The EUMETNET AutoPollen programme: establishing a prototype automatic pollen monitoring network in Europe

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Abstract Operational pollen monitoring networks have developed across Europe, and the world more generally, in response to the increasing prevalence of pollen allergy and asthma. Routine pollen observations are in large part currently still based on time-intensive manual techniques developed in the 1950s. These methods suffer from low temporal resolution and long delays in data availability. Recent technological developments are revolutionising the field making real-time high-temporal resolution measurements possible. This paper describes the rationale

behind the EUMETNET AutoPollen programme, which aims to develop a prototype automatic pollen monitoring network across Europe. We provide a brief description of the current state-of-the-art, then an overview of new technologies, and finally the main tasks of the AutoPollen programme.

Keywords Pollen monitoring network · Automatic · Real-time · AutoPollen

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1 Introduction

Over the past 30 years, the prevalence of pollen allergy and asthma in Europe has increased fourfold, now affecting between 15 and 40% of the population. This level continues to increase, with approximately 25% of the adult population being affected but nearly 30–40% of children having allergies (Laatikainen et al. 2011; Rönmark et al. 2009). The reasons for this increase remain elusive but are likely a complex combination of various environmental and lifestyle factors, including increased population susceptibility and co-exposure to anthropogenic pollutants (Laatikainen et al. 2011; Pearce et al. 2007; Sunyer et al. 2004). A range of recent studies has also shown that climate change will worsen the impact of allergy in the coming decades. This is due to a combination of factors: longer flowering periods resulting from

temperature increases, more plant productivity and higher pollen emissions due to increased CO₂ concentrations, increased allergen concentrations in pollen grains because of various stress factors such as heat or air pollution (Damialis et al. 2019; Ziska et al. 2019; Lake et al. 2017; D'amato et al. 2014; IPCC 2007; Riedl and Diaz-Sanchez 2005), and the extension of ranges of various introduced allergenic plant species, such as ornamentals or invasives (Schaffner et al. 2020; Lake et al. 2017; Beggs 2010; D'Amato and Cecchi 2008).

The burden on the European public health system is significant, with the direct and indirect health costs related to asthma and insufficiently treated allergies estimated at nearly €50 billion/year and €50–150 billion/year, respectively (Zuberbier et al. 2014; ERS 2013). Furthermore, these issues are a major concern to the European public, with 87% of Europeans seeing asthma and allergy prevalence as a serious or very serious problem—on par with cardiovascular and respiratory diseases (ERS 2013). Improved monitoring of airborne pollen is thus vital to ensure better prevention, diagnosis, and treatment of allergy-related health problems as well as to reduce associated costs. The current technology used across Europe dates back to the 1950s (Hirst 1952) and suffers in particular from low time resolution (usually daily averages, 2-hourly averages are possible, however, with significantly larger uncertainties) and large delays in data availability (typically with data from the previous week available once a week, with at least one day delay). The advent of real-time pollen monitoring, and in particular the high time-resolution of these observations, is revolutionising the information available to allergy sufferers and medical practitioners, as well as for pollen forecasts. Better diagnosis and treatment of allergies will significantly reduce the burden on the European health system and improve quality of life for an ever-increasing proportion of the population. New avenues for research, clinical studies, and education will also open up, as will the potential for synergies with the air quality and aerosol communities, resulting in an improvement of services and additional savings (Oberpriller et al. 2017).

While in its infancy, the technology behind automatic pollen monitoring is rapidly developing. At this early stage, it is essential that the opportunity be taken to establish a standardised European network that provides information corresponding to users' needs

and which avoids unnecessary duplication or harmonisation efforts in future. The EUMETNET AutoPollen programme aims to fulfil this task in a collaborative, efficient, and effective manner, covering all aspects of the information chain from the standardisation of measurements through to the provision of products co-designed with end-users.

This paper describes the rationale behind a European automatic pollen monitoring network, first providing a brief description of the current state-of-the-art, then an overview of new technologies, and finally the main tasks of the EUMETNET AutoPollen programme.

2 State-of-the-art: a critical understanding of current pollen monitoring

Airborne pollen grains are large particles, typically between 10 and 100 µm in diameter, and thus not easy to capture because of their large inertia and high sedimentation rates, as well as the fact that they tend to stick to the side walls of the monitoring instruments. Relative to other aerosol they are also present in very low concentrations, ranging from a few units to a few thousand grains per cubic metre, meaning that high volume sampling is required to ensure measurements are representative. Furthermore, it is essential that each particle is identified precisely, since allergies are provoked by different allergens present in the pollen of specific plant taxa.

The present standard method for sampling airborne pollen is based on volumetric impactors that allow up to seven days of continuous sampling (Hirst 1952). Ten litres of air per minute are sucked into the device and particles impact onto a sticky strip that is mounted on a rotating drum. The drum is usually replaced once a week, after which the strip is analysed in a time-consuming manual process in the laboratory. This method results in a delay of one to nine days between sampling and data availability, and requires specialised staff, which is expensive and thus limits the density of pollen monitoring networks. The resultant data also suffer from high levels of uncertainty because of the limited sampling area over which pollen is counted (Galan et al. 2014), and several technical and methodological issues still need to be systematically addressed (e.g., Oteros et al. 2017). A Global Earth Observation report underlined that

“these methods need to be improved, aiming at more accurate and advanced forecasting” (GEO 2009). As such, there is no “golden standard” in terms of pollen observations and no absolute reference against which new automatic measurements can be compared.

Manual pollen monitoring networks exist in almost all European countries (Buters et al. 2018), maintained by different institutions including national meteorological and hydrological services, public health institutes, universities, and private organisations. They nearly all participate in the European Aeroallergen Network (www.polleninfo.org), a voluntary association of pollen monitoring networks in Europe and beyond. This network maintains a common pollen database that currently includes data from Hirst-type instruments from over 300 sites. The network is essentially run on a private basis with next to no public funding and since the data owners are in many cases private organisations, most of the data are not freely available for the public, forecasts, or research purposes.

3 Technological breakthroughs and automatic pollen monitoring

At a time when so much information is available online immediately, publishing pollen data from up to nine days ago seems like an anachronism and operators of pollen monitoring networks are frequently approached by end-users to ask why this is the case. Furthermore, only real-time data can be integrated into numerical forecast models, which would help to considerably improve on how current forecasts are produced. Over the past few years, a handful of automatic pollen monitoring systems have become commercially available. These technologies exploit two main techniques: image recognition and/or air-flow cytometry (Huffman et al. 2019).

Image recognition is used in the BAA500 (Helmut Hund, www.hund.de) (Oteros et al. 2015; Ronneberger et al. 2002), in which an air-flow deposits particles on a surface which is then analysed by microscope imaging. Software then counts and identifies pollen taxa. The recently launched ePIN network in Bavaria, Germany, makes use of this technology and publishes 3-hourly pollen concentration information on its website continuously (Oteros et al. 2019). Another instrument, based on a somewhat similar

method, is the PollenSense Airborne Particulate Sensor (APS) (Lucas et al. 2018), which also uses an image recognition system to identify pollen particles.

A number of instruments use air-flow cytometry, including the KH3000 (Yamatronics, www.yamatronics.com) (Kawashima et al. 2017, 2007). This robust instrument has been used in the Japanese Hanakosan monitoring network since 2002, using forward- and side-scattering measurements to provide information about levels of Japanese Cedar pollen in winter. Other instruments that perform in situ measurements of pollen particles include the Droplet Measurement Technologies WIBS-Neo (DMT; www.dropletmeasurement.com) (Savage et al. 2017; O'Connor et al. 2014), Plair Rapid-E (www.plair.ch) (Šaulienė et al. 2019; Crouzy et al. 2016), and Swisens Poleno (www.swisens.ch) (Sauvageat et al. 2020). All three instruments use lasers at various wavelengths to produce scattering and fluorescence signals which are used to identify particles, while the Swisens Poleno additionally takes holographic images.

Prices for these instruments range from a few thousand to more than a hundred thousand Euros. They also vary significantly in their characteristics and capabilities. In particular, not all have demonstrated a real ability to identify different pollen taxa nor has the full potential of others been reached. Several other instruments are still under development, using technology such as liquid cytometry (Huffman et al. 2019). The Plair Rapid-E is currently operational in a prototype network between Serbia and Croatia, as part of the RealforAll project (www.realforall.com), while the Swisens Poleno is being deployed across the Swiss operational monitoring network. A number of research instruments are also located at various sites across Europe. A world map of the pollen monitoring stations, including automatic systems, is shown on the website of the European Academy of Allergy and Clinical immunology (www.eaaci.org/19-activities/task-forces/4342-pollen-monitoring-stations-of-the-world.html).

Whichever technique is used, the advent of automatic pollen monitoring, and in particular, the high temporal-resolution and near real-time availability of these observations, will revolutionise the information available to allergy sufferers and the public health area, as well as for pollen forecasts. The higher temporal resolution of these data will also help to provide a much deeper understanding of

aerobiological phenomena and the factors, such as meteorology, influencing them (e.g. Chappuis et al. 2019). The potential of some instruments to analyse aerosol other than pollen (e.g. spores or fine particulate matter) is particularly of interest since it may lead to synergies with the air quality and agricultural communities, e.g. for maintaining monitoring networks and exchanging data and information, thus improving the provision of services and resulting in additional savings. Table 1 summarises the main differences between manual and automatic pollen counting methods.

4 The EUMETNET AutoPollen programme 2018–2022

In response to the emergence of new technologies for real-time pollen observations and the growing needs of the population, the AutoPollen programme was established to serve as a platform to develop a

European automatic pollen monitoring network. The programme is part of EUMETNET, the grouping of European national meteorological and hydrological services (NMHSs), and represents a unique opportunity to significantly contribute to public health and develop the level of service provided across Europe from the very start of the use of automatic pollen monitoring systems. EUMETNET provides an optimal framework for the AutoPollen programme given the collective infrastructure, knowledge, and experience that is held by NHMSs. This includes existing infrastructure and expertise in maintaining monitoring networks, acquiring and exchanging huge amounts of data, and producing pollen forecasts using numerical models.

The ultimate goal of AutoPollen is not only to establish long-term automatic pollen monitoring across Europe, but also to provide pollen observations and model forecasts to the public, medical practitioners, and health authorities for near real-time decision support (e.g. Gilles et al. 2020). The cross-border

Table 1 Comparison of manual and automatic pollen monitoring methods

	Manual Hirst-type systems	Automatic systems (instrument dependent)
Strengths	Expertise and critical analysis	Real-time availability, high temporal resolution
Data availability	1–9 days delay	Near real-time (from minutes up to 6 h)
Sampling resolution	Usually daily averages, although up to 2-hourly resolution can be obtained (with associated error depending on the proportion of the slide counted)	From minutes up to 3 h
Logistics	Intervention on site minimum once a week for the drum exchange. A laboratory is required to prepare the sampling drums and for the pollen counting. At monitoring stations without a laboratory (and trained personnel), shipping is needed to transport samples to the laboratory (i.e. extra delay and cost)	No intervention on site for operational activities required, except for occasional maintenance (usually 1–2 times per year). Two devices, the BAA500 and APS, do, however, require the replacement of consumables every 3–8 weeks
Number of sites	Pollen counting is time-consuming and requires specialised staff thus limiting the number of monitoring sites	Denser spatial coverage is possible, with the number of sites being limited by the device costs rather than staff availability and costs
Data availability	Manual pollen counting takes between 10 and 120 min for 1 day for 1 site. Daily average values are usually made available once per week	Pollen counting is automatic and data are available in near real-time (delays of minutes–3 h)
Quality control	Requires specialised staff, time-consuming	Can be automatised to a certain degree, but may require human intervention on occasion
Number of species identified	Numerous pollen and spore taxa can be identified (more than 100 pollen species, depending on the analyst's experience)	At least the main allergenic taxa, with possible extension to additional pollen taxa and other particles (spores, air pollution) in future
Costs	Low initial investment, high personnel costs	Higher initial investment, running costs estimated lower or equivalent

nature of pollen dispersal (Mohanty et al. 2017; de Weger et al. 2016; Izquierdo et al. 2011; Rousseau et al. 2008) means that it is essential that the monitoring network extends across the entire European continent and which is why significant effort has been placed on involving participants from as many countries as possible (see Table 2 for the complete list of current participants). The participation of these groups is also vital since in most European countries, pollen monitoring networks are not operated by NMHSs or other governmental organisations, even if these institutes nearly all issue pollen forecasts. The availability of real-time pollen data from across the continent would significantly improve such forecasts, and it is thus likely that as the network grows, more

and more of these governmental organisations would be willing to establish and operate automatic pollen monitors in their country. Personnel that are currently involved in repetitive manual pollen counting could be oriented towards developing and improving the quality of products providing pollen-related information and further develop research across a range of disciplines (Šantl-Temkiv et al. 2019). This represents a significant paradigm change compared to the present situation where monitoring networks are, in many countries, maintained by private organisations or universities with limited mandate or budget for such activities. The involvement of governmental organisations will help to ensure the long-term sustainability

Table 2 List of participants to the EUMETNET AutoPollen programme

Participants	Country	Institution
	Austria	Central Institute for Meteorology and Geodynamics (ZAMG)
	Croatia	Croatian Meteorological and Hydrological Service (DHMZ)
	Czech Republic	Czech HydroMeteorological Institute (CHMI)
	Finland	Finnish Meteorological Institute (FMI)
	Germany	German Meteorological Service (DWD)
	Greece	Hellenic National Meteorological Service (HNMS)
	Ireland	Met Éireann
	Luxembourg	MeteoLux
	Poland	Institute for Meteorology and Water Management (IMGW)
	Slovenia	National Meteorological Service of Slovenia (ARSO)
	Switzerland	Federal Office of Meteorology and Climatology MeteoSwiss
	Belgium	Sciensano
	France	ATMO France
	France	Réseau National de Surveillance Aérobiologique (RNSA)
	Germany	Bavarian State Office for Health and Food Safety (LGL)
	Latvia	University of Latvia
	Lithuania	Siauliai University
	Portugal	Institute of Earth Sciences
	Portugal	Portuguese Institute for the Sea and Atmosphere (IPMA)
	Serbia	BioSense Institute
	Spain	AEA – Spanish Aerobiology Network
	Sweden	Swedish Museum of Natural History
	Turkey	Bursa Uludag University
	Ukraine	National Pirogov Memorial Medical University
	United Kingdom	University of Worcester
	International	EAS European Aerobiology Society
	International	EFA European Federation of Allergy and Airways Diseases Patients' Association
Collaborations	International	CAMS (Copernicus Atmospheric Monitoring Services), CAMS_23
	International	COST Action CA18226—New approaches in detection of pathogens and aeroallergens

of monitoring networks and the free, public availability of these observations.

5 Tasks to be carried out

The AutoPollen programme aims to cover the entire information chain from measurement through to communication of real-time pollen observations and forecasts. It will clarify the fundamentals of automatic pollen monitoring by proposing standards and measurement requirements, demonstrating the feasibility of a prototype European network by integrating ongoing and planned projects across the continent. The programme has been developed such that each step is addressed with several detailed reports or activities, which are outlined below.

5.1 Technology and measurement methods

The technology behind automatic pollen monitoring is still in its infancy and both the challenges and full potential of these measurements need to be completely understood. An intercomparison campaign to test the range of available automatic pollen monitors will be carried out in parallel with manual Hirst-type observations to compare how instruments function under different ambient conditions and to better understand limits of detection as well as levels of accuracy. Minimum requirements in terms of the pollen species to be identified will also need to be established. Furthermore, it is essential that the new methods are validated and a set of standards developed for automatic pollen measurements, as has been done for manual Hirst-type observations (CEN EN 16868:2019). Such standards will need to include a wide range of criteria including sampling height and volume, as well as calibration and maintenance standards. There needs to be common agreement across a future monitoring network for each of these aspects, all of which need to be fully documented from the start. Establishing these standards from the very beginning will prevent unnecessary duplication and harmonisation efforts in the future, thus saving considerable personnel and financial resources.

5.2 Site selection and network design

Similar to measurement standards, a set of criteria for optimal measuring sites will need to be developed as will a list of metadata to be reported at each site. The representativeness of each monitoring station will also need to be assessed and research into the best methods for doing this carried out. While the selection of individual measurement sites may depend on a number of local and regional factors, in particular vegetation, it is essential that the entire European network is designed in an intelligent way. This should ensure optimal spatial coverage and minimise related costs, all the while keeping in mind the importance of maintaining long-term records. A number of reference sites will also be established in different bioclimatic regions to provide the possibility to test and compare the various instruments available on the market. Such activities will serve to verify how different instruments operate in different climatic conditions and whether they are able to recognise, at least, the most important pollen present in the European atmosphere.

5.3 Data format and exchange protocols

To ensure data can be effectively shared, a uniform data format will need to be established, regardless of instrument or technology. Exchange protocols will also need to be developed to assure timely data availability, as will data quality control procedures, including how to quantify data quality. Existing infrastructure could be used to store and distribute data. Exploiting a joint European database would provide considerable savings, facilitating data exchange and large-scale data analysis. Such data exchange is vital also for numerical models, which require real-time observations to provide more accurate forecasts, as well as for other downstream products.

5.4 Improvement of numerical forecast models

At present, numerical forecast models use only historical climatologies, which are combined with current meteorology, to produce forecasts. However, the development of real-time pollen observations makes possible the integration of this information into numerical forecast models and, just as was the case for weather forecasts, is likely to vastly improve

the quality of pollen predictions. Such forecasts play an integral role in the day-to-day management and treatment of pollen allergies and improvement in their accuracy could have large impacts on the quality of life of allergy-sufferers across Europe. It is only through developing a network of automatic pollen monitors across Europe that the full potential of these devices can be put to use in these models.

5.5 Building a prototype network and assessing impacts

The final step will be to establish a fully functional prototype network, bringing together all current and developing automatic pollen monitoring projects from across Europe. Participants will use knowledge established through the previous activities to better understand which technology is best adapted for their needs. They may also work together on joint projects, share experience and knowledge, and jointly develop infrastructure or tools, thus saving both time and money. Finally, it will be essential to evaluate the impact of the network and the improved information it provides on the quality of pollen forecasts, the services and new products made available to end-users, as well as on new research fields (e.g. plant and ecosystem sciences, phenology, etc.).

6 Synergies and collaboration with partners

Systematic pollen observations and related activities in the fields of public health, air quality modelling and forecasting, climate change assessment, etc., have a long history dating back to the middle of the twentieth century. There are established connections among the key players and the success of the AutoPollen programme depends on the involvement of these stakeholders, which include, amongst others:

- Copernicus Atmospheric Monitoring Service (CAMS; <https://atmosphere.copernicus.eu>) whose main objective is to provide operational forecasts and assessments of atmospheric state and composition. One of the major CAMS services is dedicated to European air quality, with pollen forecasting and assessment being one of the new frontiers (Sofiev et al. 2015, 2017; Sofiev 2019).

- The Cost Action ADOPT (new Approaches in Detection Of PaThogens and aeroallergens, CA-18226) brings together an interdisciplinary network of experts involved in bioaerosol measurements, whether it is with standard manual methods or upcoming technologies. A main objective of the action is to stimulate research and development of both observation methods and numerical methods for big data analyses. There are many parallels between AutoPollen and ADOPT, and there is tight collaboration between the two projects on research activities.
- The European Academy of Allergy and Clinical Immunology (EAACI; www.eaaci.org) is an association aimed at promoting basic and clinical research; collecting, assessing, and disseminating scientific information; functioning as a scientific reference body for other scientific, health, and political organisations; encouraging and providing training and continuous education; as well as promoting good patient care in this important area of medicine. EAACI members are historically at the origin of the development of pollen monitoring networks and key users of pollen data.
- Manufacturers of automatic pollen devices. There are several companies that produce such instruments, and it is a domain in constant evolution. AutoPollen has active connections with these businesses and their integration into certain of the programme's tasks, for example, the intercomparison campaign, is essential.

Other stakeholders include various United Nations organisations such as the World Meteorological Organisation (WMO), World Health Organisation, and UN Environment.

7 Perspectives for the future

AutoPollen will establish a prototype automatic pollen monitoring network, covering the entire information chain from helping to advance observation techniques through to the final products for end-users. This growing network will likely be of hybrid form, incorporating a range of different devices and types of sites, from stations with just one monitor to larger “supersites” where a number of monitors are placed together. Such a network will benefit from the

diversity of capacity across the different devices, helping, for example, to detect new species as climate change affects their ranges. AutoPollen will thus serve as a proof-of-concept and pave the way towards a sustainable automatic pollen monitoring network that provides data in near real-time to the public free of charge. The programme is particularly innovative in its cooperation and standardisation from-the-start approach, helping to prevent unnecessary duplication and harmonisation efforts in the future, and taking full advantage of shared expertise and best practices to make advancements for the benefit of all.

At present, pollen data are practically unavailable for the general public, as well as global programmes such as the WMO and WHO. The establishment of an automated monitoring network will facilitate the transition of pollen observations from privately run initiatives to part of the world-wide effort on environmental monitoring with clear financing schemes. This will ensure the long-term sustainability of observation networks, timely availability of information for end-users, and high temporal resolution data that will open up new research avenues, allowing a much deeper understanding of, for example, aerobiological processes. Furthermore, there is potential to use some of the same instruments for air quality observations, possibly providing further areas of synergy and cost reduction in the domain of atmospheric monitoring.

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