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Atmospheric Chemistry and Physics Discussions

Interactive comment on "Ceilometers as planetary boundary layer detectors and a corrective tool for ECMWF and COSMO NWP models" *by* Leenes Uzan et al.

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Author's Response to referee #1: We wish to thank referee #1 for the comprehensive and constructive comments providing the opportunity to improve our manuscript. The comments led to a major revision of the manuscript. For convenience, our response is given by order of appearance following the structure of the manuscript.

1.INTRODUCTION

Referee's comment: P2, L46: The mentioned advantage of ceilometers over lidars must be specified! Regarding what? .... is the question! If I would have to select, I would take a sophisticated lidar because such a system is much more powerful concerning emitted pulse energies and the list of aerosol products is long compared to quite ‘simple’ and ‘weak’ ceilometers. So, please specify what you definitely mean, ... with advantage! Probably low costs, robust observations, no complex adjustments, and calibrations. However, the clear disadvantage of ceilometers, operated at water vapour absorption around 910 nm, is that the only product you can trust is the range-corrected signal, nothing else!

Author’s response: Thank you for your remark. An explanation was added to the introduction section as well as to the section describing the instrument (Sect.4.1).

Author’s changes in manuscript: Additional text in Sect.1 (Introduction): " Applicable evaluation of PBL heights can be derived either by actual measurements or estimations based on numerical weather prediction (NWP) models. On the one hand, NWP models, such as regional models, provide high temporal and spatial data resolution beyond the capability of actual measurements. On the other, they are based on mathematical equations with initial assumptions and boundary conditioned set beforehand. Hence, the models’ products require a systematic validation tool based on actual measurements. There are two main PBL height measurement methods: in-situ radiosonde launches and remote sensings such as lidars and profilers. Unfortunately, radiosonde launches are costly as successive measurements. Profilers and sophisticated lidars produce high temporal resolution profiles but are limited in space. Moreover, certain meteorological conditions may reduce their performance, such as precipitation for radio acoustic sounding systems and dust storms for Raman lidars. These limitations have led several research groups to successfully utilized ceilometers, single wavelength cloud base height detectors, as a means to recognize and determine the PBL height (Eresmaa et al., 2006, Haeffelin and Angelini, 2012, Wiegner et al., 2014). Ubiquitous in airports and meteorological service centers worldwide, ceilometers obtain a large spatial resolution per lidar (for further information see TOPROF of COST Action ES1303 and E-PROFILE of the EUMETNET Profiling Program). They produce high temporal resolution profiles about every 15 s and every 10 m, up to several km, retrieved as attenuated backscatter signals. The ceilometers are low cost, easy to maintain, and operate continuously unattended under diverse meteorological conditions (Kotthaus and Grimmond, 2018). These qualities reflect their advantages over high-cost, multi-wavelength sophisticated lidars, which require surveillance, calibration procedures, and careful maintenance. Hence, they are limited in amount and operational time (Mamouri et al., 2016) and cannot produce the spatial and temporal measurements coverage essential to validate the PBL heights generated by NWP models.". Additional text in Sect.4.1 (Ceilometers): "The PBL height detection is based on a pronounced change of the attenuated backscatter profile. This change is attributed to variations in the aerosol content providing indications for both clouds and atmospheric layers. Therefore, the limitation of a single wavelength within the spectral range of water vapor absorption does affect the PBL height detection. Nevertheless, Weigner et al., (2014) succeeded to properly derive the backscatter coefficient from ceilometers, providing signal calibrations and corrections for water vapor (Wiegner and Gasteiger, 2015)".

2.RESEARCH AREA

Referee's comment: P4, L92: Please provide longitude, latitude and height above sea level for Beit Dagan already here, and where is it located (including distance) with respect to Tel Aviv and Jerusalem.

Author's response: The location and topography of Beit Dagan were given in Fig. 1 and Table 1. Following the referee's remark, the radiosonde parameters were added to the text given in Sect. 4.2. Author's changes in manuscript: Text in Sect. 4.2 (Radiosonde): "The Israeli Meteorological Service (IMS) obtains systematic radiosonde atmospheric observations twice daily, at 23 UTC and 11 UTC, adjacent to a ceilometer. Launching is performed in Beit Dagan (32.0 ° long, 34.8 ° lat, 33 m a.s.l), situated 7.5 km east from the shoreline, 11 km southeast to Tel Aviv, 45 km northwest to Jerusalem (Fig.1 and Table 1)". the title of Table 1 was changed: "Location of measurement sites and ceilometer types". An affiliation was added to the Beit-Dagan stating it is the location of the radiosonde launch site and ceilometer measurements. The caption of Fig. 1 was changed to:"... The Radiosonde launch site is situated in Beit Dagan, adjacent to the ceilometer ".

Referee's comment: P4, L109: Please provide frequently, what UTC means in local time. Local time is needed to better follow the discussion on PBL evolution and the diurnal cycle.

Author's response: Comment accepted. Author's changes in manuscript: UTC was corrected to LST winter time (corresponding to UTC+2) in the paragraph describing the Israeli summer PBL evolution (Sect.2 Research area).

Referee's comment: P4, L110-120: There is no general PBL diurnal cycle in Israel, I speculate. But you provide such an impression! The occurrence, onset, strength, and impact of the sea breeze circulation depend on given meteorological conditions (marine westerly versus continental easterly air flows, low and high wind speeds, clear or cloudy conditions). The sea breeze event strongly influences the PBL diurnal cycle. All this must be carefully mentioned in the text. And what about the impact of dense desert dust layers (in the PBL and especially in the free troposphere)? Is there any PBL development when there is a dust outbreak event? So all in all, many factors seem to control the sea breeze events and the PBL cycle in Israel. Thus, please provide more details on this.

Author's response: The description of the PBL diurnal cycle refers solely to the Israeli summer as stated in the text (line 105): "Comprehensive research of the Israeli summer PBL...". In the summer, the east Mediterranean is dominated by rather persistent synoptic systems explained in lines 104-107: " ... a persistent Persian Trough (either deep, shallow or medium) followed by a Subtropical High aloft (Alpert et al., 2004)", combined with the sea breeze circulation. These conditions generate the PBL height diurnal cycle described in the manuscript and presented in Fig.1 and Fig.2 from Levy et. al., (2011) and Uzan et. al., (2012), respectively. In both figures, the diurnal PBL was obtained signal to noise measurements and virtual temperature profiles from an acoustic radar. The radar was stationed in flat terrain, 3.5 km inland from the shoreline, 51 km north to Beit Dagan. In Uzan et al, (2012) the profiles were classified by the three dominant summer synoptic systems at the time of research (Jun-Oct, 1997-1999, 2002-2005). Levi et al produced the average diurnal evolution for the month of July between 1997-1999. Concerning dust outbreak events, Alpert et al. (2002) investigated dust forcing over the eastern Mediterranean. They concluded: "Summer outbreaks of dust over the Eastern Mediterranean are relatively rare. This area gets frequent intrusions of dust in spring (Alpert and Ziv 1989; Alpert et al. 2000; Moulin et al. 1997) with a secondary maximum in the autumn (Ganor 1994). The dynamical system that transports the dust is primarily the Sharav cyclone, which is also called the Saharan depression, generated in the lee of the Atlas Mountains (Egger et al. 1995) and moving along the North African coast eastward (Alpert et al. 1990b). The Sharav cyclone is clearly not the associated synoptic system in summer". Moreover, dust layers that were evident over Israel in the summer were located in high altitudes.

Author's changes in manuscript: Following the referee's remark, we rephrased the text to emphasize the description of the PBL diurnal cycle refers only to the Israeli summer season: " Previous research describes the formation and evolution of the Israeli summer PBL height as a function of the synoptic and mesoscale conditions, as well as the distance from the shoreline, and the topography. Overall, the diurnal PBL height in the summer season may be portrayed in the following manner.." Details about the occurrence of dust events in the summer were added to the text: " The Israeli summer season (June-September) is characterized by dry weather (no precipitation), high relative humidity (RH, up to 80% in midday in the shoreline, IMS weather reports) and sporadic shallow cumulus clouds. On the synoptic scale, the summer is defined by a persistent Persian Trough (either deep, shallow or medium) followed by a Subtropical High aloft (Felix Y., 1994, Dayan et al., 2002, Alpert et al., 2004). Combined with the sea breeze, the average PBL height is found to be quite low. For example, the PBL

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height in Beit Dagan (33 m a.s.l and 7.5 km east from the shoreline) reaches ∼900 m a.g.l after sunrise, and before the entrance of the sea breeze front (Felix Y.,1994, Dayan and Rodinzki, 1999, Uzan et al., 2016, Yuval et al., 2019). At this height level dust plumes do not exist (Alpert et al., 2002) as summer dust outbreaks in the eastern Mediterranean are quite rare (Alpert and Ziv 1989, Alpert et al., 2000)".

(3.IFS AND COSMO MODELS- no comments)

4.INSTRUMENTS

Referee's comment: P6, L161: Why should single-wavelength lidars not allow the retrieval of mass concentration profiles ... from proper profiles of particle optical properties? Sure, they can be used for this. Ok, this is not the topic of the paper. But the statement is wrong and should be removed. The ceilometer on the other hand side cannot be used to derive proper optical and microphysical properties. That is true! A ceilometer can only be used to detect aerosol layers as a function of height. This is not much, but sufficient for PBL studies. That should be clearly mentioned.

Author's response: In order to differentiate and define the composition of atmospheric aerosols, various wavelengths corresponding to different characteristics are necessary. Weigner et al., (2014) further explains: "Whereas the detection of aerosol layers and their vertical extent requires only simple single-wavelength backscatter lidars, the derivation of extinction coefficient profiles and a series of intensive aerosol properties requires advanced lidar concepts such as high-spectral resolution lidars (HSRL, Shipley et al., 1983) or Raman lidars (Ansmann et al., 1992)". Nonetheless, Weigner succeeded to produce satisfactory estimations of the attenuated coefficient based on signal calibrations and corrections for water vapor absorption (Weigner and Gasteiger, 2015).

Author's changes in manuscript: "The PBL height detection is based on a pronounced change of the attenuated backscatter profile. This change is attributed to variations in the aerosol content providing indications for both clouds and atmospheric layers.

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Therefore, the limitation of a single wavelength within the spectral range of water vapor absorption does affect the PBL height detection. Nevertheless, Weigner et al., (2014) succeeded to properly derive the backscatter coefficient from ceilometers, providing signal calibrations and corrections for water vapor (Wiegner and Gasteiger, 2015).

Referee's comment: P7, L185: Please state again where Beit Dagan is located. P8, L184-187: It should be clearly emphasized that the radiosonde provides ONE value for the PBL height, no diurnal cycle, ... nothing! Only a snapshot of the PBL height, a few minutes after launch is provided by the sonde! In contrast, models can produce the diurnal cycle, and ceilometers can measure it. But all this is not shown and discussed!

Author's response: Lines 184-185 state:" Radiosonde (RS) type. . ..is launched twice daily at 23 UTC and 11 UTC by the IMS in the Beit Dagan site, adjacent to the ceilometer". The time differences between the models and the ceilometers were mentioned in the text as follows: P 5, lines 146-147: "IFS profiles were limited to hourly resolution, while COSMO generated profiles every 15 minutes. To compare COSMO's PBL heights, a series of trials were performed to find the correct representation of hourly values as the last 15 minutes within an hour". P 6, lines 179-181: "To compare the hourly results of the models (Sect. 3), the ceilometers' 15 seconds profiles were averaged to half-hour ones, whereas the second half-hour profile within each hour was chosen". Nonetheless, the relevant sections were rephrased to create a clearer explanation.

Author's changes in manuscript: Sect 4.2 (Radiosonde) was rephrased with additional information: "The Israeli Meteorological Service (IMS) obtains systematic radiosonde atmospheric observations twice daily, at 23 UTC and 11 UTC, adjacent to a ceilometer. Launching is performed in Beit Dagan (32.0 ° long, 34.8 ° lat, 33 m a.s.l), situated 7.5 km east from the shoreline, 11 km southeast to Tel Aviv, 45 km northwest to Jerusalem (Fig.1 and Table 1). The radiosonde, type Vaisala RS41-SG, produces profiles of RH, temperature, pressure, wind speed and wind direction as it ascends. Measurements are retrieved every 10 seconds, corresponding to about every 45 m, reaching 2 km in about 8 minutes. The horizontal displacement of the radiosonde depends on the intensity of the ambient wind speed. In this study, we analyzed the PBL height of midday summer profiles (11 UTC). The average wind speed along these profiles is about 5 m/s (Uzan et al., 2012). Therefore, the horizontal displacement of the radiosonde from its launch position is fairly low and is estimated at about 2.5 km. Moreover, the radiosonde position resolution is defined as 0.01°. As aforementioned, the PBL height in Beit Dagan for midday summer is estimated below 1 km (Dayan and Rodinzki, 1999, Uzan et al., 2016, Yuval et al., 2019). Hence, within an ascending height of 1 km, there could only be a change of 0.01° in the radiosonde position. This spatial error is in the order magnitude of the models' grid resolution. Thus, we assert the radiosonde profiles represent the Beit Dagan site and the displacement error of the ascending radiosonde can be neglected". A text was added to Sect. 6.1 (Comparison to in-situ radiosonde profiles): "Statistical analysis of the Beit Dagan PBL heights mean error (ME), root mean square error (RMSE), and correlation (R) is presented in Fig. 2 and Table 3 for 11 UTC. The analysis was based on the comparison between radiosonde measurements at 11 UTC, to Beit Dagan ceilometer average profiles between 10:30-11:00 UTC, IFS estimations for 11 UTC and COSMO results for 10:45 UTC".

5.METHODS

Referee's comment: This chapter is much too long. Textbook knowledge is presented in unnecessary detail. For each method, please provide the equation, the explanation of the equation, the link to PBL height, and a proper reference. More is not needed. A short and compact section on methods is desirable.

Author's response: Comment accepted.

Author's changes in manuscript: The method section was edited in a concise manner.

Referee's comments: P9, L247: This is confusing: A ceilometer is made to detect the base of the water cloud, but not to detect the cloud top height. In most cases of low level (liquid-water) clouds, there is no chance to detect the cloud top! This needs to be clearly stated. The maximum signal you measure cannot be interpreted as a

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cloud top. This is a very erroneous statement! The maximum backscatter signal is somewhere between the cloud base and cloud top. The maximum signal is at that height where the attenuation effect becomes so strong that the signal immediately drops to the sky background level. This needs to be clearly stated. The height of the maximum signal maybe 100, 300, or 1000 m below the cloud top. Nobody knows! P10 L268: ...Therefore, also the following statement is wrong: Our algorithm denotes the PBL height as the top of the shallow cloud. As just mentioned, you are unable to see the cloud top with ceilometer, only exceptional, in cases with optically rather thin clouds. Please improve your statements. The discussion is unacceptable in the present form.

Author's response: Thank you for this important remark. In this research, we employed the wavelet covariance transform (WCT) method on the ceilometers' backscatter profiles. The principle of this method is to calculate the derivatives between measuring points along the length of the backscatter profile. The highest derivative implies a profound difference in the atmospheric aerosol content. On clear days, this difference occurs as the transmitted light exits the well-mixed layer and enters the stable layer above. In the presence of clouds, the highest values are retrieved at cloud base height which is considered as the mixed layer height. The cloud top denotes the bottom height of the free atmosphere (Fig.3 from Stull, 1988). Therefore, in order to generate a consistent definition of the PBL height by the WCT method, our algorithm seeks the height of the transition zone in the presence of clouds as well. This height is defined here as the highest measuring point of a cloud above the cloud base height. Even though the summer clouds are relatively shallow ($\sim$ 500 m thickness based on observations, see example in Fig.4 and Fig.5), there is no guarantee the algorithm detects the actual cloud top. Therefore, to prevent misinterpretations, the phrase "cloud top" was omitted and clarified as the highest measurement point of a cloud above a cloud base height.

Author's changes in manuscript: " When clouds are present (mainly summer shallow cumulous), the algorithm defines the highest measurement point of a cloud (above the cloud base height) as the height where the signal counts decrease to the amount retrieved by background values. This signifies the ceilometer's identification of the entrainment zone (Stull, 1988)".

6.RESULTS

Referee's comment: P10, L286, and Figure 3: This is the worst case you can select in a comparison paper. There is the PBL development, there is the sea breeze effect, and there is cloud evolution! As a consequence, the PBL depth is more or less undefined at these complex atmospheric conditions. . . This case study is rather confusing and not helpful. Unambiguous, cloud-free conditions would be desirable to check the different approaches of PBL height retrieval.

Author's response: We analyzed a total of 33 cases and received good results for the majority of the data (cases of either cloud-free or sporadic shallow cumulus clouds). The largest gaps between the models' estimations and the radiosonde measurements were found on August 17, 2016, presenting an uncommon multi-layer summer cloud. As the referee correctly discerned, this complex meteorology explains the large gaps between the models and the instruments. We agree with the referee for the necessity to present a case reflecting the ability of the method. Therefore, we generated a new figure demonstrating a typical event to explain the method rather than the extraordinary results of Aug 17, 2016.

Author's changes in manuscript: Figures 3 and 5 were removed and a new figure from August 15, 2015, was added representing a typical event (given here as Fig 6).

Referee's comment: P10, L286, and Figure 3: Fortunately, the radiosonde temperature profile indicates the PBL height at about 800m because for this height range (from 50 – 800m) the layer is well mixed indicated by the almost height-independent virt. pot. temperature. Then the pot. Temperature strongly increases with height and prohibits vertical mixing higher up. However, in Fig.3, the PBL heights obtained by the authors (from radiosonde, ceilometer, COSMO and IFS model) are between 1000 and 2200m?

This is confusing! The PBL height is clearly not at 1000m, 1400m, 1700m, or even 2000m. So, the ceilometer result of 1700m is totally wrong to my opinion. The reason is obviously that the range-corrected signal (and the wavelet analysis) cannot be used at these cloudy conditions to detect the true PBL height. What you see is some arbitrary height where the range-corrected signal takes its maximum...

Author's response: The referee indicated the PBL height as the highest point aloft before the virt. pot. temperature increases. Following Stull (1988, Chapter 5, paragraph 5.5, see attached Fig.7), and the parcel method (Holzworth 1964, Seidel et al., 2010) we indicated the PBL height as the height where the virtual potential temperature reaches the value that of the surface level. By this method, the PBL height is indicated as the height where the passage from the unstable layer to the stable layer above occurs. The unstable layer is defined by the mixed layer and the entrainment zone above. This definition corresponds with the height point at which an abrupt change is measured by the ceilometers, at the transition zone between the well-mixed layer and the free atmosphere above.

Author's changes in manuscript: No changes were made in the manuscript.

Referee's comment: P10, L286, and Figure 3: If the radiosonde observations of temperature, relative humidity, wind speed, and wind direction would be shown, we would have the chance to see what is going on here. But all this is not presented. Height resolved trajectory analysis would be helpful as well in the discussion of the complex meteorological conditions. Please provide at least the wind and RH profiles of the radiosonde in the figures. The reader may want to know more about the meteorological situation.

Author's response: Comment accepted. Profiles of temperature, RH wind speed and wind direction from the adjacent radiosonde launch site are given here in Fig.8.

Author's changes in manuscript: Additional plots presenting radiosonde profiles of wind speed, wind direction, relative humidity, and temperature were added to the typical

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case on Aug 15, 2015.

Referee's comment: P11, L308: Again, Figure 5 shows a rather difficult case (PBL evolution plus sea breeze effect). There is obviously a marine boundary layer (with the top at 600m, clearly seen by the radiosonde) and, on top, the upper part of continental PBL up to about 1500m (also visible in the radiosonde profile). But, per definition, the lower PBL counts (the lowest well-mixed layer above the surface is the boundary layer, as defined by Stull 1988). And that is the marine boundary layer, indicated by the potential temperature profile and the ceilometer data. But the PBL height obtained from the ceilometer profile analysis is again around 1700 m. This is an error of more than 100%! Please show RH and wind profiles (direction and speed) so that more information about the complex PBL development at sea breeze conditions is available. Again, the selected case and the discussion are rather confusing. The results are at all not convincing, and not understandable. What is then the message of the study? Obviously, the IFS model does not simulate the impact of the sea breeze impact correctly or even ignores sea breeze effects so that the continental pot. temperature profile is obtained with this model. The IFS PBL heights seem to be in contradiction with the IFS pot. temp. profile. The COSMO pot. temp. profile is in good agreement with the radiosonde profile and shows the PBL height at 600 m. Very stable conditions higher up are simulated with COSMO so that not vertical mixing is possible above 600 m height. Surprisingly, the COSMO PBL height is at 1700 to 2100 m. This is totally confusing! This seems to be simply a mistake! Please clarify!

Author's response: We deeply apologize for this clerical error. The referee is correct. Fig. 5 contains a grave mistake. Unfortunately, the data of PBL heights of Aug 17, 2016, were mistakenly presented also for Aug 10, 2015 inevitably causing a disagreement between the virt. pot. temperature profiles, and the PBL height indicated upon the ceilometer figure. A correct figure is given in (Fig. 9) including meteorological profiles from the adjacent radiosonde (Fig.10).

Author's changes in manuscript: The corrected figure including the meteorological conditions for each study case are given in the point to point response, but not in the manuscript. Following the referee's suggestion, they were replaced by a representative case of the method on August 15, 2015.

Referee's comment: P12: Is section 6.3 needed? It is a very speciïňĄc regression approach, just applicable to Israel.

Author's response: Sect. 6.3 suggests a new approach to correct COSMO PBL height estimations by ceilometers. Actually, that is the goal of the research. The method proved as an applicable tool to validate and even correct the model's estimations. In regions with scarce profiling, there are no other alternatives to validate the model's results. Considering the simplicity of the method, it can be easily adapted in similar topographical areas by adjusting the correction factors (Eq. 6).

Author's changes in manuscript: The paragraph was rephrased to emphasize the advantage and importance of the suggested method.

Referee's comment: P12-13 The conclusions must be rewritten after clarifying all the contradictions.

Author's response: Comment accepted.

Author's changes in manuscript: The Conclusions paragraph was rephrased accordingly.

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Author's comment: In the process of responding to the referees' comments, we repeatedly examined our datasets and evaluations of the equations of each method. We found that the virtual temperature and the virtual potential temperature employed values of Rd/Cp = 287/1004 ($\sim$ = 0.28586) and surface pressure of Po =1000 mb for the radiosonde data. On the other hand, in both models, these factors were defined as Rd/Cp = 0.263, Po = 1013.15 mb. Therefore, we decided to modify the factors assimilated on the models to the same values given for the radiosonde data (Rd/Cp =

287/1004, P0 = 1000 mb). Essentially, the updated values did not change the correction method (which was based on the bulk Richardson method) or the conclusions of the research, but it altered the models' results based on the parcel method as presented below (Tables 3-5 and Fig. 11):

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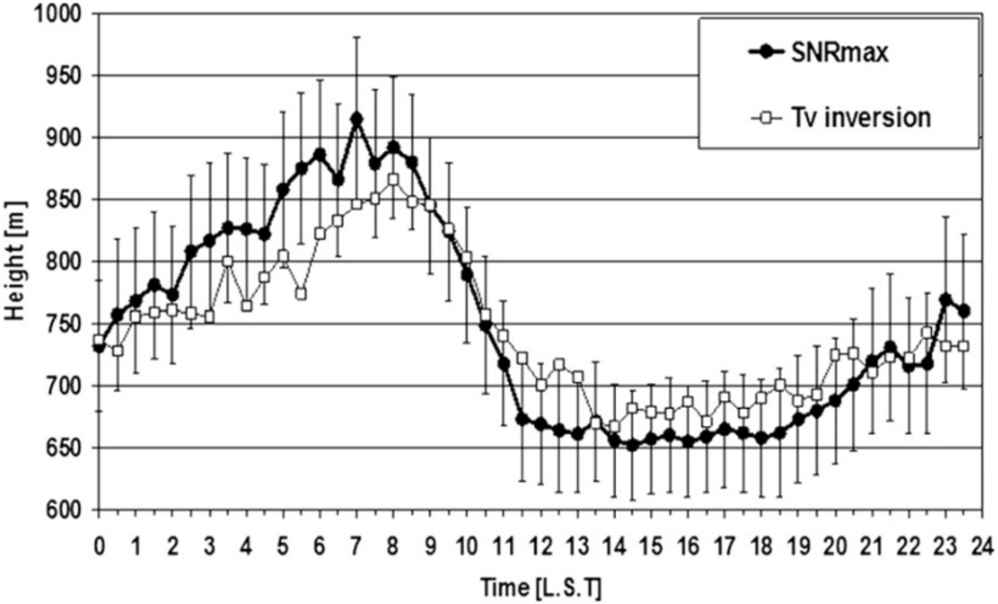

Fig.1 The average diurnal evolution of the boundary layer height during Julys of 1997–99 as defined by the height of SNRmax value (filled circles) together with the upper and lower 95% confidence limits. The inversion in the corrected virtual temperature T_v measured by the RASS is indicated by open squares.

(Source: Levi et al., 2011)

Fig. 1. The diurnal summer MLH

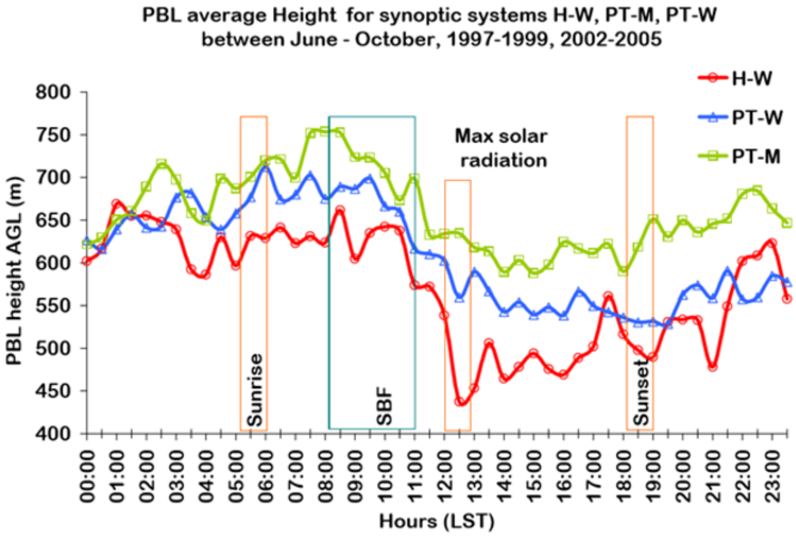

Fig.2 Lap-3000 profiler results of the average PBL height for the three main synoptic systems, Persian trough weak (PT-W, blue line, an average of 347 days), Persian trough medium (PT-M, green line, an average of 232 days) and High to the west (H-W, red line, an average of 198 days), during June-October 1997-1999,2002-2005. Also indicated are times of sunrise and sunset, maximum solar radiation and SBF entrance. (Source: Uzan et al., 2012)

Fig. 2. The diurnal summer MLH

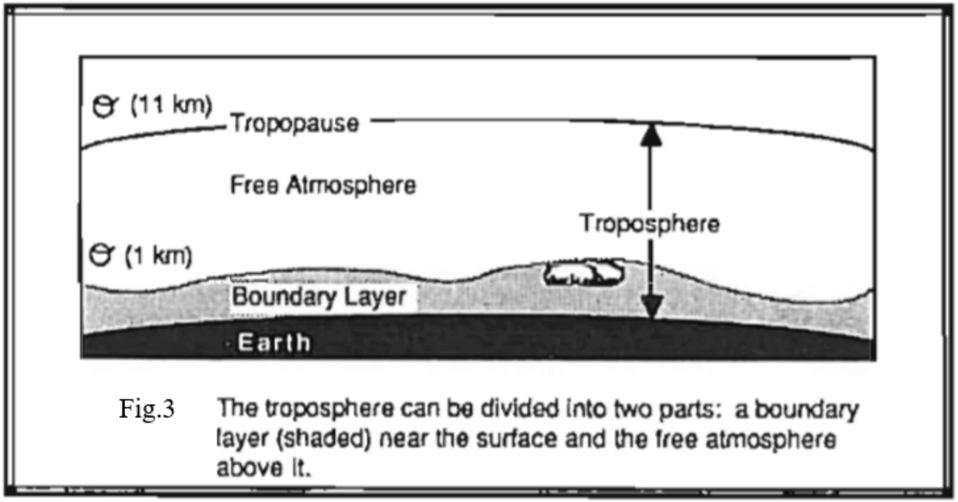

Fig.3 The troposphere can be divided into two parts: a boundary layer (shaded) near the surface and the free atmosphere above it.

(Source: Stull, 1988)

Fig. 3. PBL illustration

Fig.4 IMS photograph of the sky over Beit Dagan site on August 2, 2019, at 8 UTC presenting typical shallow cumulus clouds.

Fig. 4. Cumulus clouds - sky vision

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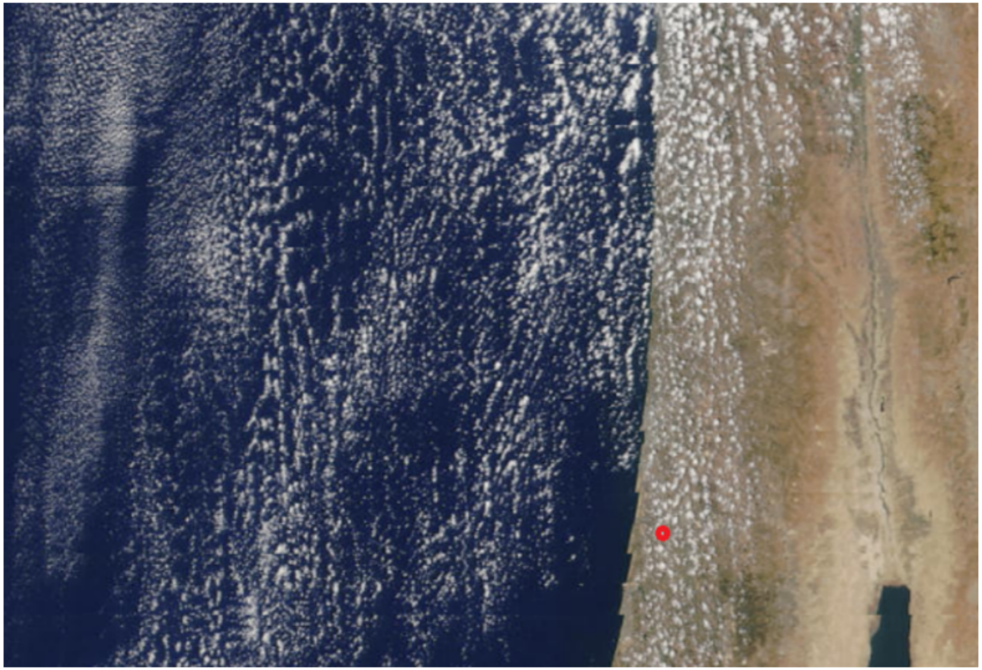

Fig.5 Terra-MODIS 250 m resolution picture over Israel on August 2, 2019, at 8 UTC. Beit Dagan site is indicated by a red dot. Adapted from @NOAA- EARTHDATA.

Fig. 5. Cumulus clouds - Terra Modis

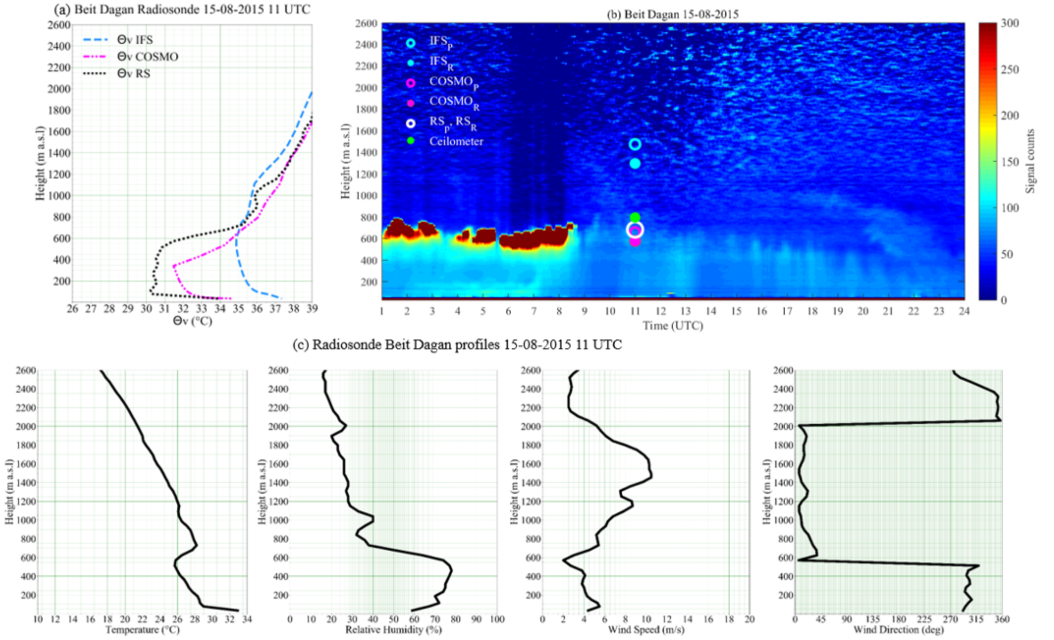

Fig.6 Meteorological measurements from Beit Dagan site on August 15, 2015: Virtual potential temperature profiles at 11 UTC generated from radiosonde measurements, IFS and COSMO models (a), ceilometer signal counts plot including indications of the PBL heights at 11 UTC from the models (IFS_R, IFS_P, $COSMO_R$, $COSMO_P$), radiosonde (RS_R, RS_P) and ceilometer (b). The bottom panel presents radiosonde profiles of temperature, RH, wind speed and wind direction at 11 UTC (c).

Fig. 6. Analysis of Aug,15,2015

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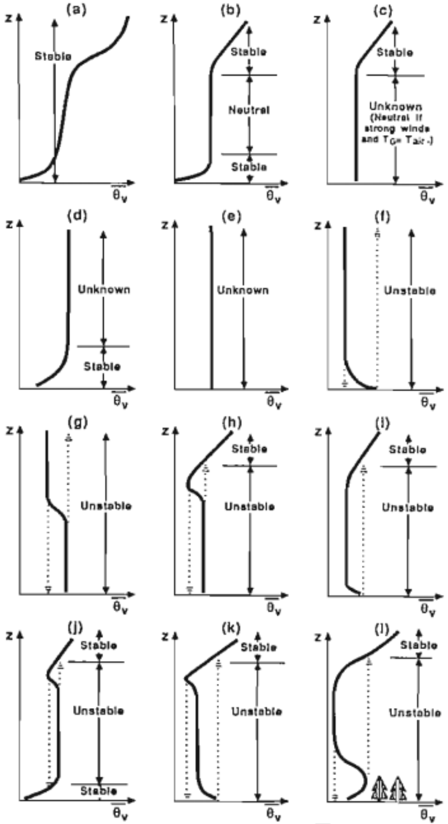


Fig. 7 Static stabilitiy as a function of the $\overline{\theta}_v$ profile. Dotted lines denote parcel movement.

Fig. 7. Virt.Pot.Temp profiles

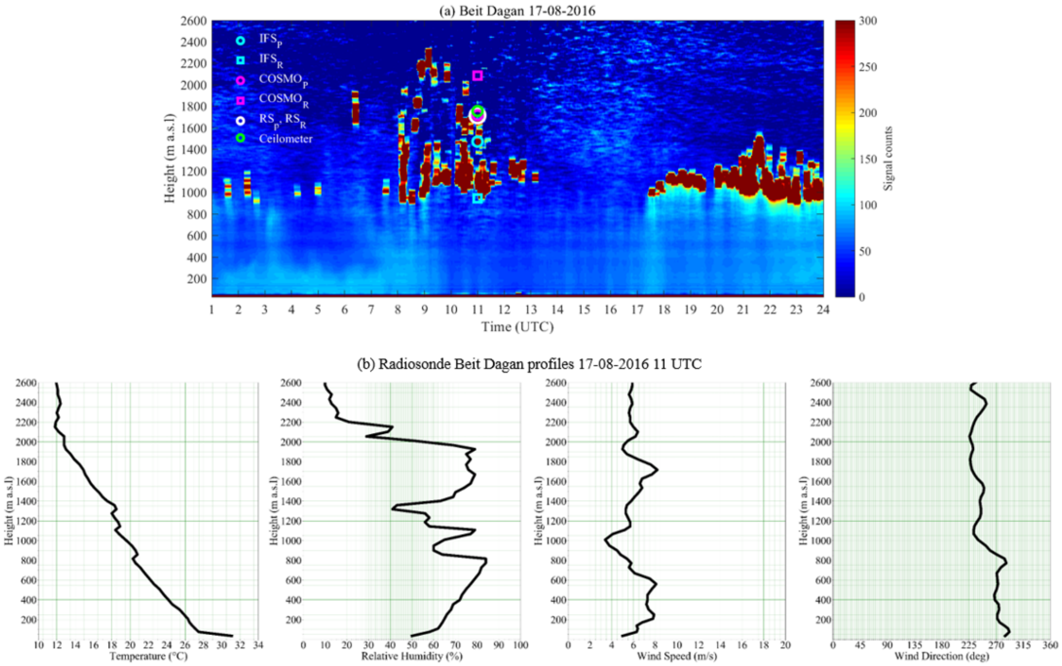
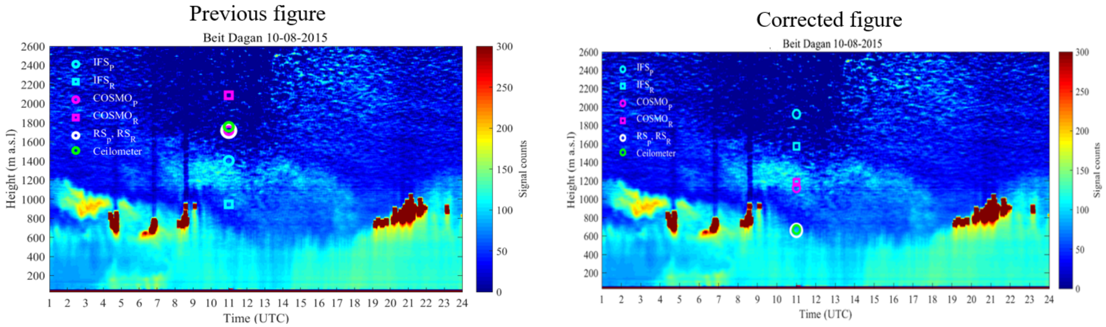


Fig.8 Ceilometer signal counts plot on August 17, 2016, including indications of the PBL heights at 11 UTC from the models (IFS_R, IFS_P, $COSMO_R$, $COSMO_P$), radiosonde (RS_R, RS_P) and ceilometer (a). The bottom panel presents the radiosonde profiles retrieved at 11 UTC on the same day (b).

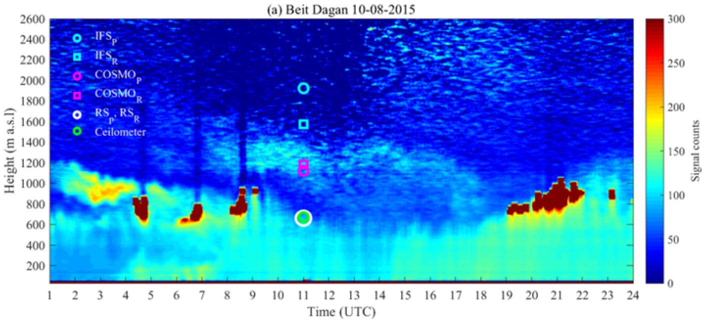
Fig. 8. Analysis of Aug,17,2016


Previous figure

Corrected figure

Fig. 9. Correction of the analysis on Aug,10,2015

(a) Beit Dagan 10-08-2015



(b) Radiosonde Beit Dagan profiles 10-08-2015 11 UTC

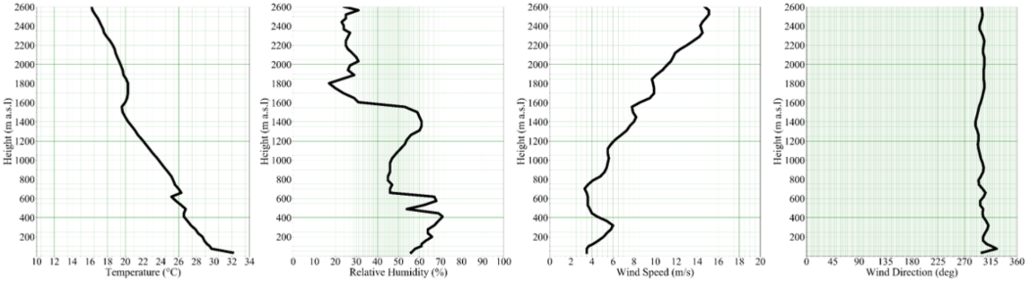


Fig.10 Ceilometer signal counts plot on August 10, 2015, including indications of the PBL heights at 11 UTC from the models (IFS$_R$, IFS$_P$, COSMO$_R$, COSMO$_P$), radiosonde (RS$_R$, RS$_P$) and ceilometer (a). The bottom panel presents the radiosonde profiles retrieved at 11 UTC on the same day (b).

Fig. 10. Analysis of Aug,10,2015

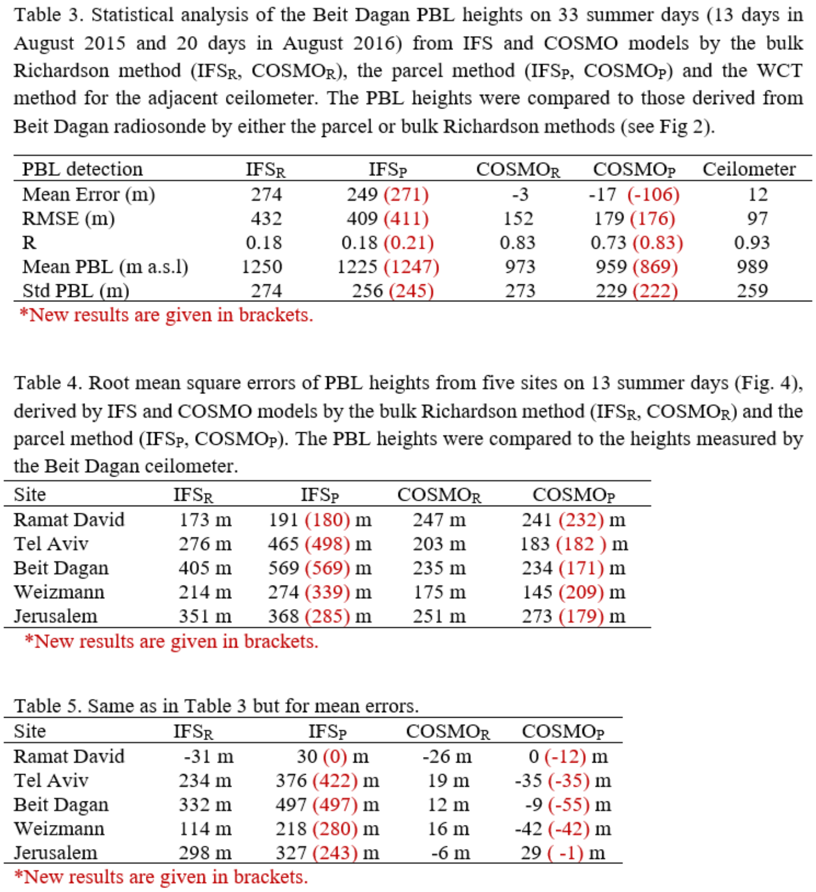


Table 3. Statistical analysis of the Beit Dagan PBL heights on 33 summer days (13 days in August 2015 and 20 days in August 2016) from IFS and COSMO models by the bulk Richardson method (IFS$_R$, COSMO$_R$), the parcel method (IFS$_P$, COSMO$_P$) and the WCT method for the adjacent ceilometer. The PBL heights were compared to those derived from Beit Dagan radiosonde by either the parcel or bulk Richardson methods (see Fig 2).

PBL detection	IFS$_R$	IFS$_P$	COSMO$_R$	COSMO$_P$	Ceilometer
Mean Error (m)	274	249 (271)	-3	-17 (-106)	12
RMSE (m)	432	409 (411)	152	179 (176)	97
R	0.18	0.18 (0.21)	0.83	0.73 (0.83)	0.93
Mean PBL (m a.s.l)	1250	1225 (1247)	973	959 (869)	989
Std PBL (m)	274	256 (245)	273	229 (222)	259

*New results are given in brackets.

Table 4. Root mean square errors of PBL heights from five sites on 13 summer days (Fig. 4), derived by IFS and COSMO models by the bulk Richardson method (IFS$_R$, COSMO$_R$) and the parcel method (IFS$_P$, COSMO$_P$). The PBL heights were compared to the heights measured by the Beit Dagan ceilometer.

Site	IFS$_R$	IFS$_P$	COSMO$_R$	COSMO$_P$
Ramat David	173 m	191 (180) m	247 m	241 (232) m
Tel Aviv	276 m	465 (498) m	203 m	183 (182) m
Beit Dagan	405 m	569 (569) m	235 m	234 (171) m
Weizmann	214 m	274 (339) m	175 m	145 (209) m
Jerusalem	351 m	368 (285) m	251 m	273 (179) m

*New results are given in brackets.

Table 5. Same as in Table 3 but for mean errors.

Site	IFS$_R$	IFS$_P$	COSMO$_R$	COSMO$_P$
Ramat David	-31 m	30 (0) m	-26 m	0 (-12) m
Tel Aviv	234 m	376 (422) m	19 m	-35 (-35) m
Beit Dagan	332 m	497 (497) m	12 m	-9 (-55) m
Weizmann	114 m	218 (280) m	16 m	-42 (-42) m
Jerusalem	298 m	327 (243) m	-6 m	29 (-1) m

*New results are given in brackets.

Fig. 11. Tables 3-5

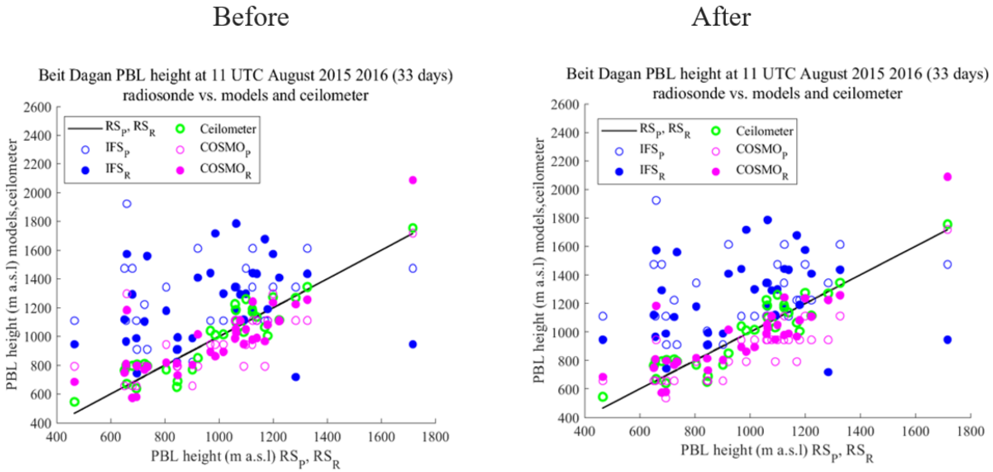


Fig 11. PBL heights over Beit Dagan site on 33 summer days (13 days on August 2015 and 20 days on August 2016), generated by the bulk Richardson method for IFS model (IFS_R, blue solid circles), COSMO model ($COSMO_R$, pink solid circles), and Beit Dagan radiosonde profiles (RS_R, black line). PBL heights generated by the parcel method for the IFS model (IFS_P, open blue circles), COSMO model ($COSMO_P$, open pink circles), and Beit Dagan radiosonde profiles (RS_P, same black line as RS_R, the results are identical). PBL heights derived from the Beit Dagan ceilometer produced by the WCT method (green circles). Results for August 17, 2016, are indicated by a circle.

Fig. 12. Analysis of 33 days