Weather, climate, and agriculture: Historical contributions and perspectives from agricultural meteorology

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Abstract
All over the world, farming communities need to adapt to a changing climate. At the same time, they are confronted by the necessity to increase food availability for a growing population, but also to ensure a sustainable use of natural resources. In this process, agriculture is not just the fiend responsible for an increase in greenhouse gas emissions, nor the victim of rising temperatures and extreme weather events. Agriculture is also an ally in climate change mitigation and adaptation because the selection of ad hoc crop varieties and livestock can lower the environmental impact of farming and the implementation of better management practices can promote soil conservation. Whether agriculture will have a positive or a negative impact on climate change adaptation and mitigation will depend on the rural policies implemented, but it will also be contingent on an adequate understanding of the interconnections existing between weather, climate, and farming. This review explores such interconnections by focusing on the history of agricultural meteorology, which is the research field that studies the impact of weather and climate on crops, livestock, farming operations, and plant and animal pests and diseases. The article discusses stakeholders, institutions, and main developments in agricultural meteorology, and describes how the agenda of agricultural meteorology has shifted over time. At the beginning of the 20th century, research in agricultural meteorology focused on increasing the profitability of farming. In the 21st century, instead, the main goal of agricultural meteorology is to ensure food security and guarantee sustainability.

This article is categorized under:
Climate, History, Society, Culture > Disciplinary Perspectives

KEYWORDS
agricultural ecology, agricultural meteorology, climate change, sustainability
1 | INTRODUCTION

Climate change and extreme weather events, such as recurrent droughts or floods, are among the main challenges faced by 21st-century agriculture. All over the world, farming communities need to adapt to a changing climate. At the same time, they are confronted by the necessity to increase food availability for a growing population, but also to ensure a sustainable use of natural resources (Kulshreshtha & Wheaton, 2018). In this process, agriculture is not just the fiend responsible for an increase in greenhouse gas emissions, nor the victim of rising temperatures and extreme weather events. Agriculture is also an ally in climate change mitigation and adaptation because the selection of ad hoc crop varieties and livestock can lower the environmental impact of farming and the implementation of better management practices can promote soil conservation (Dinar & Mendelsohn, 2011; Obasi, 2000). Whether agriculture will have a positive or a negative impact on climate change adaptation and mitigation will depend on the rural policies implemented, but it will also be contingent on an adequate understanding of the interconnections existing between weather, climate, and farming activities. Acquiring this understanding will be no small achievement. The issues under examination are complex and their study highly interdisciplinary. They require the expertise of meteorologists and climatologists, but also the skills of agronomists, plant pathologists, ecologists, and geographers, just to mention a few of the experts who have contributed to study the relationship between weather, climate, and farming activities (Frere, 1979, pp. 6–7).

It is worth, therefore, examining in some detail how this scientific research has developed over time and what its history can tell us about today’s farming and environmental challenges. This review article will focus on agricultural meteorology, which is the research field that studies the impact of weather and climate on crops, livestock, farming operations, and plant and animal pests and diseases. It will explore stakeholders, institutions, and main developments in agricultural meteorology since the beginning of the 20th century. It will also discuss the main research themes, in particular the use of weather forecasting in farming, microclimatology, and the statistical approach to study weather, climate, and agriculture. To provide a comprehensive account of how agricultural meteorology developed, this review will also consider neighboring fields such as agricultural ecology and geography, because they contributed to shape our scientific understanding of how weather and climate impact on farming.

The article will concentrate on the first half of the 20th century, when agricultural meteorology emerged as an independent research field and national and international organizations began to establish committees and institutions devoted to agricultural meteorology, but it will connect this narrative to what happened before and after, as many themes run across the entire history of this research field. As the historiography of agricultural meteorology is rather limited, the review will consider also the histories of fields that are relevant to agricultural meteorology, such as environmental and food history, and benefit from quantitative information extracted from agricultural meteorology publications printed between 1900 and 1950. The portrait of agricultural meteorology that emerges is complex, with both continuities and discontinuities in time. Interdisciplinary collaborations and close interactions with political and rural stakeholders are a feature of agricultural meteorology during its entire history, but the research questions, especially in recent decades, have become broader. Agricultural meteorology began to investigate weather and climate to increase the profitability of farming, but priorities have now changed. High on the current agenda of agricultural meteorology there is promoting a climate-smart agriculture that can ensure food security in an age of climate change, but also guarantee agricultural sustainability and reduce or remove greenhouse gas emissions (Lipper et al., 2018).

2 | AGRICULTURAL METEOROLOGY BEFORE WORLD WAR II

2.1 | Agricultural meteorology before the 20th century

The historian Theodore Feldman began his overview of agricultural meteorology with the farming calendars and the collections of weather lore dating back to antiquity (Feldman, 1998). Although not strictly scientific, these sources belong by right to the history of agricultural meteorology, because they gather the practical knowledge acquired on the subject and relied on by farmers for many centuries. Even 18th- and 19th-century natural philosophers still read and cited the authors from antiquity in their scientific works. For instance, the epigraph “Annus fructificat, non tellus” [The year produces fruits, not the land] taken from the Historia Plantarum of the Greek philosopher and botanist Theophrastus (Theophrastus., 1483) opened the treatise on meteorology applied to agriculture written by the 18th-century Italian astronomer and meteorologist Giuseppe Toaldo (Toaldo, 1775). Toaldo’s work was one of the first scientific attempts at examining problems in agricultural meteorology and won him the price of a scientific academy at the time.
Even though his theories about a lunar influence on the weather are entirely refuted today, they remain an interesting example of a meteorological handbook written for farmers. Indeed, throughout its history agricultural meteorology has been developed in the interest of farmers—or at least this has been claimed—, rather than for merely scientific purposes. Without any doubt, this was the idea of the French chemist Jean-Baptiste Boussingault, who considered knowledge of weather and climate essential in improving agricultural returns (Boussingault, 1844). Before the 20th century, the traditions that contributed to agricultural meteorology were not only those of astronomers and meteorologists, like Toaldo, or agricultural chemists, like Bossingault. Geographers, inspired by Alexander von Humboldt’s studies on climates and plant distribution (von Humboldt, 1817; von Humboldt & Bonpland, 1805), began to address problems in agricultural meteorology and their work has been explored by a growing number of historians in recent years (e.g., Güttler, 2015; Phillips, 2015). Research on plant distribution also stimulated an interest in the relationship between forests and climate (Fedotova & Loskutova, 2015) and contributions to agricultural meteorology came also from forestry throughout the 20th century, although forest meteorology is rather considered a separate discipline today.

Alongside individual scientists, national and international institutions became also interested in agricultural meteorology. In the late 1870s, the International Meteorological Organization (IMO), which was founded in 1873, began to discuss the application of meteorology to agriculture and forestry, but it took another half-century before the IMO instituted a technical commission devoted to this topic (Cannegieter, 1963). The birth of the first national agrometeorological services dates also to the end of the 19th century, when Tsarist Russia sponsored the creation of a meteorological bureau in the service of agriculture. Bureau director was the meteorologist Petr Ivanovich Brounov (“Brounov, Petr Ivanovich,” 1970). Brounov’s service organized agricultural meteorological stations, collected the observations gathered from these stations, computed correlations between weather conditions and crop growth, studied plant distribution according to the Russian climate, and monitored weather phenomena adverse to agriculture (Brounov, 1916a, 1916b, 1916c). The Russian service was considered by many early 20th-century scientists as a forerunner in agricultural meteorology and an experience to learn from (Azzi, 1912; Smith, 1920). Also the United States began to explore agricultural meteorology at the turn of the 20th century. Their weather forecasting service, the Weather Bureau, which was initially managed by military services, was transferred to the Department of Agriculture in 1891 and its primary mission was to provide weather forecasts for farmers (Harper, 2012; Weber, 1922). The French Institut National Agronomique introduced the teaching of physics and meteorology in its curriculum of studies in 1879 (Anonymous, 1924) and in the early 1910s planned the creation of an autonomous agricultural meteorological service (Anonymous, 1911). In 1877 in Great Britain the Royal Society established a committee tasked with the investigation of the weather influence on agriculture and public health (Shaw, 1933).

At the beginning of the 20th century, therefore, many of the elements that will distinguish the science of agricultural meteorology in the following decades were already in place. The interdisciplinarity of its research problems was uncontested, as it was the practical aim of its investigations. Not only weather, but also climate was an object of study in agricultural meteorology and agronomists, weather scientists and climatologists used statistical tools, correlation in particular, to make sense of this data-rich research field (Box 1).

2.2 Writing the history of agricultural meteorology in the first half of the 20th century with bibliographic data

Two world wars and the great depression indelibly marked science, politics, and society in the first half of the 20th century. After the famine and starvation suffered during World War I (WWI), European nations considered it a priority to rebuild more resilient agricultural systems. As part of this project, they increasingly promoted research on weather and climate, the environmental factors that most affect farming (Parolini, 2021). Agrometeorological and agroecological knowledge were also a requirement to successfully exploit natural resources in the European colonies (Grove, 1995). Economically valuable crops, such as tea, coffee, cocoa, and cotton, were grown in the colonies, where environmental conditions were considerably different from those of the homeland and new studies had to be carried out locally by colonial agrometeorological services to maximize productivity and returns (Parolini, 2020). International organizations, national scientific institutions, and even political authorities began to provide more funding for research in agricultural meteorology with a consequent growth of data collection efforts and scientific publications related to this field. In 1924 the British Ministry of Agriculture and Fisheries, for instance, established a Permanent Committee on Agricultural Meteorology to supervise observational and experimental schemes on weather and crops.
BOX 1 Phenology

The science of phenology studies the timing of annual life-cycle events (i.e., plant flowering and fruiting or breeding and nesting of migratory birds) and their relationship to seasonal weather and climatic changes. Phenology is considered a field technique of agricultural meteorology because it offers insights useful in agriculture by establishing correlations between biological events, weather conditions, and climate. Phenological observations, for instance, can suggest the best times to sow and harvest, and, more generally, they give indications on how to adapt the farming calendar to the seasonal weather (Chmielewski, 2013; Lieth, 1974). More recently, phenological data have become popular to study climate change (Hineline, 2018). When past record series are available and can be compared to present-day observations, phenological data can be used to track the modifications produced by climate change on biological events such as plant flowering or birds’ migrations (Primack, 2015). Phenology, therefore, is one of the areas of agricultural meteorology that interest also ecologists and climate scientists concerned with finding and assessing indicators of the changing Earth’s climate. Crop phenology, in particular, is increasingly becoming a collaborative field of research for agronomists and climate scientists in the attempt to understand and counteract negative effects of the changing climate on crop yields (Li et al., 2016).

For the following two decades the Committee managed the parallel collection of weather and crop data at several agricultural stations distributed all over the country and fostered research in agricultural meteorology. As part of this effort, scientific articles, crop-weather bulletins, and bibliographies of agricultural meteorology were regularly published (e.g., Ministry of Agriculture and Fisheries, 1929). Canada, a British dominion, has even a longer history than Great Britain in agricultural meteorology. Detailed experimental studies of the weather influence on wheat were already available by 1918 in Canada (Connor, 1918). Similarly, research on weather, climate, and farming developed in many other countries and in international circles. In Japan research in agricultural meteorology began around the 1880s, and the country regularly participated in the international committees of agricultural meteorology during the first half of the 20th century (Mihara & Ando, 1974). The Japanese Society of Agricultural Meteorology, which was established in 1942, soon began to publish a journal of its own. From 1930 onward, also Poland had a dedicated section on agricultural meteorology within its meteorological services, and this section produced many publications on the influence of climate on local crops and on harmful weather events, such as hail (Lugeon, 1935).

It is difficult to trace systematically the output of research work on agricultural meteorology in the first half of the 20th century because there was no journal specifically devoted to agricultural meteorology and articles on this subject appeared in many different scientific periodicals. The first journal of agricultural meteorology was printed in Japanese by the Japanese agricultural meteorology society in 1944 and only 20 years later an equivalent English periodical, the journal Agricultural Meteorology (renamed Agricultural and Forest Meteorology in 1984), was founded. For many decades the growing corpus of research on agricultural meteorology was published in a variety of journals and books printed by meteorological, agricultural, and forestry societies, in publications sponsored by soil science, geography, and ecology institutions, in bulletins printed by schools of farm economics and agricultural engineering. Publications on agricultural meteorology also appeared in food and gardening journals, zoology and entomology journals, and chemistry and scientific instruments reviews. Not only was the literature on agricultural meteorology widely scattered across a variety of scientific disciplines, but it was also printed in a variety of languages. English became a lingua franca of science only in the second half of the past century (Gordin, 2015), but plurilinguism was also a requirement to bring the results of scientific investigations in agricultural meteorology to the attention of the local farming organizations and rural communities that could benefit from such research.

The scientific experts and political authorities interested in weather, climate, and agriculture were aware of these issues and, since an early date, both individuals and institutions concerned with agricultural meteorology began to publish bibliographies on the subject that helped trace the literature available (e.g., Hannay, 1931; Harvey, 1936; Livingston, 1908; Ministry of Agriculture and Fisheries - Agricultural Meteorological Scheme, 1936; Ministry of Agriculture and Fisheries - Agricultural Meteorological Scheme, 1937; Reed & Feldkamp, 1915). These bibliographies collected contributions across scientific disciplines and languages. A preference to the area and language of the institution/individual that compiled the work was usually accorded given that the extraction of the bibliographic data was done manually using locally available
book and journal collections. In addition, the proceedings of the IMO Commission for Agricultural Meteorology regularly reported lists of publications authored by its members and by their colleagues (Organisation Météorologique Internationale, 1929, 1933, 1936, 1938). Bibliographic data collection in agricultural meteorology continued also in the second half of the 20th century, and the largest bibliography of agricultural meteorology published to this day was completed in the early 1960s (Wang & Barger, 1962). This collection was jointly compiled and edited by a meteorologist of the US Weather Bureau, Gerald Barger, and an environmental scientist based at the University of Madison, Jen Yu Wang. It counted almost 11,000 entries divided by subject area (radiation, temperature, microclimate, etc.), and printed between the second half of the 19th century and the publication date of the volume (Figure 1).

These bibliographies offer a wealth of data—mainly journal articles, but also reports, books, and theses—that can be quantitatively analyzed to reconstruct the developments of agricultural meteorology.

In this section I will discuss the overview of agricultural meteorology that can be gained by mining two bibliographic datasets covering the years 1900–1950. The first dataset is extracted from the Second Bibliography of Literature on Agricultural Meteorology published by the British Ministry of Agriculture and Fisheries in 1936, and the second is compiled using Wang and Barger’s bibliography mentioned above. While the former offers an insight into the multilanguage world of agricultural meteorology in the 1920s and 1930s, the latter takes a post-WORLD WAR II (WWII) perspective and prefers English-speaking publications and more recent articles (Table 1). The two bibliographies, in fact, were compiled in very different cultural climates. The British dataset of the 1930s was collected when Europe was still at the center of scientific and cultural life, while Wang and Barger’s bibliography is influenced by the Cold War climate (Oreskes & Krige, 2014).

During the Cold War, the US gained a prominent role in science, funding opportunities for scientific research sensibly increased there, and scholarly publications in English grew exponentially. English became the main language of science and continues to be the language of choice for scientific publications to this day (Gordin, 2015). This was not the case in the first half of the 20th century. In the 1930s bibliography here considered over 40% of the entries are not in English and this percentage is confirmed, and even exceeded, by other bibliographic collections compiled in the same years, such as the bibliographic lists published in the proceedings of the IMO Commission for Agricultural Meteorology. In the US bibliography printed in the 1960s, instead, only about a fourth of the publications are in languages other than English (Figure 2). Among these non-English publications, the most represented languages are German, French, Russian, and Italian, a result consistent with the British bibliography published in 1936. Before WWII, scientists regularly used German and French to produce publications for the international public, therefore the popularity of these languages should not surprise. Russia, as mentioned above, was considered a forerunner in agricultural meteorology. Many publications printed there were cited also in international bibliographies to acknowledge the relevance of the contributions made to the field.
| Entries | Wang and Barger’s dataset | Second bibliography dataset |
|---------|---------------------------|-----------------------------|
| Total number: | 3546 | 593 |
| Per category: | | |
| Journal articles | 2747 (77.47%) | 514 (86.68%) |
| Reports | 377 (10.63%) | 35 (5.90%) |
| Books | 225 (6.34%) | 27 (4.55%) |
| Book chapters | 147 (4.15%) | 16 (2.70%) |
| Theses | 48 (1.35%) | 1 (0.17%) |
| Encyclop. Art. | 1 (0.03%) | 0 (0.00%) |
| Documents | 1 (0.03%) | 0 (0.00%) |

| Languages | Wang and Barger’s dataset | Second bibliography dataset |
|-----------|---------------------------|-----------------------------|
| Total number: | 23 | 15 |
| Per language: | | |
| English | 2619 (73.86%) | 345 (58.18%) |
| German | 249 (7.02%) | 92 (15.51%) |
| French | 164 (4.62%) | 68 (11.47%) |
| Russian | 144 (4.06%) | 38 (6.41%) |
| Italian | 112 (3.16%) | 22 (3.71%) |
| Polish | 84 (2.37%) | 1 (0.17%) |
| Spanish | 54 (1.52%) | 2 (0.34%) |
| Japanese | 46 (1.30%) | 5 (0.84%) |
| Czechoslovak | 23 (0.65%) | 4 (0.67%) |
| Dutch | 13 (0.37%) | 2 (0.34%) |
| Portuguese | 9 (0.25%) | 0 (0.00%) |
| Hungarian | 7 (0.20%) | 2 (0.34%) |
| Swedish | 5 (0.14%) | 6 (1.01%) |
| Chinese | 4 (0.11%) | 1 (0.17%) |
| Norwegian | 3 (0.08%) | 4 (0.67%) |
| Greek | 3 (0.08%) | 0 (0.00%) |
| Finnish | 1 (0.03%) | 1 (0.17%) |
| Albanian | 1 (0.03%) | 0 (0.00%) |
| Belorussian | 1 (0.03%) | 0 (0.00%) |
| Danish | 1 (0.03%) | 0 (0.00%) |
| Hebrew | 1 (0.03%) | 0 (0.00%) |
| Ukrainian | 1 (0.03%) | 0 (0.00%) |
| Turkish | 1 (0.03%) | 0 (0.00%) |

| Journals | Wang and Barger’s dataset | Second bibliography dataset |
|-----------|---------------------------|-----------------------------|
| Total number | 643 | 200 |
| Per published articles: | | |
| 1 article | 358 (55.68%) | 119 (59.50%) |
| 2 articles | 107 (16.64%) | 33 (16.50%) |
| >20 articles | 21 (3.27%) | 3 (1.50%) |
| >100 articles | 3 (0.47%) | 0 (0.00%) |
by Russian scientists, although these publications were rarely read in the original language. Italy did not have a tradition comparable to Russia, but Italian still features in the list of the popular languages because several contributions on agricultural ecology, a neighboring field to agricultural meteorology, were published by the Italian agronomist Girolamo Azzi (see Section 3.2) and by his co-workers at the University of Perugia. Azzi's agroecological treatises circulated in the international circles of agricultural meteorology during the first half of the 20th century because he was also a long-term member of the IMO Commission for Agricultural Meteorology. These textbooks continued to be read after WWII, when they were translated into French and English (Azzi, 1954, 1956). Under the heading “Other” in Figure 2, almost 20 other languages, which appear in Wang and Barger's dataset, are grouped. This number should not surprise, because agricultural meteorology articles, especially those published in practice-oriented journals for plant breeders, gardeners, and farmers, could be effective only when printed in the national language, be it Polish, Spanish, or Japanese, and not in the languages of the scientific elites, mainly French, German, and English at the time.

In the bibliographic datasets examined, journal articles are the most common entries by far. In the dataset extracted from the US bibliography published in the 1960s, there are more than 2700 journal articles (over 77% of the data).
Interestingly, these 2700 articles were printed in over 640 journals. More than half of these journals published just one article on agricultural meteorology, and only a very tiny percentage, less than 5%, 20, or more articles. Among the popular publication venues (Figure 3), there are mainly English journals, with a prevalence of journals printed in the United States, although also an Italian (La meteorologia pratica [Practical meteorology]), a German (Meteorologische Zeitschrift [Meteorological Journal]), and a French journal (Comptes rendus hebdomadaires des séances de l’Académie des Sciences (Paris) [Proceedings of the Paris Academy of Sciences]) appear in the list. The subject areas of these journals are varied, they range from horticulture to geophysics, from agricultural engineering to ecology and soil science, aside from the expected agronomy and meteorology. The British bibliography of the 1930s offers a similarly fragmented scenario with 514 articles published in 200 journals. Over half of the journals only published one article, 33 (16.5%) published two articles, and just 3 (1.5%) published more than 20 articles on agricultural meteorology. Although this bibliography was compiled by a British institution, many of the articles included appeared in non-English periodicals. The component of German, French, Russian, and Italian titles among the most popular journals is higher in this case compared to Wang and Barger’s dataset, because plurilinguism in science was still widely accepted in the first half of the 20th century, when this bibliography was published.

The analysis of the publications’ authorship contributes to reinforce the view of agricultural meteorology as a very fragmented field in the first half of the 20th century. In Wang and Barger’s dataset, there are 2641 authors overall, that is, scientists who authored or co-authored one or more articles. Of those, about 75% only authored one article and a minimal percentage, 0.3%, published more than 20 articles related to agricultural meteorology. Evidently, at this stage, very few people pursued a scientific career focusing on agricultural meteorology problems only. The large majority of the authors contributed to the field while working within already established disciplines and occasionally produced an article on agricultural meteorology. This is the case, for instance, for the agronomists interested in wheat who wrote about the impact of weather and climate on wheat yields; or the plant pathologists and entomologists who studied specific crop pests and eventually published an article on the role that weather conditions had in promoting or hindering pest infestations.

Among the most prolific authors, a small number—meteorologist L. A. Ramdas (Ramanathan, 1984) and the aforementioned Azzi, most notably—deliberately positioned their work within the international circles of agricultural meteorology. Alongside them, the dataset extracted from the 1960s bibliography collected by Wang and Barger mostly mentions the work of scientists based in the US, such as the botanist Harry Alfred Borthwick (Hendricks, 1976) and the geographer and climatologist Charles Warren Thornthwaite (Hare, 1963). In the British bibliography, no author has more than eight publications to his name and none of these authors is based in the US, as a proof of the different cultural climate under which this bibliography was prepared. Among the most represented authors in the British bibliography, we find two French scientists, the agronomist Joseph Sanson, who co-authored an early textbook on agricultural meteorology (Klein & Sanson, 1925), and the bioclimatologist Léon Chaptal (Marres, 1950), a German, the (micro)
climatologist Rudolf Geiger (Autrum, 1982), and a Canadian, the plant biochemist Robert Newton, whose research specialized on wheat resistance to drought and frost (Phillipson, 2013).

Despite the fragmentation of publication venues and authorship, recurrent themes in agricultural meteorology emerge in the bibliographic datasets examined. These themes can be identified by examining frequent lemmas in the publication titles (Figure 4a,b). Results from both datasets suggest that agricultural meteorology publications mainly concerned plants and the environmental factors that determined their microclimate, such as soil, temperature, light, and moisture (see also the word cloud image opening the review). During the 20th century, in fact, microclimatology emerged as an independent field of research within climatology. The textbook, Das Klima der bodennahen Luftschicht: Ein Lehrbuch der Mikroklimatologie (Geiger, 1927), written by the meteorologist Geiger, gave name to the field. This publication discussed at length the role of microclimatological factors in the growth of plants, an area that Geiger had explored in detail working for many years in close contact with forestry institutions in Germany. Investigations in agricultural meteorology were not mere data collection efforts. On the contrary, the authors employed statistical tools and looked for “effects,” “relations,” and “influences,” all popular lemmas in the bibliographies examined, while investigating parallel observations of crop, weather, and climate data. Agricultural meteorology benefited from the blooming fortunes of statistics in early 20th-century agricultural research (Parolini, 2015), and R. A. Fisher, a founding father of modern statistics, was actively engaged in national and international institutions concerned with agricultural meteorology, namely the Permanent Committee on Agricultural Meteorology set up in Great Britain and the IMO Commission for Agricultural Meteorology. Among the recurrent lemmas in the datasets, we also find a few of the main staple food crops of the temperate regions, such as wheat and corn. This result should not surprise, as the work done in agricultural meteorology was mainly carried out in the temperate areas and agrometeorologists working in the tropics, such as the French Paul Carton, lamented the scarce attention paid to rice, the main crop for the Asian population (Parolini, 2020). In the bibliographies examined there are only a few animal-related lemmas because agricultural meteorology mainly focused on plant investigations in the first half of the 20th century.

3 THE INTERNATIONAL INSTITUTIONS OF AGRICULTURAL METEOROLOGY

Because of its inherently interdisciplinary nature, many national and international institutions fostered the development of agricultural meteorology during the 20th century. As it is not possible to list them all, this section will only consider the international organizations that set the research agenda on weather, climate, and agriculture during the first half of the 20th century and whose influence also continued later in time. The IMO and the International Institute of Agriculture (IIA) were crucial in establishing agricultural meteorology as an independent research field before WWII. Both these organizations have successors—the World Meteorological Organization (WMO) and the Food and Agricultural Organization of the United Nations (FAO), respectively—that are very engaged in discussing weather, climate, and agriculture, and this will offer the opportunity to trace the development of the international work in agricultural meteorology over the past century.

3.1 The IMO and the World Meteorological Organization

The IMO was established in the second half of the 19th century to promote exchange of scientific knowledge among nations (Cannegieter, 1963; Daniel, 1973; P. N. Edwards, 2006). Its main task was to develop international standards for meteorological observations and to promote data exchange among national weather services. The IMO also took an active interest in all the fields where weather and climate knowledge were relevant, including farming, and in the early 1910s, it created a technical commission on agriculture. The rural economist Luis Dop, who was vice-president of the IIA, was instrumental in this, because the report on agricultural meteorology he wrote and submitted to the IIA, was also transmitted to the IMO with the request to take action. The IMO then nominated a committee, of which Dop was also a member, to investigate agricultural meteorology and concluded that “the creation of such commission was justified by the novelty and complexity of the problems posed by agricultural meteorology and that required the collaboration of meteorologists, agronomists, and botanists. The creation [of the commission], furthermore, [...] [answered] the interest that a large number of countries [...] [were showing] for the problems of agricultural meteorology” (Internationalen Meteorologischen Komitees, 1913, p. 25). Although nominated in 1913, the IMO Commission for
Agricultural Meteorology began to work only after the conclusion of WWI, in 1919, and during the interwar years constantly grew and expanded its membership co-opting an increasing number of scientific experts in meteorology.
met for the first time in 1953 (Baier et al., 1991). Although the commission’s first president delivered a rather traditional address on agricultural meteorology and its scopes (Burgos, 1954), the CAgM made bold statements about its role within the WMO. It refused to merge with the WMO technical commission on climatology and remarked that “the application of meteorology in the field of world food production should be considered in itself as the most important activity of the World Meteorological Organization and it is likely to be increasingly appreciated in the future for its importance in the field of food production” (WMO, 1954, p. 28). In addition, the CAgM began to strengthen its alliances outside rather than inside the WMO. It invited to its first meeting representatives from other UN agencies, such as FAO and UNESCO (United Nations Educational, Scientific and Cultural Organization) which were also interested in the impact of weather and climate on rural communities. In addition, the CAgM made plans to involve in its work members of scientific and farming organizations, such as the International Geographical Union, the International Society of Soil Science, and the International Federation of Agricultural Producers.

The transition from the IMO technical commission on agriculture to the CAgM generated also a broader approach to agricultural meteorology. The majority of the IMO commission members were based in Europe, its colonies, and protectorates, and focused their discussions on agricultural meteorology problems encountered in the temperate areas and, to a much lesser extent, in the tropics. On the contrary, since its first meeting, the CAgM was interested in contributing to UNESCO’s program for populations in drought areas and to work closely with the FAO to support farmers worldwide and minimize the negative impact of weather and climate events on rural communities (WMO, 1954). This shift toward a more generalized interest in farming as practiced in both temperate and tropical areas, and especially in the impact of weather and climate on rural communities in developing countries, has been a distinctive feature of international agricultural meteorology over the past half-century (World Meteorological Organization, 2006). Today, the first point on the CAgM’s agenda is to manage climate risks and adapt to climate variability and change, because they threaten food security, but at the same time to promote sustainable agricultural systems (World Meteorological Organization, 2012). To achieve this result, the CAgM has strengthened the collaboration with UN agencies that share the mission to support food production and rural development, besides the FAO, also the World Food Programme (WFP) and the UNESCO. While this collaboration may seem a natural outcome for an interdisciplinary and applied rather than theoretical research field such as agricultural meteorology, it should not be taken for granted, as I will discuss in more detail in the following section examining the choices made by the IIA in the first half of the 20th century.

3.2 The International Institute of Agriculture and the Food and Agricultural Organization

The IIA was founded in Rome in 1905 with a diplomatic convention underwritten by delegates of 40 different governments. Its mission was to facilitate international rural cooperation, insurance, and agrarian credit and to collect and make publicly data related to worldwide agricultural production, labor conditions, plant and animal diseases (Hobson, 1931; Mignemi, 2017). As a “knowledge institution,” the IIA could approach agricultural questions with a transnational perspective, because its scientific focus avoided direct conflicts with the participating nations and their agrarian policies (Mignemi, 2017, p. 275). As part of its data collection work, the IIA was interested in all the scientific and technological developments that could strengthen rural economies, and the IIA’s bulletins regularly abstracted research publications related to the agricultural sciences, including publications regarding the impact of weather and climate on farming. As already mentioned, the IIA and in particular its vice-president, Dop, were instrumental in the creation of the IMO technical commission on agriculture before WWI. At that stage, both institutions conceived the commission as a collaborative enterprise, whose aim was to bring together experts in the agricultural sciences with
meteorologists and climatologists. After WWI, however, when the IMO technical commission on agriculture began to meet, the IIA did not appoint agricultural experts to it. The agricultural institution decided to create a committee of its own, the Commission for Agricultural Meteorology and Ecology, to investigate the impact of weather and climate on farming and to focus not only on agricultural meteorology, but also on agricultural ecology.

The work of the IIA was very influenced by the scientific research of the Italian agronomist Girolamo Azzi, who worked for over 10 years at the IIA as a technical writer, before being appointed to a newly created chair of agricultural ecology in the city of Perugia in 1924 (Baltadori, 1994). The Italian agronomist, who is nowadays considered a founding father of agricultural ecology (Ross, 2017), was interested in the study of the bio-environmental factors that have an impact on plant yields and in understanding how crop varieties could maximize yields if they were carefully chosen according to environmental conditions (Azzi, 1928; Azzi & Pirotta, 1924). Azzi’s most imposing publication was Le climat du blé dans le monde [Wheat Climates of the Earth], published by the IIA. The volume was over 1000 pages long and discussed wheat varieties, their yields and cultivation practices in relation to climate conditions all over the world. Yield was a key concept in Azzi’s ecological approach to agriculture because it connected the biological (suitability to the environment) and economic (profitability for the farmer) issues involved in crop cultivation. Azzi, in fact, never lost sight of the very practical aims of his ecological investigations and claimed for agricultural ecology “many interesting points of connection with genetics and rural economy” (Azzi, 1922, p. 146).

Quite interestingly, the term ‘agricultural ecology’ was not coined by Azzi, although he readily accepted it. Azzi rather qualified his work as “agricultural geography” and his theories on the bio-environmental factors that affected crops were certainly more inspired by the tradition of geographers than from that of meteorologists. From this point of view, it is not surprising that the IIA, influenced by Azzi, set up an independent commission to discuss weather, climate, and agriculture, nor the agreement made with the IMO that the IIA would focus on agricultural ecology, while the IMO would consider more meteorological aspects such as the development of instruments and observational procedures and the improvement of weather forecasts for farmers. Yet, there were scientific areas, such as microclimatology, which fell within the remit of both commissions and could not be attributed to one or the other. In this case both commissions carried out their scientific work and tried to collaborate, if possible. A few scientists belonged to both commissions. Not only Azzi, but, for instance, also the French agronomist Paul Carton based in Indochina (Vachon, 1975), the Australian geographer Thomas Griffith Taylor (Powell, 1990), and the German Paul Holdefleiss, an agronomist working at the University of Halle (Fuchs, 1972) took part in both IMO and IIA efforts in agricultural meteorology. They contributed to updating the two commissions on their respective work, but the collaboration between the IMO and the IIA was far from systematic during the first half of the 20th century. The different status of the two organizations did not help to promote common activities. In fact, while the IMO was a scientific organization based on voluntary cooperation and not officially recognized by governments, the IIA was an intergovernmental institution and was affected by the growing political tensions of the 1930s (Pan-Montojo, 2016).

With the creation of the FAO as a United Nations agency in 1945, the IIA was dissolved and its assets were transferred to the FAO. This reorganization made international work in agricultural meteorology easier in the second half of the 20th century. Both FAO and the WMO were now UN agencies with an official status, and they began to collaborate since the first CAgM meeting. Their collaboration continues to this day, and it has grown even stronger in recent years, because the agendas of both organizations are now focused on climate change, as a challenge to farming, and on the necessity to promote sustainable agricultural systems. Due to the FAO’s established tradition in working with farmers, this institution has been mostly responsible for the extension work in agricultural meteorology and now considers agrometeorological information crucial for improving the management of farming operations and for providing a timely response to the environmental transformations produced by climate change (FAO, 2019). In the following section, I will discuss in more detail the impact of agricultural meteorology on farming, and why this has not yet been as significant as anticipated (Box 2).

4 | IMPACT OF CLIMATE-RELATED AGRICULTURAL RESEARCH

The farmer has always been the (alleged) beneficiary of research studies and technological innovations in agricultural meteorology. Microclimatological investigations aimed at understanding how light, temperature, and soil affect plant growth, and the improvement of forecasting techniques for harmful weather events, such as frosts and droughts, have always been presented as efforts with an immediate practical application to farming. In some cases, farming communities have also actively contributed and sponsored work in agricultural meteorology, for instance, in the development of
BOX 2  Pests and diseases

Weather and climate significantly affect the diffusion of plant and animal pests and diseases. Therefore, since the early 20th century, weather and climate scientists joined forces with plant pathologists, mycologists, botanists, entomologists, and veterinarians to investigate this area of research in agricultural meteorology. Johanna Westerdijk, who was the only female member of the IMO Commission for Agricultural Meteorology, for instance, was a plant pathologist and her laboratory in the Netherlands an institution for phytopathology and a repository for fungal cultures renowned all over Europe (Faasse, 2014). Since the early 1910s, national and international institutions were actively monitoring the spread of plant pathogens and animal disease. The IIA even published a *Monthly Bulletin of Agricultural Intelligence and Plant Diseases* recording ongoing infections, their location, and whenever possible, remedies to the infections. In the age of climate change, the study of plant and animal pests and diseases has become more and more relevant in agricultural meteorology, because global warming facilitates the diffusion of pathogens in areas previously untouched (FAO, 2008). In addition, increased percentages of carbon dioxide in the atmosphere and rising temperatures are affecting plants and their pests with a potential for new harmful plant-pathogen interactions and increased challenges to food security (Trebbecki & Finlay, 2018).

If accurate weather forecasts were useful to farmers and crop forecasts could suggest to them how to gain higher profits and better insure crops against weather hazards, the impact of other scientific investigations in agricultural meteorology is more contested. Research on microclimatology, for instance, helped to better understand how crop varieties responded to environmental conditions and the damages that scarcity of water or high temperatures produced during the critical periods of plant development. However, this knowledge did not find an immediate application to farming practices for a variety of reasons. First of all, extension services were often at a loss to translate research in agricultural meteorology into terms that farmers could easily understand and apply. In many countries, agricultural meteorology and ecology were not systematically examined in the teaching curriculum in agriculture during the first half of the 20th century and extension officers often lacked the necessary background to provide support in agricultural meteorology. The inability of extension services to fully support agricultural meteorology has continued also in the second half of the 20th century (Stigter, 2008). In addition, farmers’ choices in farm management were not just influenced by weather and climate knowledge, also economic and political factors weighted on their decisions. For instance, the high-yielding variety of cereals that were selected in the first half of the 20th century were employed even in adverse environmental conditions in which their performance was no better, and potentially even lower, of traditional varieties, because they were tools of political propaganda, as much as scientific objects, and farmers had to align themselves with the choices made by the authorities (Harwood, 2012; Saraiva, 2010). Decades later, similar problems emerged as part of
The Green Revolution, when local farming practices and environmental conditions were disregarded to pursue a one-strategy-fits-all approach (Fitzgerald, 2016).

To make matter worse, among the scientific experts contributing to agricultural meteorology there was considerable disagreement about priorities and aims of this research field. In correspondence with Vilhelm Bjerknes, a founding father of modern meteorology, William Napier Shaw, the first chairman of the British Permanent Committee on Agricultural Meteorology, bitterly reported that: “Meteorologists obtain meteorological observations from the agricultural stations and work them up into our conventional summaries and for 10 years we have been distributing these summaries to the agriculturists in the hope that they will use the summaries to trace relations that will develop the influence of weather on crops, but nothing comes of them and the agricultural folk seem to think that they are making observations of weather which in some unexplained way will help in forecasting the weather, but have no relation to crops. And the statisticians think that what is wanted is precise observations upon special crops which after 20 years experience will yield valuable correlation coefficients that will distinguish one kind of wheat from another”. These completely different value judgments on data collection and analysis in agricultural meteorology and on the priorities of its agenda make evident the conflict existing between the scientific experts who contributed to the field. The British case here reported was not unique and reflects the difficulty to find an agreement between scientists with very different educational backgrounds and disciplinary agendas, a not uncommon situation in 20th-century interdisciplinary research (Ash, 2019). In addition, research on weather, climate, and farming was also affected by the recurrent issue of finding a balance between science and practice in agriculture (Harwood, 2005). As already remarked, in fact, while agricultural meteorology is certainly a full-fledged research field with its theoretical baggage and experimental practices, investigations in this field have been mainly sponsored and pursued for their practical applications. Taken all together, these issues did not help in providing support to the farming community and account for the limited impact of climate- and weather-related research in agriculture during the first half of the 20th century. These issues were not resolved also in the second half of the century. Scarce collaboration between stakeholders in acquiring and sharing agrometeorological data and inadequate training of the extension officers have continued to lower the potential impact of agricultural meteorology (Lomas et al., 2000). In recent years, however, the increasing concern for climate change is making communication and use of weather and climate information a cornerstone of many rural policy programs, improving this situation, as I will discuss below.

## 5 | Recent Developments in Agricultural Meteorology

A chronic scarcity of data affected agricultural meteorology during the first half of the 20th century. There was little money to provide measuring equipment and to pay observers that could take regular observations of weather and crops over a long time period. Self-recording instruments could be employed to lighten the meteorological data collection, but there was no substitute to the human eye in assessing the condition of crops or in gathering phenological observations. During the past 30 years, data availability in agricultural meteorology has considerably changed. Remote sensing techniques and geographic information systems, combined with the sustained expansion of information and communication technologies, offer today access to multiple datasets of interest to scientists working in agricultural meteorology, such as weather and climate data, soil data, crop data, water resources data, phenological data, and more. This wealth of information has made possible large crop and yield modeling efforts, which are becoming more and more popular in agricultural meteorology (Dronin & Kirilenko, 2013). Like many other branches of weather and climate research (Edwards, 2010), also agricultural meteorology is increasingly becoming a computational science, where models and simulations are as important as field research. In this informational turn in agricultural meteorology, the increasing concern for climate change has certainly played a relevant role. Forecasting the effects of climate variations has become as important as forecasting the seasonal weather, and this requires efficient use of data resources and the ability to convey this information to farmers effectively (Weiss et al., 2000).

As mentioned above, international organizations working on the impact of weather and climate on farming, such as WMO and FAO, have two main items on their agenda: climate change and agricultural sustainability. Concerns for the negative impact of climate modifications on farming coexist with an equally strong commitment to promote soil conservation, reduce greenhouse gas emissions, and safeguard plant and animal biodiversity. In this sense, agricultural meteorology has become very different from what it was a century ago. In the first half of the 20th century, agrometeorological studies considered climate a fixed entity and sustainability issues were not a priority. Azzi’s agricultural ecology, for instance, was concerned with rural economy and yield increase rather than with conservation issues
and, in general, by the close of WWI ecologists found an unfavorable environment within agricultural circles (Hersey, 2011).

During the 20th century, the spotlight of agricultural meteorology has progressively shifted from the developed to the developing countries, where fragile agricultural systems have to feed a growing population and where international organizations, such as the FAO and the WFP, have a greater interest in supporting agrometeorological research and extension. Climate change and extreme weather events, however, threaten farmers also in industrialized countries and they are posing new challenges to research and application in agricultural meteorology. A lot, in fact, may have changed in agricultural meteorology over the past century, but not the emphasis placed on supporting farmers, wherever needed, although not always with the expected results.

6 | CONCLUSION

A century ago, Girolamo Azzi wrote that “[t]he machine that produces wheat is made of two parts: one part is the plant, the other part is the environment and the two parts must match perfectly [...]”. While writing this statement, Azzi was not concerned with the consequences that farming activities have on the environment. His only aim was to understand how yields could be increased by exploiting environmental conditions. A century later, the position of agrometeorologists and agroecologists is radically different. In the age of the Anthropocene, it is widely accepted that agriculture has deeply altered the natural landscape and that farming activities and the environment mutually affect each other (Simmons, 1996). This is not a small shift in perspective. First of all, it redistributes agency among human and nonhuman actors while discussing the interconnections between weather, climate, and farming. Secondly, it transforms agricultural meteorology’s mission from mere protection of farmers’ interests into a positive support to climate change adaptation and mitigation and to agricultural sustainability. To achieve this result, the stakeholders of agricultural meteorology—scientific experts, political authorities, and farmers—must communicate efficiently. As described above, during the past century many factors hindered this communication: extension services struggled to convey agricultural meteorology research to farmers, economic and political aspects competed with climate and weather knowledge in driving farmers’ choices, and, last but not least, disagreements between scientific experts weakened the impact of agricultural meteorology.

In recent years, however, climate change and agricultural sustainability have gained such widespread relevance across scientific disciplines and in policymaking that agendas of international institutions steering the course of agricultural meteorology, such as the WMO and the FAO, have been converging toward common targets. This facilitates collaboration among scientific partners, policymakers, and farmers. The informational turn in agricultural meteorology has also contributed to improve communication among stakeholders, because a common thread joins together the scientific data collected and the crop models and forecasts built on them, the policy actions carried out by governments and international agencies on the basis of these forecasts, and the provision of weather and climate information to the end-user, the farmer, who is expected to turn policy into action with the support of extension services. Yet, the practical implementation of climate services for smallholder farmers in developing countries is still facing many challenges (Yegbemey & Egah, 2021). Nor policy interventions adequately acknowledge the role of traditional farmers’ knowledge in areas critical for climate change, such as Africa, and fully integrate it with science-based actions (Tume & Kimengsi, 2021).

It is therefore evident that implementing a climate-smart agriculture is a process that involves small steps and hiccups rather than giant leaps, that access to technology, financial resources, and scientific expertise remains unequally distributed, and that new weather and climate challenges arise every day for farmers in developed and in developing countries. However, agricultural meteorology can be an example of a proactive approach to the human-climate relationship and offer new opportunities to deal with a changing environment inasmuch as it supports climate information services that provide short and long-term forecasts and contributes to the implementation of effective management systems for soil and water resources.

ACKNOWLEDGMENTS

I am grateful to WIREs Climate Change domain editor, Matthias Heymann, for the opportunity to write this review. I thank the participants to the workshop “Exploring the Connected Histories of Meteorology, Agriculture and the Environment” (TU Berlin, 2019) for enriching my overview of agricultural meteorology and the anonymous referees who provided insightful comments on the first draft of this article. Research for this article was sponsored by the German...
Research Foundation (DFG), Project No. 321660352. TU Berlin generously supported the open access publication of this article. I am grateful to the library of the World Meteorological Organization and the Swedish Meteorological and Hydrographic Office for making available copies of the proceedings of the IMO Commission for Agricultural Meteorology. I thank the Norwegian National Library for permission to quote from the materials held in the Vilhelm Bjerknes correspondence (Ref. 469 B).

Open access funding enabled and organized by Projekt DEAL.

CONFLICT OF INTEREST
The author has declared no conflicts of interest for this article.

DATA AVAILABILITY STATEMENT
Data openly available in a public repository that issues datasets with DOIs.

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ENDNOTES
1 Sustainability has become a ubiquitous term. It can be found in the reports of international organizations concerned with food and agriculture as well as listed as a key principle in the development plans of corporations. Readers interested in the history of this term may find more information in the Routledge Handbook of the History of Sustainability (Caradonna, 2017).
2 The bibliographic datasets examined are available in csv format here: https://data.mendeley.com/datasets/gx92v4sypj/1. The Second Bibliography of Literature on Agricultural Meteorology counts almost 600 references, while over 3500 entries related to the period 1900–1950 have been extracted from chapters 1–4 and 6–8 of Wang and Barger's bibliography. All the entries in the datasets were checked as thoroughly as possible and, when available, the link to an online copy of the publication (or a related version) was added. The word cloud opening the article has been extracted from Wang and Barger's dataset. The code used in the analysis of the bibliographies is available in this GitHub repository: https://github.com/GParolini/colabs_am_bib. A larger selection of bibliographic data on agricultural meteorology is available in this Zotero public library https://www.zotero.org/groups/2204063/bibliography_of_agricultural_meteorology_1900-1950. In this library, however, the data are not curated and may contain inaccuracies or repetitions.
3 The analysis of the popular themes in agricultural meteorology is done extracting lemmas, that is, the dictionary form of words, only from the English publications in the datasets. The word cloud opening the paper has been obtained, instead, considering all the available publications and a few non-English terms, such as blé [wheat] and climat [climate], also appear in the image.
4 The quotation is extracted from a letter written by W. N. Shaw to V. Bjerknes on October 5, 1934 (Norwegian National Library Oslo, Vilhelm Bjerknes Correspondence, Ref. 469 B).

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https://agriculturalmeteorology.wordpress.com
Parolini, Giuditta (2020). Bibliographies of agricultural meteorology (1900-1950). Mendeley Data, V1. https://doi.org/10.17632/gx92v4sypj.1.
Parolini, Giuditta (2020). Membership of the IMO Commission for Agricultural Meteorology (1913-1947). Mendeley Data, V1. https://doi.org/10.17632/pds6tz443t.1.

REFERENCES
Anonymous. (1911). The status of agricultural meteorology. Scientific American, 105(8), 382.
Anonymous. (1924). Professor C. A. Angot [obituary]. Quarterly Journal of the Royal Meteorological Society, 50(211), 270–271.
Ash, M. G. (2019). Interdisciplinarity in historical perspective. Perspectives on Science, 27(4), 619–642.
Hannay, A. M. (1931). The influence of weather on crops, 1900-1930: A selected and annotated bibliography. https://archive.org/details/influenceofweath118hann/page/n1

Hare, F. K. (1963). Charles Warren Thornthwaite (1899-1963). Geographical Review, 53, 595–597.

Harper, K. C. (2012). Weather by the numbers: The genesis of modern meteorology. (Paperback. The MIT Press.

Harvey, R. B. (1936). An annotated bibliography of the low temperature relations of plants (Revised ed.). Burgess Publishing Company. https://babel.hathitrust.org/cgi/pt?id=wu.89047153788&view=1up&seq=1

Harwood, J. (2005). Technology’s dilemma: Agricultural colleges between science and practice in Germany, 1860–1934. (New Edition). Peter Lang AG, Internationaler Verlag der Wissenschaften.

Harwood, J. (2012). Europe’s green revolution and others since: The rise and fall of peasant-friendly plant breeding. Routledge.

Hendricks, S. B. (1976). Harry Alfred Borthwick (1898–1974). Biographical Memoirs of the National Academy of Sciences, 48, 105–122.

Hersey, M. D. (2011). “What we need is a crop ecologist”: Ecology and agricultural science in progressive-era America. Agricultural History, 85(3), 297–321. https://doi.org/10.3098/ah.2011.85.3.297

Hineline, M. L. (2018). Ground truth: A guide to tracking climate change at home. Chicago University Press.

Hobson, A. (1931). The International Institute of Agriculture: An historical and critical analysis of its organization, activities and policies of administration. University of California Press.

Internationalen Meteorologischen Komitees. (1913). Bericht über die Versammlung des Internationalen Meteorologischen Komitees. Behrend & Co.

Irwin, J. O. (1938). Crop estimation and its relation to agricultural meteorology. Supplement to the Journal of the Royal Statistical Society, 5(1), 1–45. https://doi.org/10.2307/2983579

Klein, P., & Sanson, J. (1925). Meteorologie et physique agricoles [Meteorology and agricultural physics]. J. B. Baillière et fils; WB 00332. https://catalog.hathitrust.org/Record/001998112

Kulshreshtha, S. N., & Wheaton, E. E. (Eds.). (2018). Sustainable agriculture and climate change (special issue published in the journal sustainability). MDPI. https://www.mdpi.com/books/pdfview/book/541

Li, K., Yang, X., Tian, H., Pan, S., Liu, Z., & Lu, S. (2016). Effects of changing climate and cultivar on the phenology and yield of winter wheat in the North China Plain. International Journal of Biometeorology, 60(1), 21–32. https://doi.org/10.1007/s00484-015-1002-1

Lieth, H. (Ed.). (1974). Phenology and seasonality modeling. Springer-Verlag. https://www.springer.com/de/book/9783642518652

Lipper, L., McCarthy, N., Zilberman, D., Asfaw, S., & Branca, G. (Eds.). (2018). Climate smart agriculture: Building resilience to climate change. Springer.

Livingston, G. J. (1908). An annotated bibliography of evaporation. Monthly Weather Review, 36; 37(6, 9, 11; 2, 3, 4, 5, 6), pp. 181–186, 301–306, 375–381; 68–72, 103–109, 157–160, 193–199, 248–252.

Lomas, J., Milford, J. R., & Mukhala, E. (2000). Education and training in agricultural meteorology: Current status and future needs. Agricultural and Forest Meteorology, 103(1), 197–208. https://doi.org/10.1016/S0168-1923(00)00112-X

Luceon, J. (1935). Les travaux de meteorologie agricole de l’institut National Meteorologique de Pologne. Wydawnictwo Specjalne Z Okazji up&seq=1974.–1989. Annales de géographie, 59(314), 148.

Mignemi, N. (Ed.). (2017). Italian agricultural experts as transnational mediators: The creation of the International Institute of Agriculture, 1905 to 1908. The Agricultural History Review, 65, 254–276.

Mihara, Y., & Ando, T. (1974). Background and history of agricultural meteorology in Japan. In Y. Mihara (Ed.), Agricultural meteorology of Japan. University Press of Hawaii.

Ministry of Agriculture and Fisheries. (1929). Conference of Empire Meteorologists, Agricultural Section: Reports and Papers. HMSO.

Ministry of Agriculture and Fisheries - Agricultural Meteorological Scheme. (1937). Third bibliography of literature on agricultural meteorology. Research, Advisory and Machinery Branch.

Ministry of Agriculture and Fisheries—Agricultural Meteorological Scheme. (1936). Second bibliography of literature on agricultural meteorology. Research, Advisory and Machinery Branch.

Obasi, G. O. P. (2000). Preface. Agricultural and Forest Meteorology, 103(1), 3–4. https://doi.org/10.1016/S0168-1923(00)00102-7

Oreskes, N., & Krige, J. (Eds.). (2014). Science and technology in the Global Cold War. The MIT Press.

Organisation Météorologique Internationale. (1929). Commission de Météorologie Agricole: Procès-verbaux del 3ème réunion. Copenhagen, 1929. Statens Meteorologisk-Hydrografiska Anstalt 276.

Organisation Meteorologique Internationale. (1933). Commission de Meteorologie Agricole: Procès-verbaux des seances de Munich, 19-21 septembre 1932. Organisation Meteorologique Internationale 14.

Organisation Meteorologique Internationale. (1936). Kommission fuer Landwirtschaftliche Meteorologie: Protokolle der Tagung in Danzig, 28–31 August 1935 (No. 24).

Organisation Meteorologique Internationale. (1938). Kommission fuer Landwirtschaftliche Meteorologie: Protokolle der Tagung in Salzburg, 8–11 September 1937 (No. 36).

Pan-Montojo, J. (2016). International institutions and European agriculture: From the IIA to the FAO. In C. Martii, J. Pan-Montojo, & P. Brassley (Eds.), Agriculture in Capitalist Europe, 1945–1960: From food shortages to food surpluses. Routledge. https://doi.org/10.4324/9781315465937-12

Parolini, G. (2015). The emergence of modern statistics in agricultural science: Analysis of variance, experimental design and the reshaping of research at Rothamsted Experimental Station, 1919-1933. Journal of the History of Biology, 48(2), 301–335.
Parolini, G. (2020). Building networks of knowledge exchange in agricultural meteorology: The agro-meteorological Service in French Indo-China. History of Meteorology, 9, 1–20.

Parolini, G. (2021). Rebuilding international cooperation in meteorology after World War I: The case of agricultural meteorology. Acta Historica Leopoldina, 78, 97–119.

Paterson, A. M. (1975). Oranges, soot, and science: The development of frost protection in California. Technology and Culture, 16(3), 360–376.

Phillips, D. (2015). Plants and places: Agricultural knowledge and plant geography in Germany, 1750–1810. In D. Phillips & S. Kingsland (Eds.), New perspectives on the history of life sciences and agriculture (pp. 9–26). Springer International Publishing.

Phillipson, D. (2013). Robert Newton. In The Canadian encyclopedia. Historica Canada. https://www.thecanadianencyclopedia.ca/en/article/robert-newton

Powell, J. M. (1990). Taylor, Thomas Griffith (1880 –1963). In Australian dictionary of biograph. National Centre of Biography, Australian National University. http://adb.anu.edu.au/biography/taylor-thomas-griffith-8765/text15363

Primack, R. B. (2015). Walden warming: Climate change comes to Thoreau’s woods. University of Chicago Press.

Ramanathan, K. R. (1984). Lakshminarayanapuram Ananthakrishnan Ramdas (1900–1979). Biographical Memoirs of Fellows of the Indian National Science Academy, 8, 181–190.

Reed, W. G., & Feldkamp, C. L. (1915). Selected bibliography of frost in the United States. Monthly Weather Review, 43(10), 512–517. https://doi.org/10.1175/1520-0493(1915)43<512b:SBOFIT>2.0.CO;2

Ross, C. (2017). Ecology and power in the age of empire: Europe and the transformation of the Tropical world. Oxford University Press.

Saraiva, T. (2010). Fascist labscapes: Geneticists, wheat, and the landscapes of fascism in Italy and Portugal. Historical Studies in the Natural Sciences, 40(4), 457–498.

Shaw, W. N. (1933). Agricultural meteorology, a brief historical review. In The Drama of weather (pp. 74–77). Macmillan.

Simmons, I. G. (1996). Changing the face of the earth: Culture, environment, history. Blackwell.

Smith, J. W. (1920). Agricultural meteorology: The effect of weather on crops. Macmillan.

Stigter, K. (2008). Policy support for capacity building in weather and climate services focused on agriculture. Journal of Agrometeorology, 10(2), 107–111.

Theophrastus. (1483). Theophrasti De Historia plantarum liber primus-decimus (G. Merula, Trans.). Impressum Taruisii: Per Bartholomaeum Confalonierum de Salodio. https://www.biodiversitylibrary.org/bibliography/62512

Toaldo, G. (1775). La meteorologia applicata all’aicultura. G. Storti. https://catalog.hathitrust.org/Record/002241266

Třebicki, P., & Finlay, K. (2018). Pests and diseases under climate change; its threat to food security. In S. S. Yadav, R. J. Redden, J. L. Hatfield, A. W. Ebert, & D. Hunter (Eds.), Food security and climate change (pp. 229–249). John Wiley & Sons https://onlinelibrary.wiley.com/doi/abs/10.1002/9781119198066.ch11.

Tume, S. J. P., & Kimengsi, J. N. (2021). Indigenous and modern agro-based climate adaptation practices in rural Cameroon. International Journal of Environmental Studies, 0(0), 1–10. https://doi.org/10.1080/00207233.2021.1977538

Vachon, M. (1975). Carton, Paul. In Dictionnaire biographique d’Outre-Mer. (Vols. 1–5). https://wbis.degruyter.com/biographic-document/R14688

von Humboldt, A.. (1817). De distributione geographica plantarum secundum coeli temperiem et altitudinem montium. Libraria Graeco-Latina-Germanica. https://reader.digitale-sammlungen.de/de/fs1/object/display/bsb10301921_00005.html

von Humboldt, A., & Bonpland, A. (1805). Essai sur la géographie des plantes. Chez Levrault, Schoell et Compagnie, Libraires https://www.biodiversitylibrary.org/bibliography/9309

Wang, J. Y., & Barger, G. L. (Eds.). (1962). Bibliography of agricultural meteorology. The University of Wisconsin Press.

Weber, G. A. (1922). The weather bureau: Its history, activities and organization. D. Appleton and Company.

Weiss, A., Crowder, L., & Bernardi, M. (2000). Communicating agrometeorological information to farming communities. Agricultural and Forest Meteorology, 103, 185–196. https://doi.org/10.1016/S0168-1923(00)00111-8

WMO. (1954). Commission for Agricultural Meteorology (CAgM). Abridged final report of the first session. WMO.

World Meteorological Organization. (2006). Commission for Agricultural Meteorology (CAgM): The first fifty years.

World Meteorological Organization. (2012). Guide to Agricultural Meteorological Practices (GAMP). https://library.wmo.int/index.php?vln=notice_display&gid=12113#X4mS8C1aaCU

Yegbemey, R. N., & Egah, J. (2021). Reaching out to smallholder farmers in developing countries with climate services: A literature review of current information delivery channels. Climate Services, 23, 100253. https://doi.org/10.1016/j.cliser.2021.100253

How to cite this article: Parolini, G. (2022). Weather, climate, and agriculture: Historical contributions and perspectives from agricultural meteorology. WIREs Climate Change, 13(3), e766. https://doi.org/10.1002/wcc.766