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The vulnerability of northern European vegetation to ozone damage in a changing climate

An assessment based on current knowledge

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Preface

This report describes an assessment of the potential vulnerability of far northern European vegetation to ozone damage in a changing climate. This assessment has been made within the framework of the research program "Swedish Clean Air and Climate Research Programme, phase 2", financed by the Swedish Environmental Protection Agency. Furthermore, results from several other ongoing research projects in the Nordic countries have contributed to the results presented and conclusions made in this report.

One important research question has been if there are increasing risks for ozone impacts on the tundra, arctic and sub-arctic vegetation as well as boreal forests in northern Fennoscandia due to climate change, in combination with high spring ozone concentrations and in relation to the advance of the start of the growing season. Another question has been if a high ozone vulnerability of northern vegetation represents an argument to further reduce ozone precursor emissions, compared to the current strategies, which are based on the risks for ozone impacts on the European vegetation in general. The assessments that are described in this report are part of the attempts to answer these research questions.

Scientists from three Nordic countries, Sweden, Norway and Finland, have joined in three workshops, in Gothenburg 11th June 2018 and 27th August 2019 as well as in Oslo 12th November 2018, to present and discuss different aspects of exposure and effects of ozone on vegetation types typical for northern vegetation zones. The assessments rely on the experience and expertise of the authors.

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Summary

The potential vulnerability of vegetation at northern latitudes to ozone damage was assessed based on current knowledge with regard to air ozone concentrations and leaf ozone uptake as well as to plant traits affecting ozone tolerance. The focus was on the northern European arctic, alpine and northern boreal vegetation zones, with a special focus on high-altitude vegetation. In particular, we analysed if there are increasing risks for ozone impacts on northern vegetation due to high spring ozone concentrations in relation to climate change induced shifts such as e.g. an earlier start of the growing season.

The ozone concentrations in these regions are characterized by the influence of a combination of conditions caused by high latitudes and high altitudes. Ozone concentrations increase with altitude and the difference in ozone concentrations between day and night are smaller at high-altitude and high-latitude sites. Summer periods with long daylight conditions potentially promote the leaf ozone uptake through the open stomata.

The aims of this report were:

- To assess the current state of knowledge regarding the potential vulnerability of far northern vegetation to ozone damage, today and in the future
- To provide advice for policy implications regarding necessary ozone precursor emission abatement
- To provide advice for future research and monitoring of ozone impacts on the vegetation at northern latitudes

Ongoing environmental changes affecting far northern latitude ecosystems were reviewed. Current and novel methods were described for how to estimate the time of year during which the ozone exposure for vegetation should be accumulated. Time trends for ozone concentrations at northern latitudes were analysed. Ozone episodes with high concentrations at far northern latitudes were described. Source attributions of northern ozone concentrations were analysed. Environmental conditions at far northern latitudes that might be important for ozone damage were evaluated. Plant traits that can influence the ozone vulnerability were discussed. Current experimental results for ozone injury on northern plant species were evaluated. Future scenarios for ozone impact on northern vegetation were discussed. Some important results from the analyses are described below.

At high altitudes and high latitudes, the ozone concentrations are relatively similar during day- and night-time. Furthermore, at high latitudes, the long daylight duration during the summer has the potential to increase the duration of the daily period with plant gas exchange and leaf ozone uptake. Therefore, the absorption of ozone through the stomata may potentially be higher at northern latitudes. However, measurements of light intensity and quality at northern sites in combination with a simple calculation example illustrated that this probably was not the case, since the potential added ozone uptake in the early morning and late evening at northern sites may be cancelled out by a lower ozone uptake in the middle of the day, as compared to southern sites.

Both data on budburst and data on ecosystem CO_2 exchange as well as meteorological observations show that there has been a development towards an earlier start of the growing season during the year, with approximately 0.5 – 1 day per year. Thus, there is clear evidence for an earlier start of the growing season, which is likely to continue. However, the timing of the spring ozone maximum is

also shifted towards earlier in the year. There is presently no evidence for an increasing overlap between the growing season and the ozone peak. Despite this, there is a potential for increased ozone uptake to vegetation in spring due to the earlier growing start of vegetation and increased uptake of ozone to vegetation in May. The impact of this on the accumulated phytotoxic ozone dose for northern vegetation needs to be investigated further.

The overall conclusions about the present and near future ozone vulnerability of northern vegetation were:

- There remain uncertainties regarding to what extent northern vegetation is affected by ozone exposure.
- According to current knowledge, we could not find evidence that expected changes in ozone concentrations and climate would make the northern arctic, alpine and subalpine vegetation substantially more vulnerable to ozone than other types of European vegetation.
- The risk of significant and lasting negative impact of the current exposure to ozone on northern boreal forests is most likely not greater than for boreonemoral and nemoral forests in southern Fennoscandia.
- However, peak ozone concentrations occurring in spring and early summer may affect vegetation at northern latitudes in Fennoscandia since the start of the growing season in the future may occur earlier during the year.

The policy implications that can be derived from these conclusions were:

- The current state of knowledge implies that ecosystems in the far north are not more susceptible to ozone than vegetation in other parts of Europe. Hence, we cannot advocate for a stronger reduction of ozone precursors emissions based exclusively on the ozone sensitivity of vegetation in the far north.
- Policies designed to reduce emissions of ozone precursors to protect vegetation in other parts of Europe as well as in the entire northern hemisphere are likely to suffice to protect vegetation in northern Fennoscandia.

There are important remaining knowledge gaps. Our conclusions are based on important, but limited observations. Experimental evidence from investigations specifically designed to study ozone sensitivity of high-altitude vegetation in northern Europe are to a large extent lacking. It is recommended that further experimental research is undertaken to directly compare the ozone sensitivity of plants of high-latitude/high-altitude origin with that of plants (species, genotypes) representative of regions of the southern part of the Nordic region. This research should include the characteristics of the high-latitude climate and other conditions.

A specific research question is if the new ozone critical levels for European vegetation based on POD_YSPEC (Mapping Manual, 2017) are correct, both regarding calculation methodology as well as impact assessments? In particular, there is a lack of information about the degree of stomata closure during nights in high-latitude area plants. This is important for the modelling of ozone uptake (dry deposition) in these areas and requires coordinated measurement campaigns in close cooperation with modelers.

Further research questions may be related to the future development of the northern regions – e.g. oil and gas extraction including flaring, shipping, more tourism and climate change – how will that affect the ozone exposure of in the northern vegetation? Do future ozone precursor emission scenarios describe this correctly? Will warm and dry summers like 2018 become more frequent in connection with climate change, and how will this affect ozone impacts on vegetation?

There are currently very few, long term ozone monitoring stations in the arctic and alpine vegetation zones, in particular at high altitudes. Given the expected increase in anthropogenic activities in these areas in combination with climate change, it is strongly recommended to increase the number of high-altitude ozone monitoring sites in these regions.

Sammanfattning

I denna rapport utvärderas riskerna för att växtligheten vid långt nordliga breddgrader i de nordiska länderna påverkas negativt av marknära ozon, idag och i framtiden. Fokus ligger på arktisk, alpin och nordlig boreal växtlighet.

Målsättningarna med de analyser som redovisas i denna rapport var:

- Att inventera och utvärdera nuvarande kunskap vad gäller riskerna för en negativ påverkan av marknära ozon på växtligheten vid nordliga breddgrader, nu och i framtiden.
- Att ge förslag vad gäller eventuella ytterligare åtgärder för att minska utsläppen av ozonbildande ämnen, som är motiverade utifrån att skydda den nordliga växtligheten mot ozonskador.
- Att ge förslag på ytterligare kunskap som behövs vad gäller bedömningar av ozonkänsligheten hos nordlig växtlighet.
- Att ge förslag på hur riskerna kring ozonpåverkan bör övervakas i framtiden.

Bedömningarna baseras på nuvarande kunskap vad gäller koncentrationerna av ozon i luften samt i vilken utsträckning ozon tas upp till växternas blad och barr. I rapporten sammanfattas pågående miljöförändringar vid nordliga breddgrader. Metodiken kring hur ozonexponeringen hos den nordliga växtligheten bör beräknas diskuteras. Förändringar av ozonkoncentrationerna i luften och dess orsaker sammanfattas. Hur egenskaperna hos den nordliga växtligheten kan tänkas påverka känsligheten för ozonpåverkan utvärderas. Kunskaper från experimentella studier med särskild inriktning på nordlig växtlighet sammanfattas.

Ozonkoncentrationerna i dessa områden påverkas av såväl det nordliga geografiska läget som höjd över havet. Ozonkoncentrationerna ökar med ökad höjd över havet, och skillnaderna i ozonhalter mellan dag och natt minskar på hög höjd. Dagsljus dygnet runt medför potentiellt att bladens klyvöppningar kan stå öppna en stor del av dygnet och därmed även att upptaget av ozon till bladen kan pågå en större del av dygnet, jämfört med vad som är fallet vid sydligare latituder.

Särskilt bör beaktas att det vid nordliga breddgrader förekommer höga – och ökande – ozonhalter på våren och att de högsta ozonhalterna förskjuts till allt tidigare datum på året. Samtidigt medför klimatförändringarna att växtsäsongen i dessa områden startar allt tidigare på året. Ett ökande överlapp i tiden mellan höga ozonhalter och en tidigare start på växtsäsongen kan medföra att riskerna för ozonpåverkan på den nordliga växtligheten ökar över tid.

Norr om polcirkeln är det under sommarmånaderna ljust, och ozonhalterna på hög höjd är höga, dygnet runt. Bladens klyvöppningar öppnar i ljus, vilket gör att ozon potentiellt kan tas upp till bladen dygnet runt. Det är därför möjligt att det vid en viss halt i luften är en större andel av ozon som tas upp till bladens inre och därmed kan skada växternas metabolism och tillväxt. Dock visade beräkningar baserade på ljusmätningar vid olika breddgrader i Norge att detta sannolikt inte är fallet. Det ökade ozonupptaget som beräknades för tidiga morgnar och sena kvällar kompenserades med ett minskat ozonupptag mitt på dagen. Detta berodde på att solen mitt på dagen står lägre vid nordliga breddgrader, vilket resulterar i lägre ljusintensiteter och ett lägre ozonupptag mitt på dagen, jämfört med vid sydligare breddgrader.

Observationer av tidpunkten för bladsprickning, mätningar av ekosystemens upptag av koldioxid samt beräkningar baserade på meteorologiska observationer, pekar på att starten för växtsäsongen vid nordliga breddgrader har förändrats och inträffar allt tidigare på året. Detta kan förväntas

fortsätta de närmaste åren i takt med den fortsatta förändringen av klimatet. Vid nordliga breddgrader förekommer de högsta ozonhalterna under våren, och halterna blir allt högre och inträffar allt tidigare på året. Det är i nuläget osäkert om överlappet mellan dessa båda processer kommer att öka i framtiden. Detta behöver utredas vidare.

Övergripande, baserat på den kunskap som sammanställts i rapporten, kan följande slutsatser dras avseende riskerna för en ökad påverkan från marknära ozon vad gäller växtligheten vid nordliga breddgrader:

- Det kvarstår betydande osäkerheter vad gäller i vilken utsträckning som nordlig växtlighet påverkas negativt av ozon nära marken.
- Baserat på nuvarande kunskap har vi inte funnit tillräckliga argument för att dra slutsatsen att de förväntade förändringarna vad gäller koncentrationer av ozon i luften, i kombination med ett förändrat klimat, kommer att medföra en större påverkan på växtligheten på nordliga breddgrader, jämfört med växtligheten i övriga Europa.
- Riskerna för betydande och bestående, negativ inverkan från nuvarande ozonexponering av nordliga boreala skogar är sannolikt inte större, jämfört med boreo-nemorala och nemorala skogar i södra delarna av de nordiska länderna
- Korta perioder med höga ozonhalter under vår och tidig sommar kan dock komma att påverka växtligheten vid nordliga breddgrader i större utsträckning, om de höga ozonhalterna sammanfaller tidsmässigt med en tidigare start på växtsäsongen.

Utifrån ovanstående slutsatser kan följande rekommendationer ges avseende åtgärdsstrategierna på Europanivån vad gäller begränsningar av utsläpp av ozonbildande ämnen:

- Nuvarande kunskap tyder på att växtligheten vid nordliga breddgrader inte är mer känsliga för ozonpåverkan jämfört med växtligheten i övriga delar av Europa. Därför kan vi inte motivera ytterligare begränsningar av utsläppen av ozonbildande ämnen baserat enbart på särskilda risker för denna nordliga växtlighet.
- Redan beslutade åtgärdsstrategier för att minska utsläppen av ozonbildande ämnen för att minska påverkan på växtligheten i Europa som helhet, såväl som för hela norra halvklotet, kommer sannolikt att vara tillräckliga även för att minska påverkan på växtligheten vid nordliga breddgrader

Det finns viktiga, kvarvarande kunskapsluckor vad gäller påverkan av ozon på växtligheten vid nordliga breddgrader. Våra slutsatser ovan baseras på viktiga, men begränsade, observationer. Det saknas i stor utsträckning resultat från experimentella studier som är särskilt inriktade på de förhållanden som råder vad gäller växtekosystem på hög höjd vid nordliga breddgrader. Vi rekommenderar att man satsar på ytterligare experimentell forskning med en särskild inriktning på att jämföra ozonkänsligheten hos olika växtslag med ursprung från hög höjd vid nordliga breddgrader med motsvarande ozonkänslighet hos olika växtslag (arter, genotyper) med ursprung från lågland vid mer sydliga breddgrader i de nordiska länderna.

En specifik forskningsfråga är om de kritiska belastningsnivåerna för ozonpåverkan på växtligheten som används på Europanivå baserat på $POD_{y}SPEC$ är korrekta, både vad gäller beräkningsmetodik och utvärderingar av påverkan. I synnerhet är kunskapen bristfällig vad gäller i vilken utsträckning klyvöppningarna står öppna nattetid, vilket i sin tur medger upptag av ozon till bladen nattetid. Detta kräver gemensam, samordnad forskning med såväl modellerare som mätinriktade forskare.

Ytterligare frågor som behöver besvaras hänger ihop med den framtida samhällsutvecklingen vid nordliga latituder – till exempel ökad förekomst av så kallad fackling vid utvinning av gas och olja, utökad fartygstrafik samt en ökad turism – hur kommer detta att påverka den framtida utvecklingen vad gäller förekomsten av ozon nära marken vid nordliga breddgrader? Är nuvarande framtidsscenarier vad gäller utsläppen av ozonbildande ämnen korrekta?

I ljuset av framtida klimatförändringar, kommer varma och torra somrar, som den 2018, att bli vanligare och kommer det att ha betydelse för hur ozonet påverkar den nordliga växtligheten?

Det finns i nuläget relativt få mätplatser för ozonhalter i de arktiska och alpina växtzonerna, i synnerhet vad gäller mätningar på hög höjd. Mot bakgrund av ökade antropogena aktiviteter i dessa områden rekommenderar vi att antalet mätplatser för ozon i dessa områden utökas.

1 Introduction

Tropospheric ozone is a photochemical pollutant produced mainly from the precursors nitrogen oxides (NO_x), volatile organic compounds and carbon monoxide, under the influence of solar radiation. Ozone has negative effects on human health (WHO, 2006) as well as on the yields of crops and forests and it may affect semi-natural vegetation (Royal Society, 2008). In addition, it is an important greenhouse gas (IPCC, 2013).

Observations as well as modelling studies show a decrease in the level and frequencies of high ozone concentration peaks in large parts of Europe (e.g. Karlsson et al., 2017). Furthermore, there is evidence that northern hemispheric background ozone concentrations have increased until about 2010 (Parrish et al., 2012; Monks et al., 2015; Derwent et al., 2018; Wespes et al., 2018). The minimum daytime ozone concentrations have increased in northern Europe during 1990–2015 (Klingberg et al., 2019), and hence the ozone exposure of the vegetation has become more chronic, with smaller variations during the course of the day as well as between days. Moreover, measurements of ozone show an annual variation, with a distinct maximum during spring in the Northern Hemisphere mid-latitudes (Monks, 2000; Vingarzan, 2004). This is particularly pronounced in the far north of Europe (Klingberg et al., 2009; 2019), with a shift over time of the spring maximum to earlier dates in the year (Andersson et al., 2017).

Presently, the vegetation growing season largely starts after the ozone spring maximum in northernmost Europe, but studies have shown an earlier onset of spring and a lengthening of the growing season at high latitudes (Menzel et al., 2006; Karlsson et al., 2007). An increasing overlap between the spring ozone concentration maximum and the growing season could lead to an increased risk of ozone impacts on vegetation in this region (Karlsson et al., 2007; Klingberg et al., 2009). Finally, increasing human activities at northern latitudes, e.g. increased shipping in the Arctic, has the potential to increase regional emissions of ozone precursors and hence increase ozone formation in the north (Tuovinen et al., 2013).

Thus, it is important and timely to assess the potential vulnerability of northern vegetation to ozone damage. This review focuses mainly on the impacts of ground level ozone on the vegetation in the far northern European arctic, alpine and northern boreal vegetation zones, according to Hagen et al. (2013). These types of vegetation cover large parts of inland northern Fennoscandia. The environmental conditions in these regions are determined by the combination of high latitudes and high altitudes. The vegetation in Denmark and on Iceland is not considered in this assessment.

Results from environmental monitoring, as well as other results, from a number of different sites in Fennoscandia are used in this report. The geographical positions as well as the altitudes of these sites are shown in Figure 1 and Table 1.

The aims of this report were:

- To assess the current state of knowledge regarding the potential vulnerability of far northern vegetation to ozone damage, today and in the future
- To provide advice for policy implications regarding necessary ozone precursor emission abatement
- To provide advice for future research and monitoring of ozone impacts on the vegetation at far northern latitudes

Figure 1. A map showing the positions for the different sites that are referred to in this report. The light blue colour indicates past and present EBAS/EMEP ozone monitoring stations, measurement campaigns including ozone observations are marked grey, while all remaining sites are coloured in black.

Table 1. Geographical positions and altitudes for the different sites that are referred to in this report.

ID	Name	Latitude	Longitude	Altitude [m asl]
1	Råö	57°23'N	11°55'E	5
2	Hønefoss	60°08'N	10°15'E	126
3	Åreskutan	63°24'N	13°06'E	1 250
4	Bredkälen	63°51'N	15°20'E	404
5	Flakaliden	64°07'N	19°27'E	310
6	Rosinedalsheden	64°10'N	19°45'E	-
7	Vindeln	64°15'N	19°46'E	225
8	Tustervatn	65°50'N	13°55'E	439
9	Myrberg	66°03'N	20°38'E	220
10	Sodankylä	67°21'N	26°38'E	179
11	Nikkaluokta	67°51'N	19°01'E	465
12	Esrange	67°53'N	21°04'E	475
13	Pallas Sammaltunturi	68°00'N	24°09'E	565
14	Abisko	68°21'N	19°3'E	385
15	Palovaara	68°13'N	22°53'E	310
16	Kilpisjärvi station	69°03'N	20°50'E	566
17	Svanvik/Pasvik	69°27′N	30°02'E	30
18	Karasjok	69°28'N	25°13'E	333
19	Kevo	69°45′N	27°01'E	100

2 Ongoing environmental changes affecting northern latitude ecosystems

This chapter contains a general description of the environmental changes, in addition to ozone, that can affect vegetation and potentially modify its responses to ozone at northern latitudes, such as climate change, air quality change, deposition of nutrient compounds, arctic greening and arctic browning. In this context, it is important to stress that the vegetation at far northern mountain areas is far from pristine in character (Kullman, 2016). It has been under human influence for more than ten thousand years and to a large extent used as pasture ground for reindeer and livestock as well as for forest management. The ecosystem recovery after human disturbance is very slow at far northern latitudes (Becker and Pollard, 2016.)

2.1 Changes in climate

The global mean temperature has increased by approximately 0.8 °C since the late 19th century, while the Arctic has warmed by 2 ° to 3 °C during the same time period (Post et al., 2019). To map climate trends in Fennoscandia we explored the gridded temperature and precipitation dataset for Fennoscandia (NGDC, Tveito and Lussana, 2018), with a high spatial resolution, 1 km. The dataset is an extension of the operational gridded datasets (called “Se Norge”) produced by MET Norway for more than a decade (Lussana et al., 2018a; 2018b). The dataset is based on station observations from Fennoscandia, Russia, the Baltic states, Poland and Germany, through Bayesian Optimal Interpolation. It is openly accessible (http://thredds.met.no/thredds/catalog/ngcd/catalog.html).

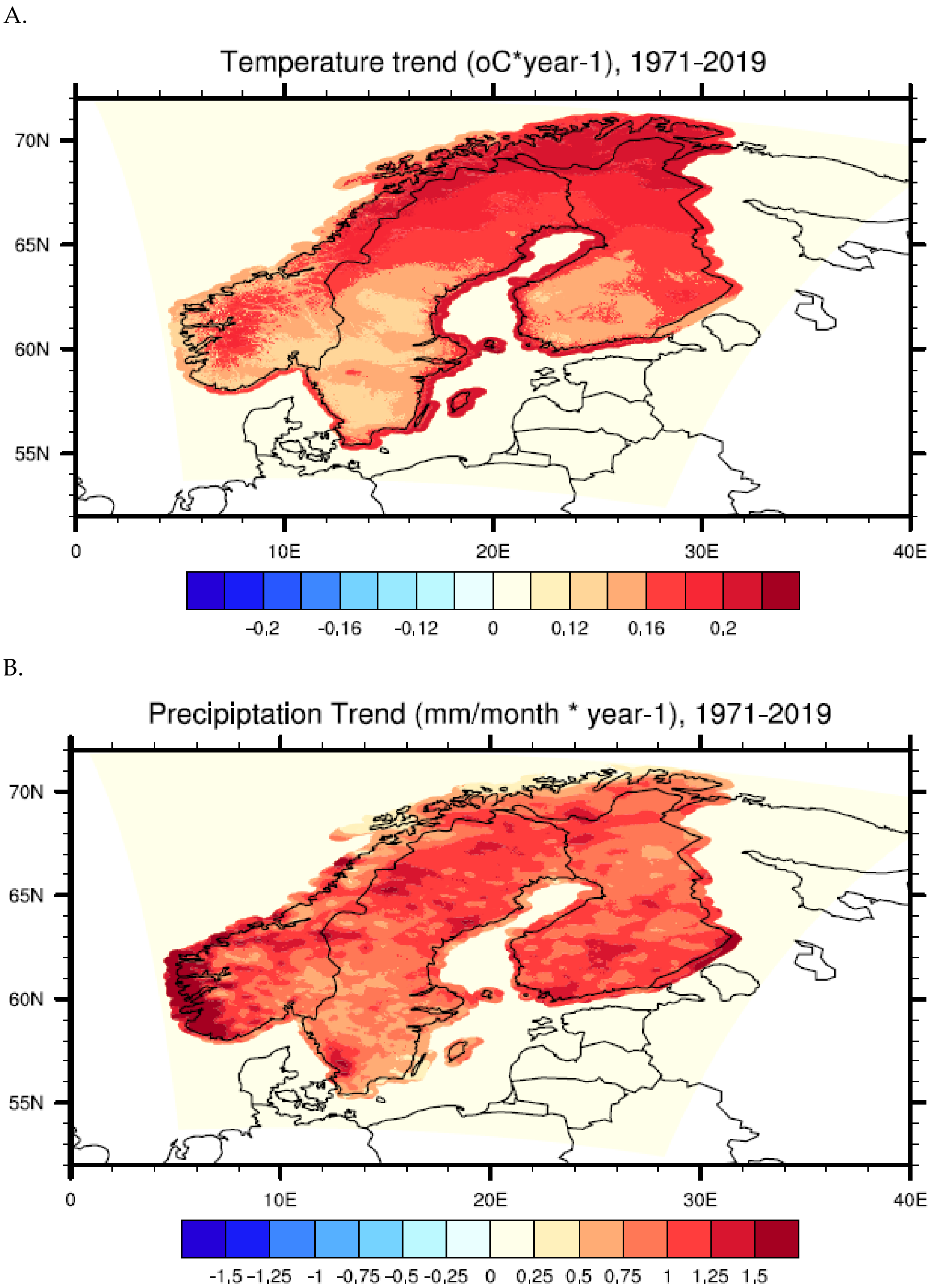


Figure 2. Trends during 1971-2019, in A, temperatures ($^oC*yr^{-1}$); B, Precipitation ($mm/month*yr^{-1}$), derived from the NGCD dataset (Tveito and Lussana, 2018). Trends are shown for May-August averages. Plots by courtesy of Hui Tang.

Figure 2 shows changes in temperature and precipitation during the period 1971-2019, for May-August, the bulk of the growing season. There is a unanimous warming in all Fennoscandia. The warming is stronger toward the north, in agreement with the global picture. Trends in precipitation follow a similar pattern, with unanimous increase in the same months. The strongest absolute increase in precipitation is on the west coast of Southern Norway, which also has the highest precipitation amounts. We have also analysed trends of total surface solar radiation from the COSMO-REA6 reanalysis (https://reanalysis.meteo.uni-bonn.de/?COSMO-REA6), based on the NWP model COSMO (Russo et al., 2019). Trends are quite scattered across Fennoscandia, although mostly negative, indicating a somewhat increased cloud cover in much of Fennoscandia (not shown). However, global radiation in Sweden has increased since 1983 based on homogenized data from the Swedish solar radiation network, see https://www.smhi.se/klimat/klimatet-da-och-nu/klimatindikatorer/stralning-1.17841.

Climate extremes may be just as important for ozone and vegetation as mean climate. In the recent decades, Europe has experienced several heat waves, known to impose stress to trees and plants, notably 2003, 2010, 2018 and 2019, indicating an increase in frequency over earlier periods (Russo et al., 2015; Dirmeyer et al., 2020). The heatwave in 2018 was particularly pronounced in Fennoscandia, with monthly mean temperatures 3–6 degrees warmer in May and July compared to the 1981–2010 period (Skaland et al., 2019; Sagen, 2020). The maximum temperatures were even more affected, with 4–7 degrees above normal in most of Fennoscandia in the same two months (Dirmeyer et al., 2020). At the same time, precipitation was lower than normal in most Fennoscandia, with the exception of the northernmost area which had normal or slightly more precipitation than normal. As pointed out by Johansson et al. (2020), warm and dry summer conditions normally promote higher ozone and larger risk of ecosystem effects. Climate projections suggest a positive trend for heat waves, including in Europe (Seneviratne et al., 2006; Lau and Nath, 2014; Wehner et al., 2018). The IPCC Special Report on Extremes (IPCC-SREX) estimated that the hot day 20-year return period will be reduced to between 5 and 10 days in most climate scenarios by the end of this century in Northern Europe. (Seneviratne et al., 2012).

An important effect of climate change in Fennoscandia is migration of vegetation. The tree line, defined as the elevation above which trees taller than 2 m do not occur, is a good indicator for monitoring the biological impact of climate change and variability (Kullman, 2017). As a consequence of increased air temperatures over the past 100 years, the tree lines of all the major species in the alpine region, i.e., mountain birch, Norway spruce and Scots pine, have shifted upslope in close accordance with the temperature rise (Kullman, 2017). Also, latitudinal northward shifts for birch and Scots pine have occurred (Hofgaard et al., 2013). The average northward advances of the birch and pine forest lines for Finnmark county in the period 1914 and 2009 were 156 and 71 m per year, respectively.

Air temperatures as well as the amounts of precipitation have increased during the summer months in Fennoscandia over the time period 1971–2019, while trends in amounts of solar radiation are more variable and uncertain. Extreme events, like the hot and dry summer 2018 in Fennoscandia, are expected to occur more frequently as a consequence of global warming.

The tree lines of all the major tree species have shifted upslope, as well as shifted northward in latitude, in close accord with temperature rise.

2.2 Deposition of nitrogen

Arctic ecosystems are nutrient limited and exhibit positive responses to nitrogen (N) enrichment, in particular in combination with phosphorous deposition (Street et al., 2015). Moreover, N addition rates at current critical loads strongly increase the grassland yield (Volk et al., 2014). The suggested critical loads, i.e. the quantitative estimate of an exposure to pollutants below which significant harmful effects on specified sensitive elements of the environment do not occur according to present knowledge, for impacts of nitrogen deposition of boreal coniferous forests in Sweden is 5 kg N ha^{-1} yr^{-1}, for deciduous forests 10 kg N ha^{-1} yr^{-1} and for mountain areas 3 kg N ha^{-1} yr^{-1} (Moldan, 2011). Finnish studies suggest a critical load of 3–4 kg N ha^{-1} yr^{-1} for boreal conifer forests based on N saturation of bryophytes (Salemaa et al., 2020) and turn off of N_2 fixation by cyanobacteria associated with bryophytes (Salemaa et al., 2019). A critical load has been suggested to protect the vegetation at high altitudes in the Rocky Mountains in the USA of 3 kg N ha^{-1} yr^{-1} (Bowman et al., 2006). Critical loads for N impact on vegetation in Alaska have been suggested to be even lower, 1–3 kg N ha^{-1} yr^{-1} (Pardo et al., 2011).

The current N deposition to coniferous forests in northern Sweden is in the order of 1–2 kg N ha^{-1} yr^{-1} (Karlsson et al., 2019; Andersson et al., 2018; Simpson et al., 2014). Estimates from a reanalysis (measurements and modelling combined) show that N deposition to coniferous and deciduous forests is slightly higher than deposition to low vegetation such as alpine areas, including meadows and wetlands. The deposition to ecosystems in northern Sweden has decreased by ca 30% from the 1980s until today (Table 2), mainly as a result of a decrease in the N emissions in Europe. However, the N deposition in the southern parts of the Scandes Mountains is still exceeding 3 kg N ha^{-1} yr^{-1}, the critical load suggested for Swedish mountain areas, and in some Swedish forests also the critical load for boreal coniferous forests (Andersson et al., 2018).

Table 2. Average deposition of reactive nitrogen to ecosystems in northern Sweden in two time periods, and corresponding change in deposition between the periods, as estimated by the MATCH Sweden system reanalysis (Andersson et al., 2017; 2018). Values extracted from Andersson et al. (2018).

	1983–1992 mean deposition [kg N ha^{-1} yr^{-1}]	2004–2013 mean deposition [kg N ha^{-1} yr^{-1}]	Change from 1983–1992 until 2004–2013
Coniferous forests	2.7	1.9	-29%
Deciduous forests	2.7	1.9	-30%
Pasture/meadow/arable land	2.5	1.7	-30%
Wetland	2.5	1.7	-30%
Water	2.2	1.6	-30%

The past decrease in reactive N deposition will not necessarily continue until the middle of the 21st century. While nitrogen oxides (NO_x) emissions have decreased strongly in Europe, ammonia emissions have not decreased as much, and may even increase in the future resulting in possible increases in N deposition in the future in northern Fennoscandia (Simpson et al., 2014; Engardt et al., 2017). Over the whole 20th century, deposition of reactive N to Sweden peaked during the mid-1980s (Ferm et al., 2019). Although the reductions in N emissions have been substantial over the last decades, the deposition of reactive N today is still 2–3 times higher than in the year 1900 in Europe (Engardt et al., 2017).

The nitrogen deposition to vegetation in northern Sweden is in the order of 1–2 kg N ha^{-1} yr^{-1} and has declined approximately 30 % since the 1980s.

2.3 Artic greening and browning

One of the most important climatic and environmental change in the Boreal and Arctic regions has been the increase in biomass and productivity of tundra vegetation and the northernmost forests, a phenomenon commonly termed "the greening of the Arctic" (Myneni et al., 1997; Myers-Smith et al., 2020). The productivity, however, have not been uniform across the circumpolar Arctic-Boreal regions and there has been substantial inter-annual variability (Bhatt et al., 2017; Park et al., 2016). This variability arises from a web of interactions linking the vegetation with abiotic and biotic processes (Duncan et al., 2019; Myers-Smith et al., 2020).

An increasing number of northern regions currently show declining productivity (browning). Such trends are evident over the circumpolar-boreal area, and some of the factors assumed to contribute to these declines include recent reductions in summer moisture or moisture stress (Verbyla, 2015), increased frequency of wild fires (Chu et al., 2016), forest insect outbreaks (Bjerke et al., 2014), increasing plant stress from winter warming events (Treharne et al., 2018), fungal infestations and moose damage on young pine forests in the Nordic region (Normark, 2019) and spring freeze damage after bud swelling (Chamberlain et al., 2019). Episodes of O_3 exposure might have contributed to local browning of different species like rowan (*Sorbus aucuparia*), birch (*Betula. pubescens*) and Scots pine *(Pinus sylvestris)* in combination with deposition of nitrogen like the events up-north in Fennoscandia in 2006 (Tømmervik pers. observations 2006; Manninen et al., 2009a; Karlsson et al., 2013). Occasional frost nights after budburst during the spring (May-June) of 2006 (annual reports: www.met.no; www.smhi.se) may also have reinforced the sensitivity and hence the injury (Manninen et al., 2009).

3 Changes in ozone exposure phenology

The time of year when the vegetation is physiologically active is called the growing season. The start of the growing season, SGS, is used as the time when the vegetation in boreal and temperate climate zones starts its activities after the winter dormancy period. Ozone does not generally affect the vegetation outside the growing season, i.e. when evergreen vegetation is in a stage of winter dormancy or when deciduous vegetation does not have leaves. Each plant species has its own specific growing season, due to genetic adaptation in combination with the meteorological conditions. However, there are ways to describe the growing season accurately for a larger number of important species.

Growing season indices can be defined through daily mean temperature, i.e. the thermal growing season. The start of the thermal growing season has been defined as the first day of the year when the daily mean temperature has exceeded 5˚C four (Sjökvist et al., 2015) or five (IMPACT2C web atlas; https://www.atlas.impact2c.eu/en/) days in a row, while the end is the last day of the year in the last four or five day period with the same requirement, and the thermal growing season length is the number of days in between these. The four-day thermal index is for example used by the Swedish Meteorological and Hydrological Institute (SMHI) in analysing changes in growing season from observed temperature as well as in historical and future climate scenarios and published on the SMHI web page. There has been an earlier start of the thermal growing season at northern latitudes (Karlsson et al., 2007; BACC 2015, Figure 3). Averaged over northern Sweden the thermal growth season start has shifted to approximately 10 days earlier from the mid-1990s until the late 2000s (Figure 3). There is a trend over the period 1994–2009 to an earlier thermal SGS (-1.13 days year^{-1}, statistically significant).

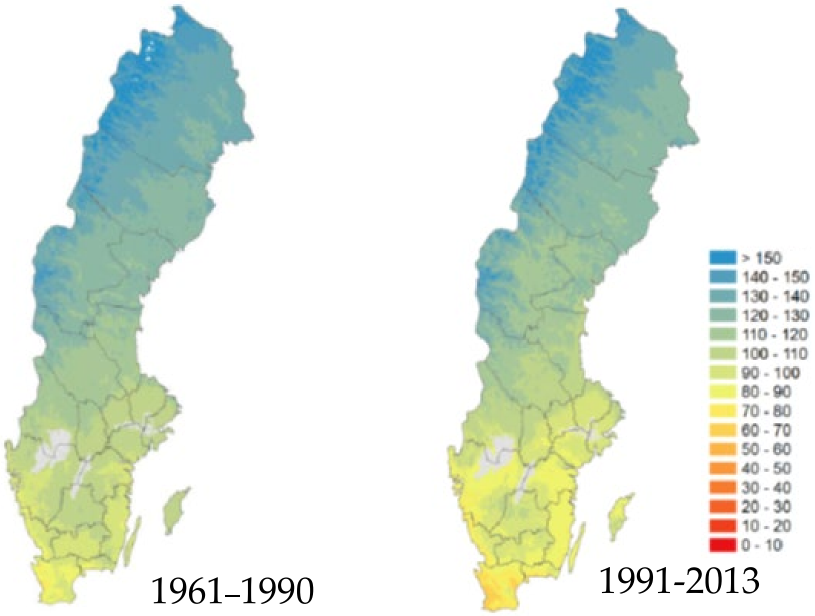


Figure 3. The estimated start of the thermal growing season calculated as when the 24h mean temperature exceeds 5 °C four days in a row, based on spatially interpolated observed temperatures in the periods 1961–1990 and 1991–2013. Extracted from the SMHI web site, http://www.smhi.se. Unit: Day of year from 1st January.

The timing and trend in the SGS may however differ substantially between individual species as compared to the thermal SGS. Species-specific methods to estimate the SGS (Karlsson et al., 2018b) resulted in later SGS for European silver birch (*Betula pendula*) and earlier for Norway spruce (*Picea abies*), compared to the thermal SGS (Figure 4). The SGS of birch and spruce has also shifted to earlier in the year over time (significantly negative trend since 1994, -0.96 days year^{-1} and -0.98 days year^{-1} respectively) in northern Sweden. The similar trend in the two species is likely a coincidence, differences in the estimates of the start of the growing season using more advanced, species-specific methods include that the thermal time is accumulated over different temperature thresholds, for birch 5 °C and for spruce 0 °C (northern Sweden) or 1.5 °C (south Sweden) (Karlsson et al., 2018a,b; Langner et al., 2019), which can lead to different trends when analysing other time windows. This is also a cause to the difference in SGS between the species.

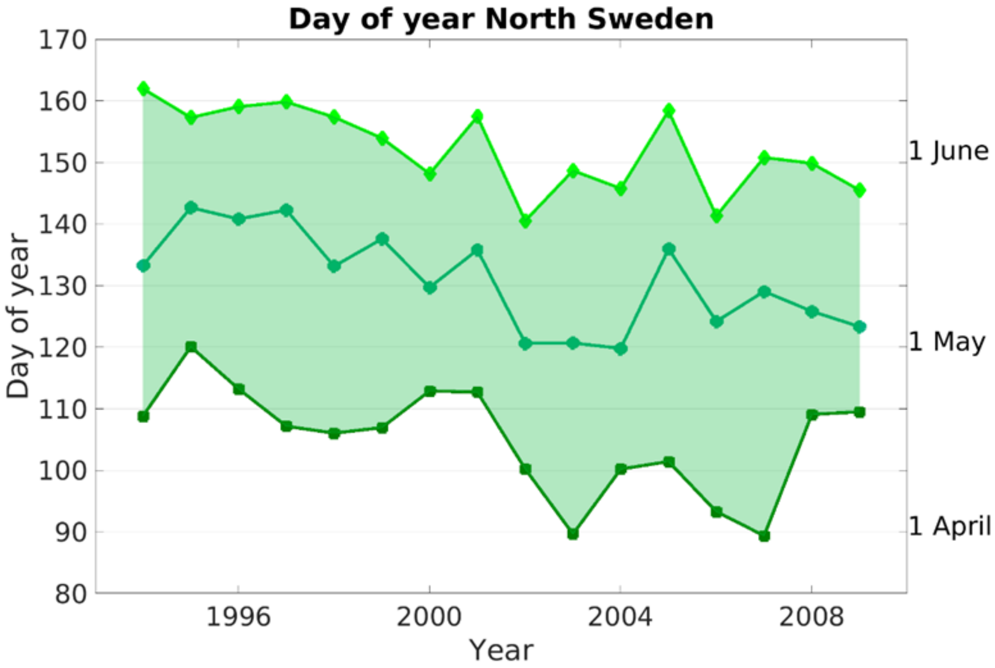


Figure 4. The start of the growing season averaged over northern Sweden (Norrland), calculated using three methods. The estimated start of the 4-day thermal growing season (middle green line). The start of the growing season for birch (top line, fair green) and spruce (bottom line, dark green) modelled by more advanced, species-specific methods (Karlsson et al., 2018b; Langner et al., 2019). Previously unpublished data, C. Andersson. All values are based on a meteorological reanalysis, combining long-term high-quality observations and modelling data (EURO4M; Dahlgren et al., 2016).

The timing of the spring bud burst of downy birch (*Betula pubescens*) observed in the field in the northern half of Finland changed annually by 0.5 day to earlier dates of the year over the time period 1997–2013 (Poikolainen et al., 2016). The timing of birch leaf colouring and leaf fall in Finland remained almost constant in the southern boreal zones, whereas it changed to earlier dates annually by 0.3 and 0.6 day in the middle boreal zone and by 0.6 and 0.4 day in the northern boreal zone, respectively (Poikolainen et al., 2016). Hence, the duration of the growth period of downy birch in Finland remained constant in all boreal zones over this 16-year period, although it was shifted to earlier dates. Böttcher et al. (2016) reported 155 as an average DOY (Day-Of-Year) for bud break of downy birch in 2001–2008 at the northernmost Finland. In other words, the buds broke between late-May and mid-June at Kevo.

The start of the thermal growing season may vary by approximately one month between years (Böttcher et al., 2016) thus affecting the cumulative ozone exposure of vegetation potentially more markedly than the average shift towards earlier start of growing season. For example, the thermal growing season started on 13 May 2018 vs. 13 June 2017 in the Kilpisjärvi biological station and 6 May 2016 vs. 6 June 2017 in the Kevo biological station, both sites in northernmost Finland (https://ilmatieteenlaitos.fi/terminen-kasvukausi).

Wallin et al. (2013) measured gas-exchange of 40-year-old Norway spruce trees with branch cuvettes in stands at Flakaliden in northern Sweden. Measurements of light-saturated photosynthesis were made during spring recovery from dormancy during three years 2002–2004. The recovery of gas-exchange from winter dormancy was non-linear over time and the first recovery, up to 60% of summer maximum gas-exchange, occurred already in March, more than a month before the start of growing season calculated as when the 24-h mean temperatures exceeded 5 °C for five consecutive days.

Additional information about the start and end of the growing season comes from micrometeorological measurements of the ecosystem exchange of CO_2. The growing season of evergreen conifers (defined from CO_2 flux measurements during 2001–2010) was estimated to start on average on DOY 123 (2001–2010) in Sodankylä in Finland Böttcher et al. (2016), and end DOY 267 (2008) and 248 (2009) in Flakaliden in Sweden (Kalliokoski et al., 2013).

Both data on budburst and data on ecosystem CO_2 exchange as well as meteorological observations show that there has been a development towards an earlier start of the growing season during the year, with approximately 0.5–1 day per year. Thus, there is clear evidence for an earlier start of the growing season, which is likely to continue.

4 Ozone concentrations at European northern latitudes

4.1 Background ozone concentrations

Ozone concentrations in the northern parts of Fennoscandia are to a large extent determined by the long-range transport of ozone from the surrounding regions. Available measurement data indicate that the background concentration of ozone was increasing in Europe during the second half of the 20th century (e.g. Cooper et al., 2014 and references therein). However, the trend in tropospheric ozone concentrations seem to have levelled off during the last decades and even started to decrease in some regions. Trend analysis of measurements of ozone in Atlantic air from 1987–2017, at Mace Head on the Irish west coast, (Derwent et al., 2018) has shown that the background ozone levels were increasing with an average annual increase of 0.2 ppb year^{-1} but that the increase slowed down during the time period and quadratic fits of the data imply that the ozone levels reached a maximum at about 2007 and started to decrease after that. Negative trends from 2008 to 2017 have also recently been reported for middle-low tropospheric ozone columns (from the surface to 300 hPa) for the Northern Hemisphere in the 40–75°N band covering Europe and North America, especially during summer (Wespes et al., 2018). For a recent review of tropospheric ozone distribution and trends on the global scale, see Gaudel et al. (2018).

Measured ozone concentrations at regional background sites in northern and central Fennoscandia vary substantially between different locations. The year-to-year variability in daytime summer half-year-mean concentrations is also relatively large, as illustrated in Figure 5. For the time period 1990–2016, 6-month (April–September) mean day-time ozone concentrations vary between ca 59 and 78 µg m^{-3} (1 µg m^{-3} equals 0.5 ppb) at five sites in mainland Norway, Finland and Sweden. The highest concentrations were mostly observed during the time period 1994–2006. After this it seems like the ozone levels during day time in summer have decreased somewhat in the region.

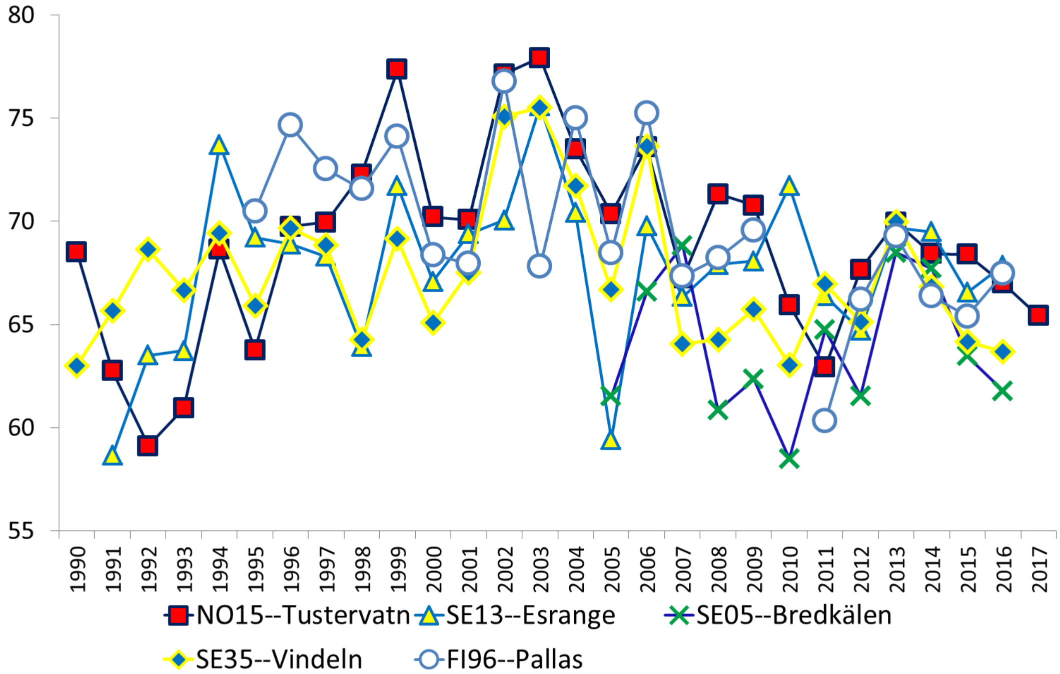


Figure 5. Measured summer half-year (April–September) mean ozone concentrations during daytime (for simplicity defined as 06:00–18:00 UTC) at five background sites in Northern/Central Norway, Sweden and Finland. Based on hourly measurement data from EMEP (www.emep.int). Sites: NO15 Tustervatn, SE13 Esrange, SE05 Bredkälen, SE35 Vindeln, FI96 Pallas (Sammaltunturi). Further information on the sites can be found in Table 1. Y axis unit: µg m^{-3} (1 µg m^{-3} equals 0.5 ppb).

At high altitudes (especially mountain tops, above the tree line) the ozone concentrations are relatively similar during day- and nighttime. This is due to a larger influence of the free tropospheric ozone at high-altitude sites and smaller loss of ozone due to surface deposition for areas with little vegetation and/or long-lasting snow/ice cover. Ozone measurements near the top of Åreskutan (1 250 m asl, 400m above the tree line) were performed during the late 1980s and early 1990s (Bazhanov and Rodhe, 1996) and the hourly mean ozone concentrations during the period April–September 1994 were essentially the same for day and night. For the same time period, the ozone concentrations were very different at the boreal, low-altitude site Vindeln (225 m asl), which had generally lower ozone concentration and a large difference between low night-time concentrations and (relatively) high afternoon concentrations (Karlsson et al., 2007). Similar differences are illustrated in Figure 6, which shows the mean diurnal variation of ozone concentrations at Vindeln (low altitude forest site), Esrange (hilltop) and Pallas (hilltop above the tree line), for the summer half-year 2016. All three sites have similar daily maximum ozone concentrations but the concentrations during night-time are much lower at Vindeln.

The 24h mean concentrations can thus be much higher at high altitudes (especially on mountains and hilltops, above the tree line) even if daytime concentrations are similar to low elevation sites at the same latitudes. This means that plants growing at high-altitude sites may potentially be subject to substantially larger ozone uptake than those found at lower altitudes.

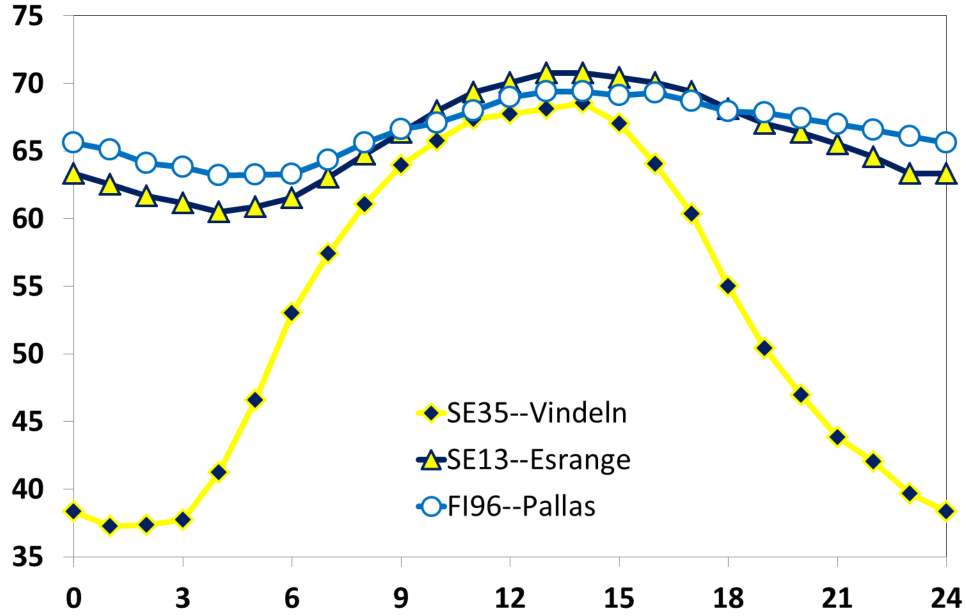


Figure 6. Mean hourly ozone concentrations calculated for the summer half-year (April–September) 2016 at the EMEP monitoring sites SE35 Vindeln, SE13 Esrange and FI96 Pallas (Sammaltunturi). Unit: µg m^{-3}. Vindeln is positioned 225 m asl in the middle boreal zone in a forested area. The Esrange site is located 475 m asl on the top of a hill, approximately 170 m above the surrounding landscape. The Pallas (Sammaltunturi) site is situated on top of a sub-arctic hill, ca. 100 m above the treeline; the vegetation on the top is sparse, consisting mainly of low vascular plants, moss and lichen (https://en.ilmatieteenlaitos.fi/ghg-measurement-sites#Pallas). More information about the sites can be found in Table 1.

Ozone concentrations in the northern parts of Fennoscandia are determined by the background concentration of ozone. The background concentration of ozone was increasing in Europe during the second half of the 20th century, but seem to have levelled off and started to decrease during the last decades.

At high altitudes the ozone concentrations are relatively similar during day- and night-time.

4.2 Seasonal variation of near surface ozone at high northern latitudes

The ozone concentration in the troposphere shows an annual variation, which in some regions exhibit a pronounced spring maximum. This spring ozone maximum is a Northern Hemispheric phenomenon common across the mid-latitudes (Monks, 2000; Vingarzan, 2004). While comparatively unpolluted sites have a pronounced spring ozone maximum and a summer minimum, polluted continental sites are characterized by a broad late spring to summer maximum (Jonson et al., 2006).

Klingberg et al. (2009) compared the seasonal variation in ozone concentrations at five sites in northern Sweden with one site in southern Sweden (Figure 7). The northern sites exhibited a more pronounced ozone spring maximum, which was higher and earlier (April maximum) compared to the site Råö in south Sweden (May maximum). During summer the ozone concentrations were higher at the southern site.

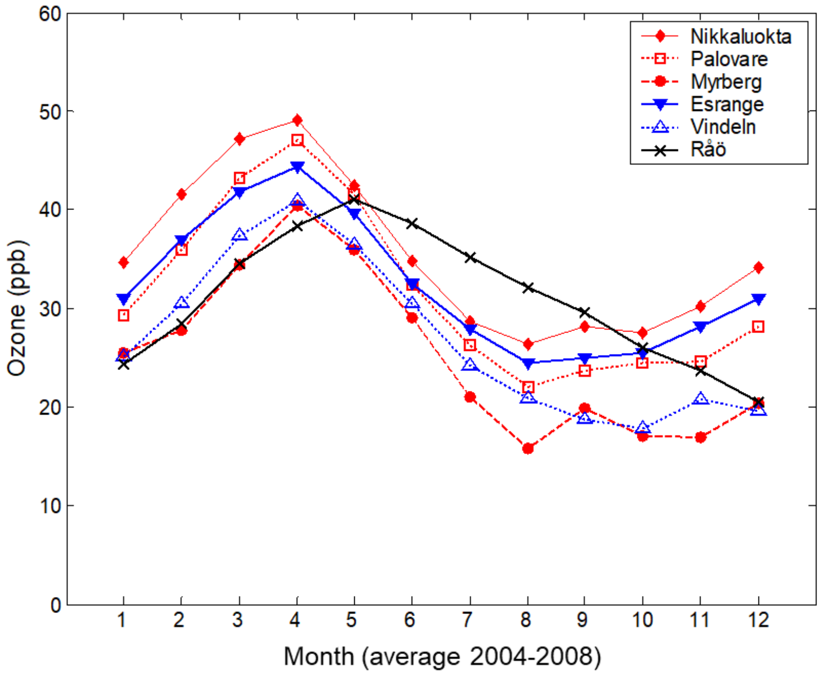


Figure 7. Variation in monthly mean ozone concentrations during the year at five sites in northern Sweden, and one in southern Sweden (Råö). The position of the different sites is shown in Figure 1 and Table 1. Measurements at Nikkaluokta, Palovaara and Myrberg were based on passive diffusion samplers. Measurements at Esrange, Vindeln, and Råö were made with UV absorption monitors. The values represent the average for each month of the year during the period from 2004 until 2008. From Klingberg et al., 2009.

As mentioned above, mountain areas have higher ozone concentrations compared to the adjacent lowland (Loibl et al., 1994; Coyle et al., 2002; Klingberg et al., 2012). However, few observations have been made in the Scandian Mountain Range. In March to September 2008, Klingberg et al (2009) measured ozone concentrations at the alpine site Latnjajaure (980 m above sea level, near Abisko, see Figure 1) in the northern Scandian Mountain Range with passive diffusion samplers. The result was compared to the nearby monitoring station Esrange and more distant Vindeln at lower altitude (Figure 8). During spring, the mean ozone concentrations at the high elevation site Latnjajaure were higher compared to the closest monitoring sites at lower altitude, Esrange and Vindeln, thus illustrating the importance of high elevation for the ozone concentrations.

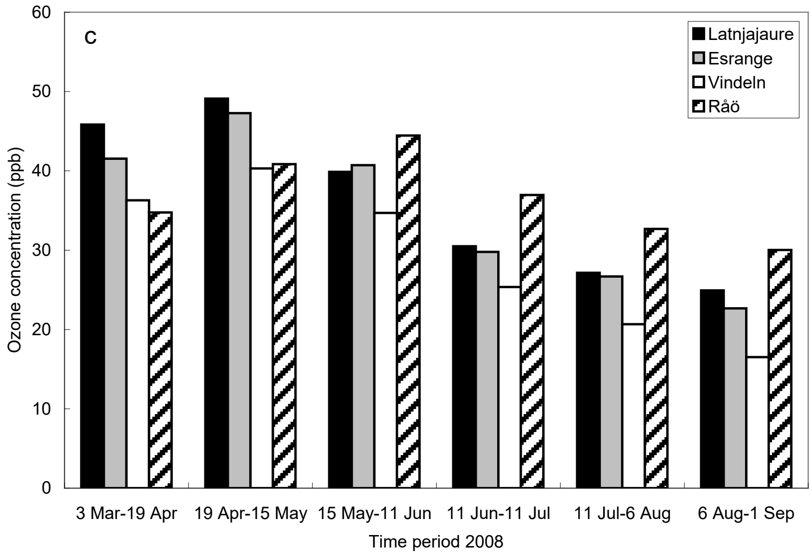


Figure 8. Ozone concentrations at four measurement sites during spring and summer 2008. Measurements at Latnjajaure were based on passive diffusion samplers (average of duplicate samplers). Measurements at Esrange, Vindeln, and Råö are averages calculated from hourly UV absorption data. For positions see Figure 1, Latnjajaure is positioned close to Abisko. From Klingberg et al., 2009.

Klingberg et al (2019) analysed the annual ozone cycle in relation to latitude, based on observations from 25 European monitoring stations north of the Alps during the 26-year period 1990–2015. The yearly maximum ozone concentrations increased towards the south of the study area, while the yearly minimum of daytime mean increased towards the north (Figure 9).

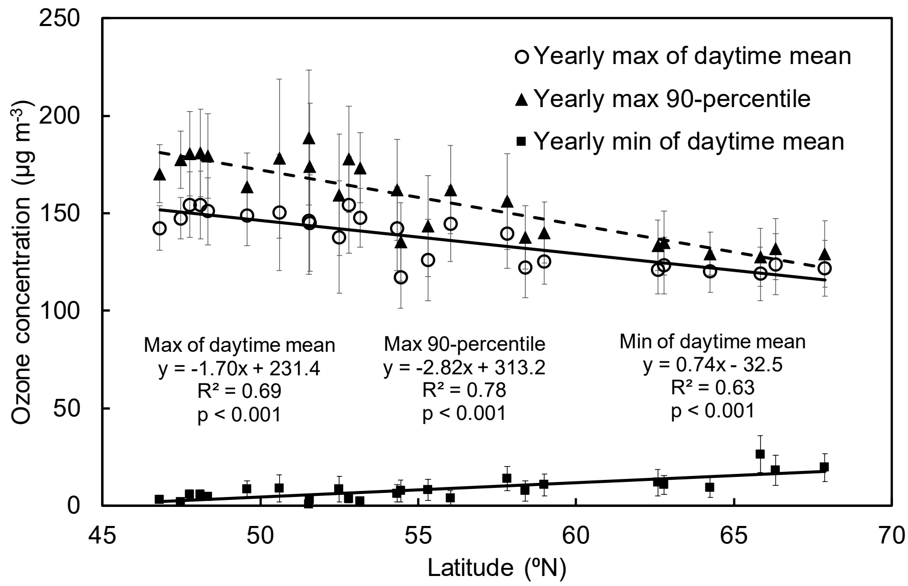


Figure 9. The yearly maximum and minimum of daytime mean as well as the yearly maximum 90-percenttile in relation to latitude, based on observations from 25 European monitoring stations north of the Alps during the 26-year period 1990–2015. Modified from Klingberg et al. (2019).

The average day of the year when the yearly maximum ozone concentration occurred declined strongly and significantly with increasing latitude (Figure 10). In other words, the annual ozone maximum was shifted from the summer in the southern part of the study area to spring in the north. The choice of ozone indicator (maximum of daytime mean, maximum of 90-percentile, maximum of 8-hour means) did not influence this result.

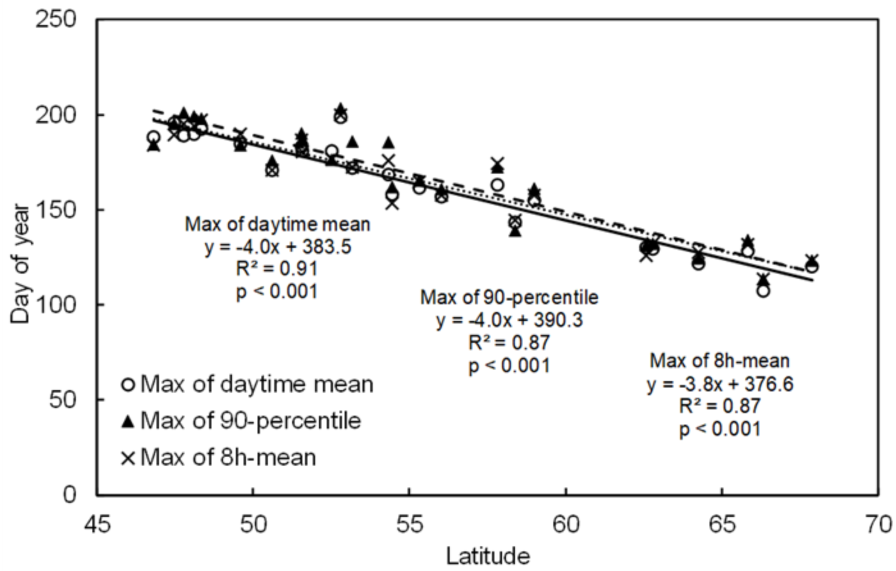


Figure 10. Day of year for the annual maximum ozone concentrations in relation to latitude. The figure is based on hourly ozone data from 25 EMEP monitoring sites north of the Alps during the period 1990 - 2015. Modified from Klingberg et al., 2019.

Northern sites exhibit a higher and earlier ozone spring maximum, compared to southern sites in Fennoscandia. During spring, the 24h mean ozone concentrations at a high-altitude site were higher compared to the closest monitoring sites at lower altitude. The annual ozone maximum occurs in the summer in the southern European regions and in spring in the northern European regions.

4.3 Changes in the seasonal variation over time and source attributions of northern ozone concentrations

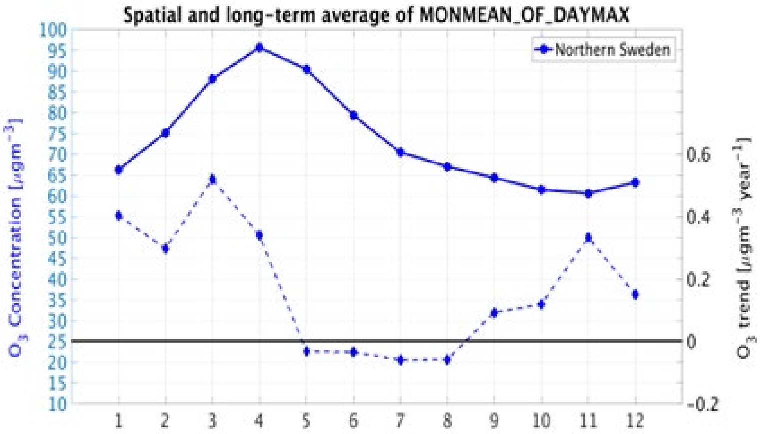
Modelled and observed background ozone concentrations have been used to construct a long-term dataset (a reanalysis) for Norway and Sweden (Andersson et al., 2017). The modelled and measured ozone concentrations in the data set are fused together and the measurement sites and other data used were selected on basis of high quality and for representing a long time period (1990–2013) on hourly temporal and 22 km spatial resolution respectively. The data-set can be used for analyzing trends in seasonal variations and ecosystem impacts. The methods are described in detail in Andersson et al. (2017). Here we have used the dataset to construct the spatial and period mean and corresponding trend in monthly mean of daily maximum (1h-mean) ozone concentrations (see Figure 11) for northern Sweden.

The monthly mean of daily maximum ozone concentrations for 1990–2013 peaks in April (Figure 11A, left-hand scale). This seasonal peak has increased over the time period 1990–2013, and there is a shift in the peak to earlier in the year. This can be deducted from the seasonal variation in the trend (increasing in September–April, and no trend or a weakly decreasing in May–August; Figure 11A, right-hand scale).

The data-set was also analyzed for causes to the trend, with model sensitivity tests. The method for this analysis is also described in Andersson et al. (2017). Here we analyzed these results for causes to the trend in monthly mean of daily maximum ozone concentrations (Figure 11B). A decrease in Swedish and European precursor emissions cause ozone to decrease in summer and increase in winter (the latter due to a decline in the ozone titration with nitrogen monoxide, NO). An increase in northern hemispheric background ozone in the period (until the year 2000; see Andersson et al., 2017) has a stronger impact on the ozone trend during winter when the deposition to vegetation is very weak. Meteorological variations cause a decrease in the ozone concentrations in May and an increase in March–April. The combination of the assumed increasing hemispheric background of ozone and observed climate variations over the period causes the increase in the spring peak. The decrease due to emission reductions in summer and the decrease in ozone due to climate variations in May cause the shift of the spring peak to earlier in the year. The main factor behind the May decrease in near-surface ozone is a decreased number of days with snow-cover and/or low temperatures, which leads to increased uptake of ozone to the vegetation (Andersson et al., 2020, manuscript & ITM 2019 conference).

Increasing hemispheric background of ozone, decreasing European emissions and meteorological variations over the period cause an increase in the spring peak ozone concentration. The decreasing ozone concentrations in summer, due to emission reductions, and in May, due to meteorological variations, lead to a shift of the spring peak to earlier in the year.

A



B

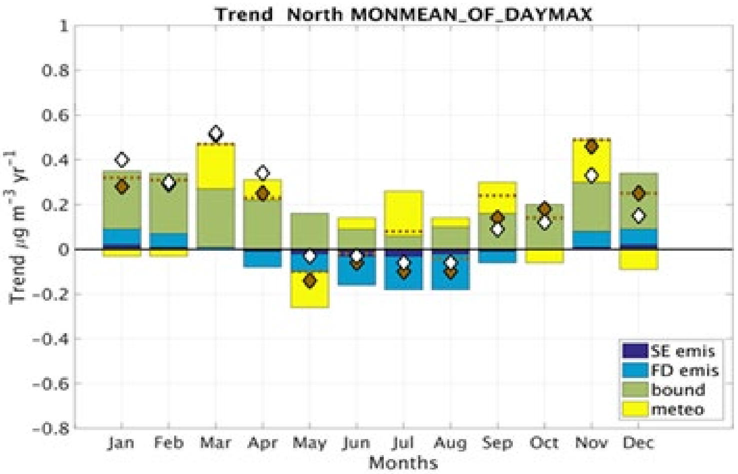


Figure 11. Seasonal variation in monthly means of daily maximum (1-h mean) ozone concentrations and their trends over the period 1990–2013 in northern Sweden. A, mean concentrations (full line) and concentration trends (dotted line) for each month over the period 1990–2013, based on a combination of modelled and observed datasets, where the spatial and hourly temporal coverage of the model data is fused with high-quality long-term observations from regional background sites in Norway and Sweden (a so called reanalysis, using 2-dimensional variational data analysis; see Andersson et al., 2017).

B, model estimates of the factors contributing to the trends in panel A. The reanalysis trends are included as white diamonds (identical to the trends in panel A); the corresponding "pure" modelled trends are shown as brown diamonds. The contributions to the modelled trend from different model factors are shown as bars for each month: trend in emissions from Sweden (SE emis, dark blue) and the rest of Europe (FD emis, light blue); assumed changes in "northern hemispheric" background (boundary) ozone concentrations (bound, green) and meteorological variations (meteo, yellow). The sums of the trends due to the four investigated model factors are shown as brown dotted lines. The results represent averages over the northern half of Sweden.

4.4 Historical ozone episodes at far northern latitudes

Northern Fennoscandia is located far from the main emission sources of ozone precursors. However, under certain meteorological conditions polluted air with very high concentrations of ozone and ozone precursors or reservoir species (e.g. PAN) can be transported also to these remote regions. During the last two decades there has been at least two occasions when the ozone concentrations at far northern latitudes in Fennoscandia has been exceptionally high, exceeding 80 ppb. In April 2003 two episodes with unusually high ozone values were measured at stations in northern Fennoscandia, Karasjok, Esrange and Pallas. The highest ozone peaks measured at Esrange and Pallas could be traced back to transport of pollution from the Iberian peninsula, superimposed on pollution transported from the Northern Mediterranean (Figure 12, Lindskog et al., 2007).

The other occasion occurred during 2006. High concentrations of ozone were detected at far northern, low and high-altitude sites in Sweden and Norway during spring and summer 2006, coinciding with polluted air from biomass burning in eastern Europe passing over central and northern Fennoscandia (Figure 13, Karlsson et al., 2013).

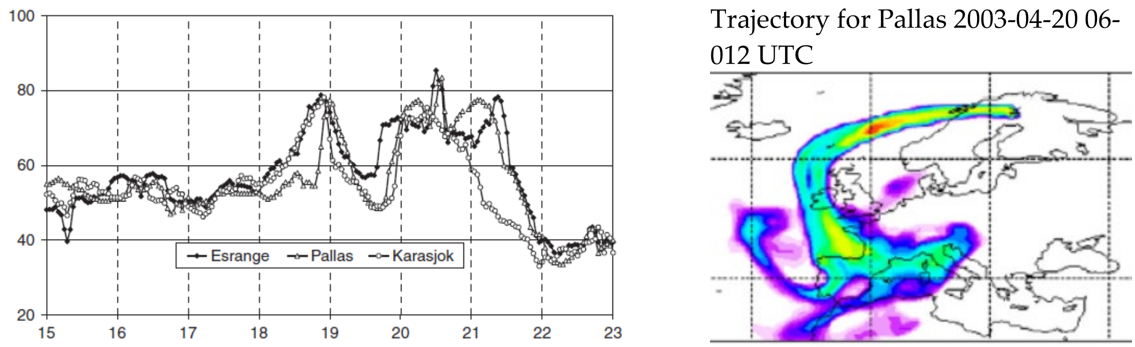


Figure 12. Illustration of an exceptional ozone episode in northern Fennoscandia 15–23 April 2003. X-axis date in April 2003. Y-axis unit: ppb. A, hourly ozone concentrations monitored at the different sites; B, A trajectory analysis for the air arriving at the site Pallas 2003-04-20. A trajectory analysis shows the origin of the air mass with polluted air arriving at the measuring site. The positions of the different sites are shown in Figure 1. From Lindskog et al., 2007.

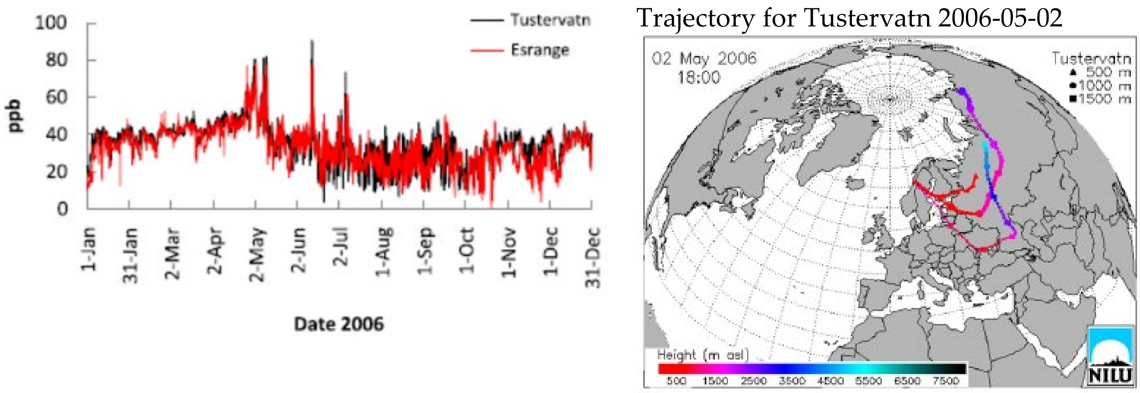


Figure 13. Illustration of the exceptional ozone episode in northern Fennoscandia during 2006. A, hourly ozone concentrations monitored at the sites.; B, A trajectory analysis for the air arriving at Tustervatn 2006-05-02. The positions of the different sites are shown in Figure 1. From Karlsson et al., 2013.

Furthermore, in the summer 2006, unusual visible leaf injuries were observed on deciduous trees and shrubs in northern Fennoscandia, such as Rowan (Figure 14). The estimated bud burst in northern Fennoscandia occurred in the beginning of May 2006, coinciding with the event of strongly polluted air passing over the area. Hence, the canopies of the deciduous trees and shrubs were not fully developed, and it is uncertain to what extent the stomatal conductance had reached the maximal values, hence may still have restricted the stomatal uptake of air pollutants. However, there were episodes with high O_3 concentrations at northern latitudes also during June and July 2006 (Figure 13). The long-lasting O_3 episode at the beginning of the growing season combined with episodes of elevated O_3 at the beginnings of June and July may have caused the observed leaf injury to rowan (e.g., stippling and necrosis). These injuries were observed in northern Norway, and in northern Sweden, from the start of June to the end of August. The observed injuries to rowan were similar to reported injuries caused by ozone. The long-term significance of irregular visible leaf injury such as exemplified in Figure 14 is however difficult to predict.

Figure 14. Rowan (*Sorbus aucuparia*) leaves showing chlorotic and brown-reddish stippling and red-brown necrotic areas in the leaf margins.

Picture taken in Tromsø, Norway, on 30 July 2006. (Photo: H. Tømmervik). From Manninen et al., 2009a.

Under certain meteorological conditions, polluted air with very high concentrations of O_3 and O_3 precursors can be transported to remote regions in northern Fennoscandia.

4.5 Ozone concentrations close to the ground

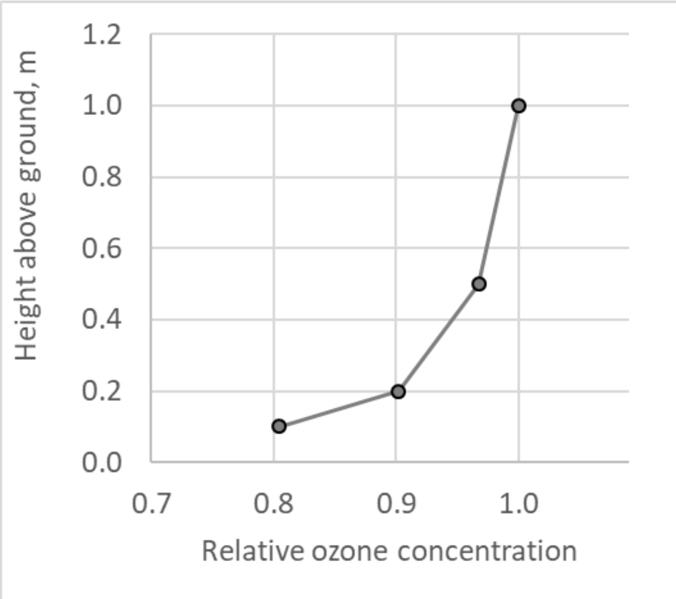
High-altitude plants generally grow close to the ground. It is well known that ozone concentrations decrease towards the ground due to the balance between dry deposition to surfaces and the supply of "new" ozone from aloft. However, measurements of ozone concentrations in the few decimeters close to the ground are scarce. In order to be able to estimate ozone impacts on grasslands, generalized relationship between ozone concentrations and height above ground are used, as presented in the Mapping Manual of the LRTAP convention. The suggested relationship is shown in Figure 15. It was estimated that under generalized daytime conditions, the ozone concentration at 0.1 m above ground would be 20% lower as compared to at 1.0 m above ground. It should be noted that ozone concentrations at 1 m above ground typically will be lower compared to 5–10 m, which is the height above ground where ozone concentrations generally are measured. More systematic measurements of height and surface type dependency of ozone concentrations are needed.

It might be argued that the lower ozone concentrations close to the ground reflect the high phytotoxic uptake of ozone to the leave through the stomata. However, a large part of the dry deposition of ozone to the ground goes to non-biological surfaces such as the soil and dead biological material and to the external plant surfaces (e.g. Fares et al., 2014), which will not cause damage to plants.

Figure 15. Representative O_3 gradients above short grasslands (0.1 m). O_3 concentrations are normalized by setting the 1.0 m value to 1.0. These gradients are derived from noontime factors and are intended for daytime use only.

Short grasslands where z_1=0.1m, g_{max}=270 mmol O_3 m^{-2} PLA s^{-1}.

Source: Mapping Manual, 2017 (chapter 3, of the LRTAP convention).



Ozone concentrations close to the ground can be substantially lower compared to the height above ground commonly used for ozone concentration monitoring.

5 Special environmental conditions at far northern latitudes affecting the vegetation vulnerability for ozone damage

Daylight duration, intensity and quality are probably the environmental characteristics that differ the most between the alpine environments at far northern latitudes, as compared to more southern alpine environments e.g. in the Alps. Long periods of daylight and the enrichment of blue light at dawn and dusk in combination with more or less constant ozone concentrations all day around (Figure 6) can potentially promote high stomatal ozone uptake and hence potential plant injuries. This raises concern about higher risks for ozone injury at a certain ozone concentration level at northern as compared to southern latitudes.

Light quantity and quality in the summer depend on atmosphere composition, for instance cloudiness, latitude and altitude, in addition to date and time of the day. Plants use the 400-700 nm part of the solar radiation spectrum for photosynthesis, i.e. the photosynthetically active radiation (PAR). The light spectrum experienced by plants at low solar elevations is shifted towards more blue wavelengths at dusk and dawn, compared to mid-day sun light (Chiang et al., 2019). At increasing latitudes, the maximum solar elevation at noon decreases and hence the maximum sunlight intensities are lower at increasing latitudes. According to Chiang et al. (2019), the light spectrum does not change significantly after the sun rises above 20° elevation. Thus, daytime spectra, when the sun is above this elevation, are expected to be similar in the north and south of our study area. At latitudes north of the Polar Circle, day length duration becomes 24 h some time before mid-summer, resulting in midnight sun conditions. During night in these areas, the sun does not set, but the solar angle is low during night. One important difference between solar light quality at low and high latitudes is the longer period of low solar angle illumination at high latitudes, be it as midnight sun or twilight (Nilsen, 1983; Belsford et al., 2019).

Light quality affects many aspects of plant growth, for instance stomatal conductance (Belsford et al., 2019). Since stomatal conductance is positively enhanced by blue light (Matthews et al., 2020), longer periods of low solar angle at higher latitudes, and the concomitant increased proportion of blue light in the spectrum, may cause increased stomatal conductance during morning and afternoon at high latitudes. This may increase the risk of ozone uptake in these areas, compared to areas at more southern latitudes.

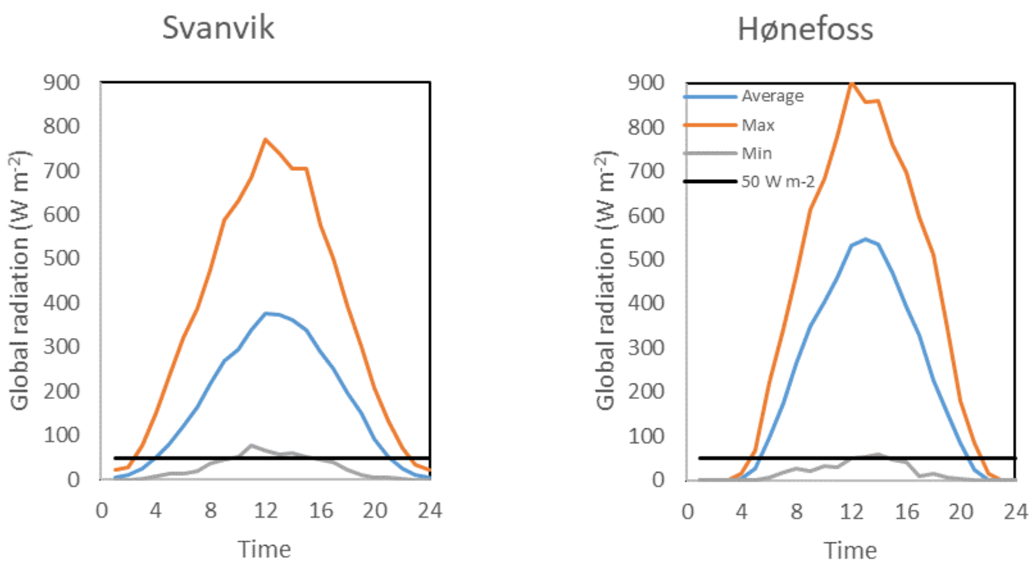


Figure 16. Global radiation (W m^{-2}, 285–2800 nm) at Svanvik and Hønefoss in Norway (see Fig. 1 for locations), plotted as average values for the time of day during the Svanvik midnight sun period (from 19th of May to 25th of July). Hourly data for Hønefoss are shifted 1 h earlier to approach the solar noon at 12 pm. Data from summer 2019, NIBIO, Landbruksmeteorologisk Tjeneste.

The maximum light-intensities decrease with increasing latitude, due to lower solar elevation. As an example, the global radiation from two sites in Norway (Figure 16) show that the maximum radiation was 17 % higher at the site at 60 °N (Hønefoss) compared to the site at 69 °N (Svanvik) during a period around summer solstice. This difference is primarily due to solar elevation, but is also affected by weather conditions the particular year studied.

For many purposes, 50 W m^{-2} is considered the lower limit of light intensity that is needed for plant activity, i.e. photosynthesis and stomatal opening (e.g. Mapping Manual, 2017), allowing carbon fixation and gas exchange from the leaves. From Figure 16, it can be seen that during the period of midnight sun at Svanvik, Norway (69 °N), the average global radiation intensity was higher than this limit from 3 a.m. to 20 p.m., giving a day length of 17 h. For the lower latitude site at 60 °N, the day length on an average radiation day lasted from 4:30 a.m. to 19:30 p.m., giving a day length of 15 h.

Maximum light intensities decrease, while maximum day lengths increase, with increasing latitude in the growing season.

6 What is known about the diurnal time course of gas-exchange for vegetation at far northern latitudes?

Plants regulate gas-exchange through the stomata by opening or closing the pores on the leaves. When the stomata are closed there is no ozone uptake to the leaf interior and hence no ozone damage to the plant (Mapping Manual, 2017). The stomata are controlled by several environmental and leaf internal factors such as e.g. light, water availability and internal CO_2 concentrations. Further, stomata are also controlled by a circadian rhythm that often promotes stomatal opening in the morning and closing in the evening (Hubbard et al., 2007). The diurnal variation in stomatal conductance in areas with midnight sun is not sufficiently described.

As mentioned above, the long daylight hours represent the basis for a hypothesis that there might be higher stomatal ozone uptake at a certain ozone concentration range at far northern vegetation, as compared to more southern vegetation in Europe. The significance of the long daylight conditions for the diurnal variation for leaf ozone uptake will depend on the parallel variation in ozone concentrations and the level of leaf conductance for ozone uptake, in relation to the threshold y, used for estimating the Phytotoxic Ozone Dose, POD_y (Mapping Manual, 2017). Light intensity is an important determinant of leaf conductance (Mapping Manual, 2017).

One way to test this hypothesis is to model stomatal ozone uptake. The leaf ozone uptake was estimated for Svanvik and Hønefoss based on the stomatal conductance model as described in the Mapping Manual (2017). The parameterization described for boreal forest/birch was used. The simulations were based on the diurnal average light conditions shown in the Figure 16 above, in combination with meteorological "dummy values", identical for Svanvik and Hønefoss. The diurnal ozone concentrations were assumed to be constant over the course of the day, as has been shown to be a reasonable approximation for several northern sites (e.g. Esrange and Pallas, Figure 6) and was in this example set to 40 ppb. An increase in vapour pressure deficit (VPD) in the middle of the day causes a reduced stomatal conductance in that period, leading to a dip in POD values in the middle of the day, as well. POD_y was calculated both as POD_1 (accumulated over a threshold of 1 nmol m^{-2} s^{-1}) and POD_0 (with no threshold).

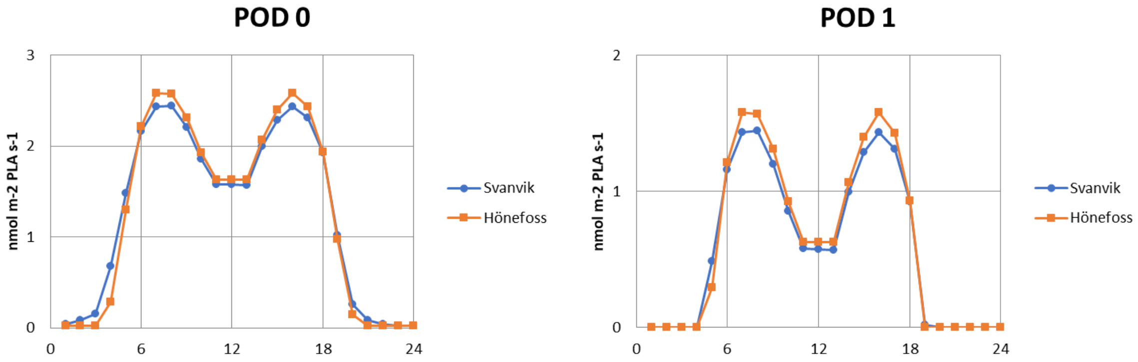


Figure 17. The simulated leaf ozone uptake for birch at the northern sites Svanvik (69°27′N, 30°2′E) and the more southern site Hønefoss (60°8′°N, 10°15′E) in Norway, based on the average diurnal light conditions shown in Figure 15, in combination with a "dummy" diurnal dataset for the other meteorological parameters (air temperature (min 5 °C, max 20 °C) and VPD (max 2.0 kPa, min 0 kPa) that were identical for Svanvik and Hønefoss. In the left diagram, no threshold for the accumulated leaf ozone uptake was used (POD_0), while in the right diagram a threshold of 1.0 nmol m^{-2} s^{-1} (POD_1) was used in the calculations.

The longer daylight conditions at Svanvik will cause a slightly higher leaf ozone uptake (POD_0) in the morning and evening, as can be seen in Figure 17. Early and late in the day the differences in POD_1 between the two sites were smaller. However, higher light intensities will result in a higher leaf ozone uptake during the middle of the day at Hønefoss. As a result, the accumulated POD_0 and POD_1 per day turned out to be similar between the two sites, based on these generalized simulations (Table 3).

Table 3. The summed POD_0 and POD_1 during a 24h simulation of leaf ozone uptake, as shown in Figure 17.

	mmol m^{-2} day^{-1}	
	SUM POD_0 24h	SUM POD_1 24h
Svanvik	0.110	0.051
Hønefoss	0.111	0.055

In conclusion, the low intensity light in the early morning at the northern site Svanvik will promote some additional leaf ozone uptake, as compared to the southern site Hønefoss, but on the other hand the lower light intensity during the middle of the day will result in somewhat lower leaf ozone uptake at Svanvik. These differences seem to cancel out and the summed POD_y over 24h was similar at the northern and southern sites. Further work would be needed to evaluate the differences statistically. It may also be noted that the VPD-induced reduction in stomatal conductance around noon was not observed in a study of birch from Southern Sweden (Uddling et al., 2004; 2005), although it is included in the Mapping Manual from 2017. Further, the same pattern was not found in *Pinus sylvestris* further north, either, as can be seen in the following.

At Rosinedalsheden in Sweden, with a *Pinus sylvestris* forest, stomatal conductance and photosynthesis were measured during some sunny summer days (Stangl et al., 2019, Figure 18). The conductance increased from a value of about 80 % of the maximum at 4 a.m. to the daily maximum at about 9 a.m., and subsequently decreased until 8 p.m to a value of about 30 % of the 9 o'clock maximum. On the other hand, net carbon assimilation increased to a plateau of highest levels between 8 a.m. and noon, before the decline started, illustrating that stomatal conductance and photosynthesis are not always correlated (see also Lombardozzi et al., 2012; 2013). Sunrise during the measurements was reported to be typically 2:15 a.m. and sunset around 11 p.m. Due to high uncertainties related to low values of CO_2 assimilation close to sunrise and sunset, the authors did not include the measurements done before 4 a.m. and after 8 p.m. in the analyses. Nevertheless, the night-time CO_2 assimilation data indicated some positive CO_2 assimilation at 2:30 a.m., 3:30 a.m. and 08:30 p.m., suggesting open stomata at early and late hours.

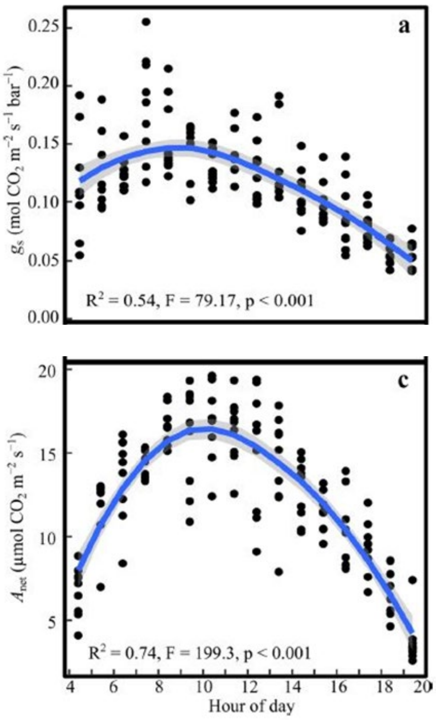


Figure 18. Diurnal variation in stomatal conductance of CO_2 (a) and photosynthesis (c) in pine (*Pinus sylvestris*) shoots at Roshinedalsheden in Sweden, measured on sunny days between 28 June and 9 July 2017 (figure reproduced from Stangl et al., 2019).

Another study, among the very few about diurnal patterns in plant gas exchange at Northern latitudes, studied the seasonal variations in the diurnal patterns of net branch CO_2 assimilation of sub-Arctic Mountain Birch (*Betula pubescence* ssp. *czerepanovii*) at Abisko in Sweden and Kevo in Finland (Poyatos et al., 2012, Figure 19). As for Scots pine (from Stangl et al., 2019), the July net carbon assimilation (DOY 189 and 198) increased from early morning to a plateau including noon, before it was reduced later in the evening. There was a clear diurnal variation in leaf CO_2 assimilation even under a 24h period with daylight. At low light intensities, low rates of CO_2 assimilation will be cancelled out by respiration. Therefore, this study did not give direct information about when the stomata were open, except that they were open for at least as long as net CO_2 assimilation was positive. Thus, we see indications of open stomata early and late in the day at both sites on sunny days with midnight sun, lending support to the hypothesis that the number of hours per day with possible uptake of ozone are higher at high latitudes.

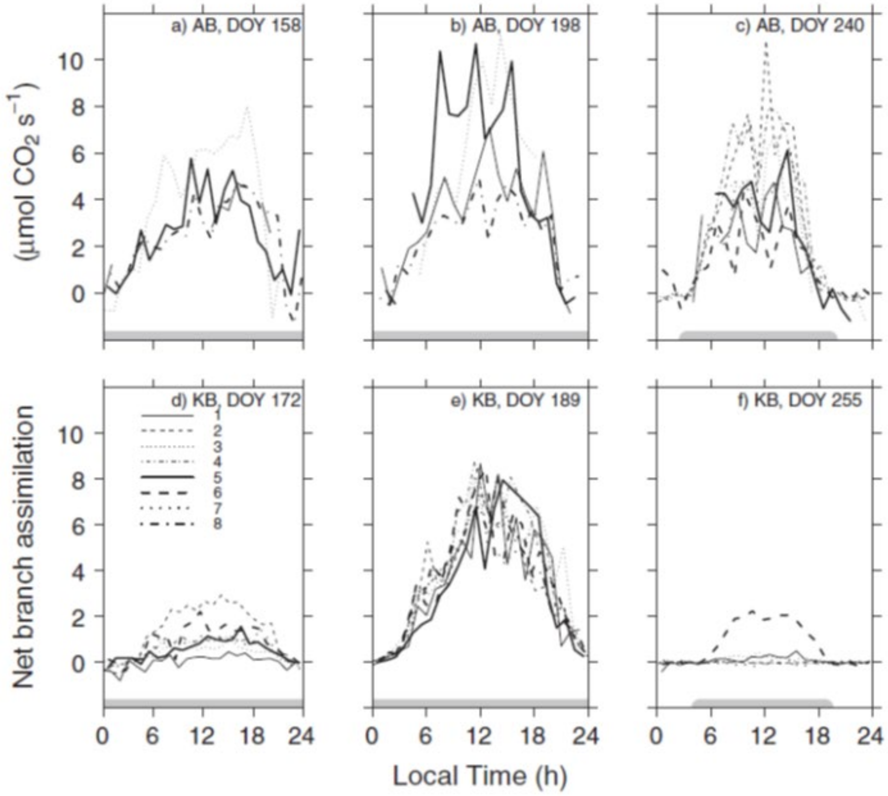


Figure 19. Seasonal variation in the diurnal patterns of net branch assimilation of sub-Arctic Mountain Birch (*Betula pubescens ssp. cherepanovii*) at Abisko in north Sweden, latitude 68° (AB, top row) and Kevo in north Finland, latitude 69° (KB, bottom row). The CO_2 measurements were made in branch bags. The panels show three sunny days selected from early, peak and late seasons. Photoperiod is shown by the shaded area above the x-axis. Different numbers represent different branch bags. From Poyatos et al., 2012.

Measurement campaigns as well as a simple modelling exercise show that at far northern sites in summer there may be higher stomatal conductance and hence potentially higher leaf ozone uptake early and late in the day, compared to more southern sites.

A simple calculation illustrated that the potential added ozone uptake in the early morning and late evening at northern sites will likely be canceled out by a lower ozone uptake in the middle of the day, as compared to southern sites.

7 Other aspects of day length on the ozone susceptibility in plants

There may be other day length related factors influencing the effect of ozone on plants at high latitudes. It has been suggested that the duration of a dark night should be above some limit value to ensure night-time repair after oxidative stress (De Temmerman et al., 2002). In addition, the dim light during night may interfere with some metabolic pathways such that programmed cell death is promoted over repair. This process has been demonstrated in *Arabidopsis thaliana* mutants with reduced capacity to handle reactive oxygen species (Queval et al., 2007; Chaouch et al., 2010). These studies showed that long days caused more programmed cell death compared to short days. Such a shift towards cell death responses may be the explanation for an increased ozone-induced visible injury development on white (*Trifolium repens*) and red clover (*Trifolium pratense*) leaves given dim light during night (Vollsnes et al., 2009; Eriksen et al., 2012). Later, the effect of oxidative stress due to ozone on development of foliar necrosis was shown to be increased also for *Arabidopsis thaliana* grown in long days compared to short days (Dghim et al., 2013), further supporting the hypothesis that day length may interfere with ozone susceptibility in plants.

Other aspects of day length that influence the ozone susceptibility in plants might be a reduction of night time repair or a physiological change in favor of programmed cell death under oxidative stress.

8 Ozone flux estimates for northern latitudes

Mapping of POD_ySPEC (Phytotoxic Ozone Dose for SPECific plant species) for tree species and crops at northern latitudes has been introduced as part of the Swedish environmental monitoring in 2019 (Langner et al., 2019). Results are available starting from 2013. The mapping follows the most recent methodology of the *Mapping Manual* (Mapping Manual, 2017) and makes use of national and Scandinavian data on vegetation periods, as suggested by Karlsson and Pleijel (2018a) and Karlsson et al. (2018b). Ozone concentrations used are hourly, spatially analyzed concentrations, based on a two-dimensional variational analysis of surface ozone concentrations, using hourly surface ozone observations from Swedish and Norwegian background monitoring stations combined with a European scale simulation of ozone concentrations, using the MATCH chemistry transport model (Andersson et al., 2015; Alpfjord Wylde et al., 2019). POD_ySPEC relevant for Norway spruce (*Picea abies*) and European silver birch (*Betula pendula*) is shown in Figure 20. Critical levels based on POD_ySPEC for spruce/pine (9.2 mmol m^{-2} PLA, PLA = plant leaf area) and birch (5.2 mmol m^{-2} PLA) forests are exceeded over most of Sweden, even over large areas in the north close to the mountain range.

The modelled exceedance of the ozone critical levels in areas so far to the north is unexpected and need to be further investigated. When the results from experimental data are compared with the estimated POD_1SPEC under field conditions there seem to be some lack of compatibility.

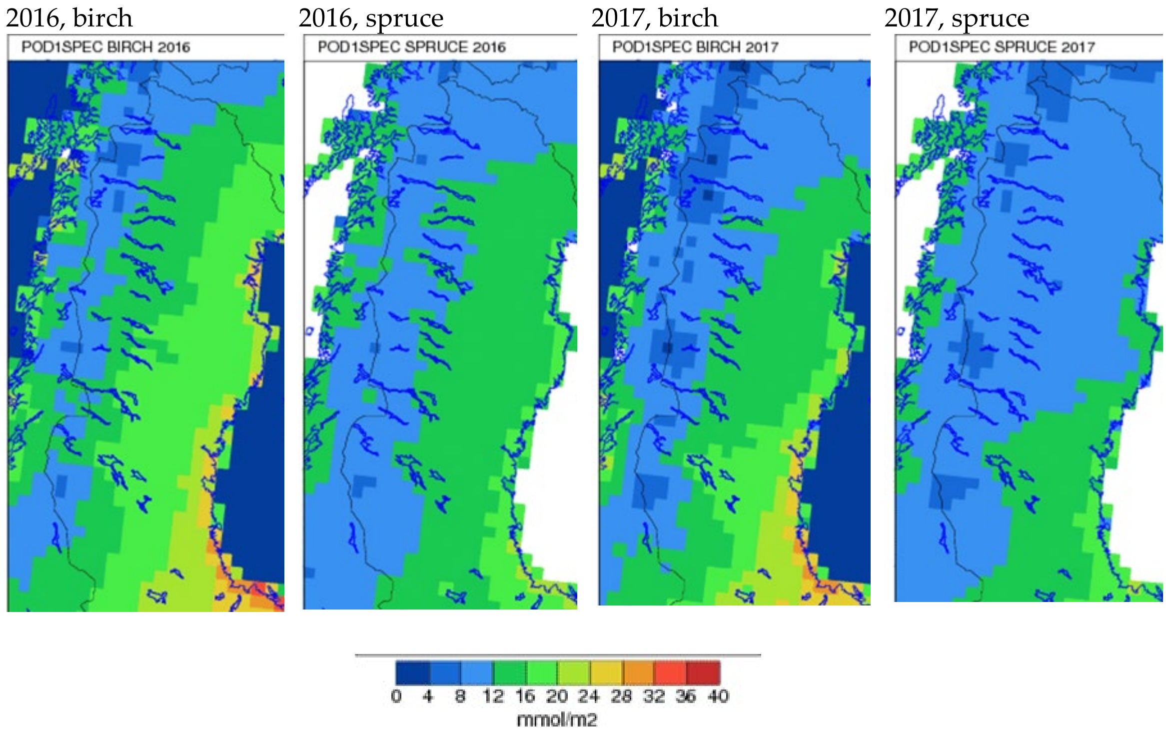


Figure 20. Estimates of the ozone flux, POD$_1$SPEC, relevant for European birch (*Betula pendula*) and Norway spruce (*Picea abies*)/Scots pine (*Pinus sylvestris*). Critical levels based on POD$_1$SPEC are for spruce/pine 9.2 mmol m^{-2} and for birch 5.2 mmol m^{-2}. From Langner et al., 2019.

The calculated critical levels based on PODySPEC for spruce/pine and birch forests are exceeded over most of Sweden, even over large areas in the north close to the mountain range.

9 Plant traits that might affect the ozone sensitivity of high-altitude plants

It is well known that there can be large differences in ozone sensitivity between plant species (e.g. Fuhrer et al., 2016). Plant traits can at least in part explain these differences. In the following we discuss how different traits of plant species that grow at high altitude may affect the ozone sensitivity.

The plants traits for the vegetation in the far northern European arctic, alpine and northern boreal vegetation zones depends on the environmental conditions caused by the combination of high altitudes and high latitudes. The environmental conditions at high altitudes are in many cases related to low temperatures during wintertime, high wind speeds, low nutrient availability and in some cases low precipitation. The different plants species have during the evolution adapted to these conditions by developing certain plants traits.

There are some plants traits of high-altitude vegetation that might point to rather low ozone sensitivity. Low ozone sensitivity in woody plants has been linked to high leaf dry mass per unit leaf area (LMA), i.e. the leaf thickness (Feng et al., 2017). High-altitude plants generally have a greater number of mesophyll cell layers, as compared to lowland plants (Körner, 1999) and therefore a high LMA. Hence, this common growth pattern of high-altitude plants species might contribute to a rather low ozone sensitivity. Furthermore, high-altitude plants generally have slower growth rates than lowland plants (Körner, 1999). High-altitude plants grow in such a way that the resources available per unit leaf area are efficiently utilized (Körner, 1999). They are "dwarfs on purpose". High-altitude plants produce fewer and smaller organs, but these are well equipped. It is the construction, differentiation and maturation of cells that represent the bottleneck of growth under thermal limitation, not the provision of raw material from e.g. photosynthesis (Körner, 1999). This would imply that negative impacts of ozone on e.g. photosynthesis might not have significant impacts on the growth rates of high-altitude plants. On the other hand, if ozone does have some negative impact on photosynthesis, a reduction for a set number of days will have larger impact on the total seasonal production in an alpine area since it would affect a larger fraction of the growing season than in a lowland area.

Selected high-altitude plant species were investigated for their anti-oxidant capacity (Wildi and Lutz, 1996). The total amount of antioxidants increased with increasing altitude. This enhancement was mainly due to ascorbic acid contents. Again, this plant trait points to a low ozone sensitivity.

On the other hand, a general hypothesis is that ozone exposure accelerates the life cycle of plants, including senescence (Skärby et al., 1995, Uddling et al., 2005). High-altitude plants to a large extent use resorption of N from old senescent tissue in order to cope with shortage of N (Körner, 1999). High ozone exposure has been shown to impair autumnal resorption of N in European silver birch (Uddling et al., 2005). Hence, disturbance of the resorption of N from old senescent tissue by ozone might represent a rather high risk for ozone vulnerability.

The aspects described above, pointing towards both a low and a high ozone sensitivity, respectively, have to be balanced against each other. However, the high leaf dry mass per unit leaf area and the slower growth rates in combination with the fact that photosynthesis in most cases does not limit alpine plant growth and finally that the leaves have relatively large amounts of antioxidants, points to a relatively low ozone sensitivity of high-altitude vegetation. This is in line with the conclusions made by Bassin et al. (2013) and Volk et al. (2014).

We conclude that most aspects of the plant traits of high-altitude vegetation point to a relatively low ozone sensitivity of this type of vegetation.

10 Studies of ozone impacts on northern European vegetation

In this section, we summarize the current knowledge about O_3 impacts on northern European vegetation. The knowledge is mainly based on experimental studies using daytime mean O_3 concentrations higher than the current daytime ambient values (<35 ppb O_3) during the growing season (Figs. 5 and 6). Northern Europe is in this context defined as Fennoscandia. In the end of this chapter, we make conclusions about the risks for negative impacts by the current O_3 exposure on northern vegetation.

10.1 Northern European trees

Manninen et al. (2009a) summarized the results from open-top chamber (OTC) experiments performed in northern Finland where Scots pine and northern birch provenances were exposed to 36–54 ppb O_3 as mean daylight concentrations. Biomass reductions of both downy birch (*Betula pubescens*) and mountain birch (*B. pubescens ssp. czerepanovii*) seedlings were demonstrated after one-season exposure. Moreover, the root/shoot ratio was reduced and the leaves of the mountain birch in the high O_3 treatments showed necrotic stipples already in June. Mountain birch has a very rapid phenological development during spring-early summer that makes it difficult for this species to compensate for damaged leaves. It is also noteworthy that N fertilization increased the total biomass production of mountain birch markedly only under the ambient O_3 both under the current climate (open-field plots) and in the about 1 °C warmer climate (non-filtered air OTCs) but not under elevated O_3 (Manninen et al., 2009b).

In contrast to mountain birches, northern Scots pine of local origin only showed invisible needle-level O_3 impacts, such as increased respiration, decreased level of polyamines and reduced chlorophyll/carotenoid ratio and increased amount of epicuticular waxes after three years of exposure (Manninen et al., 2009a). There is no field data comparing the O_3 sensitivity of birches and Scots pine from northern Europe, but both Scots pine and Norway spruce have been ranked as more O_3-tolerant species than deciduous birches and *Alnus incana* based on crown condition in a Lithuanian study (Girgzdiene et al., 2009). Despite the relatively high O_3 tolerance of Scots pine, invisible needle injuries may not be excluded in early spring conditions with high O_3 concentrations though (Augustaitis and Bytnerowicz, 2008; Huttunen and Manninen, 2013).

10.2 Northern European (semi-)natural vegetation

Mortensen and Nilsen (1992) and Mortensen (1993, 1994) screened (semi-)natural species for their O_3 tolerance by exposing them to 40–45 ppb (8 hours/day for 41 days to 8 weeks) in controlled-environment chambers (CECs). Among the O_3 injured species typical for the northern Scandinavian ecosystems were *Angelica archangelica*, *Chamerion angustifolium*, *Potentilla palustris*, *Solidago virgaurea* and *Phleum alpinum*. Growth reductions were recorded in *Carex atrofusca*, *Poa palustris*, *Silene acaulis* and *Poa alpina*. Danielsson et al. (1999) in turn showed that daylight mean O_3 concentrations of 75 ppb caused large growth reduction in *Phleum alpinum*. Mortensen (1993) also reported increased occurrence of yellow stipples/red-brownish pigmentation and/or reduction in leaf:stem fresh weight ratio in northern *Salix* species when the O_3 concentration was raised to 53 ppb.

In comparison, 78–80 ppb (8 hours/day for 43 days to 8 weeks) caused visible injuries in dwarf shrubs *Betula nana* and *Vaccinium myrtillus* (Mortensen 1994, Mortensen and Nilsen 1992). High O_3 tolerance of *Vaccinium* species was also suggested by an OTC experiment in which soil blocks with intact vegetation from a conifer forest were exposed to 75 ppb and 150 ppb (8 hours/day). The deciduous *V. myrtillus* showed visible injuries and changes in pigment contents under the high O_3 exposures, while the evergreen *V. vitis-idaea* was unaffected (Nygaard, 1994). Mörsky et al. (2008, 2011) did not find any effects of long-term high O_3 exposures (1.7–1.9 times ambient O_3) on the growth of *Eriophorum vaginatum*, a typical sedge species in northern peatlands, in an open-air field fumigation in which the conditions are more realistic than e.g. in controlled greenhouse experiments with pot-grown plants or in OTCs. Rinnan and Holopainen (2004) also suggested relatively high O_3 tolerance of peatland species (*Andromeda polifolia, E. vaginatum, Vaccinium oxycoccus*) based on responses in plant cell ultrastructure.

10.3 Northern European mosses and lichens

Mosses and lichens often dominate the ground-layer in tundra, alpine and subalpine (forest and peatland) ecosystems. Poikilohydric lichens growing on the ground (terricolous lichens) as well as on tree trunks and branches (epiphytic lichens) don't have stomata and roots. They take up gases through pores (Shirtcliffe et al., 2006), and water and water-dissolved ions through their surface and gain and lose water very rapidly. The effective antioxidant defense evolved in lichens against drought (Gechev et al., 2006, Valencia-Islas et al., 2007) may explain their high tolerance against oxidative stress caused by O_3 (Bertuzzi et al., 2013). The same probably largely applies to poikilohydric mosses under ambient O_3 concentrations even in wet ecosystems such as northern peatlands. Supporting this, Mörsky et al. (2011) did not find any effects of long-term high O_3 exposures (1.7–1.9 times ambient O_3) on peatland moss *Sphagnum papillosum* in an open-air field fumigation. The authors concluded that the high O_3 tolerance of *S. papillosum* could be due to enhanced formation of protective secondary metabolites in plant tissues during long-term O_3 exposure. Active production of O_3 scavengers, i.e. volatile organic compounds (Tiiva et al., 2007) may also partly explain the results.

Earlier growth chamber fumigation experiments by Niemi et al. (2002) and Rinnan and Holopainen (2004) also suggested relatively high O_3 tolerance of *Sphagnum* mosses. Nygaard (1994), in turn, did not find any visible injuries in *Dicranum polysetum*, *Hylocomium splendens* or *Pleurozium schreberi* under exposure to 150 ppb and 300 pbb of O_3.

10.4 The ozone vulnerability of northern European vegetation

Above, a summary is made of O_3 impacts on different northern vegetation and there are some impacts detected under experimental condition. The most prominent impacts observed in fumigation experiments are growth reductions of some northern birch provenances. Field studies that concern chronic impacts by relevant long-term O_3 concentrations are lacking but the results of open-field fumigation experiments, which are the most realistic type of experiment in terms of climatic and edaphic factors, suggest high O_3 tolerance of northern vegetation.

Northern vegetation is in general severely impacted by harsh meteorological conditions and short growing seasons. Relatively limited additional impacts by O_3 most likely have a small significance in this context. Hence, based on current knowledge cited above (as well as the review by Manninen et al., 2009a) we conclude that the current ambient O_3 concentrations are at such a low level (Figs. 5 and 6) that tundra and northern alpine and subalpine ecosystems most likely can tolerate it without significant long-term impacts. This is because of the apparent good ability to cope with oxidative stress by native species and/or their local genotypes and that the vegetation may resemble old established high-alpine grassland ecosystems from lower latitudes, showing high resilience to ozone exposure (Bassin et al., 2013; Volk et al., 2014; Körner, 1999). This includes the fact that ambient O_3 levels over the last decades may already have affected natural selection and modified especially the genetic pool of the most sensitive genotypes (Bergmann et al., 2017).

However, peak O_3 concentrations occurring in the spring-early summer may occasionally cause visible foliar injuries, particularly in deciduous trees.

The current ambient ozone concentrations are at such a low level that tundra and northern alpine and subalpine ecosystems most likely can tolerate it without significant long-term impacts.

11 Predictions of future near-surface ozone and its impacts on vegetation

A number of published studies have investigated possible future scenarios of near-surface ozone in Europe. The general conclusion from these studies is that while climate change may cause increases or decreases in near-surface ozone depending on location and climate scenario, the projected decrease in ozone precursor emissions has a much stronger impact on future near-surface ozone than the change in climate, leading to a strong decrease in near-surface ozone concentrations during summer. The robustness of future ozone projections is less compelling in areas that are located far away from European emission source regions, including specifically high northern latitudes. The evolution of ozone in northern Fennoscandia is more sensitive to changes in northern Atlantic background ozone concentrations than many other parts of Europe. It is also potentially more sensitive to changes in activity in the Arctic as climate change causes decreased sea ice and subsequent shifts in activity in the northern polar region. The number of studies focusing on northern Fennoscandia is much smaller than those focusing on the whole of Europe. We summarize future projections of ozone in subsequent sections, starting with projections based on future climate and precursor emissions, and then focus on the potential impact of changes to human activities in the polar region.

11.1 The impact of future climate and precursor emissions on near-surface ozone exposure

Colette et al. (2015) summarized eleven scientific studies, including 25 model projections, investigating the impact of climate change on near-surface ozone. The impact of changes in anthropogenic ozone precursor emissions was not included. The conclusion is that the forcing of climate is robust, leading to higher summertime near-surface ozone in large parts of continental Europe (a so-called climate penalty), and a small climate benefit or non-significant change in northern latitudes (see Figure 21).

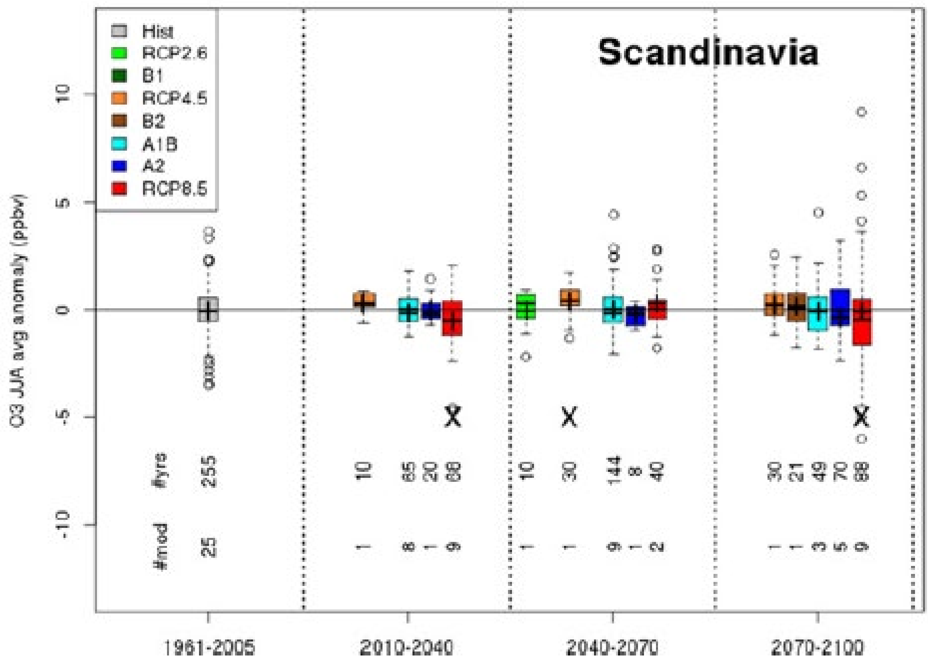


Figure 21. Evolution of summertime (June–August) ozone averages expressed as anomalies compared to the historical period for each model. The boxplots provide the median and upper and lower quartiles of all simulated years in the corresponding 30-year time window as well as whiskers at 1.5 times the inter-quartile distance and points exceeding this value. The median of the average anomaly for each scenario is also given (' + ' sign) to assess the risk of overweighting models with more simulated years by comparison with the median of all simulated years in the boxes. A cross (' × ') is drawn where the signal is statistically different from zero (see Colette et al., 2015). The colour-key of scenarios is given in the box, as well as the total number of models (#mod) and modelled years (#yrs) for each time horizon and scenario. Adapted from Colette et al., 2015.

When future anthropogenic European emission decrease is also considered, the decrease in near-surface ozone is even stronger in Fennoscandia (Figure 22). In northern Fennoscandia, the decrease in near-surface ozone is not as strong as closer to continental Europe. This is likely due to larger fractions of the ozone originating from other regions and ozone of natural origin. Note that in Figure 22, the assumed increasing trend into the future in the lateral and top boundaries used in panel d was based on old data from Mace Head – more recent trend evaluations (e.g., Derwent et al., 2018) indicate that the trend has levelled off and possibly become negative from ca 2007 (see Sec. 5.1). The model results shown in Figure 22C with an assumed zero-trend in background ozone may be more in line with an extrapolation of current tropospheric ozone trends in Europe and the north Atlantic. Newer model scenarios of future background ozone for the northern hemisphere, based on emissions from ECLIPSE V5a for the future (2030s and 2050s compared to 2015), results in decreasing ozone exposure also in high northern latitudes (Geels et al., 2021, submitted). Changes in anthropogenic activity in the polar region, e.g. shipping, may however impact the high-latitude future exposure to background ozone (next section).

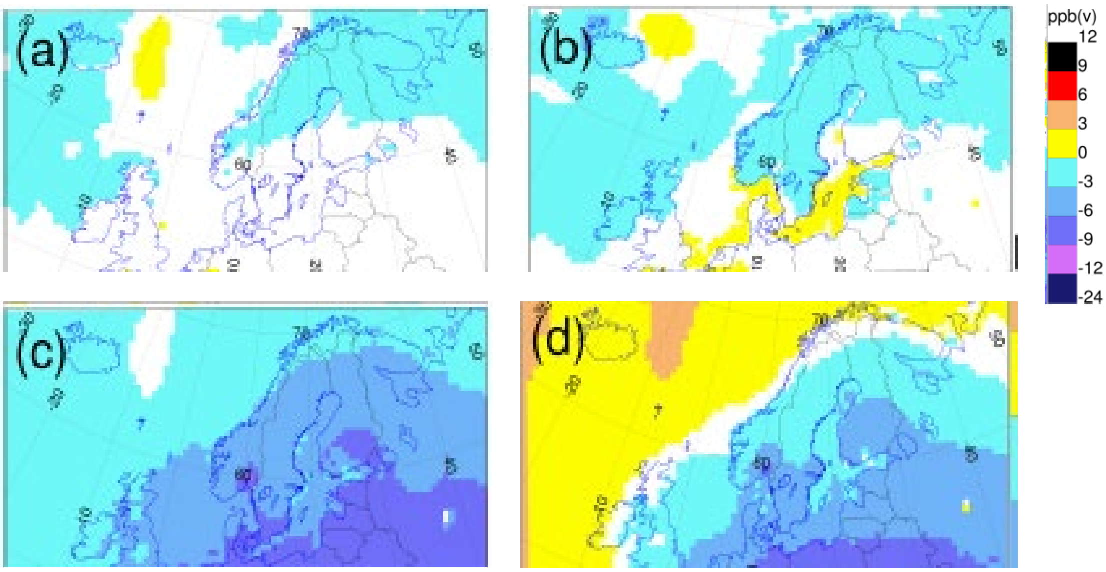


Figure 22. Change in summer (April–September) daily maximum surface ozone concentration from 1990–2009 to 2040–2059 due to changes in two possible future climates (a, b), and due to emission and climate change (c) and due to emission, climate and assumed increasing hemispheric background of 0.1 ppb year^{-1} (d). Non-significant changes are masked white. From Langner et al., 2012.

The projected decrease in ozone precursors has a much stronger impact on future near-surface ozone than the projected change in climate, likely leading to a strong decrease in near-surface ozone concentrations during summer.

11.2 Consequences of changed anthropogenic air pollution emissions in the north

Climate change will lead to less sea ice in the future. This opens the opportunity for new shipping routes and subsequent emissions in pristine areas in the polar region. Geels et al. (2021, submitted) investigated the impact of future shipping scenarios on air pollution exposure in the Nordic region (Figure 23). In the current scenario, shipping contributes by 1–2% to the annual mean near-surface ozone in northern Fennoscandia according to this study. In 2050 the contribution of shipping may increase up to 5% of the annual mean ozone (in case of high-growth in shipping if new shipping routes are included). Also, for exceedance of 40 ppb during May–July (AOT40), there is an increase in the contribution by shipping in the high-growth scenario with new polar routes, although the total AOT40 decreases from present to 2050 in all scenarios considered.

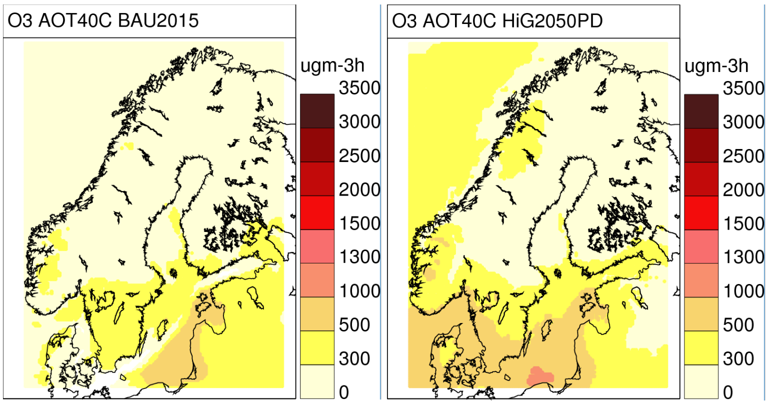


Figure 23. Shipping contribution to May-July AOT40 in 2015 (left) and 2050 (right), assuming high growth and new shipping routes through the Arctic polar region in 2050. The scenario assumes high growth for ozone precursor emissions in the northern hemisphere according to ECLIPSE V5a, modelled by the DEHM model and down-scaled by MATCH on finer resolution covering Fennoscandia. Unit: µg m^{-1} h.

The contribution from shipping to the annual mean ozone exposure in northern European latitudes can increase in 2050 compared to 2015, if shipping follows a high-growth scenario in the Arctic.

12 Overall conclusions about the ozone vulnerability of northern vegetation

The general conclusions about the aspects that may be important for the ozone vulnerability of northern vegetation that were made in this study were:

- Air temperatures as well as the amounts of precipitation have increased during the summer months in Fennoscandia over the time period 1971–2019, while trends in amounts of solar radiation are more variable and uncertain.
- The tree lines of all the major tree species have shifted upslope, as well as shifted northward in latitude, in close accord with temperature rise.
- The nitrogen deposition to vegetation in northern Sweden is in the order of 1–2 kg N ha^{-1} yr^{-1} and has declined approximately 30 % since the 1980s.
- Data on budburst as well as meteorological observations show that there has been a development towards an earlier start of the growing season during the year, with approximately 0.5 – 1 day per year. Thus, the start of the time period during the year during which vegetation ozone exposure estimates should be accumulated at northern latitudes has changed.
- The timing of the spring ozone maximum is also shifted towards earlier in the year. There is presently no evidence for an increasing overlap between the growing season and the ozone peak.
- Ozone concentrations in the northern parts of Fennoscandia are to a large extent determined by the large-scale (North Atlantic) background concentration of ozone. The background concentration of ozone was increasing in Europe during the second half of the 20th century, but seem to have levelled off and started to decrease during the last decades.

- At high altitudes the ozone concentrations are relatively similar during day and night-time.
- Northern sites exhibit a higher and earlier ozone spring maximum, compared to southern sites in Fennoscandia. During spring, the 24h mean ozone concentrations at a high-altitude site were higher compared to the closest monitoring sites at lower altitude. The annual ozone maximum occurs in the summer in the southern and continental regions of Europe and in spring in the north.
- Increasing hemispheric background of ozone, European emission decrease and climate variations over the period cause the increase in the spring peak ozone concentration. The decreasing ozone concentrations in summer, due to emission reductions, and in May, due to climate variations, lead to a shift of the spring peak to earlier in the year.
- Under certain meteorological conditions, polluted air with very high concentrations of ozone and ozone precursors can be transported to remote regions in northern Fennoscandia.
- Ozone concentrations close to the ground can be substantially lower compared to the height above ground commonly used for ozone concentration monitoring.
- Maximum light intensities decrease with increasing latitude while the maximum day length increase with increasing latitude.
- High latitude light period and light quality has the potential to increase the duration of the daily period with plant gas exchange, and therefore the period when absorption of ozone through the stomata may occur. A simple calculation example illustrated that the potential added ozone uptake in the early morning and late evening at northern sites may be canceled out by a lower ozone uptake in the middle of the day, as compared to southern sites.
- Other aspects of day length that influence the ozone susceptibility in plants might be a reduction of nighttime repair or a physiological change in favor of programmed cell death under oxidative stress.
- The calculated critical levels based on POD_ySPEC for spruce/pine and birch forests are exceeded over most of Sweden, even over large areas in the north close to the mountain range.
- Most aspects of the plant traits of high-altitude vegetation point to a relatively low ozone sensitivity of this type of vegetation.
- The current ambient ozone concentrations are at such a low level that tundra and northern alpine and subalpine ecosystems most likely can tolerate it without significant long-term impacts.
- The projected decrease in ozone precursors has a much stronger impact on future near-surface ozone than the projected change in climate, likely leading to a strong decrease in near-surface ozone concentrations during summer.
- The contribution of shipping to the annual mean ozone exposure in northern European latitudes can increase in 2050 compared to 2015, if shipping follows a high-growth scenario in the Arctic.

Based on the information and evidence compiled for this study and the general conclusions made above, the overall conclusions about the ozone vulnerability of northern vegetation were:

- There remain uncertainties regarding to what extent northern vegetation is affected by ozone exposure.
- According to current knowledge, we could not find evidence that expected future changes in ozone concentrations and climate would make the arctic and northern alpine and subalpine vegetation substantially more vulnerable to ozone than other types of European vegetation.

- The risk of significant and lasting negative impact of the current exposure to ozone on northern boreal forests is most likely not greater than for boreonemoral and nemoral forests in southern Fennoscandia.
- However, peak ozone concentrations occurring in spring and early summer may affect vegetation at northern latitudes in Fennoscandia since the start of the growing season in the future may occur earlier during the year.

13 Policy implications

The policy implications that can be identified from the overall conclusions made above are:

- The current state of knowledge implies that ecosystems in the far north are not more susceptible to ozone than vegetation in other parts of Europe. Hence, we cannot advocate for a stronger reduction of ozone precursors emissions based exclusively on the ozone sensitivity of vegetation in the far north.
- Policies designed to reduce emissions of ozone precursors to protect vegetation in other parts of Europe as well as in the entire northern hemisphere are likely to suffice to protect vegetation in northern Fennoscandia.

14 Important remaining knowledge gaps

Our conclusions are based on important, but limited observations. Experimental evidences from investigations specifically designed to study ozone sensitivity of high-altitude vegetation in northern Europe are to a large extent lacking. It is recommended that further experimental research is undertaken to directly compare the ozone sensitivity of plants of high-latitude/altitude origin with that of plants (species, genotypes) representative of regions of the Southern part of the Fennoscandia. This research should include the particular characteristics of the high-latitude climate and other conditions.

A specific research question is if the new ozone critical levels for European vegetation based on POD_YSPEC (Mapping Manual, 2017) are correct also for far northern vegetation, both regarding calculation methodology and impact assessments. In particular, there is a lack of information about the degree of stomata closure during nights in high-latitude area plants. This is important for the modelling of ozone uptake in these areas and requires coordinated measurement campaigns in close cooperation with modelers.

There is a potential for increased ozone uptake to vegetation in spring due to the earlier growing start of vegetation and increased dry deposition of ozone to vegetation in May. The trend in accumulated phytotoxic ozone dose for vegetation in spring needs to be investigate further.

Further research questions may be related to the future development – e.g. oil and gas extraction including flaring, shipping, and more tourism – how will that affect the ozone exposure of the northern vegetation? Do ozone precursor emission scenarios describe this correctly?

Will warm and dry summers like 2018 become more frequent, and what consequences will this have?

There are currently very few, long term ozone monitoring stations in the arctic and alpine vegetation zones, in particular at high altitudes. In view of the expected increased anthropogenic activities in these areas in combination with climate change, it is strongly advised to increase the number of high-altitude ozone monitoring sites in these regions.

Finally, we see an important need to finance infrastructure for long-term measurement of essential climate variables, specifically ozone and ozone precursors, for both ecosystem and climate research at far northern latitudes. With long-term we mean at least 20 years in this context.

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