Authors reply to the anonymous referee #1 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 22^{nd}, 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)."

Figures Added:

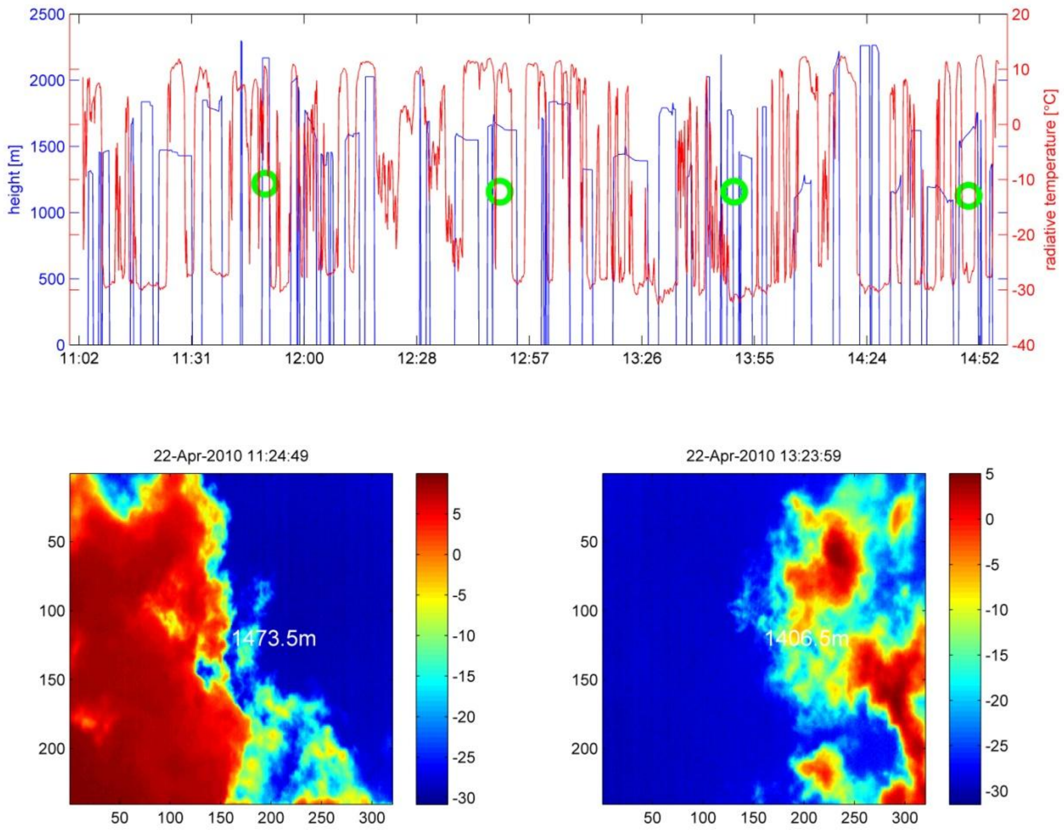

Figure 1 - Cloud base height as extracted by the proposed method during 4 hours on April 22nd, 2010. The red line is the radiative temperature of the nadir sky as

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.

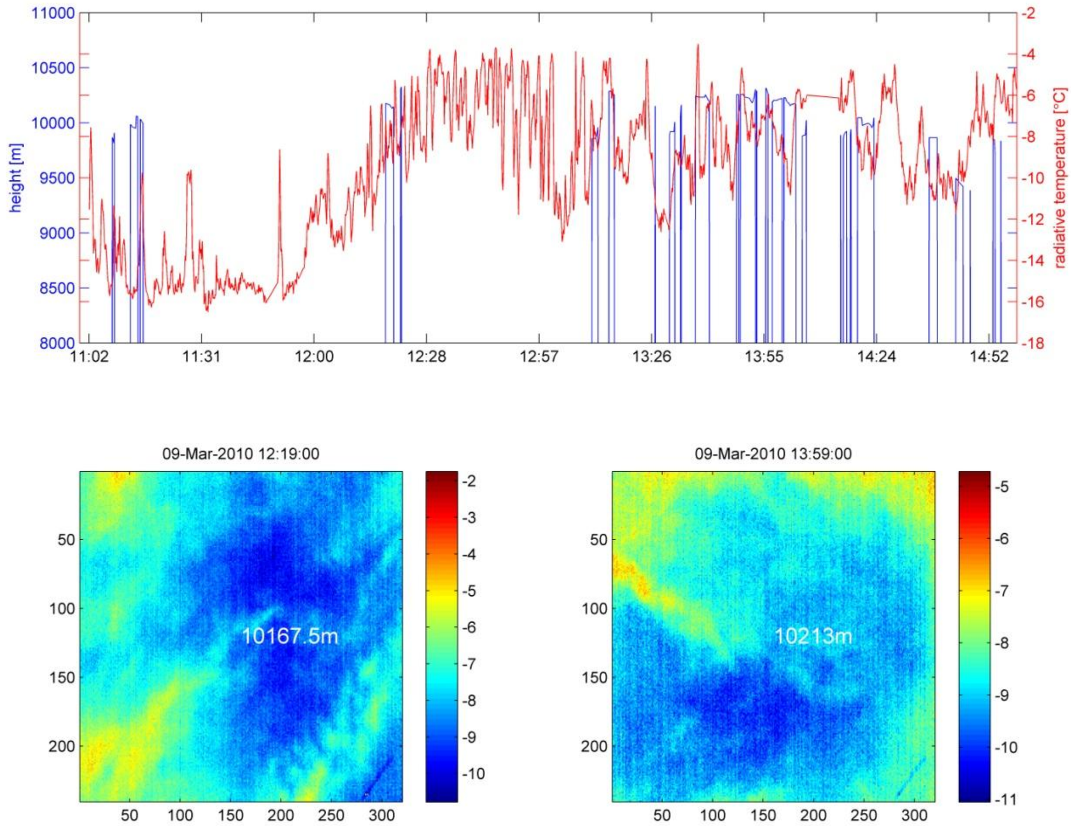

Figure 2 - Cloud base height as extracted by the proposed method during 4 hours on March 9th, 2010. The red and blue lines are as in Figure 15. During that time, dense, high cirrus clouds field passed above the sensors. The method produced an average cloud base height of 10,051m with temporal standard 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.

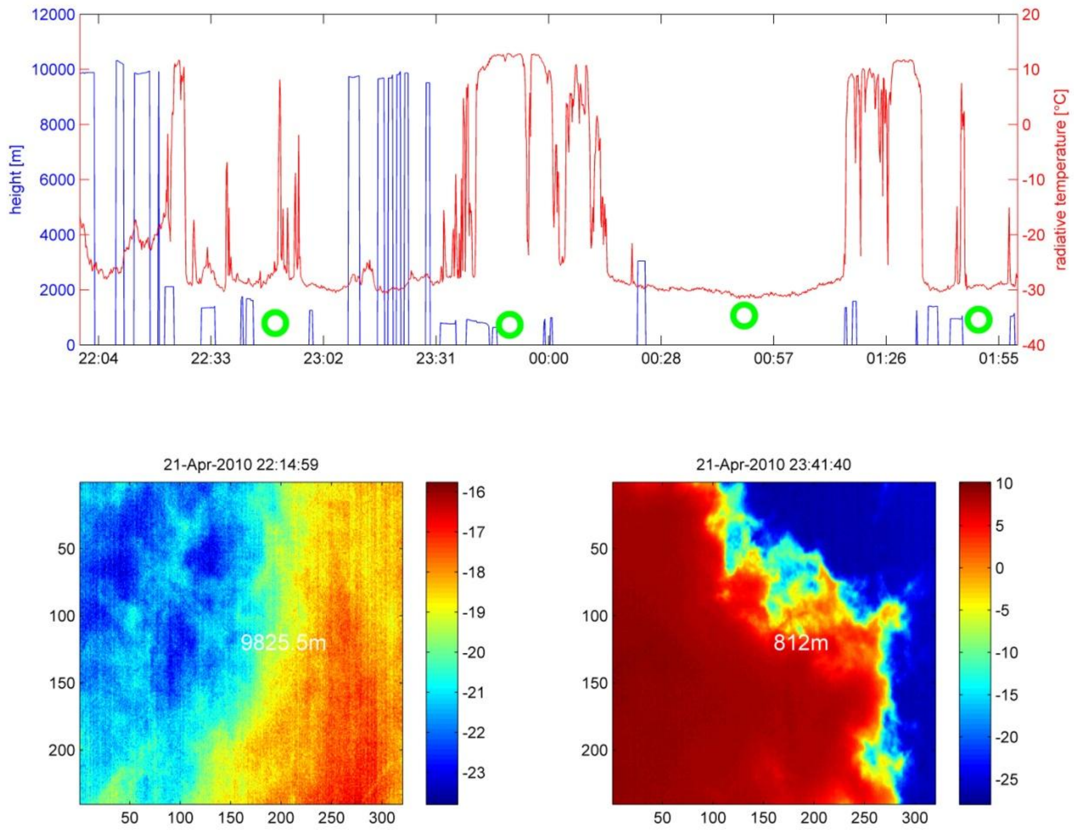

Figure 3 - Cloud base height as extracted by the proposed method during 4 hours on the night of April 21st, 2010. The red and blue lines are as in Figure 15. During that time, multilayered sparse low cumulus and high cirrus clouds field passed above the sensors. The method successfully extracted the 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*)

1. Question: "How do the authors suggest dealing with cases with no wind shear?"

Answer: The proposed method does not need wind shear to work. Indeed, wind shear was present in the examples in the paper, but this is by no means a necessity. In fact, the cases where no wind shear exists should be even easier to handle, since there will probably be only one crossing point of the hypothesized wind velocity profile and the actual wind profile. The only exception is when the actual wind profile and the hypothesized wind profile are parallel. In this scenario our method won't produce valuable information (unless the wind direction analysis will produce distinctive result).

2. Comment: In the case of multilayered clouds, the clouds may move in different directions causing the cross-correlation method to provide a compromise solution, or for any single case a multitude of solutions (as many as cloud cases). Here, more sophisticated quality control methods (as used in the derivation of cloud motion winds with satellite data) may help, and actually it may be possible to cluster the derived wind vectors according to the principally derived categories.

Reply: We agree the cloud motion vectors can be analyzed more sophisticatedly, but we believe that there are inherent differences between clouds sensing from the ground and from the space. In contrast to space borne imaging from geostationary platforms, our field of view (FOV) in terms of the effective sensed area is very small. The IR camera we have used has a field of view of 18°X24° which corresponds to an effective coverage of few hundred square meters at the lower atmosphere and up to several square kilometers at the top of the troposphere. This small field of view means that most of the time only one type of clouds will be apparent in the camera's FOV. Nevertheless, when multi-layers clouds do exist in the same FOV, the median filter applied to the motion vectors guarantees that only the dominant cloud type in the specific temporal sequence will be chosen. In subsection 4.4.3 in the revised manuscript, we demonstrate the method's utility in the presence of multilayered clouds fields.

3. Question: "Have the Author’s considered sub-pixel determination of the final speed and direction?"

Answer: Using sub-pixel determination of the final speed and direction is indeed a good idea that can reduce the marginal errors in the retrieved cloud base height, but from the same reason stated above, we believe it is not entirely necessary. Since the

IFOV is small, we think the added value of sub pixel determination in terms of the final speed will not change the produced cloud base height substantially. For example, in our analysis a typical displacement of a low cloud is of the order of 50 mrad. Since the IFOV of the imager is 1.3mrad it is obvious that subpixel determination might improve the angular speed determination by ~1.3% (1.35/2/50)

4. Question: "Why are the CC calculated using the standard deviation? How is this standard deviation calculated (a simple 3*3 local variability?) In other application areas this has not notably improved the CC results. However, it could be used to select suitable tracers (see 5)). In this approach it seems that all possible tracers (pre-defined 40 * 40 pixels) are used."

Answer:

When calculating a cross-correlation coefficient the variables must be normalized (i.e. divided by their standard deviation). The standard deviation of a 40X40 pixels region is the simple standard deviation of all pixels in this region. Specifically, if R is a region in the image which contains a total of n pixels, $\sigma(R) = \sqrt{\frac{1}{n-1}\sum_{i=1}^{n}(x_i - \bar{x})^2}$, *where* $\bar{x} = \frac{1}{n}\sum_{i=1}^{n} x_i$.

5. Comment: Using the median to determine the final displacement is acceptable, but the following steps may add value:

5a. Consistency checks (temporal and spatial)

5b. Removal of displacement vectors with peaks on the border of the correlation surface

5c. Limiting the calculation of possible solutions to what is possible within the atmosphere

Reply: We agree the above suggestions may indeed add value to the proposed analysis. We have added a paragraph dealing with temporal analysis in subsection 3.2 in the revised manuscript (page 9, line 30):

*"**3.2 Continuous operation of the extraction method***

When operating the proposed method during a long time series it is expected that some results will be invalid. These false readings might be the result of local wind perturbation, imperfect representation of the wind profile above the sensor or even *noisy data. In order to filter these false readings, we consider a reading to be valid only if it passes the following criteria: if the last 10 successive readings yielded at least 3 clouds base heights with temporal standard deviation less than 50 meters. In addition, cloud base heights above 15km are rejected as they are not reasonable solution within the troposphere. This kind of temporal analysis enables to utilize the method on long time series as demonstrated in the following subsection 4.4."*

6. Question: Within the satellite wind community the use of the cross-correlation value is often debated. There are cases where a high correlation value does not guarantee a good result, and more importantly, where fairly low values are still providing excellent winds. Which cut-off value has been used and what type of investigations have been done in this respect?

Answer: The correlation threshold we have used is 0.95 (in-light the referee's comment we have added this value to the paper. See page 8 line 14 in the revised paper). As written in the paper, this threshold was found empirically on a trial and error basis, as we searched for the best value that captures the significant signals and filters out noisy signals. As opposed to space borne imaging, where the clouds' background is the Earth's surface, ground based imaging exploits the relatively uniform sky background. Moreover, the "contamination" from different clouds is small due to the small FOV.

Comment: "A short description of cloud based height assignment using satellite data (as used with cloud motion winds) and related shortcomings would be appreciated."

Reply: We accept the referee's comment. We added a detailed overview in the introduction (see our first general remark in this document, and page 3, line 31 in the revised manuscript).

Comment: "With respect to the general approach an analysis of the errors would be required (e.g. how much does the half a IFOV accuracy contribute to the final error, or the 0.5 h vs 20*10 s, or the distance to the reference profiling station (10 km apart)."

Reply: At the end of section 3 in the original manuscript we have addressed some possible sources for errors. In-light the above comment, we considered several more issues regarding error analysis (page 9, line 16): "As in all retrieval techniques, the *proposed analysis is subject to some possible measurement errors. We assume the error in deriving clouds motion is not higher than half a pixel in every dimension (IFOV/2=0.65 mrad). Naturally, the tangential magnitude of this error depends on the distance to the cloud as illustrated by the green error lines in Figure 5. The result of this uncertainty in the angular velocity causes an uncertainty of several tens of meters for low clouds and up to several hundred meters for high clouds. 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. As pointed above, the proposed method uses an external source for the wind profile. The accuracy of this profile can be a source of errors in the produced output of the method. In the particular example presented in Figure 5, and error of 5% in the provided wind speed profile causes an error of approximately 50 meters in the cloud base height."*

In addition, we have added some temporal analysis of the error in the cloud base height in subsection 4.4 (page 12, line 10 in the revised manuscript):

"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."

Comment: "Finally, the Author’s are encouraged to familiarise themselves and to refer to work done in the context of the CGMS International Winds Workshops (http://cimss.ssec.wisc.edu/iwwg/iwwg.html) where all recent Workshop proceedings are available. These proceedings contain a significant amount of relevant information also available in the Review Journal domain e.g.

Schmetz et. Al., 1993, Operational Cloud-Motion Winds from Meteosat Infrared Images. J. App. Meteor., Vol.32, No7., pp 1206-1225

Velden et. al., 1997: Upper-Tropospheric Winds Derived from Geostationary Satellite Water Vapour Observations. Bull. Amer. Meteor. Soc., Vol. 78, No 2, pp 173 – 195,

Holmlund, 1999: The Utilization of Statistical Properties of Satelltie-Derived Atmospheric Motion Vectors to Derive Quality Indicators. Wea. Forecasting., 13, pp 1093 – 1104.

Ebert, 1989: Analysis of Polar Clouds from Satellite Imagery Using Pattern recognition and a Statistical Cloud Analysis Scheme. J. Apll. Meteor., 28, pp 382 – 399)."

Reply: We thank the referee for this valuable information. We have used some of the above references in our revised paper in the introduction section (see our first general remark at the beginning of this document).

Comment: "It may also be worthwhile to consider to present the results at the next upcoming International Winds workshop, which is currently planned for early 2012."

Reply: We are grateful for the referee's invitation and we will certainly try to present our results in the upcoming International Winds workshop.