Atmos. Meas. Tech. Discuss., 4, C2937–C2980, 2012
www.atmos-meas-tech-discuss.net/4/C2937/2012/

Atmospheric Measurement Techniques Discussions

Interactive comment on "Cloud retrievals from satellite data using optimal estimation: evaluation and application to ATSR" *by* C. A. Poulsen et al.

C. A. Poulsen et al.

caroline.poulsen@stfc.ac.uk

Received and published: 22 March 2012

The authors thank the reviewers for their comments which have undoubtedly improved the clarity of the paper. In the following response to the referees the authors hope they have addressed the deficiencies outline by the reviewers.

Given the significant number of changes made as a response to the reviewers and in order for them to see the implementation in contex. In addition to these comments I have uploaded a revised paper in the supplent section which implements the response and contains new figures and tables.

Responses to referee 1

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

Discussion Paper

Minor comments:

The introduction is referring to several cloud data sets but could be improved in giving proper reference to e.g. the cloud assessment pointing at the importance of using different sensor with its strengths and weaknesses. Recent projects to derive climate time series of cloud properties should/could be mentioned.
The authors acknowledge the lack of references to other cloud data sets in the first draft. This has been improved see question from referee no 2.

Please emphasise more the general applicability to further sensors!
The algorithm as is provides a general frame work that can be applied to other visible to mid infrared sensors. The applicability and necessary modifications have been touched on in the previous sections but will be summarised here for clarity. The algorithm has been extended to work with SEVIRI data (Watts et al., 2011) and has been applied to AVHRR and MODIS in the context of the ESA Climate Change Initiative. For instruments that have greater sensitivity to water vapour such as SEVIRI and MODIS or high values of satellite zenith angle the scheme has been modified to use RTTOV to do the radiative transfer for both the thermal and solar channels Siddans et al. (2011)

Technical comments
p. 2393 line 7: Sayer and Grainger instead Sayer et al.
p. 2393, line 12. EUMETSAT in upper case letters. Same for ENVISAT in line 22.
p. 2394, line 6: near-ir changed to infrared
p. 2394: it is not clear if the algorithm is able to be run during all conditions (e.g. day/night etc.) Please make such a statement.:
addressed in comments by reviewer no. 2
p. 2396: section 4 the authors expressed that they used a globally fixed value of 1 for

emissivity. Please explain why not using already developed and existing (e.g. SARB) MODIS based climatology. What is the expected difference to a change in emissivity of e.g. 5 $\%$ typically in desert areas?.

The implementation described here is that what was used to produce the GRAPE output. This implementation used RTTOV to define the emissivity. Future implementation uses the Seeman and Borbas emissivity data set and we are working towards implementing an emissivity error. See also response to the second reviewer.

p. 2397, line 9: Takano and Liou -done
p. 2398: line1: acknowledged -done
p. 2398, line 24: What is Tcld? Please make sure that every (!) Variable is introduced when first used
This section is rewritten p. 2404, line 18: unconstrained -done
p. 2405, line 15: do the authors know what the impact of the ice r_{eff} limitation is? How often does it occur?
In the simulations performed in this paper this was found not to be significant however in future this will be reassessed in light of later validation results.
p. 2406, line 5: Introduce GRAPE abbreviation introduced in abstract -done
p. 2407, line 22: very -done

Specific comments

p. 2413: line 25/26: how often does it happen? Is it really a problem in global application?
The situation of cloud less than 1 optical depth is not uncommon. The algorithm has subsequently been observed to detect cloud $>$ 0.3 optical depths. The frequency of this cloud will be evaluated in the future

AMTD

4, C2937–C2980, 2012

Interactive Comment

p. 2414: Although it is clear that there will be no global single number of recommended values for cost and retrieval errors. However it would be very helpful for interested readers to provide may be a range of the costs where a potential user could start with in his application.
This information can be found in Sayer et al 2011 so will not be repeated here.

p. 2416: Reference section. Sometimes the authors give references to ESA or EUMETSAT technical notes. They should be replaced by peer reviewed publication where ever possible. The reference list should be carefully checked if authors referenced in text.
The authors agree that this is not a desirable and reviewed where this is done. The references remain where no other reference is appropriate.

p. 2427: Mention the date of the overpass in all Figure captions for a better understanding.
Good idea this is implemented

Responses to referee 2

General comments

The main deficiencies of the paper consist in

1. the illustration of the retrieval algorithm
2. the description of the RTMs
3. missing literature references about further optimal estimation retrievals
4. missing quantitative conclusions about the accuracy and limitations of the retrieval as extracted from the error simulations.

In response to Reviewer number 2 comments the section of the solar radiative transfer has been completely rewritten. further literature references added and more quantitative conclusions made about the algorithm. Detailed responses to the above and to other questions can be found in the authors response below.

Specific comments

1. Retrieval Algorithm
Section 3 should contain all the issues regarding the algorithm proposed in this paper. I start with Eq. (1) describing the cost function J: All terms used in Eq. (1) should be defined, i.e. the subscript m should be explained and also the covariance matrix should be explicitly defined. This will then also explain why J represents a cost function. Furthermore, in Eq. (1) all x should be bold and also all y.
All variables are now more explicitly defined.

AMTD

4, C2937–C2980, 2012

Page 2395, line 7-9: Why do you assume / Why can you assume that errors in the measurements (and forward model) are normally distributed with zero mean?
Here we are simply stating the assumptions of the OEM. Assessing the limitations of this assumption on the quality of retrieval results goes beyond the scope of this paper.

Page 2395, line 17-24: Which values does the cost function J assume? Which range does mean that you have an accurate retrieval? Sayer et al. (2011, Table 2) provides such an information.
A typical value of a cost function with 5 measurements and 5 state variables would be 10. If none of the measurements deviated by more then their expected noise and no state variables deviated from their a priori value by more than the a priori error. Otherwise the cost value would be reduced if any of the state variables are bounded and do not have any significant a priori . The value of J can be difficult to estimate, values too low implies an overestimation of error such as the measurement noise, values too large imply underestimation of noise or convergence criteria that is too loose.

Page 2395, line 20-23: Sayer et al. (2011) give more details with respect to χ^2. I think that they should be reproduced here as well (in this or in another form) since they concern the algorithm directly.
Expanded in the above comment

Page 2395, line 17-18: How is such a linearisation performed in practice?
The rational behind the Marquardt algorithm To find the minimum we start at a first guess state (x_o) *which in the absence of other information is set to be the value of the a priori* (x_a) *and proceed to make steps, assuming the value of* (J) *decreases at each step then the updated* (x) *vector moves towards the cost function minimum. In this retrieval we use the Levenberg-Marquardt (Marquardt, 1963)(Levenberg, 1944) scheme to perform the minimisation. The rationale of the Levenberg-Marquardt is to*

AMTD
4, C2937–C2980, 2012
Interactive Comment

use the weighted combination of the steepest descent method and Newtonian descent according to the characteristics of the cost function. I.e when the cost is far from the solution the steepest descent algorithm is preferred while when the cost function is close to the solution the Newtonian scheme is used.

Page 2395, Eq. (2): What is the meaning of this equation?
The diagonals of $\mathbf{S}_x$ *provide the expected variance of each element in the state vector, assuming that the retrieval is linear within the range of its errors and the measurement and prior errors are well described by their respective assumed covariances.*

After the main principles have been explained, the authors should give details about covariances, a priori estimates and so on. This means that Section 6 and 7 should be integrated into Section 3. Sections 4 and 5, the description of the cloud model and of the RTMs, are namely not necessary to understand these issues and, most importantly, I think that Sections 3, 6 and 7 belong together. For this reason, I list here my questions regarding Sections 6 and 7:
These sections have been rearranged

Page 2402, line 20-21: Is the use of all channels compulsory? Can you apply the retrieval at night using only thermal channels?
Of course it is not compulsory to use all the channels but we do not wish to speculate here on the information which might be available from only using thermal ir observations.

Page 2403, line 8: You probably mean the sum of three terms, right? Or is there an additional fourth term that is not mentioned?
yes that is now changed in the document

AMTD
4, C2937–C2980, 2012

Page 2403, line 10-13: Which assumption do you make in order to assume that this covariance matrix is diagonal?
That there is no correlation between the different instrument channels measurements

Page 2403, line 14: Please mention the main inadequacies of the cloud model that could play a role here (3D effects, strong aerosol load...).
In assuming a plane parallel model we are neglecting the effect of high coincident aerosol layers,3-D radiative effects found at cloud edges, in strongly inhomogeneous cloud or broken cloud fields, see (Sayer et al., 2010) for an examination of the effects this assumption has and multi layer clouds. Each of these scenarios may result in the retrieval reporting a high cost as the fit to the assumed model will be poor. The specific and most common case of multi layer cloud is dealt in more detail in section detailing the retrieval scheme performance.

These comments are addressed in the revised section 4
Page 2403, line 15: Which assumption do you make in order to assume that this covariance matrix is diagonal?
That there is no correlation between channels

Page 2403, line 14-18: Please explain the origin of the numbers used here and reproduce the derivation of this term avoiding the citation to Watts et al. (1998) which is not a peer-reviewed paper.
The Co registration error for ATSR channels is small the inhomogeneity error was estimated by comparing radiances from parallax removed ATSR nadir and forward views which is described in Watts. The reference to Watts has been kept as it is the most relevant reference

Page 2403, line 19-23: Please give a justification for the numbers used here.

AMTD
4, C2937–C2980, 2012

The error on the MODIS albedo product arises from 3 separate sources, the accuracy of the MODIS algorithm, the temporal and spatial variability and the applicability of the MODIS albedo to be used for ATSR channels. The 20% error and 40% correlation values are broadly consistent with the accuracy expressed in Liu. A more advance technique for eliminating spectral differences is outlined in a paper by (Sayer et al., 2011).
The following reference has been added Liu, J., C. Schaaf, A. Strahler, Z. Jiao, Y. Shuai, Q. Zhang, M. Roman, J. A. Augustine, and E. G. Dutton (2009), Validation of Moderate Resolution Imaging Spectroradiometer (MODIS) albedo retrieval algorithm: Dependence of albedo on solar zenith angle, J. Geophys. Res., 114, D01106, doi:10.1029/2008JD009969.

These comments are addressed by the revised version of section 4. In general note the intention here is specify the assumptions made in the current version of our retrieval scheme. It goes beyond the scope of this paper to fully justify some of the detailed values given and / or to assess the implication of the assumptions made. We primarily wish to state what these assumptions are and note where they may be sub-optimal.
Note that we have corrected the definition of S_{fm} in this revised section 4. Previously the text omitted to indicate that the modelled error contribution from assumed error in surface reflectance is scaled by sensitivity of the measurements to the surface reflectance.

Page 2403, line 19-23: Sayer et al. (2011) states that the forward model error is underestimated. Please comment on this.
This comment is now addressed in the heavily revised Measurement vector and covariance section

AMTD
4, C2937–C2980, 2012

Page 2404, line 4: What do you mean by surface temperature-measurements? As part of the state vector x it represents a result of the retrieval.
This has been corrected in the text

Page 2404, line 5, line 21-22: What is the difference between a priori and first guess values? Where are first guess values used?
This question is addressed in the revised State vector and a priori constraint section

Page 2404, line 7-9: Is there a particular reason or reference for the choice of these (reasonable) values?
There is no reference for theses values, they were chosen from reviewing pdfs of retrieved optical properties. Theses values will be reviewed should further information become available

Page 2404, line 16-17: Why do you use such a value of 10^8? What does it mean in the absence of useful information? When do you encounter such a situation?
This question is addressed in the revised State vector and a priori constraint section as per previous comment

Page 2404, line 19: Please give a justification for the values of the a priori errors used here.
Comparisons we have performed between buoy and satellite data have shown that the error on SST is typically very much less than 1K. However in rare cases such as upwellings close to land this could be up to 5K. The land surface temperature over most vegetated surfaces should be reasonably accurate. The land surface temperature over deserts and other surfaces with a strong diurnal cycle could indeed have an error greater than 3K. This number will be reviewed for the next versions of

AMTD
4, C2937–C2980, 2012

the algorithm.

Page 2404, line 20: Please explain why the a priori covariance is diagonal.
There is little reason to assume otherwise. The only terms which are significantly constrained by the prior covariance are the surface temperature and the cloud fraction and we see no justification for assuming these to be correlated. Other terms are effectively unconstrained by the high assumed prior error.

Page 2404, line 5-22: Please discuss (here or elsewhere) how strong the dependence of the retrieval results on the a priori values is. This could be tested in Section 10 by means of the simulated data or shown in Section 12 for that selected example. Are there quantities that show a stronger dependency on a priori values? Is the algorithm capable of resetting a positive a priori cloud fraction (i.e. $f > 0$) to zero? In contrast, would it make sense to apply the retrieval to all pixels (even to those with $f = 0$) and see whether also cloud detection is then refined by the algorithm?
In the current setup the only variables with any dependence on the a priori are surface temperature and cloud fraction. The cloud fraction is set by estimating the number of cloudy pixels/(total number of pixels). The cloudy pixels are defined by the cloud mask. The cloud fraction a priori error is set at a relatively small value of 0.1. This is because the cloud fraction was found in initial experiments to change erroneously to compensate for other inadequacies in the retrieval. We do not expect the retrieval to provide highly accurate information on surface temperature (except in cloud-free conditions) or fraction. These quantities are included in the state so that errors on their assumed values can be considered properly in fitting the other parameters and their errors propagated into the expected error on the other parameters.

2. Description of the RTMs
Page 2398, line 21-27: I find the list of unknown parameters too long to be presented

AMTD
4, C2937–C2980, 2012

here. I would rather mention the use of LUTs to account for multiple scattering effects in clouds and present the exhaustive list of parameters at the end of Section 5.1 and 5.2 respectively.
This section has been reworded to take into account the reviewers comments and the LUT values put into a table revamped section 5.

Please notice by the way that all quantities mentioned here show an explicit dependency on τ and r_{eff} that is not present on pages 2400-2402. It would be interesting as well to know which sample points have been selected for the LUTs, i.e. the grid defined by τ , r_{eff} ω_0 and ω_r. This information cloud also be given in Section 4.
In the interest of keeping the paper concise the authors are reluctant to explicitly define the LUT points which is not essential to the description of the technique.

Page 2399, line 1-4: What does Radiative is performed in quasi-monotonically mean? Is this a standard terminology? Please give a reference to this method! What is the inaccuracy when compared to correlated-k methods? Please clarify also that you refer here to the non-DISORT part of the RTM used for the FM.
The Author has changed quasi-monotonically to quasi-monochromatically. The meaning is explained in following sentence (and the s5.1 etc). Errors from this approximation are known to be negligibly low for the AATSR channels, but may become significant for channels of other instruments with strong variations in optical properties across the spectral response. Specific tests have been carried out for the relatively extreme case of the MSG SEVIRI 3.9 micron channel (which is much wider than the AATSR 3.7 micron channel and encompasses strong CO2 absorption features as well as a strong gradient in the Planck function). These are reported in (Siddans et al., 2010) and indicate errors of generally less than (worst case 1.5 K).

Page 2399, line 5-6: How does this work? You need this in order to compute the

derivative of the cost function J, don't you?
The text has been updated with: The derivatives are require to calculate J. They are calculated by (i) differentiating the equations in the Section on Visible and near-infrared Radiative Transfer Model describing the radiative transfer models to give the derivative of the simulated radiance with respect to the LUT parameters (ii) calculating the derivatives of the interpolated LUT parameters with respect to the state variables (iii) applying chain to infer the radiance derivatives with respect to to the state variables.

Page 2400, line 12: Please discuss the uncertainty due to the neglection of Rayleigh scattering, especially in the short wave channels.
Rayleigh scattering is not neglected. The cloud layer includes the Rayleigh scattering produced by the whole atmosphere assuming a fixed surface pressure. Variations in surface pressure are not modelled for the AATSR channels, which will lead to errors of up to around 0.002 in sun normalised radiance except in locations of high surface elevation. The scheme could be easily extended to take this into account by adding a surface pressure dimensions to the LUTs.

Page 2400, line 13-14: For gas absorption you mention here the use of standard atmospheric profiles (from Anderson et al. (1986)?), while in Section 4 (page 2396, line 67) you mentioned The clear-sky atmosphere is defined by temperature and humidity profiles taken from ECMWF analyses (ECMWF, 2008). A fixed mid-latitude ozone profile is assumed (relevant for modelling atmospheric transmission in the visible channels). Does this mean that you use different gas profiles for clear-sky and cloudy-sky? I thought that for clear-sky calculations you used the same model with RCLD = 0 and TCLD = 1 (see also Eq. (13)). Can you please explain this issue?
Fixed profiles have been used (in GRAPE) for the solar channels but the thermal channels are simulated using ECMWF analyses and RTTOV. Note also that in Siddans

AMTD
4, C2937–C2980, 2012

et al. (2011). the scheme has been extended to use ECMWF+RTTOV profiles also in consistent way also for the solar channels (although this improvement is important for instruments such as SEVIRI and AVHRR which have solar channels subject to greater water vapour absorption than AATSR). This has been clarified in the text.

The following text has been added to the paper to answer questions about the descriptions of the RTM the specify questions have been addressed at the end of this text.

Please replace section 5.1 with

5.1 Visible and near-infrared channels

5.1.1 Radiometric Terminology

Consider a spherical coordinate system whose origin is centred on a small area dA. The spherical coordinates are orientated so that θ is the angle from the normal of dA and ϕ is the angle in the plane of dA. The movement of electromagnetic energy can be discussed in terms of radiance L, which is the rate of energy propagation in a given direction per unit solid angle per unit area perpendicular to the axis of the solid angle (ISO, 1992). The distribution of radiance with wavelength is expressed by the spectral radiance $L_\lambda(\lambda)$ such that $dL(\lambda) = L_\lambda(\lambda)d\lambda$ represents the radiance in the interval $[\lambda, \lambda + d\lambda]$.

To describe the reflection of radiation by dA we consider incident radiance dL^i from direction (θ_i, ϕ_i) giving rise to a reflected radiance dL^r travelling in direction (θ_r, ϕ_r). For convenience these direction pairs will be represented as $\boldsymbol{\omega}_i$ and $\boldsymbol{\omega}_r$ respectively. By using these definitions θ_i and θ_r are always in the range $[0, \pi/2]$ and this avoids their cosine ever being negative. The incident ray subtends a solid angle $d\boldsymbol{\omega}_i = \sin\theta_i d\theta_i d\phi_i$

AMTD
4, C2937–C2980, 2012

at dA while the reflected ray subtends a solid angle $d\boldsymbol{\omega}_r = \sin\theta_r d\theta_r d\phi_r$. The bidirectional reflectance distribution function (BRDF) $f^r(\lambda, \boldsymbol{\omega}_i, \boldsymbol{\omega}_r)$ is defined as the radiant reflectance per reflected solid angle (Schaepman-Strub et al., 2006)

$$f^r(\lambda, \boldsymbol{\omega}_i, \boldsymbol{\omega}_r) \;=\; \frac{dL^r(\lambda, \boldsymbol{\omega}_r)}{dL^i(\lambda, \boldsymbol{\omega}_i)\cos\theta_i d\omega_i}$$

A Lambertian reflector reflects incident energy isotropically. Its BRDF is therefore $f^r = \mathcal{R}/\pi$ which is independent of incident or reflection angle and where $\mathcal{R}$ is a constant in the range $[0,1]$. An ideal Lambertian reflector redirects all the energy that is incident on it (i.e. $\mathcal{R} = 1$) so $f^r = 1/\pi$. It is convenient to use a bidirectional reflectance factor or reflection function (Liou, 1980) which is defined as the BRDF relative to that from an ideal Lambertian surface. The bidirectional reflectance factor $R(\lambda, \boldsymbol{\omega}_i, \boldsymbol{\omega}_r)$ is then

$$R(\lambda, \boldsymbol{\omega}_i, \boldsymbol{\omega}_r) = \frac{f^r(\lambda, \boldsymbol{\omega}_i, \boldsymbol{\omega}_r)}{1/\pi} = \frac{\pi dL^r(\lambda, \boldsymbol{\omega}_r)}{dL^i(\lambda, \boldsymbol{\omega}_i)\cos\theta_i d\boldsymbol{\omega}_i} \tag{1}$$

Using this definition, the the reflected radiance for diffuse illumination (incident radiation not confined to a beam but spread over the hemisphere) is

$$dL^r(\lambda, \boldsymbol{\omega}_r) \;=\; \frac{1}{\pi}\int_0^{2\pi} R(\lambda, \boldsymbol{\omega}_i, \boldsymbol{\omega}_r) dL^i(\lambda, \boldsymbol{\omega}_i)\cos\theta_i\, d\boldsymbol{\omega}_i. \tag{2}$$

Where the notation for an integral over the hemisphere has been abbreviated as

$$\int_0^{2\pi} d\boldsymbol{\omega} \;=\; \int_0^{2\pi}\int_0^{\pi/2} \sin\theta\, d\theta\, d\phi. \tag{3}$$

If the incident field is isotropic then the integral in Equation 2 can be performed with only knowledge of the bidirectional reflectance factor. This gives the hemispherical-directional reflectance factor for isotropic illumination $R(\lambda, \overline{2\pi}, \boldsymbol{\omega}_r)$ where the argument

AMTD
4, C2937–C2980, 2012

Interactive Comment

$\overline{2\pi}$ is used to indicate the use of this term is limited to the cases where the input radiance is isotropic. Different integrations give further reflection terms which are shown in Table 1 along with equivalent terms for the diffusely transmitted radiation which are derived from the transmission function $T(\lambda, \boldsymbol{\omega}_i, \boldsymbol{\omega}_t)$ defined by

$$T(\lambda, \boldsymbol{\omega}_i, \boldsymbol{\omega}_t) = \frac{\pi dL^t(\lambda, \boldsymbol{\omega}_t)}{dL^i(\lambda, \boldsymbol{\omega}_i) \cos\theta_i d\boldsymbol{\omega}_i} \quad (4)$$

where the transmitted ray L^t is travelling from direction $\boldsymbol{\omega}_t$ $(= \theta_t, \phi_t)$. There is no consistent naming or notation of reflectance and transmittance terms in the literature so we have listed names we have encountered and have followed Schaepman-Strub et al. (2006) in adopting a notation where a diffuse (but not isotropic) energy flow incident, reflected or transmitted from a layer is indicated in the argument of a term by 2π. In this was way the redirection of energy between directional beams and diffuse fields in expression for reflection or transmission can be easily interpreted.

5.1.2 An AATSR Short Wave Measurement

The short wave AATSR signal is a measurement of energy; a weighted sum of radiance over wavelength and over the instrument field-of-view for some instrument measurement period. However as in common with most short wave imagers the reported value for a scene is a "Sun-normalised radiance" which is defined as the ratio of the measured radiance to the radiance that would be observed from a perfect Lambertian reflector illuminated by the Sun. The forward model simulation of the measured Sun-normalised radiance starts by establishing a spherical coordinate system whose origin is the centre of the scene of interest. In this system the solar direction (θ_0, ϕ_0) is abbreviate as the direction vector $\boldsymbol{\omega}_0$. The energy per unit area per unit time illuminating the scene is $\cos\theta_0 E^0_\lambda(\lambda) d\lambda$ where $E^0_\lambda(\lambda)$ is the superterrestrial solar spectral irradiance. The spectral radiance reflected by an ideal Lambertian scene would then be

AMTD
4, C2937–C2980, 2012
Interactive Comment

AMTD

4, C2937–C2980, 2012

Definition	Names
$R(\lambda,\overline{2\pi},\boldsymbol{\omega}_r)=\frac{1}{\pi}\int_0^{2\pi}R(\lambda,\boldsymbol{\omega}_i,\boldsymbol{\omega}_r)\cos\theta_i\,d\boldsymbol{\omega}_i$	hemispherical-directional reflectance factor for isotropic illumination
$R(\lambda,\boldsymbol{\omega}_i,2\pi)=\frac{1}{\pi}\int_0^{2\pi}R(\boldsymbol{\omega}_i,\boldsymbol{\omega}_r)\cos\theta_r\,d\boldsymbol{\omega}_r$	directional-hemispherical reflectance factor, reflection, local albedo, planetary albedo, black sky albedo
$R(\lambda,\overline{2\pi},2\pi)=\frac{1}{\pi}\int_0^{2\pi}\frac{1}{\pi}\int_0^{2\pi}R(\lambda,\boldsymbol{\omega}_i,\boldsymbol{\omega}_r)\cos\theta_i\cos\theta_r\,d\boldsymbol{\omega}_i\,d\boldsymbol{\omega}_r$	bihemispherical reflectance factor for isotropic illumination, white sky albedo
$T(\lambda,\overline{2\pi},\boldsymbol{\omega}_t)=\frac{1}{\pi}\int_0^{2\pi}T(\lambda,\boldsymbol{\omega}_i,\boldsymbol{\omega}_t)\cos\theta_i\,d\boldsymbol{\omega}_i$	hemispherical-directional transmittance factor for isotropic illumination
$T(\lambda,\boldsymbol{\omega}_i,2\pi)=\frac{1}{\pi}\int_0^{2\pi}T(\lambda,\boldsymbol{\omega}_i,\boldsymbol{\omega}_t)\cos\theta_t\,d\boldsymbol{\omega}_t$	directional-hemispherical transmittance factor
$T(\lambda,\overline{2\pi},2\pi)=\frac{1}{\pi}\int_0^{2\pi}\frac{1}{\pi}\int_0^{2\pi}T(\lambda,\boldsymbol{\omega}_i,\boldsymbol{\omega}_t)\cos\theta_i\cos\theta_t\,d\boldsymbol{\omega}_i\,d\boldsymbol{\omega}_r$	bihemispherical transmittance factor for isotropic illumination

Table 1. Definition of reflectance and transmittance terms. Additional transmittance terms can be created by the inclusion of the direct transmittance (the unattenuated beam) to give total transmittance terms for a layer.

$\cos\theta_0 E^0_\lambda(\lambda)/\pi$. The variation in reflectance with wavelength and geometry is expressed as

$$R(\lambda, \boldsymbol{\omega}_0, \boldsymbol{\omega}_r) = \frac{\pi L^r_\lambda(\lambda, \boldsymbol{\omega}_r) d\lambda}{\cos\theta_0 E^0_\lambda(\lambda) d\lambda} \quad (5)$$

where $L^r_\lambda(\lambda, \boldsymbol{\omega}_r)$ denotes the reflected spectral radiance propagating in direction $\boldsymbol{\omega}_r (= \theta_r, \phi_r)$.

For each short wave channel i the ATSR instruments report a Sun-normalised radiance, R_i that is formed by calibrating the observed scene signal with the signal from a near-ideal diffuse reflector illuminated by the Sun (Smith). If each channel is defined by a response function, $\varrho(\lambda)$, whose limits are $[\lambda_1, \lambda_2]$ then the Sun-normalised radiance for channel i can be expressed as

$$R_i = \frac{\pi \int_0^{2\pi} \int_{\lambda_1}^{\lambda_2} \varrho(\lambda) \varsigma(\boldsymbol{\omega}) L_\lambda(\lambda, \boldsymbol{\omega}) \, d\lambda \, d\boldsymbol{\omega}}{\cos\theta_0 \int_0^{2\pi} \int_{\lambda_1}^{\lambda_2} \varrho(\lambda) \varsigma(\boldsymbol{\omega}) E^0_\lambda \, d\lambda \, d\boldsymbol{\omega}}$$

where $\varsigma(\boldsymbol{\omega})$ denotes the geometric response function of the instrument. Note that the coordinate system used in this expression is centred on the instrument (but can be related to scene centred coordinates through appropriate geometrical transforms). If $\varsigma(\boldsymbol{\omega})$ is constant across the field-of-view then the outer integral can be completed and the expression becomes

$$R_i = \frac{\pi \int_{\lambda_1}^{\lambda_2} \varrho(\lambda) L_\lambda(\lambda, \boldsymbol{\omega}_r) \, d\lambda}{\cos\theta_0 \int_{\lambda_1}^{\lambda_2} \varrho(\lambda) E^0_\lambda \, d\lambda}.$$

In the limit of a very narrow band, the measured Sun normalised radiance is a good approximation to the bidirectional reflectance factor $R(\lambda, \boldsymbol{\omega}_i, \boldsymbol{\omega}_r)$ evaluated at the response weighted mean wavelength of the channel.

AMTD

4, C2937–C2980, 2012

Interactive Comment

5.1.3 Visible and near-infrared Radiative Transfer Model

The visible and near-infrared radiative transfer model assumes the observed scene is composed of a homogeneous cloud layer, with a fraction cover f, and clear sky. The bidirectional reflectance factor is the weighted sum of the cloudy, $R_{i\bullet}$, and clear, $R_{i\circ}$, bidirectional reflectance factors

$$R_i = fR_{i\bullet} + (1-f)R_{i\circ}. \tag{6}$$

The gaseous absorption optical depth of the atmosphere is calculated by MODTRAN (Berk et al., 1989) using standard atmospheric profiles for different latitude bands. The optical depths are weighted by the instrument spectral response function to account for the rapid variation of transmission across a channel. This total absorption optical depth is then partitioned into the above cloud optical depth τ_{ac} and the below cloud optical depth τ_{bc} based on the cloud top pressure relative to the surface pressure.

The spectral bidirectional reflectance factor for the non-cloudy portion of the instruments view is given by the surface bidirectional reflectance factor, $R_{\mathsf{SFC}_i}(\boldsymbol{\omega}_0, \boldsymbol{\omega}_r)$ attenuated by the gaseous absorption of the atmospheric column, i.e.

$$R_{i\circ} = e^{-(\tau_{\mathsf{ac}}+\tau_{\mathsf{bc}})/\cos\theta_0} R_{\mathsf{SFC}_i}(\boldsymbol{\omega}_0, \boldsymbol{\omega}_r) e^{-(\tau_{\mathsf{ac}}+\tau_{\mathsf{bc}})/\cos\theta_r}. \tag{7}$$

For the cloudy fraction of a scene the atmosphere is modelled as having three layers: a below-cloud layer, a cloud layer and an above-cloud layer. The above and below cloud layers consist of gaseous absorbers that attenuate radiation without scattering.

The surface is assumed Lambertian with reflectance $R_{\mathsf{SFC}_i}(2\pi, \overline{2\pi})$. This means that the directionality of the radiance onto the surface can be ignored. The advantage of this formulation is that the multiple scatters between the cloud and the surface are contained in diffuse terms. Ignoring the below cloud absorption the bidirectional re-

AMTD

4, C2937–C2980, 2012

Interactive Comment

flectance factor for channel i at the top of atmosphere is given by

$$
\begin{aligned}
R_{i\bullet} &= e^{-\tau_{\mathsf{ac}}/\cos\theta_0}\left[R_{\mathsf{CLD}_i}(\boldsymbol{\omega}_0,\boldsymbol{\omega}_r)\right.\\
&+ T_{\mathsf{CLD}_i}(\boldsymbol{\omega}_0,2\pi)R_{\mathsf{SFC}_i}(2\pi,\overline{2\pi})T_{\mathsf{CLD}_i}(\overline{2\pi},\boldsymbol{\omega}_r)\\
&+ T_{\mathsf{CLD}_i}(\boldsymbol{\omega}_0,2\pi)R_{\mathsf{SFC}_i}(2\pi,\overline{2\pi})R_{\mathsf{CLD}_i}(\overline{2\pi},2\pi)R_{\mathsf{SFC}}(2\pi,\overline{2\pi})T_{\mathsf{CLD}_i}(\overline{2\pi},\boldsymbol{\omega}_r)\\
&+ \left.\ldots\right]e^{-\tau_{\mathsf{ac}}/\cos\theta_r}
\end{aligned}
$$

where $T_{\mathsf{CLD}_i}(\boldsymbol{\omega}_0,2\pi)$ is the cloud directional-hemispherical total transmittance factor and $T_{\mathsf{CLD}_i}(\overline{2\pi},\boldsymbol{\omega}_0)$ is the cloud hemispherical-directional total transmittance factor. The cloud bihemispherical reflectance is given by $R_{\mathsf{CLD}_i}(\overline{2\pi},2\pi)$.

The multiple reflections between cloud and surface, shown stylistically in Fig. 1, give rise to a geometric series which can be evaluated analytically. To complete this model we parametrise the transmittance of the layer below the cloud as

$$
T_{\mathsf{bc}}(2\pi,2\pi)\approx T_{\mathsf{bc}}(\overline{2\pi},\overline{2\pi}) \quad\approx\quad e^{-\tau_{\mathsf{bc}}/\cos 66^\circ} \tag{8}
$$

where τ_{bc} is the optical thickness of the layer. This assumes the mean angle of below cloud transmittance is 66°. Including the below cloud absorption within the forward model gives

$$
R_{i\bullet} \;=\; e^{-\tau_{\mathsf{ac}}/\cos\theta_0}\left[R_{\mathsf{CLD}_i}(\boldsymbol{\omega}_0,\boldsymbol{\omega}_r)+\frac{T_{\mathsf{CLD}_i}(\boldsymbol{\omega}_0,2\pi)R_{\mathsf{SFC}_i}(2\pi,\overline{2\pi})T_{\mathsf{CLD}_i}(\overline{2\pi},\boldsymbol{\omega}_r)}{1-R_{\mathsf{CLD}_i}(\overline{2\pi},2\pi)R_{\mathsf{SFC}_i}(2\pi,\overline{2\pi})T^2_{\mathsf{bc}}(2\pi,2\pi)}\right]e^{-\tau_{\mathsf{ac}}/\cos\theta_r} \tag{9}
$$

Responses to Referee's Specific Questions cont.

The following questions concerning section 5.1 have been addressed through a complete redraft of this section. We apologise for any confusion the poor first draft created and appreciate the referee's comments in helping improve the text.

Page 2399, Eq. (6): Please define L (radiance) in general and L^r_λ in particular. What

AMTD

4, C2937–C2980, 2012

does the superscript r stand for? Reflected? It is also used in ω_r.
Radiance, L, which is the rate of energy propagation in a given direction per unit solid angle per unit area perpendicular to the axis of the solid angle (International Organization for Standardization (ISO), Quantities and units, Part 6: Light and related electromagnetic radiations, ISO 31-6:1992/Amd.1:1998, 1992). Yes 'r' stands for reflected.

Page 2399, line 20: For consistency to Eq.(6), you should use $R_{\bar{\lambda}}(\omega_0, \omega_r)$ instead of $R(\bar{\lambda}, \omega_0, \omega_r)$.
The subscript λ denotes a spectral density i.e. derivative with respect to wavelength. Reflectance is a ratio of irradiance to radiant exitance and is not a spectral density. The text has been altered to make this clearer.

Page 2399, line 17-20: This sentence says that

$$R(\bar{\lambda}, \omega_0, \omega_r) \quad = \quad \frac{L^r_{\bar{\lambda}}(\omega_r)}{E^0_{\bar{\lambda}}}$$

but in reality $R(\bar{\lambda}, \omega_0, \omega_r)$ is correctly given by Eq. (8). Please adapt the sentence.
The text has been altered to make this clear.

Page 2399, line 18: $E^0_{\bar{\lambda}}$ is an irradiance indeed but it cannot represent *the irradiance the satellite would measure if ....* A satellite can only measure a radiance. $E^0_{\bar{\lambda}}$ represents the solar irradiance at top of atmosphere on a plane perpendicular to the incoming radiation convolved with the spectral response function of the given sensor channel.
The reviewer is correct that an instrument only measures radiance. The way

AMTD

4, C2937–C2980, 2012

Interactive Comment

AATSR is calibrated (and simulated) is to ratio the scene radiance against the radiance from an ideal Lambertian reflector. The text has been altered to make this clear.

Page 2400, line 4-6: You have already introduced the "Sun-normalised radiance" and the top of atmosphere reflectance. Now you introduce the bidirectional reflectance factor $R(\lambda, \omega_i, \omega_r)$. Comparing to Eq. (8) it seems that this new quantity is simply the spectral analog of $R(\bar{\lambda}, \omega_i, \omega_r)$. However, if I look at your definition, it turns out to be something different that has nothing to do with a radiance measured in a particular solid angle as it was the case in Eq. (8) but only with radiant fluxes. Please correct this definition, take care of notation, introduce only quantities that are really needed and stick to them through the whole manuscript. By the way, I have never heard of a diffuse surface, while an ideal Lambertian surface is a well-known concept.
$R(\lambda, \omega_i, \omega_r)$ *is the (weighted) spectral analog of* $R(\bar{\lambda}, \omega_i, \omega_r)$. *We have altered the wording of the definitions to try and make this clear. The reviewer is correct in that the 2*π *notation is not strictly necessary in equation 9. However we have included it to show a term takes energy from one direction and distributes it into a diffuse field. In this we are following Schaepman-Strub et al. (2006). The text has been modified to make this notation clear.*

Page 2400, line 18: R_{SFC} is called reflectance (as R in Eq. (8)). Do you mean a bidirectional reflection distribution function (BRDF) $R_{\mathrm{SFC}}(\omega_0, \omega_r)$? Then it should not be called a Lambertian surface. Do you simply mean a surface albedo? In that case you could forget about the 2π dependency in Eq. (9).
A bidirectional reflection distribution function is a generic function. A Lambertian surface is merely a special case of BRDF i.e one where $R(\omega_i, \omega_r) = \text{constant} = R_{\mathrm{SFC}}$ *in this case.*

Page 2400, line 21: Please specify irradiance terms: which terms do you mean?

AMTD

4, C2937–C2980, 2012

Interactive Comment

Which irradiance?
By irradiance we really mean the diffuse terms whose input or output is spread over all angles. We have altered the text to make this clear.

Page 2400, line 24: $R(\omega_0, \omega_r)$ is not the spectral bidirectional reflectance factor at the top of atmosphere because the below cloud absorption is neglected. The correct form of the spectral bidirectional reflectance factor at the top of atmosphere is given in Eq. (12). So what is the meaning of Eq. (9)?
Equation 9 is the equation without below cloud absorption. We have altered the text to state this.

Page 2400, Eq. (9): Many new terms are needed in order to understand this equation. They are all defined afterwards. I think that it would be easier for the reader to know all quantities before Eq. (9) is presented. Please define the quantities prior to Eq. (9).
This has been done.

Page 2401, line 4-6: Terms like spectral directional-hemispherical total transmittance factor or spectral hemispherical-directional total transmittance factor are not immediately clear, so please explain what they mean and write down their definition as integral over ω_r or ω_i.
This has been done.

Page 2401, Eq. (10): The differentials $d\Omega$ should read $d\omega$. The two integrals (from 0 to 2π and from 0 to $\pi/2$) refer to the integration of Φ and θ, but these variables are not explicitly contained in the integrand. Furthermore, two such integrals are meant (i.e. four in total) because the variables are Φ_i, θ_i, Φ_r, θ_r. I find this notation not completely

AMTD
4, C2937–C2980, 2012

correct, so I would replace these two integrals by two integrals of the type

$$\int_{2\pi} d\omega$$

The differential $d\Omega$ implies a cosine factor is included in the solid angle integral. This is the notation of Nicodemus (Nicodemus, F. E., Richmond, J. C., Hsia, J. J., Ginsberg, I., and Limperis, T., Geometric Considerations and Nomenclature for Reflectance, U.S. Dept. of Commerce, NBS Monograph 160, 1977) however it is not often used so we have defined the integral explicitly in the text.

In addition the following questions have been addressed

Page 2401, line 12: Why $66°$?
This is taken from Watts et al 1998 It is chosen to give a reasonable approximation to the transmission appropriate to the diffuse reflection. This has been clarified in the text

Page 2402, line 6: I thought RTTOV could also provide cloudy radiances. Is this correct? If yes, why don't you use it?
to do

Page 2402, eq 15: There is an error in this equation
The reviewer has indeed found an error in the equation this has been corrected. The temperature of the cloud has been given a new variable name to distinguish it.

Page 2402, line 15: What do you mean by effective emissivity? It is usual to term $f\dot{\epsilon}$ the effective emissivity, where ϵ is the cloud emissivity and f the cloud fraction.

AMTD
4, C2937–C2980, 2012

The effective emissivity is the efficiency compared to a black body at which the cloud emits radiation. It is a function of view angle only. As in the solar case the TOA radiances are a linear combination of overcast and clear atmospheric radiation as per Eq. 10

$$R_i = fR_{i\bullet} + (1-f)R_{i\circ}. \tag{10}$$

Finally, accuracies of the short wave and thermal RTMs with respect to DISORT or other radiative transfer codes should be quantified, if possible. Is it also possible to say how large the RTM error contribution to the overall retrieval error is?
A comprehensive analysis of the accuracy of the forward model has been performed in the subsection titled Accuracy of radiative transfer model and summarised for the paper.

4. Literature References
References about other cloud optimal estimation schemes should be given. These may include but are not limited to Watts et al. (1998); Heidinger and Stephens (2000); Miller et al. (2000); Baran and Havemann (2004); Heidinger (2003); Heidinger and Pavolonis (2005). The present work should also be discussed in view of these algorithms, and differences, similarities, advantages, disadvantages and limitations should be emphasised.
References to other optimal estimation schemes have now been included. The main difference between these schemes and the one described in this paper is that we retrieve cloud top height, optical depth and effective radius simultaneously, with channels spanning the visible to mid infrared. Where the retrieval obtains a good fit to observed radiances, one can be assured that the resulting cloud properties provide simultaneously a good representation of the short wave and long wave radiative effects of the observed cloud, Ham et al. (2009) and Siddans et al. (2010) show large discrepancies between observed MODIS radiances and those predicted based on MODIS cloud retrievals. Such discrepancies are inherently avoided by the retrieval

AMTD
4, C2937–C2980, 2012

method adopted here. This has been clarified in the text.

4. Quantitative Conclusions

Sections 10 and 11 deal with the retrieval scheme performance. They are very interesting and many plots are shown. However, only a very few quantitative conclusions are taken from them. For instance, on page 2408, line 46, the authors identify cloud types that are difficult to retrieve and talk about thin clouds, clouds with small r_{eff}, and extremely thick clouds. Already these cloud classes should be specified by telling what a thin cloud is and so on. Furthermore, also underestimations and overestimations of cloud parameters as well as indications about the values of the cost function should be quantified in both Sections 10 and 11.

The definitions of thin and thick cloud have been defined in the text optically thin $<$ *1 optical depths small effective radii* $<$ *5*

5. Further Comments

Since the validation paper by Sayer et al. (2011) uses the acronym ORAC for the algorithm described here, I would recommend to introduce this acronym in the present paper as well.

The acronym is introduced in the abstract and introduction to the retrieval

Abstract: It contains a too long introduction that can be shifted to Section 1 (page 2390, line 18), and too few quantitative assertions about the retrieval itself and its performance. It also does not tell anything about the novel aspects of the scheme or about its importance. Finally, the citation of (Sayer et al., 2011) in the last line should also be removed.

The abstract has been rewritten to address these comments.

AMTD

4, C2937–C2980, 2012

Interactive Comment

Page 2396, Section 4: At some point in this section (possibly at the beginning) it should be clarified that the algorithm needs a cloud mask to start with and that cloud thermodynamic phase determination is done separately.
The following text has been added: In the current implementation of ORAC a cloud mask is required to identify regions of cloudy sky. Only regions identified cloud are processed. Subsequent experiments have shown that by processing all pixels (clear and cloudy) a good cloud mask can be derived using retrieval diagnostics but is not used here. The selection technique used to determine cloud phase is described in Sect. 8.

Page 2396, line 10: To my knowledge, Cox and Munk (1954a,b) derive BRDF parameters for water reflectance, but you treat surface as a Lambertian albedo. How do you transform BRDF into albedo?
This comment has been addressed when answering the reviewers comment Page 2400, line 18

Page 2396, line 11: Please insert a citation for the MODIS albedo product (e.g. Schaaf et al. (2002)).
The citation is now included

Page 2396, line 14: While you consider surface albedo uncertainties in your OE, you do not consider emissivity uncertainties. Why? What is the effect of this choice on retrieval accuracy?
For the infrared channels the surface is assumed to have an emissivity of 1.This is a reasonable assumption as the error on the emissivity for the 11 and 12μm channels

of ATSR will be small over sea $\approx< 1\%$. The error will be largest over bare soil, such as deserts $2 \approx \%$,. Like surface albedo uncertainties the impact will be largest in fractional cloud and thin cloud scenarios affecting the accuracy of the retrieval in these scenarios in particular the CTT will be warmer. No error was implemented in the version of ORAC applied the GRAPE ATSR climatology. The error will be considered in future applications.

Page 2396, line 19: Can you quantify how large the impact of this assumption (cloud top=cloud bottom) is for the accuracy of the radiative transfer calculations?
This retrieval performs radiative transfer under this assumption. The accuracy of the resulting parameters depends on how close the real vertical cloud profile is to fitting the single-layer assumption. Because for AATSR we are dealing with window channels there is no distinct information on cloud layer thickness. Retrieved results could be viewed as effective parameters of the single-layer representation of a real cloud. How close these are to the real properties could be assessed by detailed validation (beyond the scope of this paper). If the scheme could be extended to retrieved cloud layer thickness if absorbing (e.g. O2 A-band) channels were added (the LUTs would need to be appropriately extended)

Page 2397, line 7: Ice particle optical properties are not uniquely defined since they strongly depend on shape. Please provide here some detail about the type of ice particles described in Baran and Havemann (2004). Please also give the definition of r_{eff} used for ice particles.
The retrieval shown here uses the analytic phase function described in Baran. In which it is shown that the application of the model to ATSR-2 data fitted the visible and infrared channels better that single ice crystal type models.

Page 2397, line 13: Can you give a reference for this size distribution? Which values

AMTD

4, C2937–C2980, 2012

Interactive Comment

do you assume for rm?
Water cloud particles are calculated using Mie theory which is described in Wiscombe et al. 1980. This citation is added.

Page 2397, line 16: This definition of effective radius cannot be correct because you have the fourth moment of the particle size distribution divided by the second moment of the particle size distribution. This has a unit of μm^2. Usually, according to Hansen and Travis (1974), you use the third moment divided by the second moment of the particle size distribution. Please correct this equation.

This equation has been corrected and the reference added.

Page 2398, line 10: Good convergence means that all channels could be reproduced by the model. On the other hand, the retrieved solution must not be the only one solution of the problem: even good convergence could provide a solution that does not correspond to reality. Please comment on this.

The principle situation the reviewer is referring to here is the presence of multiple low cost minima (MLCMs) in the cost function. It is true that the search algorithm used Levenberg-Marquadt (L-M) does not inform on the presence of multiple minima in an individual case; it simply finds one of them. No doubt expensive search algorithms (e.g. the L-M algorithm employed from randomly perturbed first guess states) could be employed to establish whether MLCMs routinely exist but this has not been done and would have to be restricted to experimental studies. However, the presence of MLCMs can become apparent in the ensemble behaviour of retrieved parameters - solutions switching between minima in regions of apparently similar cloud conditions. This is generally not observed (in COT or Reff for example) but one very particular case where it is manifest is that of boundary layer cloud where CTP solutions can appear below and above the inversion at altitudes of similar temperature. It should be

AMTD
4, C2937–C2980, 2012

Interactive Comment

noted that a solution found with a low cost is as valid, from the point of view of the information available, as any other low cost solution; there is nothing in the data to distinguish them. If experiment or observation determine there are MLCMs (e.g. the BL CTPs) then the implication is an under-determined system and no algorithm based on the same information could reliably (i.e. without luck!) resolve the issue. The only possible, although impractical, improvement would be to somehow find all LCMs and report them all. Practical (and preferable) solutions to the MLCM problem must involve additional information (e.g. in the case of the Boundary layer (BL) CTPs, to identify inversion conditions in the NWP temperature profile and constrain the CTP solution into the BL). One of the advantages of the ORAC OEM approach to use all data simultaneously is that the chances that the system can accommodate more than one solution is less than when sub-sets of information are used; i.e. the system is more likely to be over-constrained. (the reviewer may also be thinking of cases where a single but very extended cost function minimum is present, i.e. the parameter(s) could take large ranges of values without affecting the radiance fits. Of course this situation is fully reflected in the solution expected error diagnostics and is far more manageable than the MLCMs described.) A paragraph summarising this has been added to this section.*

Page 2398, line 10: Why do you think that these cloud classes (with strong vertical variation of r_{eff} and phase) are among the most difficult ones? The retrieval could find an effective radius, a phase and a cloud top temperature that enable to correctly reproduce the measurements even if the link to the real cloud is difficult to understand.

The reviewer is correct and we have modified the text to take this in to account: We recognised that this simple model cannot represent all aspects of cloud three-dimensional structure. In the ideal case, the retrieved parameters should correspond to vertical (over the profile) and horizontal (over the scene) averages of the true cloudy properties. However there may be classes of clouds, particularly those with strong

AMTD

4, C2937–C2980, 2012

vertical variations in particle size and phase, for which the model may or may not be able to produce radiances consistent with observations in all ATSR channels. When it cannot, the condition can be recognised because the retrieval will not converge with satisfactory cost and the retrieved products considered invalid. When it can, the retrieval will successfully converge and there is no way to know that vertical variations existed ; the retrieved parameters will then be radiatively consistent effective values and not necessarily the physical averages desired. In Sect. 10 we specifically test the performance of the scheme under the more extreme case of varied multilayer cloud conditions, diagnosing under what conditions the retrieval provides a good solution (within estimated errors of the true state) and whether the solution cost can effectively be used to distinguish conditions in which the model assumptions are inappropriate.

Page 2403, line 7: 3 $\times$ 3 km $>$ 3 $\times$ 3 km2. By the way: is it 3 $\times$ 3 or 3 $\times$ 4 as you state on page 2404, line 11?
The author apologies for this confusing sentence. The data is processed at approximately 3x4 pixels which is approximately 3x3km. This has been corrected in the text

Page 2405, line 3 + 7 + 10: Can you give a justification for these numbers (260 K, 23 and 20μm)? Are they set empirically?
These values were derived empirically. Later comparisons with lidar observations may prompt a revision of these numbers for future retrieval runs.

Page 2405, line 12-13: Can you please state how unreliable the results are or how often this could take place?
This section has been reworded to: It is recognised that ice clouds do exist with $r_{\text{eff}} < 20\mu$m, and the retrieval will not provide reliable results in such situations. An alternative approach to the selection of cloud phase which would partly avoid this problem would be to simply run the retrieval twice, once for each phase, and select the

AMTD

4, C2937–C2980, 2012

Interactive Comment

most probable phase based on solution cost. Mixed phase clouds are not considered. Mixed phase clouds will either be retrieved as either ice or liquid and with 'average' liquid/ice values or with a high cost. In practice the boundaries on effective radius and lack of a mixed phase class make little difference to the result.

Page 2405, line 15: Is this really a solution? Couldn't there be cases where you have accurate solutions for both cloud phases?
This question has been address above

Page 2405, line 16-17: A couple of time in the manuscript you mention CPU time. Can you please give some indication about CPU time consumption of the algorithm?
The authors acknowledge that the method is more computationally expensive then some existing techniques however this will become less of a constraint with time and the benefits of the scheme will outweigh the computational expense. The authors are refraining from giving an explicit CPU time consumption as this is very machine dependant and will date the paper quickly. The CPU required is also dependant on how the algorithm is implemented and what external data is used and at what resolution for example.

Page 2406, line 10: How well is maybe not the most appropriate question to ask here. Since your model does not know anything about multilayer clouds you will always get either a liquid water or an ice cloud as a result. This is in any case wrong, so you first have to define what you mean by a good performance of the algorithmÂą in this case? Do you expect an optical thickness that is the sum of the optical thicknesses of both layers? And so on... Please specify this in the manuscript.
The text in the paper has been clarified to make clear that the "true" optical depth is the sum of the optical depths of each layer, the true effective radius and cloud top pressure are defined as the layer which corresponds to the best fitted layer as defined

AMTD
4, C2937–C2980, 2012

by the lowest cost, in this definition multi layer clouds with an optically thin upper layer of ice cloud will have the true phase defined to be water.

Page 2406, line 16-17 + 21-23: Please explain the meaning of linear error simulations and non-linear error simulations.
In linear simulations, the sensitivity of observations to cloud parameters and error sources is computed for a specific set of atmospheric profiles and observing conditions. Observation sensitivities are then transformed into retrieval sensitivity assuming that the cloud forward model is linear within some suitable range about the atmospheric/observing state. In non linear simulations the solution is found iteratively, in this case Marquardt Levenberg technique is used.

Page 2407, line 12: Which wind speed do you select for the Cox and Munk parameterisation?
The surface is assumed to have a value for the lambertian reflectance of .01 for all visible channels. This is amended in the text.

Page 2407, line 13: When you fix one of the (output) variables, like cloud fraction here, do you have to implement a new retrieval scheme with one variable less? How does this work? Please comment on this.
The same retrieval scheme is used, however in the case of fixed cloud fraction the cloud fraction is set to 1 with an infinitesimally small a priori error.

Page 2407, line 4-13: What about pc? What is the choice you make for this variable?
The same values are used as in section 6 as is mentioned in the text however the values are repeated in this section for clarity.

AMTD
4, C2937–C2980, 2012

Page 2407, line 4-13: Do you use DISORT for these simulations? Please specify.
DISORT is used in the generation of the LUTs for this analysis, but is not used explicitly in the retrieval

Page 2408, line 6-10: If in your simulation you do not vary ice crystal shape then this cannot be an issue here. However, for an application to real data this is of course an important point. Please clarify.
This paragraph is rewritten slightly to clarify. This simulation assumes that the optical models of the liquid and ice cloud are correct. When applied to real data any uncertainty in the models would add uncertainty to the state. Ice clouds are more difficult to model than water clouds due to the variation in type i.e hexagonal aggregates, rosettes. The choice of optical model could have a significant effect on the accuracy of the retrieval (Zhang et al., 2009).

Page 2408, line 11: Please re-number Section 11 into Section 10.2.
This is done

Page 2408, line 19: By simulations you mean here retrievals, don't you?
yes this is changed

Page 2409, line 1: How are cloud optical thicknesses varied? According to Section 10.1 or according to the caption of Fig. 3?
The caption of figure 3 is incorrect this has been changed. The optical depths are varied for each layer using the same values as section 10.1

Page 2409, line 11: Please specify what you mean by 'true' cloud parameters: since in your simulations you always have two parameters (for the liquid water and the ice

AMTD
4, C2937–C2980, 2012

layer) it is not clear what you mean here.
For the multi-layer cloud scenarios the 'true' phase and cloud effective radius is assumed to be that of the top layer of cloud, i.e the ice layer. The 'true' optical depth is the sum of the liquid and ice cloud layer.

Page 2411, line 13: Multilayer gives high cost functions, but conversely high cost functions could occur for different reasons. This means that high cost functions could not be reliable indicators of multilayer clouds. What about for instance the situation where the initial cloud mask incorrectly identifies a cloud in one pixel that in reality is not there? Please comment on this and make a list of possible situations producing high cost functions (unless it has been already discussed in connection with the cloud model).
This has been discussed in response to Page 2403, line 14

Page 2412, line 1: Surface temperature is missing. Please add this quantity as well. It could also be interesting to see the a priori cloud fraction and the a priori surface temperature.
In the interests of keeping the paper focused on cloud retrievals we prefer to omit this plot. the surface temperature retrieval will be the focus of a future publication. In the scenarios considered here the surface temperature is nearly always fixed to the a priori with movement only for the thinnest cloud scenarios

Page 2412, line 5: where the cloud is thin or maybe inexistent? Comparing retrieval results it seems that some pixels flagged as cloudy do not contain cloud (especially over the Mediterranean) and thus produce inaccurate results. Please comment on this. *It is difficult from the false colour image to always correctly identify cloud. One of the inherent problems of cloud masking however in these cases where this seems apparent the uncertainty an/or cost is generally high giving a low confidence to the*

AMTD
4, C2937–C2980, 2012

values as would be expected.

Page 2412, line 11: The water clouds over Africa as well as the large ice cloud over Central Europe also show some yellow cloud fraction band. Do you think this is realistic? Please comment on this.
The a priori cloud fraction is determined using the individual pixel cloud mask described in the section titled Cloud/atmosphere/surface model. Errors in this cloud mask will propagate into the retrieval and may not always be flagged with a high cost. It is now clear that the cloud mask used over land is not optimal in particular it is poor over desert surfaces. In the future it maybe more appropriate to process at pixel resolution and fix the fraction to 1.

Page 2412, line 15: shadowing: or reflection by cloud sides or ... *The text has been updated to the following: The cost is highest when the cloud is thin or where there is no cloud visible to the eye in the false colour image. Enhanced cost values are visible around the edge of identified cloud fields, possibly due to 3-D radiative transfer effects such 15 as shadowing,horizontal photon transport or the existence of multi layer clouds.*

Page 2412, line 19-20: More well tuned ...: what does this sentence mean? What is the surface forward model?
Well tuned is probably the wrong way to phrase this. As mentioned previously the error on the land surface is thought to be too high. A reduction in the surface forward model error would bring the error estimate for clouds more in line with the error over sea however some difference will remain as it is more difficult to model the land surface than the sea.

Page 2413, Conclusions: I am missing some considerations about the global applica-

AMTD

4, C2937–C2980, 2012

Interactive Comment

bility of the algorithm. Can it be applied over the poles as well as in the Tropics and in mid-latitudes?

A statement has been added: The algorithm is globally applicable, however the performance will have a dependence on the uncertainty associated with the location and the type of cloud. In the case of regions with high surface reflectance such as deserts and poles the retrieval will have a higher uncertainty, particuarly for thin clouds.

Page 2413, line 17: ice crystals: Please remind the reader of the origin of these ice cloud models by adding the reference to Baran and Havemann (2004).

added done previously

Page 2415: Baran (2005) has not been cited in the text. Please correct this.

Corrected

Page 2421: I would indicate the smallest re_{eff} retrieved and not 0 which is a sort of fill value.

The table has been modified to represent the values used in grape and subset into ice and water values.

Page 2423: Scales for r_{eff} go from 1 to 27 μm but the simulations for water clouds run from 3 to 25 μm. For ice clouds 70 μm were not simulated neither. Please correct this.

The values in the simulations have been performed for an extended range of effective radii to that used in GRAPE so the performance of the technique is illustrated for more scenarios however the GRAPE range is a subset of the values considered.

Page 2424: As already remarked, the simulated optical thicknesses mentioned in the caption and those in the text (as well as in the plot itself) differ. Please correct this.

AMTD

4, C2937–C2980, 2012

Interactive Comment

This has been corrected

Page 2425: Since the scale of cloud optical depth in panel (a) runs from -2 to +2 I assume that some difference it shown and not the values themselves. Please specify. Furthermore, in this Figure only multilayer cloud results are shown, so I think that the caption should read: Non-linear retrievals of multilayer cloud performed ...
The multi layer scenario of 0.01 optical depth upper layer cloud is representative of a single layer cloud however this has not been made clear in the text or caption. This has bee rectified by adding the statement. The scenario where the upper cloud layer is 0.01 optical depths is equivalent to retrieving a single layer cloud.

Page 2426: The sentence about the ′truth' contained in the caption should appear in the manuscript as well. Furthermore, I do not think this is the best choice you can do. For instance, when retrieving cloud optical thickness I would be happy if the scheme would give me back the sum of the optical thicknesses of the two layers. Please explain why you decided this way.
The 'truth' has not been described well in the text, thanks for pointing this out. The 'true' value for effective radius, cloud top pressure and cloud water path has been defined by the phase selected by the retrieval on the basis of lowest cost. In these cases the phase is nearly always ice except where the upper cloud layer is not opaque and the lower cloud layer certainly more opaque. For optical depth the 'true' value is the sum of both cloud layers.

Page 2427: Left panel: It seems that for some cloudy pixels (for which for instance cloud top pressure was derived) the cost function has a white colour (see the large ice cloud over Central Europe). What does this colour mean here?
The white colour shows where the region has been designated cloud free using the cloud mask this has been made clearer in the text and in the caption.

AMTD

4, C2937–C2980, 2012

Interactive Comment

Large cost functions over the Mediterranean seem to indicate the absence of clouds. It would be interesting to see the distribution (histogram) of the cost function and to get the information about how many pixels were retrieved accurately. In addition, the amount of pixels with good convergence would also be helpful to better understand the retrieval. Can you please discuss these issues for this example or more in general in the manuscript?
This has been discussed in a more rigorous statistical fashion in the paper by Sayer et al. in he interests of conciseness it is not discussed here.

Page 2429: The scale up to 1000 (In Table 2 you say the maximum range is 320!) shows the peaks but reduces the contrast. So it looks like if most clouds had an optical thickness of 10. Please reduce the scale to allow a better evaluation of optical thickness.
the plot has been regenerated using a max scale of 320

Page 2430: One has the impression that errors for liquid clouds are larger than for ice clouds. Is it really like this? Why?
In fact the errors are larger for thin clouds and in many cases the liquid clouds appear thin.

Technical corrections

Please make sure that only one version of data set, data-set or data set is used in the manuscript.
done
Please make sure that only one version of on board and on-board is used in the

manuscript.
done
Please make sure that only one version of multilayer and multi-layer is used in the manuscript
done
Please make sure that punctuation is present at the end of equations. For instance, Eq. (1) does not contain any period at the end, while Eq. (7) does.
done

Two acronyms (OE and OEM) have been introduced for almost the same thing and have been used once respectively. Please consider the use of only one of them or the complete avoidance of both of them.
The acronym OE has been replaced with OEM

The following have been corrected Page 2392, line 15: Please define SLSTR already here and not on page 2393, line 24.
Page 2394, line 6: rear-ir > near-ir.
Page 2394, line 12: record > records (?).
Page 2395, line 16: Levenberg-Marquart > Levenberg-Marquardt.
Page 2397, line 4: Size distributions > Particle size distributions.
Page 2398, line 1: acknowledges > acknowledged.
Page 2398, line 4: recognised > recognise.
Page 2398, line 26: DISTORT > DISORT.
Page 2399, line 9: field-of-view > field-of-view FOV.
Page 2399, line 1415: where ! > where the solid angle !
-section rewritten
Page 2400, line 1: Suns > SunÂćs. section rewritten
Page 2400, line 3: Sun normalised > Sun-normalised.
section rewritten

AMTD
4, C2937–C2980, 2012

Interactive Comment

Full Screen / Esc
Printer-friendly Version
Interactive Discussion
Discussion Paper

Page 2402, line 10: cloud. > cloud:
Page 2403, line 11: with values on the diagonal equal > with values equal.
Page 2403, line 14: see Smith (2005) for the origin of these values > (see Smith (2005) for the origin of these values).
Page 2403, line 25: The state-vector used > The state-vector x in Eq. (1) used.
Page 2403, line 26: optical depth > cloud optical depth.
Page 2404, line 8: are are 15 > are 15.
Page 2404, line 18: uncontrained > unconstrained.
section rewritten
Page 2404, line 18: For cloud fraction,the > For cloud fraction, the.
section rewritten
Page 2405, line 10: the the retrieval > then the retrieval. section rewritten
Page 2405, line 11: Only one change of phase ... : Please write this sentence separately from this item, on a new line, in line with line 4.
Page 2405, line 14: simple > simply.
Page 2407, line 7: 10> 10,
Page 2407, line 16: radii range > radius ranges.
Page 2408, line 5: radii > radius.
Page 2408, line 2425: Please separate the assumptions about pc and r_{eff} as you did in Section 10.1.
Page 2409, line 13: noted. > noted:
Page 2409, line 15: optical depth of > optical depth .
Page 2411, line 10: achive > achieve.
Page 2411, line 11: optical; depth > optical depth.
Page 2412, line 3: made. > made:
Page 2413, line 4: August 2002-2009 > August 2002 to December 2009.
Page 2413, line 20: measures:the > measures: the.
Page 2413, line 23: exected > expected.
Page 2414, line 16: from ATSR-2 > from ATSR-2 for the compilation of the GRAPE

AMTD

4, C2937–C2980, 2012

data set.
Page 2421: and range > and range for GRAPE.
Page 2422: though multiple scattering between the atmosphere and surface > through multiple scattering between cloud and surface.
Page 2427: results form > results from.

Additional corrections:
In addition to the corrections outlined here the authors have made the following addition corrections.
minor typos such as water > liquid corrected

A bug was found in the code that generated the plots 2 3 and 5. This was corrected and the plots redone this resulted in some minor changes to the values however the analysis and conclusions remain the same.

The author list has been revised to more accurately reflect the contributions of the authors.

References

Baran, A. J. and Havemann, S.: The dependence of retrieved cirrus ice-crystal effective dimension on assumed ice-crystal geometry and size-distribution function at solar wavelengths, Q. J. Roy. Meteorol. Soc., 130, 2153–2167, doi:10.1256/qj.03.154, 2004.

Baran, A. J., Shcherbakov, V. N., Baker, B. A., Gayet, J. F., and Lawson, R. P.: On the scattering phase function of non-symmetric ice crystals, Q. J. Roy. Meteorol. Soc., 131, 2609–2616, 2005.

AMTD

4, C2937–C2980, 2012

Interactive Comment

Ham, S.-H., Sohn, B.-J., Yang, P., and Baum, B.: Assessment of the quality of MODIS Cloud products from radiance simulations, J. Appl. Meterol., 48, 1591–1612, 2009.
Levenberg, K.: A method for the solution of certain nonlinear problems in least squares, Quart. Appl. Math., 2, 164–168, 1944.
Liu, J., C. Schaaf, A. Strahler, Z. Jiao, Y. Shuai, Q. Zhang, M. Roman, J. A. Augustine, and E. G. Dutton, Validation of Moderate Resolution Imaging Spectroradiometer (MODIS) albedo retrieval algorithm: Dependence of albedo on solar zenith angle, J. Geophys. Res., 114, D01106, doi:10.1029/2008JD009969.,2009
Marquardt, D. W.: An algorithm for least-squares estimation of nonlinear parameters, SIAM, J. Appl. Math., 11, 431–441, doi:10.1137/0111030, 1963.
Sayer, A. M., Poulsen, C. A., Arnold, C., Campmany, E., Dean, S., Ewen, G. B. L., Grainger, R. G., Lawrence, B. N., Siddans, R., Thomas, G. E., and Watts, P. D.: Global retrieval of ATSR cloud parameters and evaluation (GRAPE): dataset assessment, Atmos. Chem. Phys. Discuss., 10, 25619–25686, doi:10.5194/acpd-10-25619-2010, 2010.
Sayer, A. M., Thomas, G. E.Grainger, R. G, Carboni E., Poulsen C., Siddans R, Use of MODIS-derived surface reflectance data in the ORAC-AATSR aerosol retrieval algorithm: Impact of differences between sensor spectral response functions, Remote Sensing of Environment, doi:10.1016/j.rse.2011.02.029, 2011
Schaepman-Strub, G., Schaepman, M. E., Painter, T. H., Dangel, S., Martonchik, J. V.: Reflectance quantities in optical remote sensing- definitions and case studies, Remote Sens. Environ., 103, 27–42, 2006.
Seemann, S. W., E. E. Borbas, R. O. Knuteson, G. R. Stephenson, and H.$\frac{3}{4}$L. Huang, Development of a global infrared land surface emissivity database for application to clear sky sounding retrievals from multispectral satellite radiance measurements, J. Appl. Meteorol. Climatol., 47, 108123, doi:10.1175/2007JAMC1590.1.,2008
Watts, P.D, Bennatz, R., Fell, F, Retrieval of two-layer cloud properties from multispectral observations using optimal estimation. J. Geophys. Res., 116, D16203, doi:10.1029/201iJD015883, 2011.
Siddans, R., Poulsen, C., and Carboni, E.: Cloud Model for operational retrievals from MSG-SEVIRI, Eumetsat Final report, Eur. Organ. for the Exploit. of Meteorol. Satell., Darmstadt, Germany., 2010.
Siddans, R., Fast transmittance modelling of the MSG and MTG solar channels for cloud retrievals, Eumetsat Final report, Eur. Organ. for the Exploit. of Meteorol. Satell., Darmstadt,

Interactive Comment

Germany. 2011.
International Organization for Standardization (ISO), Quantities and units, Part 6: Light and related electromagnetic radiations, ISO 31-6:1992/Amd.1:1998, 1992.
Liou, K. N.: An introduction to atmospheric radiation, Academic Press, New York, 1980.
Watts, P. D., Mutlow, C. T., Baran, A. J., and Zavody, A. M.: Study on cloud properties derived from Meteosat Second Generation Observations, Eumetsat Report, http://www.eumetsat.int/idcplg?IdcService=GET_FILE&dDocName=PDF_SCI_97181_MSG-CLOUD-PROPS&RevisionSelectionMethod=LatestReleased (last access: 10 April 2011), 1998.

AMTD
4, C2937–C2980, 2012