Climate conditions and consequences for de-icing operations as exemplified by the situation on a motorway and airport at Gardermoen, Norway

H. K. French, H.-O. Eggestad, J. Øvstedal and P.-E. Jahren

ABSTRACT

Large amounts of de-icing chemicals are used in the northern hemisphere to maintain winter safety on roads and airports every year. At Gardermoen, potassium formate (KFo) is used on runways, sodium chloride (NaCl) on roads and propylene glycol (PG) for aeroplanes. The total use of de-icing chemicals is an important part of the risk assessment related to water contamination at Gardermoen. The objective of this paper is to examine how climatic factors affect the use of de-icing chemicals through interviews with de-icing operators and by statistical methods using data on climate variables and de-icing operations. A multiple linear regression model shows a good relationship between daily dew point temperature, precipitation, wind speed, number of departures and the use of PG. The results were less promising for the prediction of KFo. This might be explained by the human factor and insufficiency of the standard climate variables to represent the situation near the runway. An analysis of daily downscaled climate change scenarios for the Gardermoen area revealed insufficient detail for any accurate estimates of change in total consumption of de-icing chemicals. The predicted mean increase of 7.6°C during winter does, however, suggest a reduced need for de-icing chemicals in the long term (2071–2100).

Key words | contaminants, environmental risk, snow, statistical model, winter

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INTRODUCTION

In the northern hemisphere, substantial amounts of de-icing chemicals are used to remove and prevent ice formation on aeroplanes, runways and roads. The common practice in many airports of the world is still to release de-icing chemicals directly into the environment and in the US a new regulation has recently been proposed (EPA 2009). Release of organic de-icers directly into water courses creates dead zones for aquatic life and anaerobic groundwater due to the high demand for oxygen during natural degradation. Road salt and its consequences for groundwater has been documented by several groups (e.g. Howard & Maier 2007). With the implementation of the Water Framework Directive in Europe (2000/60/EC), the attention paid to these types of contaminants has increased, and airports are seen as one of the important threats to soils in the proposed EU Soil Directive (2004/35/EC). Airports and roads are therefore faced with the dual challenge of maintaining public safety and meeting demands to protect the environment. De-icing fluids used on aeroplanes are commonly based on ethylene glycol, diethylene glycol or propylene glycol as the primary constituents, while de-icers for runways are based on organic salts or urea. Contaminants in melt water from snow cover in the vicinity of airports and roads have received increased attention over the last decade (e.g. Nystén & Suokko 1998; French *et al.* 2001; Øvstedal & Wejden 2006)

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and are an important challenge to airport managers. Oslo airport was opened in 1998, and due to the presence of a large aquifer below it and better general awareness of environmental issues than what was the case during the time of the establishment of most European airports, a great deal of attention was given to the consequences for the local environment. Strict environmental control is required from the pollution authorities; hence this airport provides detailed information about de-icing practices. At Oslo airport (OSL), Gardermoen, about 80% of the de-icing chemicals used on aeroplanes is collected and treated at a local wastewater treatment plant, 10% leaves with the planes at take-off and the remaining 10% is spread diffusively on the green areas next to the runway (Øvstedal & Wejden 2006). All de-icing chemicals used on the runways are spread diffusively along the runway. Flow and transport of de-icing chemicals in the unsaturated zone has previously been monitored in field lysimeters (French *et al.* 2001) and by time-lapse electrical resistivity measurements (French *et al.* 2002; French & Binley 2004). These studies revealed a heterogeneous infiltration pattern due to ice on the ground surface (basal ice) and that chemicals can be completely degraded before reaching the groundwater levels if chemicals do not reach the groundwater during snowmelt. Field experiments and modelling have shown that there is typically a fast vertical flow during the 3–5 weeks of snowmelt followed by stagnant water during the summer months (French *et al.* 2001, 2002). In this period, the natural degradation capacity of the soil is higher because of warmer soil and there is an increased potential for degradation of de-icing chemicals. However, there is a finite capacity for degradation (limited by degradation rates, nutrient availability and reduction–oxidation levels), hence the natural filter system is vulnerable to the total amounts of de-icing chemicals added to the surface and the total amount of infiltrating water.

The Norwegian National Transportation Plan 2006–2015 (Anonymous 2002) emphasises the need to adjust to possible climate changes in the future. The adjustments may, for instance, include changed winter operation routines on roads and airports. For practical applications and impact studies local climate variables such as temperature and precipitation are required on a smaller spatio-temporal scale than provided by the global climate models (GCMs). To predict climate on a local scale, downscaled scenarios must be applied. The Norwegian Meteorological Institute have used the regional climate models from HIRHAM and Max Planck (MPI) (IPCC 2007) to perform dynamical downscaling of climate scenarios from the AOGCMs, with spatial resolution of 55 km × 55 km every 6 h. To improve the regional climate simulations to the local scale, adjustments are performed by empirical downscaling (also called statistical downscaling, described in Engen-Skaugen (2004)). The basic thesis is that the local climate can be found as a function of the global climate and local physiography. The connection, or function, is found by statistical analyses of historical observation data. The statistical properties of the simulated climate should be similar to those of the observed climate. Hence, the local adjustments try to maintain these statistical properties. The predicted mean changes in temperature and precipitation for Gardermoen from the period 1961–1990 to the period 2071–2100 are summarized in Table 1 (Engen-Skaugen 2004).

Risks of contamination of groundwater by regular use of de-icing chemicals (not accidents) as a function of climate

Table 1 | Predicted climate changes from the period 1961–1990 to the period 2071–2100 for Gardermoen. Mean is best estimate. Large difference between HAD (Hadley) and MPI (Max Planck Institute) implies large uncertainty and a risk for considerable variance

	Temperature increase in °C				Precipitation increase in mm/d			
	HADA2	HADB2	MPIB2	Mean	HADA2	HADB2	MPIB2	Mean
Yearly	3.8	3.0	4.1	**3.6**	0.7	0.8	0.9	**0.8**
Spring	3.0	3.3	3.3	**3.2**	0.9	1.2	1.4	**1.2**
Summer	1.7	−2.4	2.0	**0.4**	−0.2	0.1	−0.4	**−0.2**
Autumn	3.9	2.4	4.0	**3.4**	−0.1	0.5	0.8	**0.4**
Winter	6.8	9.0	7.1	**7.6**	2.0	1.6	1.7	**1.7**

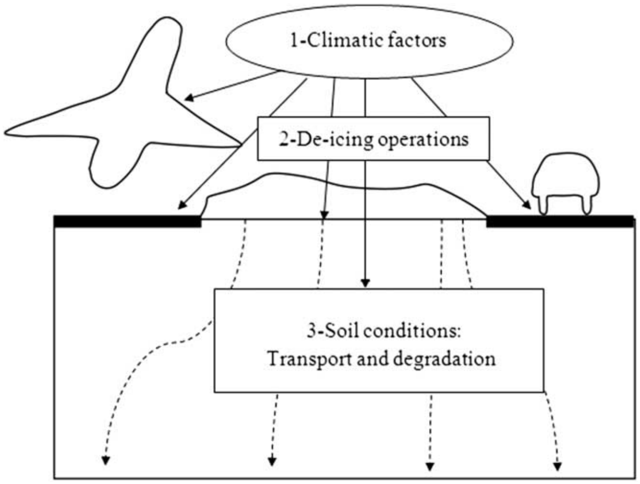

Figure 1 | Schematic diagram showing influence of climate factors (1) on de-icing of aeroplanes, runways and roads (2), which influence the total exposure of chemicals to the environment. Climate factors also influence the soil conditions (3) and its capability of diluting and degrading the de-icing chemicals.

factors consists of two parts (Figure 1). The first part is described by the need for de-icing, which is strongly linked to the climatic conditions on a specific day. According to the AOPA Air Safety Foundation (2004), icing on aeroplanes is most likely to occur when the outside air temperature (OAT) is between 0°C and −20°C, but the worst icing will usually occur between 0°C and −10°C and when freezing rain or freezing drizzle is present. A temperature dew point spread (difference between the air temperature and the dew point temperature) of less than 2°C and temperatures between 0°C and −20°C are especially important for ice. Snow and rain on frozen ground represent some of the situations when de-icing of road and runway surfaces may be required. The second part of the risk involves infiltration and transport in the unsaturated zone, which depends on a number of factors. Whether freezing occurs prior to snowfall or not determines whether the ground freezes. Water content at freezing determines the infiltration capacity during melting events and whether basal ice forms or not. This strongly influences the redistribution of snowmelt and the infiltration rate at any given location (French *et al.* 1999; French & Binley 2004), which again affects the dilution of chemicals with clean snow. The temperature and water saturation in the soil determines flow velocities and the degradation rates (French *et al.* 2001). In this paper we will only consider the first point.

In order to be able to predict possible changes in the use of de-icing chemicals due to climate change, a quantitative model describing the relationship between climatic factors and the use of de-icing chemicals is required. In this paper our main focus is to examine how weather conditions affect the total use of de-icing chemicals. The objectives addressed are: (1) whether it is possible to quantify the relationship between generally available climatic factors and the use of de-icing chemicals and (2) whether down-scaled climate scenarios are sufficient in order to predict the possible effects on the use of de-icing chemicals with future climate change.

METHODS

De-icing operator practices and guidelines

Interviews were conducted to assess the experience of de-icing operators at Oslo airport. Questions included: When are chemicals required for de-icing operations? Which weather conditions require the largest amounts of chemicals? Which weather variables are most important? How are weather forecasts being used, and, are these sufficient in time resolution and accuracy? These answers are important inputs for the general understanding of the practices and for evaluating the statistical results.

Study area

The analysis of the use of de-icing chemicals and weather conditions are based on data from Oslo airport, from managers of national road Rv35 and from the Norwegian Meteorological Institute. Both the road and the airport are situated on the Gardermoen aquifer, 40 km north of Oslo, Norway. It is the largest rain-fed unconfined aquifer in Norway, hence there has been a great concern for protecting the groundwater. The area is a glacial contact formation with sand and gravels dominating near the ground surface. Hydraulic conductivities (K_s) are in the range 10^{-3} to 10^{-5} m/s. The annual precipitation is about 800 mm/yr. In 1996, a new airport access road was opened (Rv35) and the new Oslo airport was opened in 1998, constituting two major sources of de-icing chemicals in the area. At the airport, propylene glycol (PG) is used on aeroplanes and potassium formate (KFo) is used on runways. The de-icing chemicals are easily degradable by bacteria and fungi which are naturally existent in the subsurface. Field experiments and modelling activities document velocities and degradation rates in the unsaturated zone (French *et al.* 2001, 2002; Farmani *et al.* 2009; Kitterød 2008). Depending on the infiltration pattern, degradation rates may be insufficient compared to velocities in the unsaturated zone. Focused infiltration may lead to larger concentrations in the groundwater. An infiltration system for road surface run-off has been constructed along Rv35. A kettle-hole lake fed by groundwater coming from Rv35, Skånetjern, has shown a doubling of the chloride concentration since the opening of the road in 1996 (Wike 2007). Simulations of groundwater flow in the area has shown that focused infiltration increases the risk of lake contamination (Flesjø 2007).

Monitoring de-icing operations and climate conditions

The management practice for de-icing is a function of climatic conditions and demands for aeroplane wings free of ice and sufficient friction on manoeuvring areas. Since the road (Rv35) and the airport were opened, the use of de-icing chemicals has been registered at different time resolutions. In this paper, the winter period has been defined as 1 October–30 April, which is the period when de-icing operations take place. At the airport, two companies conduct de-icing of aeroplanes, while OSL takes care of de-icing of the asphalted areas, such as runways, taxiways and parking areas. De-icing of aeroplanes is registered per time period (hour: minutes), while de-icing of runways and manoeuvring areas is registered per day. The same is the case for the de-icing of roads, although these data are not easily available. Accumulated values over the winter period are reported to the road authorities. Hourly data were available for the period 2005–2008 (only a limited number of climate variables and PG). Daily data were available for the period 2000–2005 for PG and 2005–2009 for KFo and PG, and the seasonal data from 1999/2000 till 2008/2009 for KFo, PG and NaCl. Daily registrations of NaCl were only available for the winter season 2005–2006.

The Norwegian Meteorological Institute measures standard climate variables such as air temperature, precipitation, air pressure, humidity, etc. Most of these are logged every 3 h while precipitation is generally logged every 12 h, and, occasionally, every 6 h. Only daily data were used in this study. In addition, a climate station is located at Moreppen; here data are logged every hour and some additional variables, compared to the official meteorological station, such as global radiation, are measured. While climate variables have been measured at the official meteorological station since 1940, the measurements at Moreppen started up in 1993 and have not been logged continuously.

Statistical analysis

The measured data collected at different time resolutions described above were analysed by different statistical methods. Principal component analysis (PCA) was performed in order to examine the covariance between variables. Correlation analysis and multivariate regression were used to examine the relationship between climatic factors and de-icing operations. PCA was performed using the Matlab program PLS_toolbox 3.5 (Wise *et al.* 2005): details about this method is also described here. For descriptive statistics, correlation analysis and multiple linear regression, the STAT Release 5.1 Data Analysis Programs for UNIX and MS-DOS by Perlman & Horan (1986) were used. An overview of the climate variables, and data on de-icing operations on local motorway (Rv35) and runways, are provided in Table 2.

Climate scenarios considered

The Norwegian Meteorological Institute has empirically downscaled climate scenarios for the Gardermoen climate station, and procedures and results are provided in Engen-Skaugen (2004). In order to evaluate the uncertainty of estimates of future scenarios for specific locations such as Gardermoen, for the purposes of predicting changes in the need for de-icing operations at Gardermoen, modelled daily data for the period 1960–1990 were compared to observations during the same period. Only specific winter conditions thought to be important for de-icing practices

Table 2 | Overview of the climate variables, and data on de-icing operations on local motorway (Rv35) and runways

Code	Name Climate variables (source: Norwegian Meteorological Institute)	Unit
FFM	Mean wind speed (10 m)	m/s
NNM	Cloud cover (0 no clouds, 8 completely covered by clouds)	–
POM	Mean air presssure	hPa
RR	Precipitation	mm
TAM	Mean temperature	°C
TAN	Minimum temperature	°C
TAX	Maximum temperature	°C
DPT	Dew point temperature	°C
UUM	Mean relative air humidity	%
UUX	Maximum relative air humidity	%
Airport operations (source: Oslo airport)		
	Departures	–
	Planes de-iced	–
PG	Propylene glycol, used for de-icing planes	kg
Type I	Propylene glycol used before take-off	kg
Type IV	Propylene glycol used preventively, overnight	kg
KFo	Potassium formate, used for de-icing of runways (mixture of granulated KFo and water)	l
Road de-icing (Source: Norwegian Public Roads Administration)		
NaCl	Road salt used along 21.1 km stretch of Rv35	kg

were considered, such as the number of days with precipitation and snow, mean temperatures, accumulated snow and length of frost periods. Downscaled scenarios based on the Hadley model and the Max Planck model and future scenarios for the period 2070–2100 based on the Hadley A2 scenario, B2 scenario and the Max Planck B2 global climate models were used in this study.

RESULTS

Interviews with de-icing operators

De-icing of aeroplanes

Safe air traffic requires clear wings, i.e. no frost or ice. According to de-icing operator manager Erik Ruud at OSL (SAS Ground Services) high loads of wet snow is the situation which normally requires the highest amounts of total liquid (a mixture of PG and water). At temperatures above −3°C pure hot water may be used. Heavy snowfall and temperatures below −3°C requires the highest amount of concentrated PG. A de-icing coordinator is on duty 20 h a day (air traffic period) during winter. They monitor changes in weather conditions continuously, based on measurement data provided by the Norwegian Meteorological Institute and Storm weather centre. The most important climate variables are dew point temperature, precipitation, temperature, wind speed and direction. Sensors on the de-icing vehicle nozzle measures temperature and automatically adjusts the ratio between pure glycol and hot water to a minimum according to dosing tables. Preventive de-icing, i.e. application of glycol after landing in the evening, reduces the total need for de-icing chemicals the next morning as long as there is no precipitation over night; hence accurate weather forecasts are very important. Since the opening of the airport in 1998, the impression is that the need for full-time staff on de-icing operations in the autumn starts up later now (early November) compared to earlier years (when it started in October). There also seems to be more frequent events of freezing rain (supercooled rain). High air humidity causes more de-icing. The challenge for the management of de-icing operations is to make sure there is sufficient numbers of staff at any given time in order to ensure punctual departures, etc. Intense snow events can cause delays in departure which may provoke the need for repeated de-icing operations.

De-icing of road and airport surfaces

According to Odd Hedlund, manager of the surface maintenance group of OSL, the use of chemicals on runways is controlled by friction criteria. If the friction coefficient (1 maximum friction, 0 no friction) is less than 0.25 the runways are closed, while above 0.4 is considered good friction according to ICAO Standard 9137-AN/898 Part 2 Airport Service Manual. Friction is measured on both runways every day when temperatures are below 3°C, or there is rain or snow on the frozen ground. On both runways there are three sets of measurements with three temperature sensors at the surface and three at 8 cm depth. These data are monitored by de-icing operators on a continuous basis, but have not been included in this work. To improve the friction, mechanical snow and ice removal is conducted and de-icing chemicals are applied if temperatures are above −8 to −10°C. Wet snow and temperatures around 0°C normally promote the highest demand for chemicals. The amounts applied depend on the wetness of the runway: guidelines exist but personnel usually adjust the amounts based on their experience. At the airport there is a maximum amount which can be applied on a given day based on environmental criteria; such a criterion does not exist for the de-icing of roads in Norway.

Climatic factors and influence on de-icing operations

Seasonal data

The normalised use of all de-icing chemicals in the Gardermoen area during the winter periods from 1999–2009 is displayed in Figure 2. They are shown together with frost sum and accumulated precipitation on days with mean temperature <0°C. Other mean properties of the same winter seasons (relative air humidity, daily precipitation and mean daily temperature) are displayed in Figure 3. Since both NaCl and KFo are used for de-icing road or runway surfaces, a similarity in consumption of the two chemicals might be expected. However, the seasonal data does not support this hypothesis.

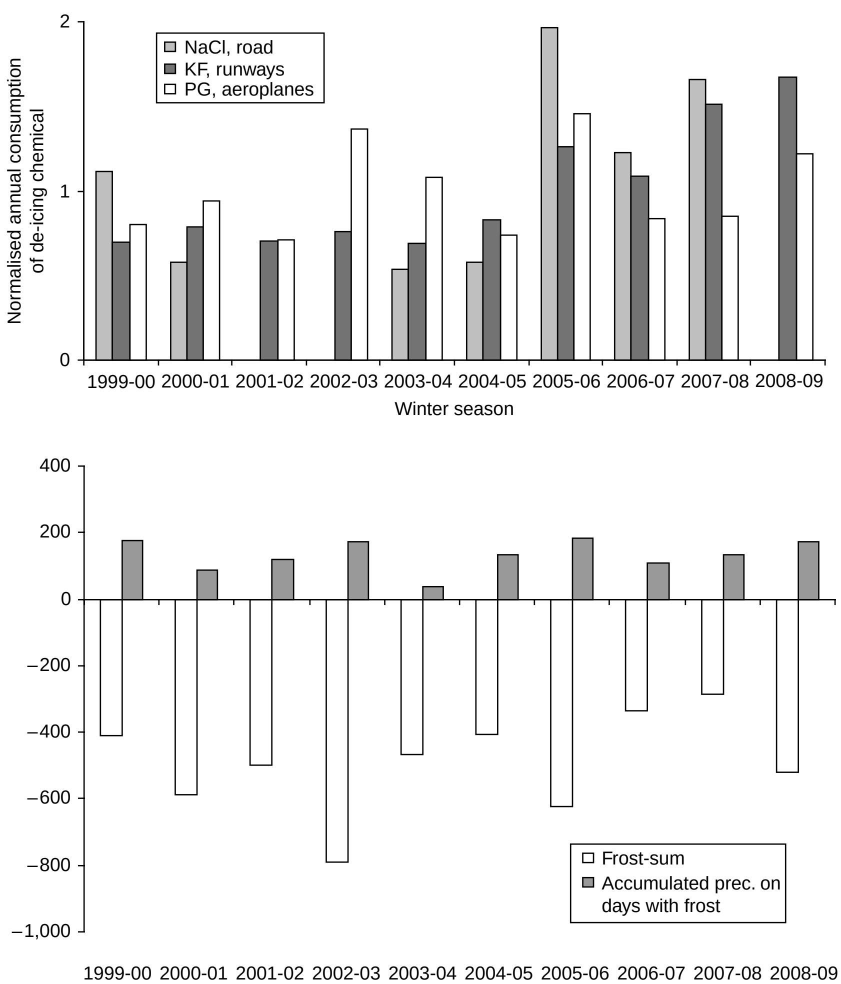

Figure 2 | Top: normalised consumption of de-icing chemicals during the winter period (1 October–30 April) at Oslo airport and Rv35 from 1999/2000 till 2008/2009, Mean consumption of de-icing chemicals over the period are: NaCl: 24.5 tonnes/km, KFo: 779 m^3 over entire airport area, PG: 1,204 m^3 total for all planes. Bottom: frost sums (accumulated mean negative daily temperatures) and accumulated precipitation on days with winter frost.

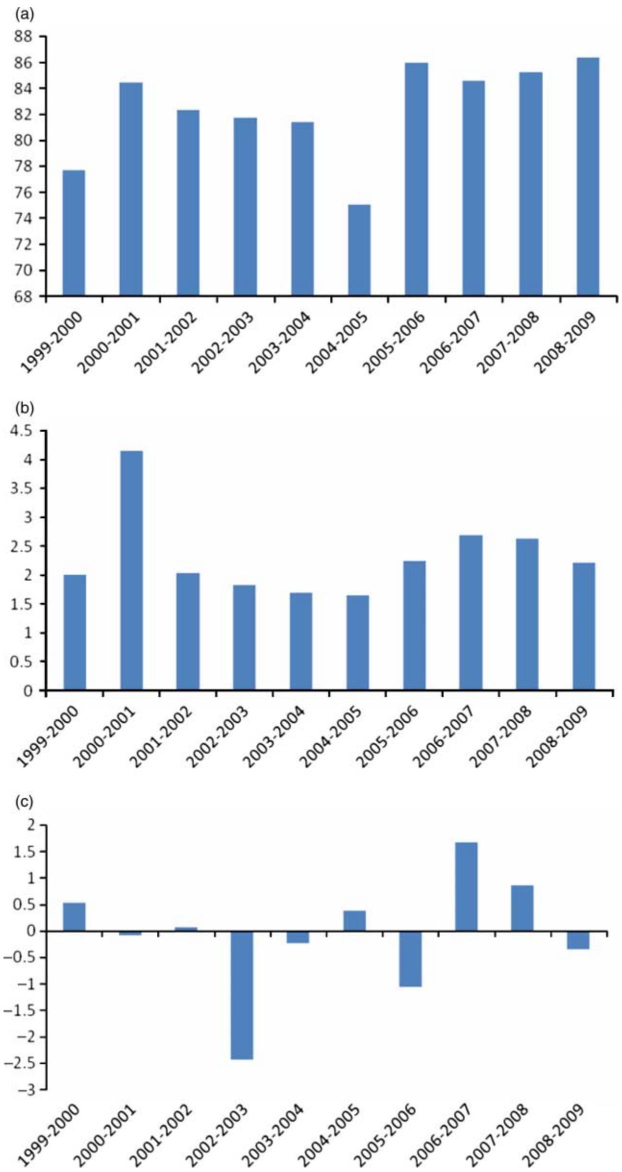

Figure 3 | Mean values of relative air humidity (a), daily precipitation (b) and mean daily temperature (c).

The consumption was higher than the mean during the last four winter seasons for both surface de-icers. There are no obvious climate patterns suggesting the specific use per winter season. The PG consumption is larger than the mean during different years than NaCl and KFo, apart from in 2005–2006 and 2008–2009, which indicates that different weather conditions may be important for the need for de-icing of aeroplanes and runways.

Daily data

Firstly the situation of de-icing or no de-icing is presented. When considering only the period between the first and last day of the use of KFo or PG accordingly, the results reveal that there is no difference in mean daily precipitation or air temperature for days with KFo use, while mean air humidity is 81% on days with no use and 89% on days with use. For PG there is no difference in mean precipitation for days with use and no use, while the mean daily air temperature is 6°C on days with no use and −1°C on days with use. Mean air humidity is 72% on days with no use of PG and 84% on days with use. The minimum and maximum daily climatic values are, however, very similar for all cases (not shown). The number of days during the entire winter period (1 October–30 April) where PG is used or not used versus mean daily temperature is shown in Figure 4(a) (data from 2000–2009). This figure reveals that PG is used on days with mean temperatures between −16°C and 12°C.

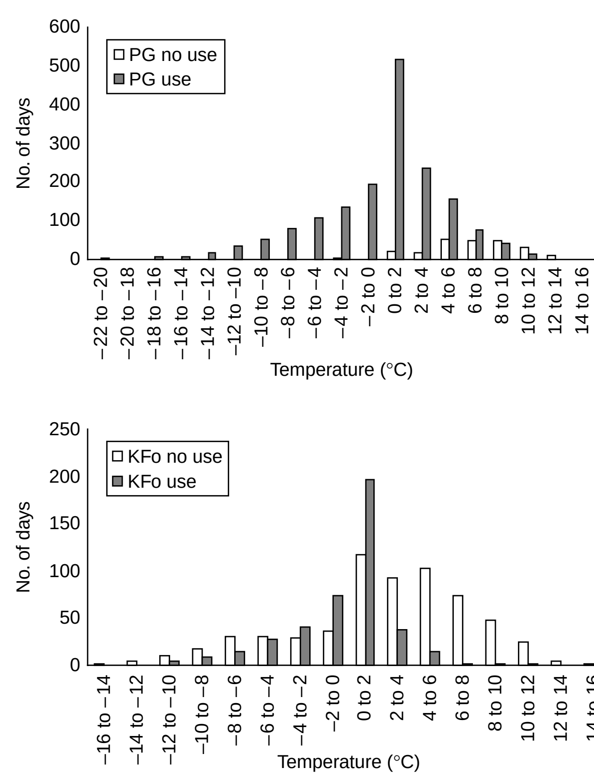

Figure 4 | Number of days with use or no use of de-icing chemicals versus temperature intervals during the winter period 1 October–30 April. Top figure shows days with de-icing of aeroplanes (PG), the bottom figure shows de-icing of runways (KFo).

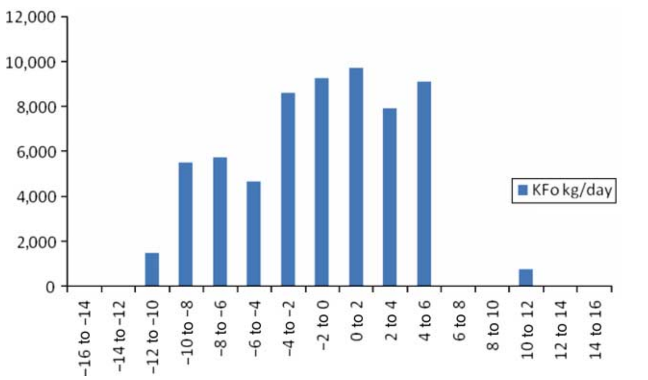

Figure 5 | Mean ammount of KFo used on days with mean daily temperatures as given along the *x* axis.

Most de-icing occurs on days with mean daily air temperatures in the interval 0 to 2°C. There are only a few days during the winter period that there is no de-icing of planes: on these days the mean air temperature is above 0°C. The most frequent use of KFo (data from 2005–2009) also occurs on days with mean temperatures in the interval 0°C to 2°C (Figure 4(b)). Most de-icing occurs from −10°C to 6°C. There are more days without any need for de-icing operations during the winter period on runways than for aeroplanes. The highest average daily consumption of KFo is used on days with mean temperatures between −4°C and 6°C (Figure 5). A daily precipitation in the range of 0–2 mm/d represents 73% of days during the winter period, and hence most de-icing occurs on such days. While PG is used on 80–90% of these days, KFo is used on about 40% of these days–the same ratio between PG and KFo use is true for most other precipitation rates (not shown).

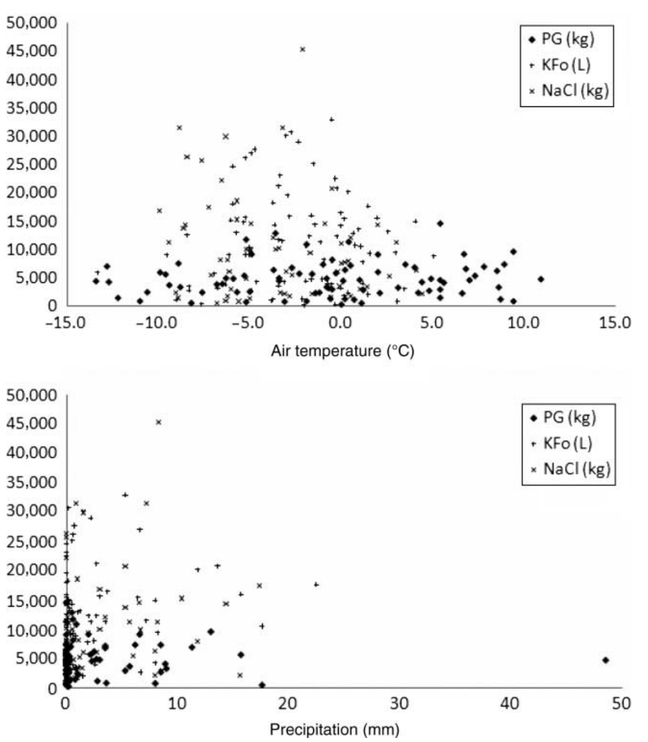

Figure 6 | Daily consumption of de-icing chemicals exemplified by data from the winter season 2005–2006 as a function of mean daily air temperature (top) and daily precipitation (bottom).

A plot of daily consumption of de-icing chemicals versus mean daily temperature and daily precipitation shown for NaCl, KFo and PG from the winter of 2005–2006 (Figure 6) shows the same pattern as above, that NaCl and KFo are used on days with mean temperatures in the interval of −10°C to 5°C, while the use of PG extends to daily means of −15°C up to 10°C. This is in agreement with the experience of de-icing operators at Oslo airport. The amount of chemicals used is not directly linked to the amount of precipitation, but whether there is precipitation or not and which form the precipitation is. Principal component (PC) analyses of the *X* variables (i.e. climatic factors and departures) revealed that 80% of the total variance was captured by four PCs (Table 3).

In Figure 7, the percentage variance described by PC1–4 is shown for each climate variable. PC1 is mainly described by temperatures (min, mean and max), but is also related to humidity, dew point temperature and wind. This is natural since, for instance, dew point is a function of temperature, vapour pressure and humidity. The Magnus-Tetens relationship is one example (Barenbrug 1974).

PC2 is mainly described by air humidity, dew point temperature and cloud cover. PC3 is described by air pressure, precipitation and wind speed, and PC4 is

Table 3 | Results of principal component analysis on daily observations of climate variables (*X* factors)

Principal component no. (PC)	Eigenvalue of Cov (*X*)	% Variance captured by this PC	% Variance captured total
1	4.98	35.6	35.59
2	3.86	27.6	63.16
3	1.32	9.4	72.57
4	0.993	7.1	79.66

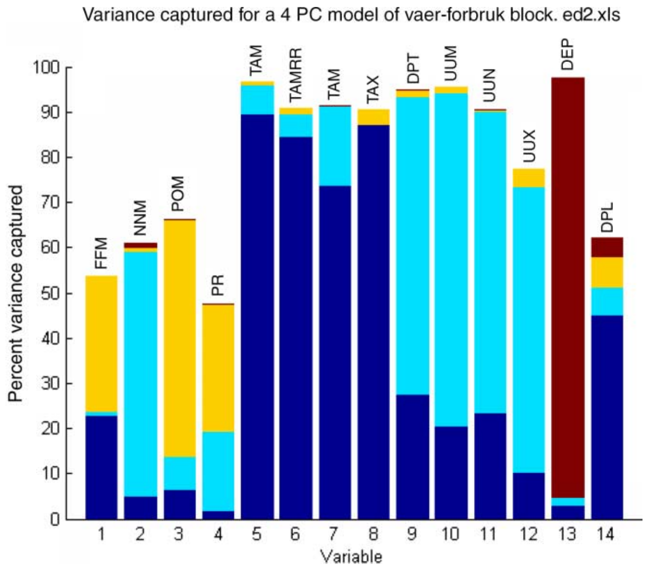

Figure 7 | Percentage of variance of climate variables captured by PC1–4 (colour shadings), variable descriptions in Table 2.

departures. Number of de-iced planes is described by all 4 PCs, but PC1 is dominant.

The same analysis for the de-icing chemicals showed that PG (types I and IV and total) and KFo were represented by two PCs. The variables which carry a high percentage of each PC were used for a multivariate linear regression model to describe the consumption of either KFo or PG as a function of climatic variables. The regression models suggested are only valid for days when de-icing chemicals are used. Different climate variables were tested for their capability of predicting PG and KFo, and the ones with the best fit are presented here:

$$PG = -83.49\,DPT + 490.5\,RR + 244.3\,FFM + 153.3\,Departures + -2156.39$$

and

$$KFo = 478\,TAM + 74.5\,UUM + 124.4\,RR + -524.2\,FFM + 29.17\,Departures + 2058$$

Symbols and units are given in Table 2. The regression model for PG has an R^2 of 0.84 while the regression model for KFo has an R^2 of only 0.08. The significance of each predictor of the regression models is provided in Table 4. The importance of the different predictors is in line with information provided by the aeroplane de-icing operators. The estimated versus observed values of PG and KFo are shown in Figure 8(a,b) and reveal that the PG model, as indicated by the significance tests, captures the main trend of the observations, but the figure also reveals that a linear model might not be the best in this case.

Table 4 | Significance tests for predictors of PG and KFo

Predictor of PG	β	R^2	*p*
DPT	−0.045	0.076	0.000
RR	0.118	0.107	0.000
FFM	0.040	0.038	0.000
Departures	0.867	0.148	0.000
Predictor of KFo			
TAM	0.186	0.335	0.001
UUM	0.082	0.285	0.146
RR	0.060	0.077	0.225
FFM	−0.097	0.338	0.095
Departures	0.200	0.242	0.000

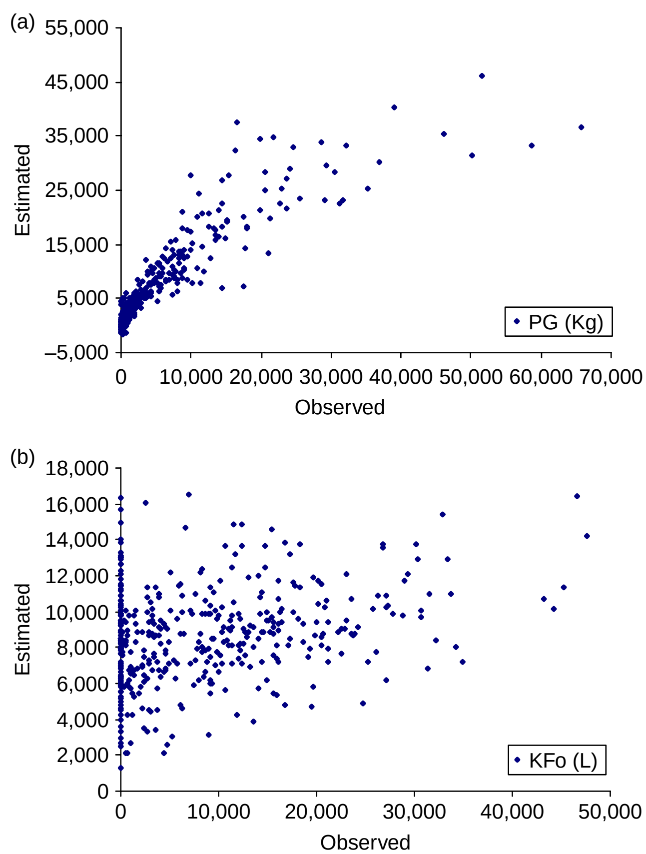

Figure 8 | Estimated consumption of de-icing chemicals from multiple linear regression models versus observed values of PG (a) and KFo (b).

In contrast to the PG model, the multiple linear regression model of climate variables is not capable of predicting amounts of KFo, also documented by the poor results of the significance tests.

Hourly data

Air traffic is not evenly distributed throughout the day: most commonly, there are two peak times, one in the morning and one in the late afternoon/evening (Figure 9). The mean amount of PG used per hour and hourly air temperatures are also shown. The figure illustrates that the maximum PG use occurs between 7.30–9.30, during which time the temperatures are likely to be less than 0°C in the winter period. The figure also illustrates that changing temperatures around 0°C causes an increased consumption of PG.

Downscaled climate scenarios

Downscaled climate variables for the Gardermoen area (Engen-Skaugen 2004) relevant to the use of de-icing chemicals were examined. Key factors based on the information above are dew point temperature (implicitly; temperature and humidity), precipitation and wind. Only temperature and precipitation are downscaled from the GCMs. The modelled number of days with precipitation (Figure 10) seems to be quite uncertain; the modelled data for 1960–1990 show a stronger similarity to the future

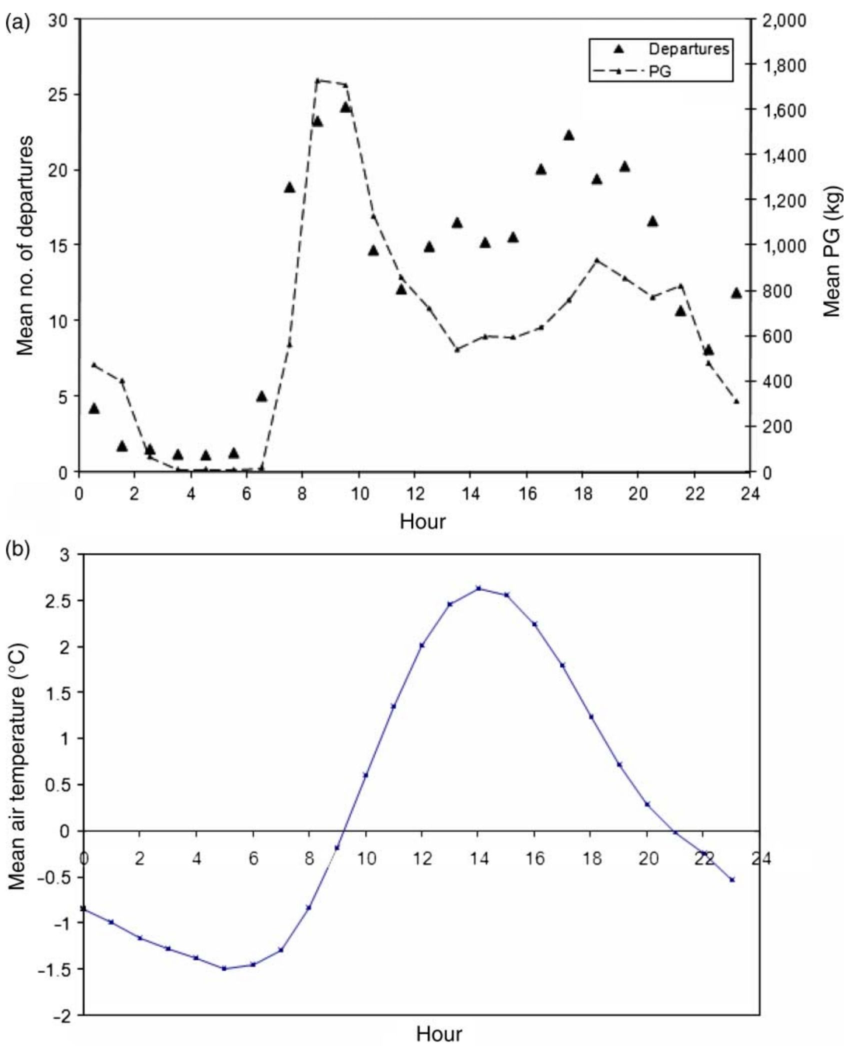

Figure 9 | Mean hourly number of departures and consumption of propylene glycol (PG, kg) (a) and air temperature (b).

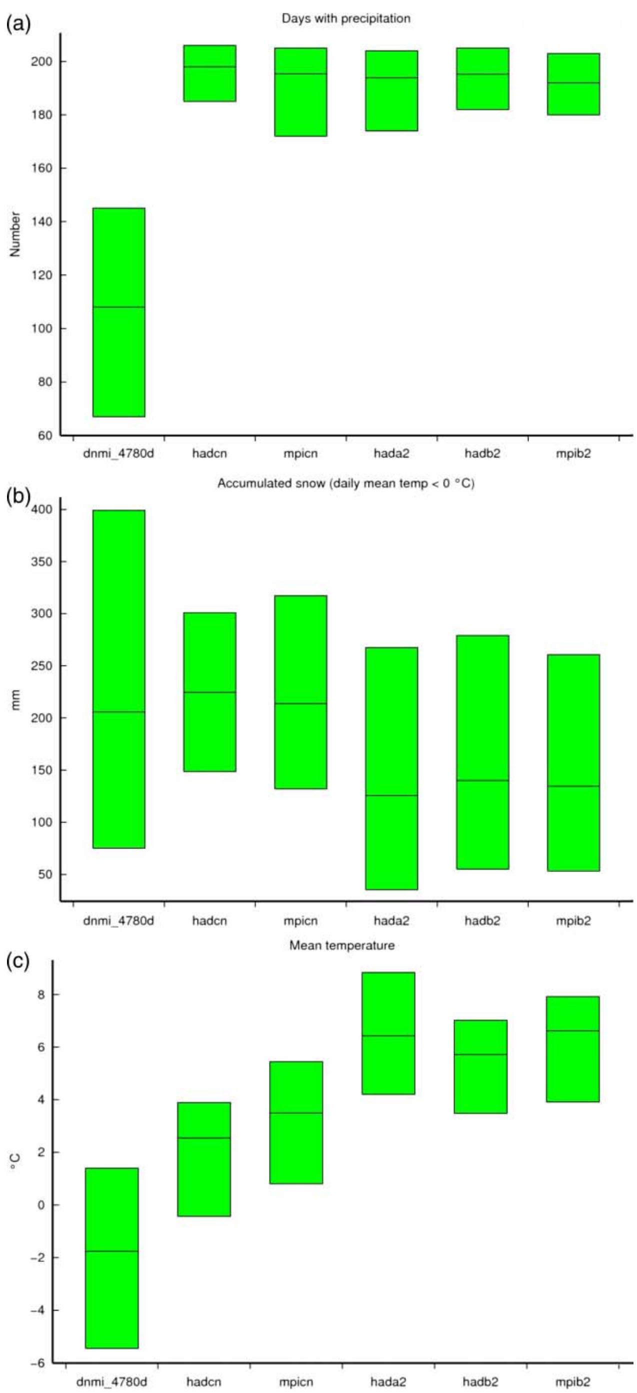

Figure 10 | (a): number of days with precipitation, (b): accumulated precipitation on days with frost and (c): mean temperature (*y* axis), along the *x* axis: observed during the period 1960–1990 (dnmi_4780d), downscaled scenarios based on the Hadley model (hadcn) and the Max Planck model (mpicn), and future scenarios for the period 2070–2100 based on the Hadley A2 scenario (hada2), B2 scenario (hadb2) and the Max-Planck B2 (mpib2) global climate models (Engen-Skaugen 2004). Centre line indicates mean value, grey box shows maximum and minimum values.

climate situation, while the accumulated precipitation on days with mean temperature less than 0°C seems to be fairly representative of the observed data. Temperature predictions show modelled daily values about 3°C higher than those observed during the 1960–1990 period. What that implies for the predicted increase of 7.6°C in mean temperatures for the winter period is beyond the scope of this paper and needs to be addressed by the meteorologist working with downscaling procedures.

DISCUSSION AND CONCLUSION

Clearly the use of de-icing chemicals is related to weather conditions: however, to quantify the relationship between climate variables and the amount of de-icing chemicals is not straightforward based on collected data on climate and de-icing routines at Gardermoen. Compiled data for each winter season from 1999/2000 to 2008/2009 does not indicate that a specific winter type, i.e. frost sum, accumulated precipitation on days with frost or mean air temperature, gives a hint about how much de-icing chemicals are to be used. The small difference between mean climatic properties on days with or without the use of de-icing chemicals supports the conclusion that it is difficult to predict change in use based on mean daily values.

During the last four winters, the use of de-icing chemicals on roads and runways is larger than the mean, but these winters do not seem different to the preceding winters. For the road sector, the contract with de-icing operators changes every 3–7 years, so this can cause a change in routines; also changes in personnel can affect the use of chemicals. Since no upper limit on accumulated NaCl consumption exists in guidelines for road de-icing operators, its use will be more affected by the choice made by the personnel in charge. For the airport strict environmental limitations apply, so procedures are likely to be more similar among staff. OSL Ground Services have been in charge over the entire period. According to comments from OSL, there has been more focus on friction over the last few years, which could have caused an increased use of chemicals lately.

Mean daily temperatures between 0–2°C gives the largest numbers of days with de-icing operations on both runways and aeroplanes. Hence increased frequency of fluctuations about the freezing point will most likely increase the use of chemicals in the future. The temperature interval of KFo and NaCl use is smaller than for PG, −10 to 6°C. Hence a shift in mean winter temperature from −2 to 1°C (observed for 1999–2009) to 7°C, as indicated by the downscaled climate scenarios for the area, would greatly reduce the need for de-icing. The transition period to a warmer climate may, however, increase the risk of temperature fluctuations about the freezing point; hence a temporary increase might be expected. While KFo is seldom used below −7°C, there is no lower limit for the use of PG; hence the temporary increase which might be seen for the use of KFo may not be observed for PG. Most de-icing operations take place with low precipitation rates, but this is merely an effect of the distribution of precipitation. Dry cold snow seldom requires de-icing operations with chemicals on runways. Again the combination of precipitation with temperatures around 0°C promotes more use of chemicals.

The linear regression model for PG had a high significance and all predictors were significant; still a linear model might not be the best in this case. The regression model suggests that lower dew point temperatures, increased precipitation and wind as well as increased numbers of departures will increase the use of PG. There were very few days when PG was not applied; hence the model may at least serve as a tool to provide a first estimate of future use due to changes in these climate variables as well as changes in the number of departures.

The regression model for KFo was weak: part of this may be explained by increased demand for friction and also the human factor. The need for de-icing is likely to increase towards 0°C from higher and lower temperatures, and the linear model does not capture the shift which occurs at the freezing point. Another important difference between the two de-icing chemicals is that standard meteorological measurements are more likely to be representative of the same situation as near aeroplane wings, where PG is applied. The use of KFo on runways depends on what the conditions are on the ground surface, not at 2 m height, where air temperature is measured. Both during freezing and thawing of the ground, heat transport in the ground due to temperature gradients within the soil and between soil and air will affect the freezing process on the ground surface. Hence spatial gradients which are important are not represented in the climate data used for our analysis. Another factor which may explain the failure in predicting the use of KFo as a function of standard climate variables is that de-icing operators act upon weather prognosis and may apply chemicals which possibly weren't required if the prognosis is wrong.

The aim of this paper was not to try to estimate changes in the use of de-icing chemicals as a function of climate change but rather to examine whether such relationships can be quantified and to illustrate some challenges with using such relationships. In conclusion the use of PG can be predicted as a function of generally available climate variables and the number of departures, while this is not the case for the use of KFo. Downscaled climate scenarios may not be of sufficient spatio-temporal resolution to be able to provide inputs for these types of models and not all relevant climate variables are provided in the downscaled climate scenarios, such as, for instance, wind speed and dew point temperature. The overall increase in mean winter temperature of 7.6°C does, however, suggest a reduced need for de-icing chemicals for the period 2071–2100, but with a temporary increase for the next decades due to increased numbers of fluctuations about 0°C in the Gardermoen area. The results of this study reveals the high uncertainty of downscaled climate scenarios and the need to improve procedures in order to provide scenarios which can be of use in practical management planning at a local scale.

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