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METEOROLOGY No. 162

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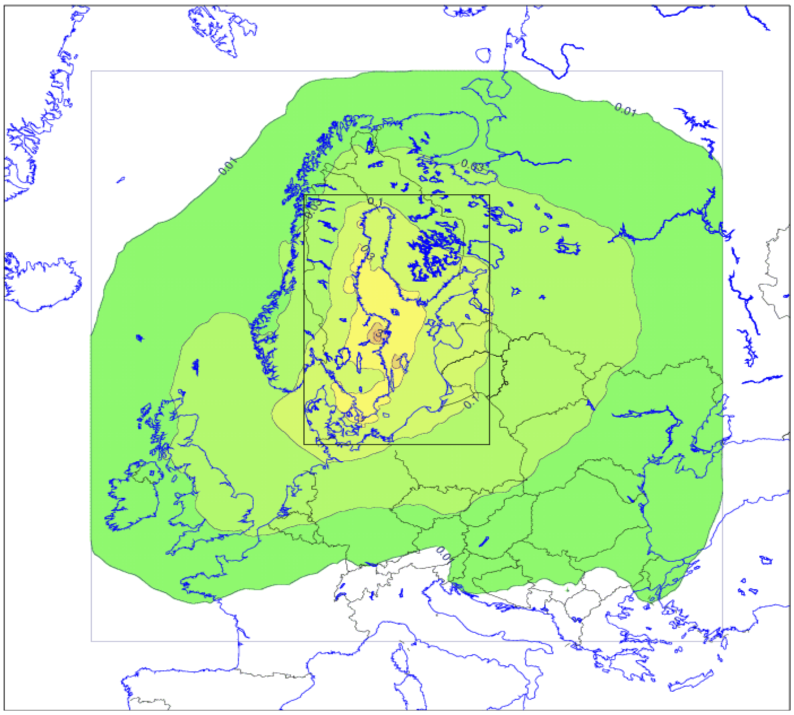

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Report Summary / Rapportsammanfattning

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Title (and Subtitle/Titel

A basis to estimate marginal cost for air traffic in Sweden. Modelling of ozone, primary and secondary particles and deposition of sulfur and nitrogen.

Abstract/Sammandrag

In this study we have investigated the effects of emissions from aviation on air quality in both Swedish and European domains. The results will be used as a basis to estimate the marginal cost for air traffic in Sweden. The vertical, geographical and temporal distribution of aviation emissions over Sweden has been estimated using a newly developed methodology. The aviation emissions have been categorized by their emission altitude (LTO, low cruise and high cruise) and flight nationality (international, national and overflight). This aviation emission information was then used as input data to the regional atmospheric chemistry model MATCH to simulate the effects of aviation emissions on ecosystem, health and climate metrics. A total of 17 model simulations over three years have been performed. There is one simulation in which all emitted species from the surface and aviation emissions are included and eight simulations in which all aviation emissions from each combination of emission altitude and flight nationality are included. There are eight simulations in which NOx aviation emissions from each combination of emission altitude and flight nationality are included. Using these simulations, contributions from aviation emissions to deposition, concentrations and a range of different air pollution metrics has been calculated. The results are calculated in both the Europe and Swedish domains for all the simulations.

The following results are included in this report:
. Deposition of oxidised and reduced nitrogen
. Deposition of excess sulfur
. AOT40 and SOMO35 and their exposures
. Concentration and exposure of primary and secondary particles
. Concentration of nitrate and sulfate particles
. Concentration of surface and above surface ozone

In summary, contributions from aviation emissions in Sweden to the different concentrations, deposition and metrics for environmental effects are generally small, on the order of a few per mille or less. However the impacts can be traced in the simulations well beyond the Swedish borders. LTO emissions give the largest contribution to deposition of oxidised and reduced nitrogen, deposition of excess sulfur and concentrations of primary and secondary particles. In particular near the major airports like Stockholm-Arlanda and Gothenburg-Landvetter. High cruise emissions give insignificant contributions to deposition and concentrations at surface level. LTO emissions give a negative contribution to surface ozone concentration locally at the main Swedish airports but give an overall increased contribution in the regions around. Aviation emissions at low cruise and high cruise levels have the largest effect on ozone concentrations at higher levels.

Key words/sök-, nyckelord

Air quality, MATCH, dispersion modelling, marginal cost, emissions, flight, air traffic

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A total of 17 model simulations over three years have been performed. There is one simulation in which all emitted species from the surface and aviation emissions are included and eight simulations in which all aviation emissions from each combination of emission altitude and flight nationality are included. There are eight simulations in which NOx aviation emissions from each combination of emission altitude and flight nationality are included. Using these simulations, contributions from aviation emissions to deposition, concentrations and a range of different air pollution metrics has been calculated.

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2 Introduction

2.1 Overview of methods

Marginal costs give a measure of the economical effects of a single vehicle.

This project aims to quantify the effects of the emissions to air from the current aircraft fleet over Swedish territory. Among these effects are the negative health effects of particles (primary and secondary), the acidification from sulfur (SOx) emissions, the eutrophication and acidification from nitrogen oxides (NOx) and ammonia (NH_3) emissions and the damage to forest and crops from the ground-level ozone formed by complex chemical reactions from several aircraft emissions, including NOx, volatile hydrocarbons (VOC) and carbon monixide (CO) [Naturvårdsverket, 2018a]. It will also quantify the effect of these emissions on the atmospheric formation of ozone in the troposphere, which contribute to the greenhouse effect.

Using the MATCH dispersion model, we have calculated the effects from different aircrafts depending on the flight type (domestic, international and overflight) and height of emissions (LTO, low cruise, high cruise). This has been done with a newly created aircraft emissions model, estimating the emissions of all aircraft traffic over Swedish territory and categorizing it by flight type and emission height. We here define the Swedish territory as the Swedish national borders plus the Swedish Exclusive Economic Zone (all sea within 200 nautical miles of the Swedish shore).

3 Non-aviation emissions

Having access to high-quality geographically distributed emissions is vital. This includes not only aircraft emissions, which is the focus of this project, but also all other sources, as the total concentrations of different species affect the reaction rate and domain of atmospheric chemistry. Geographical variations in emissions and concentrations of NOx can for example lead to ozone formation at one location and depletion at another, and it is only by correctly modelling both emissions, dispersion and atmospheric chemistry that the net effect can be determined.

This section aims to describe the aircraft and non-aircraft emissions used in this project, which serve as vital input to the MATCH model. While the MATCH model is run over three years to take into account the varying meteorology, emissions tend to be less sensitive and are calculated for a single year only. The emissions are based on input data corresponding to years 2014, 2015 and 2016.

For the Swedish non-aircraft emissions, we have used the Svenska MiljöEmissionsData (SMED) emission database [Andersson et al., 2015b]. This is a high-quality, high-resolution dataset compiled annually, containing all Swedish anthropogenic emissions at a spatial resolution of 1 km. We use data for emission year 2014, as confidentiality issues caused the very latest data to lose detail.

For the European non-aircraft emissions, we have used the European Monitoring and Evaluation Programme (EMEP) emission database [EMEP/CEIP, 2014], which is a compilation of geographically distributed emission data for Europe. This is one of the most complete datasets available, and relies on individual submissions from each country.

In both the SMED and EMEP databases, aircraft emissions are either of low quality or non-existing, which is a consequence of the difficulty involved with the modelling of its geographical distribution. For emissions outside the Swedish territory, we have therefore supplemented the data with extra aircraft emissions. This is important, as the high altitude aircraft emissions are likely to have a great effect on the atmospheric chemistry at these altitudes. For this, we use data from IPCC, Lamarque et al. [2010], which consists of global low-resolution emissions for the year 2010. These are good enough for representing European emissions, but have a very simplified methodology for the geographic distribution (both vertical and horizontal), and would not be sufficient for representing the Swedish aircraft emissions in this study.

A new methodology has therefore been developed for aircraft emissions over the Swedish territory. These emissions have been calculated based on airport arrival and departure data, flight patterns and EMEP emission factors. The methodology for this is described in the next section.

4 Modelling of aviation emissions

The new aircraft emission model aims to calculate both the total emissions for each species by means of bottom-up and determine their geographical distribution. To do this, we need to know not only how many flights are made from each Swedish airport, but also detailed information on how the aircrafts move.

We need to distinguish between three different flight 'nationalities', for example whether the flight is domestic (both departs and arrives at Swedish airports), international (departs and arrives at one Swedish and one foreign airport) or is an overflight (both departs and arrives at foreign airports). We also categorize the emissions by which altitudes they are emitted; LTO (landing and take-off) below 1000 meters, low cruise between 1000 and 10 000 meters, and high cruise at above 10 000 meters.

The model is based on five major sources of input data, described briefly below:

- **SMED national emissions inventory** is a Swedish emission database compiled by SMED for use in international reports such as the UN climate convention (UNFCCC) and the EU reporting on air quality (UNECE CLRTAP).
  The database includes emission totals (without geographic distribution) for domestic and international flights, divided into LTO and cruise. These emissions are calculated by an aircraft emissions model developed by Mårtensson and Hasselrot [2013] and is adjusted by statistics of sold fuel. Values calculated during SMED 2016, for year 2014 is used for scaling of the emissions in this project.
  As the emissions from the international flights are based on the fuel sold in Sweden, these emissions are more uncertain than the domestic emissions. They also include emissions outside of the Swedish territory, and can therefore not be used in any comparisons to the new model.
- **Swedish Transport Agency airport arrival and departure statistics** is a detailed log of all arrivals and departures from all major Swedish airports (39 in total). This data includes origin and destination of each flight as well as aircraft type, but does not include information on the flight movements.
- **Flight location data from Flightradar24** describes the movement of flights over Swedish territory.
- **EMEP aircraft emission factors** can be extracted from the EMEP/EEA air pollutant emission inventory guidebook [European Environment Agency, 2016, 1.A.3.a Aviation]. This includes an aviation emission calculator from which emission factors from various aircraft types can be extracted for the LTO and cruise steps separately.
- **Swedish Civil Aviation Administration overflight counts** include a count of monthly overflights (aircrafts over Swedish territory, without information of e.g. location and aircraft type).

The new aircraft emission model includes the following steps:

1. Calculate an average flight pattern for:
   - domestic airport pairs,
   - domestic airports to/from international,
   - overflight traffic.

   based on Flightradar24's data.
2. Calculate geographically distributed aircraft emissions for each airport pair based on average flight patterns, number of aircraft arrivals/departures and emission factors.
3. Sum all aircraft emissions into emissions over the Swedish territory and scale based on SMED national emission totals.

These steps are discussed in more detail below. Table 1 presents a summary of input parameters that are used in the calculation of aviation emissions.

Product	Source	Content	Format	Usage and other information
Swedish national emissions inventory	SMED	Total domestic and international aircraft emissions estimated based on sold fuel	xlsx workbook	Our results are scaled according to this inventory
Airport arrival and departure statistics	Swedish Transport Agency	Arrivals and departures of flights with at least one Swedish airport	flight legs	Used to calculate emissions from Swedish flights
Flight patterns (total 178,000 flights)	Flightradar24	Four weeks of all flight transponder data over Sweden	csv entry for each polled position	Used to calculate Swedish geographical distribution of the emissions 1. Domestic - based on data from 228 domestic airport pairs (8700 flights) 2. International - based on 29 international - domestic airport pairs (47 000 flights) 3. Overflight - based on data from international - international airport pairs (122 000 flights)
Aircraft emission factors	EMEP	Emission factors for flight activites (LTO, cruise)	xlsx workbook	Used to calculate aviation emissions from various aircraft types both during LTO and cruising
Overflight counts	Swedish Civil Aviation Administration	Monthly overflight counts (without geographical positioning and aircraft type)	1 value per month	Used to calculate aviation emission for OVER-LTO, -LO and -HI

Table 1: *A summary table of the input used for emission calculations.*

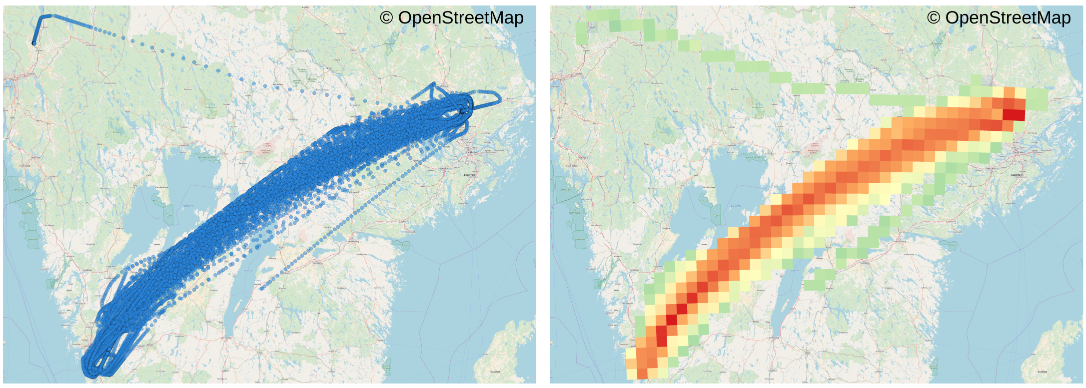
4.1 Calculate average flight patterns

We have acquired four weeks of Flightradar24 data from the year 2015, split into four one-week periods (January 5-12, April 6-13, July 6-13 and October 5-12), to calculate the average flight patterns in winter, spring, summer, and fall, respectively. This data has been collected by Flightradar24 from aircrafts before takeoff, during flight over the Swedish territory and surroundings and during docking (if inside Swedish territory).

Modern aircrafts use a system called ADS-B (Automatic Dependent Surveillance - Broadcast), similar to AIS[1] for shipping, to continuously report their location, id, aircraft type, origin and destination. There is also data available for aircraft without ADS-B via Multilateration (MLAT), which uses the Time Difference of Arrival technique (TDOA) to triangulate positions.

The data from these four weeks includes detailed information of roughly 178 000 flights. Of these 178 000 flights, only 8 700 are domestic which is an extensive amount of flights even though it is only a small fraction of the total 261 000 domestic flights registered at the Swedish Transport Agency. As we need to be able to assign geographically distributed emissions from every single flight, a generalization of the flight patterns is required.

This is done by calculating an average flight pattern for each pair of airports, i.e. one pattern for Arlanda to Landvetter and one pattern for Ängelholm to Örebro. The flight pattern is calculated from the travelled distance of all flights between each airport pair. All data points with travelled distance from the Flightradar24 data are summed up over a three-dimensional grid defined in the MATCH calculations. The pattern is finally normalized, as it is used only to distribute the emissions horizontally and vertically. An example of this process can be seen in figure 1.



(a) Flightradar24 points *(b)* Gridded average pattern for all altitudes.

Figure 1: *Conversion of raw Arlanda to Landvetter Flightradar24 data to average flight pattern.*

For each airport pair, we also calculate the median distance travelled by all flights. By combining the normalized flight pattern with the distance travelled, the total emission can then be calculated for each flight, as described in section 4.2.

[1] Automatic Identification System

This is done for all Swedish airports with at least one flight registered in the Flightradar24 data. The pattern is directional, so that we differentiate between flights from Arlanda to Landvetter and from Landvetter to Arlanda. This can be important, as wind directions can force asymmetrical departures and landings. This results in flight patterns for 228 domestic airport pairs.

For flight patterns for international flights, we create an average pattern of all international arrivals and departures from each airport. This results in 29 international-domestic airport pairs.

We also create a fallback flight pattern in the rare cases where no matching airport pair is found in the Flightradar24 data with a flight registered in the Swedish Transport Agency data. The fallback flight patterns are an average flight pattern for domestic and international flights respectivly.

For overflights, we create an average flight pattern for all flights which both arrive to and depart from foreign airports.

4.2 Calculate aviation emissions for each airport pair

In the previous step, we calculated average flight patterns for each domestic airport pair and for each international flight from each Swedish airport, as well as calculated typical flight distances for each airport pair.

To calculate the total emissions, we rely on departure/arrival statistics from the Swedish Transport Agency, which contain over 522 000 arrivals and departures at Swedish airports in 2016. As both departures and arrivals are logged, each flight is counted twice. Counting only departures, we therefore have data for around 261 000 domestic and international flights. Aircraft type is also included, which allows for different emission factors to be taken into account.

This data is aggregated into each combination of airport pairs and aircraft type. We can then differentiate between e.g. flights from Arlanda to Landvetter made by Airbus A320 aircrafts and those travelling the same route but made by Fokker 50 aircrafts.

For the aircraft emission factors, we use the emission calculators supplied in the EMEP/EEA air pollutant emission inventory guidebook [European Environment Agency, 2016, 1.A.3.a Aviation]. These calculators are used for calculating the total emissions for a single flight with a specified route distance and aircraft type. One calculator is used for calculating the total emission from the entire cruise step, and one for the LTO step divided into; taxi out, take off, climb out, landing and taxi in.

The cruise emission calculator is used to calculate emission factors given by emission per nautical mile for a number of route distances. These emission factors differ between routes of different distances, as factors like maximum altitude and time at different altitudes affect the emissions. This is done for the 38 most common (according to Swedish Transport Agency data) aircraft types over Swedish territory.

The LTO emission calculator is used to calculate the total emission for a typical Swedish airport (affecting e.g. time on runway). The emissions for the taxi out, take off and taxi in steps are aggregated into a total emission that is distributed between 0 and 100 meters for each flight. Similary, the emissions for the climb out and landing steps are aggregated into a total emission that is distributed between 100 and 1000 meters for each flight. These LTO emissions are generated for 15 of the most common aircraft types.

For each aircraft type, we look first for emission factors matching the exact aircraft type. Each aircraft type is also designated a template aircraft type with similar properties, so if no exact match is available, the template is used.

The total emissions and their geographical distribution are finally calculated for all flights at each airport pair. What flight pattern to use for the geographical distribution is determined in the following order for an example airport pair Arlanda to Landvetter:

- Look for flight pattern with the exact match (Arlanda to Landvetter)
- if no match, look for flight pattern with the airports reversed (Landvetter to Arlanda)
- if no match, use the general domestic flight pattern (Sweden to Sweden)

Emissions are distributed vertically according to the flight pattern. LTO emissions are divided equally into all layers between 0 and 100 meters for taxi out, take off and taxi in and equally into all layers between 100 meters and 1000 meters for climb out and landing. Cruise emissions are distributed proportionally to the distance travelled in each layer, so that if 5% of the total distance is travelled between 5000 and 6000 meters, 5% of the emissions are put there.

Overflight emissions are calculated using overflight counts from the Swedish Civil Aviation Administration (see table 2)

Month	Count
January	22002
February	20372
March	23781
April	24706
May	26709
June	28040
July	28964
August	28117
September	27733
October	26057
November	22758
December	22401

Table 2: *Overflight counts for year 2015 as reported from the Swedish Civil Aviation Administration.*

4.3 Calculate and scale total emissions

In the previous section, we have calculated total geographically distributed emissions for each airport pair, as well as for all international traffic from each domestic airport and for overflights. These emissions are finally summed up into the eight combinations of nationality and emission altitude;

- domestic
  - LTO
  - low cruise
  - high cruise
- international
  - LTO
  - low cruise
  - high cruise
- overflight
  - low cruise
  - high cruise

The resulting calculated emission totals for the domestic flights are compared to the SMED domestic flight emissions for each species. As the primary function of this model is to provide a geographic distribution for the emissions, this has also been the focus, and we consider the SMED national totals to be more reliable. Therefore, we create a scaling factor for each species using this comparison between the domestic totals, and then apply it also to the international and overflight traffic.

In table 3, we show the comparison between the SMED national totals and the scaled and unscaled results from the new model. Overall, we find the new model to generally perform well. For the most important species, we get correction factors of e.g. 0.90 for NOx and 1.21 for CO_2 and fuel consumption. Some species behave worse, like CO with correction factor 2.83 and NMVOC with correction factor 2.15, but these species are of lesser importance and within limits. Differences in emissions likely originate from differences in emission factors, where differently assumed engine models within a single aircraft type can lead to large differences.

Species	Domestic [t/yr]			International [t/yr]			Overflight [t/yr]		
	Unscaled	Scaled	SMED	Unscaled	Scaled	SMED	Unscaled	Scaled	SMED
NOx	1830	1650	1650	3650	3214	8740*	2772	2501	-
SOx	119	168	168	193	272	737*	123	177	-
PM_{25}	57	36	36	95	61	154*	63	40	-
NMVOC	78	168	168	97	208	499*	71	152	-
NH_3	10	10	-	16	16	-	11	11	-
CO	837	2370	2370	854	2420	7660*	497	1406	-
CO_2	$426 \cdot 10^3$	$516 \cdot 10^3$	$516 \cdot 10^3$	$708 \cdot 10^3$	$858 \cdot 10^3$	$192 \cdot 10^3$**	$471 \cdot 10^3$	$570 \cdot 10^3$	-
Fuel	$135 \cdot 10^3$	$164 \cdot 10^3$	$164 \cdot 10^3$	$225 \cdot 10^3$	$272 \cdot 10^3$	$272 \cdot 10^3$	$150 \cdot 10^3$	$181 \cdot 10^3$	-

Table 3: *Comparison of total emissions for the new model (scaled and unscaled) and the SMED national totals.* [2]
** Includes emissions also outside of Swedish territory.*
*** Only LTO emissions included.*

In order to assess which scenario has the most activity it is interesting to look at the distribution of fuel consumption between the different scenarios. The distribution of the different species and fuel can be seen

[2]Note that SMED submission 2016 for year 2014 is used for the scaling of the emissions.

Species	Domestic [t/yr]			International [t/yr]			Overflight [t/yr]		
	LTO	LO	HI	LTO	LO	HI	LTO	LO	HI
NOx	573	692	386	508	1356	1351	-	431	2070
SOx	95.7	45.7	26.6	68.0	102	102	-	30.6	147
PM_{25}	15.5	13.6	7.39	11.0	24.9	24.7	-	6.94	33.3
NMVOC	146	12.7	9.19	95.1	58.1	54.4	-	26.3	126
NH_3	4.03	3.53	1.93	2.86	6.5	6.43	-	1.81	8.69
CO	1942	292	136	973	808	638	-	242	1164
CO_2	$219 \cdot 10^3$	$192 \cdot 10^3$	$105 \cdot 10^3$	$155 \cdot 10^3$	$353 \cdot 10^3$	$349 \cdot 10^3$	-	$98 \cdot 10^3$	$472 \cdot 10^3$
Fuel	$69 \cdot 10^3$	$61 \cdot 10^3$	$33 \cdot 10^3$	$49 \cdot 10^3$	$112 \cdot 10^3$	$111 \cdot 10^3$	-	$31 \cdot 10^3$	$150 \cdot 10^3$

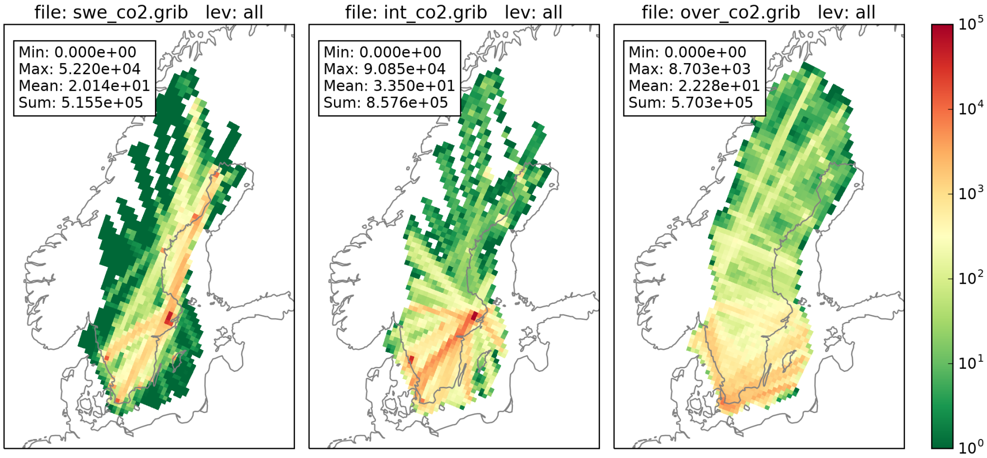
Table 4: *The scaled distribution of various emissions for different combinations of flight nationality and altitude.*

in table 4. From the table it is clear that the distribution of CO2 and fuel is the same, this is due to the fact that the CO2/fuel factor of 3.15 is used in the EMEP Guidebook [European Environment Agency, 2016, 1.A.3.a Aviation]. For an overview of the energy usage per scenario see table 5, the energy content of aviation fuel is assumed to be 43.2 MJ/kg.

Flight type	Yearly fuel use [t/yr]	Yearly fuel use [PJ/yr]	Distribution [%]
SWE-LTO	$69 \cdot 10^3$	2.98	11.2
SWE-LO	$61 \cdot 10^3$	2.63	9.9
SWE-HI	$33 \cdot 10^3$	1.43	5.4
INT-LTO	$49 \cdot 10^3$	2.12	7.9
INT-LO	$112 \cdot 10^3$	4.84	18.2
INT-HI	$111 \cdot 10^3$	4.80	18.0
OVER-LTO	0	0	0
OVER-LO	$31 \cdot 10^3$	1.34	5.0
OVER-HI	$150 \cdot 10^3$	6.48	24.3
SUM	$616 \cdot 10^3$	26.61	100

Table 5: *Scaled yearly fuel use for flight traffic over Swedish territory. Energy content of fuel is assumed to be 43.2 MJ/kg*

In figure 2, the scaled total CO_2 emissions from aircrafts for all altitudes (LTO, low cruise, high cruise) is shown. An altitude divided map can be found in section 6.1.



(a) Domestic ***(b)*** International ***(c)*** Overflights

Figure 2: *Total emissions for all altitudes (LTO, low cruise, high cruise) for CO2. Values are scaled according to table 3.*

5 MATCH calculations

5.1 The MATCH system

The Multi-scale Atmospheric Transport and Chemistry model (MATCH) is used in this project to simulate the chemical interactions of flight emissions over Sweden. It is a three dimensional Eulerian model which describes physical and chemical processes that simulate the fate of the emissions. Those processes include atmospheric transport and dispersion, chemical transformation, as well as dry and wet deposition of pollutants like ground-level ozone, particulate matter, sulfur and nitrogen species. The model includes around 70 chemistry components which photochemistry and thermochemistry are described through around 130 chemical reactions.

The MATCH model has participated in several national and international model evalutation and comparison studies. The evaluation was done through comparing gas phase components such as wet deposition and concentrations of chemical species in precipitation. It is concluded that MATCH is comparable among the best chemistry transport models in the research field (Vivanco et al. [2018], Marécal et al. [2015], Simpson et al. [2014], Langner et al. [2012]).

5.2 Dispersion modeling with MATCH

All the dispersion modeling simulations were performed with flight emissions over Sweden in 2016, flight emissions over Europe in 2010 and SMED-EMEP ground emissions in 2014 and 2015. The simulations were run with a total of 3 years of meteorological data so as to minimize the effects from varying meteorology in a year.

The following components are calculated and stored at the model's ground level:

- Concentration of primary aerosol particles which include fine and coarse particles.
- Concentration of secondary aerosol particles which include amonium sulfate, ammonium nitrate and particle form of nitrate and sulfate.
- Concentration of ground level ozone.
- Concentration of nitrate.
- Concentration of sulfate.
- Deposition of oxidised and reduced nitrogen.
- Deposition of excess sulfur.

In addition, vertical profiles of ozone are stored.

Since the effect of secondary aerosol particles is mainly dominated by that of inorganic particles [Windmark et al., 2016], SOA, secondary organic aerosols, are not included in the calculation of secondary particles in the model setup that was used.

The model is run with an update of boundary conditions of ozone, sulfur dioxide and carbon monoxide from the global atmospheric chemisty model run in the Copernicus service (CAMS 50, METEO-FRANCE and all CAMS_50 modelling teams [2017]) in every 3 hours and flight emissions in every 6 hours. The model updates its meteorological conditions every 3 hours using Hirlam C11 weather data, which has a resolution of 11 km. Hirlam C11 was the operational weather prediction model run for the European domain at SMHI for the years simulated in this study (2012-2014). All the scenarios were run with the same model domain (160x160 gridpoints). Figure 3 displays a sample of all the model domains used in this study. The model is run on a rotated latitude/longitude grid and a horizontal resolution of 22 km over both Sweden and Europe, such that the effects of swedish flight emissions over both Sweden and Europe could be investigated in a relatively high resolution.

Specific flight emissions over Sweden were being calculated and used as input data for each scenario. The "masking away" method is used to calculate the contribution from flight emissions of a certain flight type. For example, in the case of SWE-LTO, the contribution of SWE-LTO aviation emissions is calculated by taking the difference between the total contribution of all emitted species and the contribution of all emitted species except SWE-LTO aviation emissions. In other words, there is one simulation with all emitted species included and another simulation with all emitted species minus SWE-LTO aviation emissions included. By taking the difference between the results of these two simulations, we get the contribution of SWE-LTO aviation emissions.

The model results, like concentrations and depositions of air components, were saved monthly at the surface level. Ground level ozone was saved hourly, daily and monthly and ozone vertical profiles were saved every 12 hours.

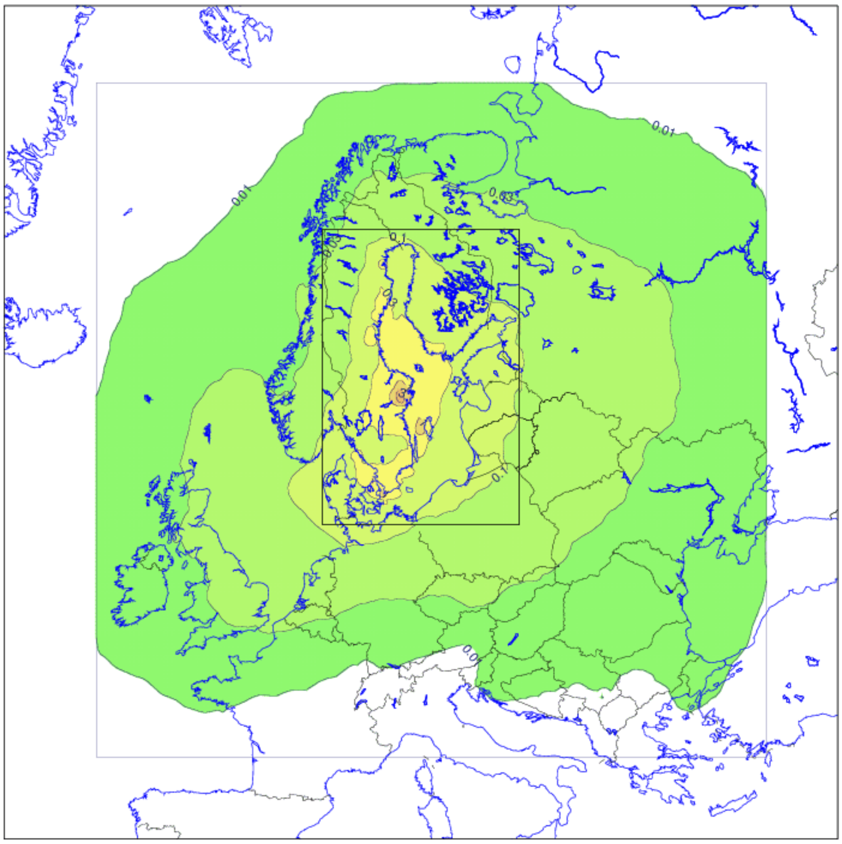


Figure 3: Model domains used in the study. All model runs have been performed over the larger domain covering major parts of Europe. Tabulated results are reported both for the European domain and also for the smaller subdomain centered over the Baltic Sea. This subdomain is identical to the one used in a previous study on air pollution from Swedish shipping.

6 Results and discussion

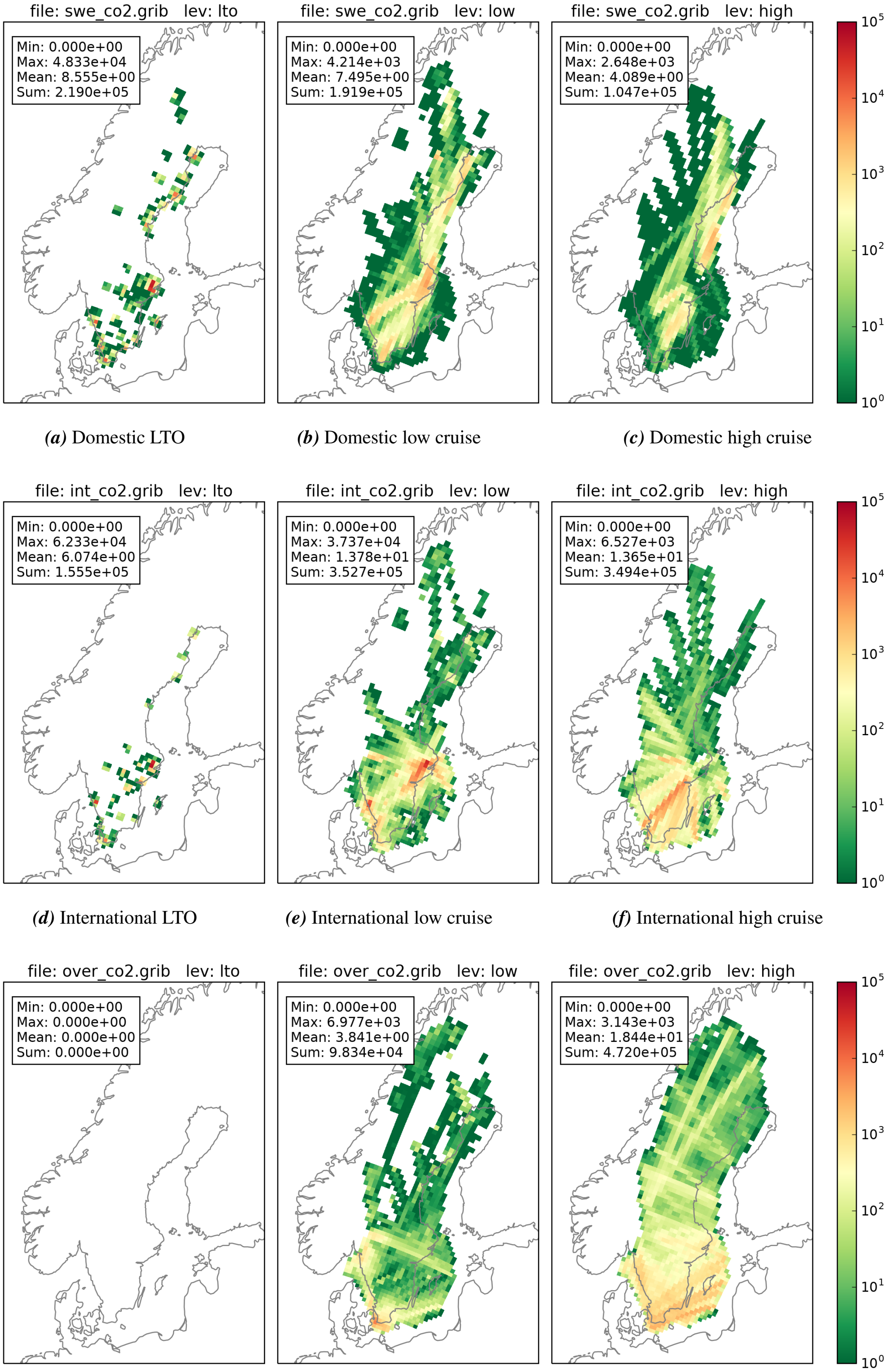
6.1 Emissions

The scaled (according to table 3) spatial distribution, both horizontally and vertically, for CO_2 emissions can be seen in figure 4. Plots for the other species emitted were left out of this report due to their spatial similairity to CO_2.

6.2 MATCH simulation results

Results from the MATCH model will be presented in this section. There are a total of 17 different simulations. The base case includes all ground and flight emissions, both European as well as Swedish, in the simulation domain. There are 8 scenarios in which emissions from a specific flight type was eliminated from the total swedish flight emissions. In addition, 8 scenarios were simulated in which NOx emissions were eliminated.

A three year average (2012-2014) has been performed on all the model results. To study the effects of flight



(a) Domestic LTO ***(b)*** Domestic low cruise ***(c)*** Domestic high cruise

(d) International LTO ***(e)*** International low cruise ***(f)*** International high cruise

(g) Overflights LTO ***(h)*** Overflights low cruise ***(i)*** Overflights high cruise

Figure 4: *CO2 emission for the different heights in the categories domestic, international and overflight. The distribution between LTO, LO and HI are 13%, 36% and 51% respectively.*

emissions in a scenario, the difference would be computed by subtrating model results from a scenario from the model results from the base case that contains total flight emissions over Swedish air space as well as European emissions.

The high-cruise scenarios (SWE-HI, INT-HI, OVER-HI) result in insignificant contributions to effects at the surface level for both deposition and air concentration. This is because the emissions are high up above 10 km and the effects gets diluted and transported out of the domain. Effects are however seen at higher levels where the emissions take place, so for changes in ozone at high levels results from high-cruise scenarios are reported.

First, the effects of flight emissions on ecosystems will be presented. The contribution to annual deposition of oxidised nitrogen NOy_N and reduced nitrogen NHx_N, which is both acidifying and eutrophying and to deposition of excess sulfur SOx_S, which mainly contribute to acidifying deposition and to particulate matters concentrations in the air will be shown. The impacts of ozone on crops and forests will be shown by AOT40 (for May-July and April-September AOT40C, AOT40F).

Next, the effects of flight emissions on health will be represented. Concentrations of ground level O_3, nitrate and sulfate and concentrations and exposure of primary and secondary particles will be presented. The impact of the daily-maximum-8-hour-average ozone concentration SOMO35 will be shown.

Lastly, the effects of aviation emissions on high tropospheric ozone will be shown. Concentration of ozone in various vertical intervals as well as vertically integrated ozone will be presented.

6.3 Air pollution from aviation with effects on ecosystems

6.3.1 Deposition of oxidised and reduced nitrogen

Nitrogen oxides NOx are mainly emitted as nitrogen monoxide NO. NO is emitted by aircrafts into the atmosphere and being transformed to nitrogen dioxide NO_2 and other oxidised nitrogen species, such as nitric acid HNO_3 and ammonium nitrate NH_4NO_3. The altitude of emissions, oxidising capacity of the atmosphere and chances of precipitation are the three main factors that determine how far a nitrogen atom can be transported through the atmosphere after its emission. It finally deposits back to the ground onto surfaces of vegetation, water and soil [Naturvårdsverket, 2018a].

The yearly mean deposition of oxidised and reduced nitrogen that is caused by LTO and low cruise flight emissions is shown in figure 5 and table 6. The relative contribution to the total is shown in figure 6. Table 7 shows the statistics on the swedish domain. The mean deposition of oxidised and reduced nitrogen from LTO flight emissions is almost a factor of 40 lower than the contribution from swedish shipping [Windmark et al., 2016] over the same domain. The NOx LTO-emissions are about a factor of 180 lower than from shipping which means that a larger fraction of the NOx LTO-emissions are deposited over the swedish domain. This can be explained by the fact that the LTO-emissions are located close to the main airports while shipping emissions to a larger extent are located close to the boundary of the swedish domain and therfore are transported out of the domain before being deposited.

The emissions from INT-LTO and SWE-LTO contribute most to deposition over Sweden. A large fraction of the emissions do not travel very far and tend to deposit close to major Swedish airports such as Stockholm

Arlanda, Gothenburg Landvetter, Malmö and Umeå etc. The rest of the emissions are spread over Sweden and its neighboring countries primarily Finland, Norway and the Baltic countries. The deposition decreases as it is further away from the sources (major Swedish airports). Minor deposition of oxidised and reduced nitrogen is found even at the British Isles and being spread over continental Europe.

Emissions from low cruise, especially INT-LO, have some contributions to oxidised and reduced nitrogen deposition in central Sweden and southern Finland. There is no significant contribution to nitrogen deposition from scenarios with high cruise flights within the model domain.

Compared to the oxidised and reduced nitrogen deposition caused by all flight and ground emissions, the deposition caused by INT-LTO and SWE-LTO emissions is only 0.03% of the total.

The results of the simulations which only NOx aviation emissions are included are very similar to the simulation results with all aviation emission species over Swedish territory included, as presented in table 6. The amount of reduced and oxidised nitrogen deposition caused by LTO-NOx emissions is highest the closer it is to the main source at Stockholm Arlanda. The deposition caused by INT-LTO and SWE-LTO emissions is about 0.02% of the total in the swedish domain.

	Contribution from all emitted species				Contribution from NOx emissions			
Emissions	Yearly mean deposition NOY_N + NHX_N		Annual total deposition NOY_N + NHX_N		Yearly mean deposition NOY_N + NHX_N		Annual total deposition NOY_N + NHX_N	
	[mg/m^2]	[mg/m^2 /GJ]	[ton]	[ton/GJ]	[mg/m^2]	[mg/m^2 /GJ]	[ton]	[ton/GJ]
INT-LTO	$1.51\cdot10^{-2}$	$7.13\cdot10^{-9}$	$1.87\cdot10^{2}$	$8.83\cdot10^{-5}$	$1.03\cdot10^{-2}$	$4.86\cdot10^{-9}$	$1.27\cdot10^{2}$	$6.02\cdot10^{-5}$
SWE-LTO	$1.89\cdot10^{-2}$	$6.33\cdot10^{-9}$	$2.34\cdot10^{2}$	$7.84\cdot10^{-5}$	$1.15\cdot10^{-2}$	$3.85\cdot10^{-9}$	$1.42\cdot10^{2}$	$4.77\cdot10^{-5}$
INT-LO	$1.24\cdot10^{-2}$	$2.56\cdot10^{-9}$	$1.53\cdot10^{2}$	$3.17\cdot10^{-5}$	$1.11\cdot10^{-2}$	$2.30\cdot10^{-9}$	$1.38\cdot10^{2}$	$2.84\cdot10^{-5}$
SWE-LO	$4.79\cdot10^{-3}$	$1.82\cdot10^{-9}$	$5.93\cdot10^{1}$	$2.25\cdot10^{-5}$	$4.55\cdot10^{-3}$	$1.73\cdot10^{-9}$	$5.64\cdot10^{1}$	$2.14\cdot10^{-5}$
OVER-LO	$3.04\cdot10^{-3}$	$2.27\cdot10^{-9}$	$3.76\cdot10^{1}$	$2.81\cdot10^{-5}$	$2.63\cdot10^{-3}$	$1.96\cdot10^{-9}$	$3.26\cdot10^{1}$	$2.43\cdot10^{-5}$
ALL Europe	$5.44\cdot10^{2}$	-	$6.75\cdot10^{6}$	-	$5.44\cdot10^{2}$	-	$6.75\cdot10^{6}$	-

Table 6: *Contributions to mean and total deposition of oxidised and reduced nitrogen (NOY_N + NHX_N) in the whole modelled region for the simulations with all flight emission species included and simulations with only NOx emissions included. The right hand subcolumns show the yearly deposition normalized by fuel energy use. ALL Europe corresponds to all anthropogenic emissions in the model domain.*

	Contribution from all emitted species				Contribution from NOx emissions			
Scenarios	Yearly mean deposition NOY_N + NHX_N		Annual total deposition NOY_N + NHX_N		Yearly mean deposition NOY_N + NHX_N		Annual total deposition NOY_N + NHX_N	
	[mg/m^2]	[mg/m^2 /GJ]	[ton]	[ton/GJ]	[mg/m^2]	[mg/m^2 /GJ]	[ton]	[ton/GJ]
INT-LTO	$7.48\cdot10^{-2}$	$3.53\cdot10^{-8}$	$1.36\cdot10^{2}$	$6.41\cdot10^{-5}$	$4.80\cdot10^{-2}$	$2.27\cdot10^{-8}$	$8.72\cdot10^{1}$	$4.12\cdot10^{-5}$
SWE-LTO	$9.38\cdot10^{-2}$	$3.15\cdot10^{-8}$	$1.70\cdot10^{2}$	$5.71\cdot10^{-5}$	$5.25\cdot10^{-2}$	$1.76\cdot10^{-8}$	$9.53\cdot10^{1}$	$3.20\cdot10^{-5}$
ALL Europe	$5.42\cdot10^{2}$	-	$9.84\cdot10^{5}$	-	$5.42\cdot10^{2}$	-	$9.84\cdot10^{5}$	-

Table 7: *Contributions to mean and total deposition of oxidised and reduced nitrogen (NOY_N + NHX_N) in the Swedish domain for the simulations with all flight emission species included and simulations with only NOx emissions included. The right hand subcolumns show the yearly deposition normalized by fuel energy use. ALL Europe corresponds to all anthropogenic emissions in the model domain.*

6.3.2 Deposition of excess sulfur

Sulfur dioxide is emitted during fuel combustion although the sulfur content of aviation fuel is low. Sulfur can be brought back down to the surface in gaseous form as SO_2 or in particle form as sulfate through either dry or wet deposition with precipitation. Excess sulfur deposition leads to acidification of soils, water streams and lakes and thus it has a negative impact on ecosystems [Naturvårdsverket, 2018a].

The SOx deposition is shown in figure 7. The SOx deposition pattern is similar to that of NOx, but absolute values are lower. The amount of deposition is higher near the source of the emissions. Significant amount of deposition from INT-LTO and SWE-LTO is found near Stockholm Arlanda and Gothenburg Landvetter. Emissions from low cruise has a minor effect on SOx deposition. There is no significant effect from emissions from emissions of high cruise flights.

The relative contribution to the total SOx deposition is shown in figure 8. Tables 8 and 9 show the yearly mean deposition and total mean annual deposition of SOx over the European and Swedish domain, respectively. The contributions by INT-LTO and SWE-LTO flight emissions on SOx deposition are around 0.1% of the deposition caused by ALL, which contains all the ground and flight emissions. The deposition of sulfur from LTO-emissions is a factor 17 lower than from swedish shipping over the Swedish domain despite the shipping emissions are a factor of 70 larger.

The NOx simulations indicate that NOx emissions have no significant impact on excess sulfur.

Scenarios	Yearly mean deposition SOx_S		Annual total deposition SOx_S	
	[mg/m^2]	[mg/m^2 /GJ]	[ton]	[ton/GJ]
INT-LTO	$2.20 \cdot 10^{-3}$	$1.04 \cdot 10^{-9}$	$2.73 \cdot 10^{1}$	$1.29 \cdot 10^{-5}$
SWE-LTO	$3.12 \cdot 10^{-3}$	$1.05 \cdot 10^{-9}$	$3.86 \cdot 10^{1}$	$1.30 \cdot 10^{-5}$
INT-LO	$1.27 \cdot 10^{-3}$	$2.62 \cdot 10^{-10}$	$1.57 \cdot 10^{1}$	$3.25 \cdot 10^{-6}$
SWE-LO	$4.44 \cdot 10^{-4}$	$1.69 \cdot 10^{-10}$	5.51	$2.09 \cdot 10^{-6}$
OVER-LO	$2.79 \cdot 10^{-4}$	$2.09 \cdot 10^{-10}$	3.46	$2.59 \cdot 10^{-6}$
ALL Europe	$3.01 \cdot 10^{2}$	-	$3.72 \cdot 10^{6}$	-

Table 8: *Contributions to mean and total deposition of excess sulfur (SOx_S) in the whole modelled region for the simulations with all flight emission species included. The right hand subcolumns show the yearly deposition normalized by fuel energy use. ALL Europe corresponds to all anthropogenic emissions in the model domain.*

Scenarios	Yearly mean deposition SOx_S		Annual total deposition SOx_S	
	[mg/m^2]	[mg/m^2 /GJ]	[ton]	[ton/GJ]
INT-LTO	$1.09 \cdot 10^{-2}$	$5.16 \cdot 10^{-9}$	$1.98 \cdot 10^{1}$	$9.36 \cdot 10^{-6}$
SWE-LTO	$1.52 \cdot 10^{-2}$	$5.09 \cdot 10^{-9}$	$2.75 \cdot 10^{1}$	$9.24 \cdot 10^{-6}$
ALL Europe	$2.49 \cdot 10^{2}$	-	$4.52 \cdot 10^{5}$	-

Table 9: *Contributions to mean and total deposition of excess sulfur (SOx_S) in the Swedish domain for the simulations with all flight emission species included. The right hand subcolumns show the yearly deposition normalized by fuel energy use. ALL Europe corresponds to all anthropogenic emissions in the model domain.*

6.3.3 AOT40 - (Accumulated Ozone over a Threshold of 40 ppb(v))

Vegetation is sensitive to ozone concentration and high ozone concentration is harmful to vegetation. Ozone is absorbed into the plants through the stomata on the leaves and needles during daytime through photosynthesis. AOT40 is a risk indicator to estimate the impacts of ozone on crops, forests and other vegetation [Naturvårdsverket, 2018b].

AOT40 is calculated as the time integrated hourly ozone concentration over a threshold of 40 ppb(v), which is equivalent to 80 $\mu g/m^3$, from 08:00 to 20:00 during the day for several summer months[3]. The summer months used in the calculation are dependent on the vegetation type. AOT40c is the index for crops and it is calculated for May - July. AOT40f is the index for forest and it is calculated through April - September. In the European Union the current goal is to keep AOT40c below 9 ppm(v)h to protect plants and eventually lower that to 3 ppm(v)h. In Sweden there is a long term goal to keep AOT40f below 5 ppm(v)h in order to protect the forests [Andersson et al., 2015a].

Figure 9 and table 10 present the ozone indices for crops and figure 10 and table 11 present the ozone indices for forest. The results show that INT-LTO, SWE-LTO and INT-LO emissions increase AOT40c and AOT40f over primarily the Stockholm Arlanda region and also over southern Sweden and the Baltic Sea. The increase is however very small. The accumulated ozone indices estimated from INT-LTO and SWE-LTO flight emissions are around a factor of 30-40 smaller than those estimated from shipping emissions in the shipping project.

AOT40c and AOT40f from the NOx emission simulations are very similar to the results from the simulations with all flight emission species included, as indicated in tables 10, 11, 12 and 13.

Scenarios	Contribution from all emitted species Yearly mean AOT40c		Contribution from NOx emissions Yearly mean AOT40c	
	[ppm(v)]	[ppm(v)/GJ]	[ppm(v)]	[ppm(v)/GJ]
INT-LTO	$4.76 \cdot 10^{-4}$	$2.25 \cdot 10^{-10}$	$4.66 \cdot 10^{-4}$	$2.20 \cdot 10^{-10}$
SWE-LTO	$5.44 \cdot 10^{-4}$	$1.82 \cdot 10^{-10}$	$5.19 \cdot 10^{-4}$	$1.74 \cdot 10^{-10}$
INT-LO	$8.10 \cdot 10^{-4}$	$1.67 \cdot 10^{-10}$	$8.96 \cdot 10^{-4}$	$1.85 \cdot 10^{-10}$
SWE-LO	$3.28 \cdot 10^{-4}$	$1.24 \cdot 10^{-10}$	$3.75 \cdot 10^{-4}$	$1.42 \cdot 10^{-10}$
OVER-LO	$2.09 \cdot 10^{-4}$	$1.56 \cdot 10^{-10}$	$2.26 \cdot 10^{-4}$	$1.69 \cdot 10^{-10}$
ALL Europe	9.96	-	9.96	-

Table 10: *Contributions to mean accumulated ozone (AOT40c) in the whole modelled domain for the simulations with all flight emission species included and simulations with only NOx emissions included. The right hand subcolumns show the yearly mean AOT40c normalized by fuel energy use. ALL Europe corresponds to all anthropogenic emissions in the model domain.*

[3] The formula of AOT40 is given below, where C_{h} is the hourly ozone concentration in within 8:00 to 20:00.

$$\mathrm{AOT40} = \sum_{h=1,N} \mathrm{MAX}(C_{\mathrm{h}} - 40\mathrm{ppb(v)}, 0) \tag{1}$$

Scenarios	Contribution from all emitted species Yearly mean AOT40f [ppm(v)]	[ppm(v)/GJ]	Contribution from NOx emissions Yearly mean AOT40f [ppm(v)]	[ppm(v)/GJ]
INT-LTO	$7.93 \cdot 10^{-4}$	$3.74 \cdot 10^{-10}$	$7.84 \cdot 10^{-4}$	$3.70 \cdot 10^{-10}$
SWE-LTO	$9.24 \cdot 10^{-4}$	$3.10 \cdot 10^{-10}$	$8.80 \cdot 10^{-4}$	$2.95 \cdot 10^{-10}$
INT-LO	$1.50 \cdot 10^{-3}$	$3.10 \cdot 10^{-10}$	$1.64 \cdot 10^{-3}$	$3.39 \cdot 10^{-10}$
SWE-LO	$6.28 \cdot 10^{-4}$	$2.38 \cdot 10^{-10}$	$6.92 \cdot 10^{-4}$	$2.63 \cdot 10^{-10}$
OVER-LO	$3.82 \cdot 10^{-4}$	$2.86 \cdot 10^{-10}$	$4.12 \cdot 10^{-4}$	$3.08 \cdot 10^{-10}$
ALL Europe	19.6	-	19.6	-

Table 11: *Contributions to mean accumulated ozone (AOT40f) in the whole modelled domain for the simulations with all flight emission species included and simulations with only NOx emissions included. The right hand subcolumns show the yearly mean AOT40f normalized by fuel energy use. ALL Europe corresponds to all anthropogenic emissions in the model domain.*

Scenarios	Contribution from all emitted species Yearly mean AOT40c [ppm(v)]	[ppm(v)/GJ]	Contribution from NOx emissions Yearly mean AOT40c [ppm(v)]	[ppm(v)/GJ]
INT-LTO	$1.71 \cdot 10^{-3}$	$8.08 \cdot 10^{-10}$	$1.59 \cdot 10^{-3}$	$7.52 \cdot 10^{-10}$
SWE-LTO	$1.93 \cdot 10^{-3}$	$6.46 \cdot 10^{-10}$	$1.75 \cdot 10^{-3}$	$5.88 \cdot 10^{-10}$
ALL Europe	7.68	-	7.68	-

Table 12: *Contributions to mean accumulated ozone (AOT40c) in the Swedish domain for the simulations with all flight emission species included and simulations with only NOx emissions included. The right hand subcolumns show the yearly mean AOT40c normalized by fuel energy use. ALL Europe corresponds to all anthropogenic emissions in the model domain.*

Scenarios	Contribution from all emitted species Yearly mean AOT40f [ppm(v)]	[ppm(v)/GJ]	Contribution from NOx emissions Yearly mean AOT40f [ppm(v)]	[ppm(v)/GJ]
INT-LTO	$2.78 \cdot 10^{-3}$	$1.31 \cdot 10^{-9}$	$2.69 \cdot 10^{-3}$	$1.27 \cdot 10^{-9}$
SWE-LTO	$3.16 \cdot 10^{-3}$	$1.06 \cdot 10^{-9}$	$2.97 \cdot 10^{-3}$	$9.98 \cdot 10^{-10}$
ALL Europe	14.8	-	14.8	-

Table 13: *Contributions to mean accumulated ozone (AOT40f) in the Swedish domain for the simulations with all flight emission species included and simulations with only NOx emissions included. The right hand subcolumns show the yearly mean AOT40f normalized by fuel energy use. ALL Europe corresponds to all anthropogenic emissions in the model domain.*

6.4 Air pollution from aviation with effects on human health

6.4.1 Primary particles

Aircraft emit soot and organic carbon as primary particles. Both soot and organic carbon are formed through incomplete combustion of hydrocarbons. In the MATCH model primary particles include both fine and coarse particles. Soot mainly falls into the category of fine particles (PM2.5) which can penetrate deep into the lungs. Exposure to these fine particles is considered to cause increased risk to lung cancer and other respiratory diseases, and even premature death [Naturvårdsverket, 2018a].

Only INT-LTO and SWE-LTO scenarios show an effect on the concentration of primary particles at the surface level. Significant primary particles concentrations are found mainly close to major airports such as in Stockholm and Gothenburg as presented in figure 11. Lower concentration amounts are found over the southern half of Sweden, the Baltic Sea and southwestern Finland. In the Stockholm region, the primary particle concentrations from INT-LTO and SWE-LTO contribute to about 70% of the total effect by all the flight emissions over Swedish air space. Figure 12 presents the relative concentration of primary particles.

The exposure of primary particles is highest in Stockholm and Gothenburg regions where the population density is high and the concentration of primary particles is also highest as shown in figure 13. Significant exposure are found southeast of Sweden across the Baltic Sea and continental Europe. Table 15 and 17 display the exposure of primary particles in whole modelled domain and the Swedish domain, respectively. The exposure is calculated by the concentration of primary particles (μg/m^3) multiplies with the population density in the unit # of people per squared kilometers (#/km^2).

NOx aviation emissions have no significant effect on primary particles.

Scenarios	Yearly mean concentration [μg/m^3]	Yearly mean concentration [μg/m$^3/GJ$]
INT-LTO	$7.24{\cdot}10^{-6}$	$3.42{\cdot}10^{-12}$
SWE-LTO	$1.01{\cdot}10^{-5}$	$3.39{\cdot}10^{-12}$
INT-LO	$1.49{\cdot}10^{-6}$	$3.08{\cdot}10^{-13}$
SWE-LO	$4.75{\cdot}10^{-7}$	$1.80{\cdot}10^{-13}$
OVER-LO	$3.13{\cdot}10^{-7}$	$2.34{\cdot}10^{-13}$
ALL Europe	$7.27{\cdot}10^{-1}$	-

Table 14: *Contributions to mean concentration of primary particles in the whole modelled region for the simulations with all flight emission species included. The right hand subcolumn shows the yearly mean concentration normalized by fuel energy use. ALL Europe corresponds to all anthropogenic emissions in the model domain.*

Scenarios	Yearly mean exposure		Yearly total exposure	
	[μg/m$^3 \cdot \#/km^2$]	[μg/m$^3 \cdot \#/km^2/GJ$]	[μg/m$^3 \cdot \#$]	[μg/m$^3 \cdot \#/GJ$]
INT-LTO	$2.09{\cdot}10^{-4}$	$9.85{\cdot}10^{-11}$	$2.58{\cdot}10^{3}$	$1.22{\cdot}10^{-3}$
SWE-LTO	$2.65{\cdot}10^{-4}$	$8.89{\cdot}10^{-11}$	$3.28{\cdot}10^{3}$	$1.10{\cdot}10^{-3}$
INT-LO	$3.26{\cdot}10^{-5}$	$6.73{\cdot}10^{-12}$	$4.03{\cdot}10^{2}$	$8.34{\cdot}10^{-5}$
SWE-LO	$1.12{\cdot}10^{-5}$	$4.23{\cdot}10^{-12}$	$1.38{\cdot}10^{2}$	$5.24{\cdot}10^{-5}$
OVER-LO	$1.01{\cdot}10^{-5}$	$7.51{\cdot}10^{-12}$	$1.25{\cdot}10^{2}$	$9.31{\cdot}10^{-5}$
ALL Europe	46.5	-	$5.76{\cdot}10^{8}$	-

Table 15: *Contributions to yearly mean and total exposure of primary particles in the whole modelled region for the simulations with all flight emission species included. The right hand subcolumns show the yearly exposure normalized by fuel energy use. ALL Europe corresponds to all anthropogenic emissions in the model domain.*

Scenarios	Yearly mean concentration [μg/m^3]	Yearly mean concentration [μg/m$^3/GJ$]
INT-LTO	$3.94\cdot10^{-5}$	$1.86\cdot10^{-11}$
SWE-LTO	$5.50\cdot10^{-5}$	$1.85\cdot10^{-11}$
ALL Europe	$5.71\cdot10^{-1}$	-

***Table 16:** Contributions to mean concentration of primary particles in the Swedish domain for the simulations with all flight emission species included. The right hand subcolumn shows the yearly mean concentration normalized by fuel energy use. ALL Europe corresponds to all anthropogenic emissions in the model domain.*

Scenarios	Yearly mean exposure		Yearly total exposure	
	[μg/m$^3 \cdot \#/km^2$]	[μg/m$^3 \cdot \#/km^2/GJ$]	[μg/m$^3 \cdot \#$]	[μg/m$^3 \cdot \#/GJ$]
INT-LTO	$1.16\cdot10^{-3}$	$5.49\cdot10^{-10}$	$2.11\cdot10^{3}$	$9.97\cdot10^{-4}$
SWE-LTO	$1.45\cdot10^{-3}$	$4.86\cdot10^{-10}$	$2.63\cdot10^{3}$	$8.81\cdot10^{-4}$
ALL Europe	15.7	-	$2.85\cdot10^{7}$	-

***Table 17:** Contributions to mean and total exposure of primary particles in the Swedish domain for the simulations with all flight emission species included. The right hand subcolumns show the yearly exposure normalized by fuel energy use. ALL Europe corresponds to all anthropogenic emissions in the model domain.*

6.4.2 Secondary particles

The secondary particles from flight emissions are mostly secondary inorganic particles of sulfate, nitrate and ammonium, which are formed by the oxidation of sulfur dioxide SO_2, nitrogen oxides NOx and ammonia NH_3. NOx emissions from aviation can form nitrate (or nitric acid) after oxidation. Most of the nitrate particles in the model are ammonium nitrate NH_4NO_3 formed by reactions between ammonia NH_3 and nitric acid HNO_3.

$NH_3 + HNO_3 \longleftrightarrow NH_4NO_3$

NOx emissions might also cause an effect on sulfate and other oxidant concentrations, which indirectly influence particle concentrations. The concentration of ozone and other oxidant concentrations decrease when NOx concentration decreases, which consequently leads to a decreasing rate of sulfate production from gaseous sulfur dioxide SO_2.

In addition, aircraft emit some amount of sulfur dioxide SO_2 that can transform to sulfate particles. When free ammonia NH_3 is present, it can produce more secondary particles by the formation of $(NH_4)_2SO_4$ and NH_4NO_3.

A large fraction of secondary inorganic particles are categorized as PM2.5, where increased amounts of PM2.5 is associated to increased risk of cardiovascular and lung diseases [Naturvårdsverket, 2018a].

Figure 14 shows the concentration of secondary inorganic particles and figure 16 shows the exposures of secondary inorganic particles.

The effect on secondary inorganic particle concentration caused by NOx aviation emissions is in the same order of magnitude and has the same pattern as the results with all flight emission species simulated. The statistics are shown in tables 18, 21, 22 and 23. The SIA concentration caused by INT-LTO and SWE-LTO emissions is a factor of 44 smaller than that caused by shipping emissions.

Scenarios	Contribution from all emitted species Yearly mean concentration		Contribution from NOx emissions Yearly mean concentration	
	[μg/m^3]	[μg/m$^3/GJ$]	[μg/m^3]	[μg/m$^3/GJ$]
INT-LTO	$4.00\cdot10^{-5}$	$1.89\cdot10^{-11}$	$2.36\cdot10^{-5}$	$1.11\cdot10^{-11}$
SWE-LTO	$5.08\cdot10^{-5}$	$1.71\cdot10^{-11}$	$2.59\cdot10^{-5}$	$8.71\cdot10^{-12}$
INT-LO	$3.43\cdot10^{-5}$	$7.09\cdot10^{-12}$	$2.77\cdot10^{-5}$	$5.72\cdot10^{-12}$
SWE-LO	$1.33\cdot10^{-5}$	$5.05\cdot10^{-12}$	$1.13\cdot10^{-5}$	$4.28\cdot10^{-12}$
OVER-LO	$8.85\cdot10^{-6}$	$6.61\cdot10^{-12}$	$7.26\cdot10^{-6}$	$5.42\cdot10^{-12}$
ALL Europe	2.33	-	2.33	-

Table 18: *Contributions to mean concentration of secondary inorganic particles in the whole modelled region for the simulations with all flight emission species included and simulations with only NOx emissions included. The right hand subcolumns show the yearly mean concentration normalized by fuel energy use. ALL Europe corresponds to all anthropogenic emissions in the model domain.*

Scenarios	Yearly mean exposure		Yearly total exposure	
	[μg/m$^3\cdot\#/km^2$]	[μg/m$^3\cdot\#/km^2/GJ$]	[μg/m$^3\cdot\#$]	[μg/m$^3\cdot\#/GJ$]
INT-LTO	$9.47\cdot10^{-4}$	$4.47\cdot10^{-10}$	$1.17\cdot10^{4}$	$5.54\cdot10^{-3}$
SWE-LTO	$1.13\cdot10^{-3}$	$3.79\cdot10^{-10}$	$1.40\cdot10^{4}$	$4.70\cdot10^{-3}$
INT-LO	$9.75\cdot10^{-4}$	$2.02\cdot10^{-10}$	$1.21\cdot10^{4}$	$2.50\cdot10^{-3}$
SWE-LO	$3.89\cdot10^{-4}$	$1.47\cdot10^{-10}$	$4.82\cdot10^{3}$	$1.83\cdot10^{-3}$
OVER-LO	$3.21\cdot10^{-4}$	$2.39\cdot10^{-10}$	$3.97\cdot10^{3}$	$2.97\cdot10^{-3}$
ALL Europe	106	-	$1.31\cdot10^{9}$	-

Table 19: *Contributions to yearly mean and total exposure of secondary inorganic particles in the whole modelled region for the simulations with all flight emission species included. The right hand subcolumns show the yearly exposure normalized by fuel energy use. ALL Europe corresponds to all anthropogenic emissions in the model domain.*

Scenarios	Yearly mean exposure		Yearly total exposure	
	[μg/m$^3\cdot\#/km^2$]	[μg/m$^3\cdot\#/km^2/GJ$]	[μg/m$^3\cdot\#$]	[μg/m$^3\cdot\#/GJ$]
INT-LTO	$6.06\cdot10^{-4}$	$2.86\cdot10^{-10}$	$7.51\cdot10^{3}$	$3.55\cdot10^{-3}$
SWE-LTO	$6.62\cdot10^{-4}$	$2.22\cdot10^{-10}$	$8.21\cdot10^{3}$	$2.75\cdot10^{-3}$
INT-LO	$8.27\cdot10^{-4}$	$1.71\cdot10^{-10}$	$1.03\cdot10^{4}$	$2.12\cdot10^{-3}$
SWE-LO	$3.41\cdot10^{-4}$	$1.30\cdot10^{-10}$	$4.23\cdot10^{3}$	$1.61\cdot10^{-3}$
OVER-LO	$2.73\cdot10^{-4}$	$2.04\cdot10^{-10}$	$3.38\cdot10^{3}$	$2.52\cdot10^{-3}$
ALL Europe	106	-	$1.31\cdot10^{9}$	-

Table 20: *Contributions to yearly mean and total exposure of secondary inorganic particles in the whole modelled region for the simulations with only NOx emissions included. The right hand subcolumns show the yearly exposure normalized by fuel energy use. ALL Europe corresponds to all anthropogenic emissions in the model domain.*

Scenarios	Contribution from all emitted species Yearly mean concentration		Contribution from NOx emissions Yearly mean concentration	
	[μg/m^3]	[μg/m$^3/GJ$]	[μg/m^3]	[μg/m$^3/GJ$]
INT-LTO	$1.51 \cdot 10^{-4}$	$7.12 \cdot 10^{-11}$	$7.58 \cdot 10^{-5}$	$3.58 \cdot 10^{-11}$
SWE-LTO	$2.01 \cdot 10^{-4}$	$6.74 \cdot 10^{-11}$	$8.31 \cdot 10^{-5}$	$2.79 \cdot 10^{-11}$
ALL Europe	2.07	-	2.07	-

Table 21: *Contributions to mean concentration of secondary inorganic particles in the Swedish domain for the simulations with all flight emission species included and simulations with only NOx emissions included. The right hand subcolumns show the yearly mean concentration normalized by fuel energy use. ALL Europe corresponds to all anthropogenic emissions in the model domain.*

	Contribution from all emitted species			
Scenarios	Yearly mean exposure		Yearly total exposure	
	[μg/m$^3 \cdot \#/km^2$]	[μg/m$^3 \cdot \#/km^2/GJ$]	[μg/m$^3 \cdot \#$]	[μg/m$^3 \cdot \#/GJ$]
INT-LTO	$2.48 \cdot 10^{-3}$	$1.17 \cdot 10^{-9}$	$4.50 \cdot 10^{3}$	$2.12 \cdot 10^{-3}$
SWE-LTO	$3.06 \cdot 10^{-3}$	$1.03 \cdot 10^{-9}$	$5.56 \cdot 10^{3}$	$1.87 \cdot 10^{-3}$
ALL Europe	44.6	-	$8.10 \cdot 10^{7}$	-

Table 22: *Contributions to yearly mean and total exposure of secondary inorganic particles in the Swedish domain for the simulations with all flight emission species included. The right hand subcolumns show the yearly exposure normalized by fuel energy use. ALL Europe corresponds to all anthropogenic emissions in the model domain.*

	Only NOx emissions are included for aviation emissions			
Scenarios	Yearly mean exposure		Yearly total exposure	
	[μg/m$^3 \cdot \#/km^2$]	[μg/m$^3 \cdot \#/km^2/GJ$]	[μg/m$^3 \cdot \#$]	[μg/m$^3 \cdot \#/GJ$]
INT-LTO	$1.15 \cdot 10^{-3}$	$5.42 \cdot 10^{-10}$	$2.08 \cdot 10^{3}$	$9.84 \cdot 10^{-4}$
SWE-LTO	$1.26 \cdot 10^{-3}$	$4.22 \cdot 10^{-10}$	$2.28 \cdot 10^{3}$	$7.67 \cdot 10^{-4}$
ALL Europe	44.6	-	$8.10 \cdot 10^{7}$	-

Table 23: *Contributions to yearly mean and total exposure of secondary inorganic particles in the Swedish domain for the simulations with only NOx emissions included. The right hand subcolumns show the yearly exposure normalized by fuel energy use. ALL Europe corresponds to all anthropogenic emissions in the model domain.*

6.4.3 Nitrate and sulfate

Nitrate and sulfate are important secondary inorganic particle species.

The concentration of nitrate is shown in figure 20. The concentration of nitrate represents the sum of nitrate and the nitrate part in ammonium nitrate. INT-LTO and SWE-LTO emissions contribute to positive nitrate concentrations over Sweden, across the Baltic Sea towards southern Finland and the Baltic countries. INT-LO emissions contribute to positive nitrate concentrations over a large area over Sweden even towards western Russia. However the concentration amount is relatively small compared to the contribution from all emitted species in Europe. The nitrate concentration by INT-LTO and SWE-LTO emissions are 30 times smaller than that caused by shipping emissions, as indicated in table 24.

The sulfate concentration in this section represents the sum of sulfate and the sulfate part in ammonium sulfate. INT-LTO and SWE-LTO emissions contribute to positive sulfate concentration at mainly Stockholm

Arlanda and even along the coast in northern Sweden, southern Sweden, across the Baltic Sea and southern Finland, as shown in figure 21. The sulfate concentration by INT-LTO and SWE-LTO emissions is 1.3 times lower than that caused by shipping emissions, as shown in table 25.

NOx aviation emissions has an effect on nitrate concentration but not sulfate concentration.

Scenarios	Contribution from all emitted species Yearly mean concentration		Contribution from NOx emissions Yearly mean concentration	
	[μg/m^3]	[μg/m^3/GJ]	[μg/m^3]	[μg/m^3/GJ]
INT-LTO	$9.72 \cdot 10^{-5}$	$4.59 \cdot 10^{-11}$	$7.38 \cdot 10^{-5}$	$3.48 \cdot 10^{-11}$
SWE-LTO	$1.21 \cdot 10^{-4}$	$4.05 \cdot 10^{-11}$	$8.05 \cdot 10^{-5}$	$2.70 \cdot 10^{-11}$
ALL Europe	$7.44 \cdot 10^{-1}$	-	$7.44 \cdot 10^{-1}$	-

Table 24: *Contributions to mean concentration of nitrate in the Swedish domain for the simulations with all flight emission species included and simulations with only NOx emissions included. The right hand subcolumns show the yearly mean concentration normalized by fuel energy use. ALL Europe corresponds to all anthropogenic emissions in the model domain.*

Scenarios	Yearly mean concentration [μg/m^3]	Yearly mean concentration [μg/m^3/GJ]
INT-LTO	$2.45 \cdot 10^{-5}$	$1.16 \cdot 10^{-11}$
SWE-LTO	$3.68 \cdot 10^{-5}$	$1.24 \cdot 10^{-11}$
ALL Europe	$8.91 \cdot 10^{-1}$	-

Table 25: *Contributions to mean concentration of sulfate in the Swedish domain for the simulations with all flight emission species included. The right hand subcolumn shows the yearly mean concentration normalized by fuel energy use. ALL Europe corresponds to all anthropogenic emissions in the model domain.*

6.4.4 Surface ozone

Ozone is toxic to vegetation and also has negative health effects on humans. Long term exposures to high concentration of ozone could cause lung damages and respiratory diseases [Naturvårdsverket, 2018a].

The emitted NO by aircrafts is quickly oxidized by ozone to form NO_2.

1: $NO + O_3 \longrightarrow NO_2 + O_2$

In the presence of daylight, NO_2 can be photolytically dissociated back to NO.

2: $NO_2 + hv \longrightarrow NO + O$

Tropospheric ozone can be regenerated by chemical reaction 3.

3: $O_2 + O \longrightarrow O_3$

Therefore NOx is needed in the formation of tropospheric ozone and increased NOx emissions could increase ozone production.

The concentration of surface ozone is shown in figure 17 and table 26. The INT-LTO and SWE-LTO flight emissions contribute to a reduced concentration of ozone near Stockholm Arlanda and an increased concentration in the rest of Sweden and over the Baltic Sea. In the proximity of the airports in Stockholm and Gothenburg where the source of NOx emissions is maximum, reaction 1 is dominating. High NO concentrations lead to the titration of ozone, which leads to the reduced concentrations especially in the winter time.

The INT-LO flight emissions contribute to an increase in ozone concentration in central Sweden and over the Baltic Sea. Other scenarios with high cruise and overflight flight emissions do not have a significant effect on surface ozone concentrations.

NOx aviation emissions has an similar effect on ground-level ozone concentration.

Scenarios	Contribution from all emitted species Yearly mean concentration [μg/m^3]	 [μg/m$^3/GJ$]	Contribution from NOx emissions Yearly mean concentration [μg/m^3]	 [μg/m$^3/GJ$]
INT-LTO	$2.43{\cdot}10^{-4}$	$1.15{\cdot}10^{-10}$	$2.14{\cdot}10^{-4}$	$1.01{\cdot}10^{-10}$
SWE-LTO	$3.17{\cdot}10^{-4}$	$1.06{\cdot}10^{-10}$	$2.79{\cdot}10^{-4}$	$9.37{\cdot}10^{-11}$
INT-LO	$6.00{\cdot}10^{-4}$	$1.24{\cdot}10^{-10}$	$5.93{\cdot}10^{-4}$	$1.23{\cdot}10^{-10}$
SWE-LO	$2.61{\cdot}10^{-4}$	$9.90{\cdot}10^{-11}$	$2.57{\cdot}10^{-4}$	$9.74{\cdot}10^{-11}$
OVER-LO	$1.25{\cdot}10^{-4}$	$9.33{\cdot}10^{-11}$	$1.23{\cdot}10^{-4}$	$9.22{\cdot}10^{-11}$
ALL Europe	69.8	-	69.8	-

Table 26: *Contributions to mean concentration of ozone in the whole modelled region for the simulations with all flight emission species included and simulations with only NOx emissions included. The right hand subcolumns show the yearly mean concentration normalized by fuel energy use. ALL Europe corresponds to all anthropogenic emissions in the model domain.*

Scenarios	Contribution from all emitted species Yearly mean concentration [μg/m^3]	 [μg/m$^3/GJ$]	Contribution from NOx emissions Yearly mean concentration [μg/m^3]	 [μg/m$^3/GJ$]
INT-LTO	$6.55{\cdot}10^{-4}$	$3.10{\cdot}10^{-10}$	$5.88{\cdot}10^{-4}$	$2.78{\cdot}10^{-10}$
SWE-LTO	$9.09{\cdot}10^{-4}$	$3.05{\cdot}10^{-10}$	$7.83{\cdot}10^{-4}$	$2.63{\cdot}10^{-10}$
ALL Europe	67.3	-	67.3	-

Table 27: *Contributions to mean concentration of ozone in the Swedish domain for the simulations with all flight emission species included and simulations with only NOx emissions included. The right hand subcolumns show the yearly mean concentration normalized by fuel energy use. ALL Europe corresponds to all anthropogenic emissions in the model domain.*

6.4.5 SOMO35

Surface ozone is harmful to humans. It could cause irritation of the eyes and mucous membranes, and even respiratory inflammation [Naturvårdsverket, 2018c]. SOMO35 is an ozone index which indicates the risk of ozone concentration for humans. It is the yearly sum of the daily maximum of 8 hours running average over 35 ppb(v). The maximum of the running 8-hours average is selected and is different everyday.

Figure 18, table 28, 29, 34 and 35 present SOMO35 and figure 19 and table 36, 37, 38 and 39 present the exposure of SOMO35. INT-LTO and SWE-LTO emissions cause higher SOMO35 close to the source in Stockholm Arlanda, and SOMO35 decreases with distance away from Arlanda. Compared to SOMO35 caused by shipping emissions, SOMO35 caused by INT-LTO and SWE-LTO flight emissions is about 26 times smaller. SOMO35 exposure caused by INT-LTO and SWE-LTO is over 40 times lower than that caused by shipping emissions.

SOMO35 caused by NOx aviation emissions is about the same as that caused by all aviation emissions.

Scenarios	Contribution from all emitted species Yearly mean SOMO35		Contribution from NOx emissions Yearly mean SOMO35	
	[μg/m^3]	[μg/m$^3/GJ$]	[μg/m^3]	[μg/m$^3/GJ$]
INT-LTO	$1.92{\cdot}10^{-1}$	$9.09{\cdot}10^{-8}$	$2.07{\cdot}10^{-1}$	$9.79{\cdot}10^{-8}$
SWE-LTO	$2.33{\cdot}10^{-1}$	$7.81{\cdot}10^{-8}$	$2.40{\cdot}10^{-1}$	$8.05{\cdot}10^{-8}$
INT-LO	$4.31{\cdot}10^{-1}$	$8.91{\cdot}10^{-8}$	$4.74{\cdot}10^{-1}$	$9.80{\cdot}10^{-8}$
SWE-LO	$2.02{\cdot}10^{-1}$	$7.67{\cdot}10^{-8}$	$2.04{\cdot}10^{-1}$	$7.73{\cdot}10^{-8}$
OVER-LO	$9.63{\cdot}10^{-2}$	$7.19{\cdot}10^{-8}$	$1.11{\cdot}10^{-1}$	$8.28{\cdot}10^{-8}$
ALL Europe	$1.00{\cdot}10^{4}$	-	$1.00{\cdot}10^{4}$	-

Table 28: *Contributions to mean SOMO35 in the whole modelled region for the simulations with all flight emission species included and simulations with only NOx emissions included. The right hand subcolumns show the yearly mean SOMO35 normalized by fuel energy use. ALL Europe corresponds to all anthropogenic emissions in the model domain.*

Scenarios	Contribution from all emitted species Yearly mean SOMO35		Contribution from NOx emissions Yearly mean SOMO35	
	[ppm(v)d]	[ppm(v)d/GJ]	[ppm(v)d]	[ppm(v)d/GJ]
INT-LTO	$9.49{\cdot}10^{-5}$	$4.48{\cdot}10^{-11}$	$1.02{\cdot}10^{-4}$	$4.83{\cdot}10^{-11}$
SWE-LTO	$1.15{\cdot}10^{-4}$	$5.42{\cdot}10^{-11}$	$1.18{\cdot}10^{-4}$	$3.97{\cdot}10^{-11}$
INT-LO	$2.13{\cdot}10^{-4}$	$1.00{\cdot}10^{-10}$	$2.34{\cdot}10^{-4}$	$4.83{\cdot}10^{-11}$
SWE-LO	$9.97{\cdot}10^{-5}$	$4.71{\cdot}10^{-11}$	$1.00{\cdot}10^{-4}$	$3.81{\cdot}10^{-11}$
OVER-LO	$4.75{\cdot}10^{-5}$	$2.24{\cdot}10^{-11}$	$5.47{\cdot}10^{-5}$	$4.08{\cdot}10^{-11}$
ALL Europe	4.94	-	4.94	-

Table 29: *Contributions to mean SOMO35 in the whole modelled region for the simulations with all flight emission species included and simulations with only NOx emissions included. The right hand subcolumns show the yearly mean SOMO35 normalized by fuel energy use. ALL Europe corresponds to all anthropogenic emissions in the model domain.*

	Contribution from all emitted species			
Scenarios	Yearly mean exposure SOMO35		Yearly total exposure SOMO35	
	[μg/m^3 ·$\#/km^2$]	[μg/m^3 ·$\#/km^2/GJ$]	[μg/m^3 ·#]	[μg/m^3 ·$\#/GJ$]
INT-LTO	3.82	$1.80{\cdot}10^{-6}$	$4.73{\cdot}10^{7}$	$2.23{\cdot}10^{1}$
SWE-LTO	4.53	$1.52{\cdot}10^{-6}$	$5.61{\cdot}10^{7}$	$1.88{\cdot}10^{1}$
INT-LO	9.69	$2.00{\cdot}10^{-6}$	$1.20{\cdot}10^{8}$	$2.48{\cdot}10^{1}$
SWE-LO	4.25	$1.61{\cdot}10^{-6}$	$5.26{\cdot}10^{7}$	$2.00{\cdot}10^{1}$
OVER-LO	2.90	$2.16{\cdot}10^{-6}$	$3.59{\cdot}10^{7}$	$2.68{\cdot}10^{1}$
ALL Europe	$3.79 \cdot 10^{5}$	-	$4.69 \cdot 10^{12}$	-

Table 30: *Contributions to yearly and total exposure of SOMO35 in the whole modelled region for the simulations with all flight emission species included. The right hand subcolumns show the yearly exposure of SOMO35 normalized by fuel energy use. ALL Europe corresponds to all anthropogenic emissions in the model domain.*

	Contribution from all emitted species			
Scenarios	Yearly mean exposure SOMO35		Yearly total exposure SOMO35	
	[ppm(v)d $\cdot\#/km^2$]	[ppm(v)d $\cdot\#/km^2/GJ$]	[ppm(v)d $\cdot\#$]	[ppm(v)d $\cdot\#/GJ$]
INT-LTO	$1.88\cdot10^{-3}$	$8.89\cdot10^{-10}$	$2.33\cdot10^{4}$	$1.10\cdot10^{-2}$
SWE-LTO	$2.23\cdot10^{-3}$	$7.49\cdot10^{-10}$	$2.77\cdot10^{4}$	$9.28\cdot10^{-3}$
INT-LO	$4.78\cdot10^{-3}$	$9.88\cdot10^{-10}$	$5.92\cdot10^{4}$	$1.22\cdot10^{-2}$
SWE-LO	$2.09\cdot10^{-3}$	$7.95\cdot10^{-10}$	$2.60\cdot10^{4}$	$9.85\cdot10^{-3}$
OVER-LO	$1.43\cdot10^{-3}$	$1.07\cdot10^{-9}$	$1.77\cdot10^{4}$	$1.32\cdot10^{-2}$
ALL Europe	187	-	$2.31\cdot10^{9}$	-

Table 31: *Contributions to yearly and total exposure of SOMO35 in the whole modelled region for the simulations with all flight emission species included. The right hand subcolumns show the yearly exposure of SOMO35 normalized by fuel energy use. ALL Europe corresponds to all anthropogenic emissions in the model domain.*

	Contribution from NOx emissions			
Scenarios	Yearly mean exposure SOMO35		Yearly total exposure SOMO35	
	[μg/m^3 $\cdot\#/km^2$]	[μg/m^3 $\cdot\#/km^2/GJ$]	[μg/m^3 $\cdot\#$]	[μg/m^3 $\cdot\#/GJ$]
INT-LTO	3.82	$1.81\cdot10^{-6}$	$4.74\cdot10^{7}$	$2.24\cdot10^{1}$
SWE-LTO	4.33	$1.45\cdot10^{-6}$	$5.36\cdot10^{7}$	$1.80\cdot10^{1}$
INT-LO	10.8	$2.23\cdot10^{-6}$	$1.34\cdot10^{8}$	$2.76\cdot10^{1}$
SWE-LO	4.79	$1.82\cdot10^{-6}$	$5.93\cdot10^{7}$	$2.25\cdot10^{1}$
OVER-LO	3.18	$2.37\cdot10^{-6}$	$3.93\cdot10^{7}$	$2.94\cdot10^{1}$
ALL Europe	$3.79\cdot10^{5}$	-	$4.69\cdot10^{12}$	-

Table 32: *Contributions to yearly and total exposure of SOMO35 in the whole modelled region for the simulations with only NOx emissions included. The right hand subcolumns show the yearly exposure of SOMO35 normalized by fuel energy use. ALL Europe corresponds to all anthropogenic emissions in the model domain.*

	Contribution from NOx emissions			
Scenarios	Yearly mean exposure SOMO35		Yearly total exposure SOMO35	
	[ppm(v)d $\cdot\#/km^2$]	[ppm(v)d $\cdot\#/km^2/GJ$]	[ppm(v)d $\cdot\#$]	[ppm(v)d $\cdot\#/GJ$]
INT-LTO	$1.89\cdot10^{-3}$	$8.91\cdot10^{-10}$	$2.34\cdot10^{4}$	$1.10\cdot10^{-2}$
SWE-LTO	$2.13\cdot10^{-3}$	$7.16\cdot10^{-10}$	$2.64\cdot10^{4}$	$8.87\cdot10^{-3}$
INT-LO	$5.32\cdot10^{-3}$	$1.10\cdot10^{-9}$	$6.59\cdot10^{4}$	$1.36\cdot10^{-2}$
SWE-LO	$2.36\cdot10^{-3}$	$8.96\cdot10^{-10}$	$2.92\cdot10^{4}$	$1.11\cdot10^{-2}$
OVER-LO	$1.57\cdot10^{-3}$	$1.17\cdot10^{-9}$	$1.94\cdot10^{4}$	$1.45\cdot10^{-2}$
ALL Europe	187	-	$2.31\cdot10^{9}$	-

Table 33: *Contributions to yearly and total exposure of SOMO35 in the whole modelled region for the simulations with only NOx emissions included. The right hand subcolumns show the yearly exposure of SOMO35 normalized by fuel energy use. ALL Europe corresponds to all anthropogenic emissions in the model domain.*

Scenarios	Contribution from all emitted species Yearly mean SOMO35		Contribution from NOx emissions Yearly mean SOMO35	
	[μg/m^3]	[μg/m$^3/GJ$]	[μg/m^3]	[μg/m$^3/GJ$]
INT-LTO	$7.04{\cdot}10^{-1}$	$3.33{\cdot}10^{-7}$	$7.14{\cdot}10^{-1}$	$3.37{\cdot}10^{-7}$
SWE-LTO	$8.40{\cdot}10^{-1}$	$2.82{\cdot}10^{-7}$	$8.21{\cdot}10^{-1}$	$2.75{\cdot}10^{-7}$
ALL Europe	$7.74 \cdot 10^{3}$	-	$7.74 \cdot 10^{3}$	-

Table 34: *Contributions to mean SOMO35 in the Swedish domain for the simulations with all flight emission species included and simulations with only NOx emissions included. The right hand subcolumns show the yearly mean SOMO35 normalized by fuel energy use. ALL Europe corresponds to all anthropogenic emissions in the model domain.*

Scenarios	Contribution from all emitted species Yearly mean SOMO35		Contribution from NOx emissions Yearly mean SOMO35	
	[ppm(v)d]	[ppm(v)d/GJ]	[ppm(v)d]	[ppm(v)d/GJ]
INT-LTO	$3.47{\cdot}10^{-4}$	$1.64{\cdot}10^{-10}$	$3.52{\cdot}10^{-4}$	$1.66{\cdot}10^{-10}$
SWE-LTO	$4.14{\cdot}10^{-4}$	$1.39{\cdot}10^{-10}$	$4.05{\cdot}10^{-4}$	$1.36{\cdot}10^{-10}$
ALL Europe	3.82	-	3.82	-

Table 35: *Contributions to mean SOMO35 in the Swedish domain for the simulations with all flight emission species included and simulations with only NOx emissions included. The right hand subcolumns show the yearly mean SOMO35 normalized by fuel energy use. ALL Europe corresponds to all anthropogenic emissions in the model domain.*

	Contribution from all emitted species			
Scenarios	Yearly mean exposure SOMO35		Yearly total exposure SOMO35	
	[μg/m^3 $\cdot\#/km^2$]	[μg/m^3 $\cdot\#/km^2/GJ$]	[μg/m^3 $\cdot\#$]	[μg/m^3 $\cdot\#/GJ$]
INT-LTO	$1.01{\cdot}10^{1}$	$4.78{\cdot}10^{-6}$	$1.84{\cdot}10^{7}$	8.68
SWE-LTO	$1.16{\cdot}10^{1}$	$3.91{\cdot}10^{-6}$	$2.11{\cdot}10^{7}$	7.09
ALL Europe	$1.35{\cdot}10^{5}$	-	$2.44{\cdot}10^{11}$	-

Table 36: *Contributions to yearly and total exposure of SOMO35 in the Swedish domain for the simulations with all flight emission species included. The right hand subcolumns show the yearly exposure of SOMO35 normalized by fuel energy use. ALL Europe corresponds to all anthropogenic emissions in the model domain.*

	Contribution from all emitted species			
Scenarios	Yearly mean exposure SOMO35		Yearly total exposure SOMO35	
	[ppm(v)d $\cdot\#/km^2$]	[ppm(v)d $\cdot\#/km^2/GJ$]	[ppm(v)d $\cdot\#$]	[ppm(v)d $\cdot\#/GJ$]
INT-LTO	$4.99{\cdot}10^{-3}$	$2.36{\cdot}10^{-9}$	$9.06{\cdot}10^{3}$	$4.28{\cdot}10^{-3}$
SWE-LTO	$5.75{\cdot}10^{-3}$	$1.93{\cdot}10^{-9}$	$1.04{\cdot}10^{4}$	$3.50{\cdot}10^{-3}$
ALL Europe	66.4	-	$1.20 \cdot 10^{8}$	-

Table 37: *Contributions to yearly and total exposure of SOMO35 in the Swedish domain for the simulations with all flight emission species included. The right hand subcolumns show the yearly exposure of SOMO35 normalized by fuel energy use. ALL Europe corresponds to all anthropogenic emissions in the model domain.*

	Contribution from NOx emissions			
Scenarios	Yearly mean exposure SOMO35		Yearly total exposure SOMO35	
	[μg/m^3 $\cdot\#/km^2$]	[μg/m^3 $\cdot\#/km^2/GJ$]	[μg/m^3 $\cdot\#$]	[μg/m^3 $\cdot\#/GJ$]
INT-LTO	$1.02\cdot10^1$	$4.81\cdot10^{-6}$	$1.85\cdot10^7$	8.73
SWE-LTO	$1.14\cdot10^1$	$3.81\cdot10^{-6}$	$2.06\cdot10^7$	6.91
ALL Europe	$1.35\cdot10^5$	-	$2.44\cdot10^{11}$	-

Table 38: *Contributions to yearly and total exposure of SOMO35 in the Swedish domain for the simulations with only NOx emissions included. The right hand subcolumns show the yearly exposure of SOMO35 normalized by fuel energy use. ALL Europe corresponds to all anthropogenic emissions in the model domain.*

	Contribution from NOx emissions			
Scenarios	Yearly mean exposure SOMO35		Yearly total exposure SOMO35	
	[ppm(v)d $\cdot\#/km^2$]	[ppm(v)d $\cdot\#/km^2/GJ$]	[ppm(v)d $\cdot\#$]	[ppm(v)d $\cdot\#/GJ$]
INT-LTO	$5.02\cdot10^{-3}$	$2.37\cdot10^{-9}$	$9.11\cdot10^3$	$4.31\cdot10^{-3}$
SWE-LTO	$5.60\cdot10^{-3}$	$1.88\cdot10^{-9}$	$1.02\cdot10^4$	$3.41\cdot10^{-3}$
ALL Europe	66.4	-	$1.20\cdot10^8$	-

Table 39: *Contributions to yearly and total exposure of SOMO35 in the Swedish domain for the simulations with only NOx emissions included. The right hand subcolumns show the yearly exposure of SOMO35 normalized by fuel energy use. ALL Europe corresponds to all anthropogenic emissions in the model domain.*

6.5 Air pollution from aviation with effects on ozone above surface level

Ozone is a greenhouse gas and absorbs both short and longwave radiation. The global average impact for year 1750 to 2011 on the radiation balance from ozone changes due to anthropogenic emissions was 0.4 W/m^2 [IPCC, 2013], which can be compared to the global average radiative forcing from the increase of CO_2 caused by anthropogenic emissions (1750-2011), which was 1.68 W/m^2 [IPCC, 2013]. To support further calculations of the climate impact of changes in tropospheric ozone from aviation emissions over Sweden, the simulated contributions to the burden of ozone for different height intervals in the model domain is reported in this section.

As a first illustration we show in figure 22 the simulated contributions from all emitted species from aviation over Sweden to three-year average ozone concentrations at different levels in the troposphere. Contributions from LTO emissions are shown at a height of ca 1km; contributions from low cruise emissions are shown at ca 5 km and contributions from high cruise emissions are shown at ca 10 km. As for surface level ozone, contributions are small and have units of ng/m^3 i.e less than 1 per mille of the total concentrations. The simulated contributions at lower levels for the LTO emissions has a geographical pattern with a clear maximum over Stockholm-Arlanda region while contributions higher up for LO and HI cruise emissions show a more uniform distribution with a maximum shift to the east due to prevailing westerly winds. Results for NOx emissions are very similar but with a slightly lower contributions.

Figure 23 shows the corresponding simulated contributions to burdens of ozone (vertically integrated amounts) as three-year averages. The vertical integration goes up to ca 19 km in the model simulation and therefore includes a substatial fraction of the lower stratosphere. The patterns of ozone burdens are similar to those of the concentrations, but with weaker horizontal gradients for LTO emissions. Results for NOx emissions only are very similar but with slightly lower contributions.

We report the corresponding simulated burdens integrated over the whole model domain in various height intervals for both the simulation with contributions from all species emitted from aviation over Sweden and contributions from only NOx emissions from aviation in tables 40 and 41, respectively. The unit used is ton of ozone which is equivalent to 10^6g ozone. As expected the contributions from emissions at different intervals, LTO, LO and HI, contribute to the burden directly at the corresponding interval. The total burden of ozone simulated in the model domain is about $27{\cdot}10^6$ ton. This includes all ozone caused by both natural and anthropogenic emissions as well as a large contribution of stratospheric ozone. The burden above 10 km is 64 % of the total and most of that is from a stratospheric origin. The simulated contributions, on the order of a factor 1 million (10^6) smaller, are thus small compared to the total amount. If the vertical domain is restricted to less than 12 km the relative contributions would increase by a factor of 3 but are still very small. The results for SWE-LTO and INT-LTO show a different vertical gradient in the burden between 5-10 km and > 10 km. This result is sensitive to how high up the vertical integration goes in the model simulation. If two more layers are used in the integration the vertical gradient would result in the same behavior for both LTO scenarios.

Height interval	INT-LTO	SWE-LTO	INT-LO	SWE-LO	OVER-LO	INT-HI	SWE-HI	OVER-HI
> 10 km	0.47	0.12	1.80	1.15	0.96	32.44	8.67	48.59
5 - 10 km	0.19	0.32	18.37	10.00	7.96	4.05	1.45	5.98
0 - 5 km	10.94	13.63	55.88	28.92	15.40	0.29	0.06	0.50
Total	11.61	14.06	76.04	40.07	24.32	36.78	10.18	55.06

Table 40: *Contributions to burdens of ozone for different aviation emissions including all emitted species. Units: ton ozone.*

Height interval	INT-LTO	SWE-LTO	INT-LO	SWE-LO	OVER-LO	INT-HI	SWE-HI	OVER-HI
> 10 km	0.20	0.15	1.94	0.53	0.59	31.29	8.49	48.40
5 - 10 km	0.19	0.27	18.34	10.04	7.90	4.00	1.36	5.95
0 - 5 km	10.27	12.49	55.66	28.95	15.33	0.40	0.07	0.43
Total	10.65	12.91	76.94	39.51	23.82	35.69	9.92	54.78

Table 41: *Contributions to burdens of ozone for different aviation emissions including only NOx emissions. Units: ton ozone.*

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Appendices

A Flight emission effects on ecosystem metrics

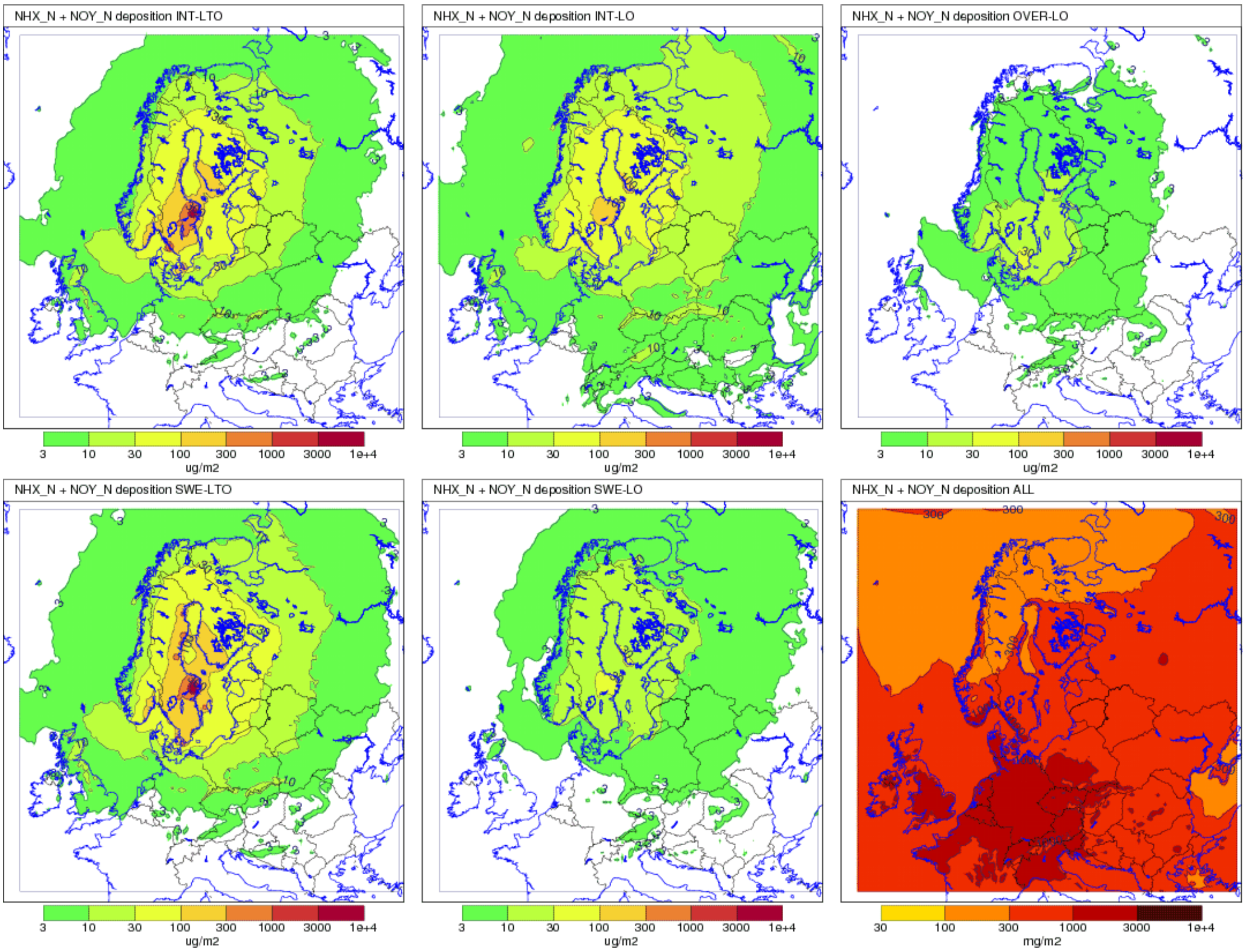

Figure 5: *Yearly mean deposition of oxidised and reduced nitrogen for year 2012-2014.*

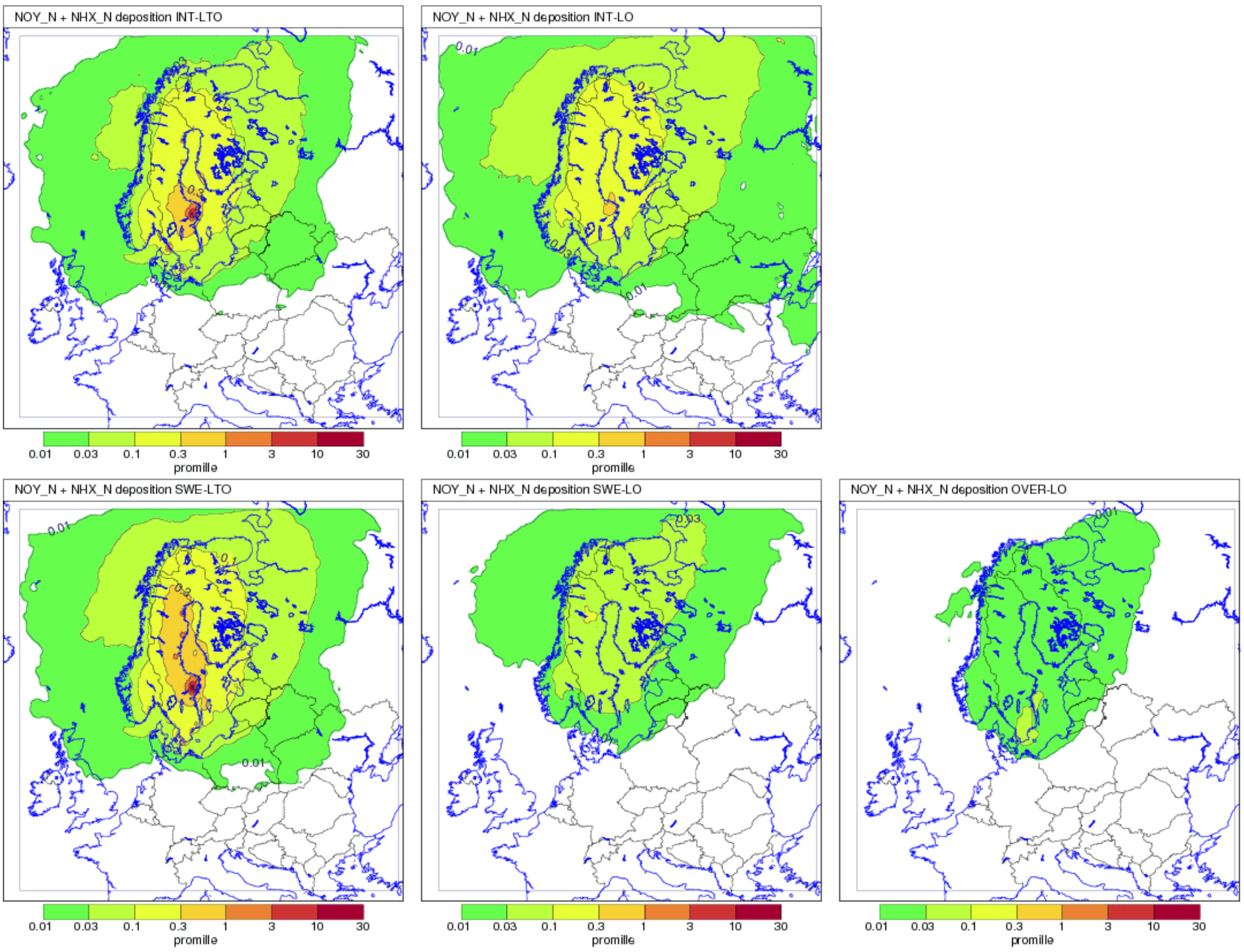

Figure 6: *Yearly relative mean deposition of oxidised and reduced nitrogen for year 2012-2014.*

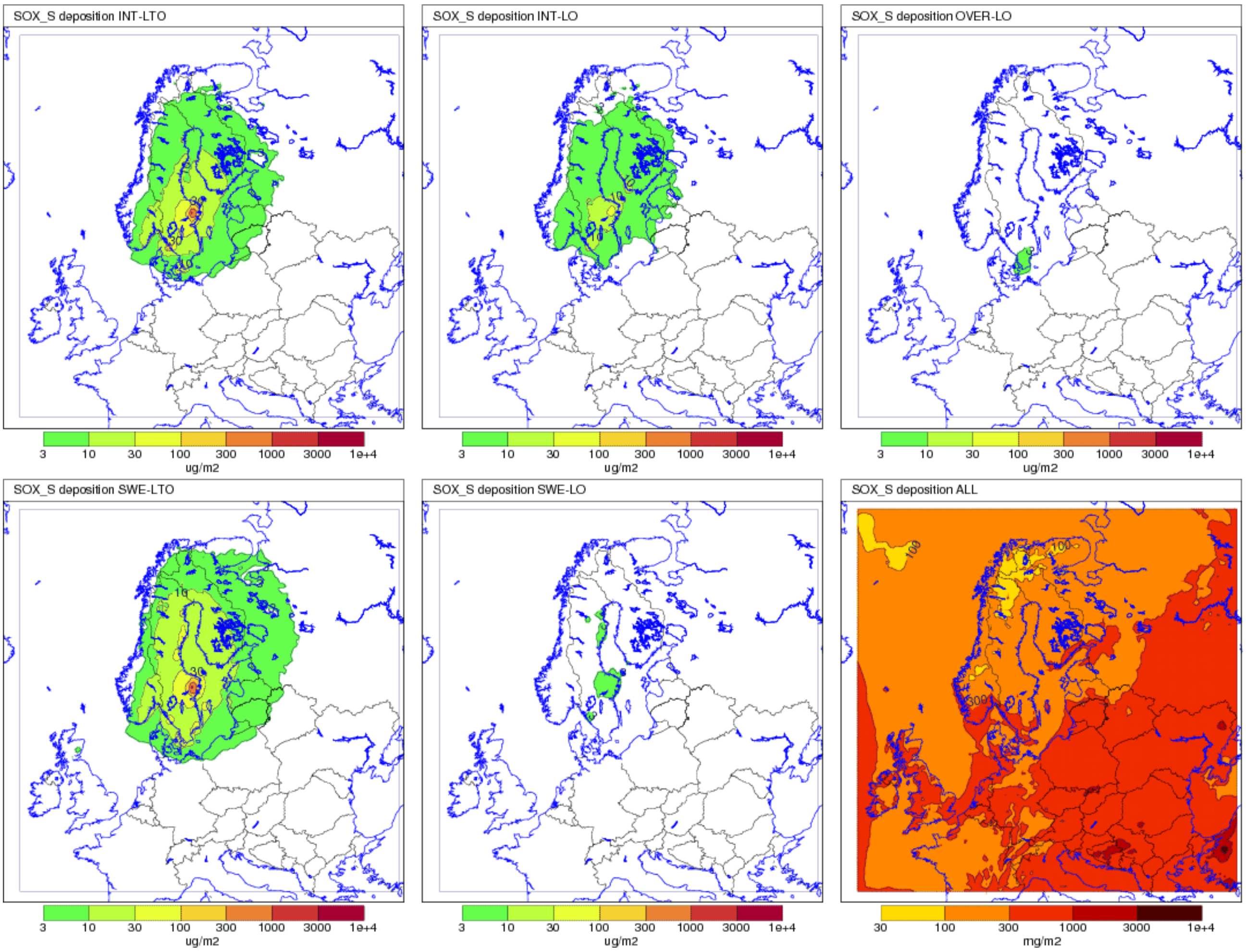

Figure 7: *Yearly mean deposition of excess sulfur for year 2012-2014.*

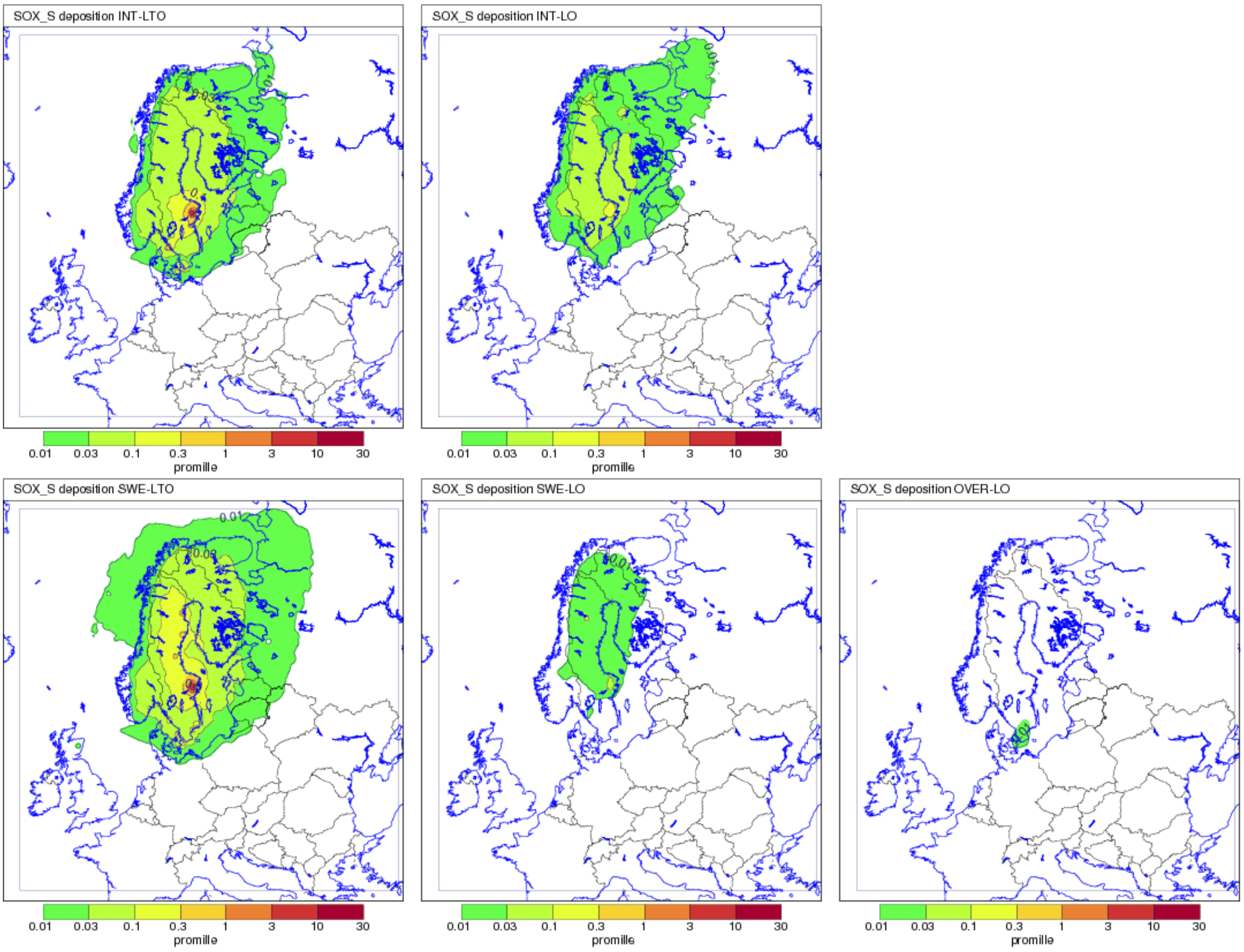

Figure 8: *Yearly relative mean deposition of excess sulfur for year 2012-2014.*

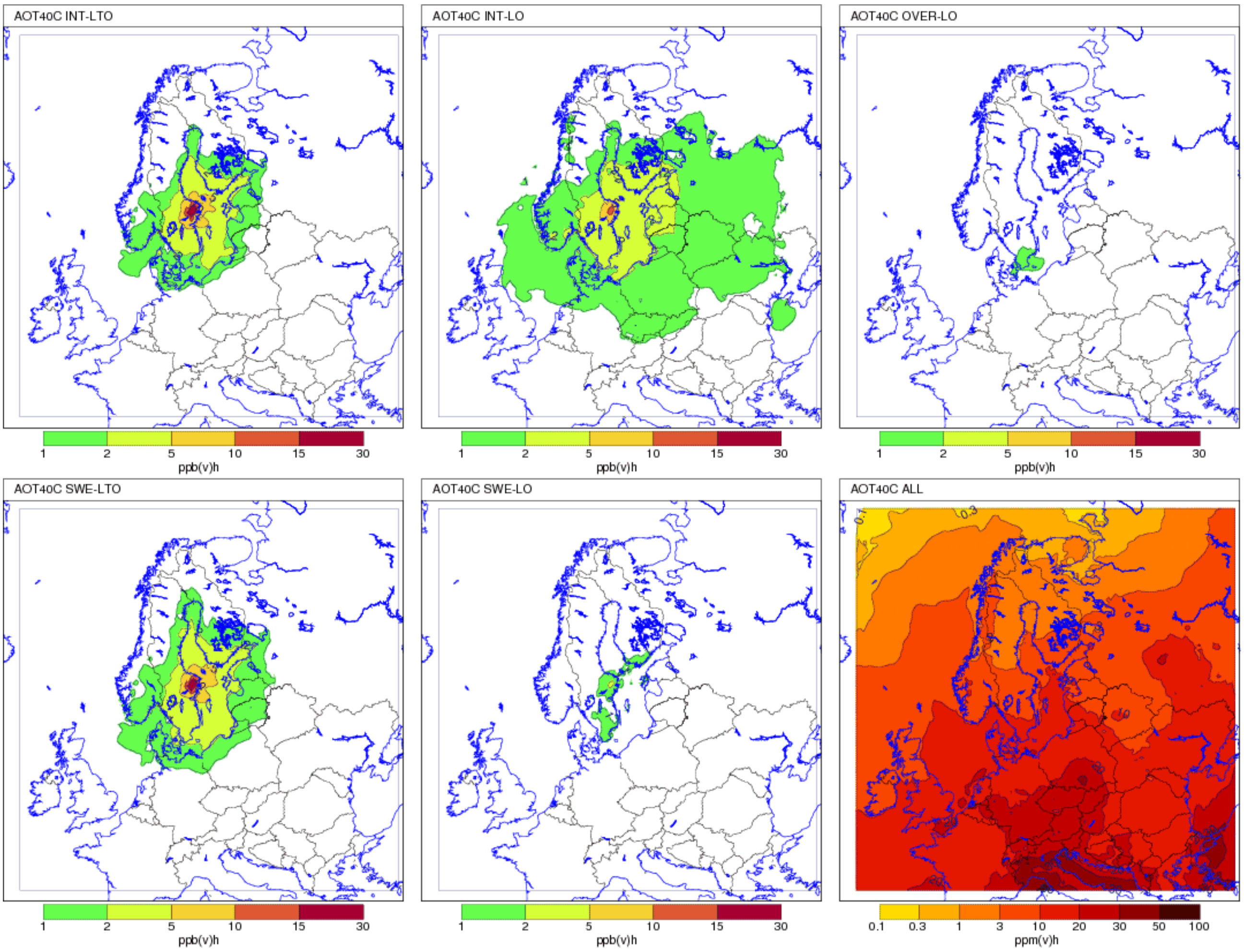

Figure 9: *Ozone index that indicates the damage on crops - AOT40C for year 2012-2014.*

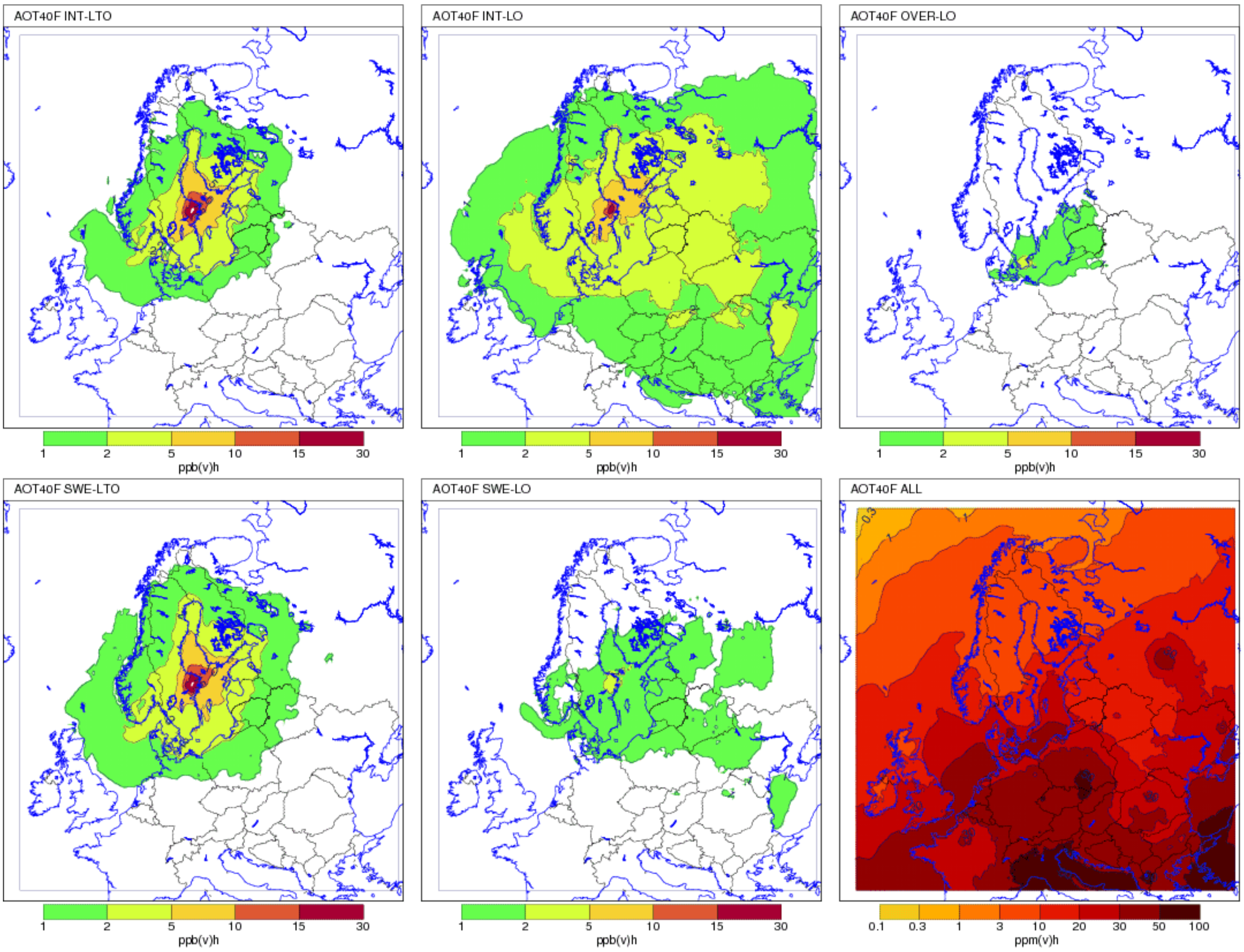

Figure 10: *Ozone index that indicates the damage on plants - AOT40F for year 2012-2014.*

B Flight emission effects on health metrics

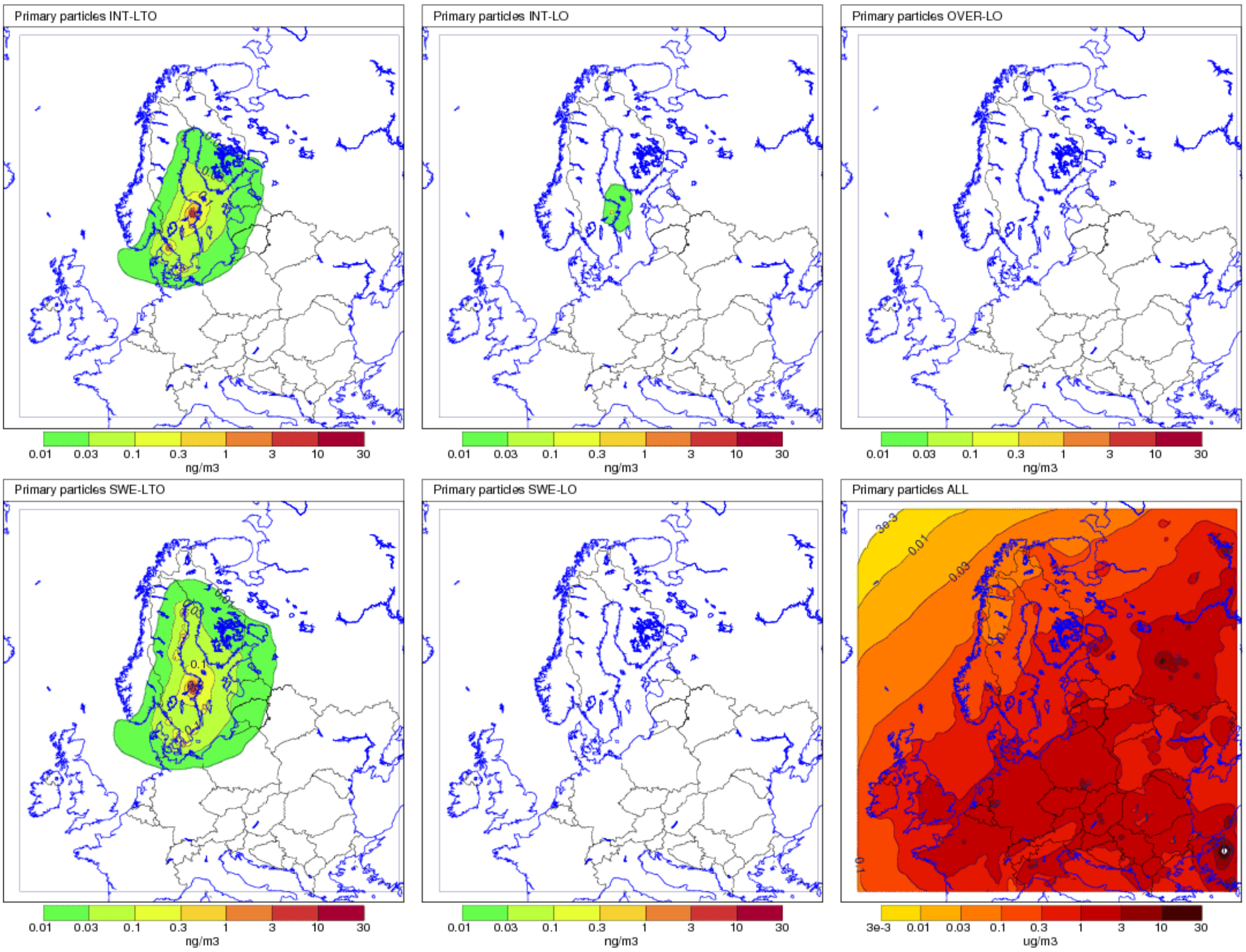

Figure 11: *Yearly mean concentration of primary particles for year 2012-2014.*

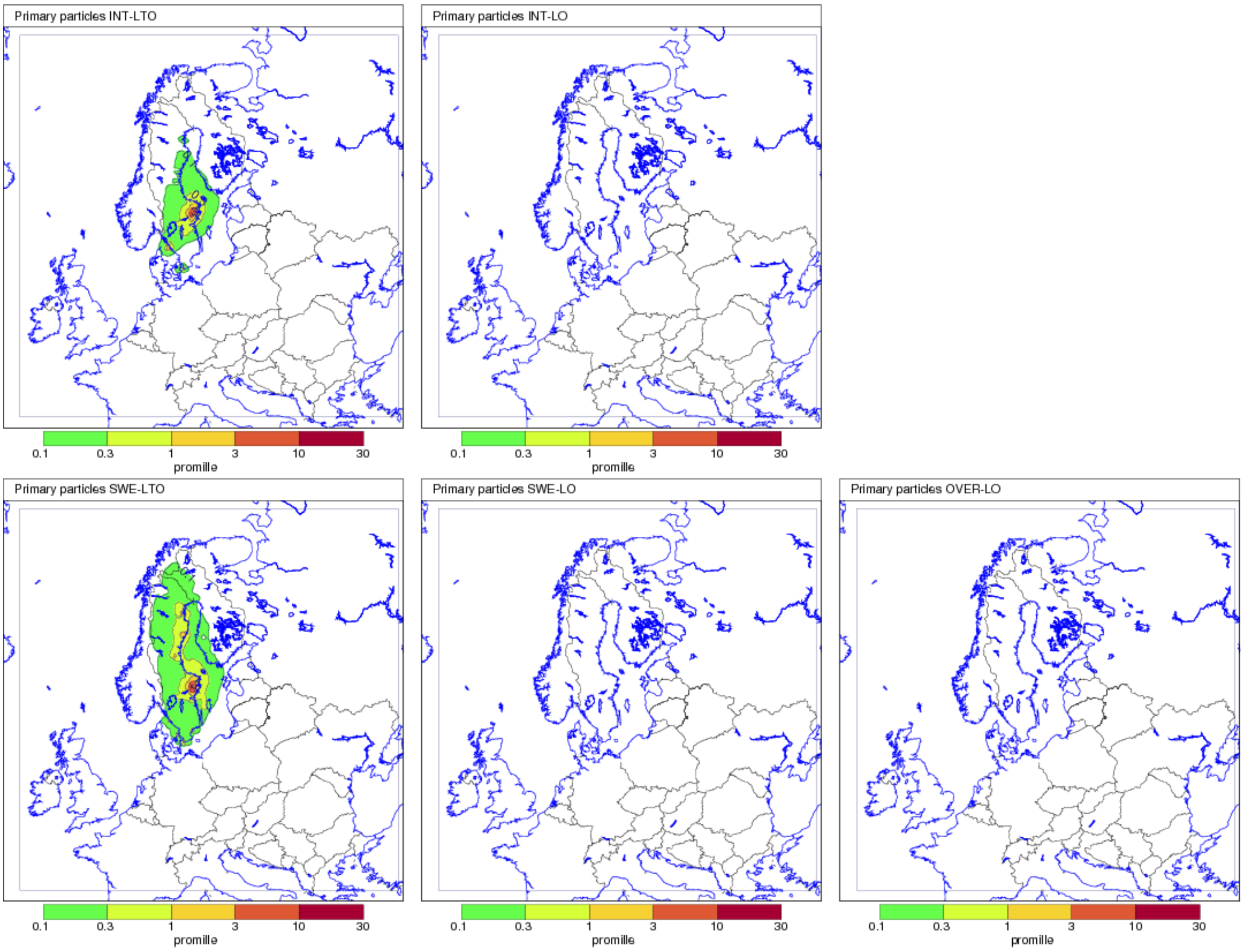

Figure 12: *Relative yearly mean concentration of primary particles for year 2012-2014.*

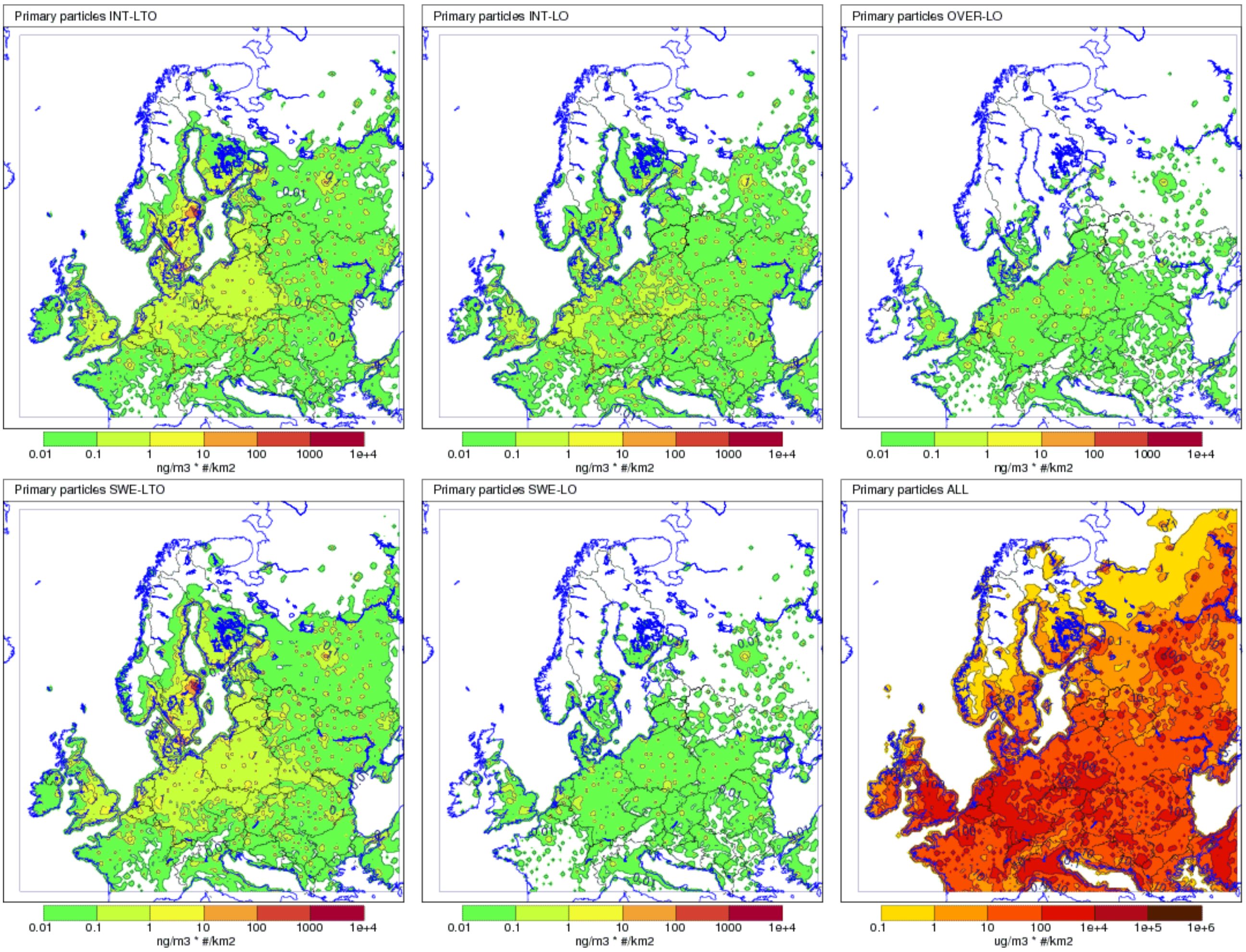

Figure 13: *Yearly mean exposures of primary particles for year 2012-2014.*

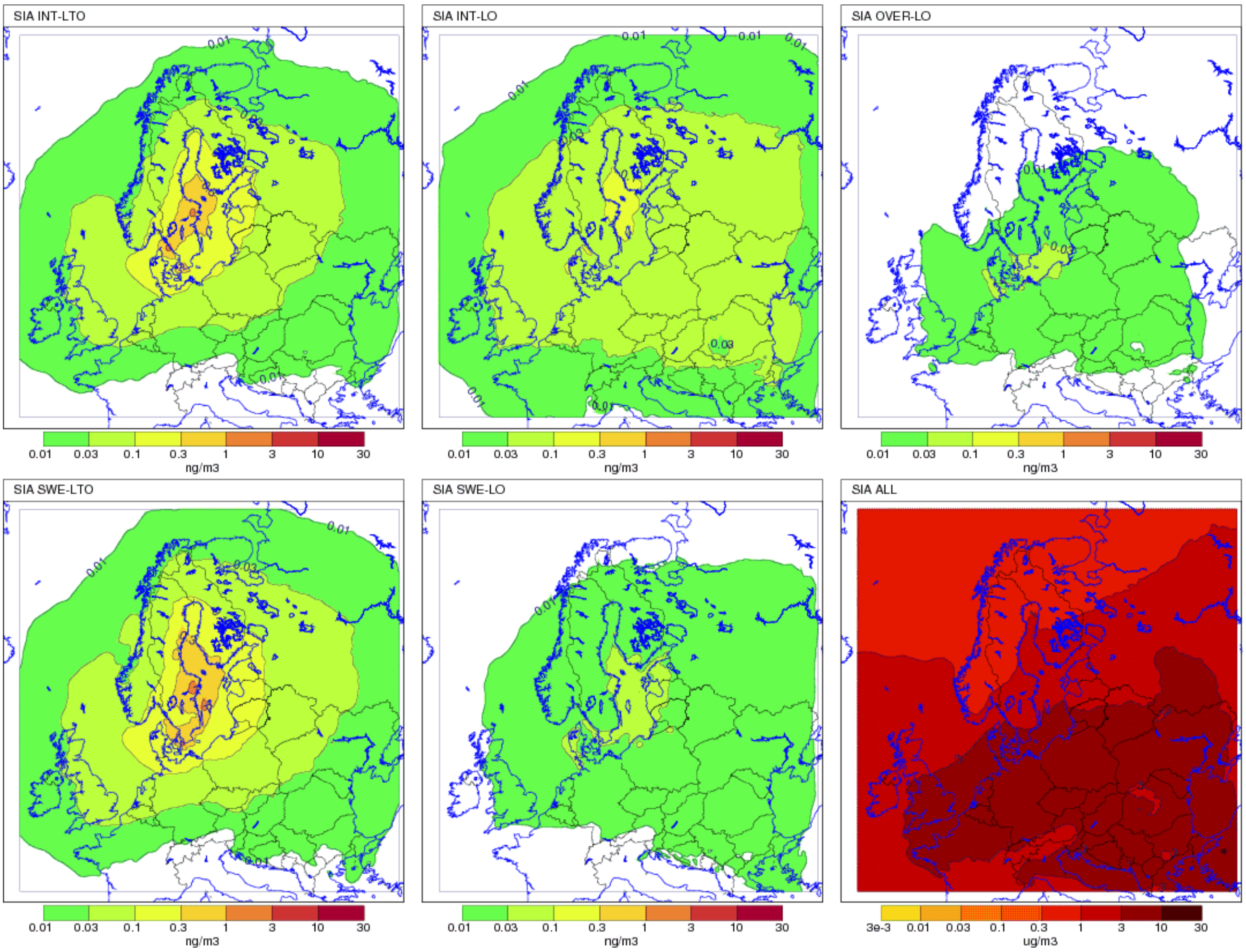

Figure 14: *Yearly mean concentration of secondary inorganic particles for year 2012-2014.*

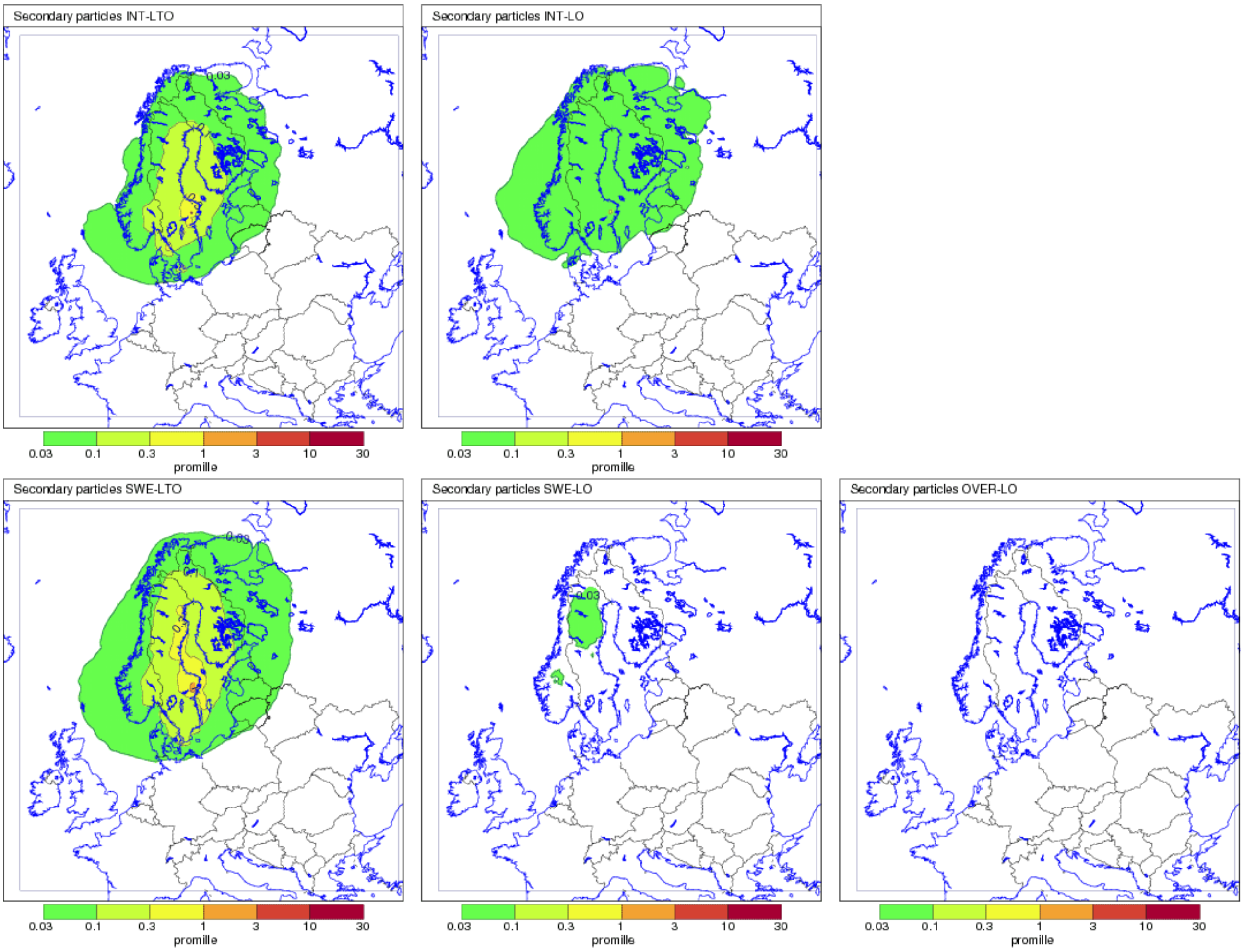

Figure 15: *Relative yearly mean concentration of secondary inorganic particles for year 2012-2014.*

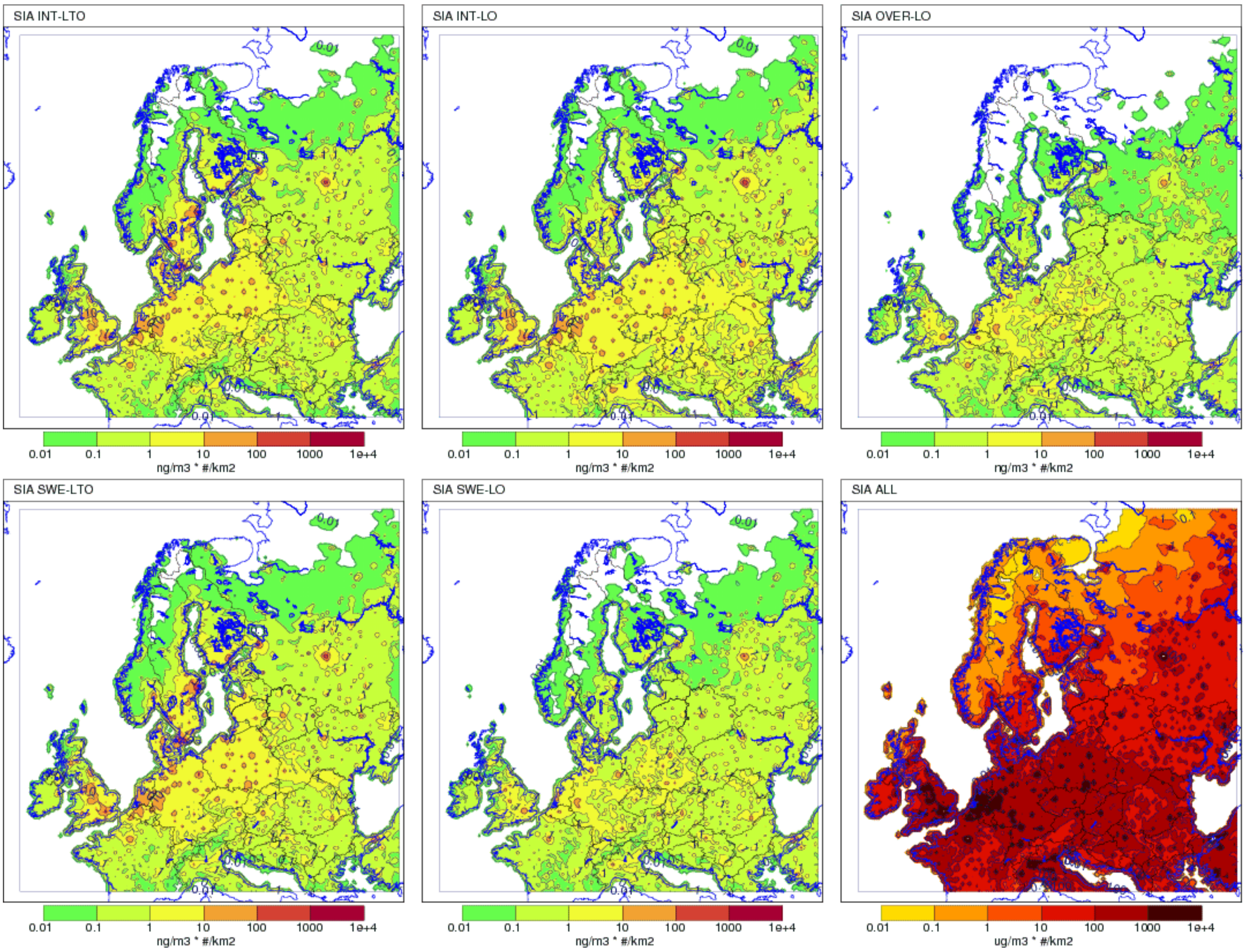

Figure 16: Yearly mean exposures of secondary inorganic particles for year 2012-2014.

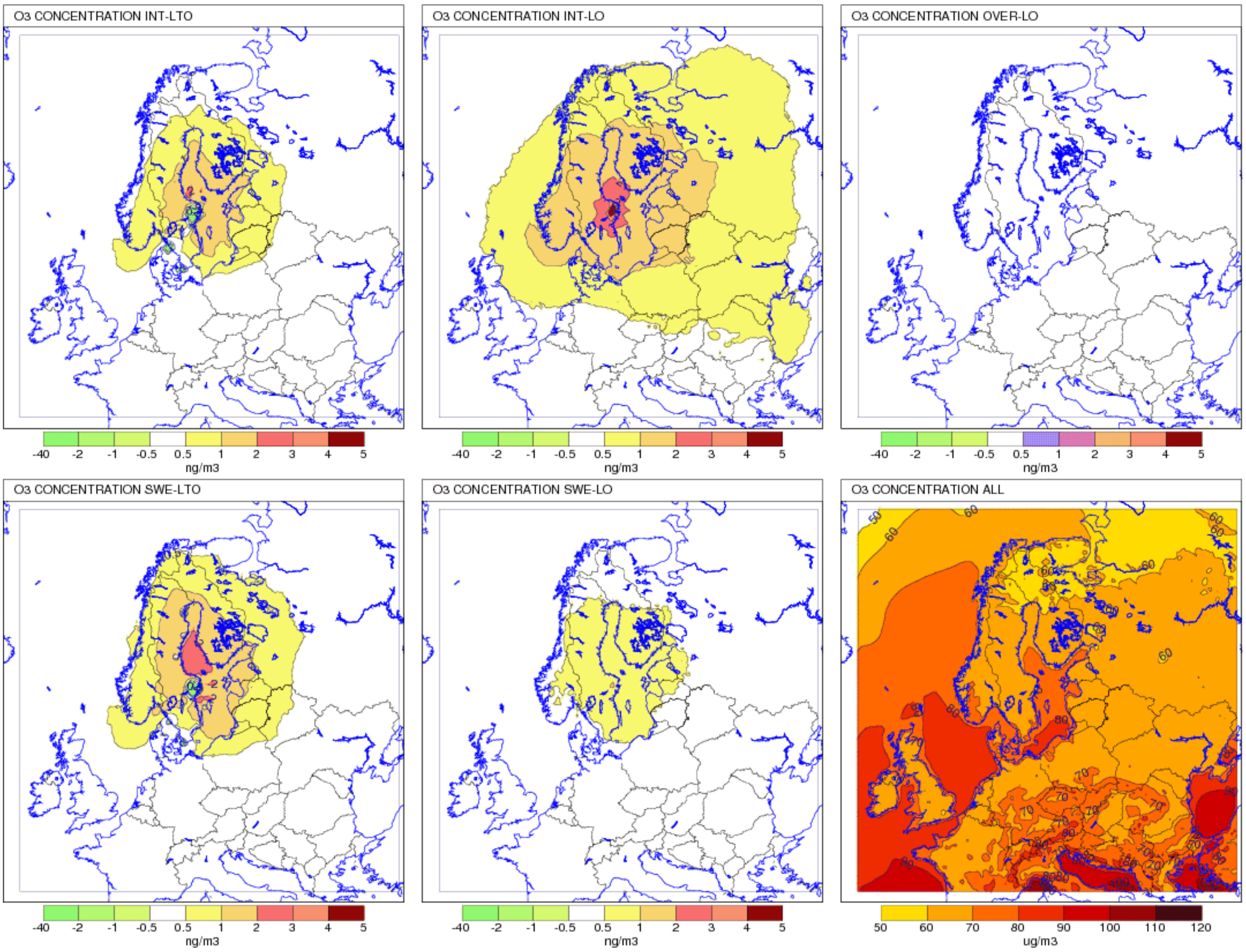

Figure 17: *Yearly mean concentration of surface ozone for year 2012-2014.*

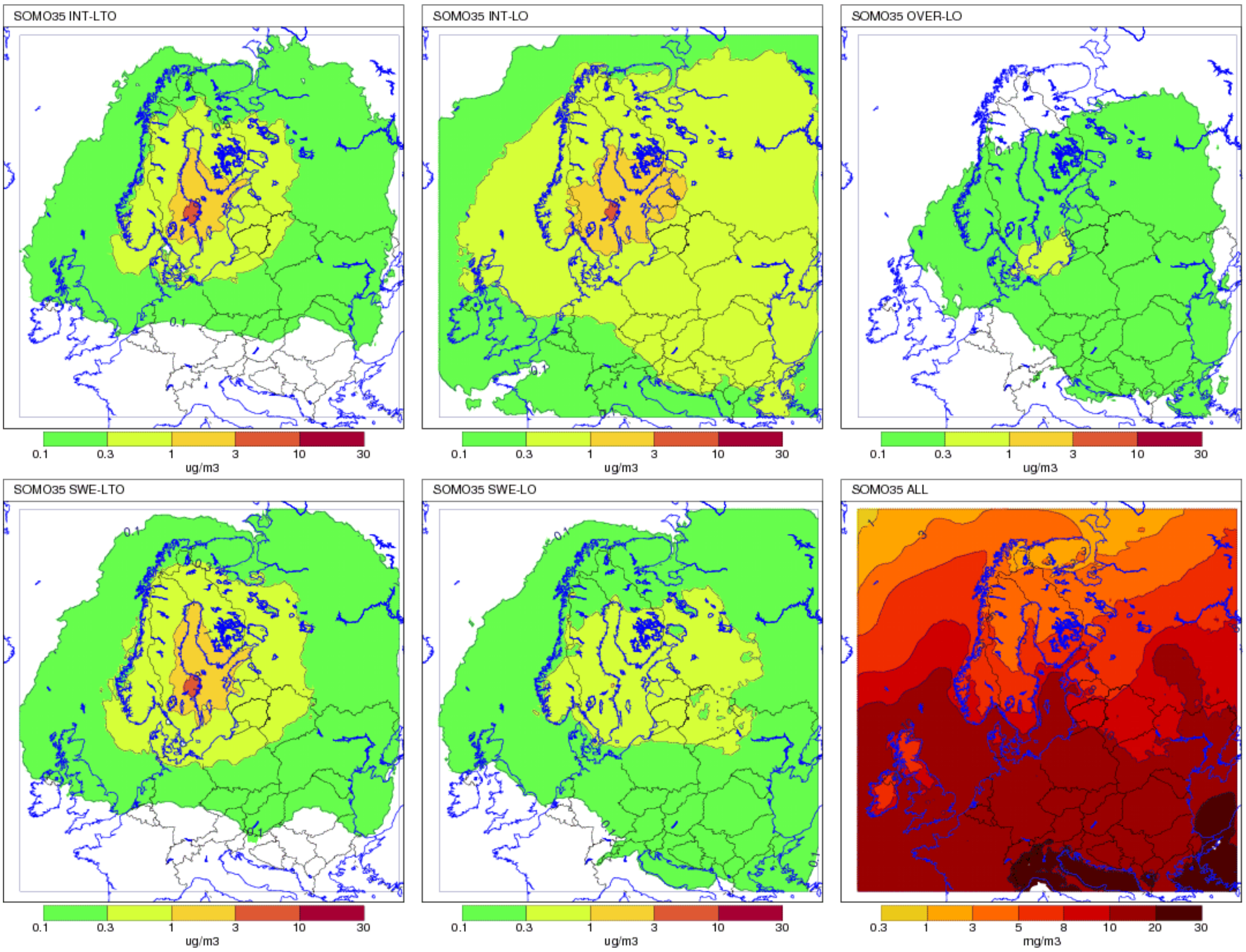

Figure 18: *SOMO35 for year 2012-2014.*

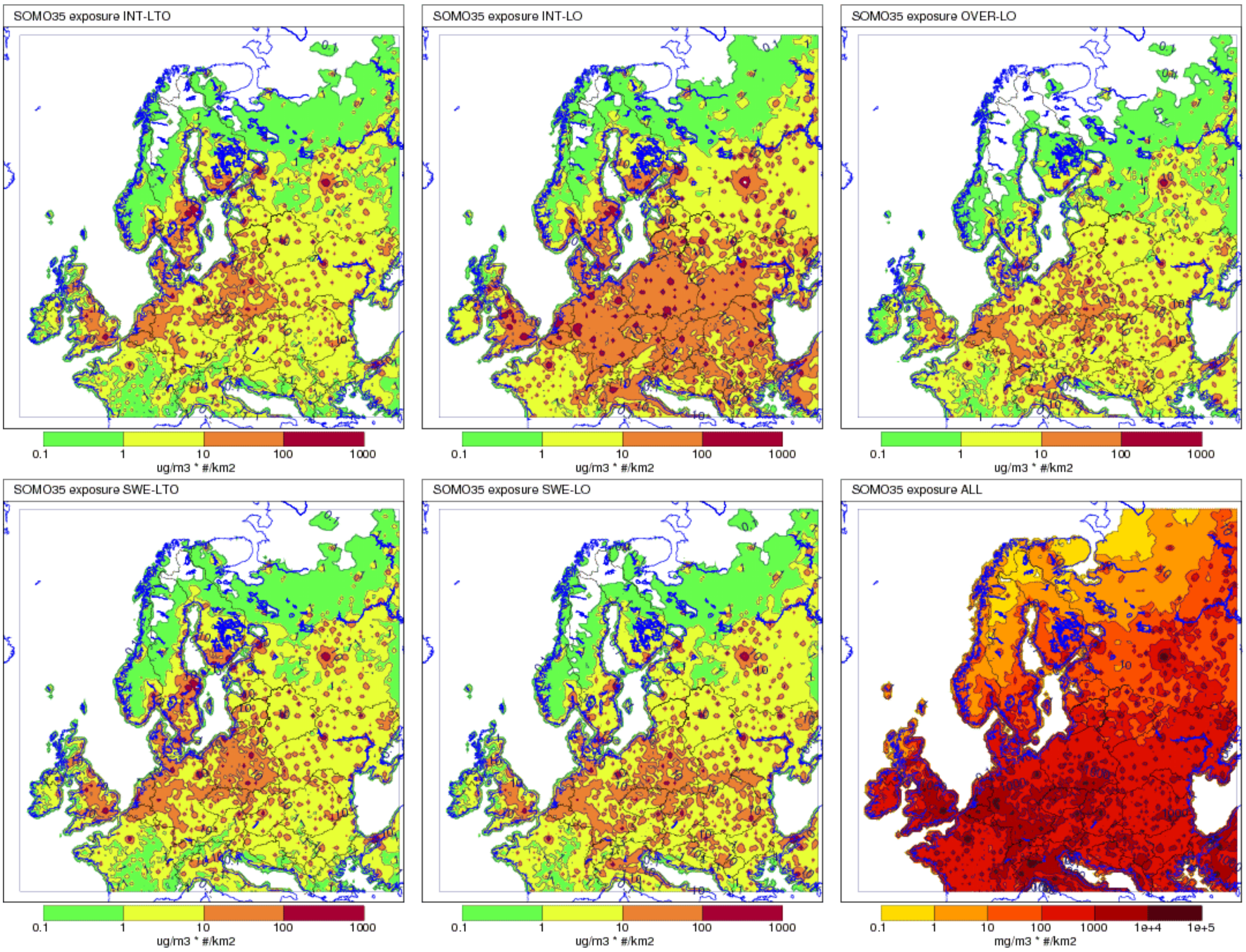

Figure 19: *SOMO35 exposures for year 2012-2014.*

C Nitrate and sulfate concentrations

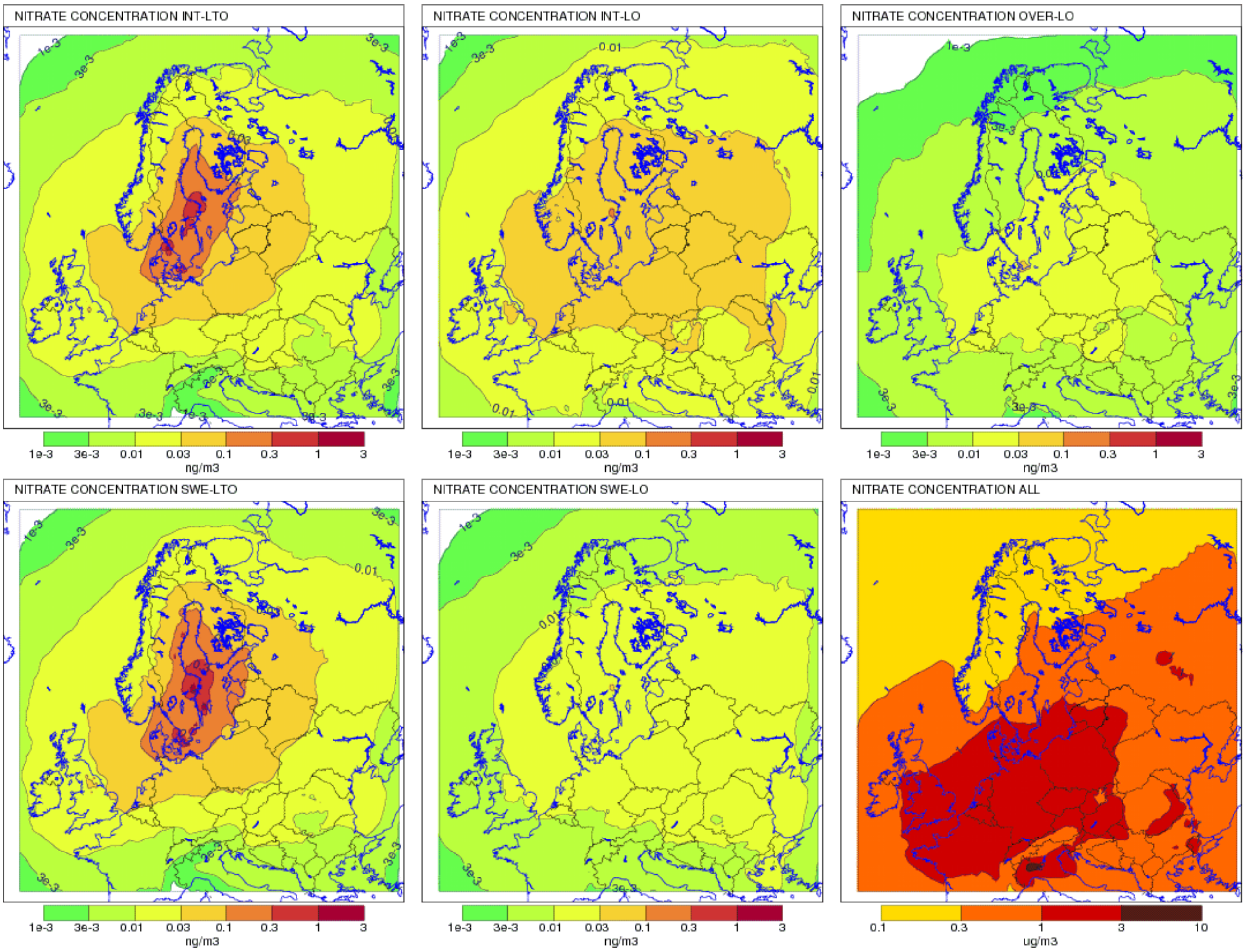

Figure 20: *Yearly mean concentration of nitrate for year 2012-2014.*

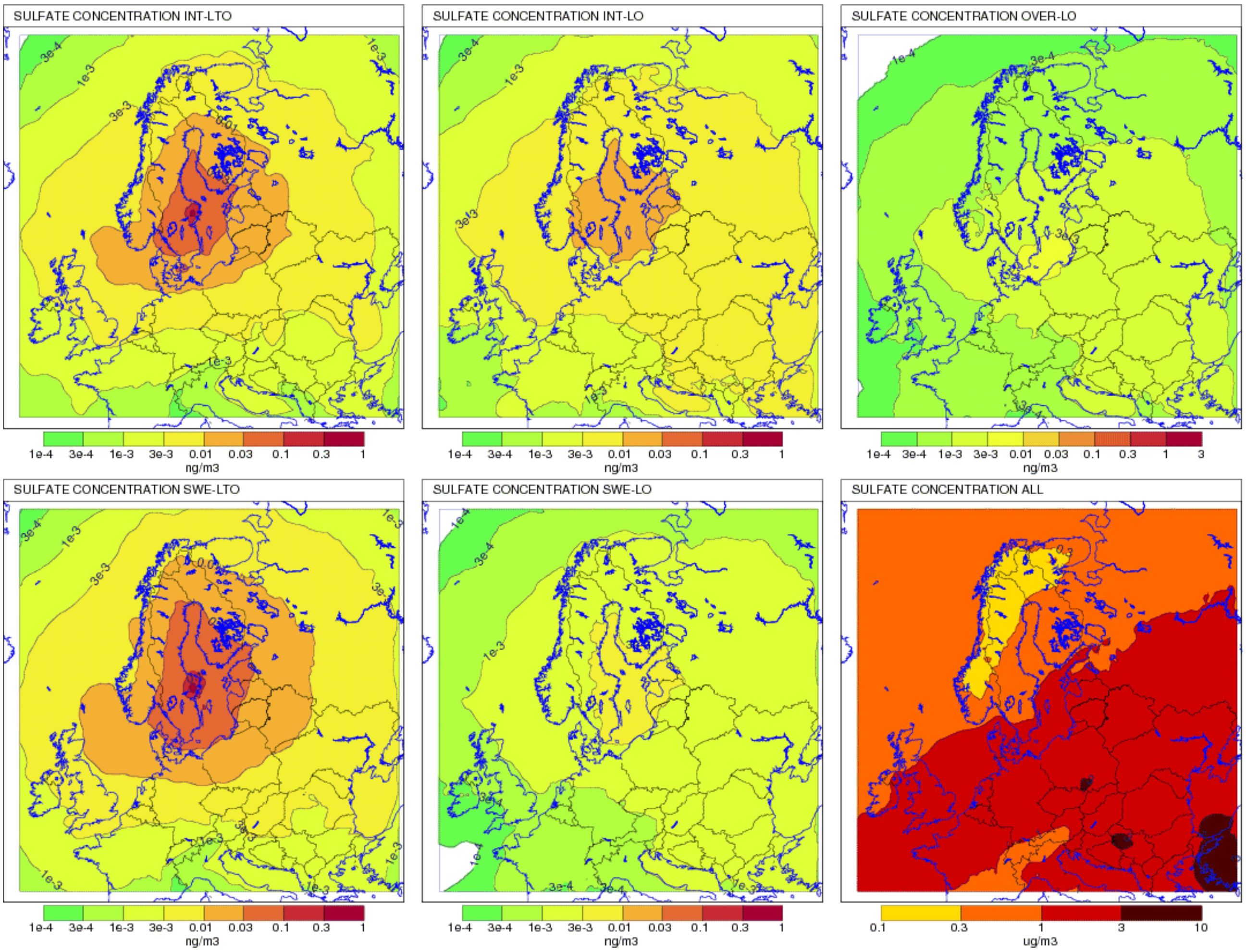

__Figure 21:__ Yearly mean concentration of sulfate for year 2012-2014.

D Ozone concentrations

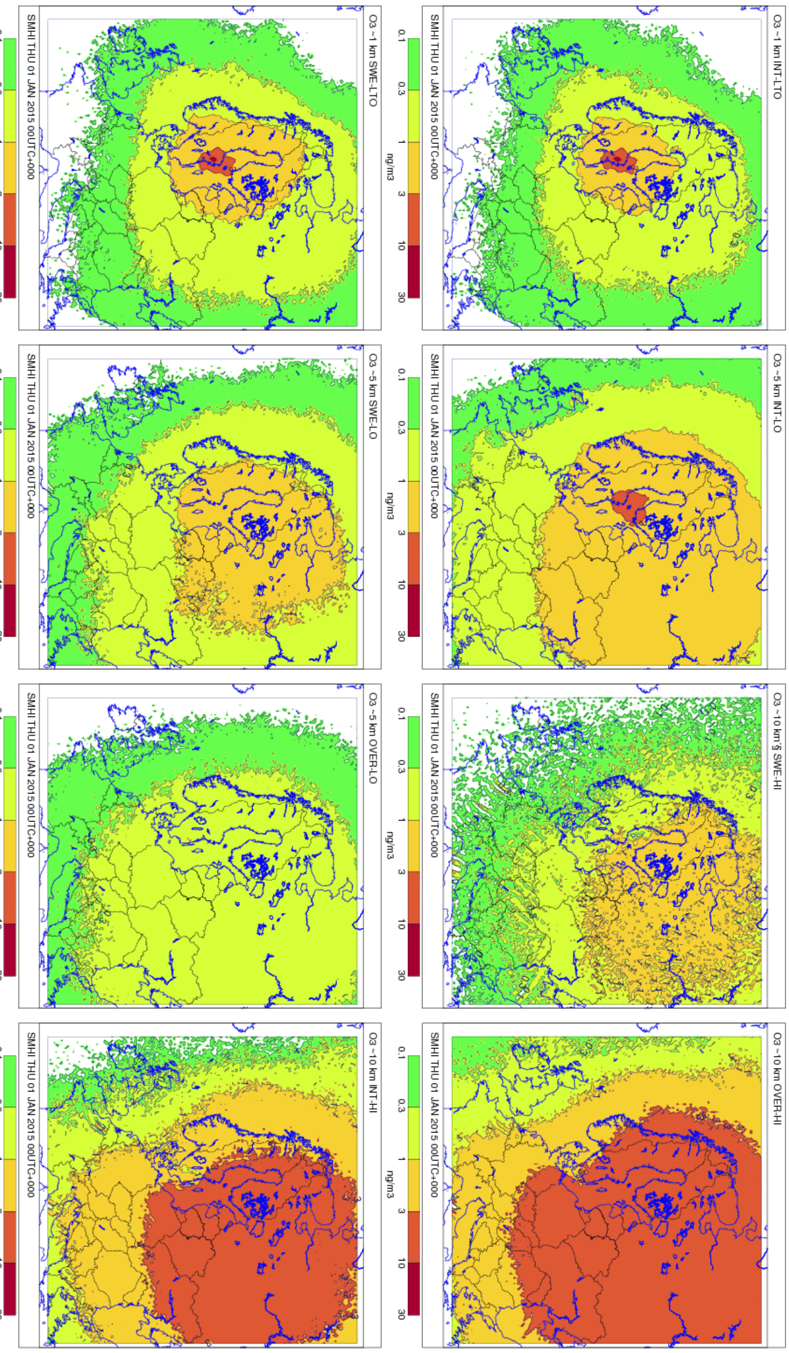

Figure 22: Three year averaged ozone concentrations at different levels for the simulations which included all emitted species from aviation.

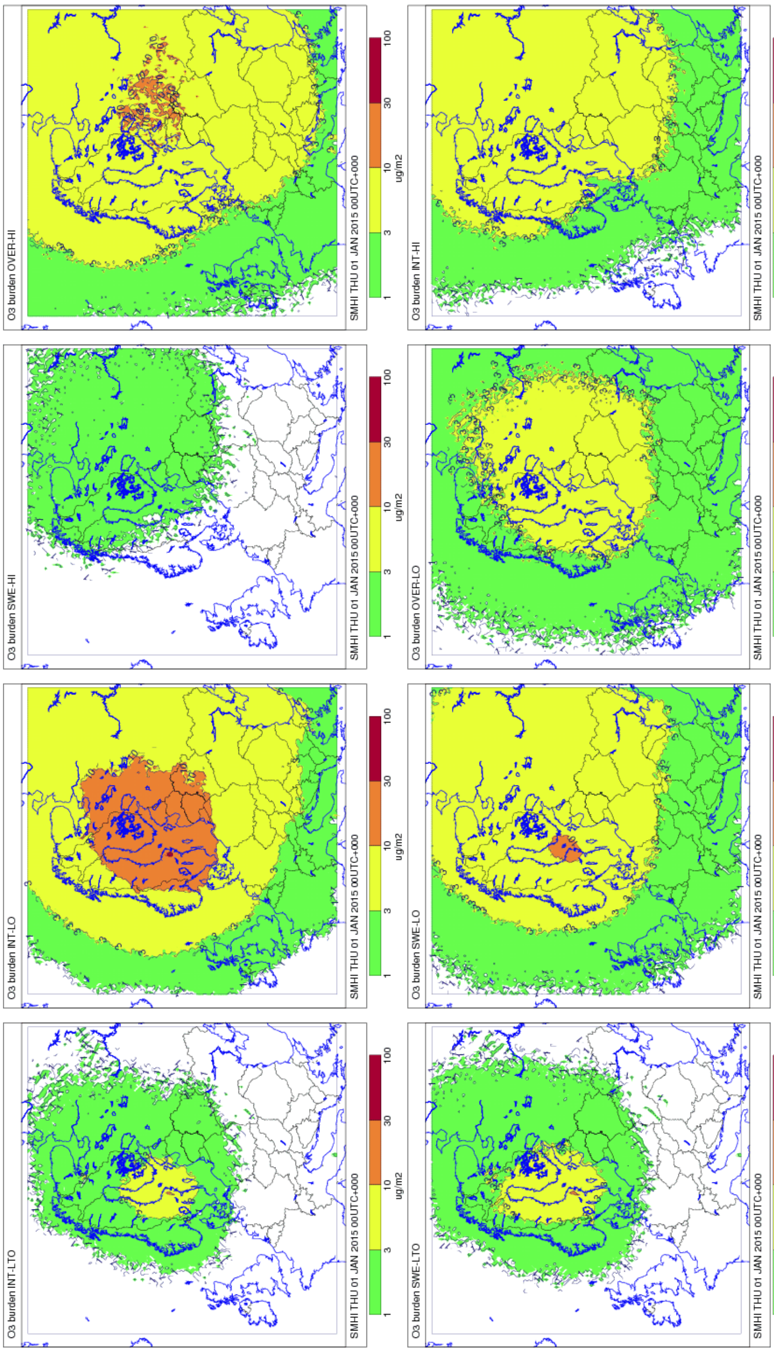

Figure 23: *Three year averaged vertically integrated ozone for the simulations which included all emitted species from aviation.*

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