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HETEROGENEITY OF ACCUMULATION AND DISPERSION CONDITIONS FOR PM10 IN THE PO VALLEY

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Abstract: In this study the usefulness of deploying a network of planetary boundary layer (PBL) profilers on the scale of the Po Valley portion of the north-eastern Italian region Veneto is addressed. This is done analyzing the regional-scale heterogeneity of accumulation and dispersion conditions for atmospheric pollutants (e.g. particulate matter) in terms of thermal stratification and mixing height (Hmix) on a five-year data set. Comparison of the temperature profiles retrieved by the microwave radiometer (MWR) network with radio soundings in homogeneous PBL conditions yields reasonable and consistent agreement over this period, with biases in the order of 1K or less at 00UTC and 1-2K at 12UTC. The inventory of winter temperature inversions shows that there seem to be more shallow (50-300m) and intense inversions in rural areas than in urban areas, whereas in the latter higher inversions (at about 700m) do prevail. The impact of the MWR-retrieved temperature profiles on the surface energy balance-based Hmix estimation yields an average difference in the order of 20% compared to the radio sounding-only estimates and regional differences of the same magnitude. Finally, the PM10 concentration distribution for the area exhibits large differences in 16%, still significant in 35%, of the episodic conditions, defined as concentrations exceeding the 90^{th} percentile value, giving an upper limit of the usefulness of local profile information. A case study is presented in which differences in the temperature inversion and Hmix are consistent with significant differences in dispersion conditions and, therefore, PM10 concentrations.

Key words: *microwave radiometer, mixing height, PM10, dispersion conditions, Po Valley, spatial variability, temperature inversion.*

INTRODUCTION

On a European scale the Po Valley can be viewed as a hot spot in relation to air pollution issues, especially during the cold seasons, which feature frequent occurrences of low wind and high static stability conditions, often accompanied by marked temperature inversions. As a matter of fact, on the basis of a documented adverse climatic dispersion conditions, the European Commission has recently granted to a number of regions, including the Po Valley, an exemption from the obligation to apply the limit values for PM10, legally binding since 1^{st} January 2005 in accordance with Council Directive 1999/30/EC. This exemption, however, is conditional to a formal commitment to take the necessary abatement action with the view of ensuring compliance with the limit values in 2011, which still constitutes a formidable challenge and requires concerted action at a national level.

It is generally acknowledged that the meteorological conditions are a very strong driver for air quality, as they determine the level of dispersion, where the dominant actors are near-surface winds and thermal static stability in the planetary boundary layer (PBL), both important source terms in the budget equation for turbulence and, thus, mixing. As air quality dispersion modelling relies on a realistic representation of these mechanisms the Regional Agency for Environmental Protection of the north-eastern Italian region Veneto (ARPAV) has installed in 2005 a PBL profiler network which consists of four passive microwave radiometers (MWRs) for retrieving temperature profiles and four SODARs for retrieving wind profiles.

In this study the quality of the temperature profiles gathered in the last five years is documented and two applications are explored. First, an inventory of temperature inversions is constructed and, second, the impact on the estimation of the PBL mixing height assessed, both strongly linked to the dispersive potential of the atmosphere. In particular, consideration is given to the spatial variability of these factors, in order to assess the usefulness of deploying a network of profilers on an area of the scale of the region Veneto (ca. 12.000km^2 for the plain).

QUALITY OF THE MICROWAVE RADIOMETER-RETRIEVED TEMPERATURE PROFILES

The HATPRO radiometer is manufactured by Radiometer Physics GmbH, Meckheim (D). It measures radiation emitted by the atmosphere in 14 channels (molecular oxygen and water vapour lines) and converts this data into profiles for temperature and humidity (Rose 2005) via a neural algorithm optimized for the measuring site. In addition, the instrument installed in Legnago performs a vertical scan every 20 minutes for temperature with variable vertical resolution (50m up to 2000m) in the PBL, where the declared accuracy is 1K. In 2009 HATPRO participated in the LUAMI campaign in order to compare temperature and humidity profiles with the COSMO model outputs. The 2 MTP-5 HE radiometers are manufactured by Attex, Moscow (RUS), and distributed by Kipp & Zonen, Delft (NL). They use a microwave receiver which is highly sensitive to radiation in the 5 mm wavelength (60 GHz frequency) band. In essence MTP-5 is ‘black-body’ thermal radiation from the atmosphere the intensity varies with the temperature. This instrument reports a good agreement (Westwater 1999, Kadygrov 2003). All instruments are set to have the first level at 50m.

The meteorological stations of Legnaro and Sant’Apollinare are manufactured by MTX, and installed following the WMO indications and the standards ISO 9001, too. These are the reference stations for meteorological conditions in Padua and Rovigo. International radio sounding stations aren’t present in Veneto region; closest points are Milano Linate (SYNOP 16080 160km West) and Bologna S. Pietro Capofiume (SYNOP 16144 at 25km South). Air quality stations are located in Padua area (urban: Padua Mandria, Arcella and Granze, rural: Monselice) and in Rovigo area (urban: Rovigo Center, Castelnuovo Bariano and Adria). Most of the stations use gravimetric technique and some beta attenuation method (Arcella and Monselice). The measuring sites are flat and rural (Legnago, Legnaro and Sant’Apollinare), flat and sub-urban (Rovigo), flat and urban (Padua).

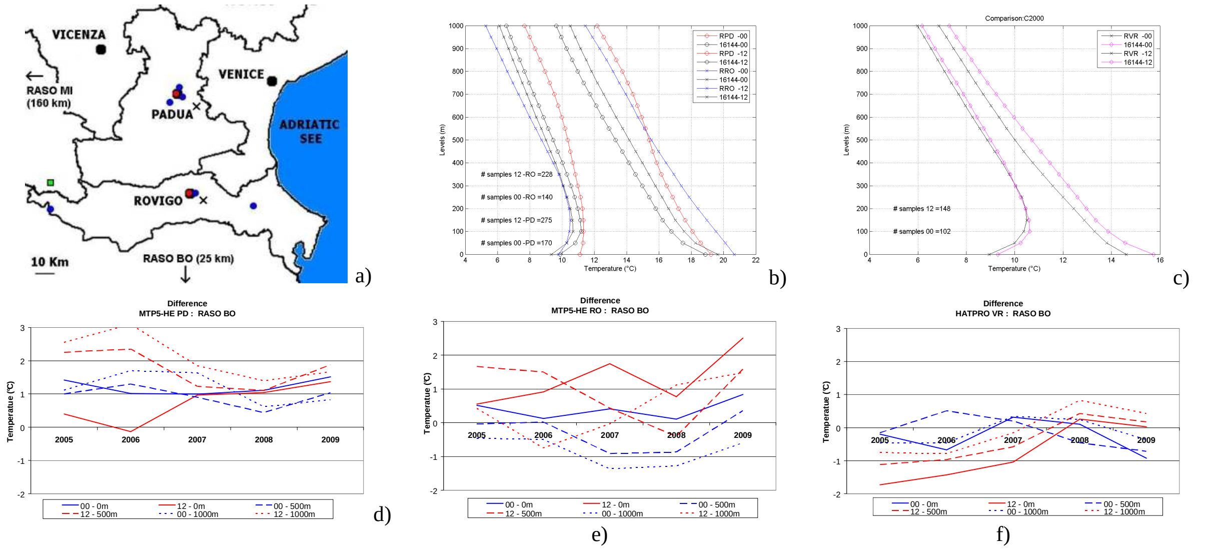

Figure 1. Panel a) shows southern part of Veneto. The blue points are the air quality PM10 stations, red points denote the MTP-5 HE radiometers, the green square the HATPRO radiometer, black crosses meteorological stations, and RASO the nearest radio sounding stations. Panels b) and c) show comparisons between the radio sounding in Bologna (black) and the MTP-5 HE radiometers in Padua (red), in Rovigo (blue) and HATPRO in homogeneous atmospheric conditions for 00UTC and 12UTC. Panels d), e) and f) show the 5-year average temperature differences between RASO and the three MWR profiles for the levels 0, 500, and 1000m.

Table 1. Data availability (%) for MTP-5 HE, HATPRO and radio soundings (Fig. 1) from 1st January 2005 (operating from *March or #August 2005).

Instrument - Station	2005	2006	2007	2008	2009
MTP-5 HE PD Padua	73.1*	100	97.4	99.5	99.7
MTP-5 HE RO Rovigo	72.8*	86.4	97.5	(59.1) 99.2	79.6
HATPRO VR Legnago	34.7 #	70.3	41.3	50.5	51.7
RASO MI+ - Linate	83	92	56	63	55
RASO BO+- S. Pietro Capofiume	100	97	99	100	98

The data set used in this study spans the year from 1 March 2005 to 31 December 2009, for which the data availability is reported in Tab. 1 at 00 and 12UTC. For the comparison exercise the radio sounding stations of Milano Linate and Bologna S. Pietro Capofiume were used (see Fig. 1a). As none of the radiometers was collocated near a radio sounding, a set of time steps were identified for which the soundings of Milano and Bologna are close to the lowermost kilometer, i.e. the temperature difference is smaller than 2K. These are taken as conditions of "thermal homogeneity" for which we can assume that the radiometers of Padua and Rovigo should both be reasonably close to the radio soundings. All data have been interpolated on a vertical grid with a level every 50m, starting at the surface (0m) and reaching up to 1000m.

The overall data quality resulting from this method is displayed for the MTP-5 HE MWRs in Fig. 1b) and for HATPRO in Fig 1c). The best correspondence is found for the MWR located at Rovigo (RO) with a BIAS of less than 1K at 00UTC throughout the entire range and 1-2K at 12UTC. In comparison, the Padua MWR (PD) shows a slightly larger and consistently warmer BIAS reaching 1-2K at night and up to 3K at upper levels during the daytime. The MWR HATPRO in Legnago (VR), on the other hand, shows excellent agreement in terms of the BIAS, which is close to zero at 00UTC and is still well below 1K at 12UTC. Fig 1d), e), and f) shows the yearly BIASs at three distinct levels as a function of the years. The data quality is quite consistent in time, with the exception that PD warm bias, clearly present in 2005 and 2006, somewhat decreases. In summary, the average structure is deemed to be adequate for the use of characterizing temperature inversions and estimating the PBL mixing height (Hmix), and is in line with the results reported in Ferrario M.E. (2006) and references therein.

INVENTORY OF TEMPERATURE INVERSIONS

An overall inventory of temperature inversions as diagnosed by the three MWRs PD, RO, and HATPRO VR are shown in Fig. 2 and further quantified in Tab. 2. First, it is remarkable that the wintertime Po Valley is characterized by the presence of temperature inversions almost 70% of the time for PD and RO, and more than 30% with no inversions, for rural VR it is even 73%-27%. In comparison, the night-time hours for the October-to-March period add up to 59%. The urban site of Padua (PD) features many more weak inversions with a top generally below 700m, while the rural site of Legnago (VR) has more intense inversions. The smaller city of Rovigo (RO) shows a somewhat intermediate behaviour. The fact that PD and, to a lesser extent, RO, have a maximum in the frequency distribution of the inversions with a top at 700m, as well as relatively many weak inversions aloft, could be an instrumental artefact of the MTP-5 HE MWR, which has a maximum range of 1000m with less resolution in the top half of the range. On the other hand, it is hypothesized that a modest urban effect could lead to such a distribution, where more mixing and even a small urban heat island effect could lead to a slightly warmer residual layer which acts as inversion top when the surface has cooled. Also, there are many more shallow inversions at the rural site of VR where the radiative cooling is more efficient.

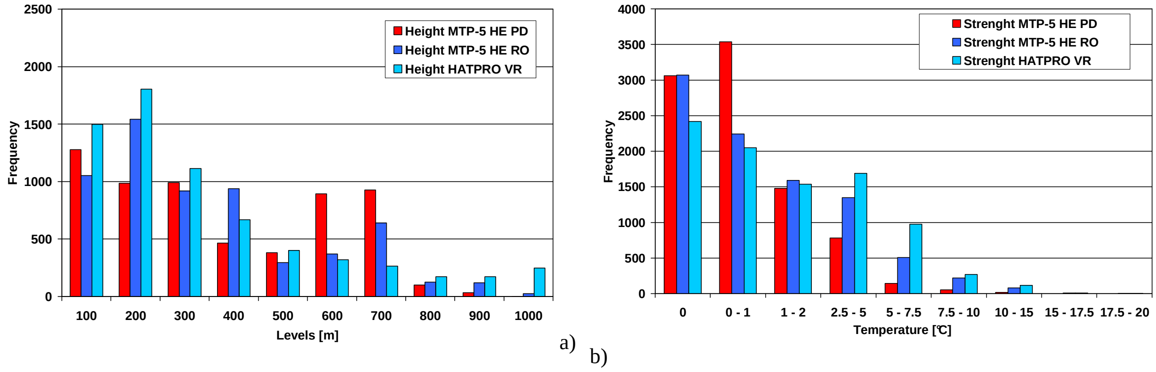

Figure 2. Frequency distribution of temperature inversions height (panel a) and strength (panel b, functioning of all MWRs required).

Table 2. Inventory of temperature inversion for the entire study period (functioning of all MWRs required). Surface-based inversions are termed 'surface', while inversions which start above the surface are termed 'aloft'. Weak inversions denote inversions with a temperature difference smaller than 1K.

	total hours	total hours with inversion	surface weak	surface strong	aloft weak	aloft strong	no inversion
Padua PD MTP-5 HE	9083 100%	6021 - 66%	1967 - 22%	1926 - 21%	1572 - 17%	556 - 6%	3062 - 34%
Rovigo PD MTP-5 HE		6012 - 66%	1372 - 15%	3122 - 34%	870 - 9%	648 - 7%	3071 - 34%
Legnago VR HATPRO		6665 - 73%	1477 - 16%	3894- 43%	574 - 6%	720 - 8%	2418 - 27%

Table 3. Differences in the frequency distribution of the presence of temperature inversions in Padua, Rovigo, and Legnago.

All 3 MWRs have inversions	2 MWRs have inversion		1 MWRs has inversion		All 3 MWRs haven't inversions
4770 - 52%	no PD	654 - 7%	yes PD	354 - 4%	1476 - 16%
	no RO	467 - 5%	yes PO	158 - 2%	
	no VR	430 - 5%	yes VR	774 - 9%	

As to the regional differences, Tab. 3 highlights that in more that half of the time all three MWRs diagnose a temperature inversion, while in only 16% no temperature inversion is present in all three sites. This leaves about a third of the time where there are regional differences in terms of presence of temperature inversions. For example, in 7% of the time only the rural site VR features an inversion, whereas in 5% of the time VR is the only MWR not diagnosing an inversion.

PBL MIXING HEIGHT ESTIMATES

The PBL mixing height (Hmix) is estimated with the energy balance method used, for instance, in the meteorological pre-processor CALMET (Scire *et al.* 2000). The method determines the sensible heat flux at the surface, as well as the Monin-Obukhov length and the friction velocity, from which Hmix is calculated for day and night time separately, each in two ways. During the day the heat flux and the temperature profile are used to determine the mixing height due to convective turbulence and, separately, for mechanical turbulence, of which the maximum value is taken as the Hmix estimate. During the night empirical relations for thermal and mechanical turbulence are used. Thereby the surface parameters, fixed in time, play an important role in inducing local differences. The variability of the long-term Hmix is, therefore, a result of these local surface parameters, the wind climatology and the vertical temperature profile, which, taken from the three radio soundings, is only weakly ranging on the scale of the Veneto plain (Fig. 1)

Figure 3 provides an overall appreciation of the impact of local MWR-derived temperature profiles for the estimates of the PBL mixing height Hmix. When the MWR data are included, the mean Hmix for PD is 100m or almost 20% lower than the estimation with method based only on the radio sounding data. For the average 95th percentile value this difference increases to about 200-300m. For the RO site the impact of the local temperature profile results to be smaller. As far as regional-scale variability in the mixing height are concerned, the study highlights systematic differences, in that average Hmix is about 100m or 15% higher in RO than in PD. For the higher Hmix values this difference increases up to 400m or about 30%. Also, a different diurnal evolutions of the PBL is suggested in that the Hmix for PD features a slightly earlier and more steady raise than RO which appear consistent with the long lasting temperature inversion in RO. Note, that these average profiles were obtained on the entire data set for all October-to-March months for the years 2005-2009, when both MWR in PD and RO data were available, including both stable and perturbed synoptic conditions.

DISTRIBUTION OF PM10 CONCENTRATIONS

In order to illustrate the impact of the differences in PBL conditions on the air quality we discuss a case study in which such differences indeed exist and are reflected in the PM10 concentrations. Fig. 4a) shows the temperature inversions of the site of PD and RO for 12th January 2009 along with the corresponding mixing height evolution for the day. It emerges very clearly

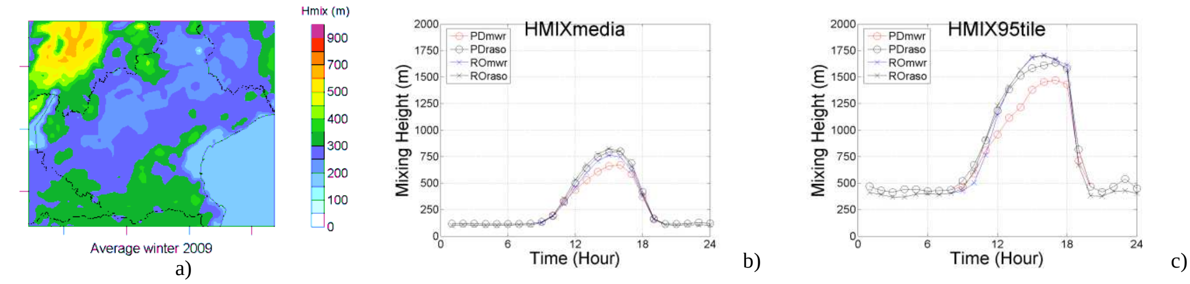

Figure 3. Panel a) shows average Hmix from cold season (Oct-Mar) 2008-09 calculated with CALMET 5.8, panel b) the 5-year cold season daily average evolution of Hmix from 2005 to 2009 for Hmix based only on radio soundings, and including MTP-5 HE data for Padua (black and red circles, respectively) and Rovigo (black and blue asterisks). Panel c) as in panel b) but for the hourly 95th percentile value.

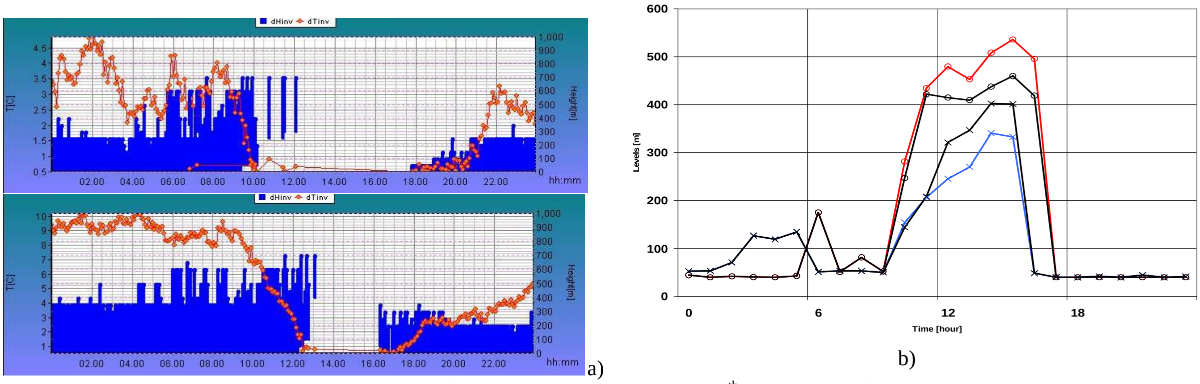

Figure 4. Panel a) shows the strength and height of the temperature inversion on 12th January 2009 for Padua (upper) and Rovigo (lower), while panel b) shows the mixing height for Padua (red circles) and Rovigo (blue crosses) calculated with MWR and with radio soundings only (same labels in black).

Table 4. 2005-2009 all-year and cold season-average of and cold-season correlations coefficients between PM10 concentrations of a number of stations in the study area (cf. Fig. 1a).

	PD Mandria	PD Arcella	PD Granze	PD G. Reni	PD Monselice	RO Centro	RO Castelnuovo	RO Adria
From 2005-2009	46.9	54.7	47.5	45.3	39.0	42.3	39.9	30.0
All winters	62.5	73.3	63.0	58.5	49.3	56.2	56.5	39.8
PD Mandria	1.00	0.96	0.93	0.97	0.83	0.88	0.86	0.62
PD Arcella		1.00	0.91	no data	no data	0.87	0.86	0.66
PD Granze			1.00	0.94	0.82	0.84	0.78	0.60
PD G. Reni				1.00	0.80	0.85	0.83	0.57
PD Monselice					1.00	0.84	0.78	0.61
RO Centro						1.00	0.92	0.69
RO Castelnuovo							1.00	0.74
RO Adria								1.00

that for RO the temperature inversion is much more persistent and the mixing height lower, both of which are consistent with the significantly higher PM10 concentration for this day. Indeed, the stagnant conditions which caused high concentrations the day before in PD, relaxed and caused a PM10 decrease (from 100 to 75μg/m^3), while they intensified in RO, consistent with a marked increase in the air pollution (from 90 to 135μg/m^3). Note that the mixing height is not the only factor determining PM10 levels (Fig. 4b, Scire *et al.* 2000).

More systematically, the regional variability of the PM10 concentrations is reported in Tab. 4. The first two rows report the average concentrations for the five year study period and the respective cold seasons, while the other rows show the correlation coefficients between the stations, greater than 0.8 for the RO city centre PM10 station and the PD stations. The smallest correlations are found between the urban stations of PD and RO with the rural station of Adria which is located towards the coast.

Table 5 reports significant PM10 concentration differences in episodic conditions. This analysis has been made for 587 days, in relative terms for the stations of PD and RO, as they have a different overall concentration level where the PD concentrations are consistently higher. Technically, the concentration time series for the two cities were ranked and the analysis made on these ranked series. It emerges that in episodic conditions (concentrations above 90%ile, i.e. 108 μg/m^3 for PD, 94 μg/m^3 for RO) most of the time (65 days or 6%) both sites exhibit high concentrations (>90%ile), whereas when RO is in episodic conditions and PD is below the 70%ile in 14 cases (below 80%ile in 23 cases), and vice-versa in 9 (24) cases. The other days with episodic conditions with smaller differences are 67 (48). Presence of large (still significant) regional

Table 5. Comparison of the frequency distribution of episodic conditions (PM10 > 90%ile) for Padua (PD) and Rovigo (RO). Significant regional differences are reported in the columns RO-PD>N% and PD-RO>N%, where the PM10 percentiles between PD and RO differ more than N%, where N=10 and N=20.

PD & RO > 90% 65 - 6%					
RO > 90% &	70% < PD < 90%	34 - 3%	RO > 90% &	80% < PD < 90%	24 - 2%
PD > 90% &	70% < RO < 90%	33 - 3%	PD > 90% &	80% < RO < 90%	24 - 2%
RO	RO-PD>20%	RO-PD>10%	PD	PD-RO>20%	PD-RO >10%
>90%	14 - 10%	23 - 17%	>90%	9 - 6%	24 - 18%
>80%	20	46	>80%	19	52
>70%	38	78	>70%	35	84

variability with differences of 20% (10%) is, therefore, in the order of 16% (35%) of the time episodic conditions are present in the region, larger for smaller differences. This analysis suggests an upper limit of 16% (35%) of the time it can be useful to dispose of local information on PBL conditions, e.g. for air quality forecasting or for meteorological pre-processors to dispersion modelling.

CONCLUSIONS

In this study a five-year data set of planetary boundary layer (PBL) temperature profiles retrieved from microwave radiometers (MWR) and their application to air quality issues, including modelling, was presented. The main findings can be summarized as follows:

- Comparison with radio sounding data located at some distance in homogeneous conditions suggest that the MWR-retrieved temperature profiles are useful and of consistent quality, with a bias smaller than 1K at midnight and up to 2-3K at noon;
- The inventory of temperature inversions over the Po Valley portion of Veneto yields a presence of inversions of up to 73% of the time for the October-to-March periods, where this value is slightly smaller for urban locations; urban inversions tend to be weaker and more detached from the ground, while rural inversions can be much more intense and are more frequently shallow; regional differences occur in the order of 30% of the time;
- The MWR temperature profiles impact the mixing height (Hmix) estimates based on radio sounding profiles in that most of the time the resulting Hmix is smaller (up to 20% for the urban site); regional differences in the order of 15% emerge from the analysis;
- A case study was shown in which differences in the temperature inversion structure and the mixing height were consistent with changes in the PM10 concentration between the cities of Padua and Rovigo (60km apart).

The usefulness of having a network of PBL temperature profilers is judged on the basis of these differences and the number of days in which significant differences in PM10 concentrations are present. The latter are found to be 16% for large, 35% for still significant PM10 concentration differences. Given the fact that PM10 concentrations are not only dependent on the mixing height and the presence of temperature inversion, this estimate has to be regarded as an upper limit. A meteorological pre-processor, like CALMET for example, would be an ideal framework to make best use of this local information.

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