POTENTIAL OF SATELLITE IMAGERY FOR STUDYING THE SPATIAL DISTRIBUTION OF FOG AND ITS ROLE IN ATMOSPHERIC DEPOSITION

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ABSTRACT

Fog is important in that it contributes significantly to atmospheric deposition, especially in mountainous areas. The aim of this paper is to provide information on the possible use of satellite imagery for the analysis of spatiotemporal changes in the occurrence of fog and for determining the areas prone to fog in the Czech Republic. Satellite imagery is used to identify fog and determine its limitations. Both the advantages and limitations of this approach in determining patterns in the spatial distribution of fog are discussed. Finally, the improvements that can be expected in the understanding of the role of fog in atmospheric deposition processes are discussed. In this context, the identification of fog-prone areas and the estimation of their spatial extent, where the fog pathway can contribute substantially to total deposition fluxes, is of utmost importance.

Keywords: atmosphere; ground-based observations; hydrometeor; satellite data analysis; spatial coverage

Introduction

Fog is important in that it has significant effects on both human society and the environment (Croft 2003; Seinfeld and Pandis 2006; Weathers et al. 2020). Fog is a hydrometeor, which consists of a suspension of tiny water droplets that reduce horizontal visibility to less than 1 km (WMO 2017). Fog droplets are very small, typically less than 100 μm in size, which is much smaller than raindrops, which can be up to 6 mm in diameter (Pérez-Diaz et al. 2017). Fog is formed when moist air cools down and its temperature reaches or approaches the so-called dew-point temperature in the presence of a sufficient number of condensation nuclei. In terms of its formation, fog is further classified into radiation (Fig. 1), orographic (Fig. 2), advection and steam (Khoury et al. 2023). As it has adverse effects on all types of transport, fog is recorded worldwide by national weather services and much effort is invested in its forecast, which is still a challenge (Steeneveld et al. 2015). Long-term temporal trends in the incidence of fog are sometimes increasing and sometimes declining, although in general they are decreasing in most places due to rising temperatures associated with climate change and decreasing ambient air pollution caused by the introduction of more stringent air quality legislation and advanced technical countermeasures (Vautard et al. 2009; van Oldenborgh et al. 2010; Klemm and Lin 2016; Hůnová et al. 2020).

Fog formation is a very complex atmospheric process depending on numerous factors, such as synoptic situation, ambient air pollution, altitude, geomorphology and water availability in the landscape (Bruijnzeel et al. 2006; Gultepe et al. 2007; Hůnová et al. 2018, 2021a, b, 2022; Pauli et al. 2022, Walzelova et al. 2025). Both the physics and chemistry of fog are still not fully understood, and the contribution of fog to the water cycle and its effects on the environment are largely overlooked (Křeček et al. 2017; Palán and Křeček 2018; Hůnová et al. 2020). However, there is a general consensus that the role of fog in atmospheric deposition is very important for ecosystems, both in terms of water, nutrient and pollutant inputs

Fig. 1 Dense radiation fog persisting over several consecutive days in Czech lowlands, end of December 2024. This dense fog event was caused by a strong thermal inversion, trapping cold air under a "lid" of warmer air. Kokořínsko Protected Landscape Area, December 28, 2024 (photographer Iva Hůnová).

Fig. 2 Fog drip can substantially enhance the deposition fluxes of both nutrients and atmospheric pollutants, especially in mountain forests, where fog occurs frequently. Fog drip wetting ecosystems in the Jizerské hory Mts., autumn 2017 (photographer Iva Hůnová).

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(Weathers et al. 2020; Chang and Schemenauer 2021). This is particularly true in mountain regions, where fog (or clouds at ground level) occurs frequently throughout the year (Fig. 2). Furthermore, it is reported that fog is more polluted than rain in the same region, which results in a significantly higher input of air pollutants (or nutrients) into fragile mountain ecosystems (Thalmann et al. 2002; Zimmermann and Zimmermann 2002; Lange et al. 2003; Blas et al. 2010).

The occurrence of fog is regularly reported by weather services around the world (Gultepe et al. 2007), either by professional observers or by PWD sensors (Present Weather Detectors). In addition to the reporting of the frequency of fog the density, physics and chemistry of fog have been studied both experimentally and in the field. However, these studies are for particular localities or small geographical areas. In order to estimate the contribution of fog to atmospheric deposition, there is an urgent need to know not only point-wise data on fog occurrence, but also how fog occurrence changes in time and space, which areas are prone to fog formation, and generally, to understand the spatial occurrence of fog. Exploring the spatial behavioral patterns of fog is challenging for many reasons (Hůnová 2024), but recently remote sensing has emerged as a promising tool for determining changes in the occurrence of fog in time and space using satellite images (Bendix 2002; Cermak 2018; Egli et al. 2019; Pauli et al. 2024). The aim of this paper is to summarise how satellite imagery can improve our knowledge of fog behaviour and its role in atmospheric deposition.

Satellite imagery

Satellite imagery has proven to be a very efficient tool for studying our environment and greatly improving our understanding of many phenomena previously based exclusively on ground measurements and observations (Burke et al. 2021). When using satellite imagery for exploring the Earth surface properties (such as in ecosystem studies, environmental conservation, urban planning, forestry, agriculture, etc.), the presence of atmospheric phenomena (such as clouds, atmospheric aerosols, etc.) often negatively affect satellite images, so efforts are needed and numerous corrections made to eliminate their effect (Stamnes et al. 2005; Li et al. 2022). However, here the challenge is different. Unlike studies of relatively stable objects on the Earth's surface, where the removal of "atmospheric contamination" is of the utmost importance, the study of fog involves observing a rapidly changing situation in time and space that needs to be recorded in detail. Satellite imagery is already used for weather analysis and forecasting, frequently in combination with other advanced approaches, such as machine learning and deep learning methods, a part of artificial intelligence, consisting mostly of artificial neural networks inspired by the functions of neurons in the human brain (Moskolai et al. 2021; Lara-Alvarez et al. 2024; Upadhyay et al. 2024). Although conventional methods for observing fog provide high-precision records of their occurrence, deficiencies in their spatial occurrence has led to research since the 1970s into the possibility of identifying fog using satellite imagery (Yao et al. 2025). So far, satellite imagery has resulted in a better identification of the fog life cycle, especially the spatio-temporal patterns of fog, although there are still issues to be addressed to refine this approach. Among the most important are: (i) the difficulty of distinguishing fog touching the ground from low stratus clouds which can be located even several hundred meters above the ground, (ii) the reduced accuracy in detection of fog and low stratus clouds (FLS) at night, and (iii) the need for ground-based validation and advanced classification methods to improve detection reliability (Bendix 2002; Bendix et al. 2005; Bendix et al. 2006; Cermak et al. 2008; Andersen and Cermak 2018; Egli et al. 2019; Pauli et al. 2022; Pauli et al. 2024).

Satellite products suitable for studying fog

A number of satellite products (processed and derived information extracted from satellite imagery) are available for the identification and analysis of fog, each with different advantages and limitations. One of the key instruments for detecting fog over Europe is the Spinning Enhanced Visible and Infrared Imager (SEVIRI), on board the Meteosat Second Generation (MSG) satellites.

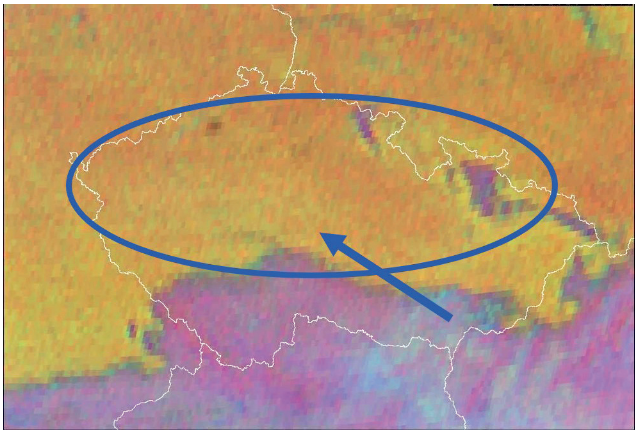

Fig. 3 Fog and low stratus clouds appear in yellowish hues, highlighting areas where these atmospheric conditions are present in the SEVIRI 24-hour Microphysics RGB imagery.

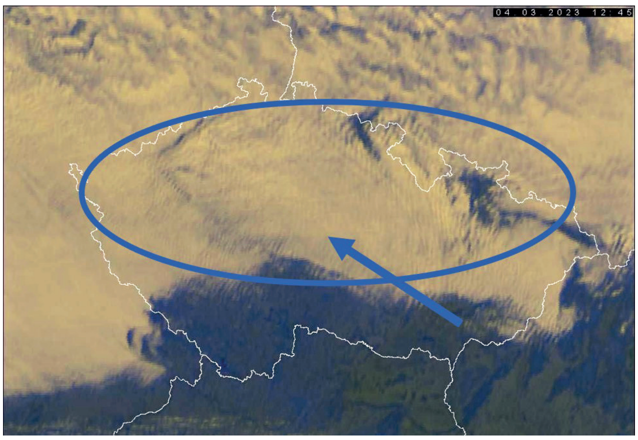

Fig. 4 Olive green areas represent fog or low cloud in the VIS-IR imagery during daytime.

One of the most widely used products for monitoring FLS is 24-hour Microphysics Red, Green, Blue (RGB). In this imagery, FLS appear in yellowish hues (Fig. 3) and therefore are easily tracked continuously during the day and night. Another useful SEVIRI product is High-Resolution Visible (HRV) Fog RGB imagery, which depicts FLS in shades of pink, which enhances the clarity of daytime assessments. In addition, the Visible-Infrared (VIS-IR) RGB combination for FLS detection is available and the HRV SEVIRI channel has a higher spatial resolution, FLS are depicted as olive green (Fig. 4), which is very different from the pinkish colours used in HRV fog-detection system.

This sensor offers a very high temporal resolution with one scan every 15 minutes and a nadir spatial resolution of 3 km (HRV channel 1 km), which makes it ideal for recording the spatiotemporal variability of fog. The nadir spatial resolution is an important term in satellite imagery, which refers to the point on the Earth's surface located vertically below the centre of the system, where the finest resolution of satellite imagery occurs. The FLS detection technique proposed by Andersen and Cermak (2018) uses the satellite-based thermal infrared data from the SEVIRI satellite, which enables the continuous and diurnal identification of FLS (Cermak and Bendix 2008; Egli et al. 2019).

VIS-IR imagery is more effective at detecting fog than 24-hour Microphysics RGB imagery. This is mainly because VIS-IR provides better resolution and contrast and can better distinguish fog from other types of cloud. The combination of visible and infrared channels in VIS-IR improves the ability to identify fog based on its specific thermal and reflective characteristics (Ellrod 2002; Cermak and Bendix 2008). In contrast, 24-hour microphysical RGB imagery uses a broader spectral range, which can sometimes mask the subtle differences between fog and other low-level clouds (Cermak and Bendix 2008).

Other satellite sensors suitable for detecting fog are the Moderate Resolution Imaging Spectroradiometer (MODIS) on the National Aeronautics and Space Administration's (NASA) Terra and Aqua satellites. This sensor returns visible and infrared data with an up to 1 km spatial resolution. The MODIS products are widely used for daytime identification of fog, since they can distinguish fog from other cloud types based on their optical characteristics (Cermak and Bendix 2008). Similar to other sensors, the Visible Infrared Imaging Radiometer Suite (VIIRS) onboard NOAA's polar-orbiting satellites is limited in its ability to track fog dynamics, as its data are available only for long periods of time. In addition to the straightforward use of SEVIRI imagery, a Self-Organizing Map, SOMs (Egli et al. 2019) has been used for the thorough analysis and classification of fog patterns derived from satellite data. SOMs belong to a category of artificial neural networks developed for reducing the dimensional complexity of complex datasets, such as the satellite-derived fog frequency maps (Hewitson and Crane 2002; Liu and Weisberg 2011). Every neuron in the SOM represents a particular pattern related to fog, while the neighbouring neurons in the SOM grid reflect similar situations regarding fog, which helps in finding transitions between different states of fog. The additional value of this approach is the classification of fog into different classes; it allows identification of persistent patterns of fog and their linkage to meteorological conditions (Egli et al. 2019). Furthermore, unlike traditional clustering methods, SOMs allow for variations in cluster sizes, making them particularly suitable for meteorological applications in which fog occurrence is highly spatially heterogeneous (Tambouratzis and Tamboutratzis 2008).

In addition, satellite fog detection is very often complemented by ground-based validation networks that provide ground-level observations of fog patterns. These ground-based measurements are used to validate and refine the accuracy of satellite-derived products of fog. For example, the FLS detection method based on SEVIRI was compared to surface net radiation measurements, which is another demonstration of its accuracy and suitability for studying fog (Egli et al. 2019).

What improvements can be expected from using the satellite approach?

The occurrence of fog is regularly observed at the professional weather stations. However, these regular observations of fog occurrence carried out at professional weather stations provide an information of a strictly point-wise character (Tolasz et al. 2007), representing only a close (and not clearly defined) area around the observer standpoint. Large areas between the weather stations are not observed at all. Although fog can be easily detected using ground-based observations, observing sites are sparse and therefore fog is missed in unobserved areas or in vertical profile (Izett et al. 2019). By contrast, the use of satellite retrievals allows us to obtain information even for these unobserved areas, and we are able to get a clear picture of the real spatial pattern of fog formation.

An example for all: in the Czech Republic we have a professional weather station Churáňov assumed to observe the whole of the Šumava mountain range, which covers about 1600 km^2, including the largest national park in the CR, which extends over 680 km^2. When we observe fog formation in Churáňov, we do not know exactly how far the fog (when observed) extends, and how large area it covers. However, from the satellite images we can see the larger area where fog is present, which is exactly what we need to know in terms of atmospheric deposition fluxes in order to understand in what areas the fog deposition pathway can contribute significantly to total deposition with potential harm effects to sensitive mountain ecosystems.

It is known that fog formation can be a very local phenomenon, showing a distinct and steep horizontal gradient (Hůnová 2024). In contrast to point-wise observations, satellite imagery provides valuable information of a spatial character, allowing us to study fog patterns over the whole regions (Pauli et al. 2024). In addition, satellite images provide more frequent temporal information, with retrievals every 15 minutes of the day, allowing us to observe fog virtually live: we can closely follow each fog event formation, its evolution, its movements and, finally, its dissipation (Andersen and Cermak 2018).

Thus, development of satellite sensors, such as SEVIRI and MODIS, which provide finer spatial resolution (3 km) and high temporal resolution (15 minutes scans) offering continuous area coverage, get around the drawbacks of point-wise ground fog observations. Furthermore, more precise identification and classification of fog patterns and their dynamics in connection to meteorological conditions are made possible by enhanced detection algorithms and machine learning techniques, such as SOMs. The development and spatial diversity of fog events may now be captured in far more detail thanks to technological advancements.

What improvements can be expected in the understanding of the role of fog in atmospheric deposition?

The use of satellite imagery can greatly improve the understanding of fog formation and could become the main way of identifying fog-prone areas where increased deposition fluxes via fog can be expected. Pauli et al. (2022) have recently identified patterns in fog formation and dissipation in Central Europe, based on a ten-year dataset. These spatial patterns reveal the important influence of the underlying topography. In addition, knowledge of the topography of a specific region can be used to identify the type of fog, radiation (in lowlands) or orographic (a cloud "sitting" on the top of a mountain), which are the most frequent types of fog occurring in Central Europe (Pauli et al. 2022). We are not able to distinguish between these different types directly from photographs (Figs 1 and 2) or satellite images. However, in combination with knowledge of the underlying terrain, this differentiation is possible.

These fogs differ in their chemistry (Hůnová 2024). Radiation fogs forming in lowlands are less frequent than orographic fogs forming in the mountains but are more contaminated as they originate in more polluted parts of the atmosphere, directly influenced by the Earth's surface (Burkard et al. 2003; Blas et al. 2010; Michna et al. 2015). For example, in Poland, Blas et al. (2010) report 3–4 times higher total inorganic ion content and even 3–6 greater total dissolved pollutant load in radiation fog than in orographic fog in the Polish part of the Giant Mts.

Although this difference in the chemical composition of radiation and orographic fog may be smaller in countries with less polluted air than Poland, it is reasonable to assume that this is a general relationship. However, in spite of their cleaner character, orographic fogs in mountains are assumed to contribute significantly more to deposition fluxes of environmentally relevant substances due to their higher frequency and presumably much larger water volume. The use of satellite imagery to observe the spatial patterns of fog in much greater detail (Fig. 5) than has been possible up to now, can reduce the underestimation of deposition fluxes in mountain regions and make them more suitable for ecological and environmental studies.

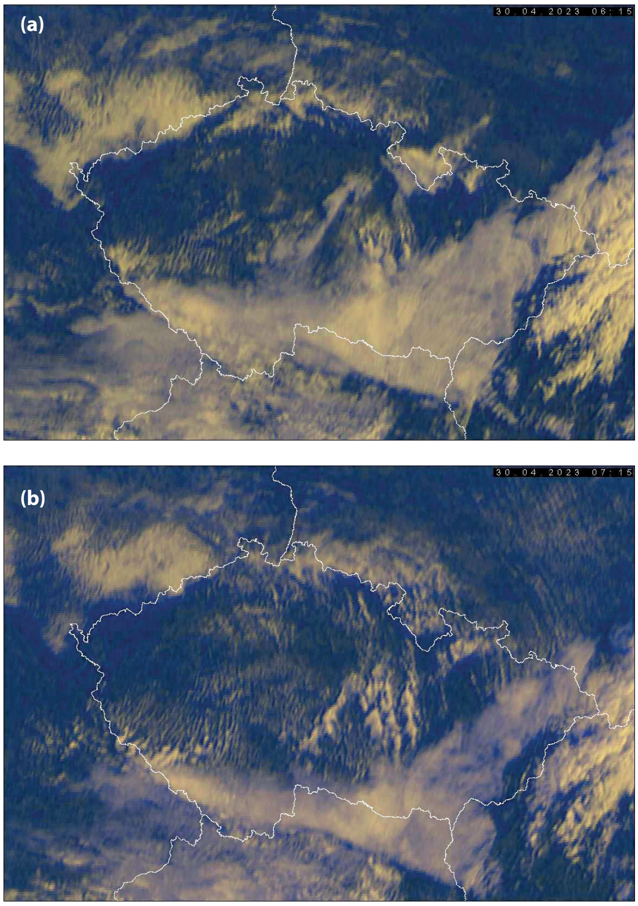

Fig. 5 VIS-IR satellite imagery showing the development of fog (olive green colour) over the Czech Republic, April 30, 2023, 6.15 a.m. (a), and 7.15 a.m. (b).

Limitations that must be accounted for

Satellite fog detection also has some limitations and drawbacks, such as the problem of distinguishing fog from low stratus clouds using thermal infrared imagery. The thermal properties of FLS are very similar, making it rather complicated for satellite sensors, such as SEVIRI and MODIS to distinguish between them (Bendix et al. 2005). Both fog and low stratus clouds have similar radiative properties in the thermal infrared spectrum, which is a common reason for misclassifying low stratus as fog and vice versa (Egli et al. 2019). When low stratus layers are directly over the surface, they tend to resemble closely the radiative characteristics of fog. Many methods have been proposed for addressing this limitation, including combining satellite data with ancillary information, such as surface observations, knowledge on underlying terrain, or using sophisticated machine learning techniques. However, distinguishing between the two still remains a significant task, especially when the auxiliary data are not available and we have to rely solely on satellite imagery (Cermak and Bendix 2011).

Another notable constraint of satellite-based fog detection is its reduced accuracy at night. In daytime, the detection of fog is enhanced by the use of data from the visible spectrum, which helps in the differentiation between fog and other hydrometeors. Conversely, at night, the absence of visible channels necessitates reliance exclusively on thermal infrared data (Bendix et al. 2006; Andersen and Cermak 2018). Night time detection is generally less accurate than that recorded during the day, because fog and surrounding surfaces, which also include low-lying clouds, often have similar thermal signatures, which make distinguishing between them even more difficult (Ellrod 1995). It follows that satellite sensors cannot rely on the unusual optical properties of fog in the visible spectrum that are particularly helpful during daytime.

In addition, nocturnal cooling of the surface may facilitate the development of fog; however, identifying this is often more difficult when relying solely on thermal infrared channels (Bendix et al. 2006). In various studies (Bendix et al. 2006; Egli et al. 2019) fog detection at night is reported to be very uncertain and requires additional information to improve the accuracy, such as temperature inversions and humidity profiles. SEVIRI's thermal infrared channels, while helpful in monitoring fog, are less effective at detecting fine-scale fog features at night, compared to when the combined use of visible and infrared data is used during the day (Cermak and Bendix 2011). Consequently, the reliance on thermal imagery alone leads to a higher likelihood of misclassification or under-detection of fog during night-time (Ellrod 1995).

Conclusions and future outlook

Satellite imagery has several advantages over the point-wise observations of fog currently routinely carried out at professional weather stations. These include continuous regional coverage, the capacity to record spatial variability, higher temporal resolution with frequent (15 min) retrievals and an enhanced ability to track the entire fog life cycle. The use of satellite images allows the study of spatial changes in fog formation at much finer temporal resolutions, which can significantly improve the understanding of fog formation and related atmospheric processes. The identification of fog-prone areas can help identify the areas where deposition fluxes of environmentally important substances have so far been underestimated or even neglected. The subsequent potential multi-step approach for fog deposition estimation in future should be based on the combination of measured and observed results from satellite imagery, ceilometers, LiDAR sensors, ground-based measurements of meteorology and air pollution, including the chemistry of fog droplets, allowing inference of both fog water volume and its chemical load, which in combination should result in fog deposition fluxes of individual chemical species. Combining knowledge of all the deposition pathways, i.e. dry, wet vertical and occult (including fog), will result in the more reliable input information needed for a better technique for accurately quantifying atmospheric deposition, which is necessary for both ecological and environmental studies.

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