, large-scale climatic processes that influence local conditions on the order of months to a season. A significant correlation exists between the standardised vertical pressure difference between mean sea-level pressures over the East African coast and central Indian regions during the months of August and September, thereby reflecting the intensity of the monsoon. Lesser values of vertical pressure have often been associated with weak or drought monsoons in India. The August–September pressure-based circulation index, computed as a simple mean of four selected pressure stations, has established significant relationships with

monsoon rainfall, countrywide thawing, and kharif rice production. The AI (teleconnection index), composed of a weighted standardised average of 500 hPa geopotential heights over the region 0°–10°N, 90°–120°E, influenced the Indian monsoon rainfall during the past half century and continued to impact rainfall variation.

A distinct rainfall linkage between monsoons in northern and southern parts of India was recognised and best illustrated by the correlation between residual rainfall series from both regions. The influence of the southern Indian summer monsoon on the northern Indian summer monsoon is evident, at least on a 10–20 year timescale, providing further evidence of significant long-range weather-linked interaction between the two regions of the Indian subcontinent. Similarly, the strong linkage between the Indian summer monsoon rainfall and the summer monsoon rainfall over the entire East Asian monsoon region was also confirmed. Bandpassing of the correlation field shows that significant dates of near- and long-range interaction, as defined by the interaction between monsoons of the southwestern United States and Mexico, are also apparent in the Indian monsoon–East Asia monsoon relationship. Such interaction, viewed with respect to the stability of monsoon conditions, has important ramifications for agricultural production over the two monsoon-dominated regions.

Temperature Extremes and Heat Stress

In a warming climate, the intensity and frequency of extremes in day- and nighttime temperatures are markedly increasing and may continue to do so in the near future and beyond. The increase in intensity and decrease in inversions are projected to result in concomitant increases in growing season length, but the main conclusion of most impact assessments is that a combination of higher mean temperatures, increased heat extremes, and heat stress during flowering will result in reduced yields of rice, wheat, and pulses, particularly in northern and central regions, with yields for maize and cotton across a wider area likely to increase, with enzyme activity and therefore growth models predicting increases of over 20% per degree of warming, subject to generalainemophilic functions remaining functional. Depending on latitude and season, increased day length could favour increased yields of certain major crops. However, model projections based on temperature analysis indicate that the risk of crop failure will increase, as predicted effects of higher maximum temperatures during flowering reduce the yield potential of wheat. In the major rice-growing regions of Punjab and west Bengal and Bangladesh, the direct infuence of increasing temperature extremes during the t–day flowering period also threatens rice production.

Increased frequency, duration, and intensity of hot events (minimum temperatures > 24°C during summer and > 20°C in winter) are observed over the Indian region and will likely affect many regions of the region. While high-temperature thresholds may limit the production of all crops, the increase in the number of high-heat-stress days is especially adverse for cotton, groundnut, chillies, sorghum, wheat, and rice. Increased post-bloom heat stress will likely reduce rice yield due to greater detioration in grain quality and reduced kernel weight. The increased risk of sub-optimal temperatures during the growing season for soybean will affect the crop regionally, and high-temperature exposure at sensitive growth stages would likely cause lower yield for chickpea. The association between high-temperature extremes and fungal diseases in plants could further aggravate crop production in the future.

Sea Surface Temperature and Ocean-Atmosphere Interactions

A significant predictor of Indian monsoon rainfall is the sea surface temperature (SST) in different oceanic regions: the eastern Pacific (usually El Niño), the equatorial Indian Ocean, and the northwest Indian Ocean. SSTs exert considerable control over the monsoon both directly, through latent heat exchanges with the atmosphere, and indirectly, through shifts in the position and strength of the summer circulation, which determines the inflow of moisture into the Indian region. The summer atmospheric circulation, including the monsoon, is largely driven by the differential heating of the land and ocean surfaces. Anomalies of summer land- and ocean-air temperatures can, therefore, change the

atmospheric heat source and affect rainfall over India.

The initiation and subsequent evolution of the monsoon are likely to be influenced by latent heat release over the continuously warm equatorial Indian Ocean at this time of the year. There are, however, other complex interactions that also shape the monsoon. Various studies show that there is a close relation between summer monsoon rainfall and SST in several regions of the tropical oceans. A year of above-normal rainfall in India is accompanied by a year of below-normal rainfall in the eastern and central Pacific, while the opposite is true for a year of below-normal rainfall in India. The characteristics of these years suggest that they may be related to the phase of the El Niño–Southern Oscillation.

Aerosols, Land-Use Change, and Surface Roughness

Anthropogenic aerosol loads in the atmosphere a function of air pollution, land-use change, soil erosion, and other activities impact the local and regional land-atmosphere systems. Many studies have illustrated the impacts of aerosols on monsoon rainfall, some positive and others negative. Although some results point to a possible increase in summer monsoon rainfall due to the combined effects of ocean warming and the presence of aerosols in the atmosphere, other studies indicate signalling a drying trend in monsoon rainfall associated with aerosol variability. Despite uncertain impacts at regional scales, there is little doubt that the transport and long-range dispersion of aerosols play a dominant role in determining regional precipitations.

Recent studies have shown a significant correlation between declines in summer monsoon rainfall and land-use changes induced by human activity in India. During its passage from northwest to southeast India over densely populated regions such as Maharashtra, Andhra Pradesh and Tamil Nadu, the Indian summer monsoon tends to weaken, a trend attributed to the land-use pattern and land degradation resulting from soil erosion and deforestation in these states. Urban expansion and human-induced land-use change can enhance surface roughness, modifying local winds and generating regional wind convergence and divergence. The associated changes in moisture transport and the re-distribution of moisture convergence can affect precipitation patterns and lead to considerable variability in rainfall.

Agricultural Production in India: A Climatic Perspective

The analysis of agricultural production risk in India reveals that deviations from normal rainfall seasons affect production variability and provide an actual basis for risk analysis in the farming and cooperative sectors. Dry spells during the kharif season significantly affect the production of coarse cereals and pulses. Across most commodities, a deviation from the normal d2 rainfall season tends to be paired with a deviation of the same sign for most rainfall parameters during the crucial crop growing months, which indicates that a climatic perspective increases the understanding of production variability in India. The production levels in India are skewed, with the kharif production season contributing relatively more towards lower agricultural production levels, while both rabi and annual production levels contribute relatively more to the upper tail.Agricultural production in India is influenced primarily by the southwest monsoon and the rabi season, which receives rainfall from the northeast monsoon and the Western Disturbances. The kharif, or summer, season is more sensitive to rainfall departures than the rabi, or winter, season. The kharif season is influenced by the southwest monsoon, which is subject to stochastic variations in strength and duration.

Years with below normal rains during the kharif season are often drought years; agriculture particularly rainfed agriculture, which constitutes 50% of net sown area and contributes around 30% of agriculture GDP is severely affected. Dry spells distributed unequally during the kharif season enhance production risks. A study at the decadal level also points to a significant association of drought years with less-than-normal water availability in the rabi season, especially in the d2 and d3 rainfall seasons, and indicates that deviations from the d2 rainfall seasons significantly affect production variability of coarse cereals, oilseeds, and pulses. Deviations from the normal d2 rainfall season account for nearly 30% of the total kharif production

variance, while relative departures in the rabi season seem to convey better information about kharif production in above-normal years.

Crop Portfolio and Seasonal Dependencies

The Indian agriculture is dominantly geared towards N.E monsoon rainfall which sustains 92, 91 and 92 per cent of the production of pulses, oilseeds and cotton respectively and 64 per cent of total food grain production (source :DGFS). Besides being dependent on the seasonal distribution pattern of these rains, the crop portfolio also closely resembles the spatial distribution of N.E. monsoon. The above aspects reflect the fact that a large percentage of crop area is under long duration crops. Investigation of area under various crops vis-a-vis area served by different school of climatological thought reveal a close manner of interaction between the them.Tantu (1987) based on multi-variate analysis ,observed that Indians monsoon rianfall with 50 per cent weightage dominates the dependent variable index of food grain production in the eastern region, whereas the southwest monsoon rain augurs well for food production in the western and central regions of India .The aggregate production of jowar , bajra, wheat, gram andcotton in all-India level is significantly determined by the southwest monsoon rainfall.The contribution of north-east monsoon rainfall to total food-grain production is limited to Tamil Nadu because a high percentage is accounted for the long-duration kharif crops grown mainly in Tamil Nadu and some parts of Andhra Pradesh.The rest of the seasons, other crops, supplied by various weather variable during various times of the seasons are positively significant for the above crops. The seasonal distribution of production of various crops are therefore determined by parameter significant for them as well as other crops produced in shallow markets.

Monsoon rain is a major determinant of interannual variations in the crops grown in Kharif season in most parts of India. It is, however, difficult to establish a one-to-one correspondence between the amount of Kharif rain and Kharif food-grain production since the proportion of area and the yields of Kharif food grains are also influenced by other factors like market conditions and behaviour of reservoirs. The area under Rabi food-grain production and thus the total food-grain production in a year depends not only on Ne monsoon rain but also on that during the preceding seasons like winter, summer and Kharif. All such other seasons and the behaviour of the above variables during other seasons of the years supply weather information to the model for Rabi production of food grain and its stability. These aspects are also reflected in the dependent function/Crop portfolio ad seaonal dependencies. The influence of monsoon rain on food-grain production is more dominant in the eastern regions of the country where proportionately larger area under rice is cultivated, compared to other regions. A large percentage of the area under these crops is also served by the rain during the months of the monsoos rather than the rest of the year.

Irrigation Dependency and Water Resource Management

A majority of most of the agricultural land in India is rain-fed. Equatorial climatic regime in most of the western part of the country contributes more than 50% of irrigation supplies during rainy season; drought years would mean a serious deficit for the next year. Other water and irrigation rich areas depend upon the monsoon wind directional stability, for duration and volume of rainfall. A possible extension of rainy Monsoon from south-west to north-east and reverse may be feasible by appropriate strategy of planning. The greater need for Irrigation during the lean months indicates a necessity for a Water Resources Management Authority, proper planning and management of the Monsoon vital for Increase in Agricultural Production.

Rain-dependent Agriculture is of great risk in India. Most water and irrigation rich areas seem to have little risk because of the long history of water conservation by building many reservoirs and canals. These water accumulation systems take care of the irrigation requirement during the lean months except during a very bad drought year. However, the monsoon Dynamics determines the direction and volume of water and affects the agriculture of huge tracts in the country. Most of the deforestation and other environmental degradation, in the Western

Ghats and in the north east, result in poor rainfall as well as poor monsoon accumulation of water. A greater concern exists in the densely populated northern and western parts of the country, where the risk remains particularly high, especially for rain-dependent cropping systems. A marked decrease in arrival of rains during the rain belt monsoon period has a direct effect on the water availability for drinking and irrigation.

Climate Sensitivity of Major Crops (Rice, Wheat, Pulses, Oilseeds)

The effects of climate variability and change on major food crops (rice, wheat, pulses, and oilseeds) in India are examined using state-of-the-art simulation models that rigorously quantify and demonstrate the sensitivity of these crops to weather variations and changes. Rice yield in India is 1.9% sensitive to changes in growing-season temperature and 0.43% to changes in precipitation. At the all-India level and for major wheat-growing states, the effects of climate change on wheat yield are small (about −1.0%/ +1.0° since the crop is grown in a near-optimal environment) or negligible. Sensitive regions, such as the western and central Indo-Gangetic plains, might sustain −2.2%/° and −1.0% change in maximum temperature. However climatic changes are manifesting primarily through changes in the means and distributions of extremes of weather variables. Uptake and post-monsoon growth of pulses and oilseeds would benefit from an increase in rainfall during these periods, while the reverse is true for the rest of the Kharif and pre-monsoon periods.

The future weather trends based on southern oscillation index (SOI) anomalies indicate that Kharif pulses might be adversely affected by a decreasing trend in rainfall from the southwest monsoon when the SOI value is very low, with unfavourable conditions for Kharif oilseeds. Overall, with atmospheric CO_2 concentration projected to reach 560 ppm by 2050, the estimated impact of climatic change is negative on crops other than rice and negative on crops other than rice at the regional scale, re-emphasising the need for adaptation measures for long-term climatic change.

Weather Signals and Yield Variability

Signals associated with weather parameters have been recognized in the yield variations of crops grown under rain-fed conditions, such as rice and sorghum. These signals strongly validate the dependence of crop yields on climatic parameters. Therefore, an attempt has been made to examine the possible relationship between various climatic signals and weather parameters associated with the sensitive growth stage of these crops. In this study, agricultural crop data for different states are analyzed with the weather parameters of those states. Area, yield, and production of crops are considered to identify the states with important crops and states responsible for the total yield of selected rain-fed crops. Principal component regression analysis has been used to build a regression model with weather parameters.

The analysis also identifies key risk and stress weather parameters responsible for the variability of the yield during the sensitive growth stage of the crops. A relationship then exists between accumulated weather parameters during the sensitive growth stage of the crops and weather-based important multidecadal cycles. Yield variability is generally high during the past-declining phase and low during the past-ascending phase of signals and cycles associated with the persistent multidecadal component. Varied-degree relationships of yield with parameters in different climatic states are identified for both monitored and unmonitored crops. These relationships corroborate well during the enhancement of the past period of twenty years. Interdecadal variation in the extent and direction of yield variability with parameters are also observed during the past century. Analysis reveals that the Indian agricultural region is prone to yield risk due to the inherent relationship with weather signals.

Agricultural Practices, Adaptation, and Risk Management

Adaptation in agriculture primarily involves changes taking place at the farm level and farmer practices. Agricultural production is influenced primarily by the temporal and spatial gradients of monsoon precipitation and temperature, wealth index of households, and interaction between crop sown area and

monsoon precipitation. Adaptation of agriculture to climate is evident in the agricultural distribution of major crops grown in India. The south-west monsoon rainfall pattern influences the sowing and harvesting of kharif crops such as rice, coarse cereals, oilseeds, pulses, and cotton. Also, production of crops such as wheat, barley, rabi sorghum, sugar-cane, soybean, and raida is carried out in the north-western parts of India where the north-east monsoon is important. Adaptation means taking care of certain parameters or characteristics in order to achieve a sustainable or desired goal of the society, economy, or ecosystem or group of people. Monsoon rainfall exerts a direct influence on Indian agriculture, as it provides about 80 per cent of the total annual rainfall received, which influences the sown area and crop productivity.

Production risk is the degree of variability in output on the farm, attributed to the vagaries of nature. The historical relationship between crop yield and monsoon precipitation has declined over time during the last three decades. Space–time interactions indicate that monsoon quantity is a significant and robust determinant of crop production. Empirical analysis of risk in kharif crop production indicates quantity of rainfall during June–July, monsoon season and partitioned rainfall, wealth of households and interactions between rainfall and sown area risk can explain risk in kharif crop production. The copula-based study on production risk indicates time-varying dependence between production and price in kharif season and monsoon rainfall plays an important role for the observed changes in the copula parameter during the period of study.

Parameter Interactions: Linking Monsoon Dynamics to Agricultural Outcomes

The analysis of parameter interactions provides insights into the link between monsoon dynamics and agricultural production. Correlation analysis establishes relationships between the monsoon parameters and key crops in the Northeastern Indian states. Subsequently, a hierarchical clustering approach, combined with an analysis of variance, examines the relative effects of the parameters identified in the correlation analysis. Finally, through path analysis, the effects of these parameters on paddy and maize yield variations in Meghalaya are investigated. Since climatic parameters act on the production of crops and, in turn, affect localized climatic parameters, the analysis is carried out in reverse order.

The rainfall, humidity, and temperature during the season preceding the paddy and maize growing periods show significant correlation with the yield variations of the respective crops. When the yield performance of the preceding maize crop is clustered with monsoon parameters of Northeast India, humidity parameters appear as the most important group, with the humidity ratio during the monsoon season emerging as the single most important parameter.

Rainfall Quantity and Spatial Distribution

The total rainfall received by India during the south-west monsoon, while large, is not uniformly distributed across time and space. Rainfall during the south-west monsoon season has averaged approximately 880 millimetres per annum for the triennium periods for the decades of the 1960s, 1970s, 1980s, 1990s, and 2000s. Large interdecadal variability is evident, with 1062 millimetres being received during the 1990s and only 738 millimetres during the 2000s. The coefficient of variation for these triennium periods is larger than 12 per cent, and other distribution measures reveal high frequency of shortfall years. Various studies indicate large intra-decadal Rainfall change during the Indian monsoon for the decades of the 1960s to the 1990s with low coherence in change. The stability of seasonal mean south-west monsoon rainfall over India is accompanied by significant decadal variation, reflect in shift of south-west monsoon rainfall contour north-west during 1980s and total dry and wet decadal phase of the Indian economy. Very recent study based on five decades of data shows that monsoon onset and withdrawal Phases over the Indian region are characterized by internally generated decadal variability. Internal feedback, particularly external forcing with likely support of enhanced aerosol-mean state interaction, is the cause of increased decadal Rainfall variability in the south-west monsoon.

Apart from the large amount of rain during

the south-west monsoon, another distinctive feature is the very distinct rainfall regimes that exist over India. A divide runs roughly north-south along the central portion of the Indian landmass. To the west of the divide (the Western Rajasthan region, west of the Aravali range and part of the Kutch and Arabian Sea coastal plain) rainfall amounts of less than 400 mm are received during the south-west monsoon. In eastern Rajasthan and northwest Madhya Pradesh, the monsoon rainfall total ranges between 400-600 mm. Within Coromandel Coast region total rainfall is less than 1000 mm, and the south-west monsoon season is important primarily in ensuring adequate moisture for raising Kharif and, to a lesser degree, Rabi crops. Monsoon failure is usually associated with drought.

Onset, Duration, and Break Monsoon Impacts

Shifting dates for the onset and end of the southwest monsoon adversely affect agricultural production. Such delays, increases, or decreases shorten the duration; during break periods rainfall is less intense than during active phases. The overall effect of these changes cannot simply be inferred from monsoon total rainfall, since the timing, duration, and intensity of rain are as important for agriculture as the total. However, the relationship is complex, revealing critical thresholds for key crops and considerable intradistrict variability for others. Indices describing onset, duration, and breaks in rainfall significantly influence food production for most states, and harvest failures can recur in successive years.

The time-series analysis assessed the correlation with agricultural production across all states, allowing for the potentially significant nonlinear relationships between rainy season rainfall and crop yield. Monsoon rainfall departure is most important early in the kharif, while the break period becomes critical when moisture demand is highest. In drought years, the onset delay index is correlated with foodgrain production in seven states. In Uttar Pradesh, the growing season starts too dry, while Andhra Pradesh, Karnataka, Maharashtra, Gujarat, and West Bengal typically face late-onset drought conditions.

Temperature Extremes, Growing Degree Days, and Phenology

The temperature extremes were evaluated in terms of annual number of cool days (nCD), nCD, fTmax ≥ 35°C, fTmax ≥ 38 °C, and fTmax ≥ 40°C. The contribution of annual nCD to total CD has decreased in all zones, with the effect being statistically significant for MAI, NBOI, DCI, and EAP. In contrast, fTmax ≥ 35 °C, fTmax ≥ 38 °C, and fTmax ≥ 40 °C have all increased, significantly so in EAP for fTmax ≥ 38 °C and fTmax ≥ 40 °C and in NBOI for fTmax ≥ 38 °C. While the changes in absolute values of the variables considered are important in themselves, the change in the ratios is also critical, as these indicate shifts in the relative importance of temperature ranges that determine reproductive stress in crops.

Growing Degree Days (GDD) has been shown to be useful for understanding changes in crop phenology, especially for rice and wheat, which are the two main crops in North India during the kharif and rabi seasons, respectively. A GDD threshold of 20°C is normally used to assess the growing season length of these crops, as temperatures below this threshold induce dormancy and appreciable plant growth takes place only above this threshold. Therefore, a GDD0 product was constructed from threshold temperatures of 0°C and 20°C, subjected to PCA and examined for changes in spatial distribution. The results revealed a consistent decreasing trend over the past 50 years, significant at the 5% level for KMAI, MAI, NBOI, and DCI. The off-season/summer crop season is characterized by relatively high temperature, so that the distribution of GDD20 is determined mainly by input from fTmin ≤ 5°C and fTmax ≥ 35°C. The GDD20 pattern has evolved in a way that the cooler areas have become warmer, whereas the hotter areas have continued to get hotter, leading to an increase in phenological stress for Kharif crops.

Soil Moisture Dynamics and Groundwater Recharge

Soil moisture is the most important variable determining agricultural productivity but has received very little attention in the monsoon context. A detailed analysis of soil moisture dynamics and groundwater recharge is made here. The soil moisture changes are

derived from an energy balance model forced by rainfall, the available soil moisture depletion before 1983, potential evaporation, and the actual evaporation after 1983. Groundwater enrichment, defined as the precipitation minus the actual evaporation, is obtained from the water balance of the total basin area. The soil moisture storage, required to sustain the agricultural productivity of the Critical zone, is defined and related to the monsoon precipitation. An interaction analysis reveals important links between soil moisture dynamics and groundwater drainage.

Agricultural production, expressed in wheat, rice, and surghum equivalents, is correlated with the various parameters, such as drainage, available soil moisture, and ground-water recharge. An analysis of the Kohli-Oommen monsoon model has revealed that soil moisture dynamics associated with agricultural production are governed by external forcing such as rainfall and evapo demand and internal feedbacks such as redistribution of vapour by the winds. The principal enhancement of the research stems from the estimation of soil moisture. The soil moisture dynamics have been derived from an 08 parameter energy balance model. The model has been forced by observed precipitation, available soil moisture depletion before 1983, potential evaporation, and actual soil evaporation.

Farmer Decision-Making under Climatic Variability

Farmers in India are thought to react in various ways to the variability of the monsoon along the spatial and temporal scale. While they have learned to deal with low rainfall, they have not developed coping mechanisms to explicitly deal with fluctuations in the timing of the start and end of the monsoon season. They take decisive decisions about changing either the crop area (intensification) or the classification of crops (adaptation) in response to poor rainfall. Both shifts are correlated with investor's profits and not with subsistence needs. For years with inconsistent patterns of rainfall the start date measured as a late onset and the end date measured as an early withdrawal there is a decline in both crop area and crop diversity, and an increase in the relative area sown to coarse cereals and pulses. The reliance on traditional crops such as bajra and jowar as a risk-minimizing strategy is particularly relevant to the analysis of these shifts.

Farmers' decisions have a long-term and implicit adaptive effect on agricultural output to climatic variability. The temporal variations in rainfall captured by indicators of distributional extremes have a significant influence on productivity. An increase in variability causes a disproportionate decline in agricultural productivity by inducing a reallocation of sown areas towards risk-minimizing coarse cereals and pulses and a reduction in the area cultivated. Changes in external investment conditions, such as a rise in world prices, reverse these shifts: an increase in variability is associated with a larger probability of intense reduction in investors' profits and a tendency towards allocation of larger areas for high-value intensive and riskier crops. As a result, areas planted with sugarcane and cotton are particularly sensitive to a definite early or late withdrawal of the monsoon.

Regional Variability within India

Traditionally, India has been identified as a country of viable monsoon. Several studies have analysed the variability in the Indian summer monsoon at different time scales, and this variability is responsible for droughts and floods during the monsoon season, which in turn affects the agricultural production during that period. The Indian botanical survey revealed the sudden death of trees in the subtropical forests, which was attributed to long drought.

In view of the importance of spatial variability in the near-surface atmospheric parameters, as well as the Indian summer monsoon at different time scales, the summer monsoon season is divided into three sub-seasons, namely, June, July and August-September. The Indian summer monsoon is subsampled into these three sub-seasons and the coefficient of variation of daily rainfall for the respective months computed for the 115-year long summer monsoon season, based on the daily rainfall for the period 1871 to 1985. The coefficient of variation for June is more than 340 and, thus, June emerges as the most variable month of the Indian summer monsoon. July and August- September are the

next variable months with coefficient of variations of around 200.

North, West, East, and South Indian Subregions

Agricultural producing or consuming resources are distributed in all parts of India, exhibiting a wide geographic variation except few commodities mainly tea and coffee which are concentrated in the northeastern region and southern Plateau of India.The cultivated area is generally higher in the northern and western parts of India compared to other parts which are relatively less populated and the cultivable area per person is thus greater. The concentration of yield and production per person of different crops are presently low in the north and northeastern parts of India, however India's production and yield of rice and wheat is equal to or higher than those of China and world averages.India is a major producer for many agricultural commodities and shares major portion of world production for commodities such as rice, wheat and pulses. The trends in agricultural production generally reflect the change in demand for agricultural products over the past few decades due to increase in population and diversification in food preferences due to rise in income.

There has been a marked increase in the area, production and yield of rice, wheat and cotton. However, the yield of pulses and coarse cereals remained below the world average and demand has been met mainly through imports. India is also importing edible oils to a large extent to meet its demand. The south western region of India produces about 43% of total coffee production, 70% of total tea production and 40% of cardamom production. The southern plateau region is the major producer of coffee and tea. The north eastern region is the only region where the area under horticultural crops is increasing, mainly due to plantation of banana and turmeric. The beef production has increased during the past four decades largely due to increase in buffalo population and boost in export.

River Basins and Agro-climatic Zones

India has eleven major river basins along with eight coastal river basins and around fifty minor river basins. The major river basins cover an area of 2.58 million square kilometres (mkm2), which is about 78.1 per cent of the total geographical area of the country. India has around five hundred million hectares (mha) of arable land, which supports about 73rd of the world population. For the purpose of agricultural planning and development, India is divided into fifteen agro-climatic zones, which are further sub-divided into thirty-one sub-zones based on physiography, temperature, rainfall, soil, and cropping pattern.

The Ganga basin is one of the major basins in the country. Originating in the Himalayas in the Ganga region, the river flows through a wide delta before emptying into the Bay of Bengal. Rainfall is high, with nearly 300 em along the eastern margin in the North-east; the remainder of the basin, however, receives less than 150 em of rain. The Ganga basin in India contains one-fifth of the country's total population, and agriculture, forestry, transport, and hydropower remain the principal economic industries. Within the Ganga basin, the Indo-Gangetic alluvial plain covers over 130 mkm2, and it lies between the eastern and western Himalyan ranges. The major tributaries of the Ganga Yamuna, Ghaghara, Gandaki, and Kosi contribute the majority of the river's discharge. The Yamuna, the principal tributary, extends through Uttar Pradesh, Haryana, Delhi, and Bihar.

Monsoon Breaks, Active Phases, and Dry Spells

A monsoon break is a ten-day period of dry weather over India during the wet season, but it varies in duration and intensity. Although generally lasting for less than a week during the June and September months, rainfall ceases completely during breaks in the July–August phase. A break pattern indicates the absence of moisture-laden air over India. The break may be accompanied by a dipole morphology of wind anomalies with an anticyclonic anomaly over India and a cyclonic anomaly over the Arabian Sea. Enhanced cross-equatorial flow and moisture convergence over the Arabian Sea during the breaks indicate the overactive state of disturbances over the basin. The tendency for the SCF indices to shift towards more negative values during breaks is consistent with the fact that they stand out as a wet phenomenon, although dry breaks occur occasionally.

The five-phase decomposition approach helps to understand changes in rainfall, moisture convective heating, and moisture convergence associated with the dry periods in the South Asian summer monsoon. Changes in organized convection, moisture, heating, and circulation that occur over India and adjoining regions during one of the drier breaks of the summer monsoon have been documented. Active and break phases in the context of monsoon dynamics are governed mainly by the spatial distribution of heating, moisture convergence–divergence dynamics, and interactions with the circulation systems which could be synoptic, intraseasonal, or interannual. Dry and wet spells during the rainy season induce large changes in land-surface temperature, sensible heat flux, and vegetation activity and are linked primarily to the concentration and position of the rain.

Climate Change Considerations and Future Projections

Climate change notably affects the Indian monsoon precipitation system and the severity of regional disturbances, with a discernible risk of extremes in both the wettest and driest regions. Direct assessments reveal decreased monsoon precipitation with changes in the seasonal cycle, as well as shorter monsoon seasons. Future ensemble mean projections indicate an increase in monsoon precipitation resulting from anthropogenic climate change, confirming previous projections of increased monsoon intensity and related changes in precipitation extremes. Nevertheless, major questions remain. Will land precipitation react to a reduction in land–sea thermal contrast as a result of monsoon warming and moistening? What role will natural variability play? How will persistent dry anomalies in the Indian monsoon region. Relative to Europe, Africa, and North America, the Indian monsoon precipitation system is poorly documented in past records, leading to differences in reconstructions and models. Yet, a confident assessment of ongoing and future changes would help the regional economy and society.

Protests raged throughout India in 2009 when the country unexpectedly experienced its second successive failed monsoon; agricultural production fell by 17% owing to drought, leading to the depletion of reservoirs and food shortages. The 2008–09 period was the driest recorded by the all-India Indian Meteorology Department Rainfall. In contrast, the 50-year record of summer monsoon precipitation at the Indian Meteorological Department's rainfall gauge station at Nagpur, Maharashtra, shows that the drought-flood cycle has intensified. Furthermore, modelling studies suggest that Indian summer monsoon rainfall has become significantly less predictable across seasons. A summer monsoon warming pattern has been identified, and both observational analyses and general circulation model (GCM) simulation studies indicate that the intensity of the summer monsoon has increased. However, future changes remain uncertain due to large inter-model differences in the projected response of the Indian summer monsoon to greenhouse gas (GHG) forcing.

Trends in Monsoon Rainfall and Extreme Events

Precipitation trends are studied to assess the impact of climate change on the monsoon across India, and trends in temperature extremes are studied to assess changes that may impact agricultural production. Also examined are trends in the frequency of extreme rainfall events.

Standardized monsoon (June–September) rainfall series covering the period 1871–2007, comprising 20 homogeneous subregions, shows a convex upward trend over the Indian land mass (2.4 mm y–1 increase), however when the two wettest decades of the rainfall series (1930s and 1940s) are excluded there is a slight downward trend. The substantial increase in intensity of wet decades is associated with a 1°C rise in SST over the equatorial Indian Ocean; corresponding consideration of the dry decades suggests a threshold behavior in the response of rainfall to SST warming. The wet extensive years of the monsoon are related to the strength of the Indian Ocean Equatorial Mode (IOT) during the preceding spring–summer. A steep increase in the occurrence of extremes with time in the late part of the century is observed, in agreement with climate change prediction/dynamics; and a hypothesis is proposed: as the oceans warm, the atmosphere thins and precipitation becomes less frequent but more intense.

Analysis of gridded CHIRPS® (Climate Hazards Group InfraRed Precipitation) 270 m resolution rainfall dataset confirms large-scale features for the period 1989–2017, showing that monsoon peak rainfall is occurring earlier and is associated with a stronger oceanic IOT during May–June, with a more intense IOT during preceding February–March and stronger El Niño decaying in September. The analysis confirms that Indian monsoon rainfall increased in frequency and intensity during the 1989–2017 period, consistent with the prediction of the IPCC.

Implications for Crop Calendars and Production Planning

The drowning phase of the Indian summer monsoon is marked by intense precipitation events of relatively short duration. In India, these short-duration extreme rainfall events, which can be considered as extreme weather events, have been partly attributed to climate change. Analysis of cyclone tracks in the North Indian Ocean reveals a frequency peak in September, suggesting that the phase transition is also marked by an increase in cyclone activity (Nirmal and Baidya, 2004) and calls for a re-examination of production risk among rabi crops. Analysis of climatic trends from 2031 to 2050 indicates a rise in maximum temperature, declining humidity, increased frequency of hot days and warm nights. which are not conducive for paddy production stability in reception stage. Climate is a significant factor affecting plant growth and development and it can deviate from the ideal with respect to soil moisture availability, light intensity, temperature and relative humidity, etc. Drought is the most important climatic hazard drastically affecting crop production.

Drought at the flowering stage and high temperature at grain filling stage have been shown to have a profound effect on yield of rice, which is the dominant crop in the area during kharif season. Recently the effect of climate on agricultural productivity in India and subsequent application towards development of a hybrid maize yield model for an Indian condition has gained importance. Seasonal rainfed agriculture in India and in some parts of South-East Asia are the world's most vulnerable eco-regions in which crop failure due to moisture stress often leads to widespread famine and starvation. This aspect assumes significance because entire population in the region massively depends on agriculture. In Bihar another analysis involving weighted regression derived climate elasticity tables for yielding of rice and wheat during kharif and rabi seasons respectively covering a period from 1980 to 1999. It was concluded that an increase of 1% in daily temperature increases the yield of rabi wheat and decrease the yield of kharif rice by nearly 0.4%.

Adaptation Strategies and Policy Implications

The development of appropriate adaptation strategies relies on a full understanding of the monsoon system and its relationships with other systems, as exemplified in India where the primary societal activity is directly dependent upon the summer monsoon which exhibits large year-to-year fluctuations and is subject to global warming. The analysis indicates that Indian agriculture has adjusted to changing climatic conditions, particularly the monsoon system, and a number of physical processes and characteristics have remained relatively constant. Predictions of monsoon rainfall for the next century tend to indicate a slight increase, possibly 8–15%, which is consistent with present trends. Thus, it appears that no major changes would be necessary.

Nevertheless these predictions need careful verification since estimates from emissions scenarios differ widely; for Southern Asia, where monsoon rains contribute greatly to the die, such inconsistencies are crucial. Factors such as extreme droughts, floods, and temporal spread of rainfall have greater impacts on the security of agriculture than millennial and centennial changes in averages and trends certainly more than feedbacks on the monsoons due to land use changes yet adaptation is not simple. Improved forecast models that combine the new data and more detailed representation of the processes involved in the monsoon system, particularly during its initiation and withdrawal phases, are being developed. The tendency for the monsoon to arrive earlier in the northwestern and later in the northeastern parts of India is already taken into account in agricultural planning and practice.

It is evident that the parameters of the interaction between the monsoon and several land-surface and hydrological systems are being examined more completely than formerly. The integration of such new knowledge in the form of process-oriented models with a proven 'chaotic' behavior offers a basis for long-term prediction of monsoon rainfall. The equations governing the Fluctuations of these processes maybe brightened together with the equation for Indian monsoon rainfall in an interaction model of Indian agricultural production.

Data, Methods, and Evidence Base

Monsoon-related parameters associated with agriculture for the states of India have been collated through the India Meteorological Department (IMD), India Production Census Bulletin, India Ministry of Agriculture, and the Indian Institute of Tropical Meteorology (IITM). Indian monsoon rainfall data at a spatial scale of 1° ×1° latitude–longitude is considered from the IMD gridded daily rainfall dataset for the period 1951–2016. The Routh-Hurwitz criterion is applied in a state-space representation of the TS model and the positive definiteness of the related Lyapunov function to estimate the number of subregions that for each monsoon season interact positively. The conditions that validate a Monsoon-Sharma–Gavrilov–Mikhaylov set of circadian oscillators are checked in an extended state-space realization. These indicate that each monsoon season can be represented as a THM of positive interaction with smaller eastern states of India and negative interaction with larger western states.

Nonlinearity and symmetry in the TS model are validated by the independent method of electronic circuit implementation. Seasonal data of total Indian monsoon rainfall is classified into phases of low, medium, and high. The Series-Parallel Random Threshold (SPRT) network model conceptually approximates total Indian monsoon rainfall as a complex dynamic system of thirteen Monsoon–Sharma–Gavrilov–Mikhaylov (MSGM) circadian oscillators, organized as a four-stage hierarchy of permanent, regional permanent, temporal–temporal, and MSGM circadian SSA–Lyapunov neighbourhoods (lanes) and so symmetry in the positive and negative temporal patterns of influence between the segments of rainfall. A climate production model for forty-three major agricultural products at state, district, and tehsil levels of India is based on the relationship of area and productivity.

Observation Networks and Reanalysis Products

The Indian monsoon observation networks spanning over the Indian subcontinent, both on land and sea, have provided long-term, high-quality datasets required for making meaningful monsoon forecasts, particularly at the seasonal scale. An upward trend in temperature and rainfall has been detected over northwest India, indicating changes in monsoon characteristics. However, the lack of long-term, high-quality datasets on many of the essential hydrometeorological parameters over the region necessitates the use of reanalysis products for studies at the seasonal and sub-seasonal scales, including for the simulation of hydro-meteorological extremes (e.g. floods and droughts). Several reanalysis products are now available, including the National Centers for Environmental Prediction (NCEP)/National Center for Atmospheric Research (NCAR) (NCEP1), NCEP Climate Forecast System Reanalysis (CFSR), the European Centre for Medium-range Weather Forecasts (ECMWF) 40-year Reanalysis (ERA-40), the First-Order Global Reanalysis constructed by the Australian National University (ANU), the ECMWF Interim Reanalysis (ERA-Interim), the Japanese 55-year Reanalysis (JRA-55), the Global Forecast System of NCEP with 6-h forecast, and the North American Regional Reanalysis (NARR). Various parameters in the reanalysis products agree well with in situ observations for the Indian region. For sub-seasonal extremes, the Climate Forecast System Reanalysis (CFSR) Dataset appears to be the most suitable among the reanalysis products for the Indian region.

The growing global internet network provides the perfect platform for the Indian meteorological scientist to request monthly climatic data of temperature, rainfall, humidity, wind speed and direction as well as their changes (anomalies and trends) from various meteorological data websites. This monthly climatic data is available on the Global

Climate and Weather Normalization Method (GCWN) servers maintained by the National Environmental Research Institute (Roskilde, Denmark), the Indian Institute of Tropical Meteorology or within India's Meteorological Department. Several centres, both in India and abroad, maintain specialized databases for El Niño/La Niña monitoring, and these can be accessed for better understanding of the link between monsoon and El Niño event. Besides, several data centers have now started generating experimental dynamic prediction of Indian monsoon for operational use using atmospheric, oceanic and coupled global models at monthly and seasonal time-scales. These forecasts can also be verified with data obtained from the Indian Meteorological Department for making meaningful conclusions.

Statistical and Dynamical Modeling Approaches

Statistical prediction models for Indian monsoon rainfall have been developed to provide reliable and timely forecasts for various applications. Rajeevan et al. (2010) have developed a simple statistical prediction model for summer monsoon rainfall and its various sub-divisional scales for India using a linear regression equation. The model uses the January–March seasonal mean of the southern Indian Ocean sea surface temperature (SST) as the predictor with a prediction lead time of about five months. Another statistical forecast model for Indo-Southwest monsoon is developed by using the February–March Southern Oscillation Index (SOI) with rainfall data for the pan India region for the period 1931–2009 to predict monsoon rainfall for the period 1931–2017. Based on a penta-decadal rainfall data set (1774–2008) for India, a model is validated by Roy Chaudhuri et al. (2013) to evaluate the performance of the El Niño-Southern Oscillation (ENSO) indices prior to the monsoon season in India.

Mishra et al. (2008) explored large-scale features of heat waves over India by examining thermal structure of the atmosphere, solar insolation and land–air temperature gradient. An ensemble technique has been used by Mishra (2010) to predict the onset date and setting-up of monsoon over the Indian sub-continent. Other aspects of statistical modeling techniques related to monsoon rainfall prediction and updatation are summarized by Chowdury et al. (2000). Sea-surface temperature anomaly patterns observed over the Equatorial Pacific and South Indian Oceans, and the relative strength of the annual cycle in surface pressure over the Northern and Southern Indian Ocean simultaneously yield useful insight into the variability of the Southwest monsoon rainfall over India. Karna et al. (2013) explored the downsizing of an ENSO-based forecasting model for the prediction of summer rainfall in India with a lead-time of two seasons, highlighting the fact that a large value of Nino-3.4 SST could lead to below-normal Indian summer monsoon rainfall.

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