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Evaluating the potential of IASI ozone observations to constrain simulated surface ozone concentrations

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Abstract

A tracer study has been performed for two summers in 2003 and 2004 with a regional chemistry- transport model in order to evaluate the potential constraint that tropospheric ozone observations from nadir viewing infrared sounders like IASI or TES exert on modeled near surface ozone. As these instruments show high sensitivity in the free troposphere, but low sensitivity at ground, our study addresses which amount of this information is transferred to ground through vertical transport processes. Within the European model domain, and within a time span of 4 days, only ozone like tracers initialised in vertical layers above 500 hPa are transported to the surface. For a tracer initialised between 800 and 700 hPa, seven percent reaches the surface within one to three days, when averaging over the whole European model domain, but more than double of it over the Mediterranean sea. These results are confirmed by a second tracer study taking into account averaging kernels related to IASI retrievals.

1 Introduction

Since many years, ozone is one of the main targets of pollution control policy. Due to its harmful character for human health but also for vegetation and materials, many efforts are made to monitor and control its concentrations. This is one of the objectives of the Global Monitoring for Environment and Security (GMES) project (http://www.gmes.info), which aims at developing integrated systems to prevent population exposure to 1) sporadic pollutant's peak concentrations and 2) recurrent high level concentrations of pollutants. In case of ozone, this requires 1) short-term forecasts to prevent exposure to heavy polluted events and to reduce punctually emissions of primary pollutants (nitrogen oxides, NO_x, and volatile organic compounds, VOC) and 2) definition of a mitigation policy and controlling its efficiency to reduce long-term exposure to high-level ozone concentrations.

Regional Chemistry-Transport Models (RCTM) can meet such requirements. Performances of these models to simulate ozone concentrations have been significantly increased in recent years. As a consequence, RCTM can now be used operationally to control and to define mitigation scenarios with prospect of reducing surface ozone concentrations. For example, the PREVAIR platform (www.prevair.org) uses two such models (CHIMERE and MOCAGE) for operational forecast of ozone and particulate concentrations (Honoré et al., 2008). Honoré et al. (2008) have compared simulated ozone concentrations to ground-based measurements for three spring/summer periods between 2004 and 2006. They showed that the mean model bias of daily ozone maxima was mostly under 5 μg m^{-3}, RMSE (root mean square error) was generally less than 20 μg m^{-3} and temporal correlation was more than 0.8 on average in Western Europe.

Nevertheless, uncertainties remain in such models. Indeed, some processes or forcings controlling ozone concentrations can still not be or are badly represented. This is the case for primary pollutant emissions, transport (especially turbulent transport), chemistry (representation of VOC's), photolysis rates (impact of aerosols and clouds), wet and dry deposition, and chemical boundary conditions. This is illustrated by the fact that comparisons between measured and modeled values of hourly ozone concentrations are worse than comparisons of daily maxima (Honoré et al., 2008; Szopa et al., 2009), or the difficulties of the model to correctly predict alert or information threshold for ozone above respectively 180 and 240 μg/m^3 respectively (Honoré et al., 2008). Considering socio-economical implications of decisions based on results from such modeling (reducing industrial production and/or motor flow), their reliability should be improved.

Data assimilation using surface ozone and other surface measurements has shown to partly correct model deficiencies (Blond and Vautard, 2004). However, these studies have shown that the set of available observations could be a limitation, and that added information decays quickly in time (at a time scale of about half a day), because fresh air masses are rapidly transported into the regional domain. Using satellite derived ozone profiles should allow us to improve this issue, because spatial coverage is in-

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creased and observations are not restricted to the surface. This is especially true for the new generation of nadir viewing infrared (IR) sounders with high spectral resolution that provide tropospheric ozone with about one to two independent pieces of information in the vertical (IMG, Coheur et al., 2005; TES, Beer et al., 2006; IASI, Clerbaux et al., 2007). In case of the IASI instrument, Europe is sampled twice a day, the horizontal resolution of observed pixels at sub satellite point is less than 20 km×20 km, and partial tropospheric column can be derived. Comparing the 0–6 km tropospheric columns of ozone retrieved from IASI observations to ozone sonde measurements, Eremenko et al. (2008) have shown that the retrieved lower tropospheric ozone partial columns are fairly consistent with ozone sonde measurements (mean bias ~3%) even for most northern stations where temperature conditions are less favourable for retrieving the 0–6 km columns. Nevertheless, IR nadir viewing instruments exhibit weak sensitivity to surface and to planetary boundary layer (PBL) ozone concentrations as indicated by the shape of the averaging kernels calculated for these instruments, but large sensitivity to free tropospheric ozone (Eremenko et al., 2008; Parrington et al., 2008). As a consequence, such satellite observations are very valuable to follow the evolution of free tropospheric ozone, but their capacity to act as a constraint for modeling surface ozone, in data assimilation, needs to be carefully assessed. Parrington et al. (2008) assimilated tropospheric ozone profiles derived from TES instrument into two global chemistry-transport models; they showed that such data could greatly help to improve simulations of free tropospheric ozone. Moreover, they demonstrated that the assimilation of TES ozone profiles in the GEOS-CHEM model has an impact on simulated ozone surface concentrations over the United States due to an increase of downward ozone fluxes (from the free troposphere) simulated in the corrected model. Boisgontier et al. (2008) also underlined the potential of assimilating simulated IASI-like ozone observations to better constrain surface ozone concentrations in a regional air quality model.

In case of mid-latitude polluted areas (Europe, United States), surface ozone concentrations are highest during summer when stable anti-cyclonic conditions dominate favouring active daily ozone production. In such conditions, high surface temperature occurs associated with an increase in PBL height. Sensitivity of satellite instruments to surface concentrations is then increased by 1) sharper thermal contrast between surface and lowest level of atmosphere (Deeter et al., 2007) and 2) mixing of surface air masses into a thicker PBL, and thus to higher altitudes with increased instrumental sensitivity. This sensitivity of the satellite measurements to high ozone concentrations in the lower free troposphere has been illustrated by Eremenko et al. (2008) during the 2007 summer European heat wave. Moreover, under subsident meteorological conditions, surface air masses efficiently sampled by the satellite are transported downward. This is the case during summer over Southern Europe (Mediterranean Basin) where persistent anticyclonic conditions are present due to a descending branch of the Hadley circulation (Ziv et al., 2004). Under such conditions, a significant part of boundary layer air masses comes from European free troposphere and can be trapped in the PBL (Lelieveld et al., 2002; Traub et al., 2003).

In this paper, we investigate the potential of observations from nadir viewing IR sounders such as IASI to be used as a constraint for modelled ozone surface concentrations. As said before, given the lack of sensitivity of these instruments to the surface, we need to assess to which extent information delivered in the free troposphere where the instrument's sensitivity is high, can affect surface ozone due to subsidence of free tropospheric air masses and/or by extension of the PBL into altitude where IASI becomes more and more sensitive. To this aim, we will introduce quasi inert tracers into the state-of-the-art RCTM CHIMERE and analyse their downward transport over the European domain, as a function of the meteorological situation. In order to obtain climatologically more robust results, two different summer seasons (2003 and 2004) are considered. Next, we will use a specific tracer which is representative of the information content provided by IASI-like measurements. Results presented in this paper will give an upper limit for the benefit of assimilating IASI or TES like satellite observations into a regional CTM, in order to improve surface ozone modelling. This study, focuses on aspects of vertical transmission of information, since this will be a key issue for the success of data assimilation.

The paper is organised as follow. In Sect. 2, we present the CHIMERE model and the general configuration of the simulations; then methodology and results of the passive tracer experiment are presented and discussed in Sect. 3; the description of the methodology and results of the IASI-like tracer experiment follows; Sect. 5 gives conclusions and perspectives.

2 CHIMERE model

To simulate ozone as well as inert tracer concentrations (the letter being described in Sect. 3, we use the CHIMERE RCTM. The version that is used here has been described in Bessagnet et al. (2008) and more details concerning the parameterization used can be obtained from www.lmd.polytechnique.fr/chimere. This state-of-the-art model allows us to simulate a wide variety of gaseous pollutants (O_3, NO_x, SO_2, CO, VOC ...) as well as airborne particulate matter (sulfate, nitrate, secondary organic compounds, mineral dust ...). It has been used for numerous air quality studies dealing with gaseous and/or particulate pollution (i.e. Vautard et al., 2005; Coll et al., 2005; Hodzic et al., 2006; Deguillaume, 2008). Moreover, it works operationally on the PREVAIR platform (www.prevair.org, Rouil et al., 2009) to produce ozone, NO_x and particulate concentrations short-term forecasts and analyses at continental scale.

For this work, the simulation is set up over a large western European domain (ranging from 10° W to 23° E and from 35° N to 58° N) as indicated in Fig. 1. To cover this domain, 3082 (67×46) horizontal grid points with 0.5°×0.5° (around 50 km×50 km) horizontal resolution are necessary. 17 vertical levels are defined following an hybrid (σ, p) scheme; their thickness varies from 50 m in the surface layer to less than 1 km in the free troposphere. Top pressure and altitude of each level are indicated in Table 1 for one grid point at 0 m above sea level.

Two summer periods are simulated: summer 2003 known as one of the hottest and most polluted summer in terms of number of days with ozone alerts in the lest decade

(Vautard et al., 2005 and references therein) while summer 2004 (June-July-August) is classified as a standard summer from the point of view of air quality (EEA report 2007). We use LMDz-INCA monthly climatology (Hauglustaine et al., 2004) to impose gaseous concentrations at domain's limit (top and boundary conditions). Primary pollutants emissions are based on EMEP 2003 inventory (Vestreng et al., 2005). Meteorological fields (pressure, temperature, wind components, relative humidity, liquid water content and precipitation) are calculated off-line by the Integrated Forecasting System of the European Centre for Medium-Range Weather Forecasts (ECMWF): analyses at 00:00 and 12:00 h UT are used and complemented by 3-hourly forecast running from each analysis.

3 Tracer simulation

The objective of this experiment is to identify transport paths of air masses for two different summers representative of extreme (2003) and standard meteorological conditions (2004). More specifically, we want to evaluate the importance of free tropospheric air mass subsidence in the domain of simulation with respect to their initial altitude. To trace this transport, we simulate the transport of passive tracer that originated from different altitude levels.

3.1 Methodology

Passive tracers represent virtual species that are dynamically transported in the model but do not undergo chemical transformations. Here, their horizontal advection is calculated using the very non diffusive and mass conserving PPM (Parabolic Piecewise Method) scheme (Colella and Woodward, 1984). Because tracers are designed to mimic ozone, dry deposition needs to be taken into account. The pseudo-resistance scheme developed by Wesely and Hicks (1977) is used in CHIMERE for ozone dry deposition. Chemical decay of ozone is not included, because free tropospheric ozone

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lifetime is in the order of weeks, thus long ompared to the 4 day time period considered here. Within the pristine marine boundary layer (NO_x<50 ppt), net ozone losses of about 3 ppb/day have been determined (Monks et al., 1998). Such loss rates could to some extent affect tracer concentrations, but they remain small compared to the advective time scale of some days (see results below).

One of the crucial points of the experiment is the way tracers are initialised. The aim of this study is to identify to what extent and at which time scale free tropospheric air masses are transported downward to the surface. To assess these points we define different tracers for each vertical model level (i.e 17 tracers). The concentration of each tracer is arbitrarily initialized at 100 ppb in each vertical level and zero elsewhere. To follow the time evolution, 4-day periods are defined (most of tracer amount is swept off the geographical domain after four days). Over one summer this corresponds to 21 periods. Tracers are "released" (initialised) at the beginning of each period, at 00 h, and reset to zero after 96 h (four days) of simulation. To analyse results, all 21 time periods in each summer have been averaged to obtain hourly means as a function of time after initialising the tracer fields (0–96 h).

3.2 Results

Figure 2a and b displays the temporal evolution of four different tracers as a function of altitude for both years. Tracer concentrations have been averaged over the whole horizontal domain and then horizontal means (as a function of time) have been plotted for different levels. We have chosen here to display results for tracers that have been initialized below 800 hPa (i.e. above the top of the boundary layer for many cases) since we want to examine transport of air masses efficiently sampled by IASI-like instruments.

Time evolution of concentrations for tracer 11 (initialized between 500 and 400 hPa) shows a general subsidence pattern, nevertheless concentrations above 900 hPa remain zero in all 4-day periods for both years. This is the case for all tracers initialized below 500 hPa (not shown). This indicates that no information from these levels reaches the surface within 4 days. Tracers initialized between 800 and 500 hPa reach the ground with a higher efficiency. The time a tracer needs to reach the ground increases with altitude at which the tracer has been initialized. Maximum tracer concentrations at the surface represent up to 10% of the initial value at 10 to 40 h after release. Thus, we can conclude that a non negligible part of tracers initialized between 800 and 500 hPa can be transported to the surface in both simulated years. That means that a significant fraction of free tropospheric air masses can reach the surface within four days.

In order to analyze horizontal patterns of downward transport, we examine (Fig. 3a and b) horizontal distribution of tracer 8 at the surface (originating in model layer extending from 3 to 4 km height above sea level). After 24 h of simulation its downward transport is significant especially over mountainous areas where its concentration can reach 15% of the initial value. Until 3 days, its concentration remains significant in particular over the Mediterranean basin reaching 5 to 12% of initial concentrations. Concentrations after 96 h can still reach more than 5% of their initial values over the Mediterranean sea and Italy. Observed patterns appear to be similar for summers 2003 (Fig. 3a) and 2004 (Fig. 3b). Analogous, albeit quantitatively different patterns, are observed for tracers 7 to 10.

Figure 4 shows mean surface concentrations of tracer 8, and the total range of its concentrations, after respectively 24, 48, 72 and 96 h of simulation for four geographical regions as indicated in Fig. 1, for both 2003 and 2004 summer periods. It shows that the south eastern European area (domain D) exhibits highest concentrations in every case with values ranging from about 5 to 8 ppb. The tracer variability at surface is large. For domain D, concentrations can range from less than 2 ppb to 14 ppb. In general, tracer levels are largest two and three days after release. Finally, it should be noted that for in north western part of the domain, tracer concentrations always remain lower than 2 ppb, i.e. the vertical information transfer from the free troposphere to the ground is small for this sector.

Results of this tracer experiment indicate that a significant part of free-tropospheric air masses is transported downward to the surface due to stable anti-cyclonic conditions over Western Europe and more especially over the Mediterranean basin during summer. This indicates that ozone observations provided by nadir IR sounders (sensitive to free-tropospheric ozone concentrations) can provide information on surface ozone via subsident air mass transport from the free troposphere to the surface.

4 IASI-like tracers

4.1 Methodology

Instead of using several inert tracers each representative of only one vertical level, we use now one inert tracer that will mimic the new information obtained from nadir IR sounders like IASI (or TES). For that purpose, we define a tracer that will contain the information content obtained from an IASI-like estimation (X_{IASI}) of the true state of the atmosphere as compared to a corresponding estimation obtained from a model simulation (X_{CHIMERE}). Following Eq. (1) from Rodgers (2000, p. 47), the retrieved profile X_{IASI} can be expressed as follows:

$$\hat{X}_{\mathrm{IASI}} = \mathbf{A}(X_{\mathrm{true}} - X_a) + X_a + \mathbf{G}_y \varepsilon_y \quad (1)$$

where X_{true} is the true ozone profile, X_a is the a priori profile used in the retrieval, $\mathbf{A}$ stands for the averaging kernel matrix that describes the sensitivity of the retrieval to the true state. $\mathbf{G}_y$ represents the gain matrix of the retrieval and ε_y the observation error. The term $\mathbf{G}_y \varepsilon_y$ will be neglected in the following making the hypothesis of an error free observation. According to the same formalism, IASI would retrieve X_{CHIMERE}, if the true state of the atmosphere was X_{ch} (the profile simulated by the CHIMERE model):

$$\hat{X}_{\mathrm{CHIMERE}} = \mathbf{A}(X_{ch} - X_a) + X_a \quad (2)$$

The term X_{ch} represents the ozone profile originally simulated by the CHIMERE model. At this step, the information content given by the satellite comparing to the model estimation can be expressed as:

$$\hat{X}_{\text{IASI}} - \hat{X}_{\text{CHIMERE}} = \mathbf{A}(X_{\text{true}} - X_{ch}) \tag{3}$$

The right hand side of Eq. (3) represents the information provided by the observation in addition to our prior knowledge of the atmospheric state in the ideal case, i.e. without any errors (instrument, retrieval method). This term can be understood as the upper limit of information that nadir IR sounders can provide and then be used as an estimator of the new information given by observations. Thus, we use this formulation for our IR-sounder-like tracer (X_T). The averaging kernel functions **A** indicates the altitude at which the satellite observations are sensitive to. An element $\mathbf{A}_{ij}$ of **A** is defined as $\mathbf{A}_{ij}=\frac{d\hat{X}_i}{dX_j}$, i.e. as the sensitivity of a retrieval at level $_i$ to the true state at level $_j$. **A** is derived during the retrieval process. In our case, this matrix is built using IASI observations inverted using an altitude-dependent regularization method as described in Eremenko et al. (2008). Two sets of averaging kernels (for ozone) produced with IASI radiance summer measurements are shown in Fig. 6. The left panel shows means for medium surface temperatures (between 15°C and 25°C) and the right panel shows means for high surface temperatures (more than 25°C). These two averaging kernels are hereafter referred to as AVK_med and AVK_high. These matrices indicate that almost two independent pieces of information in the troposphere can be obtained from IASI ozone observations with weak sensitivity to the PBL but a good sensitivity in the free troposphere from above around 4 km height, especially in cases where surface temperatures are highest (Fig. 5, showing only the tropospheric part of the AVK's). It should be noted that the low sensitivity of the IASI averaging kernels in the lower tropospheric layers results from atmospheric properties and can only slightly be changed with use of other retrieval setups (Boynard et al., 2009; Keim et al., 2009). The following study is therefore valid for any IASI retrievals.

Since the true ozone profile X_{true}) is not known, measured ozone vertical profiles are used to derive the expression $X_{\text{true}}-\mathbf{G}_{ch}$. Such profiles are routinely measured over Europe by onboard commercial aircraft in the frame of the MOZAIC program (Marenco et al., 1998). As an estimation of the difference between MOZAIC and CHIMERE ozone profiles, the root mean square (RMSE, Eq. 4) between both types of profiles is calculated.

$$\mathrm{RMSE}=\sqrt{\frac{1}{N}\sum_{i=1}^{N}(X_{\mathrm{CHIMERE}}-X_{\mathrm{MOZAICC}})^2} \quad (4)$$

The RMSE gives some more weight to large differences than the mean absolute difference. It has been calculated from around 180 MOZAIC profiles measured over Frankfurt and Paris airports during summer 2004 and the corresponding CHIMERE profiles.

The mean RMSE is then calculated for each kilometer between surface and 12 km height (cf. Table 2) and averaging kernel matrices (AVK_med, AVK_high) are applied (following Eq. 3) to build X_{T_med} and X_{T_high} profiles (cf. Table 2). Initializing an inert tracer with these values allows to follow how this information is transported within the model and how it impacts simulated surface concentrations. Using two different surface temperatures, the sensitivity variations in the averaging kernel functions is addressed. Table 2 shows that vertical profiles of both IASI-like inert tracers are very similar. In the following only results obtained using X_{T_med} will be discussed. Note that tracer values exceed values of corresponding RMSE between 3 km and 8 km. This is due to the fact that the sum of the contributions of all levels to one particular level can be higher than unity. Also the model biases in the upper troposphere (that may be rather important) are transported to the lower levels by off-diagonal elements of the averaging kernel matrix. However, tracer values below 500 hPa will have no impact on surface ozone (see Sect. 3).

The inert tracer constructed this way is initialized each day at 10 a.m. (approximately the morning overpass of IASI instrument) uniformly over the domain, supposing an overall cloud free area. To analyse the results we have calculated an average over the 92 days of each simulated summer (i.e. 2003 and 2004).

4.2 Results and discussion

Figure 6 displays surface concentrations of the X_{t_med} tracer at 6 a.m. and 6 p.m. and for both simulated years. As expected, highest concentrations are present over the Mediterranean basin and the Alps. They can reach 24 ppb at 6 a.m. in 2003 and slighty lower values (22 ppb) in 2004. At 6 p.m., higher surface concentrations are simulated (maxima up to 30 and 26 ppb for 2003 and 2004 respectively) over larger areas. This is due to the new information provided by the simulated morning passage of IASI over the domain. Such values can represent between 20 to 40% of mean surface ozone concentrations. Thus, IASI-like tropospheric ozone observations could constitute an efficient indirect constraint to correct simulated surface ozone concentrations. Nevertheless, this conclusion should be mitigated considering some of the hypotheses that have been made for our simulations. Since we have supposed that no clouds were present, we have overestimated the potential correction given by the satellite. In addition, if IASI observations were assimilated in an atmospheric model, one would need to take into account the observational error, with the effect that new satellite information could only partially be used for model correction. Thus, clearly, the obtained results correspond to an upper limit of the possible constraint IASI observations.

On the other hand, the downward transport of free tropospheric air masses over the northern and the north-western part of the domain remains low, indicating that IASI-like observations cannot be used to constrain modelled surface ozone concentrations in these regions.

5 Conclusions

A tracer study has been performed in order to evaluate the potential constraint of ozone observations from nadir viewing infrared sounders like IASI or TES on near surface ozone. As these instruments show high sensitivity in the free troposphere, but low sensitivity near ground, a key question to be answered is which amount of this information is transferred to ground through vertical transport processes. Two types of tracers have been introduced into the CHIMERE chemistry transport model: an ozone like tracer for each vertical model level, and a tracer designed to mimic information contained in IASI ozone profile retrievals. This tracer study is a pre-study and highly complementary to actual data assimilation, for which "success" will depend on a number of factors difficult to disentangle (e.g. observation errors, model errors, and actual observation – model differences).

Within the European model domain, and within a time span of 4 days, tracers are transported to the surface only if they are initialised above 500 hPa. For tracers emitted between 800 and 700 hPa, an average of about 7% reaches the surface within a half day to three days, both due to subsidence into the planetary boundary layer. After three days, surface concentrations of this tracer decrease, because of advection out of the domain. The three day time scale is larger than that was observed for assimilation of surface ozone (Elbern et al., 2001; Blond et al., 2004) where the benefit of assimilation decayed rapidly during the first day. Free tropospheric tracer levels at surface are largest (up to 15%) over mountain regions and i.e. over the south-east Mediterranean basin in the model domain. This is consistent with strong subsidence over the Eastern Mediterranean sea during summer, related to persistent anticyclonic conditions. On the contrary, tracer levels are very small over North-Western Europe. Results for years 2003 and 2004 with rather different meteorological conditions appear to be very similar. These results are confirmed by using another tracer designed to mimic useful information that would be delivered by a IASI type instrument and which take into account especially the instrument's vertical sensitivity (averaging kernel). Maximum tracer levels at surface occur again over the Mediterranean region in the south-eastern part of the model domain. All in all, this study shows the potential of IASI derived ozone profiles which are mainly sensible to the free troposphere, to constrain modeled surface ozone levels over Europe. This confirms results obtained over US from assimilation of TES ozone profiles (Parrington et al., 2009).

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Table 1. Characteristic top pressure (hPa) and altitude (km) associated to each model vertical level above sea level.

model level	1	2	3	4	5	6	7	8	
Pressure (hPa)	1008	998	983	960	925	874	797	708	
Altitude (km)	0.04	0.13	0.26	0.46	0.77	1.25	2.02	2.99	
model level	9	10	11	12	13	14	15	16	17
Pressure (hPa)	623	546	476	414	359	310	266	227	200
Altitude (km)	4.02	5.07	6.12	7.16	8.21	9.23	10.3	11.3	12.1

Table 2. Vertical profile of mean RMSE (ppb) calculated with commercial aircraft ozone measurements (MOZAIC) against simulated ozone concentrations from CHIMERE model. All data are interpolated to a 1 km vertical grid. Aircraft measurements (from landing and take-off phase) from two airports (Frankfurt and Paris) are used. This represents around 180 profiles in summer 2004 (June to August).

Z (km)	1	2	3	4	5	6	7	8	9	10	11	12
RMSE (ppb)	12	9	10	11	12	14	18	23	42	80	90	100
X_{T_med} (ppb)	4.5	9	13	17	21	24	28	31	35	40	45	49
X_{T_max} (ppb)	4	8	12	16	20	24	28	31	36	41	46	50

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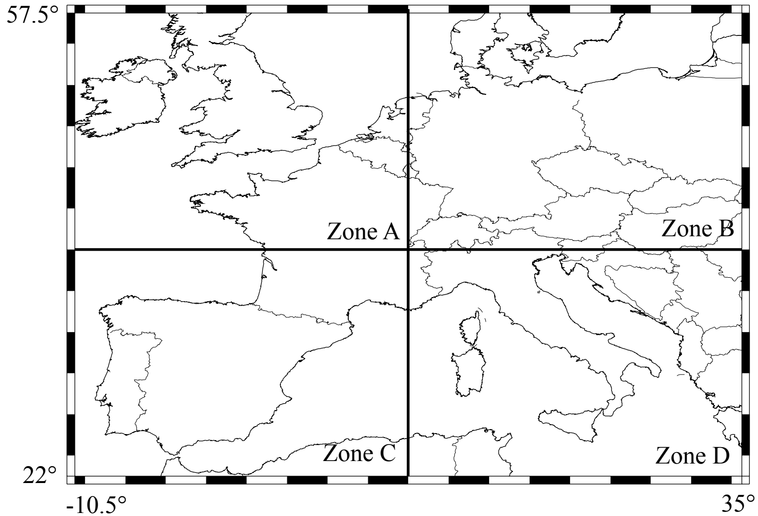

Fig. 1. Geographical map of the simulation domain.

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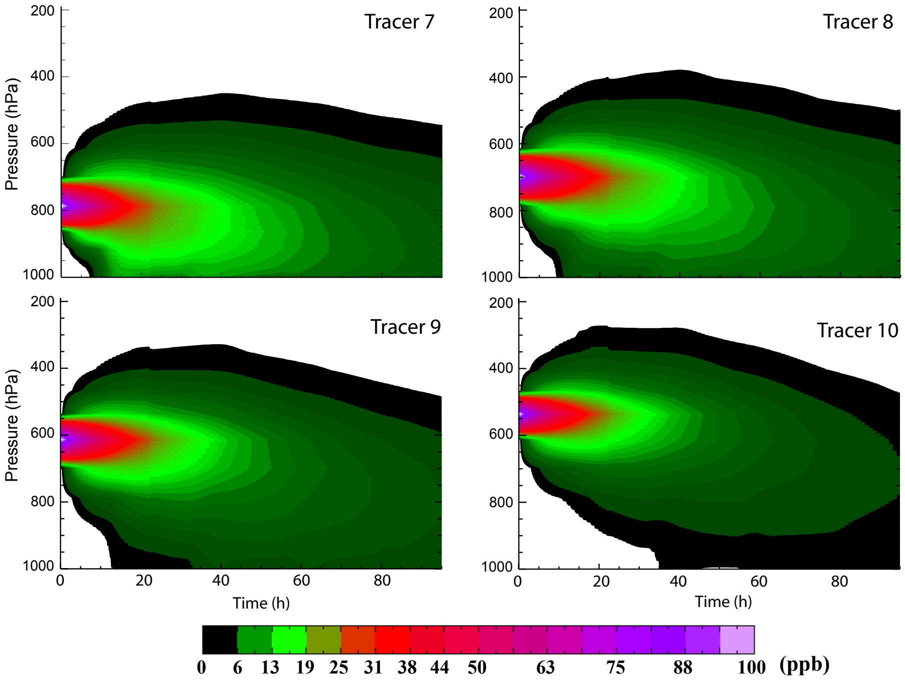

Fig. 2a. Time evolution (0–96 h) of vertical tracer distributions in summer 2003 for tracer 7 (870 hPa–800 hPa), tracer 8 (800 hPa–700 hPa), tracer 9 (700 hPa–620 hPa) and tracer 10 (620 hPa–650 hPa). For each tracer, concentrations (ppb) have been averaged over the whole geographical domain and over 21 4-day time periods.

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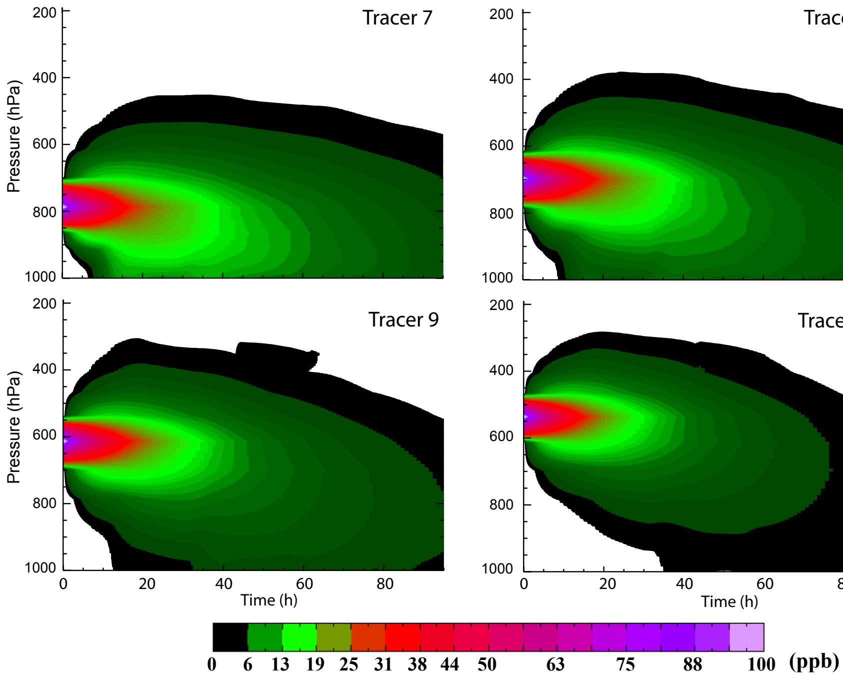

Fig. 2b. Same as Fig. 2a the summer 2004.

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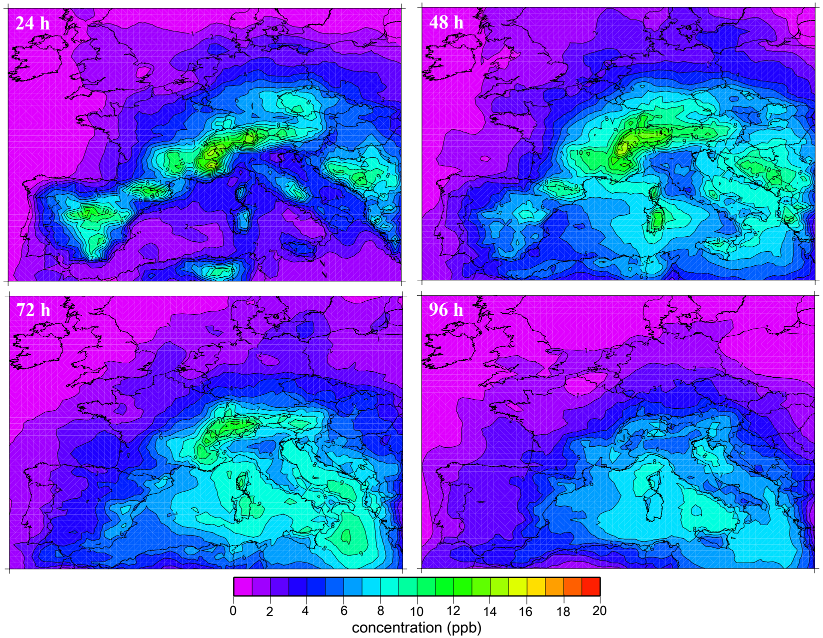

Fig. 3a. Surface concentrations for tracer number 8 (800–700 hPa) after 24, 48, 72 and 96 h of simulation, in summer 2003.

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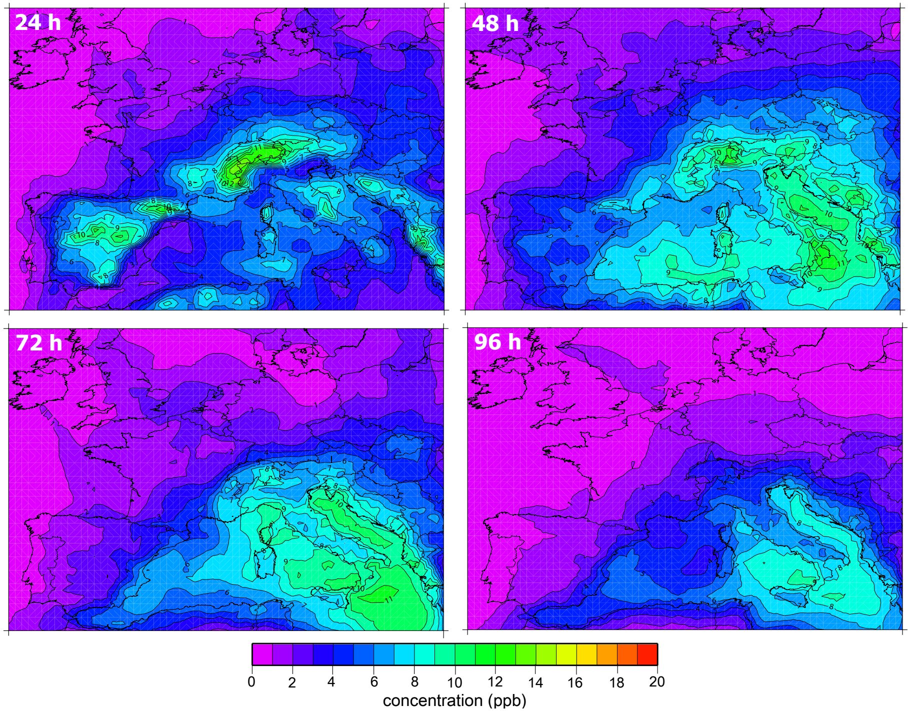

Fig. 3b. Same as Fig. 3a for summer 2004.

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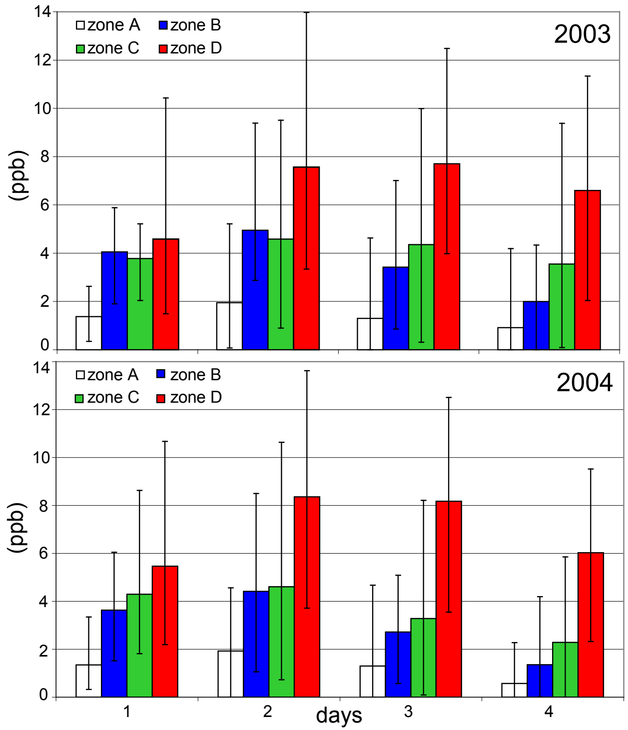

Fig. 4. For each geographical domain (A, B, C, D) indicated in Fig. 1, mean surface concentrations for tracer 8 have been calculated for each 4-day period after 24, 48, 72 and 96 h. Vertical bars associated with histograms indicate the total range of simulated values.

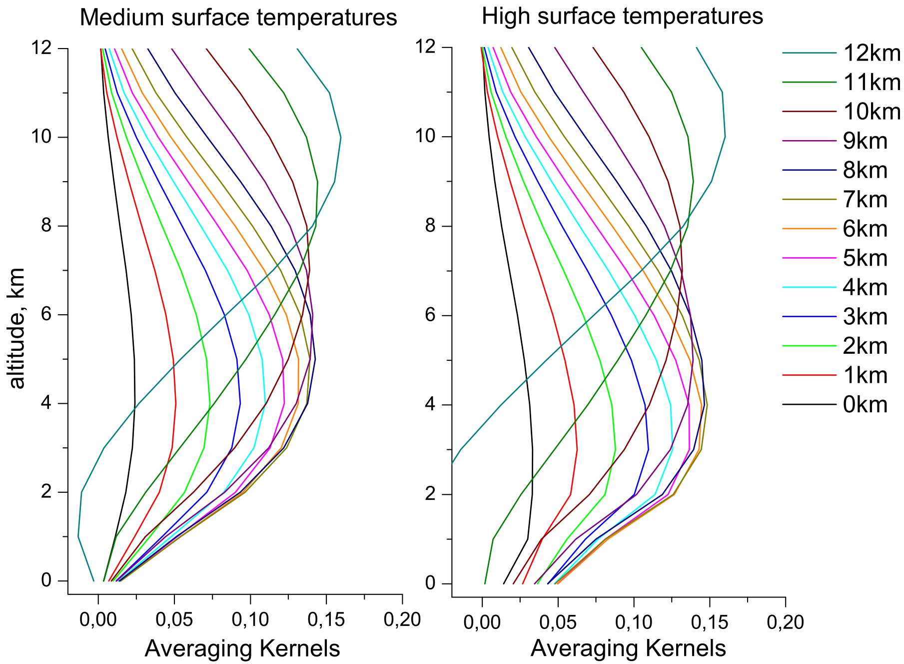

Fig. 5. IASI averaging kernels for European summer morning conditions. Averaging kernels for medium surface temperatures (between 15°C and 25°C) are shown in the left panel and for high surface temperatures (higher than 25°C) in the right panel.

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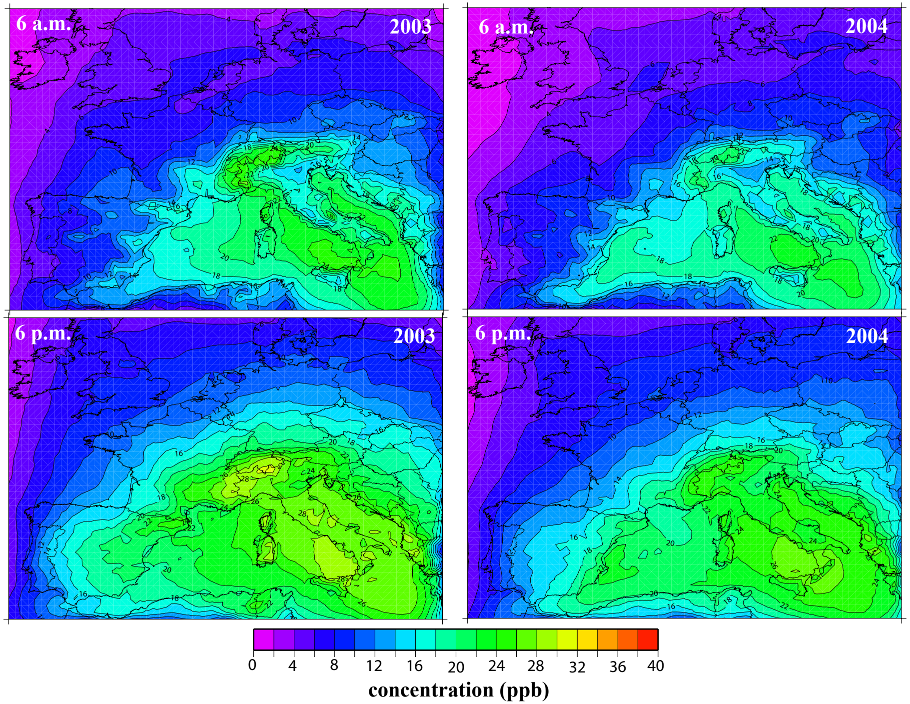

Fig. 6. Concentrations of a tracer with IASI-like vertical profile shape. The tracer is updated every morning at each satellite passage. Daily tracer concentrations are then calculated for the whole summer period (92 days). Concentrations at **(a)** 6 a.m. and **(b)** 6 p.m. are shown.