<u>General remarks to the editor</u>

We would like to thank the editor and the reviewers for their time and valuable remarks. As described hereafter, we have invested great efforts in order to improve the manuscript in light the reviewers' remarks. Several major additions have been made: the results from the validation experiment were expanded and in addition to the retrieved effective radius, we examine the retrieved LWC as well. A new section was added to the manuscript (section 5), which presents a case study of a single measurement during the passage of a natural thin cloud over our sensors. In addition, an appendix with technical details regarding the main instrumental device was added. Many additional small changes have been made, and we believe the revised manuscript is indeed more scientifically sound.

<u>Authors' reply to Reviewer #2</u>

At first, the authors would like to thank the reviewer for his helpful remarks, and we will address them point by point (reviewer's remarks in bold).

This paper uses a new technique to retrieve effective radius and liquid water path from ground-based IR spectral measurements for thin clouds (optical thickness below 5). The sensitivity to thin clouds is achieved by subtracting the background spectrum, and by matching the difference between cloud-spectrum and background spectrum to a pre-calculated library of differential spectra. It seems that the paper has many figures that are based on calculations, rather than actual data. Out of 24 Figures, only 2 (Fig 23 and 24) show actual data. A figure with a measured sample spectrum, after all the basis for the retrieval algorithm, is missing. Similarly, the instrument itself and its performance, calibration, stability etc. is not sufficiently described. Specific comments are given below. English and Grammar (word order!) are incorrect in many places; examples are given below. I suggest to accept the paper with major revisions.

Specific answers to all of the above comments are given point by point below:

Major comments:

The paper suffers from a lack of actual data and a good instrumental background. The description of the "SR5000" on p7292 is not sufficient. Is there

any literature reference that can be provided for the instrument? The only information given is that it is a "calibrated spectro-radiometer" in the range from 2.5 um - 14 um. Only later do we find out that it has 67 wavelengths. Does this mean that the spectral resolution is about 0.2 micron? What kind of spectro-radiometer is it? What is used as detector? Can the calibration be tied to any national or international standard source, and how is it done? Is the spectral calibration stable over the course of an experiment? Is the stability tracked during a field experiment? Is the noise level dependent on the temperature of the instrument, and is the temperature stabilized? (...)

Authors' reply: We have added Appendix A with a comprehensive description of the SR5000 and the calibration process:

"Appendix A

Technical description of the SR5000

The main instrumental device in this study was the SR5000 (CI-Systems, Israel), a calibrated spectro-radiometer in the range of 2.5μm-14μm (Cabib, et al., 2006). This passive remote sensing sensor employs a circular variable (interference) filter (CVF) to obtain the spectral radiance from the environment. The angular speed of the CVF is computer controllable and it determines the spectra acquisition rate of the sensor. The sensor's field of view (FOV) is selectable in the range of 0.5-6mrad and it affects the spectral resolution of the sensor, which varies from 1% to 2% of the central wavelength, depending in FOV and spectral range. The radiometer was calibrated with an extended area blackbody (SR80, CI-Systems, Israel), that enables the sensor to provide the obtained spectra in units of radiance (Watts/cm^2/str/μm). In addition, the sensor is equipped with an internal chopper which its temperature is monitored constantly. The chopper is coated by a thin layer that is characterized by a uniform, and close to unity emissivity. The radiance is chopped with the frequency of the chopper, and a lock in amplifier enhances the sensor's signal to noise (SNR) by reading the chopped signal within a small bandwidth. The spectro-radiometer uses a "sandwich" LN2 cooled detector, which includes two attached detectors: an InSb detector with high sensitivity in the spectral region of 2.5μm-5.5μm and a MCT detector in the range of 5.5μm-14μm. Throughout our measurement campaign, we have pointed the SR5000 to the zenith and operated it in a single mode: The FOV was selected to 6mrad and an acquisition rate of 0.5Hz was applied. The noise equivalent spectral radiance (NESR) under this configuration was measured in the lab, and it stands on $6.4*10^{-6}$ W/cm^2/str/µm for wavelength of 10µm.” (page 25, line 17 - page 26, line 6 in the revised manuscript)

At least one actual measurement should be shown of a spectrum and of a dark spectrum (if applicable).

Authors’ reply: In light the reviewer’s comment, we have added section 5: “A case study: A field campaign was conducted during the summers of 2010 and 2011, and the optical and microphysical properties of thin clouds were retrieved by the proposed method. A comprehensive analysis regarding the frequency and properties of such thin clouds will be published in a following paper. However, a case study of a single measurement is provided in order to demonstrate the method’s capabilities. Figure 25 presents different stages through the retrieval process of data which was acquired on 15:43 (local time) 29 June 2011. A small, thin cloud passed over our sensors (upper panel in Figure 25), while the SR5000 measured the sky zenith spectrum (bottom left panel). After calculating the differential spectra (black line in bottom right panel), the algorithm found the best solution in terms of spectral shape and magnitude (cyan line in bottom right panel), following the same scheme that was described in section 4. One can notice how the modelled and measured spectra almost perfectly match. The chosen solution represents a cloud with an effective radius of 1.35µm, LWP of 1.713g/m^3, and optical depth of 1.9 (in the 550nm wavelength).“ (page 23, line 27 - page 24, line 8 in the revised manuscript)

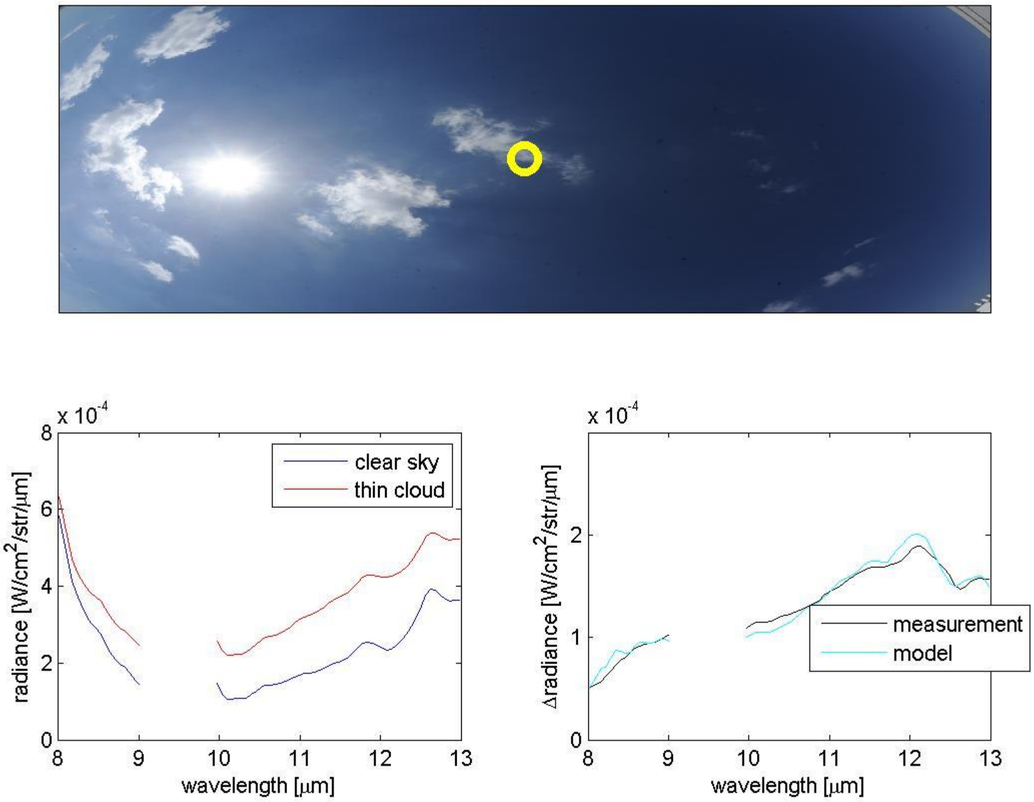

Figure 25 - A case study of a small, thin cloud which passed over our sensors at 15:43 (local time) 29 June 2011. Upper panel: a wide-angle (FOV of 180° on the diagonal) RGB image of the sky hemisphere. The yellow circle indicates the estimated field of view of the SR5000. Bottom left panel: The sky zenith spectrum when the cloud was present in the sensor's FOV (red line), and the clear sky spectrum which was measured few minutes prior to the cloud's arrival (blue line). As explained, the 9µm-10µm region was omitted since it contains a relatively strong absorption band of O_3. Bottom right panel: the calculated differential spectrum (black), and the best fit spectrum that was chosen by the algorithm from the spectral library (cyan). One can notice how the algorithm chooses a solution which fits the measurement in terms of spectral shape and magnitude of the signal. According to the proposed method the cloud was characterized by an effective radius of 1.35µm, LWP of 1.713g/m^3, and optical depth of 1.9 (in the 550nm wavelength).

Early on in the paper (p7284, l14), it is stated that a technique "similar to Rodgers (2000)" is used here. This obviously refers to optimal estimation techniques (or does it not?) - but the method used here has nothing to do with

that, at least judging from the current manuscript. The covariance matrices used in the optimal estimation scheme, as well as state and measurement vectors should not be confused with the matrices shown in this paper.

Authors' reply: The reviewer is right. The presented algorithm is not similar to Rodgers (2000), and we did **not** state that the technique is "similar to Rodgers (2000)". The correct quote is:

"The attempt to extract physical properties of remotely sensed objects is commonly referred to as solving an inverse problem. A typical approach to apply it, is composed of some forward model that predicts the expected signal under certain atmospheric parameters, and some mathematical curve fitting technique and threshold criteria to decide which atmospheric parameters present the most probable solution (Rodgers, 2000). As detailed hereafter, the presented methodology follows this general approach but with important modification prior to the stage of curve fitting technique."

As clearly stated in this paragraph, we used Rodgers only as a reference to the general approach of solving an inverse problem.

I see two impediments for a global use of this technique: (1) The technique was only analyzed for warm clouds at a fixed altitude, but clouds in nature do not occur at fixed altitude. How can cloud top/base height be disentangled in a future retrieval? (2) As shown in this paper, atmospheric profiles have a huge impact on the differential spectra. Will it be feasible to run forward calculations for any profile at any given site? Will the retrievals still be unique, given (1) and (2), or do the altitude and atmospheric profile introduce too much ambiguity? The explanation given on p7301,l5-11 is insufficient.

Authors' reply: We agree with the reviewer's remark about his concerns regarding a global use of this technique. However, the purpose of section 3.3 was to convince that our method is potentially valid for global use, although comprehensive analysis should be conducted for every specific site. At the end of section 3.3 we specifically write: "The analysis presented in this subsection suggests that the proposed methodology is applicable for global use under wide range of seasonal, diurnal, and meteorological conditions. However, the analysis emphasizes that adequate characterization of the observing system is necessary in order to retrieve valid and trustable results, and one must rely on measured representative atmospheric profiles (in terms of general location and season) and a trustworthy radiative transfer model that can incorporate user-defined profiles".

As in this paper we aimed in presenting the approach, a complete analysis of the method's performance for every possible atmospheric profile is beyond the scope of this manuscript.

Many of the "thin" clouds in nature are actually Ci (some of which subvisible). How would the retrieval perform for ice clouds?

Authors' reply: Retrieving ice clouds properties would be challenging since the expected magnitude of the signal is much smaller. Although it could be interesting to further enhance the capabilities of the proposed method, we believe it is beyond the scope of this manuscript.

State in the abstract that the retrieval only works for optical thickness values up to 5. In fact, this paper would be a nice complementary paper to the techniques proposed by the papers by Marshak and Chiu (2008, 2009), as well as McBride et al. (2011). Those techniques are based on shortwave ground-based observations. They work only when clouds are thicker than a certain threshold optical thickness (around 3).

Authors' reply: We totally agree with the reviewer and added to the summary: "The proposed method can be complementary to well established methods which were developed for thick clouds (see Yang et al., (2008), and McBride et al., (2011) for example), in order to derive a more profound analysis of the clouds properties." (page 24 lines 21-24 in the revised manuscript)

It should be stated in the paper that even though a sizable fraction of the global albedo may be due to small clouds, the thicker clouds do contribute considerably to cloud forcing, albedo and absorption. Since the technique presented here goes "blind" with respect to the effective radius above an optical thickness of 5, it is important to have complementary techniques (see comment above) that cover the higher optical thickness domain.

Authors' reply: Indeed retrieving the thicker clouds is important for cloud forcing. The problem with the smaller part of the distribution is that often, due to lack of instrumental resolution or sensitivity, they are misinterpreted as cloud free adding significantly to the aerosol forcing. Nevertheless, we accept the reviewer's comment and added: "As stated above, the main interest of the majority of the remote sensing techniques are relatively large, optically thick clouds, which contribute substantially to the total clouds forcing and to the Earth's albedo." (page 3, lines 22-24 in the revised manuscript)

The paper title suggests the retrieval of a wide range of microphysical cloud properties, but the retrieval of effective radius is the only part that is described in some detail. The retrieval of liquid water content (or liquid water path), on the other hand, is not validated. There is one figure for the validation of the effective radius retrieval; a similar figure should be added for the LWC / LWP and/or optical thickness, or some other means of discussing this aspect of the retrieval should be included. On p7288,l13 it is mentioned how to distinguish between different effective radii, but not how to distinguish between different optical thickness values. For energy budget applications, the optical thickness is even more important than the effective radius.

Authors' reply: We have expanded the analysis of the validation experiment which appears in section 4 and replaced Figure 23 with a new version: "Figure 23 presents the results of the validation experiment. The blue and green lines are the effective radius of the artificial cloud as measured by the Spraytec, and retrieved by the proposed method, respectively. The red line is the retrieved LWC of the artificial cloud. One can notice that the retrieval largely agrees with the Spraytec's readings: if we define agreement between the Spraytec's and the retrieval's effective radii as a case where the Spraytec's effective radius does not deviate by more than 30% of the retrieval effective radius range, then the Spraytec and the retrieval agree more than 70% of the time. Some of the disagreements between the graphs are likely the result of the inevitable differences between the line of sights of the two optical devices: the Spraytec was positioned horizontally in a manner that assured most of the cloud entered its field of view all of the time. The SR5000, on the contrary, was pointed to the zenith with a mere field of view of 6mrad which corresponds to approximately 100mm^2 of the passing cloud. This setup made the retrieval of the SR5000 much more sensitive to wind fluctuations (Figure 24).

Regarding the retrieved LWC (red line in Figure 23), the performance is further encouraging. The retrieved LWC varies in the range of 0.78-3.97g/m^3 while the average retrieved LWC is 1.92g/m^3. Due to technical difficulties, a continuous measurement of the LWC was not possible. However, a reasonable estimation was possible by measuring the flow rate of the water from the air nozzle (3g/s), and analysis of the spray's speed (4m/s) and dimensions (0.28m^2) by using the FLIR images. Such experimental setup is expected to create a cloud with LWC of 2.68g/m^3 (=3/4/0.28)."

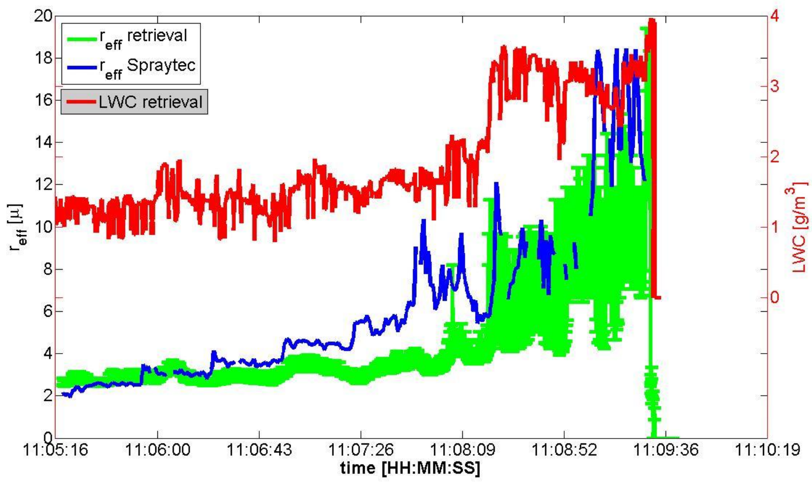

Figure 23 - The result of the validation experiment: retrieved LWC and effective radius of the artificial cloud which was sprayed during the controlled validation experiment. Blue: effective radius measured by the Spraytec. Green: effective radius retrieved by the proposed methodology. Red: retrieved LWC of the cloud. The range of the retrieved effective radius is the result of allowing 10 valid solutions (see stage "G" in section 4).

Although listed as a parameter in table 2, the impact of the thickness of the cloud layer on the spectra is not discussed in the paper. Add a discussion of the sensitivity.

Authors' reply: The geometrical thickness of the cloud is considered in the spectral library of the method. As written in the manuscript, the spectral library contains over 120,000 spectra of clouds with different geometrical depths in the range of 10-100 meters. We clarified this point in section 3.1: "For the mentioned atmospheric profile (see Figure 3), we used radiative transfer calculations to create a spectral library which included a total of 121,010 clouds. This spectral library considers the effect of varying LWC, effective radius, and geometrical thickness of the clouds" (page 13, lines 10-13, in the revised manuscript)

On p7293,l17, "inherent spectral features" are mentioned that are then analyzed by means of PCA. It remains unclear how PCA detects these features, and even what those are. Which time interval was used as a basis for the PCA? What data were analyzed: only dark spectra, or actual measurements? Also, the connection between PCA eigenvectors and SAM is unclear; the PCA are derived from the spectral variability of the data set as a whole whereas SAM constitute the spectral angle between two individual spectra. p7294,l9-11 do not seem justified, and this section needs to be improved.

Authors' reply: We have rewritten this section: "Every measuring device suffers from inherent bias. Spectro-radiometer can suffer from different biases at different wavelength which might be interpreted as inherent spectral features, and in this subsection we have analyzed the effect of such features in terms of possible misclassification of the proposed methodology. At first, a long time series of differential spectral signals of a blackbody was measured in the laboratory, using the same measurement parameters (FOV, acquisition rate) as in the field campaign. Then, the commonly used technique of PCA - principal component analysis was applied (Johnson and Wichern, 1992). PCA considers the data as a matrix which is composed of p vectors, which stands for the p variables in the data (wavelengths in our spectral analysis). Algebraically, principal components are particular linear combinations of the p random variables. Geometrically, these linear combinations represent the selection of a new coordinate system. The axes in the new coordinate system represent the directions with maximum variability in the original dataset. Technically, PCA calculates the covariance matrix of the dataset and finds its eigenvectors. Since the dataset was acquired by using a blackbody, every eigenvector represent an inherent spectral feature of the radiometer. Moreover, the eigenvalue of every eigenvector represents the amount of variance in the data which can be accounted for by the eigenvector. As stated previously, the proposed method utilizes 67 spectral bands, and therefore the PCA produced 67 eigenvectors. In order to examine whether the measuring device contains inherent spectral features that might induce bias to our methodology, we used the same analysis which is detailed previously to compare the spectral similarity between these eigenvectors and the expected spectra of thin clouds at the spectral library which was produced by MODTRAN. The spectral angle (SAM) between every eigenvector and every cloud differential signal was calculated (Figure 11). The red line in Figure 11 is the total variance of every eigenvector (sorted in descending order as commonly presented in PCA analysis), and the blue line is the lowest (spectrally closest) SAM value between every corresponding eigenvector and the clouds spectral library. One can notice that the closest SAM value between any of the eigenvectors and the clouds signals stands on 46°, while the SAM threshold applied in our study is 10°. The analysis, along with the usage of a signal to noise ratio (SNR) threshold of 3 (in wavelength of 10μm) on the measured signal, suggests that inherent noise and spectral features cannot affect our methodology" (page 14 line 16 - page 15, line 13 in the revised manuscript)

Where do the error bars in Figure 23 come from? Also, some explanation about the retrieval of the liquid water content should be given.

Authors' reply: Regarding the error bars in Figure 23, it is written in the caption: "The range of the retrieved effective radius is the result of allowing 10 valid solutions (see stage "G" in section 4)." In addition, as explained above, we have added details about the retrieval of the LWC.

Minor comments:

p7278,l7: "vast majority of remote sensing techniques are focused on thick clouds" – This is not true - lidars have been very successful in retrieving thin cloud properties up to optical thickness of 4.

Authors' reply: The reviewer is obviously correct. Some remote sensing techniques were successfully applied to thin clouds. However, this fact does not contradict our statement that most of the techniques were designed to retrieve the properties of developed clouds.

p7284,l18: What is "standoff detection"?

Authors' reply: We have eliminated this term. The sentence has been rewritten: "Therefore, we have used techniques from the field of remote sensing for detection and identification of gaseous and aerosols plumes applications..." (page 6 line 31 - page 7 line 1 in the revised manuscript)

p7294,l20-21: "The band...that its absence..." Unclear - is there an issue with word order?

Authors' reply: we have rephrased the sentence: "Since it is practically impossible to check all the permutations of the original spectral bands, a simple bands reduction iterative scheme was applied: In a specific iteration, where n wavelengths remained, n possible cross SAM matrices were calculated. Every cross SAM matrix was calculated by eliminating a different wavelength. The best cross SAM matrix was found, and its corresponding wavelength was chosen to be eliminated." (page 15, lines 19-24 in the revised manuscript)

p7294,l20: If Rodgers (2000) had truly been applied, the information content could have been determined directly, rather than gradually eliminating individual wavelengths.

Authors' reply: as noted above, we did not apply Rodger's method. Surely, there are several ways to examine the possibility of bands reduction. However, we chose to use a technique that utilizes the same methodology of the SAM in order to study how many bands are required.

p7298,l8: AERONET provides the optical thickness in the visible / NIR wavelength range. Why is that value used in the IR as well?? Surely the IR aerosol optical thickness is lower than that determined by AERONET.

Authors' reply: The reviewer is obviously correct. However, MODTRAN normalizes the aerosols properties according to their optical properties in 550nm. Therefore, the information provided by the AERONET regarding the extinction in the 500nm is (almost) exactly what MODTRAN requires. We clearly state that "These aerosol models are characterized by their optical properties in the visible and the LWIR region of the spectrum, and can be readily incorporated in MODTRAN in a certain atmospheric layer by specifying the aerosol's extinction coefficient for unit length at a wavelength of 550nm" (page 18, lines 14-17 in the revised manuscript).

p7298: In Figure 15, it is unclear what the SAM angles mean. Shown are SAM angles as a function of (cloud droplet?) effective radius, but isn't this figure supposed to illustrate and analyze the effect of aerosols, not clouds? Also, when it

is mentioned that the "SAM look similar to that of water clouds", it is unclear what the readers should compare to. Are water-cloud-only (no aerosol) SAMs shown as well in some other figure? If so, in which one?

Authors' reply: the purpose of Figure 15 is to illustrate that our algorithm will not be confused by the presence of aerosols, i.e. it will not consider aerosols as water droplets. To do so, we calculate the SAM angle between the expected spectrum caused by aerosols to clouds spectra. We have rewritten the last sentences of the caption of Figure 15: "It seems that rural and maritime aerosols do not show any spectral similarity to water clouds, as the lowest SAM values are 14.76° and 14.35°, respectively. However, since the minimal SAM value between urban aerosol spectrum and water clouds spectra is 4.79°, the urban aerosols effect might appear similar to water clouds to some extent. However, the magnitude of the expected change is relatively small, even in the extreme simulated theoretical conditions."

The word, "nevertheless" is over-used. Sometimes, "however" is the better word. For example, on p7301,l7.

Authors' reply: corrected.

p7301,l21: The explanations given about the instrument do not need to be re-iterated here.

Authors' reply: we have eliminated the repetition.

p7301,l23: What is a circular variable filter, and why is it only mentioned here and not in the paragraph about the instrument?

Authors' reply: We have added Appendix A - a technical description about the SR5000. (page 25, line 17 - page 26, line 6 in the revised manuscript)

Technical comments:

p7280,l2: "one thing in common" – too colloquial

p7283,l28: "attenuate" –> "attenuates"

p7284,l10: delete comma

p7284,l11: "some" –> "a"

p7284,l12: "some" –> "a"

p7285,l5: "It includes" –> "It is based on"

p7285,l10: "either using" –> "either by using"

p7291,l23: "in" –> "at"

p7292,l7: "Under" –> "For"

p7292,l21: "in the" –> "at a"

p7294,l16: "in light the above" –> "in light of the above"

p7295,l13: "induce bias" –> "induce a bias"

p7295,l22: "water vapors do not scatter" –> "water vapor does not scatter"

p7295,l22: "down welling" –> "downwelling"

p7295,l27: "Under" –> "for"

p7296,l5: "stands on" –> "is" (stands on doesn't make sense here)

p7296,l12: delete comma

p7296, lower part of the page has numerous issues with English (word order, use of "sounded", "clouds with LWC at most: : :", etc.).

p7297,l9: "Apart the" –> "Apart from the"

p7297,l14: "retrieve" –> "determine"

p7297,l16: "which are here" : fix word

p7300,l1: "kind of haze" –> "kinds of haze"

p7301,l9: "profile" –> "profiles"

p7301,l10: "trustable" –> "a trustworthy"

p7301,lower part of page: problems with English (e.g., "stands in the basis" –>?, word order, appending a sentence after "namely

p7302,l14: "droplets" –> "droplet"

p7302,l22: "essential the" –> "essential that the"

p7302,l22: delete "would"

p7303,l17: "whom" –> "which"

p7303,l20: delete "naturally"

p7303,l21: delete "Nevertheless, and"

Author's reply: all correction have been made