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MACC regional multi-model ensemble simulations of birch pollen dispersion in Europe

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Abstract

The paper presents the first-ever ensemble modelling experiment for the birch pollen in Europe. The 7-models strong European ensemble of MACC-ENS, tested in trial simulations over the season of 2010, has been run through the season of 2013. The simulations have been compared with observations in 11 countries, members of European Aeroallergen Network, for both individual models and the ensemble mean and median. It is shown that the models successfully reproduced the timing of the very late season of 2013, generally being within a couple of days from the observed season start. End of the season was generally predicted later than observed, for 5 days or more, which is a known feature of the source term used in the study. Absolute pollen concentrations during the season were somewhat under-estimated in the southern part of the birch habitation area. In the northern part of Europe, a record-low pollen season was strongly over-estimated by all models. Median of the multi-model ensemble demonstrated robust performance, successfully eliminating the impact of outliers, which was particularly useful since for most of models this was the first experience of pollen forecasting.

1 Introduction

During the last 30 years, the prevalence of airborne allergy and asthma in Europe has increased 4-fold reaching 15–40 % of population. According to the European Federation of Allergy and Airway Diseases Patients Associations, 80 million (24.4 %) of adults living in Europe are allergic. The allergy prevalence in children is 30–40 % and increasing (Laatikainen et al., 2011; Rönmark et al., 2009). Allergy to various types of pollen in the air, exacerbated by co-exposure to chemical pollutants and fine aerosols, is the number-one chronic disease in Europe, overshadowing allergy to house dust mite and affecting over 20 % of the population (Bousquet et al., 2007).

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Among the allergenic plants, grass and birch pollen affect about 40 and 25 % of all hay fever sufferers in Europe, respectively (Heinzerling et al., 2009). Birch is a strong allergy-provoking plant with population-wide sensitization of approximately 15 % (WHO, 2003). The distribution of silver birch (*Betula pendula* Roth.) and downy birch (*B. pubescens* L.) extends from mountains in temperate climate of Southern Europe to Fennoscandia and Siberia (Atkinson, 1992; OECD, 2003).

It is long since known that the bulk of pollen is deposited near the source plant (Raynor et al., 1970; Tampieri et al., 1977; Wright, 1953, 1952). However, birches, as well as other species (*Alnus, Carpinus, Corylus, Ostrya, Fagus, Quercus, Castanea*) belonging to the order Fagales, are wind-pollinated trees generating vast amounts of pollen to ensure sufficient level of fertilization of female flowers over receptor regions. Their pollen grains are sufficiently small and light to facilitate the transportation of up to 1 % of the released material over thousands of kilometres if weather conditions are suitable (Sofiev et al., 2006a). This phenomenon has been noticed in the middle of the previous century (Erdtman, 1937, 1935, 1931; Gregory, 1961). Later, it was recognised that the long-range transported pollen can have a substantial health impact (Viander and Koivikko, 1978) and facilitate a large-scale redistribution of genetic material (Lindgren et al., 1995). The pollen long-range transport is practically unpredictable with local observations or statistical models. However, until last two decades, no practical instruments were developed for its quantitative evaluation and forecasting.

Starting from 1990s, episodes of pollen dispersion at regional and continental scales were addressed in numerous studies (Belmonte et al., 2000; Corden et al., 2002; Damialis and Gioulekas, 2005; Hjelmroos, 1992; Latalova et al., 2002; Mahura et al., 2007; Ranta and Satri, 2007; Ranta et al., 2011; Rantio-Lehtimaki, 1994; Siljamo et al., 2008c; Skjøth et al., 2008; Sofiev et al., 2006a, 2012b; Yli-panula et al., 2009), see also reviews (Smith et al., 2014; Sofiev and Bergmann, 2013). It was shown that, although the features of each specific long-range transport episode vary widely, there may be a systematic pattern in the springtime pollen redistribution in Europe with prevailing transport directions, main source and receptor regions, etc. There were several

attempts to reveal such a pattern via a multi-annual analysis (Sofiev et al., 2006a; Siljamo et al., 2006, 2008; Skjøth et al., 2007, 2008, 2009; Damialis and Gioulekas, 2005; Stach et al., 2007; Smith et al., 2008; Yli-panula et al., 2009b) but the picture is still largely incomplete.

The main tool for analysing the pollen distribution at regional and continental scales is numerical modelling that combines phenological models covering the pollen maturation and presentation (the pollen source term) with the atmospheric dispersion model. To-date, there exist four comparatively independent formulations of the source terms for birch pollen. The European-scale source term used in the current study was developed for System for Integrated modeLling of Atmospheric coMposition (SILAM) by an international consortium within the scope of the POLLEN project of Academy of Finland (Siljamo et al., 2012; Sofiev et al., 2012a). Various versions of the model have been used for forecasts of pollen distribution in Europe starting from 2005 (Sofiev et al., 2006a) and reanalysis of the flowering seasons back to 1997 (Siljamo et al., 2008c; Veriankaitė et al., 2010). The COSMO-ART birch module has been developed at the University of Karlsruhe (Helbig et al., 2004; Vogel et al., 2008) and MeteoSwiss (Pauling et al., 2012; Zink et al., 2013) and is presently used for pollen forecasting for Central and South Western Europe. Development is also going on in Denmark with the regional ENVIRO-HIRLAM system (Mahura et al., 2009) applied for forecasting over Northern Europe. Finally, combining the COSMO-ART and SILAM source terms, Efstathiou et al. (2011) developed a regional-scale model for the US and applied it to birch and ragweed.

The MACC (Monitoring of Atmospheric Composition and Climate, http://www.gmes-atmosphere.eu) pollen simulations are based on the SILAM source term. Its formulations and input data have been shared among the seven regional modelling teams of MACC and, in co-operation with European Aeroallergen Network (EAN), set into operational multi-model ensemble forecasting of birch pollen in Europe.

The goal of the current paper is to present the results of the first ensemble modelling of birch pollen in Europe during the season of 2013.

The next section shall present the models and setup of the simulations, as well as the observation data used for evaluation of the model predictions. The Results section will present the outcome of the simulations, quality scores of the individual models and the ensemble. The Discussion section will be dedicated to analysis of the results, considerations of efficiency of the multi-model ensemble for pollen, and identification of the most-pressing development needs.

2 Materials and methods

This section presents the regional models used in the study, outlines the birch pollen source term implemented in all of them, and introduces the pollen observations used for evaluation of the model predictions.

2.1 Dispersion models

The dispersion models used in the study comprise the MACC-II European ensemble, which is described in details in Marecal et al. (2014, GMD MACC special issue). Below, only the model features relevant for the pollen transport calculations are described.

The ensemble consisted of seven models.

CHIMERE is an Eulerian regional-scale chemistry-transport model for gaseous and aerosol species (Menut et al., 2013). Pollen is implemented as a special aerosol with a prescribed species-specific size (currently birch or ragweed) between 20 and 22 µm and density prescribed at 800 and 1050 $kg\,m^{-3}$, respectively. The resulting gravitational settling velocity is 1.2–1.3 $cm\,s^{-1}$. The transport processes affecting pollens, such as advection, turbulent mixing, and wet deposition, are implemented in the same way as for other aerosols. The dry deposition is described via gravitational settling only, which is dominating for pollens (Sofiev, 2006a), whereas resuspension is parameterized following Helbig et al. (2004).

EMEP is a chemical transport model described by Simpson et al. (2012). It is flexible with respect to the choice of projection and grid resolution. Dry deposition is handled in the lowest model layer. A resistance analogy formulation is used to describe dry deposition of gases, whereas for aerosols the mass-conservative equation is adopted from Venkatram (1978) with the dry deposition velocities dependent on the land-use type. Wet scavenging is dependent on precipitation intensity and is treated differently within and below cloud. The below-cloud scavenging rates for particles are calculated based on Scott (1979). The rates are size dependent, growing for larger particles.

EURAD-IM is an Eulerian meso-scale chemistry transport model involving advection, diffusion, chemical transformation, wet and dry deposition and sedimentation of tropospheric trace gases and aerosols (Hass et al., 1995; Memmesheimer et al., 2004). It includes 3d-var and 4d-var chemical data assimilation (Elbern et al., 2007) and is able to run in nesting mode. The positive definite advection scheme of Bott (1989) is used to solve the advective transport and the aerosol sedimentation. An Eddy diffusion approach is applied to parameterize the vertical sub-grid-scale turbulent transport (Holtslag and Nieuwstadt, 1986). Dry deposition of aerosol species is treated size dependent using the resistance model of Petroff and Zhang (2010). Wet deposition of pollen is parameterized according to Baklanov and Sorensen (2001).

LOTOS-EUROS is an Eulerian chemical transport model (Schaap et al., 2008). The advection scheme follows Walcek and Aleksic (1998). The dry deposition scheme of Zhang et al. (2001) is used to describe the surface uptake of aerosols. Below-cloud scavenging is described using simple scavenging coefficients for particles (Simpson et al., 2003).

MATCH is an Eulerian multi-scale chemical transport model with mass-conservative transport and diffusion based on a Bott-type advection scheme (Langner et al., 1998; Robertson and Langner, 1999). For birch pollen, dry deposition is mainly treaded by sedimentation and a simplified wet scavenging scheme is applied. The temperature sum from March onwards, driving the birch pollen emission, is determined outside the model and fed into the emission module.

MOCAGE is a multi-scale dispersion model with grid-nesting capability (Josse et al., 2004; Martet et al., 2009). The semi-lagrangian advection scheme of Williamson and Rasch (1989) is used for the grid-scale transport. The convective transport is based on the parameterization proposed by Bechtold et al. (2001) whereas the turbulent diffusion follows the parameterization of Louis (1979). Dry deposition including the sedimentation scheme follows Seinfeld and Pandis (1998). The wet deposition by the convective and stratiform precipitations is based on Giorgi and Chameides (1986).

SILAM is a meso-to-global scale dispersion model (Sofiev et al., 2008, see also the review Kukkonen et al., 2012). The Eulerian advection–diffusion core used in this study is based on algorithms of Galperin (2000); Sofiev (2002). The dry deposition scheme (Kouznetsov and Sofiev, 2012) is applicable for a wide range of particle sizes including coarse aerosols, which are primarily removed by sedimentation. The wet deposition parameterization distinguishes between sub- and in-cloud scavenging by both rain and snow (Sofiev et al., 2006b). For coarse particles, the impaction scavenging is dominant below the cloud. The model is capable of 3-D- and 4-D-VAR data assimilation (Vira and Sofiev, 2012), also applicable to birch.

ENSEMBLE models were generated of arithmetic average and median calculated out of 7 model fields for each hour.

2.2 Birch source term

All models of this study are equipped with the same birch pollen source term (Sofiev et al., 2012a) verified for the season of 2006 by Siljamo et al. (2012). The formulations and input data are open at http://silam.fmi.fi/MACC. The main input dataset is the birch habitat map compiled by Sofiev et al. (2006a) with the spatial resolution of $0.5° \times 0.5°$ longitude–latitude. The birch productivity is assumed to be the same in all years and equal to 10^9 pollen m^{-2} season^{-1}.

The flowering description follows the concept of Thermal Time phenological models and, in particular, the double-threshold temperature sum approach of Linkosalo et al. (2010) modified by Sofiev et al. (2012a), which determines the flowering prop-

agation during the whole spring season. Within that approach, the heat accumulation starts at some day in spring (1 March in the current setup) and continues throughout the season. Flowering starts when the accumulated heat reaches the starting threshold and continues until the heat reaches the ending threshold. The rate of heat accumulation is the main controlling parameter for pollen emission: the model establishes direct proportionality between the flowering stage and fraction of the heat sum accumulated to-day.

Apart from temperature, the pollen release rate is modulated by ambient humidity, precipitation, and wind speed. Higher humidity and rain reduce the release, completely stopping it for RH > 80 % and/or rain > 0.1 mm h^{-1}. Strong wind promotes it by up to 50 %. Atmospheric turbulence is taken into account via the turbulent velocity scale and thus becomes important only in cases close to free convection. In stable or neutral stratification and still conditions the release is suppressed by 50 %.

Local-scale variability of the flowering results in necessity to include probabilistic description of the flowering propagation (Siljamo et al., 2008b). In the simplest form, the probability of an individual tree to enter the flowering stage can be considered via uncertainty of the temperature sum threshold determining the start of flowering for the grid cell.

The end of the season is described via the open-pocket principle: the flowering continues until the initially available amount of pollen is completely released.

2.3 Pollen observations

The observations for the model evaluation in 2013 have been provided by the following members of European Aeroallergen Network EAN: Austria, Estonia, Germany, Finland, France, Latvia, Lithuania, Russia, Spain, Switzerland, and Ukraine. Additionally, the data for the initial model testing for the season of 2010 were provided by Austria, Finland, Germany, Latvia, Lithuania, Russia, Spain, Switzerland, and Ukraine. In-total, the information of 165 sites in 2010 and 186 sites in 2013 was made available to the modelling teams. Among these, 21 stations in mountain valleys of Alps and Pyrenees

were flagged as not representative at the regional scale and excluded from the analysis (see Sect. 4). The analysis below is concentrated on the season of 2013 as the data of 2010 were mainly used for setting-up and verifying the pollen source term implementations. However, comparison of these years is used to illustrate the variability of pollen seasons and models ability to reproduce it.

Pollen monitoring was performed with Burkard 7 day and Lanzoni 2000 pollen traps of the Hirst design (Hirst, 1954). The pollen grains were collected at an airflow rate of $10\,L\,min^{-1}$. The observations covered the period from March to September, with some variations between the countries. Daily observations were used. Following the EAN recommendations (Galán et al., 2014; Jäger et al., 1995), most of samplers were located at the height from 10 to 30 m on roofs of the suitable buildings. The places were frequently downtown of the cities, i.e. largely represent the urban-background conditions (not always though). With regard to microscopic analysis, the EAN recommendation is to count at least 10 % of the sample using horizontal or vertical strips (Galán et al., 2014). The actual procedures vary between the countries but generally comply. The counting in 2013 was performed along 12 vertical strips (in most countries), 2 to 4 horizontal traverses (Switzerland, Spain), or using a bi-hourly stratified random sampling (Finland) (Mandrioli et al., 1998). In all cases, the data were expressed as mean daily concentrations (pollen m^{-3}).

2.4 Setup of the simulations

Simulations followed the standards of MACC regional ensemble (Marecal et al., 2014, GMD MACC special issue). The domain spanned from 25° W to 45° E and from 30 to 70° N. Each of the 7 models was run with its own horizontal and vertical resolutions, which varied from 0.1° to 0.25° of the horizontal grid cell size, and had from 3 up to 52 vertical layers within the troposphere (Table 1). This range of resolutions is not designed to reproduce local aspects of pollen distribution, instead covering the whole continent (the MACC domain spans from 25° W to 45° E and from 30 to 70° N) and describing the large-scale transport events.

In the forecasting regime during the spring of 2013, the simulations time range was 96 h from 00:00 UTC of the Day 0 (D0) with hourly output on 8 vertical levels (surface, 50, 250, 500, 1000, 2000, 3000 and 5000 m). After the end of the season, it was re-analyzed by most of the models to correct technical problems experienced in the forecasting regime. For the re-analysis simulations (discussed in this paper), the models were run through the whole period without separation to individual forecast cycles. For those models that were not rerun, the first 24 h of each forecast were picked. In all cases, only near-surface concentrations were analyzed.

All models considered pollen as an inert water-insoluble particle 22 µm in diameter and density of 800 kg m^{-3}.

3   Results for the flowering season of 2013

3.1   Observed peculiarities of the season

The season of 2013 had three major specifics, which distinguished it from "typical" pollen seasons and, in particular, from the training year of 2010:

 – Cold spring resulted in late flowering. In Central Europe, the flowering started up to 2–3 weeks later than usual. For instance, in Switzerland, it was among the latest years since 1993 (at 5 stations, the latest), 9 days later than in 2010. In Moscow, the cold start of the spring was compensated by its faster progression, so that the early-flowering alder was shifted for about 2 weeks but the birch season was delayed by only a few days. In Lithuania, however, the season started 10 days earlier than in 2010, almost simultaneously with France, which was probably caused by early long-range transport event(s).

 – The season was short, up to a week shorter than usually. Thus, in Switzerland it lasted for ∼ 30 days (22–35 for different stations) as compares with 37 days of the

long-term average. In Finland, the difference between the season length in 2010 and in 2013 reached a factor of 2.4.

– Anomalously low pollen season was recorded in Northern Europe and Russia. The Seasonal Pollen Index (the sum of daily pollen concentrations over the whole season, SPI) was 10–1000 times lower than in 2012 and about 10 times weaker than in 2010 (that year was comparatively usual). The SPI in Central Europe was moderate, which resulted in inverse load pattern: the SPI in the north was tens of times lower than that in the central regions.

These peculiarities posed substantial challenges to the models. The phenological model of the source term has the mechanism that accounts for the season shift though it still went beyond the verified range. The season strength, however, is currently not a predicted quantity, which made it impossible to capture the anomalously low season in the north.

3.2 Model results

All models predicted quite standard load pattern for the seasonal pollen index (Fig. 1). Its maximum is located over Central Russia and Fennoscandia and the SPI gradually decreases towards the south-west. In Central Europe, there is a substantial inhomogeneity of the SPI, which reflects the patchy birch habitat in the region.

Comparison with the observed pollen index shows the challenge mentioned above: the very low observed concentrations in the north that were not reproduced by the models (Fig. 2, model predictions are overlaid by the observations – circles colored following the same palette). This is in contrast with the previous years, in particular, 2010, when the observed and modelled patterns were both typical and agreeing very well (see example for SILAM, Fig. 3).

An example of the hourly concentrations at noon of 20 April 2013 is shown in Fig. 4. It depicts the middle of the season in Central and Eastern Europe. The models also

showed the long-range transport of pollen to the south that reached Africa in most predictions.

Propagation of the season is illustrated in Fig. 5, which depicts 5-days-mean concentrations predicted by the ensemble median for four time moments: 1–5 April, 20–25 April, 10–15 May and 1–5 June. The season propagation in 2013 was quite usual, from south-west to north-east of the continent, though delayed by up to two weeks due to cold slow spring. The models successfully reproduced this development.

Primary parameters describing the season are its start and end days, often defined as the dates when 5 and 95 % of the cumulative seasonal pollen counts are reached, respectively (Fig. 6). Outside the main source areas, the season timing is almost completely dictated by the episodes of pollen long-range transport, similar to the southern blow shown in Fig. 4. The "fingerprints" of the plumes bringing the first pollen to the regions and those concluding the season are well seen in Southern Europe, where Spanish stations show presence of pollen almost as long as in Finland.

Considering the model-measurement comparison statistics, one has to keep in mind that the time series of pollen concentration represent strongly non-stationary and non-ergodic process, i.e. the usual statistics (bias, RMSE, correlation, etc, all relying on the process stationarity and ergodicidy) can be computed only within the main season and even then have to be taken with care. A series of such "standard" statistics was computed for the ensemble (Fig. 7), as well as for all individual models (Fig. 8).

4   Discussion

Within this section, we consider: (i) ability of the model ensemble to predict the key features of the pollen season, (ii) major uncertainties of the current ensemble, (iii) specific features of the individual ensemble members, (iv) parameters of the season, for which the use of the ensemble predictions are the most-beneficial in comparison with single-model simulations.

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4.1 Model predictions for the key parameters of the 2013 birch pollen season

The parameter of primary importance for the users of pollen forecasts is the season start. Comparison of the panels of Fig. 6, as well the upper-left panel of Fig. 7, demonstrate that the ensemble captured the season onset over majority of Central and Western Europe with an error or just a couple of days. This is in agreement with the source term evaluation by Siljamo et al. (2012).

Both in the north (Finland and Baltic States) and in Spain the pattern is very irregular: the error of the season start at the stations located few hundreds of kilometres from each other can differ by more than a week. The main reason of such inhomogeneity is that the season start over these areas was largely decided by remote sources in Central Europe and long-range transport. A single episode affecting or passing by the station can result in a few weeks of the apparent-season shift.

The end of the season is more uncertain: the concentrations usually fall slower at the season end than grow at its start, with substantial small-scale variability unresolved by the continental-scale simulations. As seen from the Fig. 6, the error usually stays within some 5 days, but also can reach several weeks, especially in the mountainous regions (Pyrenees, Alps). Fortunately, this parameter is also less important for practical applications.

Representation of the absolute concentrations strongly varies over the continent (Fig. 7). In its central part (Germany, Austria, part of France), there is a slight underestimation. In southern France and Spain, it gradually turns to a slight over-prediction suggesting somewhat too long transport distance in the majority of the models. Finally, in the north, all models strongly over-predict. These tendencies are practically not dependent on the longitude: (few) available observation points in the east follow the same pattern: very slight over-prediction in Ukraine and substantial over-statement in Moscow. The RMSE largely follows the bias field (Fig. 7).

Correlation coefficient (Fig. 7) should be taken with care due to evident non-stationarity of the process. However, it also highlights Central and Western Europe (as

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well as part of Northern Europe) as the best predicted areas. Mountains are the most-difficult regions, along with the areas with few birch stands (Southern Europe), where the habitat map is highly uncertain. Northern Europe is usually a well-predicted area but not in 2013: as seen from Fig. 7, correlation of time series in the Baltic States and southern part of Finland is quite low. It is high only in Moscow and northern Finland.

4.2 Main uncertainties of the ensemble

From the above analysis, one can deduce the main sources of uncertainties of the presented multi-model ensemble: (i) missing inter-annual variability of the birch productivity, (ii) errors in the mountainous regions.

To-date, there is no model for year-to-year variation of the birch productivity. A few studies reported in literature – e.g., Masaka (2001), Ranta et al. (2008, 2005) – concentrate on predicting the seasonal pollen index, which is a different quantity, significantly affected by the current-year meteorological conditions. The total amount of pollen stored in catkins, to the contrary, is decided by the previous-year summer and, to some extent, the following winter conditions. The second complication is that the existing studies are based on limited number of observation points, which makes it difficult to generalize them to the continental scale. The work is on-going but so far the only way to obtain reliable absolute level of concentrations is via data assimilation performed retrospectively.

The large uncertainties in the mountains originate from the insufficient resolution of both meteorological and dispersion models. As an illustration, the time series for Zams station in Austria (one of the 21 sites flagged out of the comparison) shows that all models have shifted the season by several weeks: mid-June instead of late-April-early-May (Fig. 9). Some models also predicted peaks shortly before the season but these were the plumes from remote sources. This error is exacerbated by strong under-estimation of the absolute values. The reason for poor performance of all models is the complex-terrain environment with characteristic width of the valley of barely 2 km. Continental-scale dispersion models, as well as the global meteorological model, all

have resolution 10–20 times coarser than that (Table 1). As a result, the grid-cell-scale temperature is not representative for the valley bottom (it is biased low), which leads to late predicted start of the season. Moreover, pollen released at the bottom of the narrow valley is usually trapped inside it – in reality, – whereas in the models it is mixed over the whole grid cell, which leads to strong under-estimation despite the total released amount of pollen is reasonable.

4.3 Behavior of individual models

Following the MACC standards, the setup of the ensemble members is largely harmonized. The emission term was implemented in all models with minimal differences from the one described in (Sofiev et al., 2012a). The only known deviation was made in SILAM, where the pollen maturation and discharge were separated as two processes controlled by different environmental parameters, similar to (Prank et al., 2013; Zink et al., 2013). However, the impact of this variation at daily averaging is bound to be small. The other parameter that depended on the models was the thickness of the emission injection layer. The recommended layer was from the surface up to 50 m height but the model's geometry affected it.

Meteorological input data were the same – the IFS forecasts. Meteo data pre-processing was based on comparatively simple embedded diagnostic procedures embedded in all models, except for EURAD, which used WRF model nested into IFS. The tasks of the pre-processors were: (i) to derive the boundary layer characteristics missing from the IFS, (ii) for some models, re-diagnosing the vertical wind component or refining the 3-D wind fields to ensure satisfaction of continuity equation.

In that light, the differences between the model predictions visible at the Figs. 1, 4 and 8 should be mainly attributed to: (i) model treatment of the 3-D pollen transport, (ii) vertical mixing, (iii) removal mechanisms.

In general, the model results are quite similar and the main features of the pollen distribution are well visible in the individual-model patterns. In closer look, one can notice a few tendencies, such as: (i) higher-than-average concentrations predicted by EURAD,

(ii) lower-than-average values of MOCAGE, (iii) longer lifetime and farther atmospheric transport of CHIMERE, (iv) the shortest transport distance indicated by SILAM (Fig. 1), (v) about 10 % lower-than-others correlation coefficient of EMEP, EURAD and LOTOS-EUROS (Fig. 8), (vi) a general tendency of a couple of days early start of the season for most models except for CHIMERE (6 days too early season) and for EMEP and SILAM (1–2 days late season) (Fig. 8).

Interpretation of these tendencies is not unequivocal but some of them are connected. For instance, the season start is largely controlled by the long-range transport episodes, so that the model reporting the longest pollen transport (CHIMERE) predicts too early season start, especially in remote regions. Conversely, SILAM with its shortest travelling distance would report fewer such events, leading to later season onset. The same is true for EMEP, which also reported quite short transport distance. The high predictions of EURAD lead to somewhat higher RMSE and low predictions of MOCAGE – to lower RMSE, owing to the high bias of all the models in the north.

In a few cases, available observational information allows evaluation of these features. In particular, quick north-to-south reduction of observed seasonal pollen index in Spain (Fig. 2) suggests that the transport distance of pollen is indeed short (see also Fig. 3). This would also reduce the early-bias of the season start shown by most models. Secondly, about 10 % higher correlation coefficient of SILAM might possibly be attributed to the more articulated impact of local birch since the long-range effects are of lower importance for that model, owing to its short transport distance. These observations might be also projected to the resuspension process suggested by Helbig et al. (2004) but never explicitly verified or confirmed, as pointed out by Sofiev et al. (2012a). Among the 7 models, only CHIMERE included it, which may be one of the reasons for its longer transport distance. The above comparison raises further doubts regarding this process.

Evaluation of absolute concentrations is hardly conclusive due to the very specific season and overall uncertainty of this parameter.

4.4 Ensemble added value

Compilation of the multi-model ensemble out of individual models has proven beneficial. As seen from Fig. 8, ensemble median, together with the ensemble mean and SILAM, have the highest correlation coefficient. It also showed among the smallest shifts of the season start and among the smallest RMSEs. Its robustness to outliers also turned to be a very strong asset for pollen forecasting, which is a comparatively young area of modelling and which has many unknowns in the governing processes.

However, the ensemble can be only as good as the majority of the individual models. As follows from the rank histogram (the Talagrand diagram, Fig. 10, left panel), the current ensemble is not perfect. The diagram shows the generally under-estimating ensemble (tendency towards higher ranks of the observations), simultaneously with a fraction of observations being substantially over-estimated (0th rank is also frequent). The later feature is due to the northern sites (albeit few), but also due to southern Spanish stations, where the over-estimation is also systematic. Moderate under-estimation takes place mainly in Central Europe (Fig. 2), where most of the stations are located. However, even this imperfect ensemble outperformed most of the individual models.

Construction of the rank histogram for pollen faced a methodological problem: pollen concentrations long before and long after the flowering season are zero. One should also keep in mind quite high detection limit for the microscopic analysis (about $0.5\,\text{pollen}\,\text{m}^{-3}$ for daily mean), which increases frequency of observed zero concentrations. In 2013, about 15 % of observations and 10–15 % of model predictions were below this limit. For the all-zero cases (zero observations and below-detection-limit bulk/all of the models), determination of the observation rank is meaningless: the ensemble variance collapses and its mean perfectly matches the observations. Neither these cases can be ignored: they have clear physical meaning and manifest excellent ensemble behavior. Therefore, for such cases, the observation rank in Fig. 10 was picked as a random number from 0 to 7, i.e. it corresponded to a "perfect" ensemble. To illustrate the ensemble behavior when the observations were below the detection

limit, the histogram of the corresponding model values is shown in Fig. 10, right panel. As one can see, in over 80 % of zero observations models were also showing the concentrations below $0.5\,\text{pollen}\,\text{m}^{-3}$. Such peculiarity has to be kept in mind for future pollen-related ensembles.

5 Summary

The first-ever multi-model ensemble is created for predicting the concentrations of birch pollen in Europe. The ensemble is constructed of 7 European chemistry transport models of MACC and follows the main rules of MACC regional ensemble: the models share the same source term, use the same meteorological input, and cover the MACC domain with similar resolution.

The ensemble is evaluated against the observational data of European Aeroallergen Network for the year 2013 and the basic statistical indicators are computed for each individual ensemble member, as well as for the ensemble mean and median.

The ensemble has demonstrated good skills in predicting several main characteristics of the pollen season of 2013: the season start and propagation, the pollen distribution pattern in Central, Eastern, and Southern Europe, and characteristic concentrations over these regions. The season timing is captured despite the anomalously late flowering due to cold spring of 2013.

Representation of the pollen concentrations in Northern Europe, Baltic States and Central Russia was jeopardized by the anomalously low flowering intensity in 2013. As a result, all models have strongly over-estimated pollen levels there. This was in contrast with the usual pollen distribution pattern in Europe and with the quite typical year of 2010 reproduced much better.

The experiment has shown high added value of the ensemble. For most of participating models this was the first experience of pollen simulations, which affected the reliability of their results. The ensemble median proved to be robust to the outliers, fi-

nally showing among the highest correlation coefficients, one of the smallest errors in the season timing and RMSEs.

The main areas of improvement refer to the inter-annual variation of the birch productivity, as well as to the representation of the flowering timing in the complex-terrain conditions.

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Table 1. Setup of the simulations for the participating models.

Model	Horizontal grid	Vertical	Meteo input	Meteo grid	Meteo vertical
CHIMERE	$0.15° \times 0.15°$	8 levels up to 500 hPa	ECMWF IFS 00 operational forecast, internal pre-processor	$0.125° \times 0.125°$	IFS vertical
EMEP	$0.25° \times 0.25°$	20 levels up to 12 km	ECMWF IFS 00 operational forecast, internal pre-processor	$0.25° \times 0.125°$	IFS lvs 64–137 up to 100 hPa
EURAD	15 km on Lambert conformal proj.	23 layers up to 100 hPa	WRF based on ECMWF IFS	Same as CTM	Same as CTM
LOTOS-EUROS	$0.5° \times 0.25°$	3 dyn. layers up to 3.5 km, srfc layer 25 m	ECMWF IFS 00 operational forecast, internal pre-processor	$0.5° \times 0.25°$	IFS levels up to 3.5 km
MATCH	$0.2° \times 0.2°$	52 layers up to 7 km	ECMWF IFS 00 from MARS, internal pre-processor	$0.2° \times 0.2°$	IFS levels
MOCAGE	$0.2° \times 0.2°$	47 layers up to 5 hPa (7 in ABL)	ECMWF IFS 00 operational forecast, internal pre-processor	$0.125° \times 0.125°$	IFS levels 0–137 up to 0.1 hPa
SILAM	$0.15° \times 0.15°$	8 layers up to 6.7 km	ECMWF IFS 00 operational forecast, internal pre-processor	$0.125° \times 0.125°$	IFS levels 69–137 up to ~ 150 hPa

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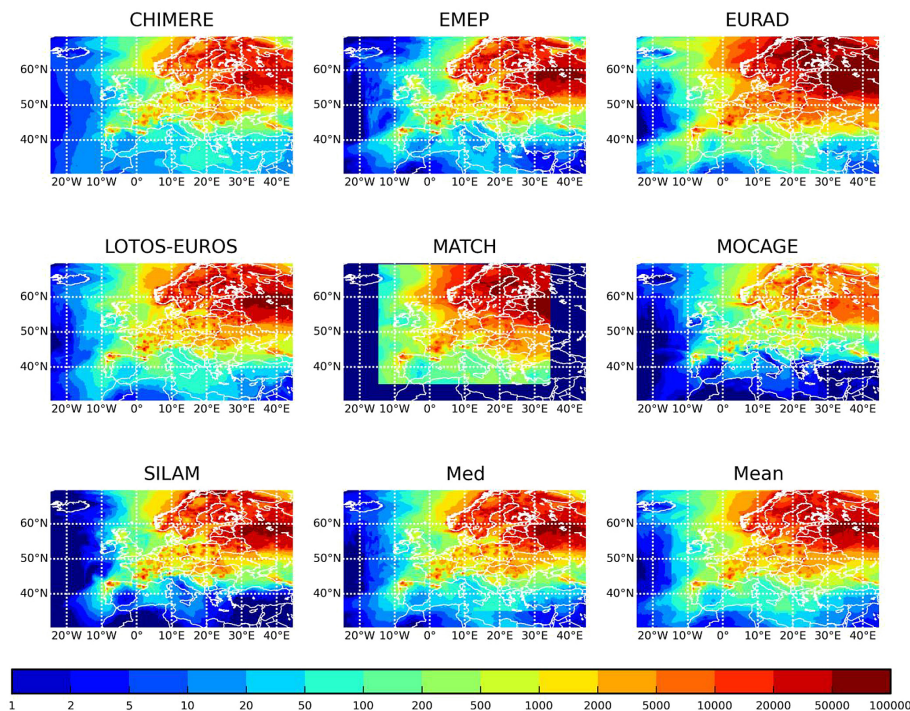
Figure 1. Seasonal pollen index (SPI, sum of daily concentrations), 2013, [pollen day m^{-3}].
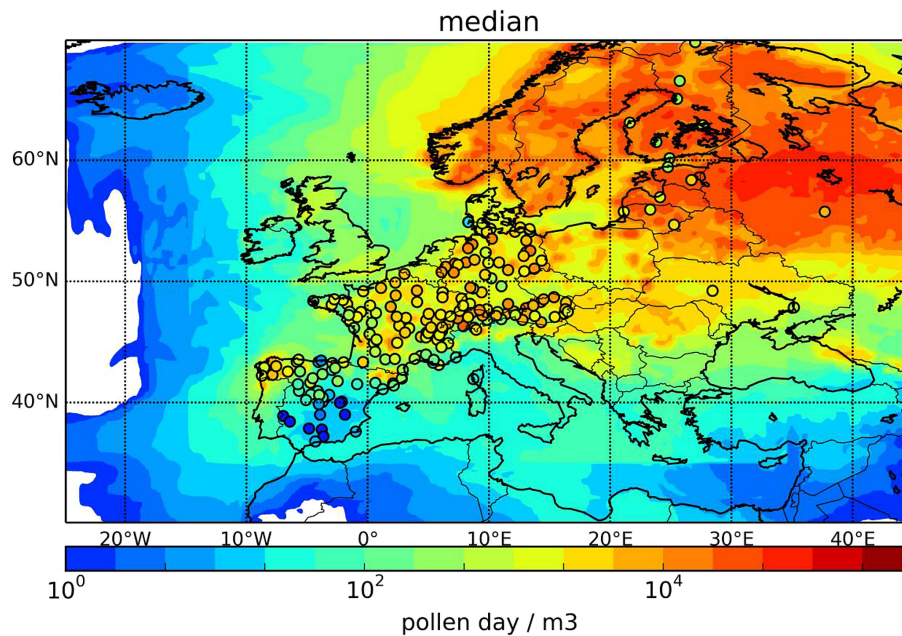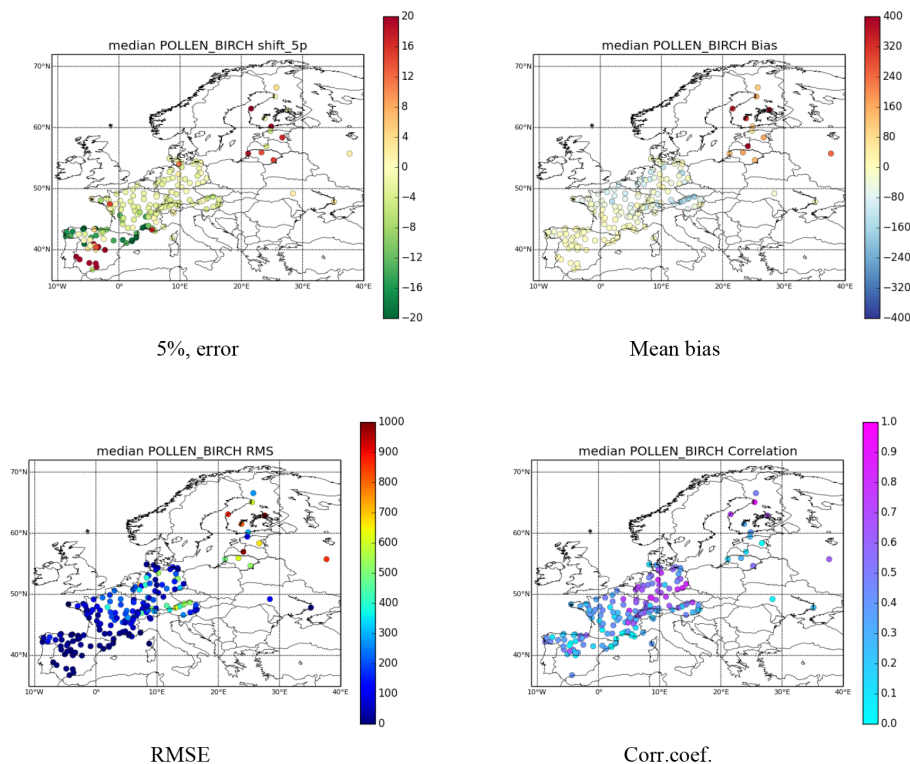
Figure 2. Comparison of SPI for the ensemble median with the observed pollen load, [pollen day m^{-3}].
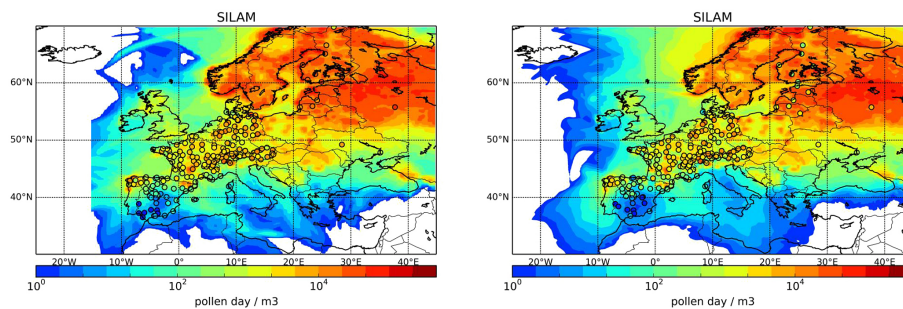
Figure 3. Seasonal pollen index in 2010 (left) and 2013 (right) observed at the EAN stations available for the study and predicted by SILAM.

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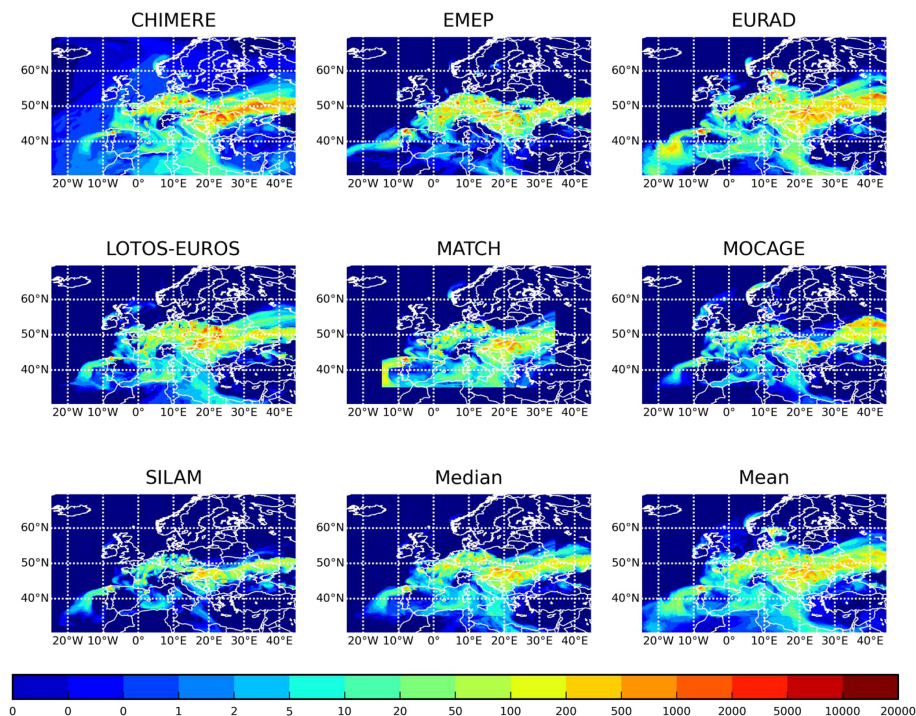
Figure 4. Example of hourly birch pollen concentration maps, 12:00 UTC 20 April 2013, [pollen m^{-3}].
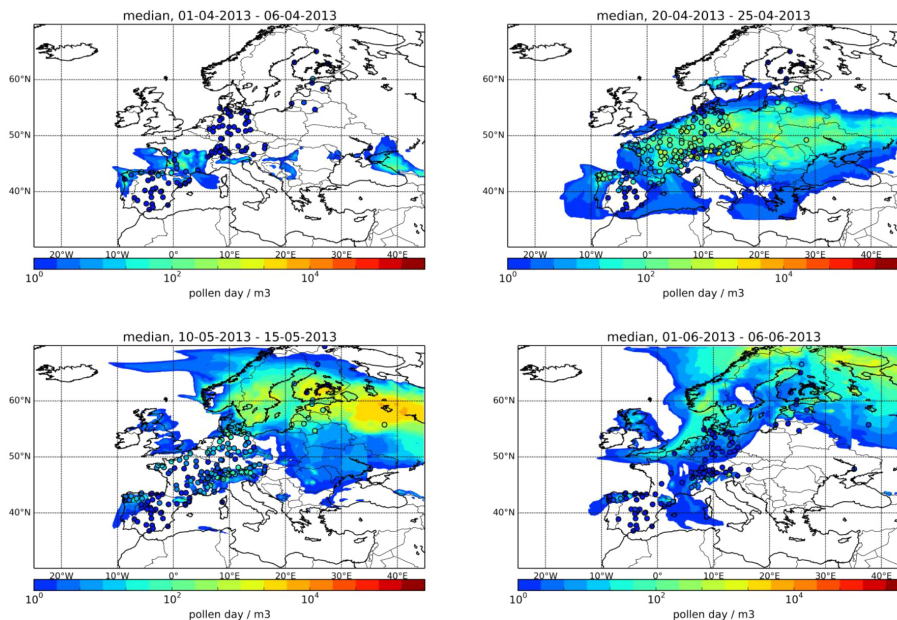
Figure 5. Season progression, the ensemble median and observations: 5-days mean pollen concentrations, [pollen m^{-3}].
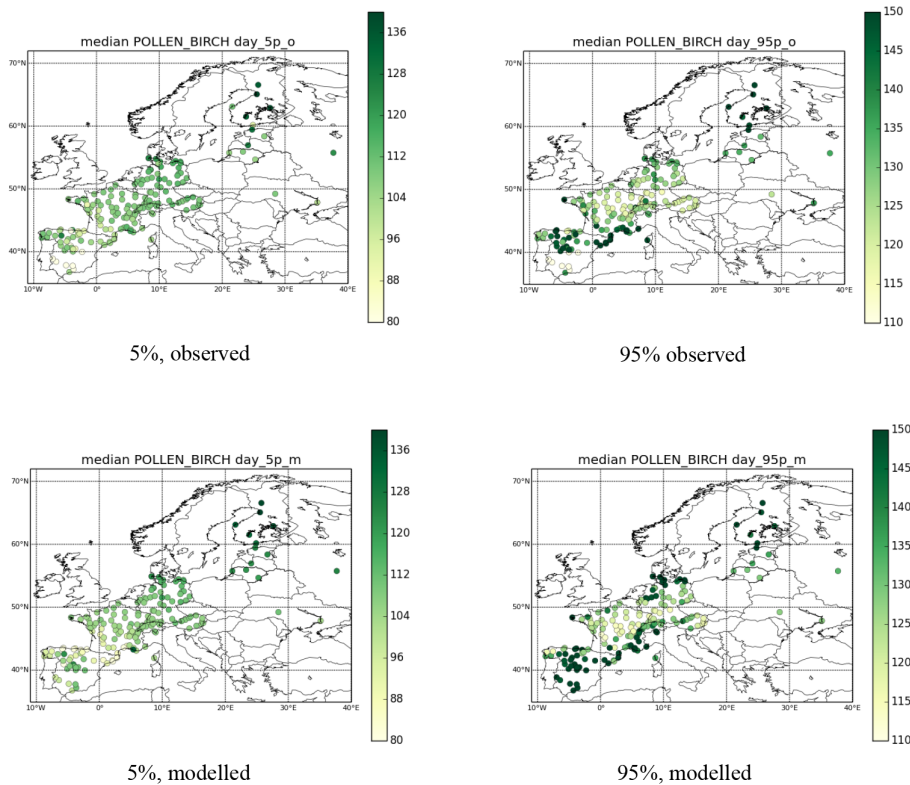
Figure 6. Start (left) and end (right) Julian days for the 2013 pollen season. Observed (upper row) and predicted by the ensemble median (lower row).

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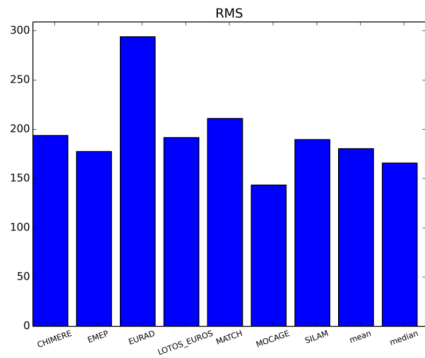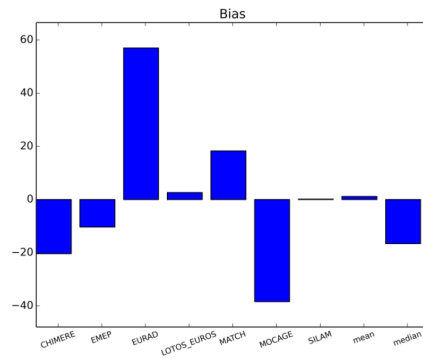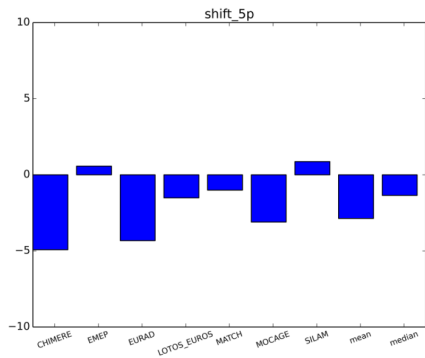Full Screen / Esc

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Figure 7. Results of model-measurement comparison for the ensemble median: error in the season start (upper left, days), season-mean bias (upper-right, pollen m^{-3}), RMSE (lower left, pollen m^{-3}), correlation coefficient for daily time series (lower right).
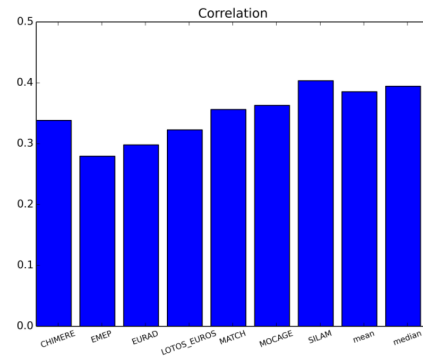
Figure 8. The scores of the individual models, mean over all stations. The same parameters as in Fig. 7.

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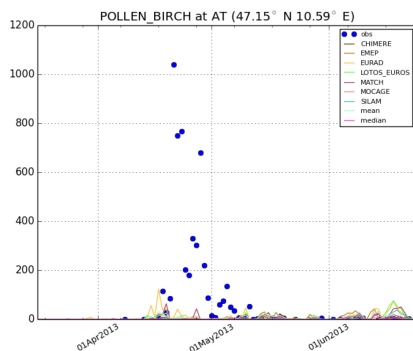
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Figure 9. Daily time series for Zams station in Austrian Alps (left, pollen m^{-3}), location of the station (yellow pin) in the 2 km-wide valley (right).

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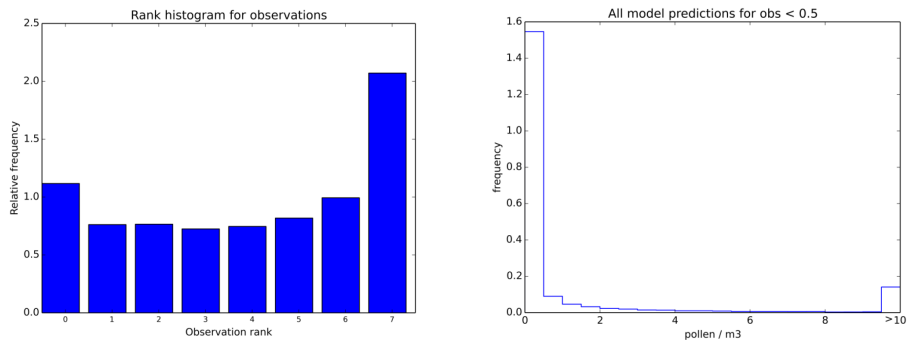
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Figure 10. Ensemble characteristics. Left: Talagrand diagram for the constructed ensemble (daily concentration statistics), right: histogram of model predictions when observations were below the detection limit $0.5\,\mathrm{pollen\,m^{-3}}$.