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INTEGRATING INDIGENOUS AND SCIENTIFIC METHODS OF WEATHER PRACTICES IN ETHIOPIA

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ABSTRACT

Ethiopia's rain-fed agriculture system is highly vulnerable to climate variability. Weather forecasting, derived from both indigenous and modern sources, plays a critical role for Ethiopian farmers, with each method having its own strengths and limitations. This study bridges the gap between indigenous knowledge and scientific methodologies by focusing on rain prediction and rainmaking practices in Ethiopia. By examining ecological indicators, ethnobotanical knowledge, and the role of smoke in cloud formation from a meteorological lens, the study identifies potential synergies between indigenous and modern meteorological techniques. The research highlights the significance of indigenous knowledge in sharpening the coarse resolution of satellite-based data and suggests strategies for integrating these practices into modern meteorological systems. These strategies include detailed surveys of flora and fauna, controlled experiments, and incorporation of ethno-meteorology into the educational curriculum and operations of the Ethiopian Meteorological Institute. This study enhances the development of effective, sustainable weather forecasting and climate adaptation strategies, fostering dialogue between indigenous and scientific knowledge in Ethiopia.

Keywords: Indigenous knowledge, Rain forecasting, Rainmaking, Ethno-meteorology, Ecological indicators.

1. Introduction

The ability to collect, interpret, and apply environmental information is fundamental for human survival and prosperity. This information, whether derived from sensory observations or advanced technological sensors, often requires human expertise to filter, analyze, and synthesize meaningful insights. This process allows for the identification of patterns that form the foundation of adaptive strategies critical for survival, especially in regions reliant on rain-fed agriculture where accurate rainfall prediction is crucial for successful crop cultivation.

In recent years, the scientific community has increasingly recognized the value of indigenous practices, acknowledging their potential to complement scientific, data-driven methods (Hoppers, 2002). This recognition raises a key question: how can indigenous practices be systematically integrated with scientific data-driven technologies to enhance the accuracy and relevance of rainfall predictions in rain-fed agricultural areas?

Indigenous knowledge systems are vital for managing rainfall variability in rural Ethiopian communities. These systems interpret natural signs such as animal behavior, plant growth patterns, and celestial movements, offering localized weather insights. However, scientific meteorology in developing countries like Ethiopia faces constraints such as inadequate infrastructure and scarce meteorological stations, further complicated by complex topography.

Indigenous knowledge systems are facing modern challenges. Intergenerational transmission is declining as younger generations, influenced by Western education, often dismiss these practices as outdated. This erosion threatens the knowledge base of indigenous weather forecasting. Climate change, environmental mismanagement, unsustainable land use, population pressures, and erratic weather patterns further disrupt the environmental cues these systems rely on (Fernández-Llamazares et al., 2015). Studies such as Ayal et al. (2015) revealed a 79% mismatch between indigenous forecasts and actual rainfall records over 27 years in Ethiopia, potentially undermining public confidence in these methods.

Scientific weather forecasting systems are also facing challenges, particularly in Africa. The primary issue is the gap in understanding tropical meteorological processes, which differ significantly from those of mid-latitude systems (Sobel, 2012). The World Meteorological Organization (WMO), acknowledges that African weather forecasting suffers from poor representation of tropical systems in numerical prediction models, particularly concerning rainfall (Meque et al., 2021; Igri et al., 2018). Moreover, the African research community often lacks the capacity to develop localized forecasting solutions, relying on external models that may not capture local weather nuances (Parker, 2008; Dike, 2018; Lamptey et al., 2024).

Despite their sophistication, scientific meteorological systems face challenges akin to indigenous weather practices, particularly in terms of public trust and accuracy. In developing nations, a pervasive lack of confidence persists in scientific weather forecasts. This mistrust often originates from misinterpretations of probabilistic language in forecasts, such as "70% chance of rain," which can be perceived as ambiguous or unreliable (Joslyn & Savelli, 2010). Moreover, the inherent complexity of atmospheric processes, involving many variables, such as temperature, humidity, and wind patterns, renders precise weather prediction, especially at localized scales, a formidable challenge (Slingo & Palmer, 2011). This complexity not only affects forecast accuracy but also contributes to public skepticism, as the nuances of meteorological science often elude general comprehension.

The integration of indigenous knowledge with scientific meteorological practices presents a promising approach for weather forecasting. Indigenous knowledge rooted in local environmental observations offers valuable place-based insights, particularly in regions with sparse data or complex topography (Orlove et al., 2010). Kalanda-Joshua et al. (2011), Maldonado et al. (2016) and McPherson et al. (2016) demonstrated the credibility and practicality of rural farmers. Conversely, scientific meteorology contributes comprehensive data collection through advanced technologies, thereby enhancing the forecast accuracy. The synergy of indigenous wisdom and scientific methods could potentially refine local forecasts and improve overall prediction accuracy.

A significant research gap in Ethiopian and sub-Saharan African studies is the lack of identification and explanation of the shared parameters and convergence points between indigenous and scientific weather forecasting systems. To address this, this study proposes a deep exploration of indigenous weather practices by examining ethnoscientific and ecological indicators in relation to atmospheric processes of weather and climate elements. This approach aims to facilitate the identification of common ground between indigenous and scientific methods, paving the way for a more successful integration of these complementary forecasting systems.

Despite the importance of indigenous knowledge in climate adaptation, its integration into meteorological systems remains limited. This study posits that indigenous forecasting methods offer localized information where scientific meteorology falls short, whereas scientific approaches provide broader, empirically supported regional insights in Ethiopia.

While organizations such as the Intergovernmental Panel on Climate Change (IPCC) acknowledge the potential of indigenous knowledge, they offer little practical guidance for integration. Similarly, Article 8(j) of the Convention on Biological Diversity advocates the preservation of indigenous knowledge but lacks a concrete framework for merging it with scientific practices (Nakashima & Roué, 2002). This gap underscores the need for a structured approach to integrating indigenous and scientific weather forecasting methods in Ethiopia, leveraging the strengths of both systems for more comprehensive and locally relevant weather predictions.

This study employs a systematic review of the existing literature on indigenous weather practices in Ethiopia and evaluates them from a scientific perspective. A comprehensive search on Google Scholar using the keywords "Rain Forecast," "Rainmaking," and "Ethiopia," yielded 36 peer-reviewed studies published up to September 2024. The research meticulously analyzes each article for reference to meteorological variables embedded in indigenous practices, with particular emphasis on the spatialities of Ethiopia's diverse agroecological regions and rainfall regimes.

By identifying potential areas of intersection between indigenous and scientific weather practices, this study seeks to bridge the gap between indigenous knowledge and contemporary meteorological techniques for rainmaking and rain forecasting by examining the strengths and limitations of both approaches. The goal is to propose a holistic framework that seamlessly integrates indigenous wisdom with advanced technology, addressing gaps in current literature and enhancing the applicability and accuracy of weather forecasting across Ethiopia's diverse landscapes.

This paper is organized into seven sections. Following a brief introduction, section 2 highlights the critical role of rainfall in Ethiopia's agriculture, economy, and societal well-being. Section 3 analyzes the geographical distribution of the existing research on indigenous weather practices across the country's diverse agroecological regions. Sections 4 and 5 critically assess the strengths and limitations of both indigenous and scientific weather-forecasting systems. Section 6 explores potential strategies for integrating these two systems with a focus on rainfall forecasting and rainmaking. The final section concludes by synthesizing key findings and proposing recommendations for future research and practical implementation of integrated weather forecasting approaches in Ethiopia.

2. The Role of Rain in Ethiopia's Economy

Ethiopia's agriculture, the backbone of its economy, relies heavily on rainfall. Approximately 40% of the country's GDP, 80% of exports, and 75% of the workforce are tied to this rain-fed sector (USAID, n.d.). The country's vulnerability to climate variability is well documented, with catastrophic famines, such as those in 1974 and 1986, highlighting the devastating consequences of rainfall fluctuations. These events underscore the need for accurate and timely weather information.

Rainfall variability poses a significant challenge to agricultural production in Ethiopia. The lowlands of Ethiopia, located in the peripheral and Rift Valley regions (Moron & Robertson, 2020; Alley et al., 2019), are particularly susceptible to inadequate and erratic rainfall, leading to severe food shortages. Furthermore, even the densely populated highland areas, despite experiencing higher annual rainfall, remain vulnerable to fluctuations in rainfall timing and distribution, which can significantly disrupt agricultural productivity.

The economic impact of rainfall variability was profound. Sadoff (2006) demonstrated a strong correlation between rainfall variability and GDP growth, underscoring the link between rainfall fluctuations and national food security. Subsequent studies (Brown and Lall, 2006; Thornton et al., 2006; Brown et al., 2011) corroborate these findings, revealing an inverse relationship between rainfall variability and economic growth. Aragie (2013) further emphasized this connection, reporting a strong correlation between rainfall patterns and economic performance, with fluctuations in real GDP and agricultural output closely linked to long-term precipitation trends.

Despite the potential of irrigation to mitigate these challenges, Ethiopia's irrigation infrastructure remains underdeveloped, with less than 12% of irrigable land currently under irrigation (Haile & Kasa, 2015). The country's rugged topography hinders the expansion of large-scale irrigation systems.

Compounding these challenges, climate change exacerbates rainfall variability. The early onset of rainy seasons (Dunning et al., 2018), unexpected dry spells (Trenberth et al., 2014), and premature cessation of rainfall (Serdeczny et al., 2017) pose significant risks to agriculture.

In response to these challenges, many Ethiopian farmers and pastoralists continue to rely on indigenous weather-forecasting methods. These methods, often rooted in local observations and traditional knowledge, are considered more accessible and relevant to local needs. However, the marginalization of indigenous weather practices in favor of scientific approaches has limited their potential to contribute to modern weather forecasting.

3. Survey of Indigenous Weather Practice Studies in Ethiopia

Despite the rich generational knowledge embedded in indigenous weather forecasting, research in this area remains limited in Ethiopia, particularly when compared to neighboring countries such as Kenya (Kwanya, 2018; Ombati, 2017). Existing studies are not only sparse but also unevenly distributed across the nation's diverse agroecological zones and rainfall regimes.

Of the 36 studies reviewed, a significant majority (77.8%) were conducted in Cool Sub-Humid agroclimatic zones (Map 1, Table 1). In contrast, only 8.4% of studies focused on the more drought-prone agroecological zones, including Warm Arid, Warm Semi-Arid, and Warm Sub-Humid regions. This geographic imbalance contrasts with the research focus in Kenya, where studies have predominantly concentrated on areas that are directly impacted by rainfall variability (Akong, 1987).

Several factors may have contributed to this uneven distribution of research in Ethiopia. Firstly, conducting field research in arid and semi-arid regions is often hindered by the mobility of communities in those localities, making data collection logistically challenging. Secondly, many researchers originate from highland regions, limiting their cultural familiarity with and access to remote and often harsh environments in the lowlands. Thirdly, these areas are prone to security problems, further discouraging scholars from conducting research in these regions.

Analyzing the distribution of studies in relation to rainfall regimes (Map 2, Table 1) provides additional insights. Most of these studies have concentrated on areas with "Spring and Fall" rainfall regimes, which exhibit a bimodal distribution. These regimes, characterized by shorter growing seasons and increased sensitivity to deviations in rainfall timing, have compelled local communities to develop and diversify indigenous weather forecasting and rainfall practices. Consequently, these regimes have attracted considerable research interest. In contrast, "Rain Most of the Year" regimes, characterized by unimodal rainfall and longer growing seasons, have received minimal attention from Ethiopian researchers.

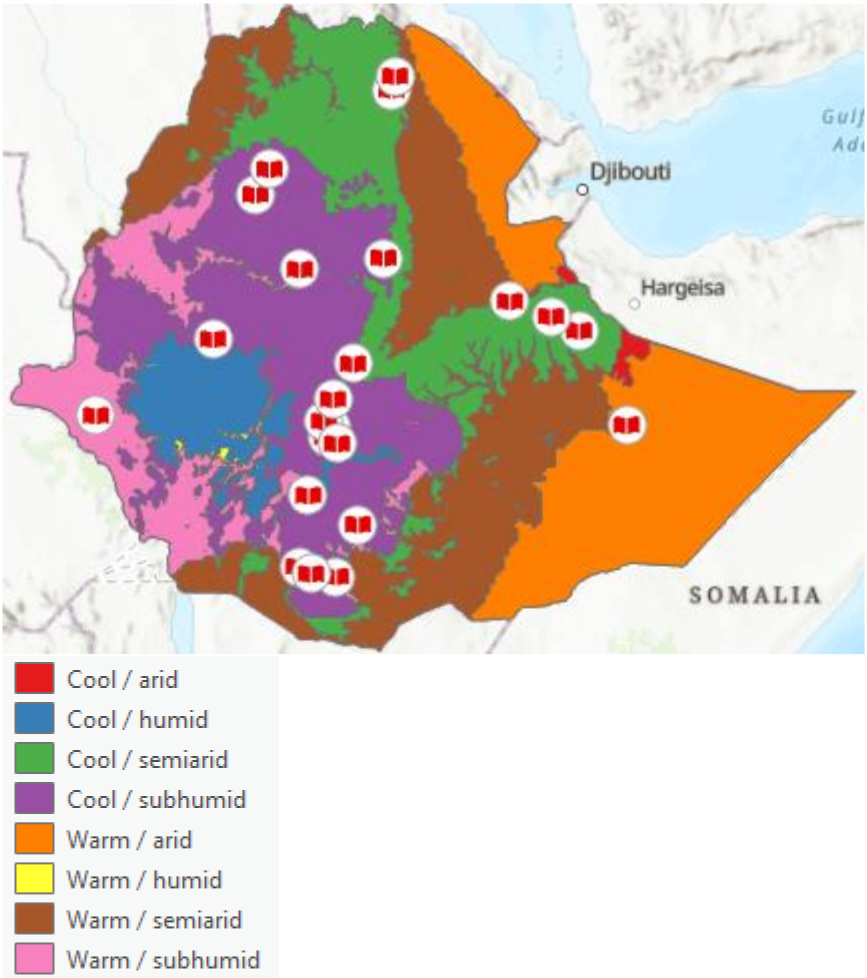

Figure 1: Distribution of indigenous weather practices studies across agroecological regions of Ethiopia.

Table 1. Distribution of indigenous weather practice studies along agroclimatic zones and rainfall regimes

Agroclimatic Zones	**No of Studies**	**Rainfall Regimes**	**No of Studies**
Cool Humid	1 (2.8%)	Rain Most of the Year	2 (5.56%)
Cool Semi-Arid	4 (11.1%)	Spring and Fall Rain	22 (61.1%)
Cool Sub Humid	28 (77.8%)	Summer and Spring Rain	9 (25%)
Warm Arid	1 (2.8%)	Summer Rain	3 (8.3%)
Warm Semi-Arid	1 (2.8%)		
Warm Sub Humid	1 (2.8%)		

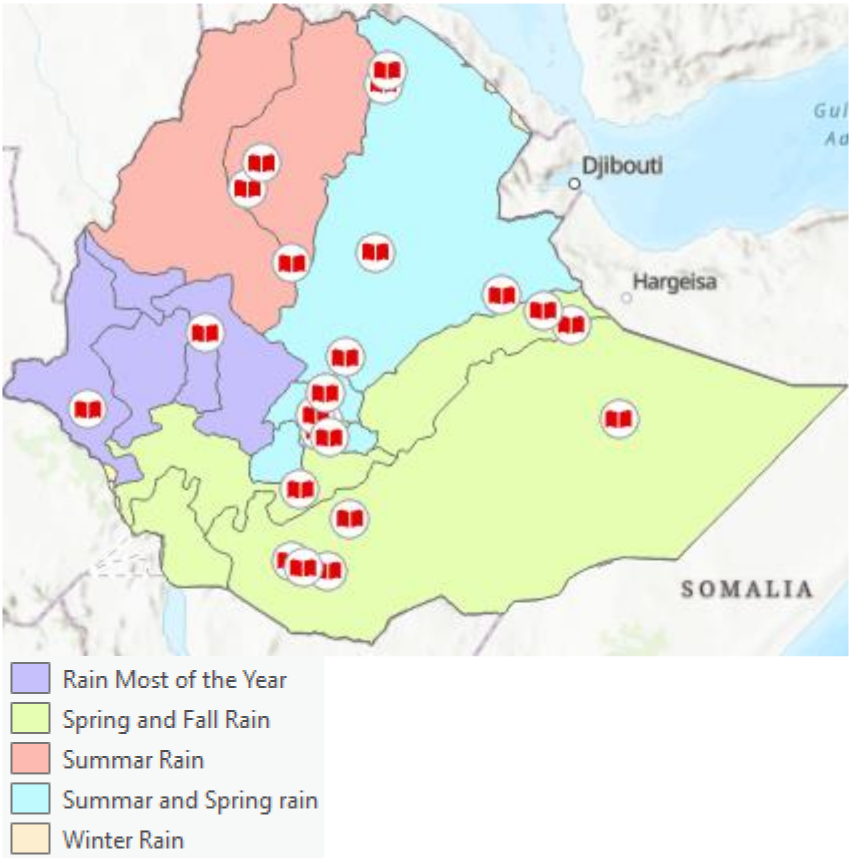

Figure 2. Distribution of indigenous weather practices studies across rainfall regimes of Ethiopia

4. The Underlying Science of Indigenous Weather Practices

4.1 Indigenous Rain Forecasting

Indigenous weather practices often rely on careful observation of natural indicators, including animal behavior, plant changes, and celestial observations. These practices are deeply rooted in local knowledge, treat animals and plants as conduits of environmental wisdom, and interpret subtle signals to forecast weather patterns. Local prophets, revered within their communities, often use these indicators to predict rainfall patterns, timing, and intensity.

Animal behavior is one of the most reliable indicators of weather forecasting. Various species exhibit heightened sensitivity to atmospheric changes such as shifts in air pressure, temperature, humidity, and wind (Costa, 2006). For instance, donkeys, known for their highly sensitive skin (Navas González et al., 2018), can detect changes in the atmospheric pressure. Communities note that if donkeys exhibit restlessness, shake themselves, or bray more frequently, rain is likely to occur. Such behavior is attributed to the animal's ability to sense increased humidity preceding rainfall.

Different animals possess varying sensitivities to environmental changes, a concept encapsulated in Dolbear's Law (Dolbear, 1897). This principle, named after physicist Amos Dolbear, explains the relationship between the temperature and the rate at which crickets chirp. By counting the number of cricket chirps per minute, the following formula is applied:

$$T_f = 50 + (N60 - 40)4$$

where Tf is the temperature in degrees Fahrenheit, and N_{60} is the number of chirps per minute; one can estimate the temperature in degrees Fahrenheit. This phenomenon highlights how indigenous communities have observed and utilized natural indicators, such as insect behavior, to forecast weather conditions.

Insects, particularly those with high surface-area-to-volume ratios, are highly responsive to barometric pressure. Changes in abiotic factors such as temperature, humidity, and pressure can significantly influence behavior, affecting activities such as mating, host-seeking, and flight initiation (Pellegrino et al., 2013).

Birds, reptiles, and fish also exhibit altered behavior in response to shifts in environmental conditions. These biological indicators, combined with celestial observations, form the foundation of indigenous weather forecasting systems and provide valuable insights into weather patterns and seasonal variations.

Communities with strong ties to their environment often incorporate observations of animal and plant behavior into indigenous weather practices. A study by Pennesi (2011) in Brazil revealed that subsistence farmers valued their observations and predictions of local prophets over official meteorological forecasts. The study documented 930 different rain indicators surveyed in NE Brazil, ranging from frogs peeping out of their burrows to donkeys' ear sweating. The integration of indigenous knowledge with local experience forms a rich, cumulative system of understanding that passes through generations via oral traditions and experiential learning (Ingold, 2003; Sillitoe, 2006, 2007). Ethnoscience, which studies culturally embedded principles, highlights a blend of empirical and spiritual elements in indigenous ecological knowledge.

From the foregoing correlation, it can be inferred that barometric pressure is a crucial factor in both indigenous and scientific forecasting. Standard atmospheric pressure at sea level is 1013.3 millibar, but it fluctuates due to temperature changes and atmospheric dynamics. The predictable daily "barometric tide" contrasts with irregular fluctuations associated with weather changes. Notably, a steeper decline in surface air pressure often precedes rainfall. Crespo & Castelo (2012) demonstrated a correlation between changes in barometric pressure and the behavior of parasitoid soil-dwelling larvae, showing that a steeper-than-expected drop can reduce their orientation to host cues. Such pressure drops can trigger significant behavioral shifts in sensitive animal species (Gillot, 2005).

While indigenous prophets may not have explicitly articulated the objective mechanisms behind their routine observations, the repeated correlation between changes in plant or animal behavior and the occurrence of rainfall allowed them to make predictions that were sharpened through intergenerational practices. Unfortunately, most studies on indigenous weather knowledge fail to fully explore and document these hidden science-relevant mechanisms, which is a crucial missing element in effectively integrating traditional and scientific forecasting systems.

4.2 Indigenous Rainmaking

Rainmaking rituals hold significant importance in many societies, particularly those reliant on subsistence agriculture, where livelihoods are intricately connected to rainfall. These rituals are performed to invoke rain during droughts or to promote favorable weather for significant celebrations. Common practices include prayers, sacrifices, the use of sacred objects, and the burning of plants or incense, with the belief that the rising smoke carries prayers to the heavens. While scholars such as Hong et al. (2021) often view these practices as primarily symbolic, further investigation could reveal their potential scientific basis and the cultural insights they offer regarding weather and rainfall.

Upon closer examination of these rituals described in the published sources, this study uncovered three underlying scientific elements of indigenous rainmaking, such as the timing of the ceremonies, the elevated locations often chosen for their performance, and the practice of burning materials that produce smoke, which could potentially trigger or catalyze the rainmaking process.

First, rainmaking rituals are time-specific practices, typically performed when expected rainfall is delayed or interrupted. Communities possess a deep understanding of local rain patterns based on generational experience, and they prepare for planting in anticipation of rain. This period is marked by the abrupt or gradual buildup of clouds in the sky, though not all clouds yield rainfall. Occasionally, patches of cloud or humid air may dominate the sky without producing precipitation.

These communities are acutely aware that a prolonged delay in rain onset can significantly affect the length of the growing season, influencing the types of crops that can be cultivated and the land management practices required. It is under such circumstances and timing that indigenous rainmaking rituals are practiced.

For instance, Fernández (2011) and Gumo (2017) observed Ethiopian and Zimbabwean communities, respectively, performing these rituals when seasonal rains were delayed. This timing aligns with indigenous knowledge that recognizes cloud presence as a sign of favorable conditions for precipitation. Such practices suggest that the rituals serve to enhance existing weather conditions rather than create rain from an entirely arid atmosphere.

Second, fire occupies a central role in numerous indigenous rainmaking rituals. It serves as a symbolic and spiritual tool, used to communicate with deities or spirits believed to control weather patterns. Seen as a purifying element and a catalyst for transformation, fire mirrors the life-giving properties of rain and the sun. By burning offerings, practitioners seek to influence meteorological phenomena, underscoring the interconnectedness between the spiritual and natural worlds. Many studies on indigenous rainmaking rituals delve into various aspects of the ceremony, including the rain dance, attire, food offerings, and prayers[1].

A deeper examination of fire-based rainmaking rituals may reveal a potential natural mechanism underlying these practices. These ceremonies, often conducted in open spaces, involve the burning of wood or twigs to produce not only fire but also smoke. While traditional studies often focus on the spiritual aspects of these rituals, it is worth

1 For a comprehensive review of studies on traditional rainmaking ceremonies in Africa, see Kwanya (2018).

considering the potential role of smoke in influencing local weather patterns.

Wood combustion emits a complex mixture of gases and aerosols into the atmosphere, including carbon dioxide (CO2), carbon monoxide (CO), nitrogen oxides (NOx), sulfur dioxide (SO2), and particulate matter. Solid particles such as ash and char are released, along with secondary particles like sulfates, nitrates, and organic carbon compounds (Andreae & Merlet, 2001; Jacobson, 2014). These emissions can rise due to their lower density and act as cloud condensation nuclei (CCN), providing surfaces for water vapor to condense and form cloud droplets. This process can eventually lead to precipitation, highlighting the importance of microscopic particles like dust, smoke, salts, and chemical compounds as CCN (Thornton et al., 1996).

This atmospheric mechanism may help explain how indigenous rainmaking rituals involving the burning of offerings could influence local weather patterns. While further research is needed to fully understand this relationship, the role of wood smoke as a CCN offers a foundation for integrating indigenous and scientific weather practices. By exploring these interactions, researchers can bridge gaps in meteorological science and traditional knowledge, fostering a more comprehensive understanding of weather prediction and environmental management.

Third, elevated locations are often chosen spots for indigenous rainmaking ceremonies in many parts of the world. Elevated places like hills and mountains are often chosen for rainmaking rituals due to their symbolic, cultural, and practical significance. These locations are perceived as closer to the heavens, facilitating communication with deities or weather-controlling spirits. For instance, the Ihanzu people of Tanzania and the Meru elders of Kenya conduct their rituals on hilltops, suggesting that higher altitudes may facilitate atmospheric moisture (Sanders, 2002; Gumo, 2017). Furthermore, their visibility and association with sacred or holy sites is believed to enhance the communal and spiritual impact of the rituals. The elevated setting is believed to offer a sense of control over the unpredictable weather, providing psychological reassurance. Additionally, mountains symbolize strength and permanence, reinforcing the power of the invoked deities (Eliade, 1959).

Indigenous communities often select elevated locations for rainmaking rituals, a practice rooted in intergenerational knowledge that correlates these sites with increased rainfall. The meteorological processes at play in these mountainous regions may contribute to the perceived success of such rituals. Orographic lifting, where moist air is forced to rise and cool, leading to cloud formation and precipitation (Cotton et al., 2011), is a key factor. Additionally, the thinner, cooler air at higher altitudes facilitates quicker moisture condensation, enhancing cloud formation compared to warmer, denser lowlands. The thermal effects of mountains can also trigger convection, further supporting precipitation.

Modern techniques like cloud seeding validate the choice of high elevations for rainmaking. For example, releasing agents such as silver iodide from mountaintops capitalizes on natural orographic lifting to promote precipitation (French et al., 2018). This demonstrates the practical significance of mountainous terrain in both traditional and contemporary rainmaking practices.

In conclusion, indigenous weather forecasting and rainmaking practices, often perceived as purely spiritual, may contain underlying scientific principles that are not immediately apparent to both scientific scholars and practitioners. By identifying these scientific elements, we can bridge the gap between indigenous and scientific weather practices, as advocated by many scholars.

5. Advantages and Limitations of Scientific Weather Practices

Advances in weather forecasting and artificial rainmaking have revolutionized the ability to predict and influence weather patterns, with each approach offering unique benefits and challenges. This section explores the current capabilities and limitations of both rain forecasting and artificial rainmaking, particularly within the context of developing regions, where infrastructure and data access remain limited.

5.1 Rain Forecasting

Scientific rainfall forecasting relies on a network of ground-based observation stations, satellite imagery, and sophisticated numerical weather prediction (NWP) models to simulate atmospheric processes. Technological innovations, including data assimilation techniques and supercomputing, have significantly improved short- and medium-term forecasting accuracy. The UK Met Office (2023), for example, reports that four-day forecasts are now as reliable as one-day forecasts were 30 years ago due to advancements in high-resolution atmospheric data and complex algorithms.

Despite these advances, certain challenges persist. In developing regions, low public confidence and trust in meteorological forecasts result from issues with forecast accuracy, communication, and societal relevance. Often communicated in probabilistic terms, such as a "70% chance of rain," forecasts can be misinterpreted, reducing public reliance. Joslyn and Savelli (2010) found that probabilistic language can lead to skepticism, even in developed countries like the United States, further complicating forecast communication.

An example illustrating the vagueness of scientific weather forecasting issued to the Ethiopian population can be found in a recent report obtained online (www.ethiomet.gov.et/documents/253/21-31_October_2024_.pdf):

> **Oct. 31, 2024.** Tomorrow, rain-producing weather events will have better strength in our country's south and southeast areas, which are the second rainy season of the Bega. Similarly, there will be widespread cloud coverage over the western, southwestern, northwestern and eastern parts of the country. Along with this, from the Oromia region west Arsi, Bale and east Bale, Guji and west Guji, Borena and east Borena zones as well as Jimma, ….Illubabor zones; from the south west Ethiopia region Bench Sheko, …Sheka zones; from Benishangul Gumuz region Metekel, Asossa, Kamashi … zones will receive light to moderate rainfall (1-29 mm) in many places. In addition, Pawe, Bullen, Wenbera, Asossa, …. and Mesela will receive heavy rainfall of over 30 mm in 24 hours. On the other hand, due to the intensifying weather events Tsegede, Tselemt, … will experience light to moderate unseasonal rainfall. Therefore, the Ethiopian Meteorological Institute suggests that the community collect the ripe crops.

In the forecast, the geographic unit utilized is the zonal administrative area. Ethiopia is divided into 62 zones, with an average size of 12,248 km^2, ranging from the smallest, Dire Dawa Urban Zone, to the largest, Dollo in the Somali regional state. Issuing a weather forecast for an area averaging 12,248 km^2, which may encompass significant elevational differences and diverse biophysical characteristics, rarely reflects the actual conditions on the ground. Moreover, the terminology used, such as "will receive light to moderate rain," offers vague information that lacks clarity and precision, making it difficult for the urban population to interpret, let alone the rural population.

The complexity of tropical weather systems, particularly in Africa, poses another challenge. Unlike mid-latitude regions, tropical systems are less studied, leading to knowledge gaps that limit forecasting effectiveness (Sobel, 2012; WMO, 2022). Inaccurate rainfall forecasts are common, largely because NWP models inadequately represent tropical atmospheric dynamics (Meque et al., 2021; Igri et al., 2018). Furthermore, the chaotic nature of atmospheric systems restricts forecast reliability to about one week, especially in regions with high rainfall variability, such as the Ethiopian lowlands (Moron & Robertson, 2020; Alley et al., 2019).

Capacity constraints also hinder effective forecasting in Africa. Many countries lack the scientific infrastructure and local expertise necessary to support sophisticated meteorological research, leading to dependence on external solutions that often lack regional relevance (Parker, 2008, 2022; Dike, 2018). Lamptey et al. (2024) emphasize the need for African ownership of scientific advancements, which would enhance local relevance and application.

Data scarcity remains a critical limitation. The limited distribution of meteorological stations across Africa results in significant data gaps, reducing the accuracy of localized forecasts. Studies in Ethiopia highlight persistent issues with missing data points, which hinder effective forecast model initialization (Tadesse et al., 2022; Mohammed et al., 2022). Many of the diverse microclimates in Ethiopia outside the cities do not have meteorological stations. Sisay et al (2017) explained the problem of inadequate meteorological data, citing how insufficient weather data restricts studies (Ayalew, 2012; Ayalew et al., 2012; Taye and Zewdu, 2012) in restricting them to smaller areas. Additionally, the coarse spatial resolution of global satellite data limits the utility of forecasts for local decision-making in heterogeneous landscapes, where microclimates differ significantly over small areas (Irumva et al., 2021).

To enhance the accessibility and relevance of weather forecasts for non-expert users, greater efforts are needed to simplify scientific information and improve public understanding. The integration of indigenous knowledge, which offers localized insights, may also support more community-specific forecasts, enhancing resilience in vulnerable regions. By refining the tools and communication strategies within both rain forecasting and artificial rainmaking, scientific meteorological practices can play a more significant role in global climate resilience efforts.

5.2 Artificial Rainmaking (Cloud Seeding)

Artificial rainmaking, particularly cloud seeding, is a weather modification technique that has gained interest in regions facing water scarcity. Cloud seeding involves introducing substances like silver iodide into clouds to stimulate precipitation by altering cloud microphysical properties (Rosenfeld et al., 2018). This method shows promise in mitigating drought, supporting agriculture, and enhancing water security, especially in water-stressed areas (Garstang et al., 2005).

A key research question here is understanding the specific atmospheric conditions under which cloud seeding is most effective. Such knowledge would enhance the precision of cloud seeding operations, making it a more viable option for regions with water scarcity. However, cloud seeding's success depends heavily on atmospheric conditions. Optimal moisture content and favorable cloud dynamics are essential, and, without these, seeding efforts often fail to yield significant precipitation (Rosenfeld et al., 2018).

Economic constraints further challenge the feasibility of cloud seeding. The costs associated with dispersal agents and weather monitoring often outweigh the potential benefits in regions with limited resources (Mielke et al., 2015). Moreover, the complexity of real-world atmospheric systems makes it difficult to predict cloud seeding success accurately. While laboratory studies confirm precipitation inducement, the variables in natural cloud systems introduce uncertainties that remain unresolved (Rosenfeld et al., 2018).

In a notable example, Ethiopia experimented with cloud seeding in 2021, using drone technology and ground-based generators to produce artificial rainfall, reported by the Information Network Security Administration (INSA). While this experiment initially showed positive results, it was not part of Ethiopia's 2021–2030 Meteorological Master Plan, raising concerns about its long-term integration into the national weather strategy.

Additional concerns associated with cloud seeding include environmental impacts, such as potential chemical contamination of soil and water resources, and the unintended consequences of altering local climate patterns. These issues necessitate a cautious approach, with comprehensive assessments of environmental risks before large-scale implementation.

Both scientific rain forecasting and artificial rainmaking face substantial challenges. Public skepticism, data scarcity, and the chaotic nature of atmospheric processes continue to limit the accuracy and utility of rainfall forecasting. Similarly, cloud seeding's potential remains constrained by specific atmospheric requirements, cost considerations, and uncertainties surrounding its effectiveness. Addressing these limitations requires further research, particularly in data-scarce regions, to improve both forecasting accuracy and the feasibility of artificial rainmaking as a climate adaptation tool.

6. Bridging the Gap: Fusion of Indigenous and Scientific Weather Practices

The convergence of indigenous and scientific weather forecasting methods presents a promising frontier in climate science, especially for regions with pronounced local climate variability and limited meteorological data. Recognizing the potential for synergy between these approaches, numerous studies have explored and recommended the benefits of integrating indigenous and contemporary meteorological systems. This approach gained traction as climate change impacts intensified, underscoring the importance of adaptive, community-responsive forecasting models (Nyong et al., 2007).

Modern regional weather information systems, when enriched with place-based indigenous weather knowledge, not only assist farmers in optimizing agricultural activities—such as timing for planting, harvesting, and animal herding to align with favorable weather conditions—but also help mitigate the impact of increasingly erratic rainfall patterns driven by climate change. This integration is crucial for preventing agricultural planning from becoming a gamble that risks pushing Ethiopia's overwhelming population toward food insecurity and hunger.

A critical research question arises in exploring the role of indigenous practices within contemporary weather models: How can weather forecasting models improve in bridging the gap between global-scale predictions and local variability, particularly in data-sparse regions? (Orlove et al., 2010). As previously discussed, both indigenous and scientific weather forecasting methods have limitations when used independently, underscoring the necessity for genuine integration to enhance the accuracy and relevance of weather predictions.

6.1 Limitations of Indigenous Weather Practices Studies

The integration of indigenous and scientific meteorological knowledge has gained increasing attention, yet significant challenges remain in bridging these two systems (Briggs & Moyo, 2012; Jiri et al., 2016). This study posits that indigenous weather practices in Ethiopia and Sub-Saharan Africa often lack the scientific rigor necessary for seamless integration with modern meteorological methods. Current research tends to document observed events and rituals descriptively, without delving into the ethno-meteorological foundations of these practices, limiting the extraction of scientifically relevant elements.

Indigenous weather practices, rooted in centuries of observation and experience, offer valuable insights into local climate patterns. These practices often rely on interpreting natural indicators such as animal behavior, plant growth, and celestial phenomena. For instance, in Ethiopia's Borana Zone, intestinal readings have been used to predict drought (Galgalo & Mekuria, 2021), while Ayal (2017) reported the use of celestial observations for weather forecasting.

However, while these practices provide valuable local insights, they often lack rigorous scientific validation. Studies like Ayal (2017) and Radeny et al. (2019) document the use of indigenous knowledge but do not explore the underlying scientific principles. The specific connections between traditional indicators (such as intestinal readings or celestial observations) and meteorological conditions remain unclear, highlighting a critical gap in our understanding.

Attempts to bridge this gap, such as the study by Iticha & Husen (2019), have highlighted the potential for integrating traditional knowledge with contemporary methods. However, the specific mechanisms by which this integration can improve forecast accuracy and applicability require further investigation.

Numerous studies have documented indigenous weather forecasting practices in Ethiopia, including works by Ayal et al. (2015), Balehegn et al. (2019), Guye et al. (2022), Opiew et al. (2021), Radeny et al. (2019), Tilahun et al. (2019), Endris and Ahmed (2019), and Kidemu et al. (2020). These studies provide valuable insights into the diverse range of indigenous weather indicators used by different communities. However, they primarily focus on documenting these practices rather than rigorously testing their efficacy or demonstrating verifiable causal links between these practices and accurate weather predictions.

To address this limitation, future research should aim to systematically evaluate the accuracy and reliability of indigenous weather forecasts, comparing them to modern meteorological predictions. By employing rigorous scientific methods, researchers can uncover the underlying mechanisms and principles that underpin these traditional practices, facilitating their integration with modern forecasting systems.

Several studies support the integration of indigenous knowledge as a vital coping mechanism for addressing climate change impacts. Abate (2016a) highlighted how indigenous knowledge serves as a resilience strategy in the Guji Zone of Oromia, Southern Ethiopia. Bekuma et al. (2023) identified variables influencing farmers' climate change adaptation decisions, while Debela et al. (2021) emphasized the role of indigenous institutions in framing climate change problems and facilitating adaptive responses in Borana pastoral and agropastoral systems. These studies underscore the importance of indigenous knowledge in climate resilience but often fall short of detailing the specific variables and mechanisms through which indigenous practices align with and complement scientific climate models.

Research methodologies in this field have primarily relied on surveys, interviews, and focus group discussions. For example, Abate (2016a, 2016b) examined climate change impacts and adaptation strategies in the Oromia region. Alemayehu et al. (2023) and Alemayehu & Hizekeal (2022) investigated traditional weather forecasting practices among farmers and pastoralists. Ayal (2017) studied the interpretation of indigenous weather indicators in South Ethiopia, while Balehegn et al. (2019), Gemedo-Dalle et al. (2006), and Tafesse (2021) explored Borana pastoralists' perceptions and practices related to drought risk reduction. While these studies provide valuable insights, they often rely on descriptive statistics and lack a deeper exploration of the underlying mechanisms that generate causal relationships.

To effectively integrate indigenous knowledge with scientific weather forecasting, future research should focus on identifying and understanding the underlying mechanisms behind these traditional practices and bolstering this understanding with rigorous scientific study. Empirical testing and validation of these observations would enhance the credibility of indigenous practices and their potential for integration with meteorological science[2].

Furthermore, the approach to studying indigenous weather practices should move beyond simple descriptive accounts, often employed by journalists. A more in-depth and rigorous research approach is necessary to fully understand and appreciate the nuances of these practices.

6.2 Towards Integrated Weather Intelligence

In this section, we explore three areas of integration between indigenous and scientific weather practices pertaining to: spatial resolution mismatch, rainfall forecast, and rainmaking.

The first avenue for integration addresses the spatial resolution mismatch. While scientific weather forecasting systems offer broad geographic coverage and relatively high accuracy, they often lack the micro-level specificity crucial for regions like the Ethiopian highlands, where subsistence farming dominates an intensely diverse biophysical environment. Large-scale rainfall predictions may not be directly applicable to smallholder farmers due to their coarse spatial resolution. Conversely, indigenous knowledge systems, though finely tuned to local conditions, may struggle to capture larger-scale atmospheric processes. However, there is potential for a synergistic approach that combines the strengths of both systems. By integrating indigenous knowledge with scientific meteorological techniques, it is possible to address these limitations and develop more accurate and locally relevant weather forecasts, ultimately benefiting smallholder farmers and regional planners alike.

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2 For instance, during the commonly held inspection of animal intestines, the tone, texture, and color are used as clues for weather forecasts. Researchers could easily identify the type of plant material present or its absence within the intestines and utilize this information for further investigation. As plant species have their own weather-dependency and weather phenomena is operating in a cyclic pattern, their presence or absence within animal intestines could signal impending weather patterns. Researchers could further investigate the response of these plants to variations in moisture, air pressure, and temperature, both in field situations and through controlled experiments. This approach could not only identify correlations with the weather predictions made by local people but also help uncover the causative factors underlying these observations.

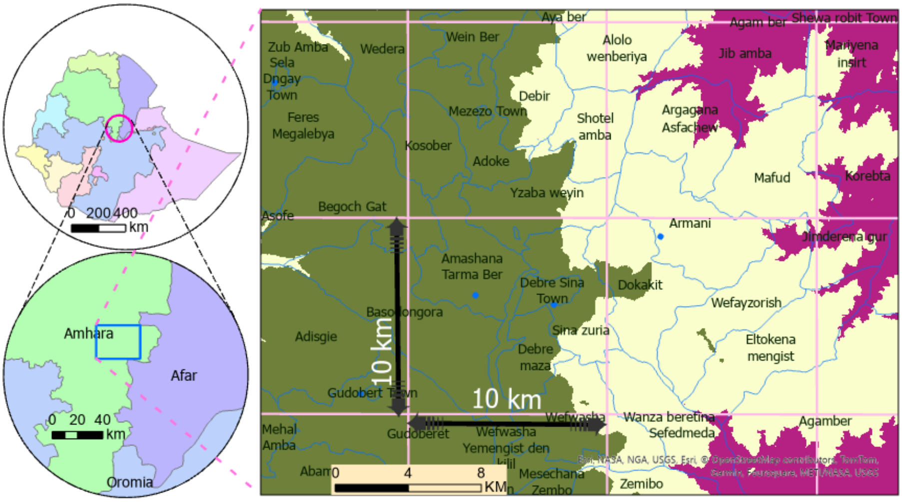

Figure 3. Covering local agroecological and administrative units by a coarse spatial resolution of satellite imagery in North Showa.

Figure 3 illustrates the spatial mismatch between indigenous knowledge systems and scientific meteorological models. Weather satellites, depicted by the graticules, function at a coarse resolution of 10 km by 10 km. Each cell, covering an area of 100 km², blends diverse agroecological zones, elevation changes, and local administrative areas into a single spectral output. For instance, Tarmaber and Debre Sina, which are only 3.1 km apart, are represented by a single pixel, implying uniform weather conditions despite a significant elevational difference of 700 meters—3,324 meters and 2,630 meters, respectively.[3]

The generalized representation by the weather satellites oversimplifies the landscape, failing to capture the substantial local variations experienced by communities and reducing the relevance of modern weather predictions for end users. Integrating community-level weather data derived from indigenous systems could help overcome

3 For instance, when comparing January 5 temperatures between Tarma Ber and Debre Sina, a significant contrast emerges. The daily minimum temperature in Tarma Ber is approximately 50 C, while in Debre Sina it reaches around 140 C. Similarly, the daily maximum temperature in Tarma Ber is approximately 150 C, whereas in Debre Sina it can reach around 250 C. This temperature disparity leads to notable differences in soil moisture, agricultural practices, succeptibility to malaria, among other factors.

these limitations, improving the precision and local applicability of weather forecasting.

The second avenue for integration is rainfall forecasting practices. Traditional methods are often dismissed as superstitions and seen as incompatible with modern techniques. However, as discussed in section 4.1, indigenous communities rely on observing plant and animal behavior for rainfall predictions, bypassing modern metrics such as air pressure changes—critical data for scientific forecasting. These practices are based on centuries of empirical observation tied to local ecosystems, soil conditions, and topographic variability. While traditional forecasting may lack the scientific terminology of modern meteorology, expecting indigenous forecasters to adapt to these standards is misguided. Instead, the scientific community should take the lead in extracting and validating the scientific elements inherent in traditional practices to enable meaningful integration. The failure to do so in contemporary education has contributed to the underutilization of this rich body of indigenous knowledge.

Despite methodological differences, indigenous and scientific weather forecasting share core principles of observation, experimentation, and validation. Research by Irumva et al. (2021) demonstrates that both systems use environmental indicators to predict major climate events. Figure 4 indicates that both approaches rely on declining low-pressure levels as a predictor of imminent rainfall. The key distinction is that while scientific meteorology constantly monitors air pressure with barometers, traditional systems infer changes in air pressure indirectly through observations of plant and animal behavior.

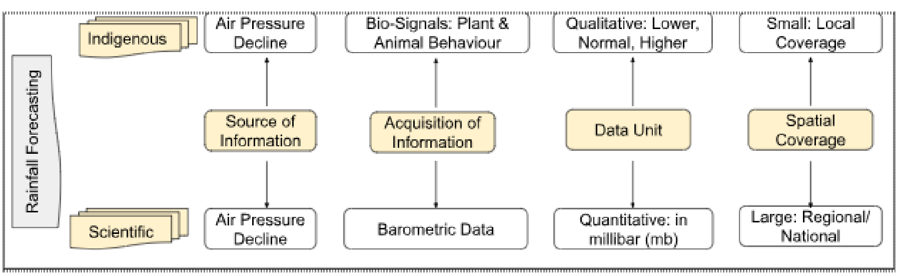

Figure 4. Schematic representation of commonalities between indigenous and scientific rainfall forecasting approaches.

The third avenue for integration lies in rainmaking practices. As discussed in section 4.2, both systems rely on the formation of CCN, as shown in Figure 5. In both practices, rainmaking is performed within a critical time window when atmospheric moisture is present but unable to coalesce due to insufficient CCN. Indigenous communities may not articulate the underlying processes of rainmaking, which often include activities like cooking, prayer, dancing, and feasting. However, smoke from these rituals acts as an aerosol that catalyzes cloud formation and precipitation. This process mirrors modern cloud seeding, where scientists use chemical agents to induce rainfall. These shared principles suggest that traditional practices could be incorporated into scientific models, enhancing their precision and local relevance (Hinkel et al., 2007).

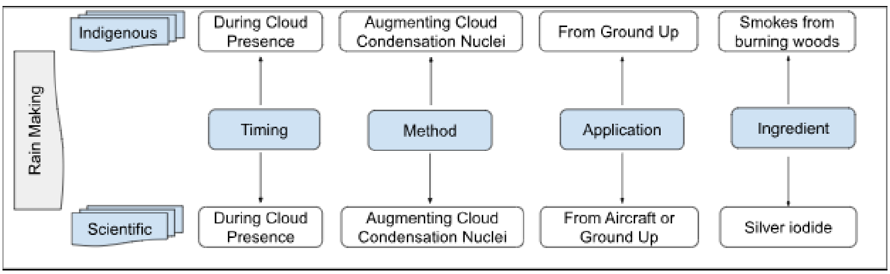

Figure 5. Schematic representation of commonalities between indigenous and scientific rainmaking approaches.

Integrating indigenous and scientific forecasting approaches has the potential to create a more resilient and effective predictive framework. Nakashima et al. (2012) emphasize the spatial depth indigenous knowledge offers, which complements the extensive coverage of scientific models. This integration could lead to a forecasting system that is both scientifically rigorous and locally applicable, addressing the limitations of each approach.

Examples from other regions demonstrate the feasibility and benefits of integrating indigenous and scientific forecasts. In Kenya, rainmakers and meteorologists collaborate to improve forecast accuracy, enhancing local relevance for smallholder farmers (Ombati, 2017). Similarly, studies from Uganda illustrate that indigenous insights on drought and rainfall patterns can refine satellite-based predictions, supporting climate adaptation efforts and increasing forecast utility among rural farmers (Orlove et al., 2010; Jiri et al., 2016).

7. Conclusion

This study is based on the premise that Ethiopia's economy is heavily reliant on agriculture, which is highly sensitive to fluctuations in rainfall amount and distribution during the growing season. This dependence is further exacerbated by the increasing unpredictability of rainfall due to climate change. Adding to this challenge is the decline in the use of indigenous weather knowledge, marginalized by the spread of modern education, and the rapid loss of biodiversity, which endangers many ecological indicators essential to traditional practices. These factors underscore the urgent need for immediate solutions to prevent the mounting demographic pressure from pushing the nation toward a full-scale crisis.

The study advances the integration of indigenous and scientific weather forecasting practices as a crucial frontier in meteorological research and climate adaptation strategies, particularly in Ethiopia. It explores the potential synergies between indigenous knowledge systems and scientific methods in weather prediction, addressing significant gaps in the current understanding and application of indigenous weather practices.

The research reveals three major limitations in the existing literature on Ethiopian indigenous weather practices. First, there is a scarcity of studies compared to neighboring countries like Kenya (Ombati, 2017), which hampers a comprehensive understanding of these indigenous methods. Second, the current body of research lacks representation across various agroecological regions, which could significantly benefit from timely weather information derived from indigenous practices. Lastly, much of the existing research simply reports observed practices without analyzing the ethno-meteorological principles underpinning each method, thereby hindering any potential integration with scientific meteorological approaches. These gaps highlight the urgent need for more comprehensive and geographically diverse research on indigenous weather practices in Ethiopia.

This study provides calls for deeper investigations into ecological indicators and ethno-meteorological aspects of indigenous weather forecasting, offering a scientific basis for integrating these practices with scientific meteorological methods. Key findings include the interaction between low atmospheric pressure and plant and animal behavior as indicators for rain prediction. Additionally, the research delves into the scientific principles underlying rainmaking rituals, identifying critical elements such as the timing of rituals during cloudy periods, the selection of elevated areas conducive to cloud formation, and the role of smoke in producing cloud condensation nuclei. These discoveries form a bridge toward integrating indigenous knowledge with contemporary techniques such as cloud seeding technology.

Furthermore, the study demonstrates how fine-grained, locally relevant data from indigenous weather practices can complement the coarse spatial resolution of weather satellites, potentially enhancing the specificity and accuracy of satellite-based weather monitoring. By incorporating insights gained from indigenous knowledge, meteorological systems can become more responsive to local conditions.

To further advance this integration, developing a comprehensive database that systematically catalogs ecological indicators in Ethiopia is essential. Future multidisciplinary research involving botanists, zoologists, meteorologists, geographers, and anthropologists should include controlled experiments that quantify plant and animal responses to changes in air pressure and humidity. Incorporating indigenous environmental signals into school curricula would foster greater appreciation and understanding of these practices among younger generations.

Furthermore, establishing an organizational framework within the Ethiopian Meteorological Institute to integrate indigenous environmental observations into ground-based forecasting practices is crucial. Drawing inspiration from successful models, such as the Ethiopian Ministry of Health's approach [4] to integrating traditional medicine and Kenya's structured system for merging traditional and scientific weather practices, can offer valuable guidance for this integration.

4 The Ethiopian Public Health Institute (EPHI) was formed through the merger of three institutes, including the Department of Traditional Medicine, which conducts research on traditional remedies. Additionally, the Ethiopian Food and Drug Authority (EFDA) oversees the regulation of various products, including traditional medicines.

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