



Long-term Changes in Fog Frequency at Swedish Airports and its Potential Drivers

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Abstract. Fog is a major hazard at airports that can result in delays, financial losses and even fatal accidents. In this study we have investigated changes in fog occurrence at 12 Swedish airports from the 1970's to 2022. In this study we have utilised meteorological data from the airports, sulphate data from five measurement stations in Sweden and sulphur dioxide emissions data over Europe. The meteorological data consist of recordings of visibility, temperature, pressure, dew-point temperature, wind speed, and wind direction.

The results show that fog frequencies at airports in southern Sweden have decreased by about 50 % when comparing the periods before and after the year 2000. The decline is primarily associated with fog occurring at wind speeds above 2 ms^{-1} , that is, advection fog. Our investigation indicate that these changes are driven by decreasing concentrations of aerosol particles. At the airports in the mid-Sweden, we do not find any changes in fog frequency. This is also true for two of the airports in northern Sweden. Nevertheless, three airports in northern Sweden are experiencing increasing fog frequencies. For two of these airports, this is an increase in radiation fog during late summer and autumn. We find this to be coupled to increased moisture transport from warming rivers adjacent to the airports, in combination with low wind speeds. For the third airport, warmer air temperatures, coupled to climate change, can explain the weak increase in the fog frequency. Thus, both climate change and decreasing air pollution impact fog formation at Swedish airports.

1 Introduction

Clouds in contact with the ground are classified as fog and can decrease visibility down to tens of meters. Reduced visibility is often defined as fog when the horizontal visibility at surface is below 1000 m (e.g. WMO, 2019). Low visibility at ground level can have a substantial impact on society, in particular on transport (Gultepe et al., 2007). Reduced visibility affects transport on roads, rails, and water, but also air traffic is substantially impacted, since good visibility conditions are required for take-off and landing. Fog can cause great economic losses for the aviation industry (Kulkarni et al., 2019) due to flight delays, diversions, and cancellations, and can ultimately result in loss of human lives.

Fog forms in a variety of conditions, but generally requires air to be cooled down or acquiring additional water vapour (Koračin and Dorman, 2017). Radiation fog is one of the most common types of fog. It occurs when the ground cools due to radiative loss and reduces the temperature of the air closest to the ground (Roach et al., 1976). This type of fog requires low



25 wind speeds to prevent mixing of the cool air at ground level with the warm air above fog (Duynkerke, 1991). Radiation fog
therefore often forms during clear, calm evenings or nights and is often dispersed in the morning when the solar radiation starts
warming the surface and induces mixing. Another common fog type is advection fog, which forms when warm, moist air is
advected over a cooler surface (Gultepe et al., 2007). This causes a cooling of the bottom part of the air-column which can lead
to fog formation. Advection fog is often formed when warm moist air from the ocean is transported in over cold land surfaces
30 in autumn or winter. Since this type of fog is dependent on the transport of air, it persists as long as there is ongoing advection
and therefore often have longer lifetimes than radiation fog. Wind speed is often used to classify whether the fog is advection
fog or radiation fog. There is no strict set wind speed limit between the two fog types but values between 2 and 2.5 ms⁻¹ are
often used (e.g. Román-Cascón et al., 2016; Hao et al., 2024; Tardif and Rasmussen, 2007)

Fog forms when the relative humidity (RH) increases and water vapour condenses onto aerosol particles, increasing their size.
35 Cloud droplets are generally considered to form when aerosol particles are activated, i.e., have grown through condensation
past the critical diameter of activation, or passed the level of critical supersaturation in the Köhler curve (Köhler, 1936). When
the aerosol particles have been activated they grow rapidly, limited only by the available water vapour (Lohman et al., 2016).
Fogs form similarly to other clouds, but studies have found that fog can consist of unactivated aerosol particles that have grown
enough through condensation to substantially reduce visibility but not to pass the critical diameter of activation (Frank et al.,
40 1998; Klemm and Lin, 2016).

Since all cloud droplets form on aerosol particles, the particle concentrations and composition can substantially impact
cloud properties. A higher number of aerosol particles in the air results in clouds with more but smaller droplets compared to a
cloud formed in air with lower aerosol number concentrations (Twomey, 1974). Clouds with many small droplets have a larger
surface area and cause more light reflection. Also fog that form in aerosol rich environments tend to contain a greater number
45 of smaller droplets (Klemm and Lin, 2016) and increasing RH would reduce the visibility more in aerosol rich environments
compared to environments with lower aerosol particle concentrations (Gultepe et al., 2006; Stolaki et al., 2015). Moreover,
different types of aerosol particles have different hygroscopicity and can attract water vapour through condensation at different
RH (e.g. Swietlicki et al., 2008). Very hygroscopic aerosol particles can take up water at lower RH than less hygroscopic
aerosol. High levels of hygroscopic particles can therefore lead to reduced visibility at lower RH than if less hygroscopic or
50 very few aerosol particles are present in the air (Klemm and Lin, 2016). Sulfuric acid, nitric acid, ammonia and sea-salt particles
are considered highly hygroscopic and have been found to act as seeds for fog droplets (Bai et al., 2018; Gilardoni et al., 2014;
Ebert et al., 2002). Both the particle concentrations and the particle composition can thus impact the RH at which fog is formed.
Nevertheless, a study on aerosol impact on fog microphysics revealed that the size distribution of aerosol particles was more
important than aerosol composition in determining activated fraction of the available aerosol particles (Mazoyer et al., 2019).

55 Changes in fog frequency have been reported from various regions of the world. Several studies have found fog frequency
to be decreasing in Europe (Vautard et al., 2009; Van Oldenborgh et al., 2010; Hůnová et al., 2022; Giulianelli et al., 2014).
Similar trends has been seen over parts of North America (LaDochy and Witiw, 2012; Baldocchi and Waller, 2014; Hanesiak
and Wang, 2005; Forthun et al., 2006). Other parts of the world, such as India and China, have instead seen an increase in fog
events (Niu et al., 2010; Smith et al., 2023; Kutty et al., 2020). Many studies try to determine the factors driving the changes



60 in fog frequency, which vary between studies and locations. The drivers of changes in fog frequency vary with location but
include modifications in meteorological conditions (LaDochy and Witiw, 2012; Kutty et al., 2020) often associated with climate
change or urbanisation. Other common drivers are changes in aerosol loading (Vautard et al., 2009; Van Oldenborgh et al.,
2010; LaDochy and Witiw, 2012) and alterations in large-scale atmospheric circulation patterns (Niu et al., 2010; LaDochy
and Witiw, 2012). Commonly, several of these drivers simultaneously contribute to changes in fog frequency (Smith et al.,
65 2023; Van Oldenborgh et al., 2010; Niu et al., 2010; Hůnová et al., 2018; Bokwa et al., 2018).

Sweden is an elongated country in northern Europe that extends far in the north-south direction. The northernmost parts of
Sweden are located inside the polar circle and experience long winters with rather short and cold summers. The southernmost
parts of Sweden are located close to continental Europe and have mostly snow-free winters and average summer temperatures
between 15-20 °C. Swedish weather is dominated by the west-wind belt with frontal systems and cyclones approaching from
70 the west (e.g. Chen, 2000). Westerly and South-westerly are the most common wind directions in most of Sweden (Achberger
et al., 2006). Nevertheless, high pressure systems over Eastern Europe occasionally dominate the weather in Sweden, often
bringing calm weather and south-easterly winds (Linderson, 2001). Temperatures are on the rise in Sweden, just like in most
of the world. Comparing the periods 1991-2020 with 1961-1990 the temperatures in most of Sweden changed between 1.0 °C
and 1.5 °C (SMHI, 2012). The temperature increase was larger in winter than in summer, particularly in Northern Sweden.
75 Not only the climate in Sweden is in transition - air pollution levels have declined dramatically in Sweden over the past 50
years, in particular in southern Sweden (Lövblad et al., 2004). This is primarily a result of decreasing emissions of pollutants
in continental Europe with changes in the sectors south of Sweden impacting Swedish air pollution the most (Lövblad et al.,
2004; Amann, 2001). Thus, aerosol particle concentrations and meteorological conditions, both important for fog formation,
have changed since the 1970's.

80 In this study we investigate changes in fog occurrence at Swedish airports during more than 50 years. For this, we use
visibility data recorded at 12 Swedish airports, from southern to northern Sweden. The aim of our study is to investigate
whether the fog frequency at Swedish airports has changed and which factors that drives changes in fog frequency at Swedish
airports. To achieve this, we investigate temperature, wind speed, wind direction, pressure, and RH, recorded at the airports.
Moreover, to investigate possible aerosol particle influence on fog, we use measurements of sulphate aerosol at 5 stations across
85 Sweden and emissions of the aerosol precursor SO₂ over Europe.

2 Method

In this study, we mainly rely on measurements of meteorological parameters at Swedish airports, which is described in the
first, followed by descriptions of the aerosol sulfate data and the SO₂ emission data over Europe.

2.1 Meteorological Data

90 We have utilised meteorological data from 12 airports across Sweden. The data is provided by the Swedish Meteorological
and Hydrological Institute (SMHI) database (<https://www.smhi.se/data/hitta-data-for-en-plats>). To enable studies of long-term



Figure 1. Airports (black) and SO_4^{2-} measurement stations (magenta) included in the study.

changes in fog frequency, we required each airport to have at least 40 years of visibility data with a substantial amount of data from both the early and late time span of the investigation. We initially looked at data from 26 airports, but only 12 of these were included in the study. Excluded airports did not have long enough data records of visibility. Airports were also excluded because the airport and the instrumentation had moved substantially and did not provide continuous measurements from a single location. The airports included in the study are shown in Fig. 1.

From each airport, we investigated visibility, temperature, wind speed, wind direction, pressure, and RH calculated from dew point temperature data. These measured variables' time resolution differ between airports and time periods, between 6-hour, 3-hour and hourly resolution. Moreover, the datasets from SMHI are provided with two quality flags. The green flag indicates that data have been quality controlled and are approved. The yellow quality flag indicates that data can be suspicious or aggregated. It contains roughly checked archive data. There is also a red quality flag but data with this flag are not shared by SMHI. The quality control has been applied with different frequency during different time periods. Prior to 2010 green flagged



data is available at a 3-hour resolution while after 2010 green flagged data is provided at hourly resolution. We cannot compare datasets with different time resolution for different time periods. We have therefore created one dataset with 3-hour resolution that includes data with green quality flags. However, to obtain a higher time resolution and a longer data coverage, we have included data with the yellow quality flag at hourly resolution. These datasets most often display similar results. Many airports are missing more than 10 years of data between 1995 and 2007. During this period, visibility data from some of the airports were not reported to SMHI.

All meteorological variables used in the study are direct measurements of the variable, except for RH, which was calculated from the dew point temperature. There were RH data measured at some of the airports during certain time periods. However, since there was better data coverage from the dew point temperature measurements, we decided to use these and calculate the RH from the dew point temperature and temperature.

2.1.1 Sulphate and sulphur dioxide data

In this study, we include daily measurements of SO_4^{2-} in aerosol samples from five Swedish stations. The data was measured by the Swedish Environmental Institute and is provided by SMHI through the service "Datavårdskap luft" (<https://datavardluft.smhi.se/portal/>). Since the airports included in the study are all located outside of major cities, we only used aerosol measurement stations classified as rural or rural-regional. Moreover, we included only measurement stations with data coverage of more than 30 years, including substantial amounts of data both before and after 1995. Such long-term SO_4^{2-} measurements are rare but five datasets are used in the study. One of the datasets used is a combination of data from two measurement stations. Measurements were taking place at the Rörvik measurement site from 1977 to 2001 and were then continued 3 km south of Rörvik at Råö measurement site. We combined data from these two sites into one joint dataset. The locations of the SO_4^{2-} stations are marked with magenta dots in Fig. 1. Southern Sweden have a better coverage by these stations compared to the north, where only one station is located. However, the stations in southern Sweden are located closer to major sources of sulphate aerosol (SO_2 emissions) and the concentrations are thus expected to vary more in southern Sweden. Nine of the airports included in the study have an SO_4^{2-} measurements station located within 200 km distance from the airport.

To complement the SO_4^{2-} measurements we have used a dataset of SO_2 emissions - the EDGAR v6.1 Global Air Pollutant Emissions dataset (Crippa et al., 2026). We used annual averaged emissions files with $0.1^\circ \times 0.1^\circ$ resolution and focused our study on the emissions over Europe.

2.2 Statistical methods

Due to the missing meteorological data for several airports for major parts the middle of the study period (1995-2010) a linear trend could not be validated from observations. Thus, to assess temporal changes in fog frequency, with minimal assumptions, we applied two-sample t-tests to compare mean annual fog frequency, defined as the frequency of 3-hour observations with fog, between an early period (1970–1999) and a late period (2000–2022). Results are reported as 95% confidence intervals for average difference and corresponding p-values; no correction for multiple testing was applied. Annual means were used in



order to reduce the effects of serial correlation in the underlying time series. Model validation confirmed that the assumptions of independent errors and normality were satisfied. In line with current recommendations for statistical reporting, inference is framed in terms of effect estimates, confidence intervals, and the strength of evidence provided by p-values, rather than binary significance thresholds.

140 3 Results and Discussion

3.1 Fog Occurrence

We will start by discussing the general condition in which fog forms and how this varies between the airports included in the study. Figure 2 displays the average number of fog hours per year for different values of meteorological and temporal variables. The results from airports (on the x-axis) are displayed from south to north from left to right. It is evident that fog is most common at the airports in southern Sweden. From Fig. 2a it can be seen that fog is most commonly formed at temperatures
145 most common at the airports in southern Sweden. From Fig. 2a it can be seen that fog is most commonly formed at temperatures between $-5\text{ }^{\circ}\text{C}$ and $10\text{ }^{\circ}\text{C}$. Nevertheless, at some airports located in the north (Östersund-Frösön and Luleå) fogs are also formed at temperatures lower than $-5\text{ }^{\circ}\text{C}$.

Fog generally forms at relatively high surface pressures (1005 - 1030 hPa), in particular in southern Sweden (Fig. 2b). High pressure weather conditions with calm winds are required for fog formation, in particular radiation fog. Further north in
150 Sweden, the pressure during the fog events is somewhat lower. The RH at fog formation is predominately above 95 %, (Fig. 2e). Most airports have the majority of fog occurrence at 99-100 % RH but it is not unusual that fog occurs at lower RH than this. At Göteborg-Landvetter airport the most common RH for fog formation is 96-97 %.

At most airports, fog is most common at low wind speeds ($0\text{-}2\text{ ms}^{-1}$), see Fig. 2c. This is expected, since radiation fog mostly forms during conditions with low wind-speed and this is the most common fog type over land (Gultepe et al., 2007).
155 For some airports in the south, in particular at Malmö Airport and Göteborg-Landvetter Airport, fog often occur at slightly higher wind speeds than this ($2\text{-}6\text{ ms}^{-1}$). Thus, advection fog is more common there compared to the other airports, as seen in Fig. A1, where the annual fog frequency for advection fog (wind speeds $> 2\text{ ms}^{-1}$) is shown. In Sweden, the source of warm moist air during advection fog is primarily the North Sea and Kattegatt, located west of southern Sweden. Both Malmö and Göteborg-Landvetter are favourably located to receive airmasses originating from this direction. Notably, Ängelholm Airport is
160 also located in the same region but does not experience as much advection fog (Fig. A1). A plausible reason is that Ängelholm Airport is located only kilometres from the ocean (see Fig. 1). The close proximity to the ocean hinder advection fog formation since there would not be sufficient cooling from below of the warm marine air masses before they reach the airport. For airports further east and north in Sweden, the air masses from the North Sea need to travel over a mountain ridge or over large land areas, which change the air mass properties and make advection fog less likely to form.

The dominant wind direction during fog formation varies between the airports. For wind speeds equal to zero, the wind direction is not included in the analyses. This means that there is less fog data included in Fig. 2d compared to the other sub-figures. For the 4 southernmost airports, it is noticeable that fog most commonly form when the wind direction is between $90\text{-}270\text{ }^{\circ}$. This is in particularly visible in Fig. A2e which is similar to Fig. 2e but showing the relative distributions of fog

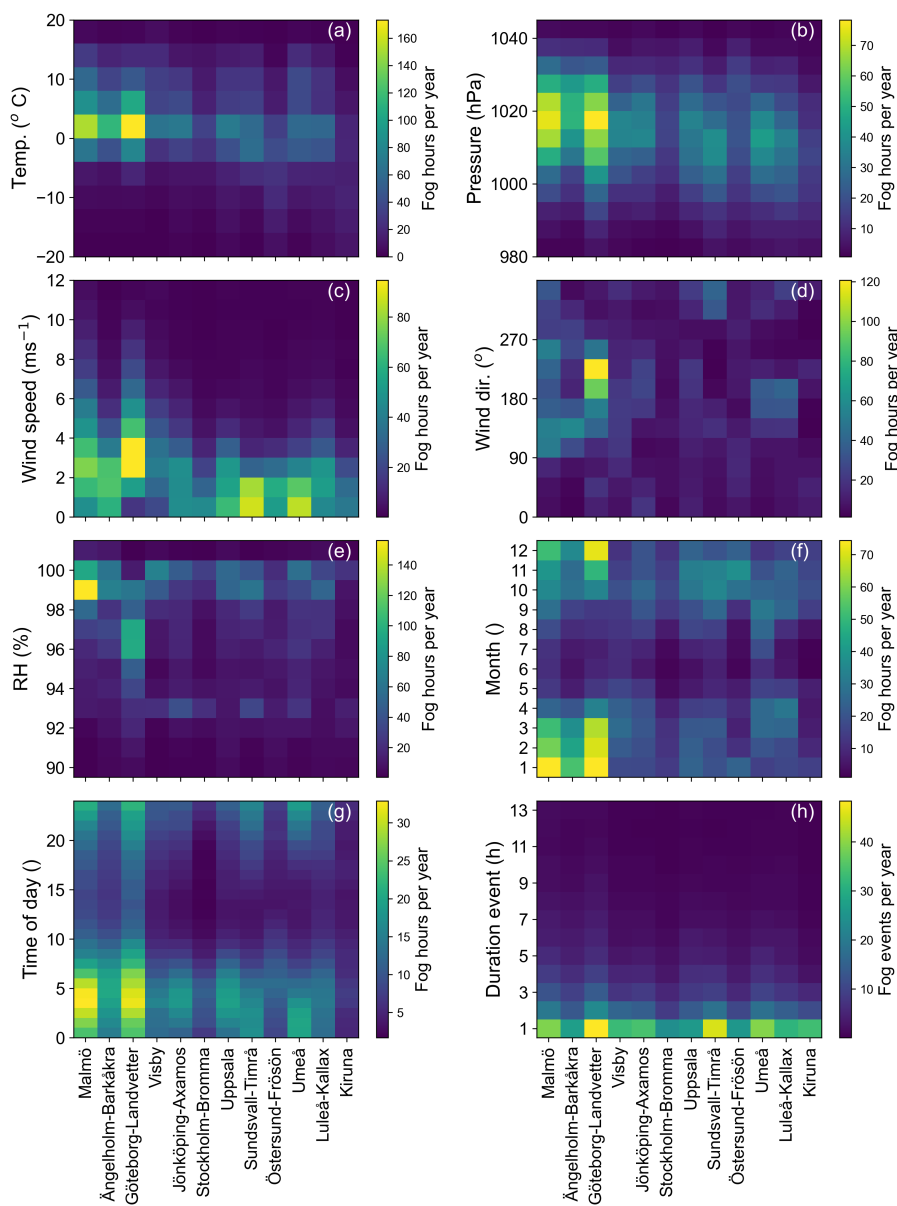


Figure 2. Histograms of number of fog hours per year for different meteorological and temporal conditions for the different airports. The airports are ordered according to their latitudes with the southernmost airport located furthest to the left on the x-axis. The data with one-hour resolution is used in this figure.

170 observations rather than absolute ones. Both Fig. 2e and A2e show that fog at Göteborg-Landvetter Airport is particularly common during south westerly winds. More than 40 % of the fog formation at this airport occurs in wind directions between 180 and 240 °. For the airports further north, the fog occurrence is in general not as strongly dependent on wind direction,



but in Sundsvall, fog is more common when there are northerly winds while in Umeå and Luleå-Kallax airports fog is more common when the winds are coming from the south.

175 Fog is most often formed during the winter and at nighttime. Figure 2f shows that for most of the southern airports, fog forms primarily during October to March, while at the airports further north, fog formation become common earlier in autumn and last longer into spring (Fig A2f). The nighttime temperatures become cooler earlier in autumn and stay cool longer in spring at the airports in the north. At most airports, fog is most common between 3 am and 6 am (A2g), but the fog often starts forming already in the evening and can last until 10 am. The most common fog duration is one hour (i.e. a single observation), although airports with the highest fog frequencies also experience a substantial number of longer-lasting fog events (Fig. 2h).

180 3.2 Variation over Time

We will now turn our attention to changes in fog occurrence over time, with a focus on decadal changes. In Fig. 3, the annual fog frequencies at the airports are shown. Airports are ordered from the southernmost at the bottom to the northernmost at the top, revealing higher fog frequency at southern locations compared to northern ones. Malmö Airport and Göteborg-Landvetter Airport display the highest fog frequencies, reaching up to 9% during the 1970's and 1980's. In the winter data these values reach over 20 % (not shown). Also Ängelholm airport had fog frequency well above 4 % for multiple years in the 1970's and 1980's, while most airports have annual fog frequencies between 2-4 %. The annual fog frequencies vary substantially, but for the three airports with the highest fog frequencies, the extreme years are identical. This indicates that it is large scale weather situations that are driving the variability in the annual fog frequency. Data is missing from many airports between the years 1995 and 2007 since the airport data was not reported to SMHI.

190 The results from the airports in southern Sweden show a decrease in fog frequency from the 1970's and 1980's to present day, Fig 3c. Due to missing data in the late 1990's and early 2000's it is hard to do a trustworthy trend analysis. We instead compare the years before 2000 with the years after. For the four southernmost airports, the estimated changes in fog frequency are all negative, with p-values (Malmö Airport $p < 0.0001$, Göteborg-Landvetter Airport, $p < 0.0001$, Ängelholm Airport $p = 0.0001$, and Visby Airport $p = 0.01$) indicating strong evidence for a decrease in fog frequency between the two periods, see Table 1. 195 In contrast, for the airports in Fig. 3b, as well as Östersund-Frösön Flygplats in Fig 3c, p-values exceed 0.3, providing little evidence against the null hypothesis, so even the direction of change remains uncertain. Finally, for the northernmost airports (Fig. 3c), several airports show higher fog frequencies during the years after 2000. The changes in Umeå ($p = 0.0008$) and Sundsvall-Timrå Airport ($p = 0.005$) provide strong evidence for an increase in fog frequency. For Kiruna Airport, which has one of the lowest fog frequencies, there is a slow increase in fog formation over the years, though the evidence of a difference 200 between periods is moderate ($p = 0.06$).

We have also studied how other meteorological parameters have changed over the years. For the yearly average temperature, we see an increase at all airports (Fig. 4). The temperatures are in general higher at the airports in southern Sweden with average temperatures between 5 °C and 10 °C, while the annual average temperatures in the north is between 0 °C and 5 °C at most airports. Kiruna Airport is substantially colder than the other airports during the entire period and has annual averages 205 between -4 °C and 1 °C. There is a slightly larger temperature increase at the airports in the north compared to those in the

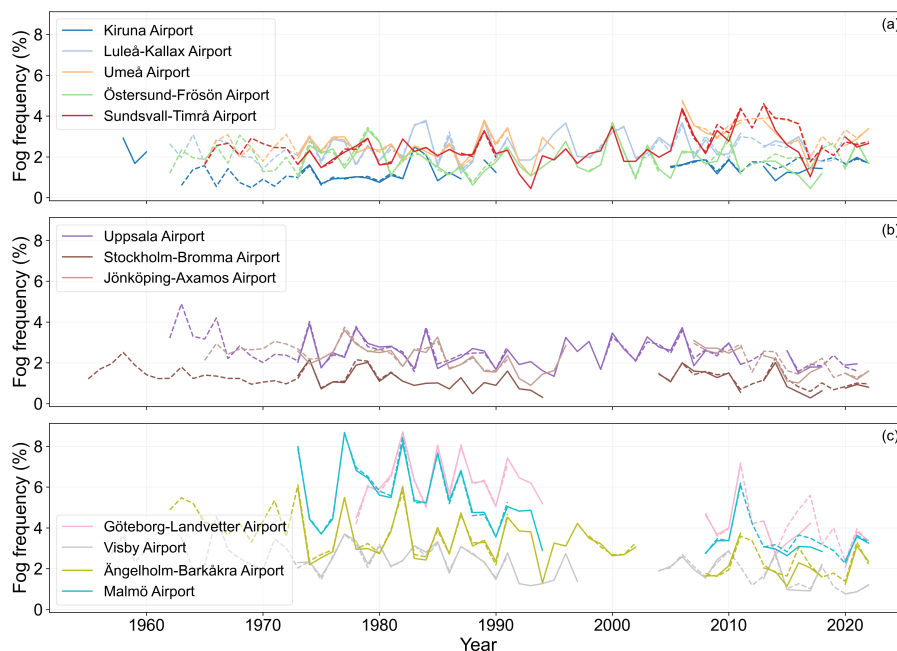


Figure 3. Yearly fog frequency for the 12 airports. Only years with more than 90 % data coverage is included in the figure. The solid lines display the data with three-hour resolution and the dashed lines show the data with one-hour resolution.

south. The yearly average wind speeds are shown in Fig. 5. Many of the airports had decreasing wind speeds from the 1980's to around 2005 but after this there are no clear trends in the winds speeds. Similar results were found in studies focusing on wind conditions in Sweden over this time period (Minola et al., 2016, 2021). Minola et al. (2016) found that the decrease in wind speeds were largest in coastal regions and in southern Sweden and similar results can be seen in Fig. 5c where Malmö and
 210 Visby airports show the largest changes in wind speeds. There are no major changes in the average air pressure at the airports though the average pressure varies somewhat from year to year (not shown).

There has been a decrease in SO_4^{2-} aerosol concentrations in Sweden over time, as can be seen in Fig. 6, displaying measurement stations from south to north. Measurements of the SO_4^{2-} aerosol started in the 1970's and 1980's and thus, don't go as far back in time as some of the meteorological data at the airports. There is a clear trend of decreasing aerosol
 215 concentrations, with the largest drop occurring during the 1980's. The highest SO_4^{2-} concentrations, and the largest reduction in these, were measured in southern Sweden (Vavihill, Hourgen, and Rörvik/Råö) where peak annual concentrations in the 1970's and 1980's reached 6-8 $\mu\text{g}/\text{m}^3$. After 1995 the maximum values at these stations have not surpassed 3 $\mu\text{g}/\text{m}^3$. The values at Aspvreten are somewhat lower than those in southern Sweden (no values above 4 $\mu\text{g}/\text{m}^3$). At Bredkålen, located in
 220 the north of Sweden, the values never exceed 3 $\mu\text{g}/\text{m}^3$ and are lower than at the other stations even today. A large degree of the SO_4^{2-} aerosol in southern Sweden does not have local sources but is transported from emission sources in other European countries. The higher concentrations of SO_4^{2-} aerosol in southern Sweden can be attributed to its closer proximity to major



Table 1. Yearly fog frequency (% of 3 h measurements with fog), comparing early period (1970 - 1999) to the later period (2000 - 2022).

Airport	Fog frequency (%)			p-value
	1970 - 1999	2000 - 2022	Difference (95% CI)	
Kiruna Airport	1.22	1.50	0.28 (-0.02, 0.58)	0.0634
Luleå-Kallax Airport	2.44	2.64	0.20 (-0.18, 0.58)	0.2928
Umeå Airport	2.42	3.09	0.67 (0.19, 1.15)	0.0082
Östersund-Frösön Airport	1.79	1.79	0.00 (-0.43, 0.43)	0.9982
Sundsvall-Timrå Airport	2.08	2.76	0.68 (0.22, 1.14)	0.0051
Uppsala Airport	2.42	2.45	0.03 (-0.37, 0.42)	0.8926
Stockholm-Bromma Airport	1.11	1.11	0.00 (-0.33, 0.33)	0.9927
Jönköping-Axamo Airport	2.21	2.00	-0.21 (-0.68, 0.26)	0.3631
Göteborg-Landvetter Airport	6.33	3.90	-2.43 (-3.36, -1.49)	< 0.0001
Visby Airport	2.33	1.72	-0.61 (-1.09, -0.13)	0.0145
Ängelholm-Barkåkra Airport	3.46	2.20	-1.26 (-1.83, -0.70)	0.0001
Malmö Airport	5.58	3.27	-2.31 (-3.16, -1.45)	< 0.0001

There is not data for all years at all airports, see Figure 3.

European emission regions and the greater transport of aerosols to this part of the country. In Fig. 7 it can be seen that SO₂ emissions in Europe decreased substantially from the 1970's to the 2000's, in particular in countries to the south-west of Sweden. The emission changes in Fig. 7 indicate that SO₄²⁻ aerosol concentrations in southern Sweden were even higher in the 1970's but at most of the stations, the measurements had not started at that time.

After this discussion on how the fog, meteorological variables and SO₄²⁻ aerosol have varied over time, we will study and discuss the fog changes in the different regions separately.

3.3 Fog Changes in Southern Sweden

In Fig. 3c it is clear that the fog frequency has decreased at the airports in southern Sweden since the 1970's and 1980's. For the airports in southern Sweden, we will consider Malmö, Ängelholm, Göteborg-Landvetter and Visby airports. Jönköping-Axamo Airport (57.7514 N, 14.0733 E) is located at similar latitude as Göteborg-Landvetter (57.6678 N, 12.2963 E) and Visby (57.6678 N, 18.3516 E) airports. However, since there are no significant long-term changes in fog frequency at Jönköping-Axamo Airport, we will discuss those results together with Stockholm-Bromma and Uppsala airports.

For the airports in southern Sweden, temperatures have increased, aerosol concentrations has decreased and the wind has decreased at some of the airports during the investigated period. To determine potential drivers of the changes in fog frequencies, we have created datasets similar to the ones shown in Fig. 2 and Fig. A2 but for the fog events before the year 2000 and the fog events after the year 2000 separately. We have then subtracted the data of the early period from the data of the late period. These differences are shown in Fig. 8 and Fig. A3. We have also created a similar figure to these two figures showing the fog

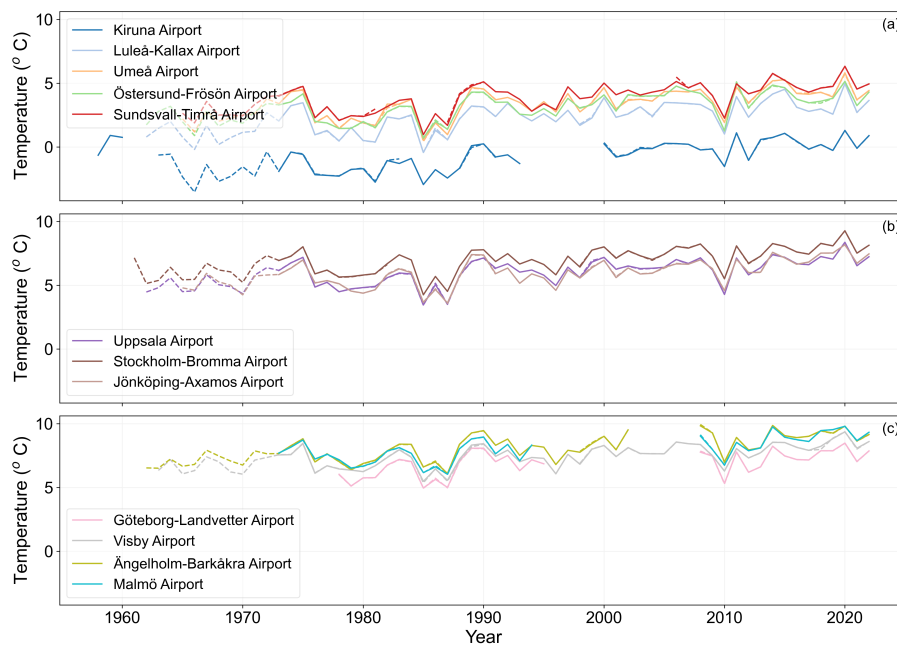


Figure 4. Yearly average temperature for the 12 airports. Only years with more than 90 % data coverage is included in the figure. The solid lines display the data with three-hour resolution and the dashed lines show the data with one-hour resolution.

frequency, i.e. the number of fog hours occurring in different bins divided by the overall number of observations in those bins.
 240 This is shown in Fig S4. We will use these figures to establish the primary drivers of the change in the fog frequencies observed in Fig. 3.

We will start by examining how temperature affects fog, noting that temperatures at the southern airports have been increasing over time (Fig. 4). In Fig. 8a we can see that for the four southernmost airports, the absolute number of fog hours per year has decreased across all temperatures. If air temperatures would be the primary factor controlling fog frequency, we would
 245 expect the fog frequencies for each temperature bin to stay constant. The increasing temperatures in the region should then lead to an increase in fog occurrence at higher temperatures. However, both the occurrence (Fig. 8a) and the fog frequency (Fig. A4a) is decreasing across essentially all temperature bins. This implies that temperature change is not the main driver of the decrease in fog formation in Southern Sweden.

Secondly we will investigate how the fog is impacted by wind speed. Malmö and Visby airports have a decrease in wind
 250 speed while neither Göteborg-Landvetter, nor Ängelholm airport, show any decrease in the annual wind speed (Fig. 5c). Nevertheless, all these airports have a decrease in fog occurrence at wind speeds greater than 2 ms^{-1} (Fig. 8c) and small changes in fog occurrence at wind speeds below this limit. The fog frequency is decreasing at all wind speeds at all these airports (Fig. A4c). This, and that only 2 out of 4 airports has changes in the annual wind speeds make it unlikely that changes in wind speeds drive the decrease in fog frequency in southern Sweden. When investigating the trends in advection fog (Fig.

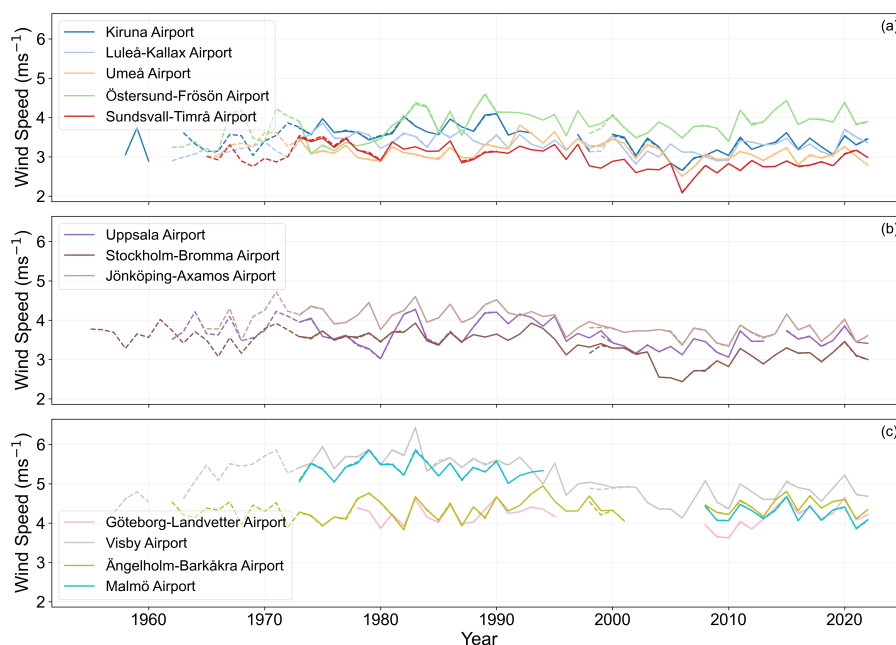


Figure 5. Yearly average wind speed for the 12 airports. Only years with more than 90 % data coverage is included in the figure. The solid lines display the data with three-hour resolution and the dashed lines show the data with one-hour resolution.

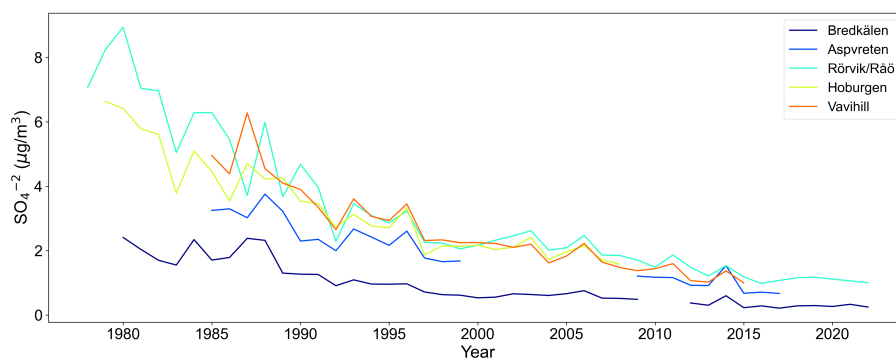


Figure 6. Yearly average SO_4^{2-} from the 5 measurement stations in Sweden. Only years with more than 80 % data coverage is included in the figure. The measurement stations are displayed from north to south in then legend.

255 A1) and radiation fog (Fig. A5) it is clear that there is a greater decrease in advection than in radiation fog at Malmö and Göteborg-Landvetter airports. Advection fog events often last longer than radiation fog, and our analysis indicates that long lasting fog events have become less common (Fig. 8h and Fig. A2h). Radiation fog is more common during nighttime while advection fog is more independent of the time of day. Figure A3g shows that fog has decreased more during daytime than

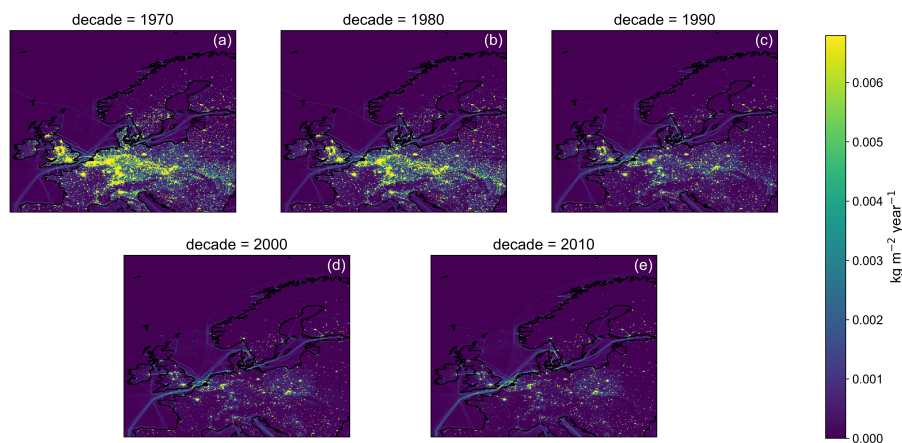


Figure 7. Decadal average SO₂ emissions over Europe.

during nighttime for the airports in southern Sweden. This further supports the conclusion that it is primarily advection fog that
 260 is decreasing in the south of Sweden.

Next, we will look into if changes in fog frequency vary with the origin of the wind. Fog in southern Sweden shows a
 decrease for all wind directions, but the magnitude of the change varies with direction as can be seen in Fig. 8d. For Malmö,
 Ängelholm and Göteborg-Landvetter airports, there is a substantially larger reduction in fog occurrence (Fig. 8d) and frequency
 (Fig. A4d) when the winds are arriving from the south and south west. The areas located south and south-west of Sweden are
 265 also the regions that show the strongest decreases in emissions of the aerosol precursor SO₂ between the 1970's and the 2010's
 (Fig. 7).

Lastly, we will investigate whether the RH at which fog forms has changed between the periods. Klemm and Lin (2016)
 showed that in the presence of aerosol rich air, fog forms at lower RH. Our results show that at Malmö, Ängelholm, and
 Göteborg-Landvetter airports, the fog frequency has increased at high RH (~98-100 %) and decreased at RH below 98 % (Fig.
 270 A4c). The fog occurrence show similar results but the increase at higher RH is not as clear. Since measurements of dew point
 temperature become uncertain at high RH (Lin and Hubbard, 2004) and the instrumentation at the airports have been changed
 during the studied periods, the reliability of RH data is not ideal, especially for high RH. As the instruments may have had
 different abilities to measure high RH values, fog frequency is a more reliable measure of the changes than fog occurrence, as
 fog frequency conditions on the total number of observations in each RH bin. Fig. A3c shows that there is a shift towards fog
 275 formation at higher RH also at Visby Airport, but the results regarding occurrence and frequency show only small changes.
 The large change in fog frequency at 101 % RH at Visby Airport occur since there are no observations at these conditions at
 all post the year 2000, most likely a result from changing dew point temperature instrumentation. The results in Fig. A3c and
 Fig. A4c show that after year 2000, when aerosol concentrations were considerably lower, fog formed at higher RH.

The results coupling the decreases in fog frequency in Southern Sweden to specific wind directions in combination with
 280 changes in RH during fog formation leads us to conclude that the changes in fog formation in southern Sweden is likely related

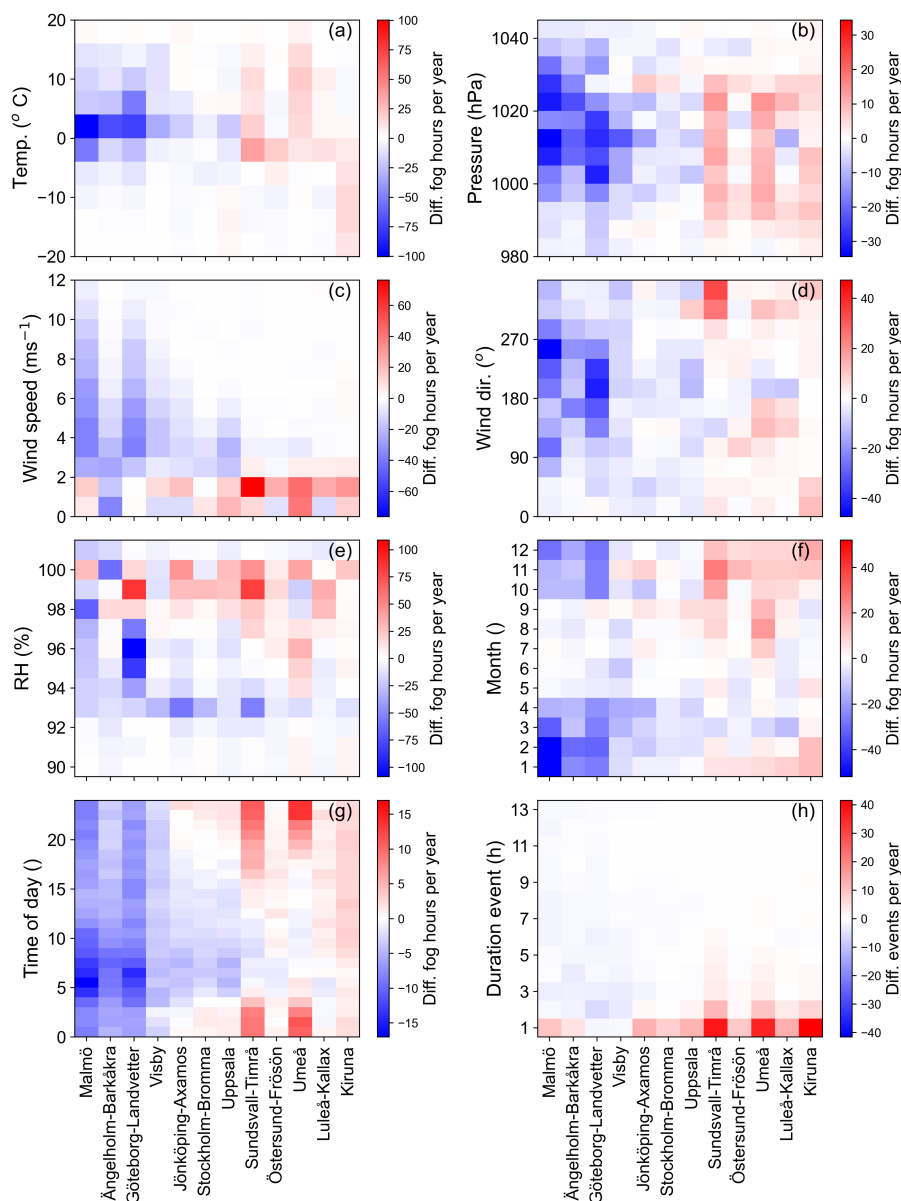


Figure 8. Difference in histograms of number of fog hours per year between the years from 2000 and the years before 2000 for different meteorological and temporal conditions for the different airports. The airports are ordered according to their latitudes with the southernmost airport located furthest to the left on the x-axis. The data with one-hour resolution is used in this figure.

to decreasing concentrations of aerosol particles. This is supported by the results in Fig. 6 which display large reductions in SO_4^{2-} at Vavihill (close to Malmö and Ängelholm airports) and Rörvik/Råö (close to Göteborg-Landvetter Airport) between



the 1980's and the 2000's. Large reductions in concentrations of hygroscopic SO_4^{2-} aerosol in the southern regions of Sweden, as a result of decreasing emissions over continental Europe, likely have a strong impact on the fog frequencies.

285 Our analysis show that there is a larger reduction in advection fog frequency than radiation fog frequency (see Fig. A1 and A5). One could hypothesize that advection fog is more impacted by a reduction in aerosol concentrations in the air than radiation fog. Advection fog at these airports forms through cooling of humid warm air as it moves over cold land surfaces. As the RH of the air increases during the cooling, there is condensation on the particles that eventually grows large enough to reduce visibility to below 1000 m. However, if there is less hygroscopic aerosol in the air, the RH must reach high values
290 to induce fog formation. Hence, the air must be cooled more, before the same reduction in visibility is achieved. But as the airmass moves inland, its properties change due to mixing and the temperature may not cool enough to reach the RH required to reduce visibility to fog levels. Radiation fog, on the other hand, forms as the air is cooled by the ground until it reaches high enough RH to induce aerosol growth that reduces visibility below 1000 m. If higher RH is required to create the same visibility reduction in present day conditions, then the air can reach that RH later in the night when the air has been cooled to lower
295 temperatures. The results from southern Sweden show that after the year 2000, there is relatively more fog formed in the late evenings and early mornings compared to during the daytime (Fig A3g), although the fog occurrence is decreasing at all hours (Fig 8g). This indicate a larger reduction in advection fog, that more often form during daytime than radiation fog. This could indicate a larger sensitivity of advection fog to changes in aerosol concentrations. Nevertheless, advection fog could also be impacted to warmer ground temperatures during autumn, winter, and spring after the year 2000, which reduces the cooling of
300 the bottom of the marine air masses and the formation of advection fog.

The reductions in fog frequency in southern Sweden are supported by several other studies of central Europe (Vautard et al., 2009; Van Oldenborgh et al., 2010; Giulianelli et al., 2014; Hůnová et al., 2018; Bokwa et al., 2018). Several of these studies found that reduction in fog frequency correlates well with SO_2 emissions or other measures of air pollution (Van Oldenborgh et al., 2010; Vautard et al., 2009; Hůnová et al., 2018; Bokwa et al., 2018). A study in the Po Valley in northern Italy also found
305 decreasing concentrations of aerosol compounds in fog water (Giulianelli et al., 2014). Not only aerosol levels are pointed out as drivers of the decrease in fog frequency in Europe but changes in atmospheric dynamics, RH, temperature and wind speed were found to impact fog frequency (Vautard et al., 2009; Van Oldenborgh et al., 2010; Giulianelli et al., 2014; Hůnová et al., 2018; Bokwa et al., 2018).

3.4 Fog Changes in mid-Sweden

310 At the airports in the middle of Sweden (including Jönköping-Axamo Airport) there are no distinct changes in the fog frequency (Fig. 3b). The temperature is increasing at all these airports (Fig. 4b) and all experience decreasing average wind speeds, during some years between 2000 and 2010 (Fig. 5b). Even though the fog frequency does not change, there are still some changes in the conditions in which the fog forms at these airports. Fog occurs at lower wind speeds also in this part of Sweden where fog occurrence at wind speeds above 2 ms^{-1} decrease while occurrence below 2 ms^{-1} increase (Fig. 8c, A3c and A4c). Similarly
315 to the southern parts of Sweden, fog at these airports are formed at higher RH after the year 2000 (Fig. 8e, A3e) and there has been a shift towards less fog during daytime and more fog during nighttime (Fig. 8g and A3g). This indicate that there



is less advection fog forming at these airports and more radiation fog post the year 2000. Advection fog is nonetheless much less common at these airports compared to those further south. The aerosol concentration in this region is also decreasing, see results from Aspvreten in Fig. 6. However, the changes are smaller than for the stations further south as Aspvreten is located
320 further away from the large source regions of SO₂ in continental Europe.

3.5 Fog Changes in Northern Sweden

In northern Sweden, Umeå, Sundsvall-Timrå, and Kiruna airports experience increasing fog frequencies while Östersund-Frösön and Luleå airports do not see any changes in fog frequency (Fig. 3). Umeå and Sundsvall-Timrå airports display the strongest increase in fog frequency at wind speeds below 2 ms⁻¹ Fig (8c and A4c). The increase in fog frequency is
325 mainly associated with north-westerly winds in Sundsvall-Timrå airport while at Umeå airport, the changes are associated with south-easterly winds (Fig. 8d and A3d). Moreover, the increase in fog occurs during late summer and autumn and during nighttime, see Fig. 8f and 8g. When considering the conditions at the two airports under which fog frequency changes most, an increase in radiation fog occurrence is apparent, consistent with Fig. A5. In this figure, we can see that there were a few years between 2005 and 2015 when the radiation fog frequency reached 3-4 % instead of 1-2 %. Both Umeå and Sundsvall-Timrå
330 airports are located very close to large rivers (Fig 1). Due to climate change, temperatures in rivers in the north of Sweden are increasing (Hallerbäck et al., 2022) which leads to less ice-coverage in the autumn and winter. Higher water temperatures and ice-free conditions result in more evaporation from the rivers. The increase in fog occurrence at both airports is linked to wind directions in which the airflow passes over the adjacent rivers. These two airports have the lowest wind speeds of those in Northern Sweden and show lower than usual annual average wind speeds in years when fog frequency was higher
335 (Fig. 5). The combination of more moisture supply and lower wind speed is highly favourable for the formation of radiation fog. The two airports that do not experience any increase in fog frequency (Östersund-Frösön and Luleå-Kallax airports) are also located close to large water bodies but with greater distance and more forest between the water bodies and the airports compared to Umeå and Sundsvall-Timrå airports. Östersund-Frösön and Luleå-Kallax airports also lack substantial changes in annual average wind speeds during the years that fog frequencies are high at Umeå and Sundsvall-Timrå airports.

340 At Kiruna airport, there is a weak increase in fog frequency. The change is an increase in annual fog frequency from around 1 % to almost 2 %, see Fig. 3. This increase mainly occurs in winter at low temperatures, low wind speeds, and during all times of the day except in the early morning (Fig. 8). The wind direction during the increase is mainly from the north. The annual average temperatures at Kiruna airport are substantially lower than at any other airport, and they are steadily increasing (Fig. 4a). The increasing fog frequency at Kiruna airport during winter could be related to global warming making temperatures between -15
345 °C and 0 °C here more common. Fog is more commonly formed at these temperatures compared to lower temperatures (Fig. 2a). Even though there is an increase in fog frequency at this airport, the levels are still very low, see Table 1.



4 Conclusions

We have investigated fog frequency at 12 airports in Sweden since the 1960/70's. The visibility data used in the study was combined with temperature, wind speed, wind direction, RH and pressure data, as well as sulphate measurements from five stations and sulphur dioxide emission data. Annual fog frequencies at Swedish airports range between less than 1 % to slightly above 8 % and is highest in southern Sweden. Fog most often forms during the winter months, at temperatures between -2 and 8 °C. Most airports experience fog primarily at low wind speeds ($< 2 \text{ ms}^{-1}$) which is characteristic of radiation fog. However, at some airports in southern Sweden, fog frequently occurs at higher wind speeds, indicating a stronger influence of advection fog at those airports.

This investigation shows that in southern Sweden, fog frequency at several airports is substantially lower in the post 2000 period compared to pre 2000. The lower fog frequencies are mainly caused by a lower occurrence of advection fog. The cause for the decrease can be related to a decrease in concentrations of hygroscopic aerosol particles, due to reductions of sulphur dioxide emissions in central and western Europe. Some of the airports in northern Sweden (Kiruna, Umeå, and Sundsvall-Timrå airports) are experiencing higher fog frequencies in the period after the year 2000 compared to pre 2000. This increase is primarily driven by changes in the occurrence of radiation fog. For Umeå and Sundsvall-Timrå airports, the increase is most likely a result of increased moisture transport from nearby rivers, in which the temperatures have increased in the past decades, in combination with low wind speeds during late summer and autumn. For Kiruna Airport, which experiences substantially lower air temperatures than the other airports, the increase over time is probably coupled to increasing air temperatures that facilitate more fog formation. In mid-Sweden, we do not see any significant changes in fog frequencies.

Our study indicates that changes in both meteorological conditions and atmospheric chemistry have impacted fog occurrence at Swedish airports over the past 50 years. We have studied the changes in sulfate aerosol in southern Sweden but also the concentrations of other aerosol types has decreased over the past 50 years, but not to the same extent (Lövblad et al., 2004). Since sulfate aerosol is highly hygroscopic, the reduction in these particles is expected to have reduced the overall hygroscopicity of the ambient aerosol. This in combination with high particle number concentrations most likely contribute to the lower RH during fog events during the early period investigated in this study.

Climate change can impact fog formation in numerous ways. The most straight forward impact is that higher air temperatures allow the air to retain more water vapour, potentially lowering fog occurrence. Nevertheless, in this study we find that fog is most common in temperatures between -5 °C and 10 °C. This implies that increasing temperatures could lead to increases in fog formation if conditions between -5 °C and 10 °C become more common, like we saw at Kiruna Airport. Nevertheless, if the temperature increases makes conditions in this temperature range less common, then temperature increases could lead to decreasing fog frequencies. The direct connection between temperature and fog frequency is thus not so straightforward. In this study we also find a more indirect way in which climate change can impact fog formation. In the north, climate change induces changes in river temperatures that result in more evaporation that during conditions with lower wind speeds increase the fog formation. This highlights the strong local nature of fog and its drivers. These results indicate that making predictions about climate change impact on fog frequencies on a global or even regional scale is an intricate challenge that

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require an understanding of overall trajectories air pollution, fog response to air temperature changes and climate impact on local conditions.

Code and data availability. The data used in this study has been downloaded from SMHI meteorological archive (<https://www.smhi.se/data/hitta-data-for-en-plats>) and the SMHI air concentration portal (<https://datavardluft.smhi.se/portal/>). The SO₂ emissions data (EDGAR v6.1 Global Air Pollutant Emissions) used has been downloaded from the European Commission Joint Research Centre Data Catalogue (<https://doi.org/10.2905/JRC.967BWXG>). The compiled data used in this study and the code used to produce the figures are available here: <https://doi.org/10.5281/zenodo.18195192>

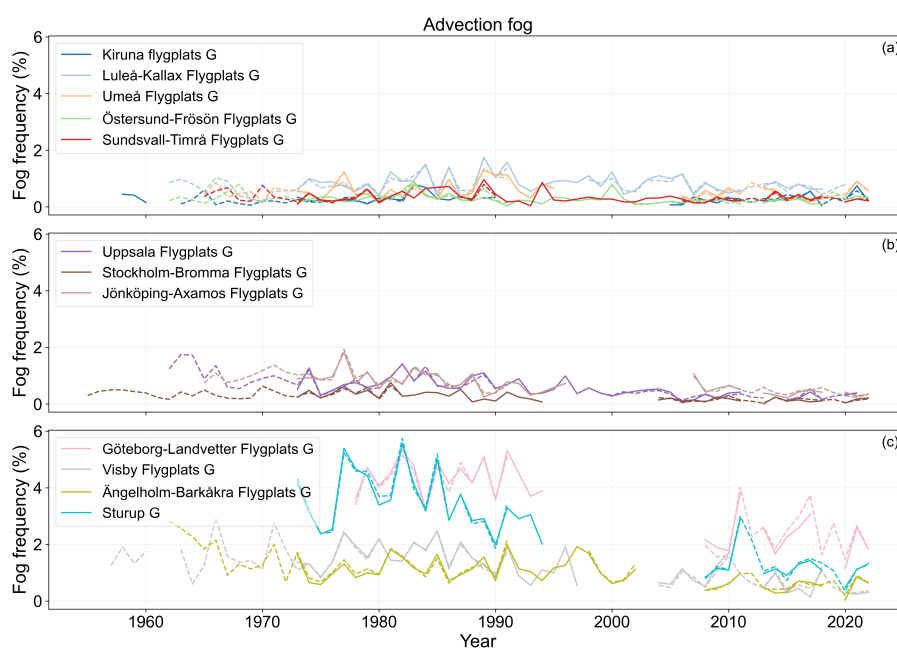


Figure A1. Yearly advection fog frequency (fog formed in wind speeds $> 2 \text{ ms}^{-1}$) for the 12 airports. Only years with more than 90 % data coverage is included in the figure. The solid lines display the data with three-hour resolution and the dashed lines show the data with one-hour resolution.

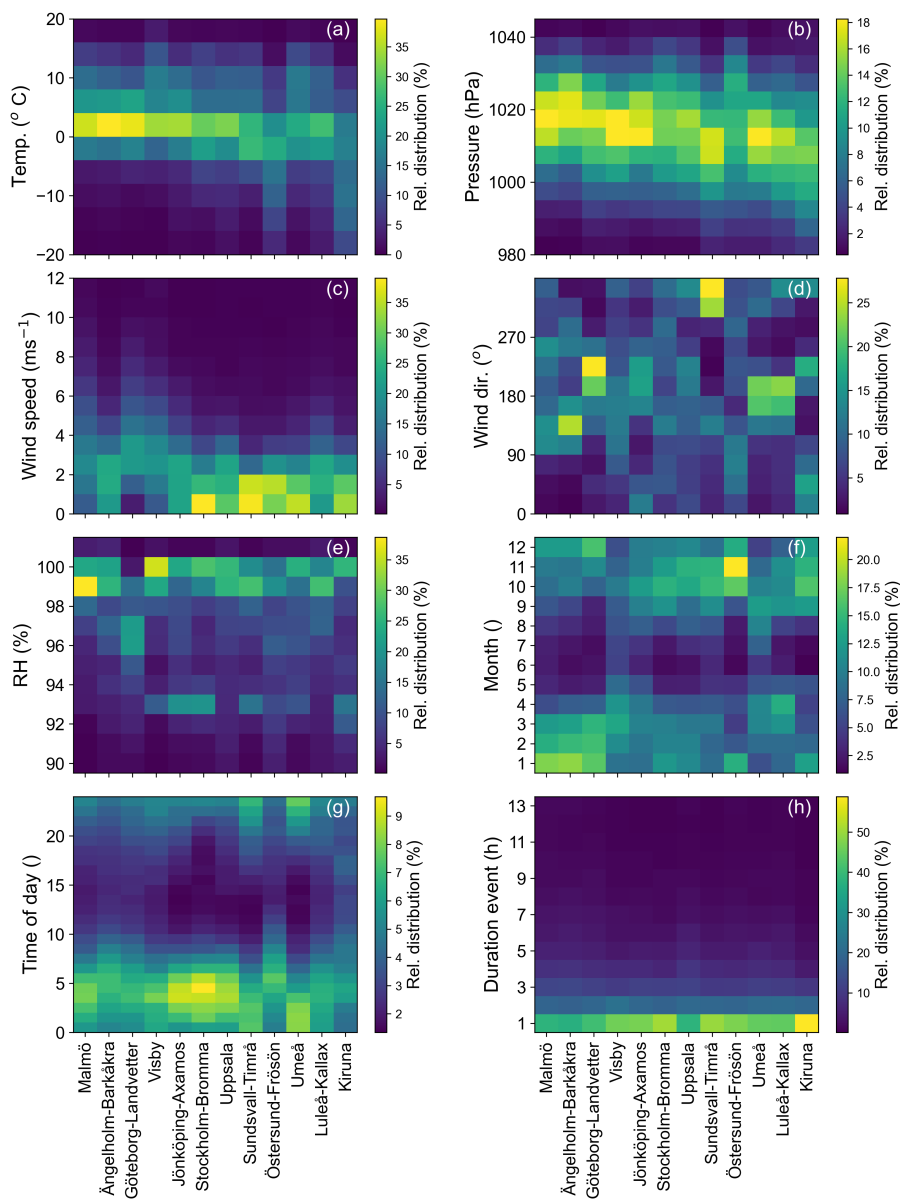


Figure A2. Histograms of relative distribution of fog events for different meteorological and temporal conditions for the different airports. The airports are ordered according to their latitudes with the southernmost airport located furthest to the left on the x-axis. The data with one-hour resolution is used in this figure.

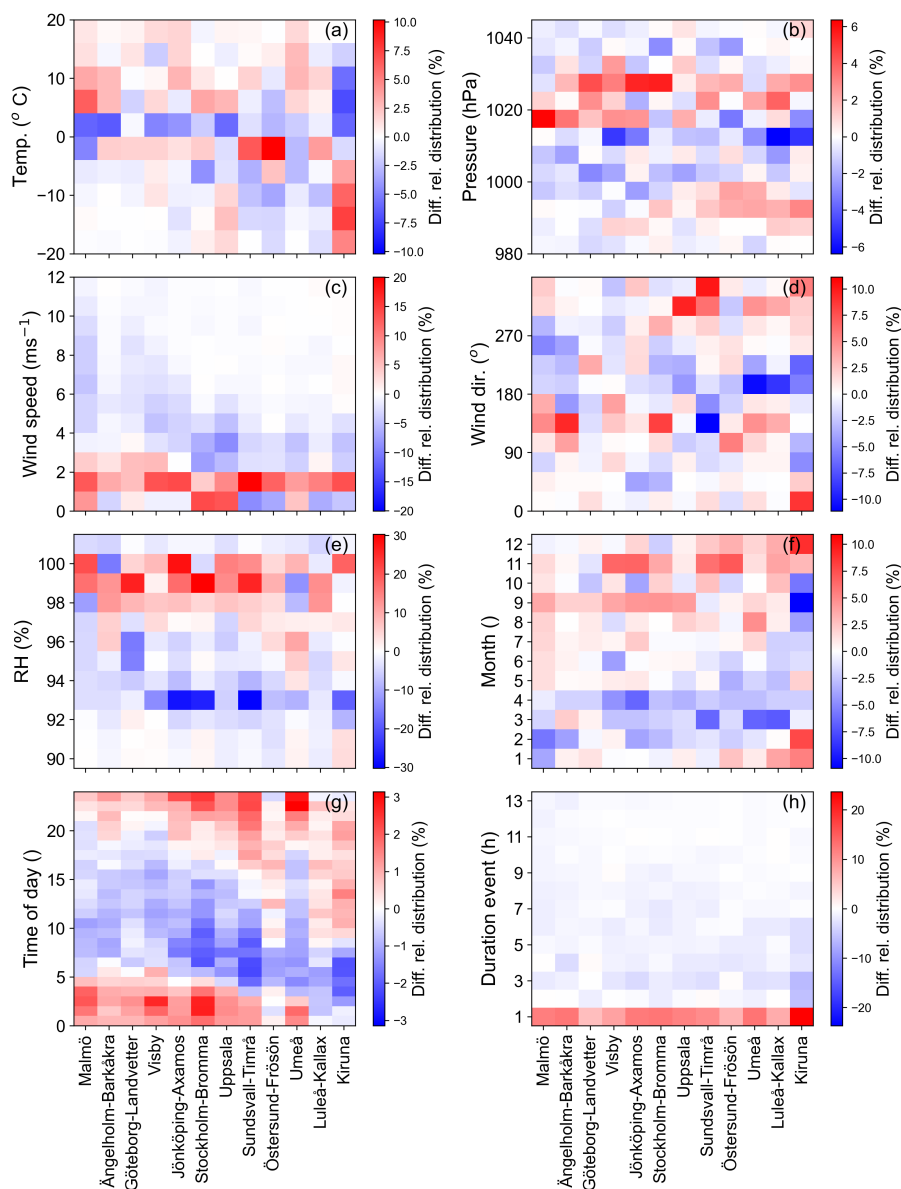


Figure A3. Difference in histograms of the relative distribution of fog hours from the year 2000 and the years before 2000 for different meteorological and temporal conditions for the different airports. The airports are ordered according to their latitudes with the southernmost airport located furthest to the left on the x-axis. The data with one-hour resolution is used in this figure.

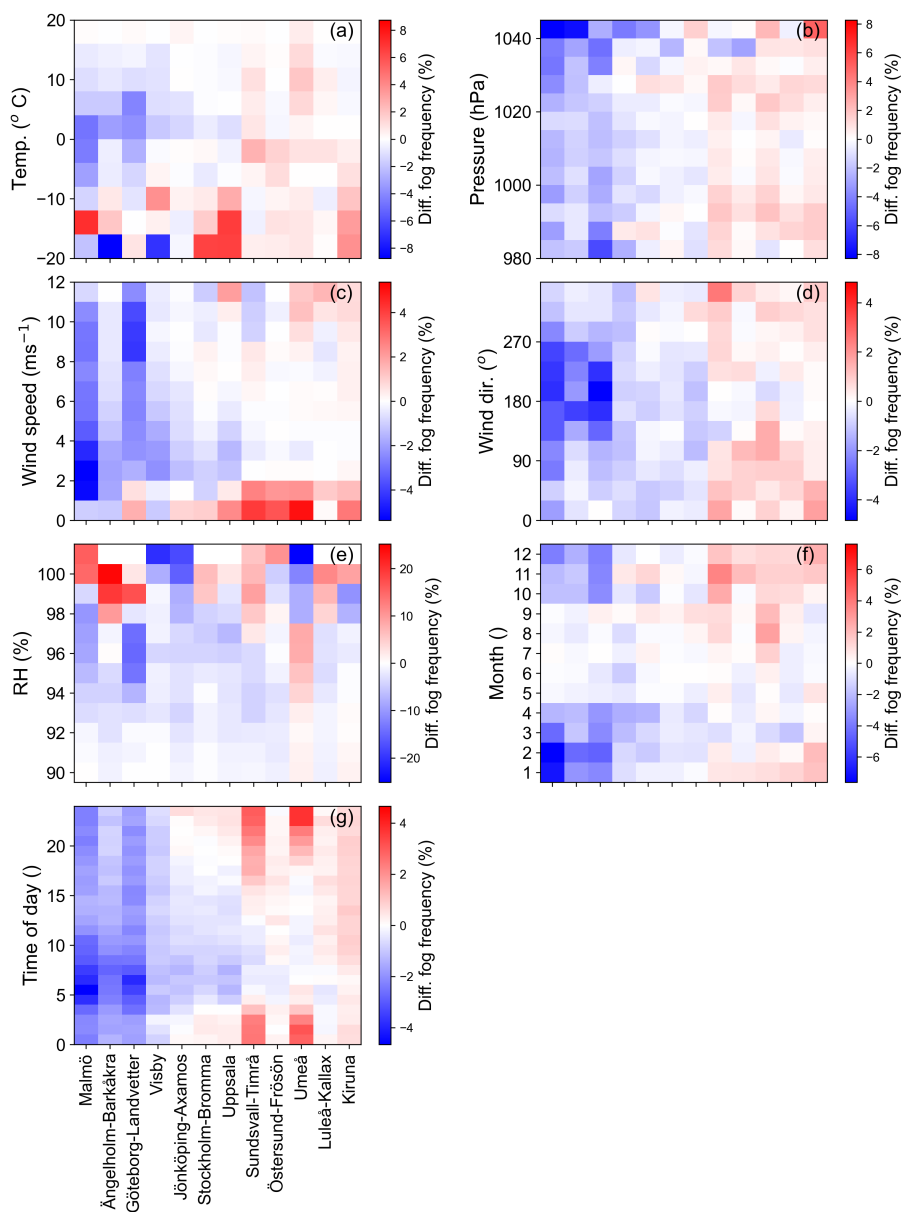


Figure A4. Difference in histograms of the fog frequency from the year 2000 and the years before 2000 for different meteorological and temporal conditions for the different airports. The airports are ordered according to their latitudes with the southernmost airport located furthest to the left on the x-axis. The data with one-hour resolution is used in this figure.

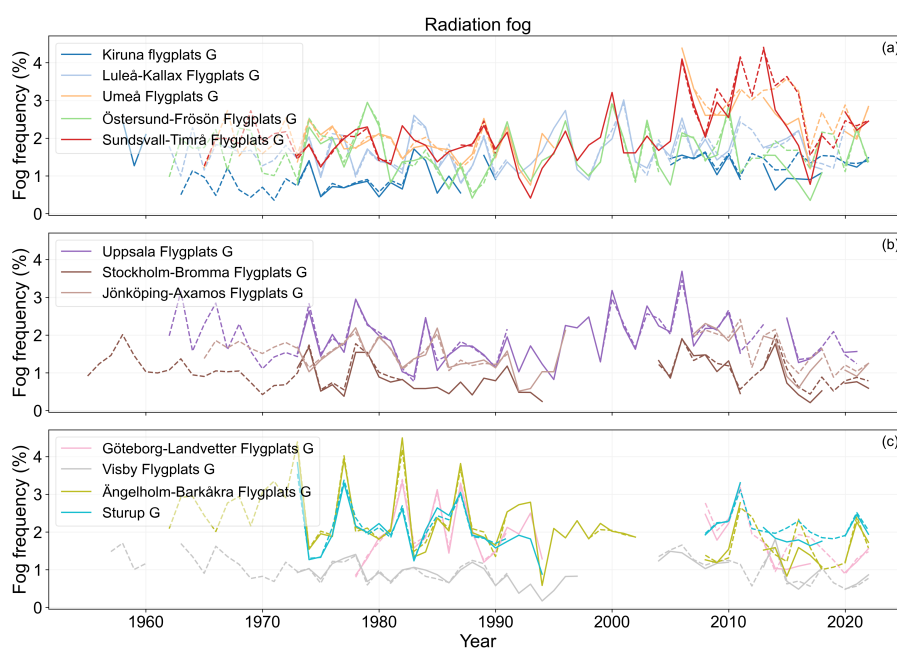


Figure A5. Yearly radiation fog frequency (fog formed in wind speeds $\leq 2 \text{ ms}^{-1}$) for the 12 airports. Only years with more than 90 % data coverage is included in the figure. The solid lines display the data with three-hour resolution and the dashed lines show the data with one-hour resolution.



Author contributions. MKS designed the research idea. MKS downloaded all the data and performed most of the data analysis. LH has performed the statistical analysis of the data. SS and JF has contributed with fruitful discussions during the data analysis. MKS wrote the majority of the manuscripts. LH, SS and JF has read and commented on the manuscript.

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Competing interests. The authors do not have any competing interests.

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