Urban air quality and meteorology on opposite sides of the Alps: The Lyon and Torino case studies

Research Papers

Urban air quality and meteorology on opposite sides of the Alps: the Lyon and Torino case studies

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Abstract

Several European urban areas are characterised by low air quality due to high local emission per unit surface. A further key feature can be related to the pollutant load due to adverse local meteo-climatic conditions. This study aims to compare the two urban agglomerations of Torino and Lyon – located on opposite sides of the Alps and characterised by similar size and population – to enlighten the role of meteorology on local pollutant dispersion. The assessment of air quality has been developed by monitoring network data, emissions analysis and the SIRANE urban dispersion model. Although the two agglomerations have similar NO_X and PM10 emissions, the simulation results show higher ground level concentrations in Torino. To quantify the effect of meteorology on this excess of concentrations, we run simulations in Torino imposing the meteorological conditions of Lyon and vice versa. This implies an overall reduction of ground level concentrations in the city centre of Torino between 20% and 40% (analogously, Lyon concentrations increase by a similar amount). These results show the peculiar difficulties faced by Po valley's cities in maintaining pollution levels below regulatory thresholds and highlight the need of systemic policies and site-specific mitigation to reduce air pollution health risks.

Keywords: atmospheric stability; dispersion modelling; NO_X; PM; urban air quality; urban canopy.

1. Introduction

Several studies highlight the positive association between the long-term exposure to air pollution and the increased risk of morbidity and mortality (IARC, 2016). The climate crisis and the growing number of people living in metropolitan areas (UN, 2018) increase the need for progress in the assessment and management of urban air quality. The challenge regards the development of integrated approaches to assess overall human exposures in indoor and outdoor work and life environments using state-of-the-art reference technologies, IoT tools, real-time measurements and computational models (Bo et al., 2017).

Many areas in Europe are characterised by low air quality (WHO, 2016). As shown in Fig. 1 this includes almost all major urban agglomerations (ESA, 2019), and particularly several megacities (urban and suburban areas spreading over hundreds of kilometres): Ile de France, South East England, Rhine-Ruhr and Benelux regions and Po valley. This scenario led the European Commission to renewed actions such as the recent enforcements to protect citizens due to the excess of Nitrogen Dioxide (NO_2) and Particulate Matter (PM) in 18 of 28 countries (EU, 2018). Despite the application of enduring policies aiming to reduce direct pollutant emissions, concerns for European ambient air pollution persist (EEA, 2018). A main factor determining these critical pollution levels is the high population density, which implies high pollutant emission per surface area. Another key feature is instead related to peculiar meteo-climatic conditions, that can induce the stagnation of pollutant at the regional and/or at the local scale. The extensive literature on the influence of meteorology on air quality focuses on the observation of circulation patterns, precipitation, solar radiation and surface air temperature, pressure and humidity (Kalabokas et al., 2008; Pearce et al., 2011a; Wang et al., 2017; Wise and Comrie, 2005). Indeed, the concentration of air pollutants (NO_2, PM and O_3) follow seasonal variations due to i) the role of photochemistry in the formation of secondary pollution and ii) the ventilation conditions governing the long-range or regional transport of pollutants (Otero et al., 2016; Pearce et al., 2011b; Zhang et al., 2012). Particularly adverse conditions are actually present in the Po valley, in Northern Italy (Bigi and Ghermandi, 2014; Diémoz et al., 2019b).

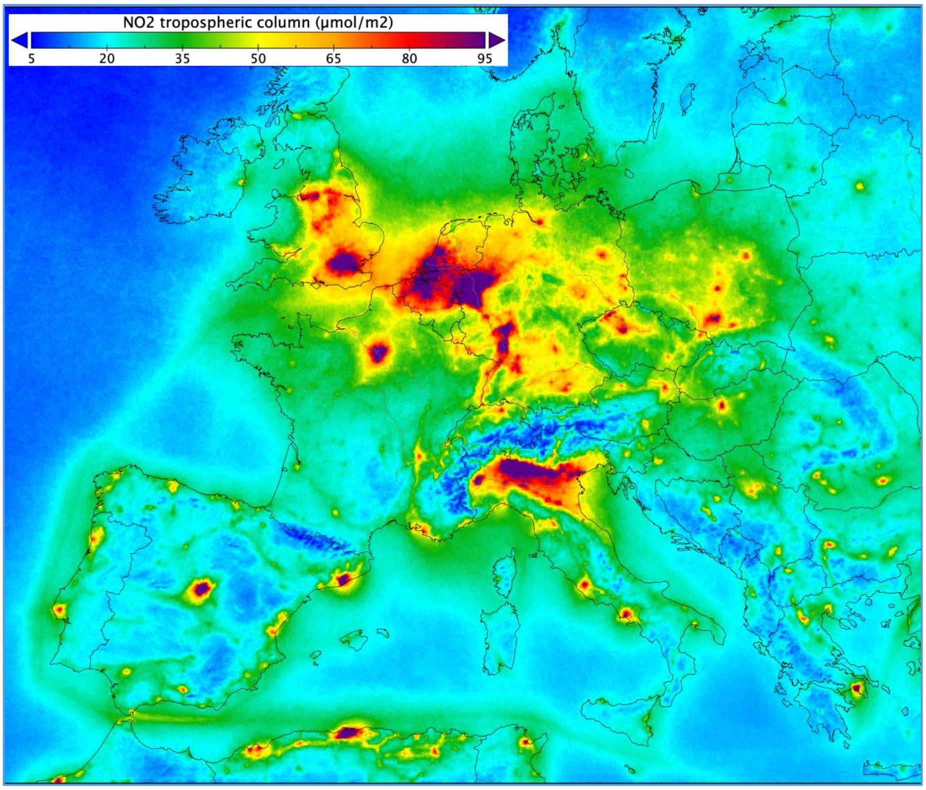

Fig. 1. NO_2 EU concentration from ESA Copernicus Sentinel-5P (ref period 04-2018 to 03-2019)

This megacity region is burdened by intense and diffuse wintertime daily and annual NO_2 and PM10 concentrations due to different factors. Primary emissions, which are common in the most densely urbanised territories, are coupled with the formation of secondary pollutants favoured by the high persistence in air of gaseous precursors and urban ventilation (Buccolieri et al., 2015). This is the result of the combination of atmospheric stability, precipitation regimes and the particular ventilation forced by the proximity of the Alps.

The high air pollution in the large urban and suburban agglomerations of Torino (Turin) and Milano (Milan) derives both from local emissions and a relevant background pollution, defined as the contribution from all pollutants sources located outside these agglomerations. Thus, the definition of effective policies to improve air quality requires the identification of main contributors and their localisation. To that purpose, previous studies in the region have focused on the apportionment of sources and distribution of concentrations in urban agglomerations and side valleys (Amato et al., 2016; Diémoz et al., 2019a).

To further explore the influence of the specific meteo-climatic condition of Po valley on urban air quality, this study aims to compare the air pollution scenarios related to two urban agglomerations: Torino and Lyon. These two cities are very similar in terms of size and population but are located on the opposite sides of the Alps and are therefore subjected to very different meteorological regimes.

The comparison is based on the simulation of air pollution over a whole year (2014) using the SIRANE model, with a spatial resolution of streets and buildings (10 m) and an hourly time-step. This model has been developed in last 20 years by the Atmosphere, Impact & Risk research group of the Laboratoire de Mécanique des Fluides et Acoustique (LMFA-AIR) of the Ecole Centrale de Lyon. Currently it represents the only operational urban air-pollutants dispersion model based on a street network approach which is applied over real cases (Coudon et al., 2018; Soulhac et al., 2017, 2011). It has been validated against wind tunnel experiments (Carpentieri et al., 2012; Garbero, 2008; Salem et al., 2015) and in-field studies. The city of Lyon represents the main target domain for validations, performed so far for the years 2008 and 2014 (Nguyen et al., 2018; Soulhac et al., 2017, 2012). In the last decade, SIRANE has been applied continuously in various European urban areas, with some pilot studies developed in Italy (Biemmi et al., 2010; Castagnetti et al., 2008; Garbero et al., 2010; Giambini et al., 2010; Pognant et al., 2018, 2017).

In what follows, the context and main characteristics of the two case studies are first described (§2). The input data for the two scenarios, developed by means of an original bottom up and top down approach, are presented (§3). The "transboundary" comparison aims to analyse meteorological indicators (§4), local emissions (§5) and modelled concentrations of NO_2 and PM10 (§6).

2. Contexts analysis

The population of the urban agglomeration of Torino is 1.44 million (2011) over an area of 636.42 km^2 while in Lyon the population is 1.37 million (2015) over an area of 533.70 km^2. Both the cities are located in flat territories close to hills and crossed by rivers (Dora Riparia and Po; Saone and Rhone). The city centres present Romanic-squared schemes and the development of their suburbs led to a continuative extended urban area with surrounding municipalities.

The trends in NO_2 and PM10 measured concentrations have been investigated. The dataset derives from the public monitoring networks of the Regional Agency for the Environment (ARPA Piemonte) and of ATMO-Auvergne-Rhone-Alps. These networks are composed of 10 to 15 Air Quality Monitoring Stations (AQMS) measuring the main air quality indicators (PM10, PM2.5, NO_2, O_3, SO_2 and CO). Note that the time period of PM10 Lyon dataset is shorter than in Torino. Part of AQMS (shown in Fig. 3) have been selected for the purposes of the study, according to: typology (background, traffic); location (urban, suburban); evaluation of main district area (commercial, industrial, residential); dataset consistency (> 90% hourly records by year).

A first insight of the evolution of air pollution levels in both cities can be achieved by analysing data provided by these AQMS. This is shown in Fig. 2, where we plot the ensemble average of annual concentrations together with the relative minimum and maximum value of the dataset. The NO_2 and PM10 annual mean concentrations show a clear decreasing trend over the last two decades in both urban areas. PM10 levels in Torino were particularly high in 2000 with values almost reaching the double of the current limit of 40 $\mu g/m^3$ (Fig. 2a). Then, concentrations have almost halved between 2000 and 2013 and oscillate in recent years around the limit value.

Conversely, the annual limit is respected in all the AQMS of Lyon stations since 2012 (from 2007 considering their average). It can be noticed that many of Lyon stations have progressively reached the French air quality objective of 30 μg/m^3 and some of them (Lyon Centre and Lyon Gerland) the WHO recommended value of 20 μg/m^3 in 2018. In Torino, values under 30 μg/m^3 were recorded only in 2018 in two urban background AQMS and the WHO objective has never been reached. Considering the whole dataset, the average share between Torino and Lyon PM10 measured concentrations is 40-45%.

Despite the improvement in PM10 yearly concentrations, the daily values have persistently exceeded the normative threshold of 35 days/year over 50 μg/m^3 in all the AQMS of Torino (Fig. 2b). This result confirms the enduring issue for seasonal particulates pollution in the city. On the contrary, most of the AQMS of Lyon reported the respect of EU 35-days limit since 2014 (except for few traffic stations in some specific years).

The decrease of NO_2 concentration (Fig. 2c) has been less pronounced in the past 10 years. All AQMS denoted as traffic stations proved values over the annual limit of 40 μg/m^3. Meanwhile, some of the urban background stations report values below the limit but mostly have stationary trends. The percentage rate of measured NO_2 was 27% higher in Torino for 2014 and narrowed for following years.

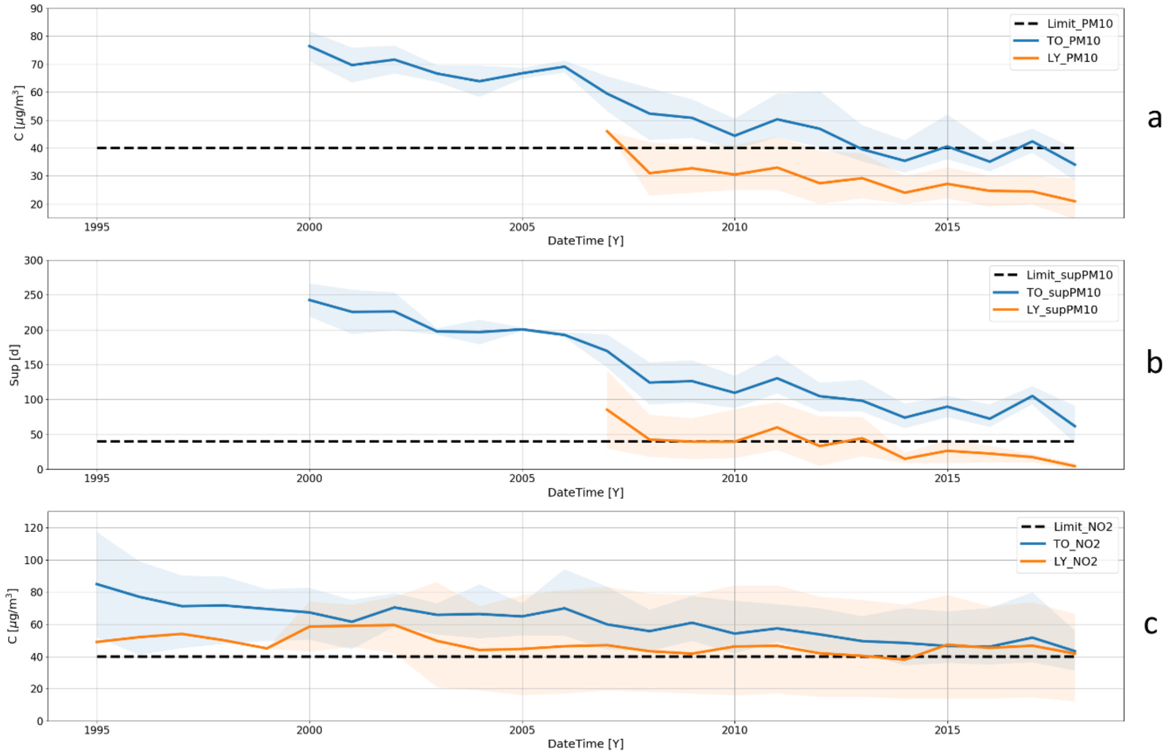

Fig. 2. Torino (blue) and Lyon (orange) urban agglomerations mean and relative maximum and minimum trends of (a) PM10 annual value (b) PM10 daily limit exceedances (c) NO_2 annual value

3. Materials and Methods

3.1 Torino case study

The Torino case study concerns a 24 x 24 km^2 domain including 36 municipalities (8 of them marginally) (Fig. 3). The street network is made up of 12148 roads, among which 6049 have been classified as street canyons. Most of them are located in the Romanic-squared city centre of Torino. Linear emissions using COPERT IV classification (Ntziachristos et al., 2009) of the metropolitan vehicular fleet database (published by the Automobile Club d'Italia, ACI), the emission factors (from ISPRA National Emission Inventory) and the traffic matrix (elaborated from raw data by 5T s.r.l.) have been developed. Then, they have been projected to the street network and refined considering the real geometry and roads classification (pedestrian patterns, cycling roads, etc.).

Nine urban tunnels, the chimney of the incinerator (TRM) and the three main plants of the district heating network (TLR) have been treated as point sources. All other pollutant releases have been included as surface emissions. The heights of both point and surface releases have been assigned on the corresponding chimneys, roof tops and tunnel entrances. Surface emissions have been developed by an integration of bottom-up (using buildings and roads data, for the sole city of Torino) and a top-down (based on ARPA's Regional Emission Inventory "IREA", for the surrounding municipalities) approaches. The need for two separate methodologies is justified by the poor resolution of available data for the external urban agglomeration. Meteorological data and background pollutants concentration have been implemented after the sensitivity analysis using ARPA's regional model and measurement sites.

3.2 Lyon case study

The model set-up is equivalent to that adopted by Soulhac et al. (2017), presenting an extended validation over the whole agglomeration for the year 2008 (Soulhac et al., 2017, 2012, 2011). The updates of input data include: extension of the simulation domain from 36x40 km^2 to 40x48 km^2; meteorology; measured concentrations; emissions; reshaping of streets and squares following the urbanisation, which has occurred in the past 6 years (Fig. 3). Whereas this case study is the third validation of the model in the city of Lyon (after 2001 and 2008), SIRANE is currently applied for real-time AQ monitoring and a fourth case study is under development for 2019.

The Lyon street network accounts 28330 roads, 4996 of them classified as street canyons. Linear emissions are estimated based on COPERT IV methodology and 2014 vehicular fleet of "Grand-Lyon" metropole. Six different traffic modulations based on road types have been parametrised. Furthermore, only urban tunnels have been modelled as point emissions: industrial sites, domestic heating and other sources are handled as surface emissions. The background concentration is based on St-Exupery Airport measurement dataset, located around 30 km east of the city. The meteorological input is provided by the Meteo-France station of Bron.

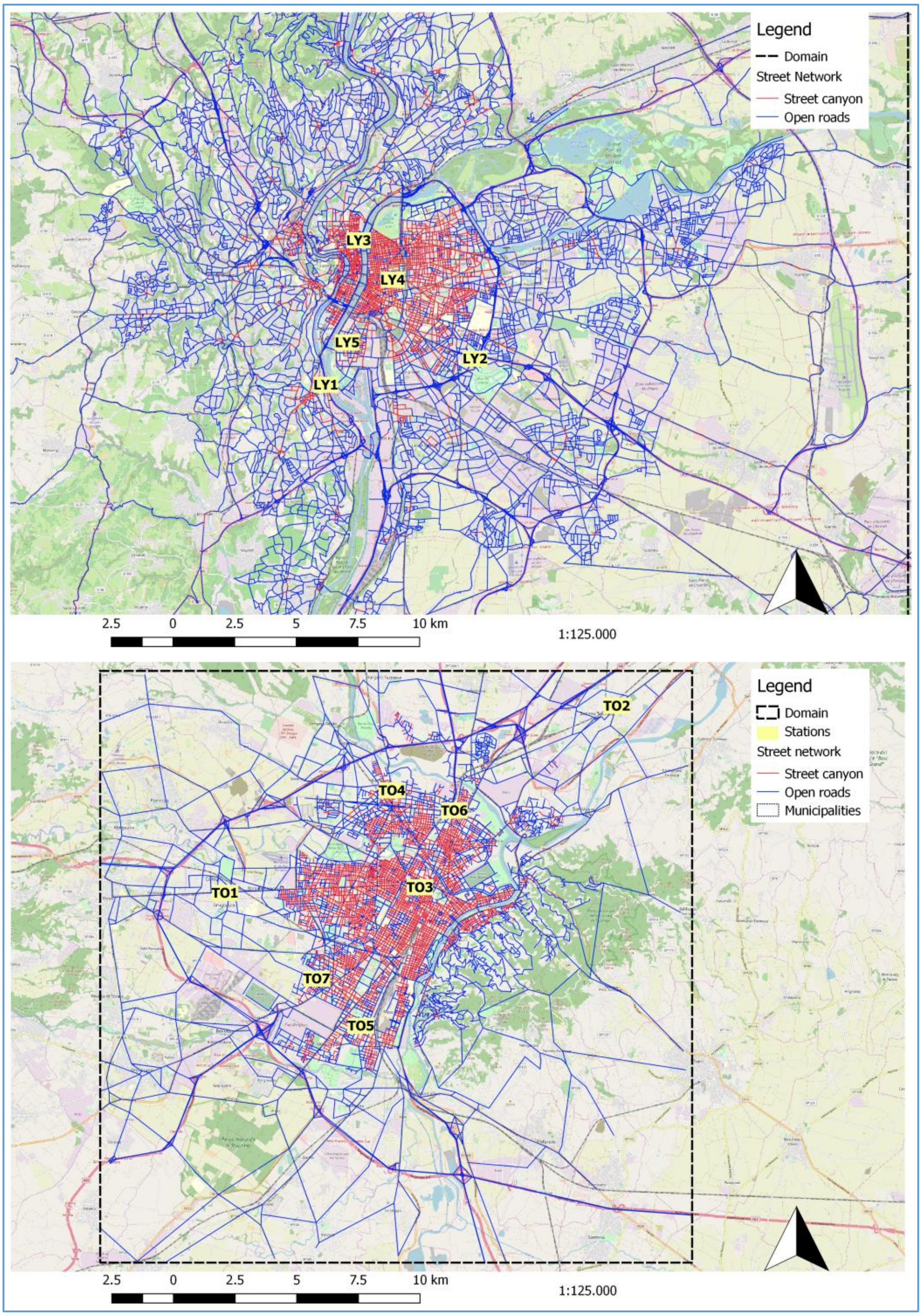

Fig. 3. Lyon (top) and Torino (bottom) case study domains

4. Meteorological analysis

The Torino urban agglomeration is located in the western part of the Po valley, which is surrounded by the Alps on three sides. The regional climate is classified as humid subtropical i.e. "Cfa" according to Köppen-Geiger (Pražnikar, 2017). The Lyon agglomeration is indeed located further away from the mountains, characterised by an Oceanic climate (i.e. "Cfb").

Focusing on the reference year 2014, a comparison of the meteorological conditions has been developed. The preferential direction of airstreams is aligned North and North-East in Torino and North-South and Northwest-Southeast in Lyon (Fig. 4). A more intense wind regime is observed for the French urban agglomeration. Particularly, the hourly average wind speed (Lyon 3.2 m/s; Torino 1.5 m/s) and the maximum hourly mean wind (Lyon 18.1 m/s; Torino 11.2 m/s) are significantly higher in Lyon.

The total annual and the monthly distribution of precipitations are similar (Torino 1198 mm; Lyon 1099 mm) with 823 hours with non-zero precipitations (settled to values > 0.1 mm/h) in Torino and 1017 h in Lyon. The annual mean temperature is higher in Torino (14.3 °C) rather than Lyon (12.2 °C). It should be noticed that the year 2014 represented – at that time – the second hottest (after 2011) and the third rainiest (preceded by 1960 and 1977) year since Torino record begun in 1958 (ARPA Piemonte, 2019).

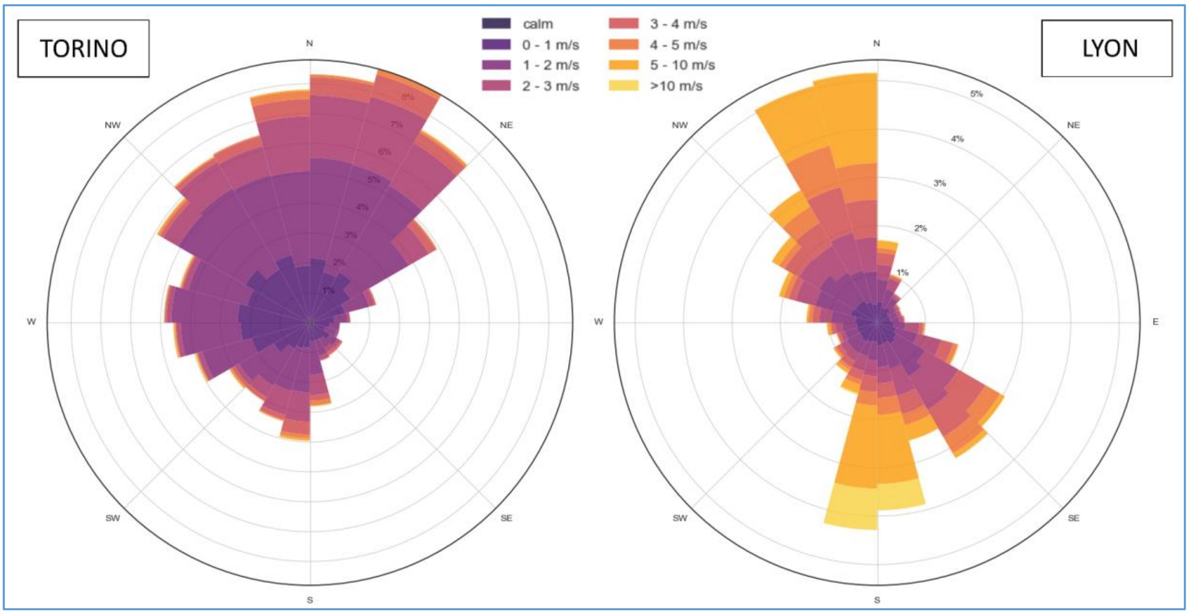

Fig. 4. Wind roses of Torino (left) and Lyon (right)

The stability conditions, as expressed by the inverse of the Monin-Obukhov length ($1/L_{MO}$), show similar averaged annual results in the two cities. However, we can note significant difference when analysing wintertime data (Fig. 5). In the cold season, prominent stable or very stable conditions are observed in Torino. Note that, for both datasets, the maximum value of $1/L_{MO}$ is settled to 0.2, since we assume that shear induced turbulence generated typical of urban areas prevents too high stability conditions (Soulhac et al., 2017).

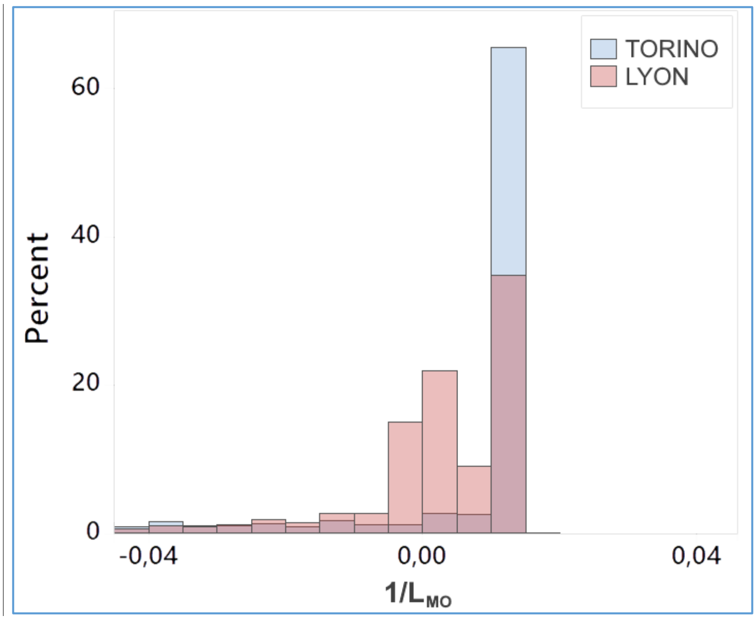

Fig. 5. Wintertime distribution of $1/L_{MO}$ hourly data in Torino (blue) and Lyon (red)

5. Emissions analysis

A significant contribution to NO_X and PM emissions comes from road traffic. The two scenarios considered show intense emissions close to main roads and minor releases associated to secondary ones. In particular, the ring-roads and highways of Torino and Lyon are responsible of NO_X normalised emissions per unit length higher than 2 $g*h^{-1}*m^{-1}$. This data depends on the severity of traffic and the types of circulating vehicles, with a higher rate of heavy vehicles compared to that in the city centres. Some roads segments corresponding to the "Autoroute du Soleil" (A6-A7 French highways) and the Lyon ring-road presents normalised emissions higher than the maximum assessed in the domain of Torino. The PM10 emission results are analogous, despite the PM10 traffic-related direct emissions are in absolute values lower than NO_X.

Likewise, in both domains, the normalised mean road traffic emissions per unit length present similar values for all the selected pollutants (Tab. 1). This data should be ascribed to equivalent emissions factors from circulating fleets with local differences derived from the networks (roads types, speed limits, traffic saturation) and boundary conditions (slopes, climate).

The street network emissions can be also displayed considering a regularly squared spatial normalisation [$g*s^{-1}*km^{-2}$]. The normalised NO_X traffic emissions are dominated by the higher share of road traffic in the centres, particularly for Torino (Fig. 6). Similar results have been observed also for PM10 (Fig. 7) with a remarkable delta between more densely urbanised districts and suburban areas.

Considering other sources, the greatest values among the domains match the cells of TRM and TLR main plants of Torino. On the other hand, the corresponding development of the district heating network has favoured the reduction of NO_X emissions from residential buildings in many districts of Torino (Noussan et al., 2017). Further analysis of these data, which derive from the AQ departments of the regional public agencies (ARPA Piemonte, ATMO-Auvergne-Rhone-Alps), is beyond the scope of the present work.

Tab. 1. Mean normalised road traffic emission per length [g*h^{-1}*m^{-1}] for the two case studies

	NO_X	**NO_2**	**NO**	**PM10**	**PM2.5**
	*[g/(m*h)]*	*[g/(m*h)]*	*[g/(m*h)]*	*[g/(m*h)]*	*[g/(m*h)]*
Torino	0.2118	0.0532	0.1586	0.0319	0.0172
Lyon	0.1856	0.0586	0.1270	0.0226	0.0163

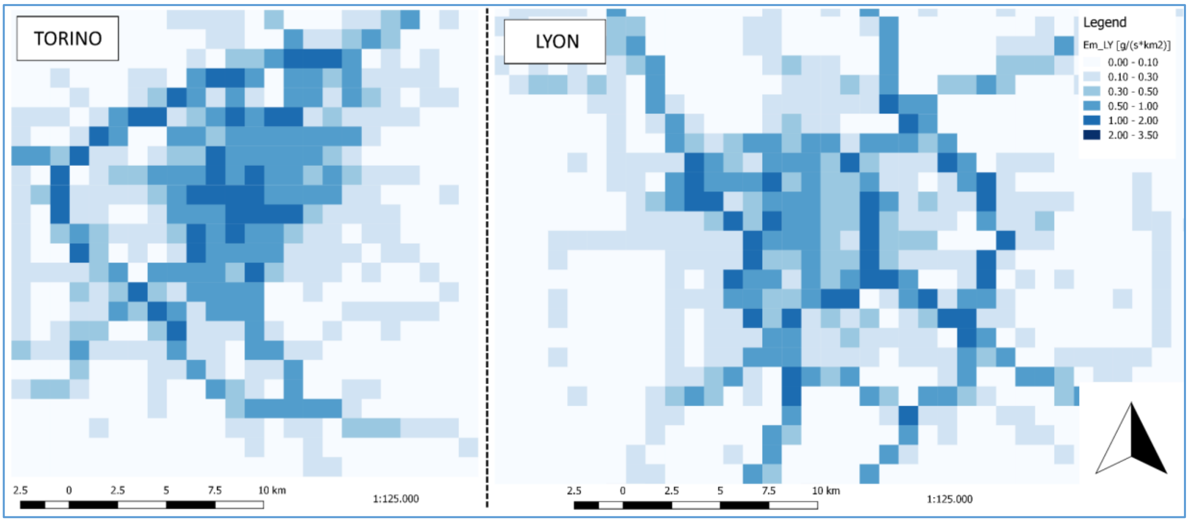

Fig. 6. NO_2 normalised traffic emissions by surface in Torino (left) and Lyon (right)

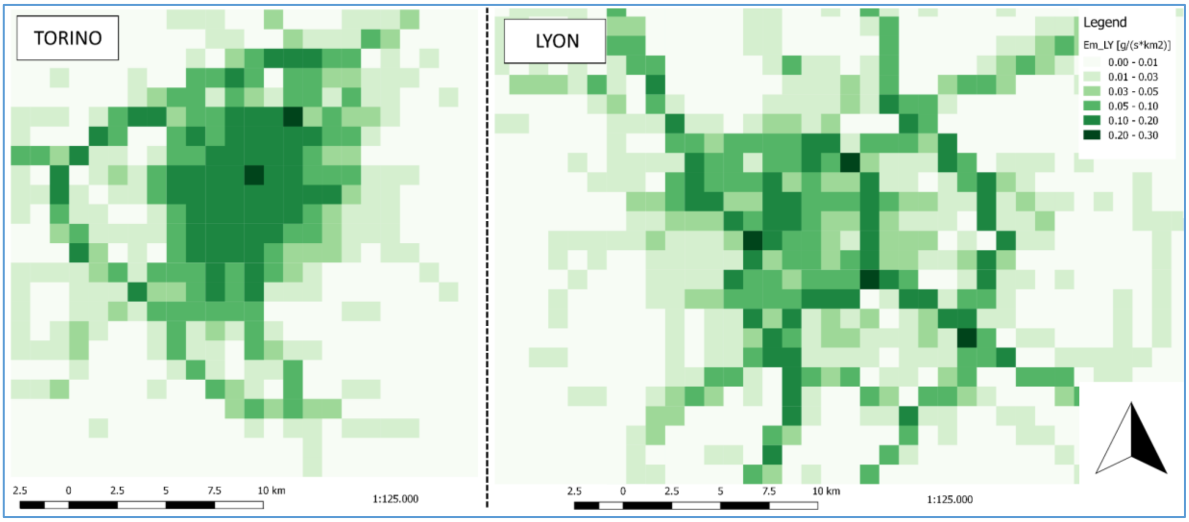

Fig. 7. PM10 normalised traffic emissions by surface in Torino (left) and Lyon (right)

6. Model results

Evaluation of the model performance

The model outcomes have been validated against experimental data collected by local authorities (ARPA and ATMO-Auvergne-Rhone-Alps). As customary in the literature, the performance of the model has been assessed using statistical indices (Chang and Hanna, 2004; Willmott et al., 2012) quantifying the discrepancies between the measured concentration C_m and the predicted concentration C_p. These are the fractional bias (FB), the normalised mean square error (NMSE), the relative error (ER), the correlation coefficient (R), the geometric mean bias (MG), the geometric variance (VG), the Fraction of data that satisfy $0.5 < C_m/C_p < 2$ (FAC2) and the Willmott's Index (WI). Details on how these indices are computed are given in the Appendix.

Since the model performance for the Lyon case were evaluated for different years (Nguyen et al., 2018; Soulhac et al., 2017, 2012), in what follows we will mainly focus on the statistical indices concerning the Torino case.

The comparison between numerical and field data show the good performance of SIRANE in reproducing the air pollution scenario in Torino, for both NO_2 and PM10. Indeed, the PM10 modelled values respect entirely the criteria at all selected receptors. A high correlation (R = 0.86 – 0.91) associated with limited relative errors (ER = 0.21 – 0.30) is observed for particulates data. Similarly, all NO_2 data fall within Chang and Hanna (2004) performances except for the mean geometrical bias for three receptors (TO2, TO5, TO7) and the geometrical mean squared variance for two (TO5, TO7). The TO7 site slightly exceeds fractional bias performance (FB = 0.314). These results are confirmed by the Willmott's Index of agreement which is higher for PM10 (WI = 0.75 – 0.81) rather than NO_2 (WI = 0.44 – 0.59). Furthermore, seeing that TO5 and TO7 are urban background stations, the NO_2 model performance is higher for traffic stations, according to previous studies (Soulhac et al., 2017). Details about model performance for NO_2, which are similar for the two case studies, are presented in Tab. 2.

Tab. 2. NO_2 model performance (in red the exceptions)

AQMS	Cod	FB	√NMSE	ER	R	MG	VG	FAC2	WI
Collegno - Francia	TO1	-0.016	0.453	0.373	0.503	1.053	1.294	0.841	0.57
Settimo - Vivaldi	TO2	0.187	0.424	0.404	0.67	1.338	1.369	0.794	0.59
Torino - Consolata	TO3	-0.075	0.373	0.281	0.559	0.931	1.144	0.937	0.56
Torino - Grassi	TO4	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Torino - Lingotto	TO5	0.269	0.584	0.518	0.401	1.511	1.848	0.688	0.47
Torino - Rebaudengo	TO6	0.03	0.385	0.318	0.459	1.029	1.181	0.914	0.45
Torino - Rubino	TO7	0.314	0.578	0.507	0.438	1.547	1.739	0.685	0.44
Lyon - A7 Sud lyonnais	LY1	0.402	0.705	0.586	0.505	1.501	1.830	0.589	0.52
Lyon - Peripherique Est	LY2	0.214	0.547	0.45	0.635	1.158	1.401	0.716	0.62
Lyon - Tunnel C. Rousse	LY3	0.384	0.785	0.517	0.393	1.462	1.732	0.596	0.54
Lyon - Centre	LY4	-0.307	0.575	0.535	0.597	0.654	1.746	0.638	0.50
Lyon - Gerland	LY5	0.193	0.515	0.431	0.627	1.248	1.391	0.737	0.60

The trends of NO_2 and PM10 agree with the performance analysis. Using the stations of TO3 and TO5, the seasonal variability of air pollution is clear. The results of the model, except for the unavoidable under-estimation of some peaks of pollution, fit the measured NO_2 and PM10 data in the whole year. The great difference between concentrations of NO_2 measured at urban stations (orange) and at background pollution (out of the city, green), is also confirmed by modelled values in the urban area (blue) seeing timeseries (Fig. 8). Whereas for PM10, despite the higher emissions made in the city centre, the delta between urban and suburban concentrations is smaller. Under this assumption, the computed contribution from local sources of particulates in the centres has a limited incidence compared to the significant PM10 background concentrations. Then, using scatterplots (Fig. 9), the response of measured against modelled values is good both for annual values (blue) and focusing to wintertime (red). Similarly, there is no discrepancy between day time and night time hours. Comparisons of SIRANE versus AQMS observations for the other selected stations and pollutants are reported in supplement (S1).

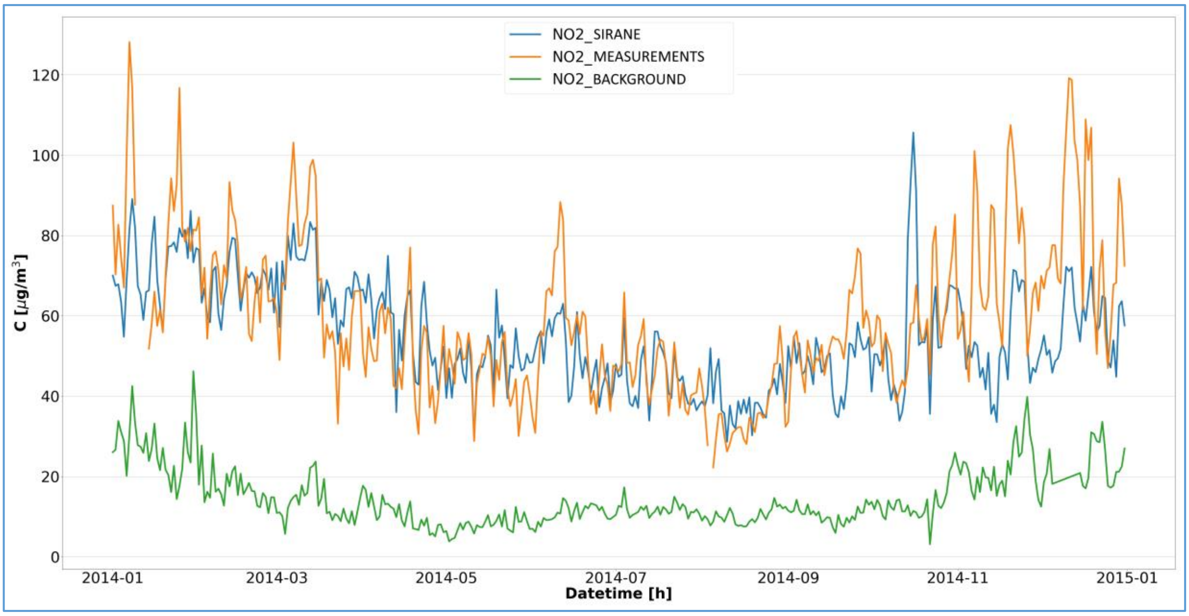

Fig. 8. Timeseries of modelled (blue) and measured (orange) concentrations of NO_2 in TO3 site and background values (green)

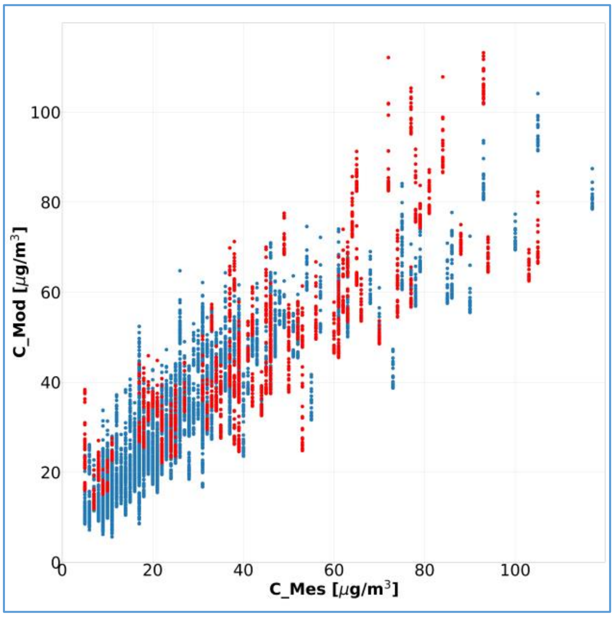

Fig. 9. Scatterplot of modelled and measured concentrations of PM10 in TO5. The red points correspond to the winter period

Comparison of modelled ground level concentrations in Torino and Lyon

To analyse the difference between air pollution levels in Torino and Lyon we compare the maps of concentration statistics at ground level. The two case studies present substantial differences. The model estimates higher annual concentrations of NO_2 and PM10 in Torino rather than Lyon, both in the city centres and suburban areas. This result is in line with the trends in concentrations measured by public monitoring networks.

The NO_2 annual mean concentrations in the two cities depend mostly on road traffic (Fig. 10). In Lyon, hot-spots exceeding two times the annual limit are represented by the A6-A7 highway sections close to Perrache train station and Fourviere hill (centre-left of the map) and extended parts of the two ring-roads “Périphérique Laurent Bonnevay” / “Rocade E” (eastward). This result is corroborated by the map of concentrations exceeding the hourly limit of 200 μg/m^3 (Fig. 11). In fact, the threshold of 18 hours beyond this limit is extensively respected in the domain excluding sections of highways, ring-roads and urban tunnels, particularly for the hot-spot of Perrache (and part of southern Vieux Lyon district). Most of the suburban areas respect the WHO limit of 20 μg/m^3. On the other hand, Torino is subjected to generally higher NO_2 pollution levels. The annual (mean concentration) limit is exceeded in a large part of the domain and in most of the urban area comprised between the hill (East) and the ring-road (West). Despite this, the hourly limit is exceeded to a lesser extent than in Lyon, in some sections of the ring-road and close to tunnel entrances.

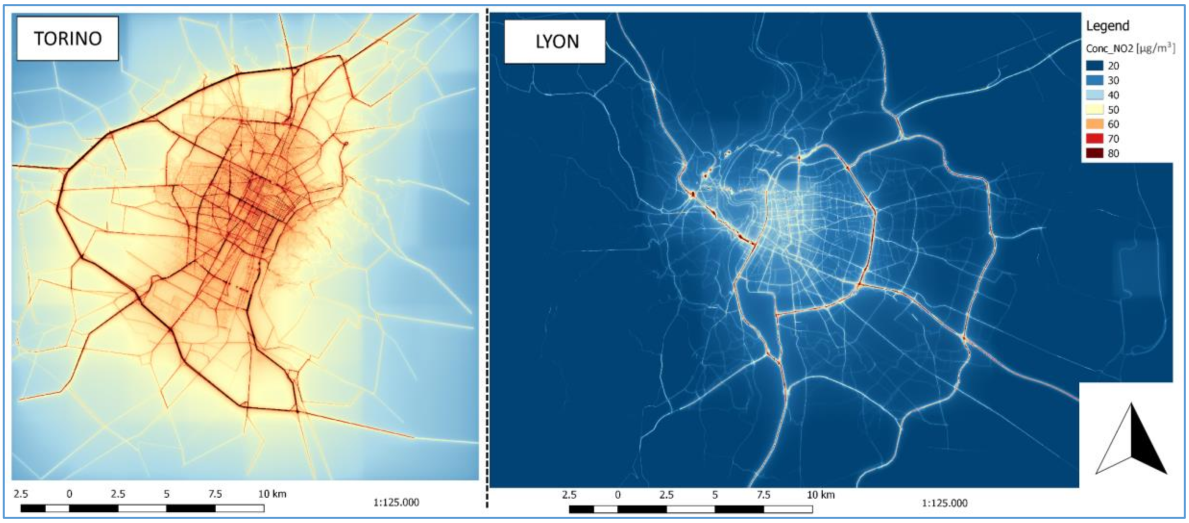

Fig. 10. NO_2 annual mean concentrations in Torino (left) and Lyon (right)

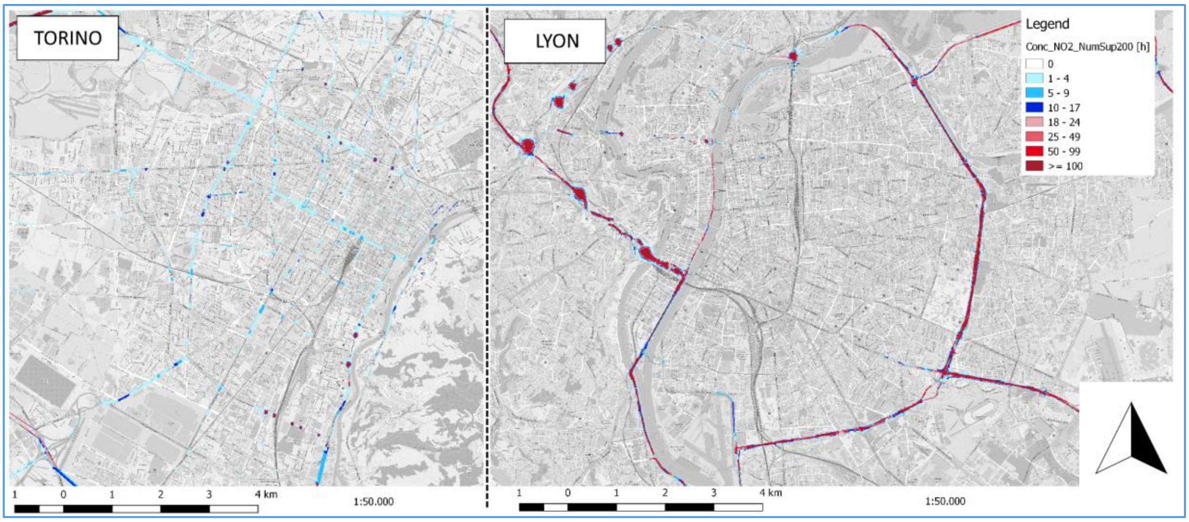

Fig. 11. NO_2 hourly threshold exceed in Torino (left) and Lyon (right)

Similarly, the PM10 concentrations (Fig. 12) decrease from the city to the neighbourhoods (but with reduced gradient compared to NO_2). Even though the two city centres present comparable concentrations, suburban districts and the countryside of Lyon have annual PM10 concentrations lower than in Torino. Therefore, regarding the pervasiveness of pollution episodes throughout the year (Georgopoulos et al., 1997), we have spatialized the amount of daily limit exceedances in the whole domain (Fig. 13). In Lyon, values over 50 $\mu g/m^3$ for more than 35 days per year are reached only in the central districts and close to main roads. In Torino, this limit has been exceeded also in peripheral areas, suggesting that pollutant episodes are more intense in Torino rather than Lyon.

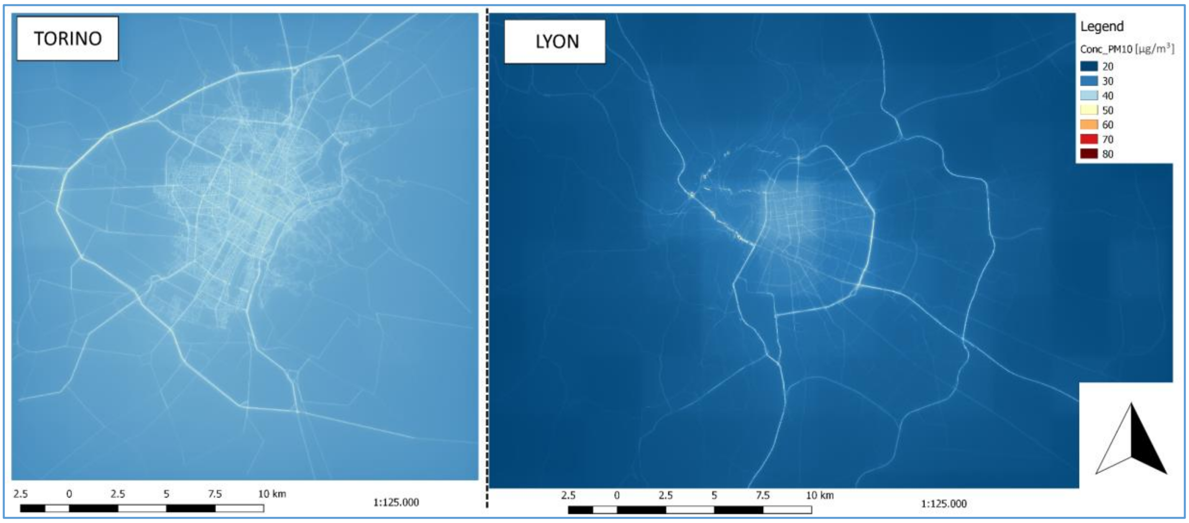

Fig. 12. PM10 annual mean concentrations in Torino (left) and Lyon (right)

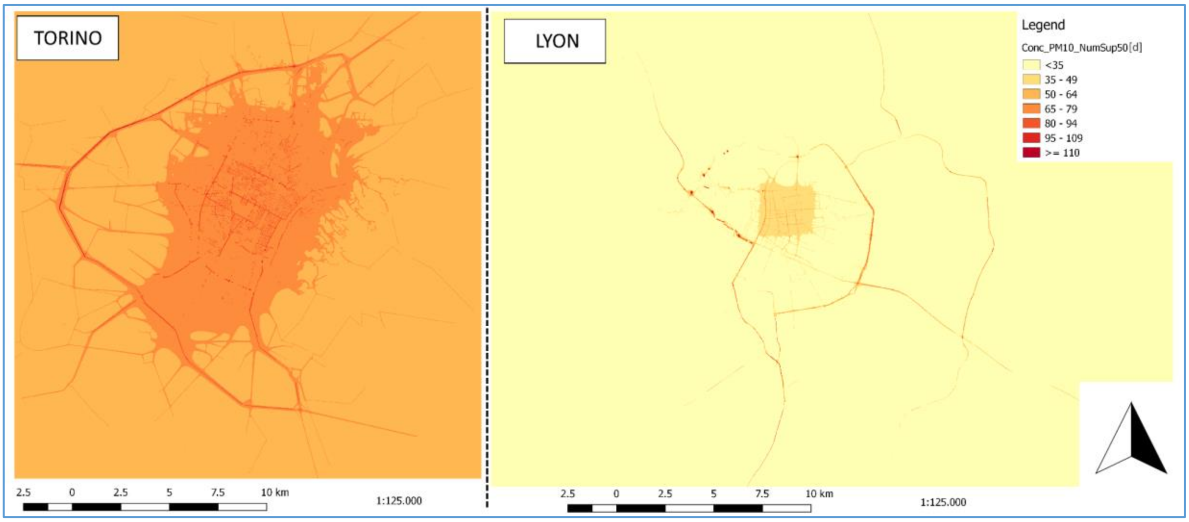

Fig. 13. PM10 daily limit exceedance in Torino (left) and Lyon (right)

From an overview of seasonal cartographies, the intensification of wintertime air pollution, favoured by domestic heating emissions, is observed in both the city centres (Fig. 14). However, a general increase of NO_2 and PM10 concentration in the whole domain is reported mostly for Torino boosted by its peculiar meteorological condition (§4). Accordingly, the suburban areas of Lyon further from traffic and heating sources present values under the annual limits also during the cold season.

The improved air quality during the hot season is similar in both scenarios. For Torino, NO_2 values under 40 $\mu g/m^3$ are observed in the external neighbourhoods and in some areas of the city, while intense pollution persists only close to the main roads. PM10 concentrations are computed under 30 μg/m^3 in most of the domain. In Lyon, the decrease of modelled values is larger than Torino. However, PM10 concentration in its city centre are slightly higher than in Torino (Fig. 15).

Finally, we stress that the significant differences in the two scenarios are related to the background concentration as clearly visible by the annual and seasonal concentration maps. NO_2 background concentration is almost twice as large in Torino and this off-course results in an overall increase of concentrations in the whole urban area. Similar results, which however are characterised by lower local emissions in the centre for Torino rather than Lyon, can be observed for PM10.

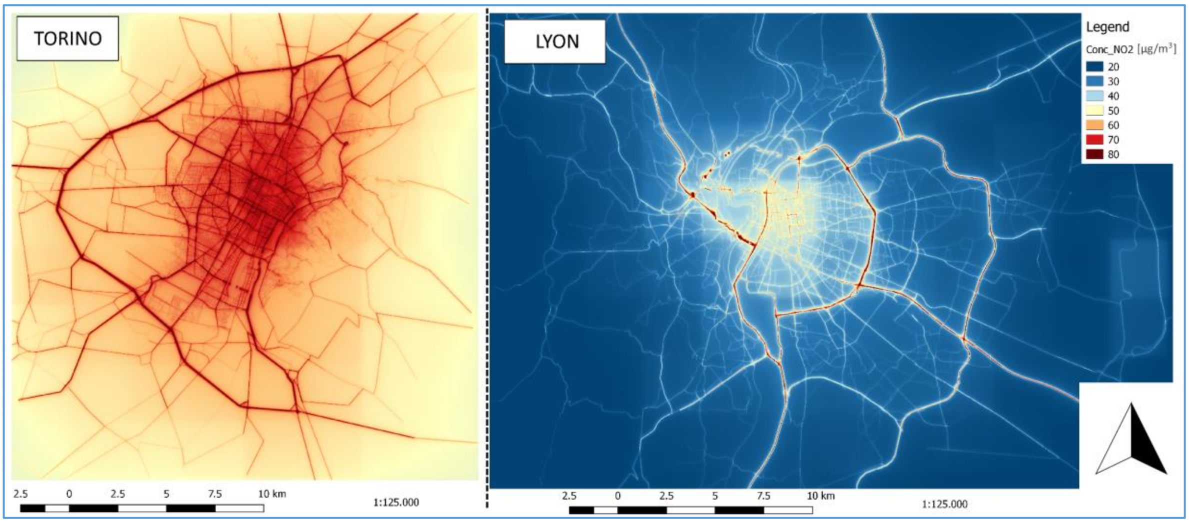

Fig. 14. Wintertime NO_2 concentrations in Torino (left) and Lyon (right)

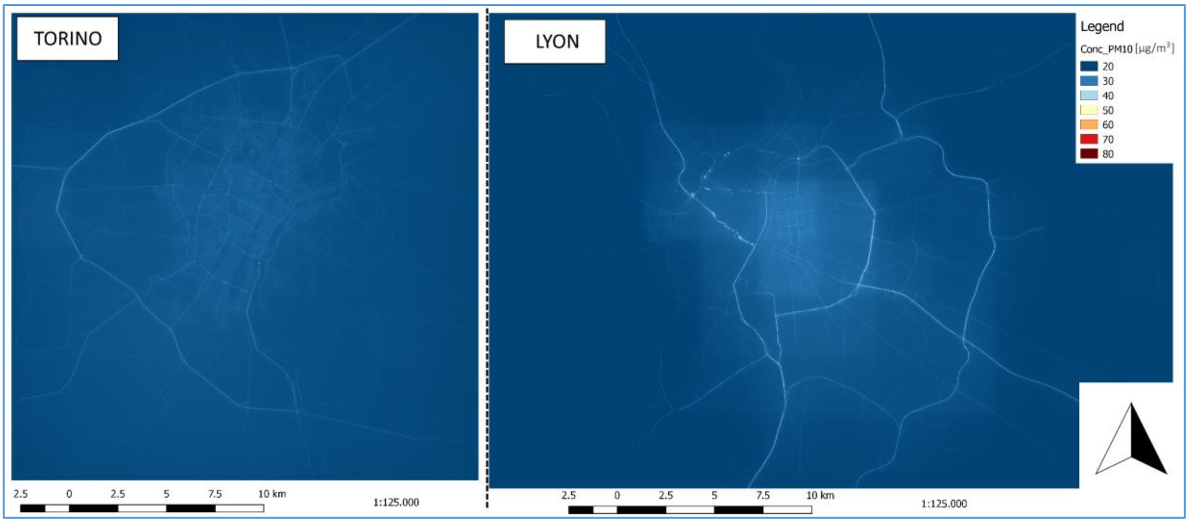

Fig. 15. Summertime PM10 concentrations in Torino (left) and Lyon (right)

On the influence of meteorological conditions

The analysis of the simulation results clearly shows that even though NO_X and PM10 emission levels are similar, ground level concentration in Torino are significantly higher than in Lyon. This statement can also be qualified considering the ratio between the measured concentrations at the selected AQMS (§2) and the local emissions within the simulation domains. In agreement with concentration trends (Fig. 2), the NO_2 concentration-emission ratio of Lyon and Torino are similar ($2.9\ 10^{-3}$ and $4.2\ 10^{-3}$ respectively). For PM10 the ratio in Torino ($2.3\ 10^{-2}$) is one order of magnitude higher than Lyon ($4.9\ 10^{-3}$). Therefore, the role of meteorological conditions forcing pollutant load has been enlightened.

In order to quantify this influence, we have simulated an ideal scenario by imposing Lyon meteorology on the Torino case study. In performing this analysis there are two main *caveats*. Firstly, we have to exclude the role of background pollution and consider only the contribution of local emissions. Indeed, this analysis at the local scale is meaningful as so far we can decouple the local urban geometry from the meteorological regimes. For obvious reasons this does not hold when considering pollutants dispersion on a regional scale. Secondly, we have to refer to passive pollutant species, which again allows us to decouple the local dispersion from possible interactions with the background pollution.

The results show an overall reduction of NO_X and PM10 concentrations. Focusing on the selected receptors, wintertime decreases range between -15% and -47% for NO_X and -18% and -43% for PM10. During summertime the share is comprised between +10% and -26% for both pollutants. No significant deviation among background and traffic stations is observed. The share of reduction between the two scenarios, represented with regards to the city centre where the contribution by direct sources is dominant (Fig. 16), agrees with the results at receptors. Most of the reduction in the city centre is included between 20% and 40% which can therefore be assumed as a reference value when estimating the overall influence of the local meteorology (Fig. 17). Deviation from this range can be observed locally (i.e. close to urban tunnels) but is mainly due to the effect of the variations of the wind rose (Fig. 5) on ground level concentrations.

Similarly, we have performed an analog simulation in Lyon imposing the meteorology of Torino (Fig. 17). Consistently with what observed in Torino, the results show an increase of both NO_X and PM10 concentrations. We can identify two main effects. Firstly, a general increase over the whole urban agglomeration of Lyon (between 25% and 40%) due reduced wind speeds and altered stability conditions. Secondly, we clearly observe an accumulation of pollutants in the southern part of the city, in which ground level concentrations are enhanced by 40%, an effect due to the fact that the wind rose in Torino is not characterised by dominant winds in the north-south direction as those in Lyon (Fig. 5) Overall, the general increase of ground level concentrations corroborates the significant contribution of the adverse meteorology of Torino to its low air quality.

According to the above, the need for integrated actions considering both the extended territory of the Po valley and the urban agglomeration of Torino is evident. The focus of air quality policies should be directed towards systemic interventions in the entire region rather than "when needed" and localised actions during acute pollution events. In fact, seeing the limited efficacy of temporary and discretional emissive sources rationing (Davis, 2008; Li et al., 2018; Wembo, 2019), which have been the predominant mitigations implemented in this area in last decades, a change in the AQ intervention paradigm must include site-dependent mitigation actions over a spread area and considering, at least, seasonal scenarios and the reshaping of population behaviour. An analysis of systematic community interventions is currently being developed supported by measuring and modelling activities (i.e. a further validation of SIRANE in Torino for 2019), including a participative project of citizen science in collaboration with a local civic committee (Bo et al., 2020).

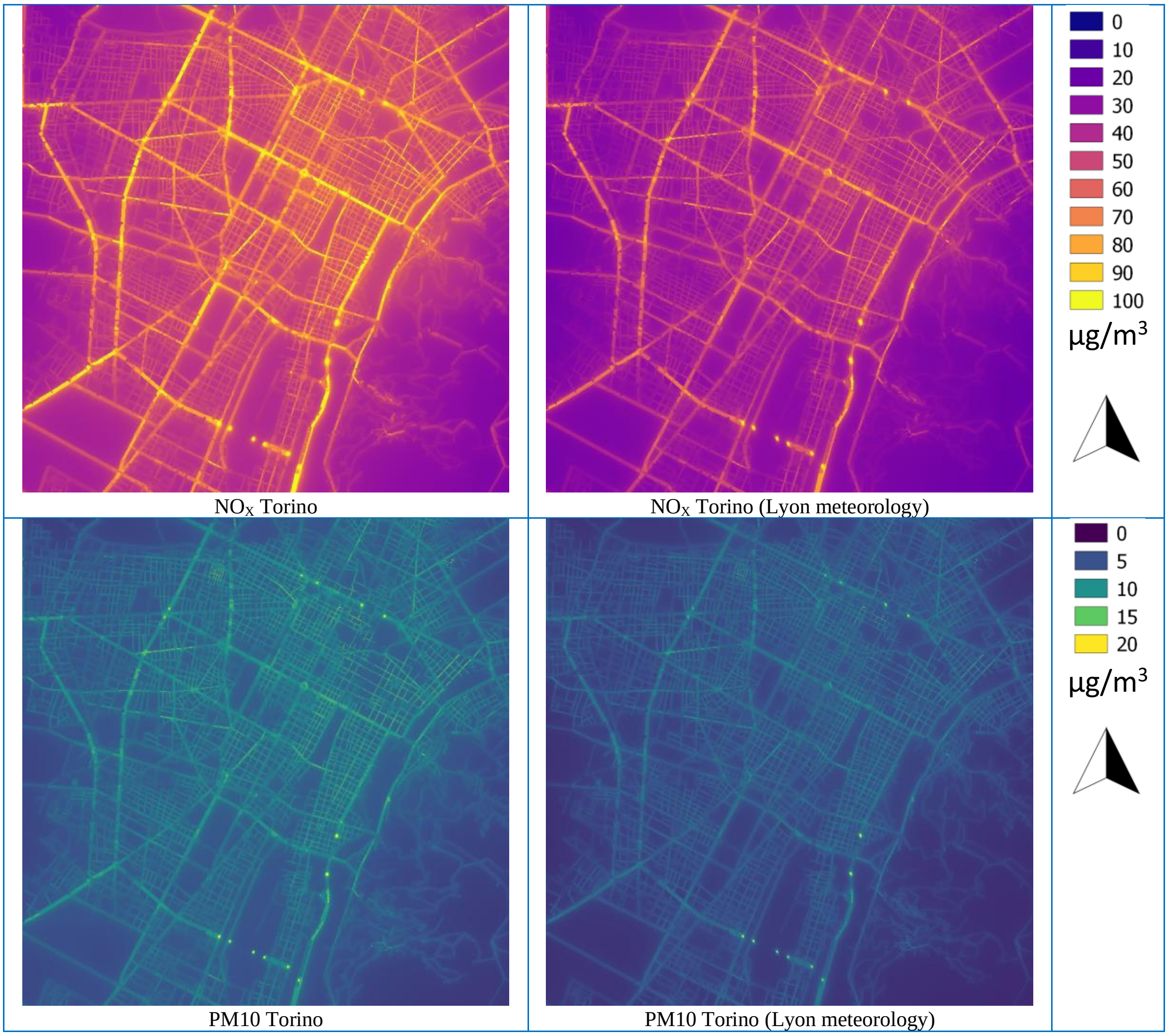

Fig. 16. Comparison between NO_X (above) and PM10 (below) reduction using Torino (left) and Lyon (right) meteorology

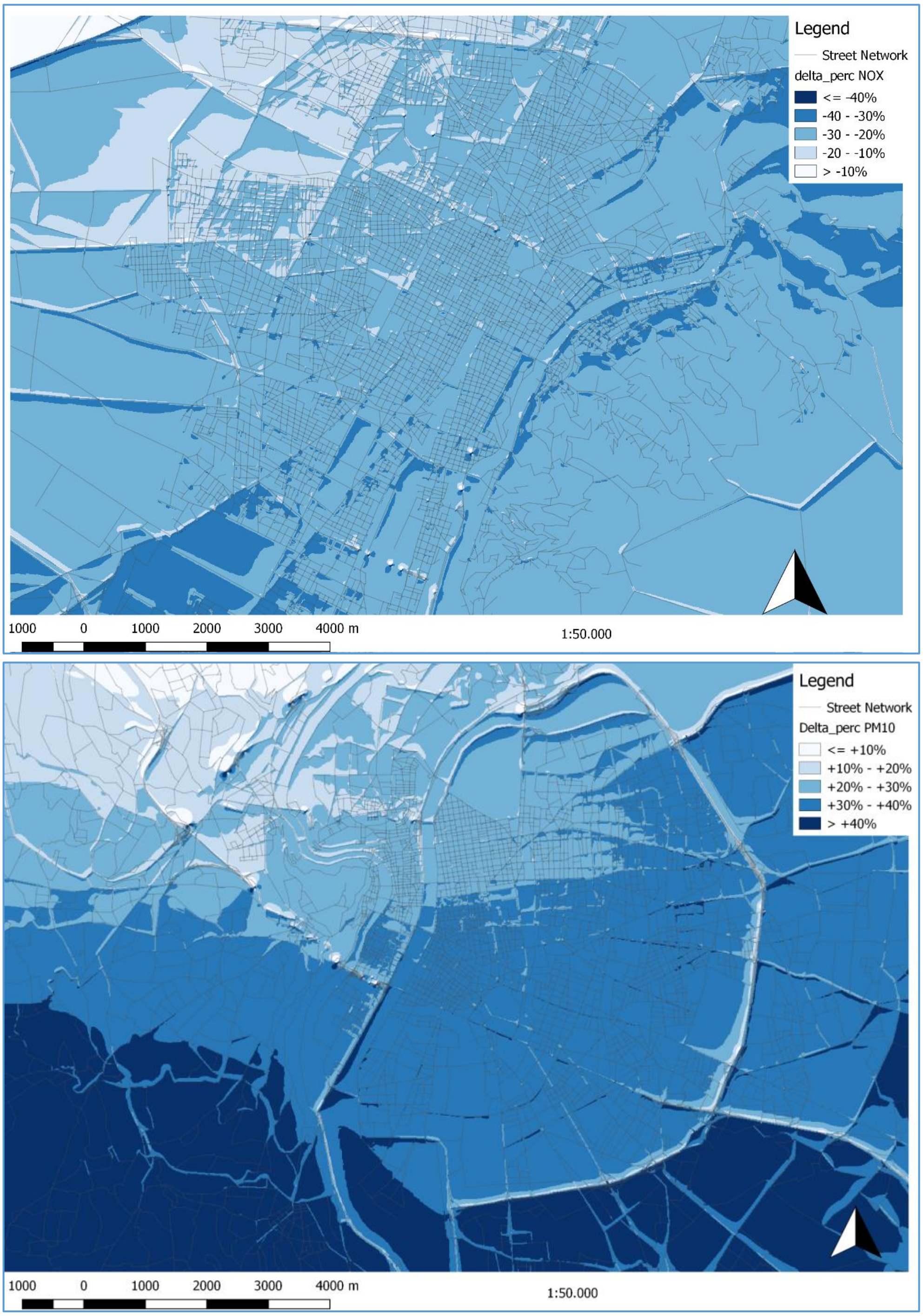

Fig. 17. Relative decrease in percentage of NO_X concentration in the Torino city centre imposing a meteorological field identical to that of Lyon (top) and counter-evidence simulation in Lyon using meteorology of Torino (bottom)

7. Conclusion

The aim of this study was to compare the air quality of two urban agglomerations in order to demonstrate the role of meteorology on pollutant dispersion. The study assessed two cities located on opposite sides of the Alps with similar characteristics in terms of size and population. A preliminary picture of air quality is provided by the analysis of the historical trends of concentrations measured in AQMS. Both the datasets are characterised by a similar reduction trend in the past decades but the values in Torino are systematically higher than the values in Lyon.

To get further insights on these differences in concentrations simulations of various scenarios have been performed, focusing on NO_X and PM10 pollution for the year 2014, with the urban dispersion model SIRANE. This model based on a street network approach (Soulhac et al., 2011) requires four kinds of input data: urban geometry, local meteorology, pollutant emissions and background concentrations. Despite emissions were shown similar, simulation results show that mean annual concentrations of both pollutants are significantly larger in Torino. This is due to the peculiar meteorological regime of the Po valley characterised by a high percentage of wind calm conditions evenly distributed throughout the year and severe atmospheric stability during wintertime.

The role of these factors is directly taken into account in our simulations for what concern the dispersion of pollutants emitted within the domain (that we have been referring as local pollution) and indirectly by considering background pollution levels provided by AQMS out or close to the domain (therefore located away from main sources of emissions).

In order to quantify the role of meteorological conditions we have performed simulations in Torino and in Lyon by inverting the meteorological dataset characterising the atmospheric circulation over the two urban agglomerations. As an outcome we observed a general reduction of ground level concentration in the range 20-40% in Torino, and an equivalent increase in Lyon. We can therefore assert that the difference between the two meteorological regimes implies a burden load of pollutants over the Torino urban area ranging between 20-40%.

Based on the results, the design and application of systemic emissions' control policies and pollutants concentration mitigations should be strengthened at all institutional levels in order to comply with both normative and guide limits for health protection. Ambitious and severe actions should be undertaken with regards to the large urban and suburban agglomeration of Torino and the entire Po valley. In this sense the cross-regional agreement between the regions belonging to the megacity represents a first step (Regione Emilia-Romagna et al., 2017). However, the operational effectiveness of formal acts depends on financing and vision beyond what is currently done in terms of "as-needed" approaches and market interests.

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Appendix

Statistical indices used to evaluate model performance (C_m is the measured concentration and C_p is the predicted concentration)

Index	Definition	Optimal value	Criteria

Fractional bias	$FB = \frac{(\overline{C_p} - \overline{C_m})}{(1/2\,(\overline{C_p} + \overline{C_m}))}$	0	$\lvert FB\rvert \leq 0.3$
Normal mean square error	$NMSE = \frac{\overline{(C_p - C_m)^2}}{\overline{C_p}\,\overline{C_m}}$	0	$\sqrt{NMSE} \leq 2$
Relative error	$ER = \overline{\left(\frac{\lvert C_p - C_m\rvert}{1/2\,(C_p + C_m)}\right)}$	0	
Correlation coefficient	$R = \frac{\overline{(C_p - \overline{C_p})(C_m - \overline{C_m})}}{\sqrt{\overline{(C_p - \overline{C_p})^2}\,\overline{(C_m - \overline{C_m})^2}}}$	1	
Geometric mean bias	$MG = e^{\overline{[\ln(C_p) - \ln(C_m)]}}$	1	$0.7 \leq MG \leq 1.3$
Geometric variance	$VG = e^{\overline{[(\ln(C_p) - \ln(C_m))^2]}}$	1	$VG \leq 1.6$
Fracion in a factor of 2	$FAC2 = \frac{C_p}{C_m}$	1	$0.5 \leq FAC2 \leq 2$
Willmott's index	$WI = \begin{cases} 1 - \frac{\sum_{i=1}^{n}\lvert C_{p,i} - C_{m,i}\rvert}{c\sum_{i=1}^{n}\lvert C_{m,i} - \overline{C_m}\rvert}, & \text{when } \sum_{i=1}^{n}\lvert C_{p,i} - C_{m,i}\rvert \leq c\sum_{i=1}^{n}\lvert C_{m,i} - \overline{C_m}\rvert \\ \frac{c\sum_{i=1}^{n}\lvert C_{m,i} - \overline{C_m}\rvert}{\sum_{i=1}^{n}\lvert C_{p,i} - C_{m,i}\rvert} - 1, & \text{when } \sum_{i=1}^{n}\lvert C_{p,i} - C_{m,i}\rvert > c\sum_{i=1}^{n}\lvert C_{m,i} - \overline{C_m}\rvert \end{cases}$	1	

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