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Comparison of indirect methods for the estimation of Boundary Layer height over flat-terrain in a coastal site

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Abstract

In this paper an analysis of different indirect methods for the calculation of the boundary layer height (BLH) using sodar, ultrasonic anemometer and a prognostic model based on single point surface measurements is presented. In particular the automatic spectral routine developed for Remtech sodar is compared with the results obtained with the parameterization of the vertical velocity variance of a minisodar, with the calculation of a prognostic model, with a parameterization based on horizontal velocity spectra and with the BLH evaluated from the intensity of minisodar echoes in stable conditions. The data of a radiosonde system taken in a nearby site was also analysed to get an independent evaluation of BLH for comparison. There is a significant scatter in the data for both the evaluation through the variance of vertical wind speed and the spectral analysis of the horizontal wind velocity although created by different effects. In unstable conditions the different methods give a similar pattern even if the prognostic model in some days predicts a significantly higher BLH with respect to the other methods. In stable nocturnal conditions the performances of the Remtech routine are worse than those in unstable conditions with an evident overestimation of the BLH that it is likely related to the overestimation of vertical turbulence and to the use of multiple range gates in the algorithm. Taking as reference the evaluation of BLH of the sodar, the spectral method applied to ultrasonic anemometer data seems to be affected by the lowest biases and it is a possible candidate, for the development of automatic routines for operational evaluation of BLH possibly with a different parameterisation for stable and unstable cases.

Zusammenfassung

Eine Analyse verschiedener indirekter Methoden zur Berechnung der Grenzschichthöhe (GH) aus Sodar, Ultraschallanemometer und Punktmessungen (letztere zusammen mit einem Vorhersagemodell) wird präsentiert. Insbesondere wird der automatische spektrale Algorithmus für ein Remtech-Sodar verglichen mit Ergebnissen aus der Parametrisierung der Varianz der Vertikalgeschwindigkeit aus MiniSodar-Messungen, mit den Berechnungen eines Vorhersagemodells, mit einer Parametrisierung basierend auf horizontalen Geschwindigkeitsspektren und mit der GH abgeleitet aus der Rückstreuintensität von einem MiniSodar bei stabilen Bedingungen. Die Daten einer nahegelegenen Radiosonde werden ebenfalls zum Vergleich der GH herangezogen. Die Varianz der Vertikalgeschwindigkeit und die horizontalen Geschwindigkeitsspektren weisen aus unterschiedlichen Gründen eine erhebliche Streuung auf. Unter instabilen Bedingungen ergeben die verschiedenen Methoden ähnliche Ergebnisse, sogar dann, wenn das Vorhersagemodell an einigen Tagen eine größere GH vorhersagt als die anderen Methoden. Bei nächtlich-stabilen Bedingungen ist der Remtech-Algorithmus schlechter als bei instabilen Bedingungen und überschätzt GH, vermutlich auf Grund einer Überschätzung der Turbulenz und der Verwendung von Daten aus mehreren Höheninterwallen. Wenn man die GH vom Sodar als Ausgangspunkt nimmt, dann erscheint die spektrale Methode angewendet auf die Ultraschallanemometerdaten den geringsten Bias aufzuweisen und ein möglicher Kandidat für die Entwicklung automatischer Routinen zur operationellen Bestimmung der GH zu sein, vermutlich mit unterschiedlichen Parametrisierungen für stabile und instabile Fälle.

1 Introduction

In the past few decades a great effort has been made to obtain detailed descriptions of the atmospheric boundary layer (BL) properties starting from surface parameters. This is considered an important goal from both a scientific and a practical point of view (MELAS et al., 2000; BEYRICH, 1997). Evaluation of the boundary layer height (BLH) is useful in several research applications, such as chemical studies, meteorological modelling at different scale and simulation of pollution dispersion and transformation. For example the BLH is important in characterising pollution levels from aerosol optical thickness (DANDOU et al., 2002; EMEIS and SCHÄFER, 2006). The BLH has a direct impact on pollution dispersion phenomena and its daily evolution can affect ground-level pollutant concentrations in specific conditions (CONTINI et al., 2006a). This work is specifically oriented in the analysis of different indirect method for the evaluation of the BLH in a coastal site. The geographic position and the absence of relevant orography in the Salentum peninsula (Apulia, south of Italy, see Figure 1), where our measurement site is located, are

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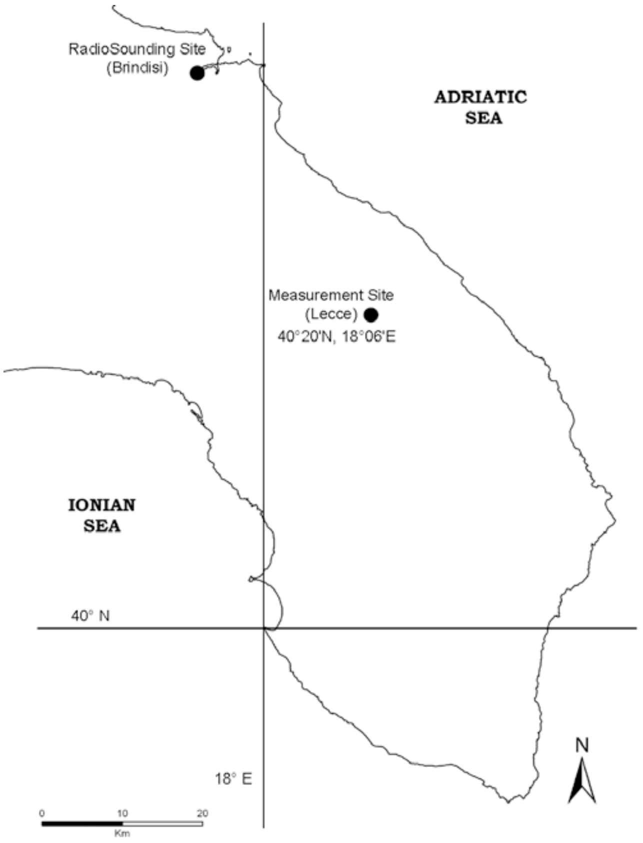

Figure 1: Map of the Salentum Peninsula showing the position of the measurement site (40°20’N–18°06’E) and of the radio-soundings site.

the main causes of advection of air masses from the sea that limit the growth of the boundary-layer and the differences between the BLH in winter and summer. Therefore the influence of the BLH on air quality could also be stronger with respect to other sites. Radio soundings are the most common source of data for operational determination of the BLH (Seibert et al., 2000) because data is continuously controlled and measurements are relatively wide distributed in Europe. However in the Apulia region is only available one radio sounding station close to the sea of Brindisi and data are available only three times a day at specified synoptic times (0 UTC, 6 UTC and 12 UTC). Therefore these data have been analysed to extract the information and BLH to be used as starting point for the analysis reported in this paper and as a term of comparison with the other methods.

Remote sounding systems (lidar, sodar, rass and wind profiling radar) are an interesting alternative for BLH estimations given the increase of high performances remote sensing devices on the market. Furthermore the progress in acoustic sounding techniques has led to the development of advanced devices for monitoring the main properties of the atmospheric boundary layer (Emeis et al., 2008). The basic advantages of remote sounding systems are the continuous operation and the ability to measure without affecting the investigated flow. However in several cases some kind of parameterisation is actually needed to extract the information about the BLH from remote sensed data.

Simple parameterization based on standard micrometeorological single point surface observations as well as numerical models are widely used in meteorological and in environmental service. Diagnostic models (like CALMET for example) are also widely used for BLH evaluation and they could operate on a grid interpolating the input of a surface sensors network. However very often a network of surface measurements is not available, being sensors concentrated in single sites, and in these cases the advantage of grid interpolation vanishes and it could be more appropriate the parameterisation through single point surface measurements.

In this paper different methods to calculate the boundary layer height, starting from single point surface measurements, have been tested in a period during which two sodar systems and two micrometeorological stations were operating together in the same experimental field. A comparison between the results obtained with the different indirect methods has been performed to get information about the correlation of the results and of the main limits and potentialities of the methods. The analysis has been performed separating the stable cases from the unstable ones. Results show the difficulties of the development of reliable automatic routines for BLH estimation from indirect data and that further research is needed for the development/improvement of BLH calculation especially in stable conditions.

2 Measurement site, instrumentation and data processing

Measurements discussed in this paper were collected during the period between 6 May 2005 and 9 June 2005 in the experimental field of the Istituto di Scienze dell’Atmosfera e del Clima (ISAC-CNR) located inside the University Campus in a rural area about 4 km from the city of Lecce (Figure 1). The Salentum peninsula is a relatively flat region with maximum height of 209 m (asl) reached in the central area of the southern part of the peninsula. Most of the land is devoted to agricultural activities: mainly olive trees and grape cultivations. The site analysed is located in the countryside and it is relatively homogeneous at large scale (several kilometres). At smaller scale, it is characterised by the presence of short vegetation and the surrounding area is constituted for at least 1–2 km by patches of trees and small two-storied buildings (Donateo et al., 2006). A 16 m high micro-meteorological mast, equipped with a sonic anemometer (Gill Solent), a KH20 (Campbell Scientific) fast hygrometer and a Rotronic detector (for temperature and relative humidity measurements), was located close to two acoustic sounders and used for long-term data collection. The sampling rate of the anemometer was 20.8 Hz and it provided a direct method (eddy-correlation) for estimating sensible and latent heat vertical turbulent fluxes as well as momentum flux. A second micro-meteorological mast was equipped with a Gill R3 ultrasonic anemometer operating at 100 Hz in calibrated mode and a CO_2-H_2O fast detector (Licor LI-7500), at a measurement height of 10 m. This second station was used to store raw-data series for short-term measurement campaigns and its data were used for the evaluation of the BLH using the spectral analysis of horizontal wind velocity. All recorded measurements were processed in the streamlines reference system on both 30 and 60 minutes averages. A Remtech PA1 sodar was placed over the roof of ISAC-CNR building (8 m tall), inside the Campus about 200 m apart from the experimental site, and it was operating in order to provide 30 minutes average at 50 m vertical resolution with the first available range gate at 33 m above the ground. The PC-MTSodar, developed at ISAC-CNR (CONTINI et al., 2006b; CONTINI et al., 2007), was operated with a single vertically oriented antenna, emitting pulses at 4000 Hz (0.1 s long) with a 2 s repetition rate. This minisodar, in the configuration used, had the first range gate at about 24 m above the ground, with a vertical resolution of 13.4 m. The Doppler shift and the Signal to Noise ratio (S/N) is calculated according to the two-step procedure described in (MASTRANTONIO and FIOCCO, 1982) after correction of the received signals using the transfer function correction that has proven to be useful for the analysis of vertical wind velocity (CONTINI et al., 2004).

3 BLH calculated by the radio soundings

Radio sounding measurements were available in a location (Brindisi) about 40 km far from our site (cfr. Figure 1) at a rate of three per day (0 UTC, 6 UTC and 12 UTC). The radio sounding site is nearest to the sea with respect to our site and the fetch for the growth of the boundary-layer is very different especially for wind directions in the sector between NNW and SE. Therefore these directions have been eliminated in the analysis relative to the radiosonde data. The distance between our site and the radio sounding site is relatively large, however there are indications that BLH calculated from these radio soundings is well correlated with BLH in our site calculated from lidar profiles (DE TOMASi and PERRONE, 2006). Several methods for the determination of BLH from radiosonde data have been developed and a discussion on them is reported in SEIBERT et al. (2000) and, more recently, in LOKOSHCHENKO (2002). For the convective boundary-layer a widely applied technique is to analyse the potential temperature vertical profiles with the parcel method that has been used in this work without using any excess temperature as in HENNEMUTH and LAMMERT (2006). The BLH is evaluated as the height of the intersection of the actual potential temperature profile with the dry-adiabatic ascent starting at near surface temperature (i.e. the temperature of the lowest level of the radio sounding profile). Also the maximum of the gradient of the potential temperature profile has been evaluated, as an alternative indicator of the BLH, and generally the two results are well correlated. In stable or near-neutral conditions the BLH has been evaluated as the height of the first significant change in the potential temperature gradient or the base of the first elevated inversion. Each radiosonde profile has been analysed manually and wind speed, wind direction and humidity profiles have been used, in specific cases, to help in the determination of the BLH. Some cases with low vertical resolutions have been eliminated from the analysis because of relevant uncertainty in the calculated BLH.

4 BLH calculated by the Remtech sodar

Remtech sodar software (number 817) provides an internal routine for the determination of BLH based on the spectral analysis of the vertical wind velocity (REMTECH, 2000). According to (BAUMANN and PIRINGER, 2001) and to (KEDER, 1999) the characteristic time-scale of eddies containing most of the turbulent kinetic energy is evaluated from the power spectrum of the vertical velocity. This time-scale is characteristic of the largest eddies in the flow which, for their size, are correlated with the height of the boundary layer (ASIMAKOPOULOS et al., 2004). Finally the mixing height can be obtained, apart from a proportionality coefficient, as the product of the time scale and the velocity scale. This allows the calculation of the BLH even when it is well above the maximum range reached by the sodar. A particularity of the routine is that it uses the vertical velocity measured at different range gates in order to evaluate an average length scale. It must be said that the method based on the relationship between the size of the most energetic eddies and the BLH was suggested for unstable boundary-layer in KAIMAL et al. (1982a), however the Remtech software uses this approach without any respect for stability conditions (KEDER, 1999). In the scientific literature different points of view are reported about the efficiency of this routine. In KEDER (1999) poor performances are reported for both stable and unstable boundary-layer while in ASIMAKOPOULOS et al. (2004) good performances in unstable boundary-layer have been observed during daytime but poor performances during night-time in stable conditions. In BAUMANN and PIRINGER (2001) it is reported that Remtech routine often results in spurious estimates of BLH and shows an high variability from one hour to the other. In our measurement site the Remtech PA1 sodar was operated for several years and the daily pattern of BLH, obtained averaging three years (2003,

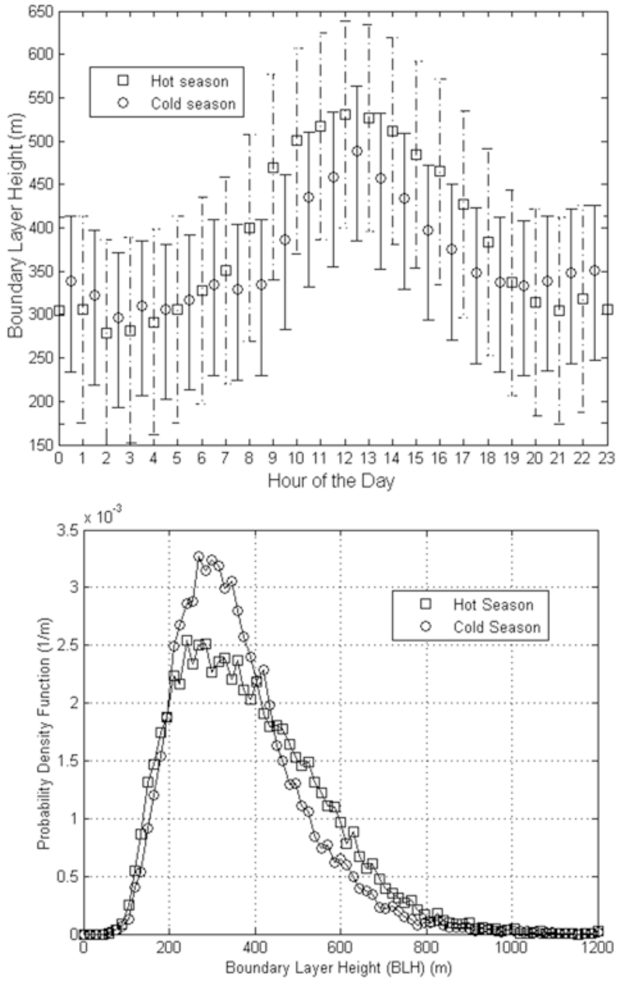

Figure 2: Top: Typical daily patterns of BLH (agl) for hot (April to September) and cold (October to March) season determined by the Remtech software over a statistics of three years (2003, 2005 and 2006). The bars represent the inter-quartile range. The results for the cold season are shifted of 1/2 hour backwards to improve the readability of the picture. Bottom: Typical pdf of BLH in the two seasons.

2005 and 2006) of data, is reported in Figure 2. The error bars represent the inter-quartile range. The analysis has been performed separating the cold season (October to March) from the hot season (April to September). Results indicate that the diurnal change in the maximum BLH is, on average, around 20 % between the two seasons and that the BLH is generally low considering the sensible heat fluxes involved in the summer period (often more than 300 W/m^2). This is due to the presence of relatively intense winds, over short fetch, with a subsequent advection of air masses from the Mediterranean sea that contribute in keeping the BLH low. There are also independent experimental evidences, obtained by lidar and radiosoundings (DE TOMASI and PERRONE, 2006), that the mixing height in the area analysed is almost always somewhat lower than those expected from a simple 1-dimensional vertical growth model (infinite fetch) even in summer days. The probability density function (pdf) of BLH during the hot and cold season are also reported in Figure 2. The BLH estimated by the Remtech routine is rarely lower than 150m even in nocturnal stable boundary layer and this could be due to the limitations of the automatic routine rather than a limitation of the spectral method and they will be discussed later on.

5 BLH calculated from prognostic equations based on single point surface measurements

To calculate the boundary layer height h for the daily cycle the algorithm described in MARTANO (2002) and in MARTANO and ROMANELLI (1997) has been used. This model is based on the growth equations of the Tennekes-Carson scheme (TENNEKES, 1973), and the subsequent works by GRYNING and BATCHVAROVA (1991) and LUHAR (1998). The basic equations are written in total (material) derivatives to take into account advection effects (limited fetch) from coastlines, $D/dt = \partial/\partial t + U\partial/\partial x$, where U is the average wind speed in the mixing layer (STEYN and OKE, 1982; GRYNING and BATCHVAROVA, 1990):

$$h\left(\frac{D\theta_m}{Dt}\right) = Q_s - Q_i \tag{5.1}$$

$$\Delta\left(\frac{D\theta_m}{Dt}\right) = -Q_i \tag{5.2}$$

$$\frac{D\Delta}{Dt} = \gamma\left(\frac{Dh}{Dt}\right) - \frac{D\theta_m}{Dt} \tag{5.3}$$

Here, Q is the potential temperature flux at the surface (subscript s) and at the upper temperature inversion (subscript i), Δ is the inversion strength above the mixing height (the upper inversion layer supposed as collapsed in a temperature jump Δ), θ_m is the average potential temperature in the mixing layer and $\gamma = d\theta/dz|_{z=h}$ is the lapse rate above the temperature jump. Knowing the surface fluxes, the model can be mathematically closed by an expression for the heat flux Q_i in the upper inversion based on a parameterization equation for the turbulent kinetic energy budget (ZILITINKEVICH, 1975):

$$\frac{g}{T}Q_i = -C_K\frac{w_m^3}{h} + C_T U\frac{w_m^2}{h}\frac{Dh}{Dt} \tag{5.4}$$

where $w_m^3 = w_*^3 + C_N u_*^3$, u_* is the friction velocity, $w_*^3 = ghQ_s/T$ is the convective velocity scale, g is the gravity acceleration, T the absolute temperature and C_N, C_K, C_T, are constants (LUHAR, 1998). Inserting

(5.4) in (5.2) an expression for Dh/Dt as function of h and Δ can be obtained:

$$\frac{Dh}{Dt} = \frac{\partial h}{\partial t} + U\frac{\partial h}{\partial x} = \frac{C_K w_m^3}{C_T w_m^2 + gh\Delta/T} \tag{5.5}$$

This equation can be transformed in an ordinary differential equation in time using stationary solution and a parameterized expression for Δ (LUHAR, 1998), and then solved by direct numerical integration in time, as described in details in MARTANO (2002). After sunset the algorithm assumes as boundary layer height the values of the equilibrium height dependent on local atmospheric conditions (ZILITINKEVICH et al., 2002). The required input data are time series of single point values of the surface momentum and sensible heat fluxes, wind speed and temperature. The vertical lapse rate $(d\theta/dz)$, that controls the mixed layer growth, can be either entered as external parameter or estimated within the model algorithm by a proper routine simulating the nocturnal inversion development on the base of the night-time surface cooling rate (MARTANO and ROMANELLI, 1997). In the present simulations the vertical lapse rate is calculated from the estimated nocturnal inversion when the BLH is still growing within the calculated nocturnal inversion height, while the sounding temperature profile from Brindisi WMO sounding station at 06:00 am is used to estimate the lapse rate above the inversion. This procedure appeared to give slightly better results than using the sole sounding profiles down to the ground, as they are measured about 40 km apart from the experimental site and possibly affected by the close presence of the coastline.

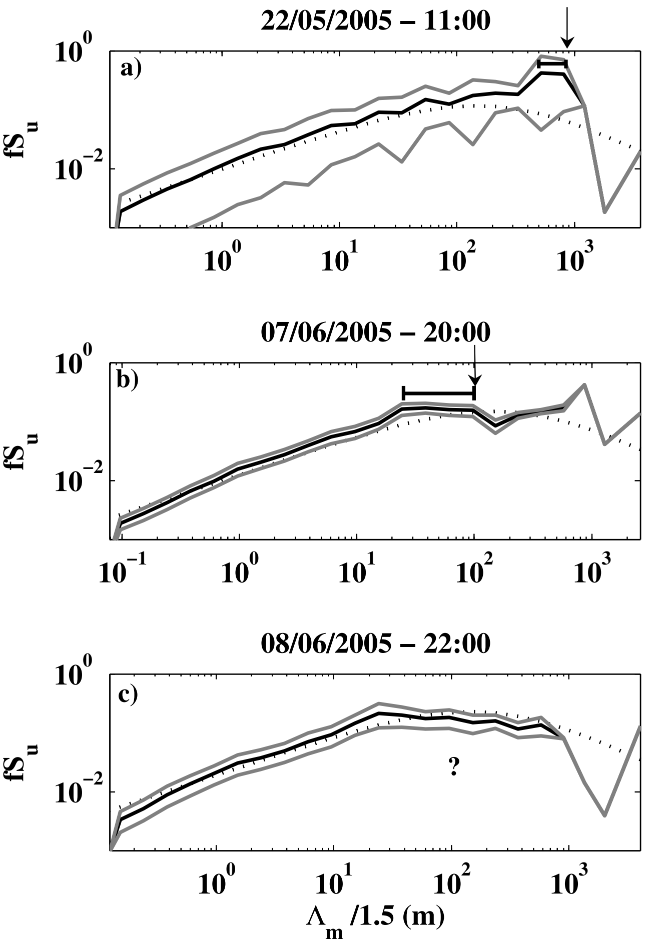

Figure 3: Examples of hourly spectra computed from the sonic anemometer longitudinal wind component as a function of $h = \Lambda_m/1.5$, (a) May 22, 11:00 (local time), (b) June 07, 20:00, (c) June 08, 22:00. Black continuous lines represent mean spectral values and the continuous grey lines indicate the confidence intervals around the mean (mean ± standard deviation of the mean). Horizontal bars represent the range of length-scale associated to the most energetic turbulent eddies and vertical arrows indicate the spectral wavelength chosen for BLH derivation. The question mark indicates the impossibility to detect a clear turbulent maximum, because of the superimposition of nocturnal turbulence and other non-turbulent transient phenomena. Dotted lines represent the Kaimal reference spectrum for neutral conditions (KAIMAL et al., 1972).

6 BLH calculated in unstable conditions by a σ_w-based parameterization

Many of the existing similarity methods, used to estimate turbulence parameters and the BLH from sodar measurements, are presented in (MELAS, 1993) and discussed in review papers (BEYRICH, 1997; SEIBERT et al., 2000). According to similarity scaling (MELAS et al., 2000; ASIMAKOPOULOS et al., 2004), the relationship, in a convective boundary layer, between the standard deviation of vertical wind component σ_w and its velocity scaling w_* is the following:

$$\frac{\sigma_w^2}{w_*^2} = C_1\left(\frac{z}{h}\right)^{2/3}\left(1 - C_2\frac{z}{h}\right)^2 \tag{6.1}$$

where $C_1 = 1.8$, $C_2 = 0.8$, z is the height above the ground and h is the boundary layer height. The above equation is valid in the vertical region between $0.1h$ and $0.7h$ (MELAS et al., 2000). In MELAS and KAMBEZIDIS (1994) an integration of Eq. (6.1), in the range of z between $0.1h$ and $0.7h$, provided the relationship:

$$\frac{\sigma_w^2}{w_*^2} = b \tag{6.2}$$

where b is a parameter with an average value of 0.4–0.45 (MELAS et al., 2000). Equations (6.1) and (6.2) are valid in unstable boundary-layer (MELAS, 1993) and they have been used in this work when $h_R/L < -2$ being h_R the BLH evaluated by the Remtech sodar and L the Monin-Obukov length. Assuming a constant value for b it is possible to use equation (6.2) for the determination of the BLH using as input parameter the σ_w measured by the sodar in a specific range gate and the heat flux measured by the sonic anemometer. In some application the sensible heat flux is calculated, using a parameterisation, from sodar measurements of CT^2 providing that the sodar is properly calibrated (MELAS, 1990).

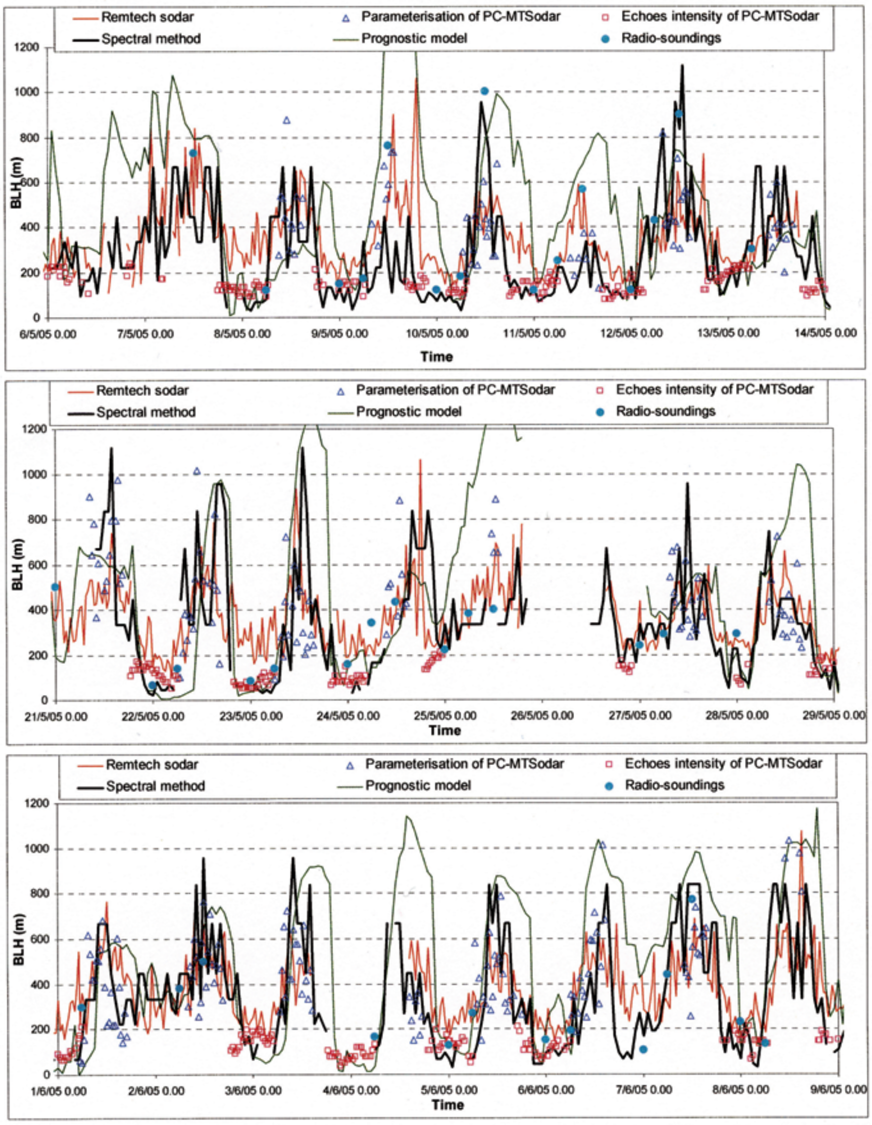

Figure 4: Values of the BLH computed by different methodologies for selected periods of the measurement campaigns.

The parameter b has been evaluated, with the available data-set, using a scaling velocity w_* calculated starting with the BLH provided by the Remtech sodar (h_R), the heat flux measured by the sonic anemometer and the σ_w measured by the PC-MTSodar. Results indicate that the average value of b, at about 100 m above the ground, is 0.39 (+/- 0.14 standard deviation). When using the σ_w of the Remtech sodar a similar scatter is observed in the values of b but with a lower average: 0.3 (+/- 0.12). This is due to the underestimation of σ_w in convective conditions caused by the incomplete coverage of the turbulence spectrum that is particularly relevant for the Remtech sodar (CONTINI et al., 2007) and also Figure 5.

The values of $\varepsilon = \frac{\sigma_w^2}{w_*^2} - C_1 \left(\frac{z}{h_R}\right)^{2/3} \left(1 - C_2 \frac{z}{h_R}\right)^2$, the difference between Eq (6.2) and Eq. (6.1), has been calculated and the values obtained using the PC-MTSodar are near zero (especially at z around 100 m) even if a large standard deviation is present in ε as it was for b. The values of calculated using σ_w measured by the Remtech sodar are slightly larger than those obtained with the PC-MTSodar. This means that there would not be significant differences, on average, in using Eq. (6.1) or Eq. (6.2) in our analysis. The evaluation of BLH through this parameterization has been performed only using the PC-MTSodar data collected in the fifth range gate (78 m) and no significant differences have been observed for the different range gates providing that the opportune values of b are used. This is because b is slightly increasing with the level above the ground at least in the analysed range (23 m–180 m).

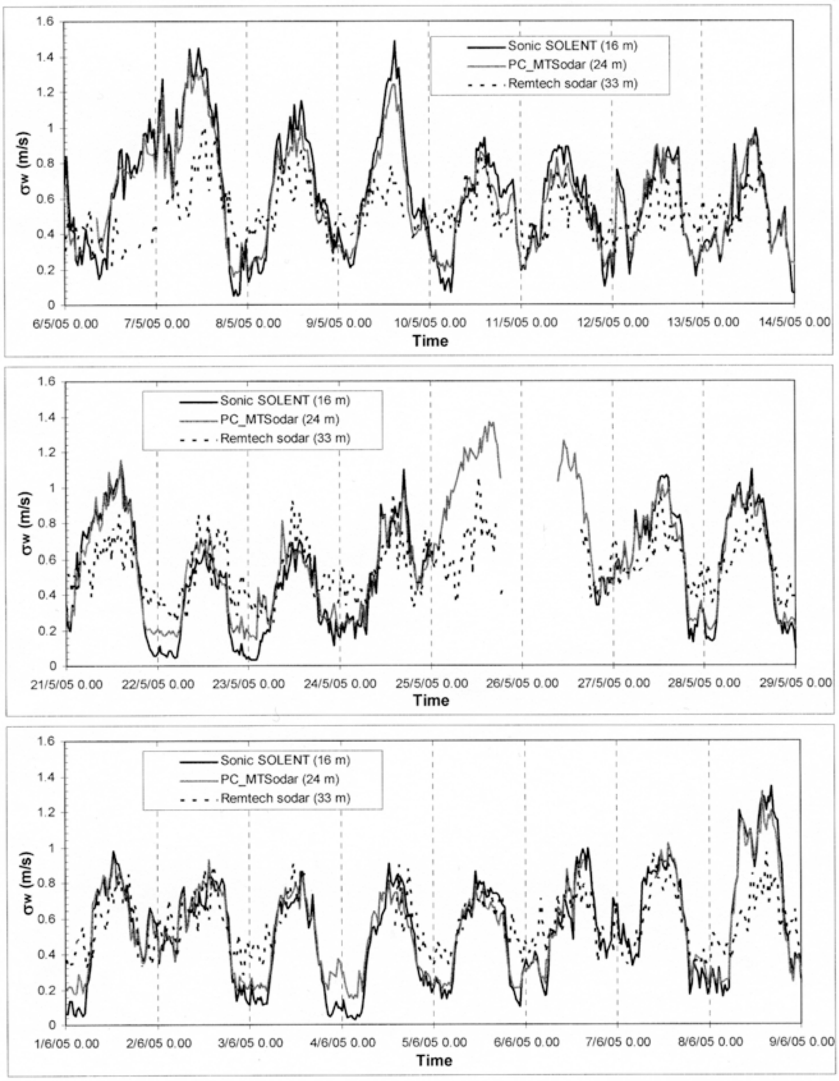

Figure 5: Values of σ_w measured by different instruments in the same selected periods of Figure 4. The data of the two sodars refer to the first available range gate in each instrument.

7 BLH calculated from spectral analysis of the wind velocity

A further estimate of BLH can be obtained from spectral shape of horizontal wind velocity components, by using the empirical relationship firstly developed in KAIMAL et al. (1982a); KAIMAL et al. (1982b); KAIMAL et al. (1976) for convective conditions:

$$\Lambda_m = Kh \tag{7.1}$$

that relates the wavelength of maximum energy (Λ_m), in the u- and v-spectrum, to h through a proportionality constant $K \approx 1.5$. This approach has the advantage of being convenient in field experiments (LIU and OHTAKI, 1997; CINQUE et al., 2000) and it could be applied, in theory, to both sodar data (see section 4) and sonic anemometer data collected in the surface layer, where the horizontal velocity spectra obey the Monin-Obukhov (MO) scaling at high, but not at low frequencies. In fact the wavelengths of the maximum are insensitive to the height changes, in contrast with the MO similarity requirements, while they seem to be influenced by the thickness of the mixed layer. The spectral method proposed in KAIMAL et al. (1982a), like other spectral relationships proposed in literature, see for example LIU and OHTAKI (1997), hold for convective conditions. In stable stratification the spectra of horizontal wind velocity components obey MO similarity theory. As stability increases the spectral maximum, corresponding to the energy containing eddies, shifts systematically towards higher frequencies. This is consistent with the progressive reduction of BLH due to the decrease of mechanical turbulence damped by buoyancy in stable atmosphere. Unlike unstable conditions, a relationship between the wind velocity spectral maximum and BLH has not yet

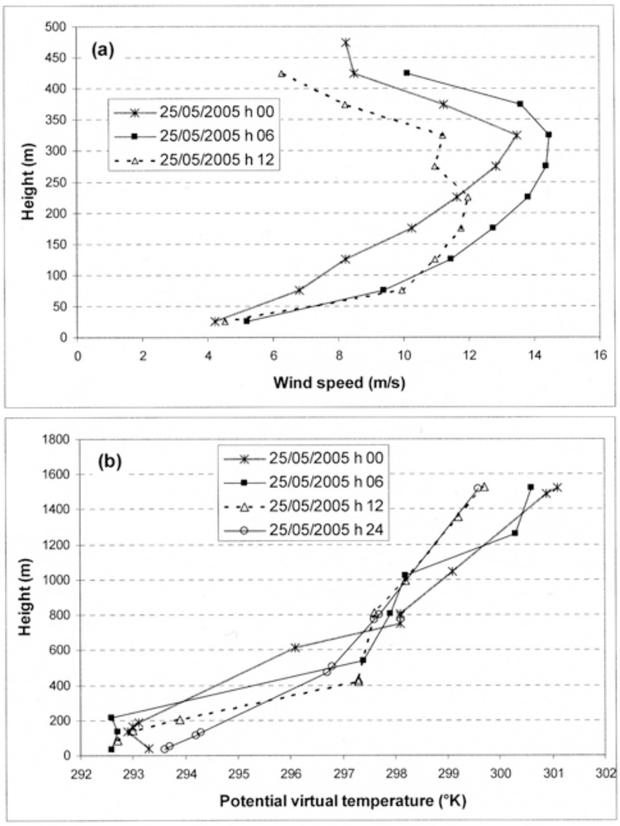

Figure 6: (a) Wind speed profiles measured by the Remtech sodar at different hours of the day 25/05/2005. (b) Potential virtual temperature profiles at different hours of the same day from the radiosoundings of Brindisi (40 km from the measurement site).

been derived in stable stratification, also because often the stable boundary layer has a poorly defined top that smoothly blends into the residual layer above (STULL, 1988). Therefore often Equation (7.1) is also used in stable conditions, like for example in Remtech routine (see section 4).

In this study the spectral methodology has been applied to the longitudinal spectrum computed by the sonic anemometer data by means of Fast Fourier Transform. Spectra of longitudinal wind component have been computed by using hourly time series. Prior to the transformation, spikes have been removed and a linear detrending has been applied in order to minimise the red noise effect on the resolved low-frequency spectral range. Equation (7.1) has been used to obtain BLH independently from the atmospheric stratification, in order to test this relationship in stable conditions and to compare the obtained results with those of the other methods. Therefore the proposed analysis is intended to be only a first approach towards obtaining a spectral parameterization that can be extended also in nocturnal conditions.

The spectral maxima have been visually identified in order to analyse the critical aspects and the problems arising in this procedure if a more desirable automatic detection method should be developed. Figure 3a shows an example of a typical spectral shape of the longitudinal wind component during convective conditions. The horizontal bar represents the range of length-scales associated to the most energetic turbulent eddies and the vertical arrow indicates the spectral wavelength chosen to derive BLH. It should be noted that it has been chosen the maximum wavelength before the energy decay at large length scales, as representative of the size of the most energetic eddies in the turbulent flow.

Our analysis demonstrated that the application of an automatic methodology could often lead to 'false detections', in particular during stable conditions when the detection of the spectral maximum is more difficult. This happens because the stable boundary layer is complicated by numerous transient phenomena that produce non-stationarity (and as consequence spectral noise at large scale), including 'external' intermittency, and non-turbulent phenomena such as meandering or wavy motions (MAHRT, 1999). Filtering these motions is an arduous operation because often their characteristic length scales reside in the turbulent spectral range of interest in BLH evaluation. In these cases the turbulent spectral maximum is often undistinguishable because masked by the energy of the large scale motions, thus limiting the applicability of the methodology. Figure 3b shows an example of longitudinal spectrum relative to stable conditions exhibiting a double spectral maximum. The first is relative to a length scale of about 150 m (associated to nocturnal turbulence); the second one to a length scale of about 1300 m (associated to non-turbulent phenomena during the night). It is evident that in this case the application of automatic detection methodologies could lead to a false detection of the largest turbulent length scale. In other more complicated cases the absence of a spectral gap produces a 'broad' spectral maximum that makes impossible to distinguish between turbulence and other transient phenomena. An example is shown in Figure 3c where spectral energy is almost constant in the range between 25 m and 700 m and where a question mark indicates the impossibility to detect a clear turbulent maximum.

8 Discussion of results

In Figure 4 the BLH values estimated with the described methodologies have been shown for selected periods of the measurement campaign. In nocturnal boundary layer, when it presents a ground level (or near ground) inversion, the BLH has also been evaluated by a visual analysis of the intensity profiles of the intensity echoes (fax) measured by the PC-MTSodar. In Figure 5 the σ_w values measured by the ultrasonic anemometer (at 16 m above the ground), by the Remtech sodar (in the first available range gate at 33 m above the ground) and by the PC-MTSodar (in the first available range gate at 24 m above the ground) are reported. Results of radio sounding measurements show that the diurnal BLH is relatively low in average terms and this is in agreement with the results of the other indirect methods of evaluation. There is a reasonable correlation between radiosonde results and the other methods, the Pearson correlation coefficients are: 0.90 with the spectral method, 0.70 with the prognostic model, 0.86 with the Remtech routine and 0.87 with the PC-MTsodar results (obtained by the analysis of the fax during the night and with the w-method during the day). The spectral method also shows the lowest bias with respect to the radiosonde results. Results clearly show the presence of scatter in the evaluation of BLH with both the spectral methods and the σ_w method. The origin of this scatter for the spectral methods is due to the difficulty of a clear determination of the spectral maximum, as mentioned in section 7. For the σ_w method the scatter is due to the large standard deviation of the parameter b. This scatter together with the limited stability range in which the method is usable severely limits its applicability in operational evaluation of BLH.

In unstable diurnal conditions there are differences in the BLH calculated by the different methods and, even if all of them show the same general pattern, only a limited agreement between them is observed. The prognostic model calculations seem to be better at high wind speed and the differences in the other cases are likely due to the uncertainty in the lapse rate estimation, from either an approximate evaluation of the nocturnal inversion in the numerical algorithm, or from the sounding temperature profile, 40 km apart from the experimental site. The level of scatter in the Remtech routine is similar (and in some cases smaller) with respect to the ones observed in the other parameterised models (spectral method and σ_w method).

In nocturnal stable boundary layers the BLH calculated by the Remtech sodar is never lower than about 150 m and rarely lower than 200 m for all the measurement period. Compared with the other methods the Remtech routine seems to overestimate the nocturnal BLH especially in low turbulence conditions. It agrees with BLH computed with the other methods mainly in certain periods characterised by relatively high levels of vertical turbulence. In other periods the Remtech BLH is higher than the equilibrium height computed by the mathematical model and also higher than the mixing height evaluated through the analysis of the echoes intensity profiles and with the spectral method. This is particularly evident in cases of low wind speed and low vertical turbulence. As shown in Figure 5 in these conditions the w measured by the Remtech sodar is highly overestimated probably because of the system errors and of the efficiency of the Doppler-shift retrieval routine (CONTINI et al., 2007). It is likely that in these conditions noisy spectra of vertical velocity are obtained by the Remtech routine with consequent problem in the identification of the largest eddy scale. Another potential limit in its performances in stable boundary layer could be due to the simultaneous use of several range gates that, in shallow boundary-layer, could produce a mixing of vertical wind velocity spectra in the actual boundary layer and in the residual layer.

There is a good agreement between nocturnal BLH evaluated from the measured intensity of echoes, the spectral method and the radiosonde data. The prognostic model seems to give better results with respect to the Remtech routine even if, on average, there is an overestimation of nocturnal BLH.

In the following the peculiar pattern of BLH observed in particular days will be discussed. The day 06/05/2005 does not show a significant daily pattern of BLH according to both the results of the Remtech sodar and the spectral method. This happens because this day is characterised by precipitations and the presence of clouds so that the sensible heat fluxes are negligible during all the day. Also latent heat fluxes are relatively small with respect to the other days. The day 25/05/2005 shows a relatively high BLH during the night and slowly varying during the day according to both Remtech routine and data of spectral analysis. However the prognostic model shows a significant increase of the BLH. This day is characterised by strong wind and a strong temperature inversion located between 200 m and 400 m. This is shown in Figure 6 where the velocity profiles measured by the Remtech sodar have been reported for different hours of the day together with the virtual temperature profiles obtained by the radio-soundings in Brindisi. The maximum of the wind velocity profile is at about 330m and this is expected to be just below the height of the inversion beeing there. Therefore in reasonable agreement with the BLH obtained by the spectral method (around 350 m). The BLH evaluated by the Remtech sodar is also in a reasonable agreement even if it is slightly higher. On 25/05/2005 conditions with $h_R/L < -2$ have been found only for two hours during daytime. Even if the wind speed is high there are significant turbulent heat fluxes (250 W/m^2 of sensible heat flux and about 80 W/m^2 of latent heat flux) and the measurements of w reported in Figure 5 show that the vertical turbulence is growing to relatively large values during daytime increasing the estimation of the BLH with the σ_w method. It seems that the prognostic model is not able to correctly predict the BLH in this situation. Probably the jet-like high wind condition persisting for the whole day with a strong almost stationary inversion above cannot be adequately described by a model in which the evolution of the upper inversion is described as a consequence of the mixed layer deepening (see Eq. (5.3)).

In order to obtain a more quantitative comparison between the different BLH estimates the diurnal and nocturnal averages of BLH have been computed. Values obtained by the model, by the Remtech software and by the spectral method have been plotted against the values obtained with the PC-MTSodar using different methods for diurnal and nocturnal boundary-layer. The σ_w method has been considered during the day and the analysis of the received echoes intensity as reference for the night. The number of data used for the calculations of the averages has been conditioned by the number of estimates of BLH obtained by PC-MTSodar during the day and during the night, in order to have a better comparison of the averages from different methodologies. Both the BLH averages obtained by the model (Figure 7a) and by the Remtech routine (Figure 7b) appear not correlated with the BLH averages obtained by the PC-MTSodar. Specifically the prognostic model seems to overestimate (in average terms) the BLH during the night while the Remtech software shows a clear average overestimation with an almost constant value during the different nights. On the other hand, the BLH averages computed by the spectral analysis of longitudinal wind component show the lowest biases with respect to the reference. It should be noted that Equation (7.1), even if derived for unstable conditions, has been used also in nocturnal conditions without any change in the proportionality constant. These results encourage further investigation to improve the applicability of spectral method during the night investigating the possibility to use a different coefficient K in Eq. (7.1) for stable conditions.

9 Conclusions

The different methods used for the evaluation of BLH show, in unstable conditions, an agreement of the general patterns indicating a relatively low boundary layer even when strong surface heat fluxes are measured. This is a consequence of the advection effect due to the reduced fetch from the coastline that is typical of the region. The analysis of BLH from radiosonde data confirms the relatively low values of the diurnal BLH and it shows a good correlation with the other methods. The maximum correlation and minimum bias is obtained with the spectral method. Significant scatter has been observed in the BLH evaluated through the σ_w parameterisation due to the variance of the parameter b. This, together with the limited range of stability in which the method can be used severely limits its applicability for the determination of evolution of BLH even in diurnal hours. Also the BLH values calculated with the spectral method show a significant level of scatter due to the difficulties of the individuation of the position of the maximum in different spectra. The scatter observed in the results of the Remtech routine is similar, and in some cases smaller, than that of the other parameterised methods.

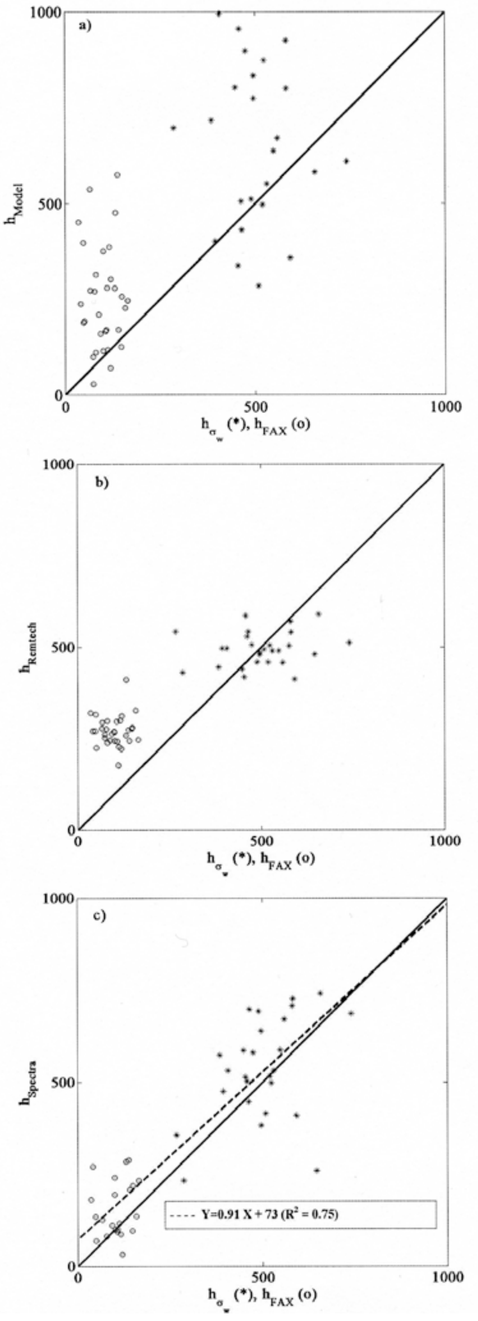

Figure 7: Scatter-plot between average BLH calculated with the analysis of the echoes intensity (during the night) and with the analysis of σ_w (for convective conditions) with the other different methods: (a) prognostic model; (b) Remtech routine and (c) spectral method. Results include the diurnal (*) and nocturnal averages (filled marks). In the graphs it is included the (1:1) continuous line and a linear fit is calculated only for case (c).

A closer examination of Figure 7 shows that taking the σ_w parameterization (day time) and the visual fax analysis (night-time) from the PC-MTSodar data as reference, both the model and the Remtech sodar results show some limits: overestimation in nocturnal hours for both and, in diurnal hours again overestimation of the model. In the case of the model they are probably due to the uncertainty in the estimation of the vertical lapse rate from radio sounding and/or in the evaluation of the inversion height. In the case of the Remtech sodar the problems in the automated selection of the spectral maximum and high noise in night-time have been discussed as possible cause of the discrepancy. It could also play a role the use of vertical wind measured in multiple range gates that could be not appropriate for shallow boundary layers. The spectral method was originally developed for convective conditions only, however reasonable results have been obtained applying the method also to nocturnal cases. Therefore the spectral methodology seems to be a good candidate for the development of automatic routines for operational BLH evaluation, possibly using a different parameterisation for stable and unstable cases. A more detailed analysis with a direct estimation of the reference BLH in the same site with a sufficient time resolution (1–2 hours) through temperature profiles would be useful to confirm these conclusions and assess accurate values of the used coefficients, particularly in stable conditions.

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