

# Latest Advances in Weather Forecasting and Their Application in Agriculture

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## ABSTRACT

The evolution of weather forecasting has progressed from traditional methods to advanced technology, significantly benefiting modern agriculture. Initially, predictions relied on indigenous knowledge, which proved inaccurate for extreme weather. The development of numerical weather prediction (NWP) enhanced forecasting accuracy, particularly through global models like the Global Forecast System (GFS) and regional systems such as the Bharat Forecast System (BFS). Recent technologies, including remote sensing, satellite technology, artificial intelligence (AI), big data, and IoT, have enabled real-time monitoring. Nevertheless, improved forecasting is crucial for crop planning, irrigation management, and disaster mitigation in climate-resilient agriculture. Sophisticated weather forecasting technologies make weather prediction a reliable decision support system for climate-resilient agriculture.

## INTRODUCTION

**W**eather and climate play a decisive role in shaping agricultural productivity, resource management, and food security, particularly in a country like India, where a large proportion

of farming remains dependent on monsoon dynamics and seasonal variability. The increasing frequency of extreme weather events such as heavy rainfall, droughts, heatwaves, and cyclones has amplified the

vulnerability of agricultural systems, necessitating robust and reliable weather forecasting mechanisms. Accurate weather forecasts enable farmers to make informed decisions regarding sowing time, irrigation scheduling, fertilizer application, and pest management, thereby reducing risks and enhancing productivity (World Meteorological Organization, 2025).

Over the past few decades, significant advancements have been made in numerical weather prediction (NWP), which uses mathematical models of the atmosphere to forecast weather conditions. Organizations such as the India Meteorological Department (IMD), Indian Institute of Tropical Meteorology (IITM), European Centre for Medium-Range Weather Forecasts (ECMWF), and National Oceanic and Atmospheric Administration (NOAA) have developed sophisticated models such as the Bharat Forecast System (BFS), Integrated Forecasting System (IFS), and Global Forecast System (GFS). These models assimilate vast amounts of observational data from satellites, radars, and ground stations to produce high-resolution forecasts (IMD, 2022; IITM, 2024; ECMWF, 2024; NOAA, 2024). Additionally, initiatives like the Copernicus Programme provide global climate monitoring and data services, further strengthening forecasting capabilities (European Union, 2024).

Despite these technological advancements, challenges remain in accurately predicting localized weather events, especially in complex terrains and diverse agro-climatic zones. To address these gaps, emerging technologies such as artificial intelligence (AI) and machine learning are being increasingly integrated into weather forecasting systems. AI-based models can process large datasets, identify hidden patterns, and improve forecast accuracy, particularly for short-term and

extreme weather predictions (Jain et al., 2019). Furthermore, blending modern scientific forecasting with indigenous knowledge systems—such as traditional indicators based on animal behavior, plant phenology, and celestial observations—can enhance the reliability and acceptance of forecasts among farming communities (SCIRP, 2021; ISDS, 2022).

The importance of weather forecasting extends beyond agriculture to disaster risk reduction and climate resilience. Institutions like the National Disaster Management Authority (NDMA) emphasize the development of multi-hazard early warning systems to minimize loss of life and property (NDMA, 2024). With global temperature trends showing a consistent rise, as reported by Berkeley Earth (2026), the urgency for accurate and timely weather and climate services has become even more critical.

In this context, the integration of advanced forecasting models, AI technologies, and traditional knowledge systems presents a holistic approach to improving weather prediction and its application in agriculture. This study aims to explore the evolution, current advancements, and future prospects of weather forecasting systems, with a particular focus on their role in enhancing agricultural decision-making and resilience.

## 1. EVOLUTION OF WEATHER FORECASTING

### 1.1 Traditional and Indigenous Methods:

Early forecasting relied on Indigenous Knowledge Systems (IKS), including observations of clouds, wind, animal behavior, and astronomical patterns such as Panchang-based predictions (SCIRP 2021). Farmers used indicators such as bird movement, plant phenology, and halo formation around the sun or moon to predict rainfall.

However, these methods were localized and lacked scientific validation, making them unreliable under changing climatic conditions.

**1.2 Classical Scientific Methods:** The development of meteorology introduced physical principles such as thermodynamics and fluid dynamics to explain atmospheric processes. Instruments such as thermometers, barometers, and radiosondes enabled systematic data collection (IMD 2023).

Synoptic meteorology further improved forecasting by analyzing large-scale weather patterns using maps and observations from multiple stations.

**1.3 Statistical Methods:** Statistical forecasting established relationships between predictors (temperature, pressure, humidity) and predictands (rainfall, temperature) using regression and correlation techniques. Models such as Model Output Statistics (MOS) improved forecast accuracy by correcting systematic errors.

However, these methods depend on historical data and fail under changing climate conditions

#### 1.4 Limitations of Traditional Methods:

- Low accuracy in long-range forecasts
- Inability to predict extreme events such as cloudbursts
- Poor spatial resolution
- Dependence on historical patterns

## 2. MODERN ADVANCES IN WEATHER FORECASTING

### Numerical Weather Prediction (NWP) and Major Global Models

Numerical Weather Prediction (NWP) is the most advanced method of weather forecasting, which involves solving a set of mathematical

equations that describe atmospheric processes such as motion, heat transfer, moisture dynamics, and pressure changes. These equations are based on the principles of **thermodynamics and fluid dynamics**, and they simulate the future state of the atmosphere from given initial conditions (IMD 2022).

The NWP process consists of several key steps:

1. **Data Collection** – Observational data is collected from satellites, weather stations, Doppler radars, radiosondes, and ocean buoys.
2. **Data Assimilation** – The collected data is processed using advanced techniques such as **4D-Var (four-dimensional variational assimilation)** to generate accurate initial conditions.
3. **Model Simulation** – Supercomputers solve complex differential equations on a three-dimensional grid covering the Earth's atmosphere.
4. **Forecast Generation** – The model outputs variables such as temperature, rainfall, wind, and pressure for future time steps.

NWP models differ in their resolution, forecast range, and accuracy. The major global models used worldwide include:

#### 2.1 Global Forecast System (GFS)

The Global Forecast System (GFS) is developed by the National Oceanic and Atmospheric Administration (NOAA), USA. It is one of the most widely used global weather models due to its open access and frequent updates.

- **Resolution:** ~13 km (recent upgraded version)
- **Forecast Range:** Up to 16 days

- **Update Frequency:** Every 6 hours

**Working Mechanism:** GFS integrates observational data from satellites, weather stations, and radiosondes, and uses data assimilation techniques to initialize the model. It then solves atmospheric equations globally to simulate weather evolution.

**Key Features:**

- Provides global coverage
- Freely available data
- Widely used in operational forecasting

**Limitation:**

- Slightly lower accuracy compared to ECMWF in medium-range forecasts

**2.2 ECMWF Model (Integrated Forecast System – IFS)**

The ECMWF model, developed by the European Centre for Medium-Range Weather Forecasts, is considered the most accurate global weather prediction model.

- **Resolution:** ~9 km
- **Forecast Range:** 10–15 days
- **Data Assimilation:** Advanced 4D-Var system

**Working Mechanism:** ECMWF uses one of the most sophisticated data assimilation systems, combining vast global datasets and running simulations on high-performance supercomputers.

**Key Features:**

- Highest accuracy among global models
- Strong ensemble prediction system
- Better representation of atmospheric physics

**Applications:**

- Medium-range forecasting
- Climate monitoring (Copernicus Programme)
- Agricultural planning

**2.3 Bharat Forecast System (BFS – India)**

The Bharat Forecast System (BFS) is India's next-generation global weather model developed by the Indian Institute of Tropical Meteorology under the Ministry of Earth Sciences.

- **Resolution:** ~6 km (very high for a global model)
- **Forecast Range:** Up to ~10 days
- **Supercomputing Support:** ARKA (next-generation system replacing Pratyush & Mihir)

**Working Mechanism:** BFS integrates high-resolution data from satellites, Doppler radars, and surface stations using hybrid data assimilation techniques. It provides finer-scale simulation of atmospheric processes, especially over the Indian region.

**Key Features:**

- High-resolution global forecasting
- Improved representation of monsoon dynamics
- Better prediction of extreme rainfall events

**Significance for India:**

- Designed specifically for Indian climate conditions
- Improves forecasting of monsoon variability, cyclones, and cloudburst-prone events

## 2.4 Remote Sensing and Satellite Technology

Satellite systems such as INSAT and global programmes like Copernicus provide real-time atmospheric data, including cloud cover, temperature, and moisture (European Union 2024). Doppler weather radars enhance short-term forecasting and nowcasting.

## 2.5 Artificial Intelligence and Machine Learning

AI-based models such as GraphCast and Pangu-Weather enable faster and data-driven predictions, often outperforming traditional models in certain scenarios (Jain et al. 2019).

## 2.6 Big Data and Cloud Computing

Big data integrates information from satellites, radars, and sensors, while cloud computing enables real-time processing and forecasting at large scales.

## 2.7 IoT-Based Forecasting

IoT devices provide hyper-local data, enabling farm-level forecasting and precision agriculture.

## 2.8 Advanced Models and Early Warning Systems

- WRF: High-resolution regional model
- HWRF: Cyclone-specific model
- CFSv2: Coupled ocean–atmosphere model
- Multi-Hazard Early Warning Systems (MHEWS): Provide real-time alerts (NDMA 2024; WMO 2025)

## 3. APPLICATIONS IN AGRICULTURE

Modern weather forecasting supports:

- Crop planning and sowing decisions
- Irrigation scheduling

- Pest and disease forecasting
- Disaster preparedness

Agro-advisory services provided by IMD and ICAR help farmers make informed decisions based on forecast data.

## CONCLUSION

Weather forecasting has evolved into a sophisticated science integrating physics, data, and advanced technologies. While modern systems have significantly improved accuracy, challenges remain in predicting localized extreme events. The integration of advanced forecasting technologies is essential for sustainable and climate-resilient agriculture.

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