Authors reply to the anonymous referee #2 comments

First of all, we are thankful to the anonymous referee for his helpful comments, and will address them point by point, following a general overview.

Overview

1. The aim of this paper is to introduce a new technique for the assessment of clouds base heights that is applicable by ground measurements with off the shelf mobile equipment, without the need for complicated calibration procedures. As the focus of the paper is clouds, the introduction surveys other methods which offer alternative approaches. Indeed, as pointed by the referees, there are some similarities in the technical analysis we propose and techniques used in the field of wind extraction by cloud motion vectors. However, the proposed method is ground based, with quite different sensing parameters compared to space borne sensing (see next paragraph). In light the similarities, we have added a detailed overview of methods commonly applied in space borne imagery to the introduction, starting on page 3, line 31 in the revised manuscript:

   "An essential part of our analysis is tracking clouds motion in a sequence of successive images. This machine vision challenge has been addressed for few decades mostly due to the availability of the geostationary meteorological satellites (such as METEOSAT and GOES). Usually, the main application of this technique is to produce cloud motion vectors that can be used in numerical weather prediction. Fujita et al. (1968) were the first to use meteorological satellite to measure large scale cloud motion. Since then, numerous methods have been suggested to extract cloud motion vectors: Schmetz et al. (1993) have used local cross correlation between three successive METEOSAT images to derive the motion vectors. Ottenebacher et al. (1997) suggested that low clouds over the ocean are better tracked by using high resolution visible imagery due to higher radiative contrast and better spatial resolution than with IR imagery. Horvath and Davies (2001) suggested using near simultaneous multi-angle satellite images to retrieve both clouds height and velocity. Moreover, Velden et al. (1997) demonstrated utilizing cloud tracking methods to derive high winds by tracking water vapors patterns in the upper troposphere. An initial step in all of the above techniques is to determine the height of the observed cloud (Schreiner et al., 2002). Most of these methods use model's input of the atmospheric temperature and humidity profile to link between the measured radiative temperature of the cloud and its vertical position. Several key differences exist between the above space borne methods to track clouds motion and the method proposed in this paper. First of all, the methods differ by their purpose. While space borne methods consider the height of the clouds as an input and use the clouds as a tracer to the wind field, we use some external source for the wind profile and derive the cloud base height. Second, the temporal resolution of the space borne imagery is 15 min (Schmetz et al., 2002), while the proposed method utilizes acquisition rate of 0.1Hz. Third, and most important, the techniques largely differ by their sensor's instantaneous field of view (IFOV). While space borne imagers' typical IFOV is several kilometers (and frequently many IFOVs are summed to create one large effective IFOV for cloud motion analysis), ground based imaging with standard IR imager benefits from an IFOV of 10-20 meters at the top of the troposphere."

2. An important point made by the associate editor as well as the referees is the validity of the proposed technique. Our purpose was to demonstrate the feasibility of the technique rather than provide a complete performance analysis of it. As we except the referees comments regarding the method's performance we have added a complete subsection in the results section (subsection 4.4) where we provide 3 examples of continuous operation of the method. Specifically we added (page 11, line 26):

   "4.4 Continuous retrieval of clouds' base height

   In this subsection we provide 3 examples of obtained clouds' base height during 4 hours of continuous operation. The utilization of the method is demonstrated for: low cumulus clouds field during daytime, high cirrus clouds during daytime, and multilayered cumulus and cirrus clouds during nighttime. The purpose of these examples is twofold. First, it enhances the confidence in the robustness and validity of the method and second, it enables to estimate the variance of the obtained clouds' base height.

4.4.1 Shallow cumulus clouds field during daytime

Figure 15 presents the clouds' base heights which were retrieved during 4 hours on April 22nd, 2010. The red line is the brightness temperature of the sky as measured in the centre of the field of view of the IR imager, and it is a sensitive proxy to cloud's presence exactly above the sensor, when the radiative temperature rises sharply. The Green circles denotes the Ben-Gurion ceilometer's readings (Website: "Station Observations"), and the blue line is the extracted cloud base height. During that time, dense, shallow cumulus clouds field was present, as can be seen by examining the radiative temperature of the nadir sky (red line). The ceilometer's readings during these 4 hours indicate an average cloud base of 1,166m. Our method produced average cloud base height of 1,602m with a temporal standard deviation of 285m, considering only the times when valid cloud base heights (as described in subsection 3.2) were obtained. Assuming there were no temporal fluctuations in the clouds' base height during that time and that the ceilometer provides their actual height, the proposed method overestimates the clouds height by 436m. This kind of over estimation is probably the result of imperfect representation of the boundary layer wind profile, as our method relies on the wind profile which is measured by a radiosonde from a meteorological station which is located approximately 8 km from our actual measurement site.

4.4.2 High cirrus clouds field during daytime

Figure 16 demonstrates the continuous operation of the method when dense, high cirrus clouds are present (as indicated by the increase and fluctuations in the sky radiative temperature). During the noon hours of March 9th, 2010, an average cloud base height of 10,051m with standard deviation of 210m was obtained. While we cannot validate the method's results during the complete 4 hours period, the relatively low variability increases the confidence in the method's robustness.

4.4.3 Multilayered cloud field during nighttime

Figure 17 provides an example for the method's utility under multilayered clouds fields at nighttime. During 4 hours in the night of April 21st, 2010, sparse cumulus clouds passed above the sensor along with a high cirrus clouds field. The presence of these clouds is indicated by small fluctuations in the radiative temperature of the sky for the cirrus clouds (as noticed around 22:15 P.M. and 23:15 P.M.), and large fluctuations for the low cumulus clouds (as noticed at 0:00 A.M and 1:30 A.M.). The sparse cumulus clouds field enabled the method to extract the upper layer height as well as the correct base height of the shallow clouds themselves, as validated by the ceilometer's readings (green circles)."

<u>Figures Added:</u>

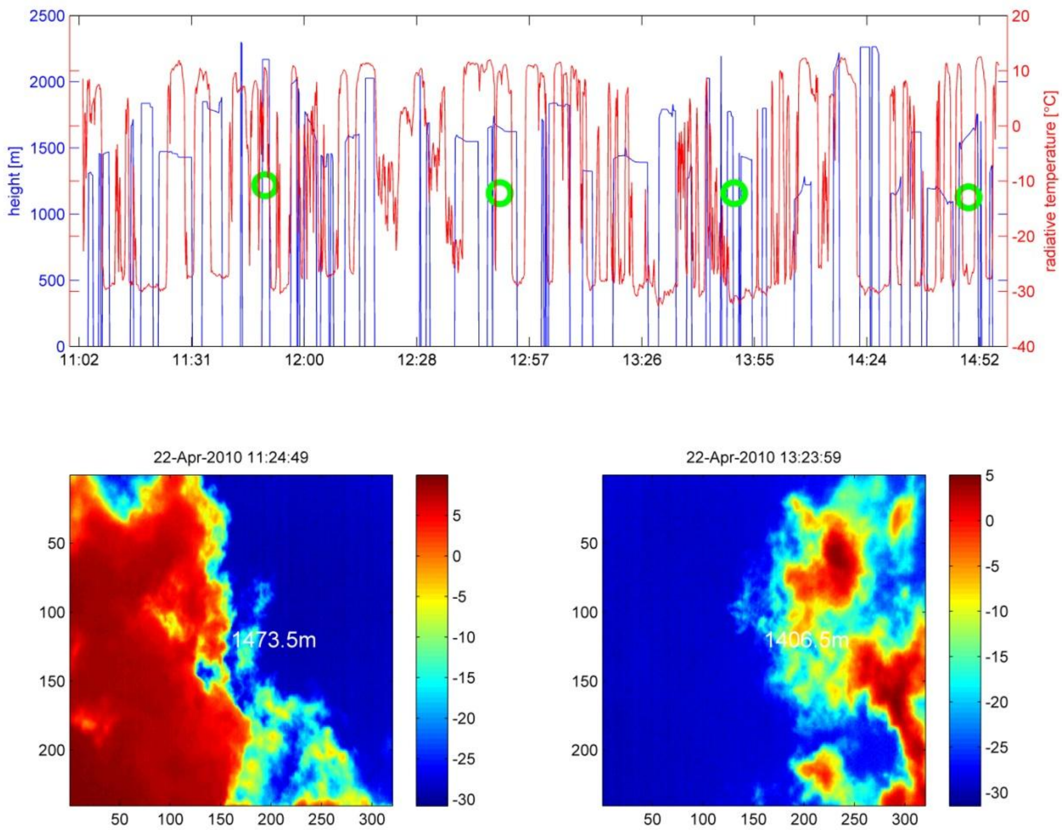

Figure 15 - Cloud base height as extracted by the proposed method during 4 hours on April 22nd, 2010. The red line is the radiative temperature of the nadir sky as measured by the middle pixel of the IR imager. It provides a sensitive proxy for the

presence of a cloud above our sensors, as the radiative temperature rises sharply. The green circles are the Ben-Gurion ceilometer readings (Website: "Station Observations"), and the blue line is the clouds base height as extracted by the proposed method. During that time, dense, shallow cumulus clouds field passed above the sensors. The method produced an average cloud base height of 1,602m with temporal standard deviation of 285m. The two images at the bottom of the figure are examples of specific clouds in that time frame that were extracted by the method.

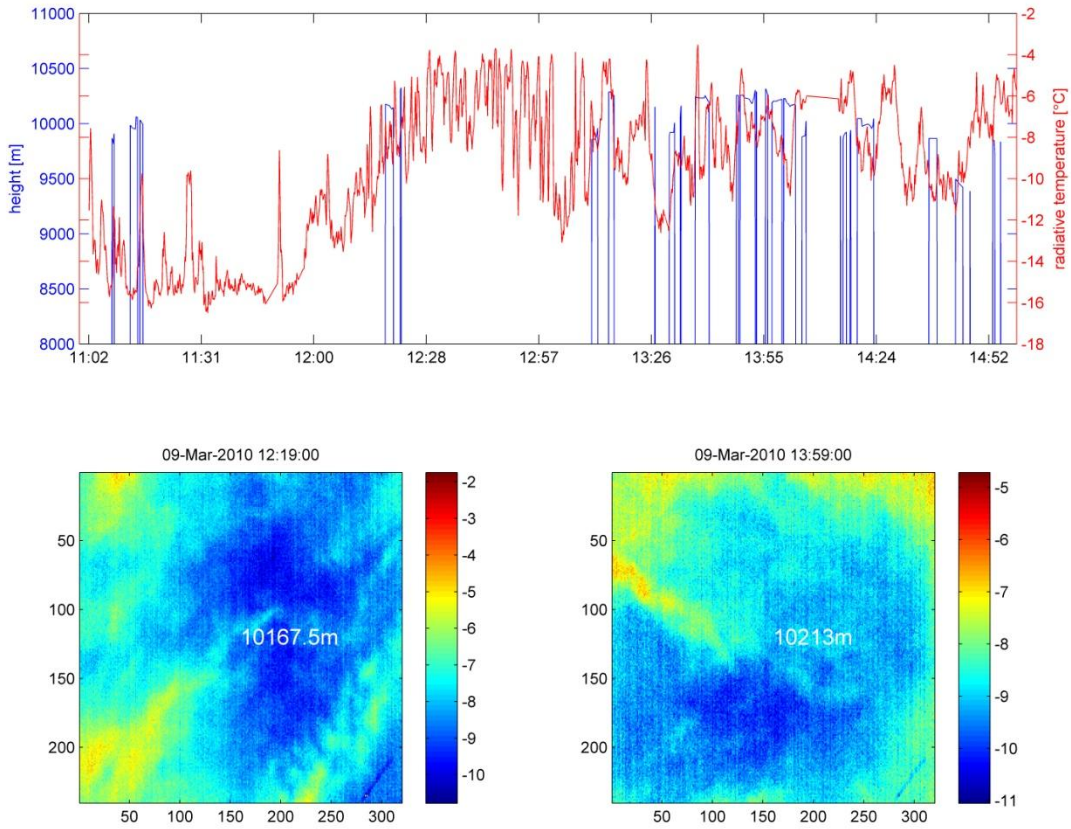

Figure 16 - Cloud base height as extracted by the proposed method during 4 hours on March 9th, 2010. The red and blue lines are as in Figure 15. During that time, dense, high cirrus clouds field passed above the sensors. The method produced an average cloud base height of 10,051m with temporal standard deviation of 210m. The two images at the bottom of the figure are examples of specific clouds in that time frame that were extracted by the method.

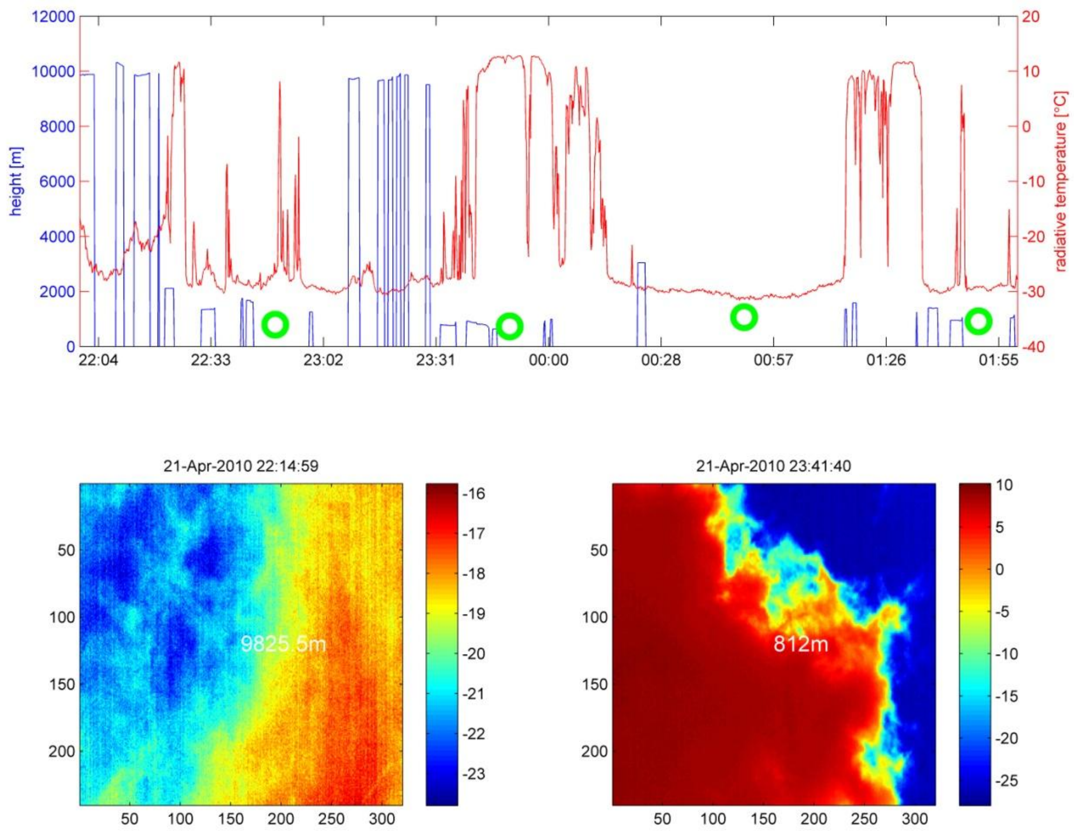

Figure 17 - Cloud base height as extracted by the proposed method during 4 hours on the night of April 21st, 2010. The red and blue lines are as in Figure 15. During that time, multilayered sparse low cumulus and high cirrus clouds field passed above the sensors. The method successfully extracted the cloud base for both types as the sparse cumulus clouds enable to analyze the high cirrus clouds as well. The two images at the bottom of the figure are examples of two distinct cloud types which were extracted during the above time frame.

Specific issues pointed by the referee (*answers in italics*)

Comment: "P4234, top: In my opinion the main limitation of a ceilometer measurement is the extremely small field-of-view of the lidar. The range limitation is due to the usage at airports, as high clouds are of no interest there. Modern ceilometers can provide a much wider range."

Reply: We agree the range is limited because of the commercial usage at airports and modern (yet expensive) ceilometers have wider range. Although it has a small field of *view (FOV) it is considered as a practical and reliable instrument to measure both cloud's base height and cover (in a low spatial resolution over one point on the ground).*

Comment: "P4235, l 18: If the wind information is provided by a wind lidar, also the information for the cloud base height is available from the backscatter information."
Reply: We agree that if a current measurement of a wind lidar exists, it would provide the clouds base height anyway, but our intention was (and therefore we have clearly wrote " space-borne Doppler wind LIDAR " and cited the Tan and Anderson paper) that if wind information from space borne wind lidars would provide low temporal resolution measurements of the wind profile in remote locations, than our method could utilize these measurements in the same manner that ground base radiosondes are used. To emphasize this point we added (page 5, line 8 in the revised manuscript): "Such wind LIDAR can provide wind profiles at relatively low temporal resolution, which can be further exploited by the proposed method.".

Comment: "P4237, top: Is there any calibration for the positioning of the camera and on the quality of the mapping? The impact of these geometrical considerations on the quality of the cloud motion vectors should be discussed."
Reply: We agree with the reviewer that geometrical considerations might impact the quality of the cloud motion vectors. Nevertheless, since the proposed method utilizes ground based imaging (the clouds are relatively close, as opposed to space borne imaging) and our FOV is relatively small, the impact of these geometrical considerations are less crucial. In any case, we specifically pointed in the original manuscript: "Another possible error might arise in determining the direction of the clouds movement, either from imperfect position of the SPECTATOR board with regard to the north, or from imperfect alignment of the IR camera within the body of the SPECTATOR itself. To encapsulate these errors we allow margins of ±15° in the wind direction retrieval."

Comment: "Page 4237, l 10: Not every reader knows the distance between the site and the Beit-Dagan station"
Reply: We have added the distance to the revised manuscript (page 6, line 23)

Comment: "P4238, l 5: The 'low bias' of cloud motion vectors in comparison to the real wind is widely known. In particular the cloud motion vectors of low level clouds deviate substantially."

Reply: All space borne methods which determine cloud motion vector consider the height of the clouds as an input (for example by measuring the brightness temperature of the cloud and comparison to forecast of the atmospheric profile or by CO_2 slicing method). The 'low bias' of cloud motion vectors is associated to the fact it is hard to determine the height of semi-transparent or subpixel clouds from space borne imagery, as their radiative temperature contains signal from the warm Earth below the cloud. Our method avoids this problem altogether, as the whole purpose of the method is to determine the cloud's height, without any usage of the radiative temperature of it. We made it clearer in the revised manuscript (see our first general remark in this document).

Question: "P4239, top: How does this method of feature selection compare to the traditional methods applied to satellite data? How does such a rank selection work, if there are no clouds?"

Answer: We have added a paragraph in the introduction section (please see our first general remark above) that overviews space borne methods. Our proposed method works fine when no clouds are present, as the cross correlation values for clear sky images are far below the threshold.

Comment: "P4239, eq. 2 and 3 without further explanation these equations do not make much sense."

Reply: We have added some comments in the revised manuscript (page 8, line 5) that clarifies eq. 2 and 3.:

- *"Due to its high sensitivity to the object's shape, rather to its magnitude, we use spatial cross correlation (Jahne, 1997) to calculate the temporal displacement of these blocks: Let R be a 40X40 pixels block in the thermal image Img^t. The cross correlation matrix C_R of this block is calculated with every 40X40 region in the image Img^{t+1}:*
  First, we define all possible blocks in the thermal image Img^{t+1}:

  $$\forall i,j: R_{(i,j)}^{t+1} = Img^{t+1}(i:i+39, j:j+39) \quad (2)$$

Second, we build the matrix C_R by calculating the cross-correlation values of the original block R with every possible block $R_{(i,j)}^{t+1}$.

$$C_R(i,j) = \frac{1}{40*40} * < \frac{R-\bar{R}}{\sigma(R)} > \cdot < \frac{R_{(i,j)}^{t+1} - \overline{R_{(i,j)}^{t+1}}}{\sigma\left(R_{(i,j)}^{t+1}\right)} > \qquad (3)$$

If the maximal value of C_R exceeds an empirically predefined threshold (0.95), we consider its spatial coordinates (i_{max},j_{max}), as the horizontal displacement in the image plane $D_h=j_{max}-j$ [pixels], and the vertical displacement $D_v=i_{max}-i$ [pixels]. Typical results of this process are illustrated in Figure 4."

Comment: "P4240, l 26: The error in deriving the motion vector is larger."

Reply: Although it is hard to reply to this comment because it is not based on any quantitative reasoning, or explanation, we have recalculated the error. As in most space-borne methods, we consider the clouds as rigid objects (this is a valid assumption considering acquisition rate of 0.1Hz). Motion estimation of rigid objects by cross correlation of the object's edge is bounded by 0.5 IFOV (pixel) in every dimension. To the best of our knowledge, the error estimation we have pointed is correct.

Comment: " P4241 and 4242: From 54 days of observation the authors provide only 3 examples without any information on the perfomance in the rest of the time. This leaves the reader with the impression, that the 'novel technique' was not applicable on a regular basis."

Reply: The 5 examples presented in the original paper (one in section 3 and four in section 4) are typical examples of the method's performance. However in order to clarify the performance limitations, we have added subsection 4.4 in the revised manuscript that demonstrates continuous operation of the proposed method (please see our second general remark in the beginning of this document).

Comment: "P4243, l 12: I would avoid the term 'validated' in the context with only 3 examples"

Reply: We have added subsection 4.4 in the revised manuscript that demonstrates continuous operation of the proposed method (please see our second general remark *in the beginning of this document).We think that the previous examples along with the 3 additional ones improve the validation.*

Question: "P4244, l 1: The necessity to use wind profiles for the determination of the cloud base height is the main obstacle for the usage at 'remote locations'. Is it possible to check the performance of the technique in combination with vertical wind profiles from weather model data?"

Answer: Following the referee's suggestion, we have used the NCEP Reanalysis data (Kalnay et al., 1996) and compared it to the sounded wind profile, for the examples provided in subsections 4.1-4.3 in the manuscript. Examining the following figure reveals that the sounded and modelled profiles appear similar to some extent. However, using the NCEP profiles as an input to the retrieval method, results in substantial differences in the obtained clouds base height. Such discrepancy might be the result of two reasons. First, and especially important for low boundary layer clouds, the radiosonde data is provided with a better vertical resolution than the NCEP data. The low vertical resolution is a disadvantage as short wind patterns might be missed (see the difference at ~1,000m in the top left panel in the figure for example). Second, the NCEP profiles are provided with a spatial resolution of 2.5ºX2.5º (which corresponds to approximately 62,500km^2), while the Beit-Dagan radiosonde measures the wind profile in relatively close proximity to our measurement site. We believe this spatial difference is responsible for most of the wind profiles deviations.

Regarding the usage of the proposed method in remote locations, we believe that space-borne platforms, such as the ALADIN wind Lidar in the ADM-Aeolus mission (which is scheduled to be launched in 2011), might prove useful in providing wind profiles with spatial and temporal resolution that might be sufficient for our method.

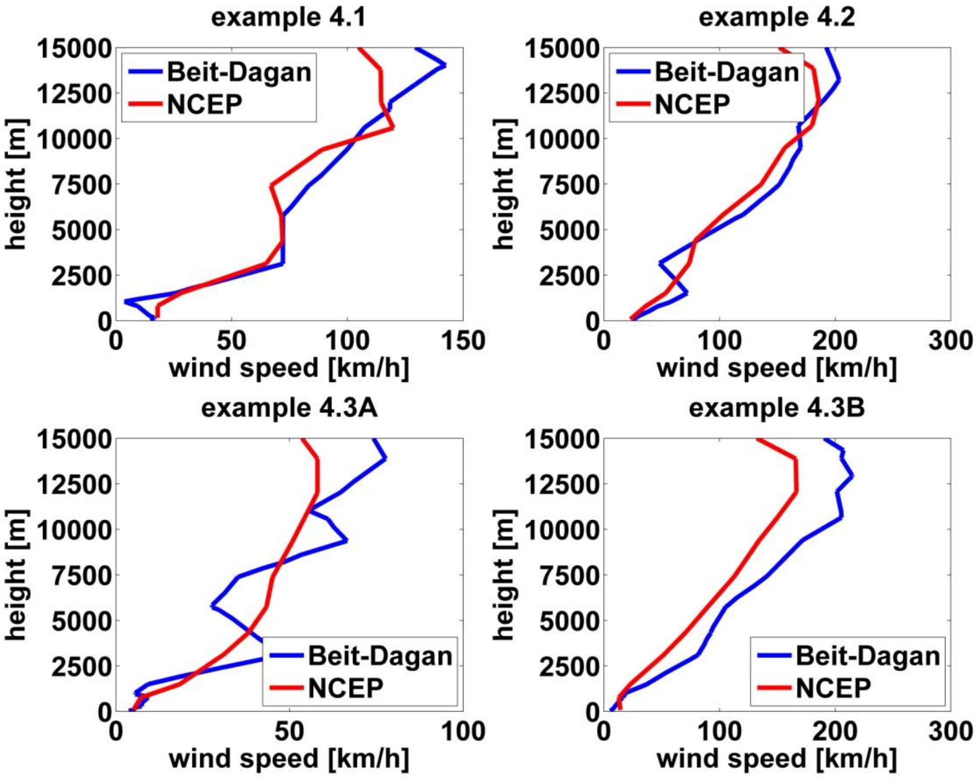

Figure - Comparison of the sounded wind profile with weather model profile. This figure presents the wind profiles for the 4 examples provided in Section 4 in the manuscript. The blue line in every subfigure is the sounded wind profile which was measured by a radiosonde in Beit-Dagan meteorological station. The red line is the wind speed profile derived by NCEP Reanalysis data. One can notice that for examples 4.1 and 4.2 the wind profiles appear similar, but relatively larger deviations exist for examples 4.3A and 4.3B

Comment: "References: I miss references to the techniques applied for cloud motion vector determination from satellite data. See also referee #1"

Reply: We have added a detailed overview of cloud motion vector determination in the introduction (please see our first general remark in this document). This overview includes 7 relevant references.

Comment: "Figs 7,9,11, 13 and 14: It is very hard to read the labels. The zoomed version does not add information."

Reply: We have deleted the zoomed version and enlarged the figures.

References

Kalnay, E., Kanamitsu, M., Kistler, R., et al.: The NCEP/NCAR 40-year reanalysis project, Bull. Amer. Meteor. Soc., 77, 437-470, 1996