CLIMATOLOGY OF THE STATIC STABILITY OF THE NIGHT-TIME PO VALLEY PBL FROM RADIO SONDES AND PASSIVE MICROWAVE RADIOMETERS

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1. INTRODUCTION

The Po Valley is well known for air quality issues due to scarce ventilation and frequent very stable conditions of the planetary boundary layer (PBL). In this study the static stability of the near surface layer is evaluated based on the night-time radio soundings (00 UTC) for the period 1973-2011, and on microwave radiometers (MWR) installed by ARPA Veneto (ARPAV) in 2005. Five radio soundings are analyzed of which only three (Milan, Bologna, Cuneo) are in the Po Valley, while two (Rome, Udine) are not (Tab. 1).
For the radio soundings the Bulk Richardson number is evaluated, too, to assess the relative importance of the near-surface wind shear, counteracting static stability, for the generation of turbulence, main mechanisms to prevent accumulation of air pollutants.
The MWR data from the three ARPAV MTP-5 HE passive radiometers [1] are located in the Po Valley and Val Belluna (Fig. 1) and are generally in good agreement with the radio sounding profile [2]. Also, temperature inversions can be reliably retrieved by these instruments [3].

2. DATA AVAILABILITY

Data of the Milan and Udine sounding are available from 1973 with an availability above 95% since the '90-ies. The Rome and Bologna soundings were started in 1988, where for Bologna data availability is variable, especially in 1990, 1998 and 2011. Starting in 1998 Cuneo is the most recent sounding station with a constantly improving data availability until 2009, but had some issues that reduced values to 87% (2010) and 67% (2011).
The MWR network proved to be quite robust, with data availability often higher than 90%, especially for 2007-2008 for Padua and Rovigo. The MTP-5 HE located in the major Alpine Valley Val Belluna worked fine until the antenna broke down in April 2010.

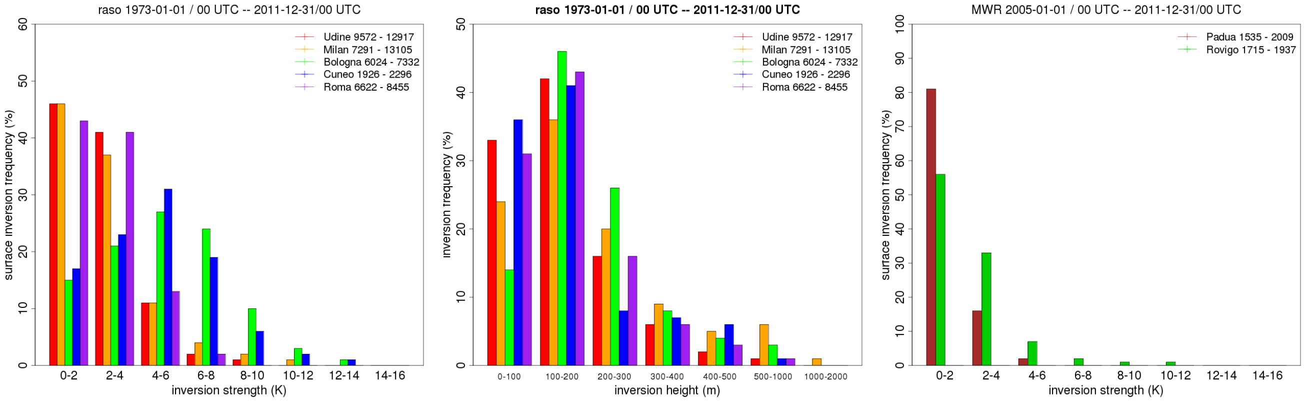
Figure 1. Position and code of the profiling stations analysed: radio soundings in white, passive radiometer MTP-5 HE in blue (out of order in red).

3. PO VALLEY TEMPERATURE INVERSIONS

The wintertime Po Valley is well known for frequent stable conditions with mist, fog, and air pollution episodes [4], where fog and/or low clouds can often cover large portions of the basin form Cuneo to Venice for an area of 48.000km^2, stretching into the region Friuli Venezia Giulia, but rarely reaching Udine. These conditions are notoriously associated with very confined surface temperature inversion.
In this study, for each 00 UTC sounding, temperature inversions starting from the surface are taken and characterized by the level to which the temperature is increasing with height, as well as the temperature difference (strength) between this level and the surface. Tab. 2 reports very high frequencies for surface inversions with values reaching 80% and more, while another approximately 15% of the soundings feature a temperature inversion, whose base is confined within first 3000m above ground. An exception is observed for the Milan sounding, for which the surface inversions amount to 64%, but have about 25% of inversions with a base detached from the surface but within the first 3000m.
Analysis of the MWR temperature profiles confirms this finding. In fact, the Rovigo MWR and Bologna, closest sites in our data set, show similar values (Tab. 2). For

Table 1 Code, altitude (masl), start of operations, and managing institutions of the radio soundings (RASO) and microwave radiometers (MWR) used in this study.

RASO	code	H	from	Manager
Cuneo	16133	386	1994	ARPA Piemonte
Milan	16080	103	1973	Aeronautica Militare
Bologna	16144	38	1988	ARPA Emilia Romagna
Udine	16044	92	1973	Aeronautica Militare
Roma	16245	12	1987	Aeronautica Militare
MWR				
Padua	25	30	2005	ARPA Veneto
Rovigo	27	23	2005	ARPA Veneto



a) b) c)

Figure 2. Distribution of the surface based inversions as seen by the radio soundings in terms of intensity (K, panel a) and height (m above ground, panel b) for the period 1973-2011. Panel c) shows the inversion intensity as retrieved by the MWRs for the period 2005-2011 (numbers denote 'surface inversions' – 'available profiles').

the city of Padua the inversion frequency is between that of Milano and Bologna. The annual time series of the surface inversion frequency exhibit a fair variability, but do not show clear trends (not shown).

4. INVERSION STRENGHT

Inversion strengths for Milan and Udine share a similar distribution with most inversions within the classes between 0-4 K, and extremely rare cases for which they are stronger than 8-10K (Fig. 2a). Cuneo and Bologna feature a bell-shaped distribution which peaks for the class 4-6 K and has a significant number of very strong inversions in the tail up to more than 14K. The Bologna sounding station is on a rural site in the centre of the Po Valley close to sea level, while Cuneo is at 300masl surrounded by Western and Maritime Alps well screened from synoptic flows. Both sites exhibit frequent strongly stratified air masses with elevated vertical static stability.

The difference between Summer and Winter emerges well in the distributions (not shown), being concentrated on weaker to moderate inversions in Summer, with strengths larger than 6-8K, virtually absent for Milan and Udine, rare, but possible for Bologna and Cuneo. In

Table 2. Frequency of occurrence of temperature inversions from radio soundings at (sfc) and detached from (up) the surface for less than 3000m for the entire year (all) and the cold season (cold) for the period 1973 – 2011. From the MWRs at the surface for the entire year (all) and the cold season (cold) for the period 2005 – 2011.

	Cuneo	Milan	Bologna	Udine	Roma
sfc all	87%	64%	84%	79%	82%
up all	8%	26%	14%	13%	14%
sfc cold	87%	60%	85%	77%	81%
up cold	8%	26%	12%	14%	14%
			Padua 25		**Rovigo 27**
sfc all			76%		88%
sfc cold			77%		81%

Winter weak inversions with strengths 0-4K are very frequent in Milan and Udine, while Cuneo and Bologna, as for the full year (Fig. 2a), feature stronger inversions reaching up to 14K.

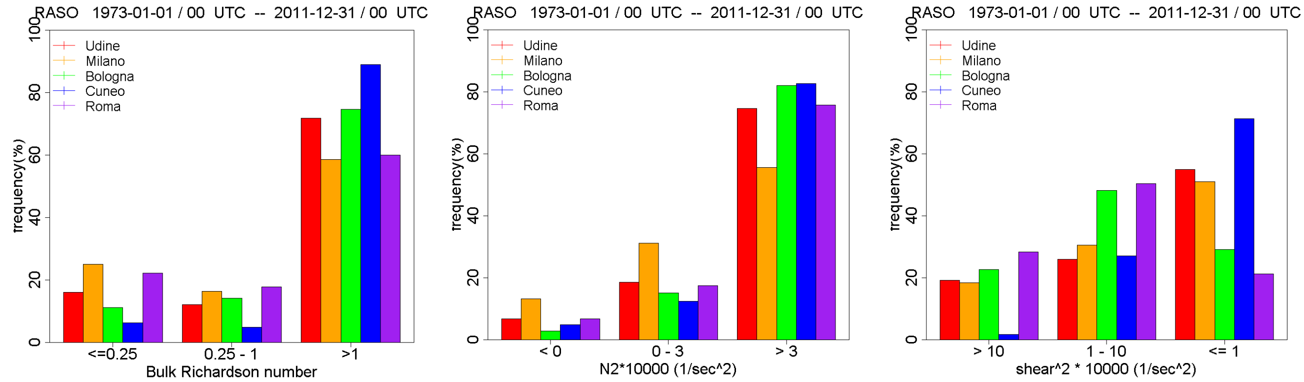
The MWR data cover only last 7 years and are, therefore, not directly comparable to the radio sounding data. Nonetheless, the distribution of the inversion strength from the MWR (Fig. 2c) is consistent with the distributions found for Milan and Udine. Rovigo, the more rural of the two sites, features stronger inversions, reaching 12-14K, while the urban site Padua concentrates most inversions in the weakest classes. In Winter the distribution broadens significantly to include stronger inversions, with more than 10% more with values above 4K (not shown).

The Rome and Udine soundings were included in the study as extra-Po Valley sites for comparison. The Rome site is located close to a big city with air quality issues akin to the North Italian plain. The annual pattern is similar to Milan and Udine (Fig. 2a), while the Winter distribution shows more than 80% of the inversions to be weak (0-4K, not shown). This difference may result from not being immersed in the frequent cold pool of stagnant air of the wintertime Po Valley.

5. INVERSION HEIGHT

Wintertime inversion height at 00 UTC in the Po Valley is an important parameter for air quality assessments, as the lower the stable non mixed layer, the more difficult the dispersion of atmospheric pollutants. In a closed basin as the Po Valley, this level may define the maximum volume into which pollutants as gases and aerosols are diluted.

The annual distribution of inversion heights shows that for all Po Valley radio soundings the 100-200m is the most populated class (Fig. 2b). The Milan distribution has a long "tail" with several occurrences in the class 500m and higher. For Bologna the most populated classes lie between 100-300m, while class 0-100m is less populated than for the other sites. For the MWR



a) b) c)

Figure 3. Distribution of near-surface Bulk Richardson Number (1, panel a), static stability (10^{-4} s^{-2}, panel b), and squared wind shear (10^{-4} s^{-2}, panel c) as calculated from the radio soundings for the period 1973-2011. The three classes denote, from the left to the right of each panel, dispersive, potentially dispersive and stagnant conditions.

data set, both the total annual and the DJF distributions show that the inversion height classes 100-300m are the most populated. For Padua the lowest inversions (0-100m) are more frequent than for Rovigo, while for both sites an anomalous behaviour appears for heights over 500m, especially for Padua. This may be due to the vertical resolution of these instruments, which degrades significantly with increasing height, especially for levels above a few hundreds of meters.

Extra-Po Valley site Rome is, like for the inversion strength, similar to the Udine site, coherent with the a less frequent stagnant cold air pool. Similarity with the Milan sounding both for strength and height of the inversions may stem from the urban heat island effect of Milan, which is coherent with more frequent weak and higher temperature inversions (Figs. 2a and b).

6. MIXED VS. STAGNANT CONDITIONS AND AIR QUALITY

A climatology of the temperature inversions is relevant on its own, but linkage of such stable conditions to air quality in a heavily industrialized area as the Po Valley is of immediate interest. Dispersion of atmospheric pollutants is governed not only by the static stability of the near-surface boundary layer, but also by the wind, more precisely its shear, which induces mechanical turbulence and, therefore, mixing.

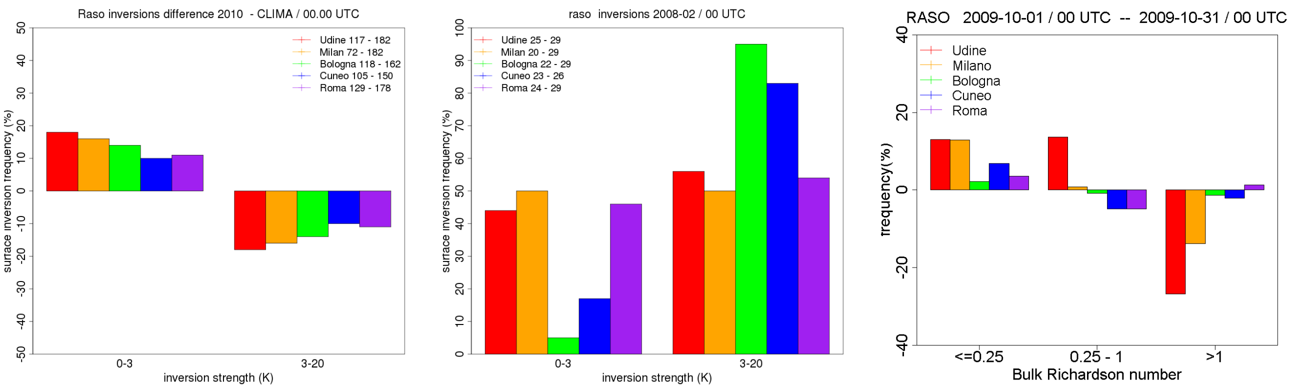
A commonly used and relatively straight forward to calculate indicator for the presence of turbulence is the Bulk Richardson Number (BRN) [5][6]. It is defined as the ratio between the static stability expressed in terms of the squared Brunt Vaisala frequency and the squared vertical wind shear, both evaluated as finite differences between two near-surface layers. Fig. 3 shows the climatological distributions of these parameters grouped into three classes, a dispersive, a potentially dispersive and a stagnant class. It can be readily seen from the BRN that the Po Valley climatology suffers from very frequent (60-80%) stagnant conditions with BRN > 1 and infrequent (10-20%) well mixed conditions, which is consistent with the frequently present surface inversions in the temperature profiles.

The near surface sounding information is now applied to 'explain' the air quality measured in Po Valley portion of Veneto from 2003 onwards. Since then ARPAV operate an air quality measurement network of some 30 stations for atmospheric pollutants as required of the EU, in particular the PM10 aerosols, the major cold season pollutant. The monthly distribution of average concentrations of the air quality stations was analysed, the median of the distribution taken as air quality indicator. If this value was >1.5 or within (1.25-1.5, 1.0-1.25), or (1.0-0.75, 0.5-0.25) times the EU limit of 50 μg/m^3 the air quality was defined respectively as ('bad' (---), or 'poor' (-- or -), or 'good' (+ or ++). All the cold season months since 2003 were so classified and reported in Tab. 3.

For the total of 54 months, 31 resulted 'poor' and 7 'bad'. Taking in account the cases where the number of days with strong surface inversions (>3K) of the closest radio sounding (Bologna) is larger than the number of days with light inversions (<3K) 'explains' more than 68% of the months with 'poor' or 'bad' air quality. Considering only 7 months with 'bad' air quality, strong inversion condition are able to explain all the cases. 'Missed' explanations are for March and October

Table 3. Classification of median of concentration of air quality network in Veneto.

	Oct	Nov	Dec	Jan	Feb	Mar
2002/03	//	//	//	---	-	---
2003/04	+	-	-	--	--	-
2004/05	-	-	--	---	--	--
2005/06	-	-	--	--	--	+
2006/07	+	---	--	---	--	+
2007/08	+	-	--	-	---	+
2008/09	-	+	+	-	-	+
2009/10	+	-	+	-	-	-
2010/11	++	++	+	-	---	+
2011/12	++	-	--	//	//	//



a) b) c)

Figure 4. Distribution of the deviation of the surface based inversion strength from the climatology 1973-2011 for the cold season 2010 as seen by the radio soundings (K, panel a), and the partition of weak and strong inversions for the month February 2008 (K, panel b, numbers denote 'surface inversions' – 'available profiles'). Panel c) shows the distribution of the near-surface wind shear for the month October 2009 (10^{-4} s^{-2}, panel c).

months with good air quality. As a matter of fact, accounting for the near-surface wind shear in the BRN 'explains', or yields a consistent picture for, most of the 'missed' cases. In addition, the 12 UTC soundings would probably add more helpful information.

Fig. 4 shows the deviation from climatology for a particularly 'good' air quality year (panel a) with significantly less moderate to strong inversions, a 'bad' month (panel b) with a predominance of strong inversions, as well as the BRN for October 2009, when the static stability was high (above climatology) and the air quality was 'good'. Here the near surface wind shear was significantly higher than normal in much of the Po Valley.

7. CONCLUSIONS

Surface-based temperature inversions and high static stability, resulting in stagnant conditions, are very frequent in the nighttime Po Valley (00 UTC), both in Summer and Winter ranging from 64% in Milan to 87% in Cuneo with typical heights between 100-300m and strengths up to 12-14K for rural sites (Bologna), much more frequently 0-4K. The MWRs yield smoother profiles and result in a distribution with slightly weaker strengths and higher tops. Winter months with very bad air quality are very often consistent with stagnant conditions as retrieved from the sounding profiles. In some 70% of the cases the average thermal structure 'explains' the average air quality on a monthly basis. Adding the near-surface wind shear which counteracts the stagnant effects of elevated static stability 'explains' another about 15% of the months, especially those for which the high static stability would have favoured accumulation, but lower concentrations were observed.

The fact that the 00 UTC near-surface temperature and wind profiles contain sufficient information about the PBL to identify between 80 and 90% of the cold season months with elevated pollutant concentrations, offers an interesting pathway to assessing trends of the atmospheric forcing on air quality in a changing climate. This is of particular importance for heavily industrialized areas like big cities or, on a larger scale, basins like the Po Valley. Analysis of the midday sounding may add interesting information and interpretation of air quality episodes, and will be investigated in future work.

8. REFERENCES

1. Troitsky, A.V., K. P. Gajkovich, V.D. Gromov, E.N. Kadygrov, A. Kosov. (1993). Thermal Sounding of the Atmospheric Boundary Layer in the Oxygen Absorption Band Center at 60 GHz. *IEEE Transactions on geosciences and remote sensing*, vol. 31, no. 1.

2. Ferrario, M.E., A. M. Rossa, M. Sansone, A. della Valle. (2010). Heterogeneity of accumulation and dispersion conditions for PM10 in the Po Valley. In *Proc. 13th Conference on Harmonisation within Atmospheric Dispersion Modelling for Regulatory Purposes.*

3. Yushkov V. P., Kouznetsova I. N. (2008). Comparison of nocturnal inversion characteristics obtained by SODAR and microwave temperature. In *Proc. 14th Int. Symposium for the Advancement of Boundary Layer Remote Sensing profiler.* IOP Conf. Series: Earth and Environmental Science.

4. Giuliacci M. (1989). Climatologia fisica e dinamica della Val Padana. *ERSA Servizio Meteorologico Regionale, Bologna.*

5. Stull R.M. (1994). An introduction to boundary Layer Meteorology. *Atmospheric Science Library, Kluvier Academic Publishers.*

6. Steeneveld G.J. (2011). Stable Boundary Layer Issues *In proc. ECMWF Workshop on Diurnal cycles and the stable boundary layer 7-10 Nov. 2011.*