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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 #2:

We wish to thank referee #2 for the constructive comments. Although the referee suggested the article should not be published in its current form, the referee took the time and effort to present a list of comments. The manuscript was intensely reexamined and has gone over a major revision. We thank both the referee and the editor for the opportunity to reply and improve the paper. Our point to point response is given by order of appearance.

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Discussion paper

Referee's comment: Although there is no doubt that determining the mixing height is important, the scientific community has done extensive research and progress so far on the daily boundary layer. However, there are still significant problems as well as gaps in the night boundary layer (stable conditions) and in the transitional periods. These periods cannot be omitted in a study when referring to the importance of mixing height in the formulation of concentrations and even more when one of the main initiatives is to designate ceilometers as a correction for NWP. The statement on line 218 is not appropriate for the exclusion of the nighttime period. Also, the methodology applied by the authors for the reliability of PBL estimation from ceilometers data raises many reservations. I personally could not find the value of this research effort. Concluding, I believe that the whole processing of the subject is rather limited, covers a very short period and is of local interest only. Therefore, I do not agree that this study is published in the ACP Journal.

Author's response: The analysis of the PBL heights from NWP models over diverse terrain and the ability of the regression tool (Eq. 6) to produce adequate corrections presents an interesting study case and a preview of the great potential of ceilometers as a validation and correction tool to discern PBL heights derived by NWP models. The distribution of ceilometers in Israel is at its first stages. Data for the summer season from as many ceilometers as possible over a heterogeneous area concluded with a time span of two months (August between 2015-2016). Initially, we analyzed the diurnal evolution of the summer PBL height. The models' PBL scheme is based on the bulk Richardson method. Thus, the models estimated the nocturnal surface boundary layer (SBL) as the first model level for all dates examined. Moreover, the ceilometers' detection of the SBL height in ground-level sites was found mainly within the first range gates. At these range gates, a perturbation exists due to the overlap of the emitted laser beam and the receiver's ïňĄeld of view. This constrained our ability to determine the low SBL height of the summer season. Consequently, the research focused on convective daytime hours (09-14 UTC).

Author’s changes in manuscript: The manuscript has gone over a major revision to address the referee’s reservations.

Referee’s comment: I wonder if we could perform a similar exercise for an area with restricted characteristics, thus no general applicability. This is the case here, where local flows are developed but there are not taken into consideration. In particular, both sea breeze and/or anabatic winds are expected to develop in this area during the summer period. (1) For this reason, I am not sure what ceilometer is measuring. (2) For example, at the station of DB just 7 km away from the shore, the PBL depth is measured at 1km. To my knowledge, this is an unrealistic value (too high) under the presence of sea breeze (or IBL). Thus, I wonder if this instrument finally shows the off-shore current of the sea breeze flow.

Author’s response: (1) Local flows are taken into consideration by the models and the ceilometers. While the models simulate the physical parameters generating them (for example, see Fig.1), the ceilometers measure the results of these flows expressed as backscatter signals. Uzan et al, (2012) studied the ability of the wavelet covariance transform (WCT) method to delineate the evolution of the summer mixed layer height (not the PBL height) based on ceilometers’ profile. The results are presented in Fig.2. This figure demonstrates the diurnal summer mixed layer height between July-August in 2014. The analysis was carried out by two ceilometer sites: Tel Aviv (50 m from the shoreline, 5 m a.s.l) and Beit Dagan (7.5 km from shoreline, 11 km southeast to Tel Aviv,33 m a.s.l). The ceilometers’ measurements succeeded to capture the inflation of the mixed layer height after sunrise followed by subsidence as the sea breeze front prevails. A height difference of 200 m was measured between the two sites at midday. This difference is attributed to the greater distance of Beit Dagan from the shoreline (7.5 km) enabling the convective thermals to develop and inflate the mixed layer height. Tel Aviv site, on the other hand, is practically on the shoreline, therefore the sea breeze promptly surmounts the convective thermals preventing from the mixed layer to inflate. The apparent height difference of the mixed layer height in Beit Dagan in July (dashed blue line) compared to August (dashed pink line) was ascribed to the fact that August was cloudier than July after sunset.

(2) The assertion Beit Dagan PBL height reaches 1000 m a.s.l is based on the following studies:

a) Felix Y, 1994 stated: " The daily inversions over the coast of Israel have been studied by Shaia and Jaffe (1976). Their analysis was based on 10 years of observations of temperature profiles measured by the afternoon radiosonde (1200 UTC) at Bet Dagan (7 km inland from the central coast of Israel). According to their statistics, in 81% of the summer days (June-August), inversions occurred. The base height of most of these inversions was between 500 and 1000 m and their mean thickness was about 400 m.

b) Yuval et al., (2019) evaluated monthly median values of the PBL height (denoted as CBL for midday PBL) as evaluated by the midday Beit Dagan radiosonde profiles, based on the W&W method. Fig. 3 presents the median value of the PBL heights (green line) in August reach 900 m a.s.l.

c) The sea breeze effect is evident by the ceilometers' attenuated backscatter profiles as shown in Fig.4 depicted from Uzan et al., 2016. Note the Beit Dagan PBL height reaches 1000 m a.g.l.

Author's changes in manuscript: The text was rephrased in Sect. 2 (Research area): " 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 effect, the average PBL height is found to be quite low. For example, the PBL height in Beit Dagan (33 m a.s.l and 7.5 km east from the shoreline) reaches ∼900 m a.s.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).".

Referee's comment: (1) The PBL depth is a non-specific parameter, the definition and estimation of which is not straightforward. The simulated PBL depths are mainly determined, based on the definition that each PBL scheme applies (in this study, no information is provided regarding the PBL parameterization schemes considered by the two models). (2) This also applies between measurements from different instruments (ceilometer and radiosonde) as they do not have the same operating principles. The ceilometer measurements mainly present the mixed PBL that does not always coincide with the simulated PBL depth. (3) On the other hand, has it been taken into account that the radiosonde moves with the flow? As it ascends the measurements do not correspond to the vertical position above the launch point. This is another reason for a possible discrepancy between the radiosonde and the ceilometer measurements.

Author's response: (1) Comment accepted: Descriptions of the models' PBL parameterization schemes were added to Sect. 3 (IFS and COSMO Models). (2) We addressed the same methods on the models and radiosonde measurements (the bulk Richardson method and the parcel method). These methods cannot be imposed on the ceilometers' attenuated backscatter profiles, therefore we generated a specific method based on the WCT method, and compared the results to the heights generated by the radiosonde. Results for 33 days (presented in the manuscript in Fig.2 and Table 1) revealed a high correlation between the two instruments (0.93) and low RMSE (97 m). (3) Radiosonde profiles 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°. The PBL height in Beit Dagan for midday summer is estimated below 1 km (Felix Y.,1994, Dayan and Rodinzki, 1999, Uzan et al., 2016, Yuval et al., 2019). Hence, within an ascending height of 1 km, the change in the radiosonde position will be below 0.01°. This spatial error is in the order of 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.

Author's changes in manuscript: (1) Concise descriptions of the models' schemes were added to Sect. 3 (IFS and COSMO models): a) IFS PBL parameterization scheme: "The turbulent diffusion scheme represents the vertical exchange of heat, momentum, and moisture through sub-grid scale turbulence. In the surface layer, the turbulence fluxes are computed using a first-order K-diffusion closure based on the Monin-Obukhov (MO) similarity theory. Above the surface layer, a K-diffusion turbulence closure is used everywhere, except for unstable boundary layers where an Eddy-Diffusivity Mass-Flux (EDMF) framework is applied, to represent the non-local boundary layer eddy fluxes (Koehler et al. 2011)". b) The COSMO turbulent scheme: "The turbulence scheme, based on Mellor and Yamada (1982) at Level 2.5, uses a reduced second-order closure with a prognostic equation for the turbulent kinetic energy. The transport and local time tendency terms in all the other second-order momentum equations are neglected and the vertical turbulent ïňĆuxes are derived diagnostically (Cerenzia I., 2017)". (2) Sect. 6.1 (Comparison to in-situ radiosonde profiles) was rephrased and the following sentence was added: " In order to evaluate the daytime PBL heights produced by the models and the ceilometers, the results were compared to the radiosonde's evaluations. Consequently, the investigation was held in Beit Dagan at the time of the midday launch (11 UTC). For this comparison, the ceilometer's 15 s profiles were averaged as half-hour profiles between 10:30-11:00 UTC. COSMO's results referred to the profiles of 10:45 UTC, and IFS estimations were given at 11 UTC. The analysis was carried out for 33 summer days, 13 days from August 2015, and 20 days from Aug 2016. The PBL heights were produced by the same methods: the parcel method (denoted by subscript P) and the bulk Richardson method (denoted by subscript R). These methods require meteorological parameters such as temperature and pressure profiles generated by the models and the radiosonde. Ceilometers, on the other hand, produce only backscatter signals. Therefore, they were analyzed by the WCT method. The results were statistically analyzed by mean error (ME), root mean square error (RMSE), and correlation (R) presented in Fig. 2 and Table 3. Good agreement was found between the ceilometer and the radiosonde (ME = 12 m, RMSE = 97 m, and R = 0.93), although they produced the PBL heights by different methods. ". (3) Sect. 4.2 (Radiosonde) was rephrased: " 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, the change in the radiosonde's horizontal position would be under 0.01° which is in the order of magnitude from 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. ".

Referee's comment: Therefore, the same criteria should be used for the estimation of both measured and simulated PBL depth. In particular, the same criteria should be applied to the profiles of certain atmospheric parameters, such as temperature, wind and mixing ratio profiles that depict the atmospheric boundary structure. These criteria should not necessarily be the same for all atmospheric conditions. For example, the gradient of potential temperature profile is inadequate to provide the turbulent ABL depth. Therefore, for the comparison with ceilometer, it would be more appropriate to consider the eddy-viscosity simulated profiles or even better the aerosol layering from chemistry transport model simulation. In particular, under convective conditions, the mixing height determined by ceilometer is strongly related to the aerosol stratification.

Author's response: We employed the parcel method to evaluate the transition zone between the mixed layer and the free atmosphere, as presented in Fig.5 from Stull (1988). In this method, the virtual potential temperature at ground level is crucial while the models' lowest grid point is above the surface layer (IFS begins at 10 m a.g.l. and COSMO at 20 m a.g.l.). Therefore, the virtual potential temperature at ground level height (2 m a.g.l) was evaluated by the temperature and dew point temperature (or RH) derived by the models based on the similarity theory. As explained in the previous comment, we addressed the same methods on the models and radiosonde measurements (the bulk Richardson method and the parcel method). These methods cannot be imposed on the ceilometers' attenuated backscatter profiles, therefore we generated a specific method for the ceilometers' PBL heights evaluations based on the WCT method. To ensure the WCT method addressees the same PBL heights generated by the other methods, we compared the ceilometer's evaluations to the radiosonde's heights. Results for 33 days (presented in the manuscript in Fig.2 and Table 1) revealed a high correlation between the two instruments (0.93) and low RMSE (97 m).

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

Referee's comment: How much value does the global model have in such a small analysis to take part in the comparison, especially in a strongly heterogeneous area?

Author's response: The main goal of the study was to utilize ceilometers as a correction tool for NWP models. Therefore, two types of models were tested, global and regional. The limited ability of the global models to correctly simulate complex terrain was taken into consideration. Therefore, we did not anticipate the significantly large overestimations of IFS over flat grid points under fairly "simple" meteorological conditions characterizing the summer in the East Mediterranean. This disclosed the advantages of the regional model as well as the limitations of the global model in regard to PBL height estimations.

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

Referee's comment: (1) Also, there are several arbitrary statements on the text, without any justification (no measurements of wind speed and direction are provided) or any reference. (2) For example: Line 105: "As a result, the average PBL height is comparatively low (∼1000 m a.g.l)". Line 116: "Through the day, the sea breeze circulation steers clockwise and the wind speed is enhanced by the west-north-west synoptic winds". Line 119: "Due to the large distance (∼30-50 km inland), the SBF reaches the eastern elevate complex terrain only in the afternoon (∼11-12 UTC). Line 170:" However, the PBL detection algorithm utilized here (see Sect. 5.3) is based on a significant signal slope, therefore can be determined from uncalibrated ceilometers".

Author's response: (1) Comment accepted. Moreover, following the comments from referee # 1, the study cases of August 10, 2015, and August 17, 2016, were removed and replaced with the description of a typical case on August 15, 2015, provided with radiosonde profiles of wind, temperature, and relative humidity. (2) Comment accepted. The whole paragraph was rephrased accordingly and the references were inserted within the text rather than the list given in the previous form.

Author's changes in manuscript: (1) The study case of August 15, 2015, was provided with radiosonde profiles of temperature, relative humidity, wind speed, and wind direction. (2) Sect. 2 (Research area) was rephrased in the following manner: "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: After sunrise (∼4-5 LST, where LST=UTC+2) clouds initially formed over the Mediterranean Sea are advected eastward to the shoreline. As the ground warms up, the nocturnal surface boundary layer

(SBL) dissipates and buoyancy induced convective updrafts instigate the formation of the sea breeze circulation (Stull, 1988). The entrance of the sea breeze front (SBF) is estimated between 7-9 LST (Felix Y., 1993, Alpert and Rabinovich-Hadar, 2003, Uzan and Alpert, 2012), depending on the time of sunrise and the different synoptic modes (weak, medium and deep) of the prevailing system – the Persian trough (Alpert et al., 2004). Cool and humid marine air hinder the convective updrafts, thus clouds dissolve and the height of the shoreline convective boundary layer (CBL) lowers by ∼250 m (Felix Y., 1993, Felix Y., 1994, Levi et al., 2011, Uzan and Alpert, 2012). Further inland, the convective thermals continue to inflate the CBL (Hashmonay et al., 1991, Felix, 1993, Lieman, R. and Alpert, 1993) while the sea breeze circulation steers clockwise and wind speed is enhanced by the west-north-west synoptic winds (Neumann, 1952, Neumann, 1977, Uzan and Alpert, 2012). By noontime (∼11-13 LST), the sea breeze and the synoptic wind merge and produce maximum wind speeds which suppress the CBL (Uzan and Alpert, 2012). In the afternoon (∼13-14 LST), the SBF reaches ∼30-50 km inland to the eastern elevated complex terrain (Hashmonay et al., 1991, Lieman, R. and Alpert, 1993). At sunset (∼18-19 LST), as the insolation diminishes, the potential energy of the convective updrafts weakens and the CBL height drops (Dayan and Rodnizki, 1999). After sunset, the CBL finally collapses and a residual layer (RL) is formed above the SBL (Stull, 1988). As the ground cools down, the high humidity and low RL create low condensation levels which produce shallow evening clouds".

Referee's comment: Line 203-Does the bulk Richardson refers to a certain height or layer?

Author's response: The bulk Richardson method refers to a certain layer in the models and to a specific height in the radiosonde profiles.

Author's changes in manuscript: Sect 5.1 (The bulk Richardson number method) was rephrased as follows:" The IFS model defines the PBL height as the lowest height level at which the Rb (Eq. 1) reaches a critical threshold of 0.25 (ECMWF-IFS documentation – Cy43r3, Part IV: Physical Processes, July 2017). The PBL height is distinguished by scanning the bulk Richardson results from the surface upwards. When the PBL height is found between two levels of the model, it is determined by linear interpolation. Radiosonde's profiles were analyzed in the same manner by a Rb threshold of 0.25 to detect a specific height rather than a certain layer. COSMO estimates the Rb based on the dynamic conditions of the first four levels (10, 34.2, 67.9, 112.3 m a.g.l.) signified by a threshold of 0.33 for stable conditions and 0.22 for unstable ones. If no level is found, then a missing value is assigned for the PBL height".

Referee's comment: Lines 265-end of this paragraph. I am confused.

Author's response: The end of the paragraph states: "However, as previously mentioned, our algorithm denotes the PBL height as the top of the shallow cloud (Stull, 1988)". We assume the confusion regards the term "cloud top". We agree with the referee this definition is confusing within the context it was used and apologize for the misunderstanding we have caused. The term was changed given the explanation as follows: 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 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 (see Fig. 6 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.7 and Fig.8 below), 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)".

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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 equations employed values of Rd/Cp = 287/1004 (∼ = 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 in Tables 3-5 and Fig. 9.
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Interactive comment on Atmos. Chem. Phys. Discuss., https://doi.org/10.5194/acp-2019-790, 2019.

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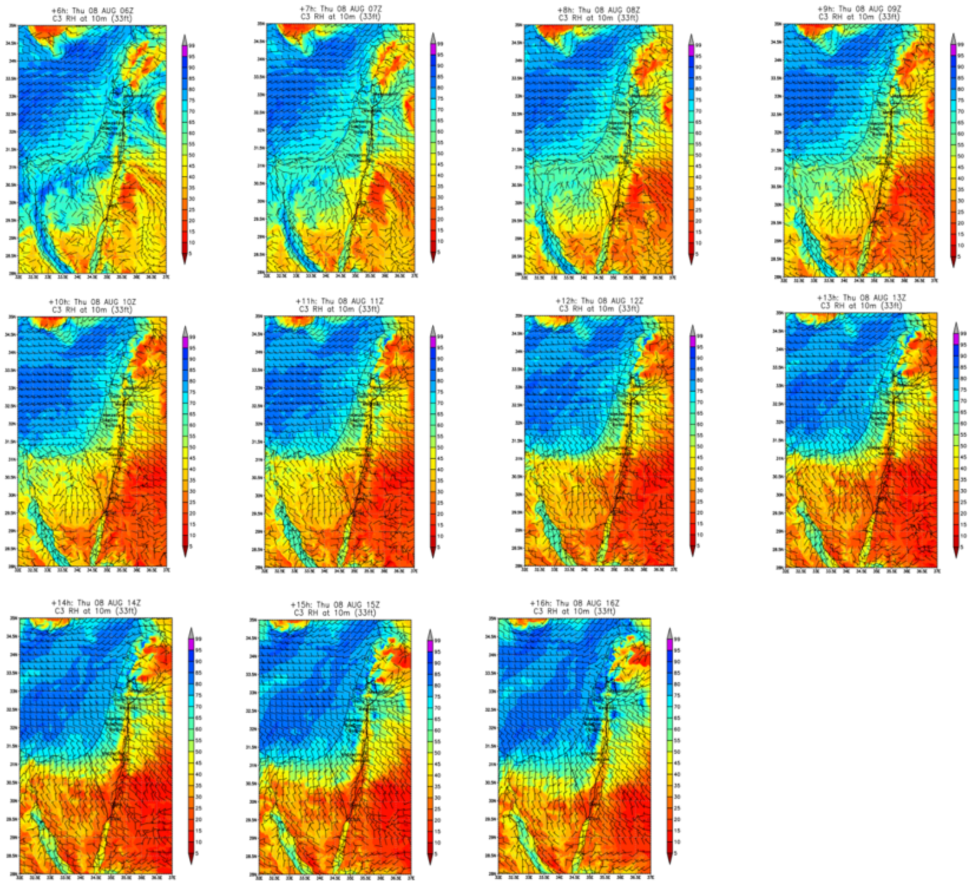

Fig. 1. COSMO model maps of RH, wind speed and wind direction over Israel in August 2019 between the hours 07 Z-15 Z (LST=Z-2). Source: Dr. Pavel Khain, Israeli Meteorological Service.

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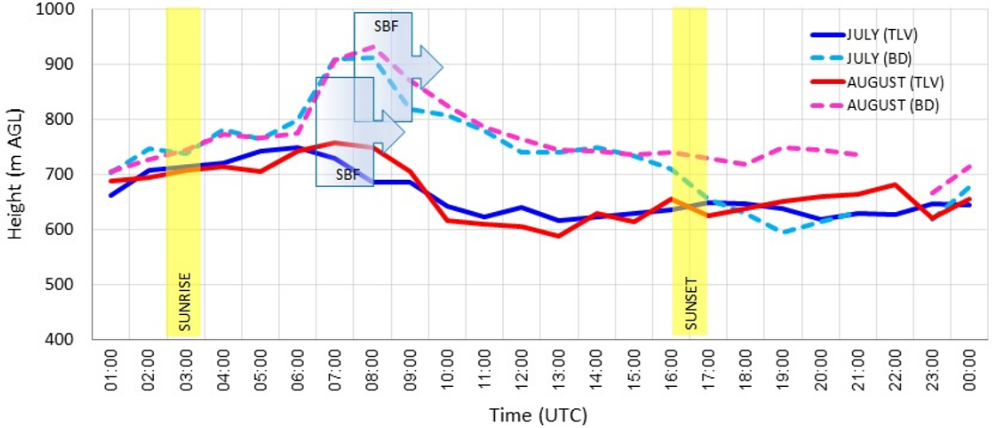

Fig.1 Hourly averaged mixed layer height (MLH) for the east Mediterranean summer season (July – August) 2014. Dashed lines indicated ceilometer measurements in Beit Dagan (BD) and solid lines indicate the measurements in Tel Aviv (TLV) for July (blue and light blue) and August (red and pink). TLV and BD plots are based on 19, 31 days in July and 24, 30 days in August, respectively. Indications of the time of sunrise, sunset and the SBF entrance time are given.

Fig. 2.

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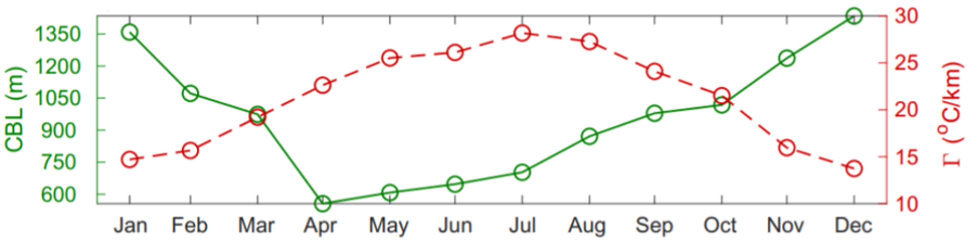

Fig 3. Monthly median values of the PBL height (continuous lines) and the lapse rate Γ (dashed lines) under CBL conditions. The PBL heights were estimated using the W&W method. The lapse rate was calculated between the temperature at the 12th radiosonde reporting level data (24 s from launch, on average at 108 m) and the second level (two seconds, on average 6.2 m).

Fig. 3.

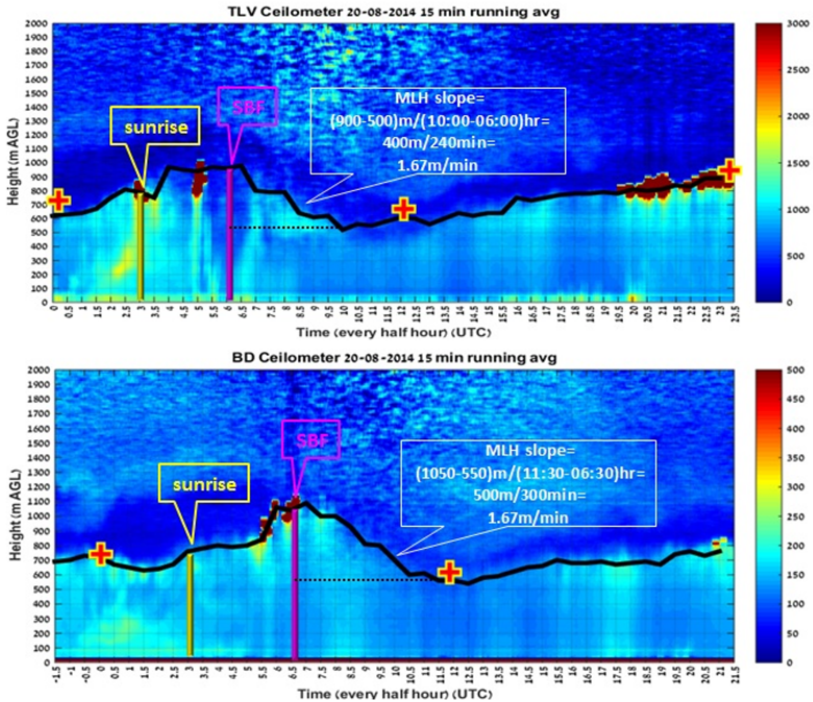

Fig. 4. Mixed layer height (MLH, solid black line) on the 20.08.2014 for Beit Dagan (BD) and Tel Aviv (TLV). The MLH line is laid upon half hourly averaged attenuated backscatter profiles (units 10-6 m-1 sr-1). The BD plot is shifted 2 hours to coincide with UTC time. The plot includes indications of the sunrise (yellow bar) and the sea breeze front (SBF) entrance time (pink bar), MLH evaluation by radiosonde profiles at 0 and 12 UTC (red plus) and calculation of the MLH subsidence rate due to SBF entrance.

Fig. 4.

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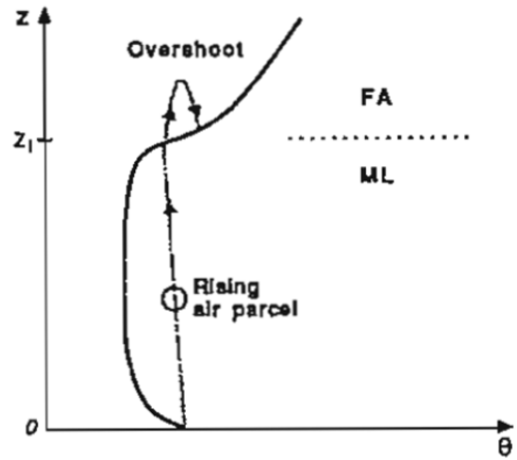
Fig. 5
Penetrative convection is associated with an air parcel rising from the surface layer. The solid line is the mean background state, and the dashed line shows air parcel evolution including its penetrative overshoot into the FA.



(source: Stull, 1988)

Fig. 5.

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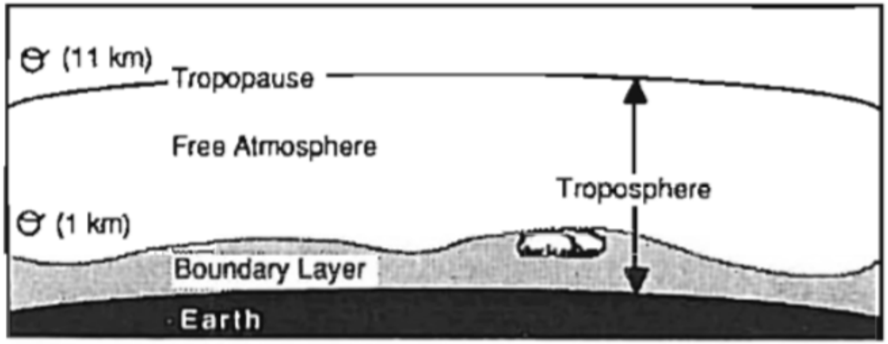

Fig.6 The troposphere can be divided into two parts: a boundary layer (shaded) near the surface and the free atmosphere above it.

(Source: Stull, 1988)

Fig. 6.

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Fig. 7. IMS photograph of the sky over Beit Dagan site on August 2, 2019, at 8 UTC presenting typical shallow cumulus clouds.

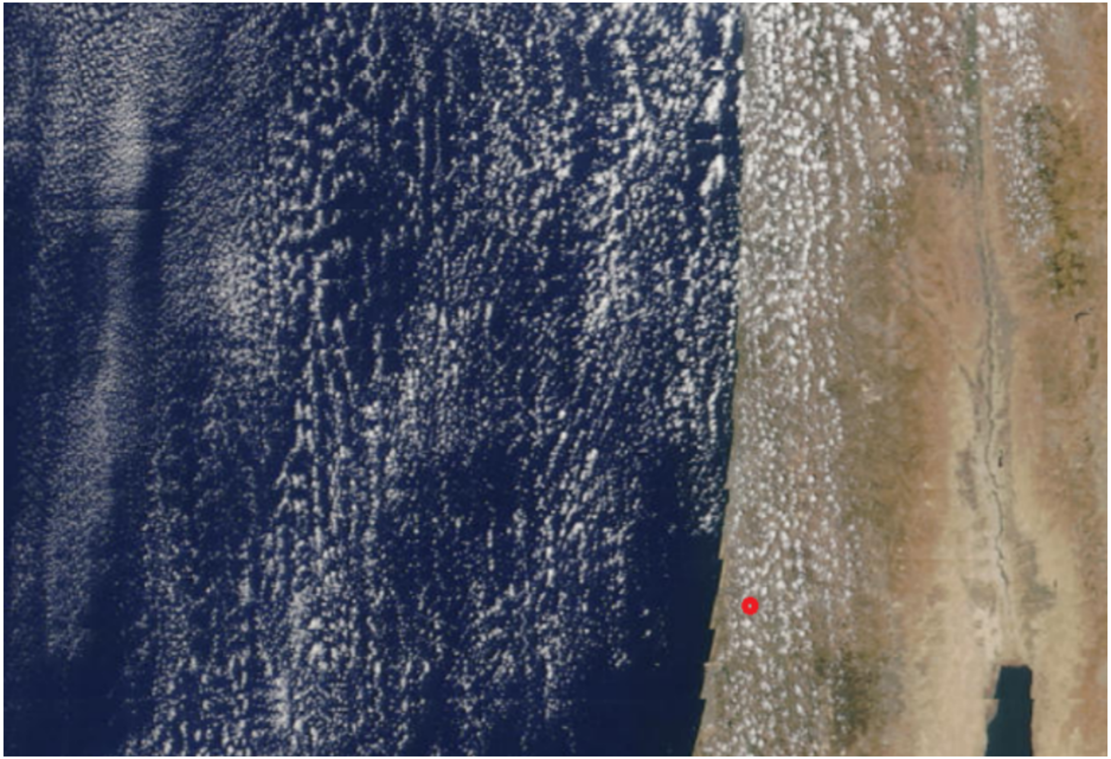

Fig. 8. Terra-MODIS 250 m resolution picture over Israel on August 2, 2019, at 8 UTC. Beit Dagan site is indicated by a red dot. Adapted from @ NOAA- EARTHDATA.

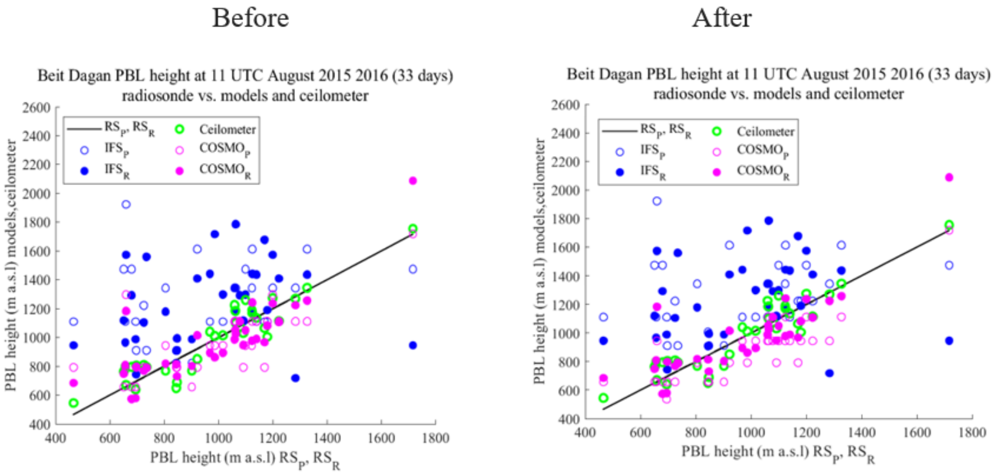

Fig 9. PBL heights over Beit Dagan site on 33 summer days (13 days on August 2015 and 20 days on August 2016), generated by the bulk Richardson method for IFS model (IFS$_R$, blue solid circles), COSMO model (COSMO$_R$, pink solid circles), and Beit Dagan radiosonde profiles (RS$_R$, black line). PBL 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 given in right end of the plot.

Fig. 9.

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. 10.

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