Comparison of the mixing layer heights estimated by sodar and simple parameterizations at Dome C, Antarctica

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1- INTRODUTION

The height of the atmospheric boundary layer (ABL) is an important variable as it is commonly used in dispersion, climate, or numerical weather prediction models. The ABL height is often identified with the mixing-layer height (*MH*). After the Cost action 710 the definition adopted for the MH regarding both convective and stable conditions is (Seibert et al. 2000):

"the mixing height is the height of the layer adjacent to the ground over which pollutants or any constituents emitted within this layer or entrained into it become vertically dispersed by convection or mechanical turbulence within a time scale of about an hour".

On the Antarctic plateau, during the summer, the ABL shows the typical mid-latitudes behaviour.The daytime convective mixing layer is characterised by a *MH* up to about 400 m. On the contrary, during the night the depth of the turbulent layer can range from an altitude of less than 10 meters up to several tens of meters. This range of investigation is too large to use the measurements of a meteorological tower, and at the same time too limited to use common acoustic or optical remote sensing systems.

To resolve the fine structure of the *MH* behaviour, an improved acoustic remote sensing device (Argentini et al. 2012) named Surface Layer Mini-Sodar (SLM-sodar) was specifically developed. In the framework of the *ABLCLIMAT (Atmospheric Boundary Layer Climate)* project, an experimental campaign started at the French-Italian station of Concordia (74° 06' S, 123°20' E, 3233 m a.s.l) on December 2011 to end on December 2012. The SLM-sodar was operated continuously during the summer 2011-2012, allowing the monitoring of the ABL evolution with the adequate resolution during the entire diurnal cycle.

Due to the severe environmental conditions and the large effort needed to retrieve the *MH* from sodar profiles, these measurements cannot be performed on a routine base. The improvement of simple and well tested parameterizations, based on standard surface observations or turbulent parameters, can be a possible way to overcome this difficulty.

For the convective cases, a new diagnostic equation, based on a dimensional analysis that takes into account the time-averaged integral of the near-surface turbulent heat flux, $\left(\overline{w'\theta'}\right)_s$, the background static stability, and the buoyancy parameter is used.

The stable case is more complicated due to the nature of turbulence. In these conditions, the MH estimated using the sodar measurements was compared with the values obtained using five parametrizations proposed in literature under different stability conditions.

As suggested by Zilitinkevich (1972) and Arya (1981), the dimensionless stratification parameter $\mu = \frac{\lambda}{L}$ ($\lambda = \frac{k u_*}{f}$, k=0.4 is the Von Karman constant, u_* is the friction velocity and f is the Coriolis parameter, L is the Obukhov length), was used to categorize the nocturnal data in four stability classes :

near neutral	(nn)	μ <10
moderately stable	(ms)	10<= μ <=50
very stable	(vs)	50< μ <=100
extremely stable	(es)	μ >100

2 - EXPERIMENTAL DETERMINATION OF MH

A SLM-sodar, developed at the ISAC – CNR laboratory of Rome, is able to investigate surface and boundary layer turbulent phenomena. During the summer period of the *ABLCLIMAT* experimental field, the emission frequency was set to 2000 Hz, the pulse duration to 50 ms and the pulse repetition rate to 3 s. The system configuration allowed a vertical resolution of about 8 m in the range between 8 and 360 m. SLM-sodar data were used to investigate the mixing layer evolution and to detect its height in both convective and stable conditions. The MH was determined using the technique proposed by Beyrich and Weill (1993) to the range corrected signal (RCS). Under stable conditions (Fig. 1a) the shape of the RCS can continuously decrease with the height or shows an elevated maximum depending on the ABL evolution. In the first case the *MH* is determined from the maximum RCS curvature, in the latter as the minimum of the first derivative. Under convective conditions (Fig. 1b), as the shape of the RCS shows a clear secondary maximum, the *MH* is determined as the height at which this elevated maximum occurs, corresponding to the zone of strong turbulence at the capping inversion.

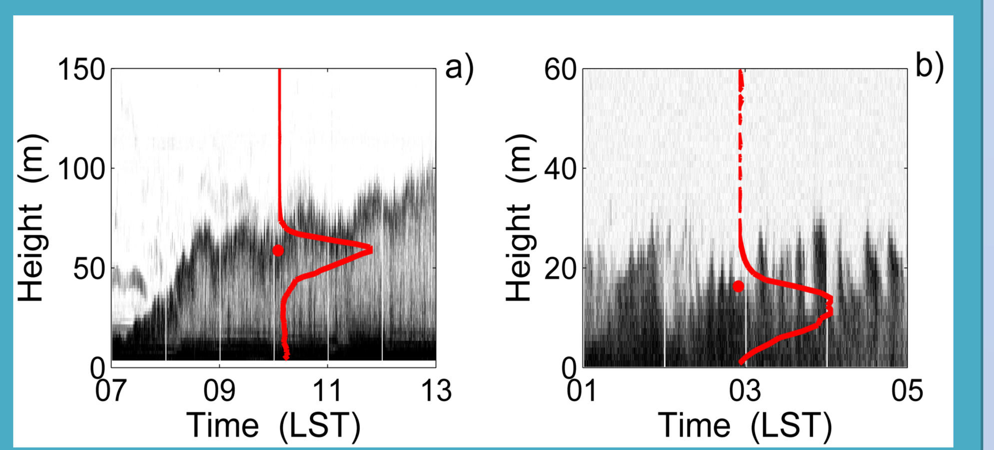


Fig. 1 – Determination of MH by sodar profiles under convective (a) and stable conditions (b).

3 – DIURNAL BEHAVIOUR

The mixing layer behaviour evidences a daily cycle whit the formation of a convective layer during the central part of the day and a stable layer during the night. Fig. 2a shows the 24-hours distribution of the measured *MH*. From 0600 LST a convective mixing layer develops and the *MH* increases gradually until about 1300 LST, when the maximum is reached and maintained for the following two hours. Between 1000 LST and 1600 LST the *MH* values are more dispersed than those observed in stable conditions, and the value of the maximum ranges between 75 and 250 m with a median of 125 m. Around 1600 LST the *MH* collapses, and a stable layer forms near the ground. A zoom of the MH in stable conditions observed between 1900 LST and 0600 LST is shown in Fig. 2b. The MH is comprised in the first 50 m above surface. In the first part of the night the MH tends to decrease having a more scattered behavior than in the second part of the night. In the time period comprised from 2000 and 0200 LST the MH is near constant having a value around 10 m. In the first part of the morning (0200 – 0600 LST) as the stability softening the MH starts to increase and presents a wider distribution.

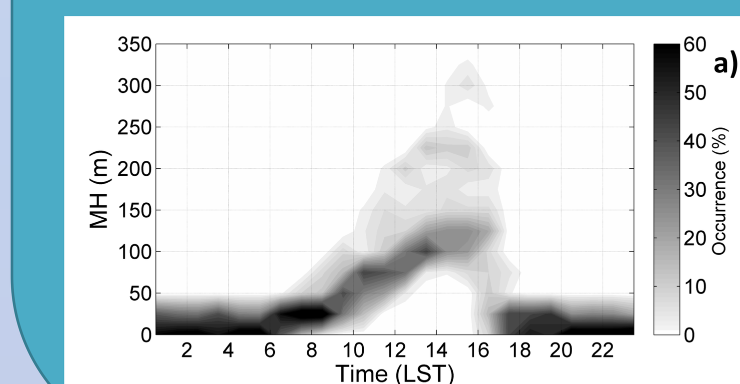
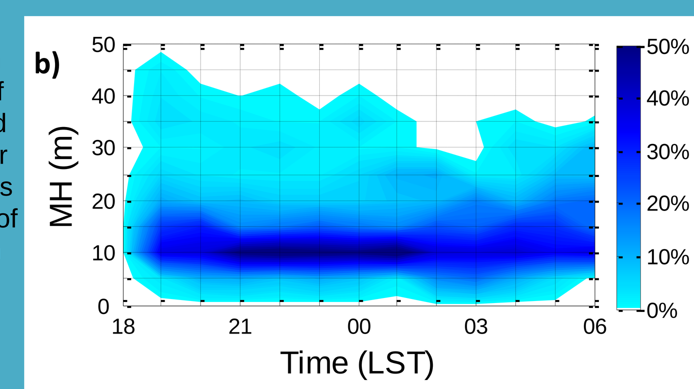


Fig. 2 – 24-h distribution of MH estimated by SLM-sodar measurements (a) and zoom of the first 50 m (b).



4 – INFLUENCES OF SURFACE PARAMETERS

The dependences of MH on $\left(\overline{w'\theta'}\right)_s$ and u_* in both unstable and stable cases are shown in Fig. 3 (red and blue dots respectively). The scatter of the points in Fig. 3a is due to the different daily behaviour of $\left(\overline{w'\theta'}\right)_s$ and MH; while the first shows a maximum around midday, followed by a decreasing trend in the afternoon, the MH peaks approximately in the same period, but maintains this value at least for 2 h. An analogous scatter is shown in the u_* values under convective conditions (Fig. 3b).

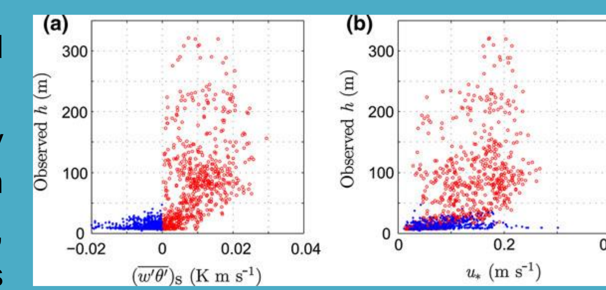


Fig. 3 – Scatterplot between MH and $\left(\overline{w'\theta'}\right)_s$ (a) and between MH and u_*(b).

In Fig. 4 the scatterplot between MH and $\left(\overline{w'\theta'}\right)_s$, u_* and its powers usually used in the parameterizations, and L during the four stable conditions are shown. MH is not correlated (linearly) with L nor with $\left(\overline{w'\theta'}\right)_s$. The correlation between MH and u_*, and its power is slightly greater than 0.5 considering all the case, increases considering only the nn and ms cases, and drops in the vs and es cases. This can be partially explained by the density of population of each group: in fact the nn-cases have only 51 points, in contrast the es-cases are 537. Moreover in case of extreme stability the fluxes have little intensity and the relative error in computation is higher than in the nn and ms cases. Considering the correlations observed, u_* seems to drive the MH in stable conditions.

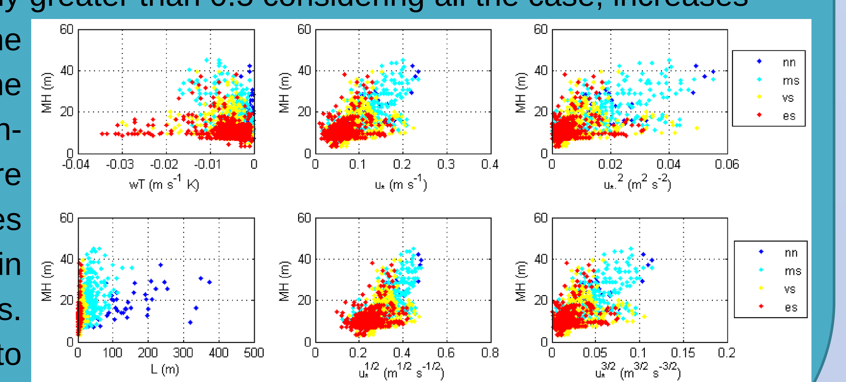


Fig. 4 – Scatterplot between MH and the turbulent parameters.

5 – CONVECTIVE MIXING HEIGHT

The relevant processes to consider for the convective ABL development and evolution are the exchange of heat between the land surface and the atmosphere, the background static stability, and the buoyancy effect, represented by $\left(\overline{w'\theta'}\right)_s$, the lapse rate γ , and the buoyancy parameter $\beta = g/T$, respectively.

In the framework of the Buckingham Pi theorem, the selected parameters lead to a single non-dimensional group, that can be rewritten as:

$$h = \alpha\, Q\, \gamma^{-3/4} \beta^{-1/4} = \alpha B$$

Where the instantaneous turbulent kinematic heat flux is substituted with a history scale defined by the time-averaged integral:

$$Q = \frac{1}{t_m - t_s} \int_{t_s}^{t_m} \left(\overline{w'\theta'}\right)_s^{1/2} dt$$

where t_m is the time at which the measurement are taken, and t_s depends on the time scale of the mixing layer (5 h).

The experimentally determined coefficient: α = 11.20 ± 0.30, (R2 = 0.86), (Fig.4a).

Fig. 4b shows the scatter plot of measured against estimated MH. The diagnostic model is in good agreement with the observed data (*IoA* = 0.84), although it tends to slightly underestimate.

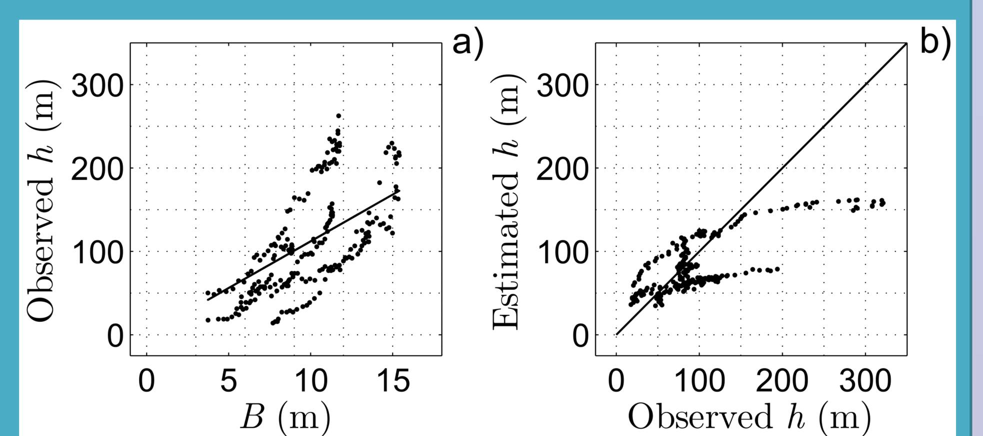


Fig. 4 – Scatter plots of measured MH against the dimensional group *B* (**a**), and against the *MH* values (**b**) estimated by the equation.

More details in POSTER Z74

6 – STABLE MIXING HEIGHT

The diagnostic equations for the stable layer are derived starting from the Ekman formulation of the equilibrium height. The eddy viscosity is estimated as the product of a turbulent velocity scale and a turbulent length scale chosen taking into account of the stability regimes. The first is usually set equal to u_*. In the classical equation derived for nocturnal boundary layer the turbulent length scale is the Obukhov length, so that the MH depends on friction velocity, buoyancy flux and Coriolis parameters (Zilitinkevich, 1972):

$$h_1 = c_2 \left(\frac{u_* L}{f}\right)^{1/2}$$

A large number of values was derived experimentally for the constant c_2, and the exact value appears to be quite sensitive to model assumptions. Analysing the Dome C data the value of 0.13 is the most suitable having the best score in all the statistical parameters considered (Fig. 5, Table 1). h_1 is a good estimator of MH in ms cases, but moderate in more stable conditions.

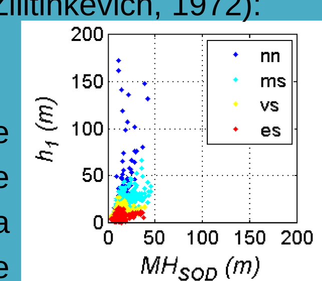


Fig. 5 – Scatter plots of measured MH against h_1

h_1	RMSE	IoA	FB
nn	56.79	0.21	-1.04
ms	9.37	0.74	-0.11
vs	7.37	0.54	0.31
es	7.57	0.43	0.76
all	13.92	0.55	0.11

Table 1 – Performance of the h_1.

Venkatram 1980 starting from the equation for h_1, parameterized L as the square of u_* and derived the formulation $h_2 = c_* \sqrt[3]{u_*^2}$. The clear advantage of this equation is the dependency on a single parameter, avoiding the uncertainties due to the evaluation of $\left(\overline{w'\theta'}\right)_s$. The value of $c_* = 429$ (m$^{-1/2}$ s$^{3/2}$) is derived from c_2. The h_2 works very well in nn and ms cases (Fig. 6, Table 2).

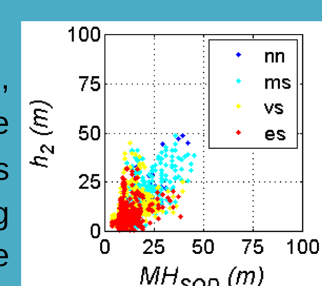


Fig. 6 – Scatter plots of measured MH against h_2

h_2	RMSE	IoA	FB
nn	8.13	0.81	0.02
ms	8.76	0.78	0.02
vs	8.42	0.54	0.09
es	6.94	0.50	0.39
all	7.87	0.74	0.16

Table 2 – Performance of the h_2

Using vertical profiles of the eddy viscosity based on numerical simulations of stable boundary layer, Nieuwstandt (1981) derived :

$$\frac{h_3}{L} = \frac{0.3\, u_*/fL}{1 + 1.9\, h_3/L}$$

The IoA of h_3 is maximum for ms cases and decreases as the stability increases (Fig. 7 , Table 3).

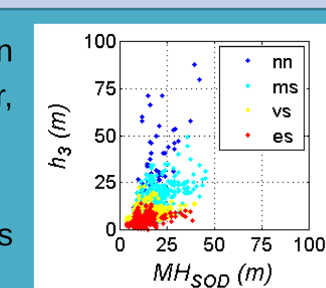


Fig. 7 – Scatter plots of measured MH against h_3

h_3	RMSE	IoA	FB
nn	23.5	0.47	-0.63
ms	8.03	0.75	0.11
vs	8.04	0.52	0.46
es	8.09	0.41	0.88
all	9.22	0.68	0.35

Table 3 – Performance of the h_3.

Considering the Brunt-Vaisala frequency, N, and interpolating between equations proposed for different degree of stability (from the near neutral to very stable boundary layer), Zilitinkevich and Mironov (1996) proposed:

$$\left(\frac{f h_4}{C_n u_*}\right)^2 + \frac{h_4}{C_s L} + \frac{N h_4}{C_i u_*} = 1$$

having satisfactory performance also during vs and es cases (Fig. 8 , Table 4).

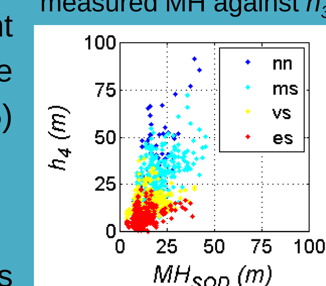


Fig. 8 – Scatter plots of measured MH against h_4

h_4	RMSE	IoA	FB
nn	27.65	0.43	-0.76
ms	13.26	0.66	-0.37
vs	7.26	0.57	-0.04
es	6.49	0.49	0.50
all	10.26	0.71	-0.08

Table 4 – Performance of the h_4.

An analogous formulation proposed by Handorf (1996) is:

$$\frac{f h_5}{C_h u_*} + \frac{f h_5^2}{C_{sr}^2 C_s L u_*} + \frac{N f h_5^2}{C_{ir}^2 u_*^2} = 1$$

For es cases, h_5 give good results (Fig. 9 , Table 5).

The use of standard equations to derive MH in stable conditions that take into account for u_*, seems to be suitable in moderate and very stable cases.

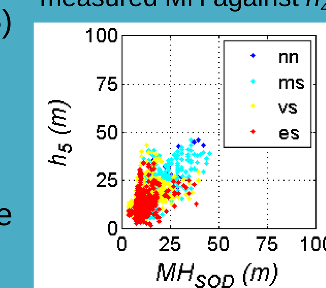


Fig. 9 – Scatter plots of measured MH against h_5

h_5	RMSE	IoA	FB
nn	8.22	0.78	-0.19
ms	8.95	0.76	-0.19
vs	8.83	0.54	-0.26
es	6.16	0.55	-0.11
all	7.77	0.74	-0.18

Table 5 – Performance of the h_5.

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