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Sensitivity of cloud radiative forcing to changes of microphysical parameters measured by the CLOUDS mission

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Summary. — CLOUDS (a Cloud and Radiation monitoring satellite) is a study for a satellite mission designed to provide the gross vertical profile, the internal structure, the radiative and the imaging features of clouds. This subject is addressed by several missions designed for process study intent. CLOUDS, instead, is designed for providing data of routine use in long-term Numerical Weather Prediction (NWP) and General Circulation Model (GCM). User requirements have been collected from various sources, and instruments concepts derived to meet those requirements. However, to establish the sensitivity of a GCM to the targeted parameters and confirm the soundness of the specified requirements (mainly accuracy and vertical resolution), special effort had to be placed. The present paper offers a rather complete assessment of the range of usefulness that CLOUDS measurements may have on the radiative calculation. To this purpose, the cloud forcing was computed as a function of cloud parameters by using a radiative model that has been applied in the GCM of the Laboratory for Atmospheres at the NASA Goddard Space Flight Center. The results show that, in most cases, the model response to the addressed cloud parameters is good if the error is within the specified limit. This is better demonstrated for relatively large particle sizes, for ice better than for liquid water, for low optical thickness and for low cloud cover. The model, however, suggests that more stringent requirements would be appropriate when small particles are considered.

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1. – Introduction

Clouds and how the atmosphere recycles water vapour play a crucial role in the Earth Radiation Budget (ERB). They have a major effect in reducing both the solar radiation reaching the ground (thereby, modifying sensibly the planetary albedo) and the outgoing long-wave radiation.

Moreover, clouds have an important effect also on the atmospheric circulation. The movement of water in its solid, liquid and vapour forms, and the phase changes from one to another state, are responsible for a considerable fraction of the heating and cooling of the atmosphere, which in turn drives the winds affecting the climate.

Unfortunately, climate models are unable to represent all of the physical laws governing the behaviour of clouds with the detail needed to describe them (if it were possible) exactly. Thereby, many physical processes are approximated using simplified parameterised equations. The values of the parameters are determined by a gross simplification of the basic physical laws, or they are estimated from field experiments.

A first study on the impact of clouds on an atmospheric general circulation model (GCM) is due to Hunt [1] who integrated a model forced with the annual mean external forcing, removing, however, the effect of the zonal-mean clouds from the radiative computations. Surprisingly enough, the results of the integration showed modest changes on the atmospheric circulation.

This study, however, has been criticised as misleading by Hunt *et al.* [2] who noted that these calculations neglected many important feedbacks such as: holding of a constraint on water vapour amount, using of a flat geometry and neglecting land-sea contrast.

Thereafter, many modelling studies have been devoted to a better analysis of this issue (see Wang and Rossow [3], for an account of these efforts). These works have brought up a better understanding of the role of clouds on the atmospheric circulation. Overall, it appears that the climate response to clouds is strong and it is critically dependent on the detailed structure of clouds cover, on their microphysical structure, on the vertical distribution and overlapping [4].

Moreover, a limit in modelling successfully the atmospheric circulation is due to an existing gap in the measurements of the relevant clouds parameters, specially the ones describing their vertical profiles. Nowadays, the measurements of clouds structure, composition and radiative properties are not available at the required accuracy for a good simulation of the atmospheric conditions and a climate change scenario [5].

The existing observations relate to the total incoming and outgoing radiation at the top of the atmosphere. Clouds feedbacks, the vertical distribution of the energy and its partition between the atmosphere and the surface are yet unknown [6, 7].

The improvement in the representation of clouds in climate models is recognised as an issue of priority and it is one of the major goals of many forthcoming space missions. Space-based instruments, in fact, are the only tools by which the global distribution of clouds can be adequately monitored on a global scale [8].

Current and near-future operational meteorological satellites (both polar and geostationary) show different gaps such as poor cloud top height determination (indirectly measured through cloud top temperature), only occasionally discrimination of ice from liquid water, scarce insight of the properties of the clouds interior and of the physics related to precipitation processes. Moreover, only occasional aerosol observations are taken simultaneously.

The scientific satellites carrying advanced meteorological instrumentation, such as the NASA EOS-Aqua, the NASDA ADEOS-II and future operational NPOESS, will probably reduce the gap on the issues related to precipitation, aerosol and ERB. However, main gaps remain on the detection of an accurate cloud top height, on the aerosols observation and on the discrimination of ice from liquid water. Also, the NASA/NASDA TRMM, the ESA proposed Earth Radiation Mission and the NASA approved Picasso-Cena and CloudSat will be of little relevance for monitoring purpose, since their coverage is not global and their data collection is incomplete (for instance, no water vapour profiling is considered) [5].

Therefore, the CLOUDS (a Cloud and Radiation monitoring satellite) project has focused on long-term monitoring of clouds internal structure (liquid, ice and precipitating water) and their interactions with atmospheric radiation. The primary goal of the mission is to collect data needed to evaluate and improve the way clouds are represented in a global model, thereby contributing to a better prediction of clouds and their poorly understood role in the climate variability.

The project activity, under the financial support of the European Commission from 1998 to 2000, carried out three work phases (Phase 0, Pre-Phase A and Phase A). During the first phase mission objectives and user, mission, instrument and system requirements were defined; during the second phase mission objectives and requirements were consolidated and a baseline system was defined for a full feasibility study. Finally, the work of Phase A completed the mission objectives, requirements, and the feasibility study. The satellite preliminary design was also provided by the industrial partnership.

The aim of this study is to evaluate the effect of measurements that will be carried out by CLOUDS (consolidated in the objectives and requirements documents) on a radiative code generally used as a part of a climatic GCM. The radiative scheme, developed by Chou and Suarez [9, 10], has been used as a tool to analyse the model sensitivity to the foreseen accuracy of the measurements as proposed by CLOUDS.

The paper is organised as follow: in sect. **2** the satellite mission, the mission objectives and requirements are briefly described. In sect. **3** the model used for the sensitivity study is presented, while in sect. **4** there is a description of the method used for the analysis. The main results obtained are shown in sect. **5** and in the final section some conclusions and plans for future work are drawn.

2. – The CLOUDS mission

Let us summarise the outcomes of the work completed under the CLOUDS project [11].

According to the agreed mission objectives, the principal quantities that CLOUDS will be able to measure are summarised as follow:

- the cloud "classical" parameters mostly referring to the top surface, with emphasis on the ice/liquid discrimination and particles size;
- the cloud interior; specifically, the water phase (ice or liquid) and the drop size that likely produce precipitation;
- the outgoing radiation at the Top of the Atmosphere (TOA);
- the main parameter affecting both clouds and radiation in the atmosphere, *i.e.* aerosol;
- the primary source of clouds, *i.e.* water vapour;
- the indicator of the final removal of water from the atmosphere, *i.e.* precipitation.

Associated to the above objectives, in table I we show the reference user requirements for the mission. For each geophysical parameter the horizontal and vertical resolution (both for weather and climate prediction), the accuracy (r.m.s. and bias) and the observing cycle are specified.

TABLE I. – *Reference user requirements for the CLOUDS mission. For each geophysical parameter the horizontal resolution (for weather and climate study), the vertical resolution, the accuracy (r.m.s. and bias) and the observing cycle are listed. Geophysical parameters also available from METOP are included, as well as parameters internal to processing (i.e. not to be delivered). Parameters assumed to be available from other systems also are mentioned.*

Geophysical Parameter	Horizontal resolution		Vertical resolution	Accuracy (r.m.s.)	Accuracy (bias)	Observing cycle
	Weather	Climate				
BASIC (mostly from CLOUDS)						
Cloud water (< 100 μm) gross profile	30 km	100 km	3 km	30%	5%	3 h
Cloud water (> 100 μm) gross profile	30 km	100 km	3 km	30%	5%	3 h
Cloud ice profile	30 km	100 km	3 km	30%	5%	3 h
Cloud water (< 100 μm) total column	30 km	100 km	N/A	5 g m^{-2}	1 g m^{-2}	3 h
Cloud water (> 100 μm) total column	30 km	100 km	N/A	5 g m^{-2}	1 g m^{-2}	3 h
Cloud ice total column	30 km	100 km	N/A	0.5 g m^{-2}	0.1 g m^{-2}	3 h
Cloud optical thickness	30 km	100 km	N/A	30%	5%	3 h
Cloud cover	30 km	100 km	N/A	5%	1%	3 h
Cloud drop size (at cloud top)	30 km	100 km	N/A	5μm	1μm	3 h
Cloud ice content (at cloud top)	30 km	100 km	N/A	30%	5%	3 h
Water vapour total column	30 km	100 km	N/A	500 g m^{-2}	100 g m^{-2}	3 h
Precipitation rate at the ground	30 km	100 km	N/A	3 mm h^{-1}	0.5 mm h^{-1}	3 h
Precipitation index (daily cumulative)	30 km	100 km	N/A	1 mm d^{-1}	0.2 mm d^{-1}	3 h
Short-wave outgoing radiation at TOA	30 km	100 km	N/A	3 W m^{-2}	0.5 W m^{-2}	3 h
Long-wave outgoing radiation at TOA	30 km	100 km	N/A	3 W m^{-2}	0.5 W m^{-2}	3 h
Aerosol total column	30 km	100 km	N/A	30%	5%	3 h
Aerosol profile	30 km	100 km	3 km	30%	5%	3 h
Short-wave cloud reflectance	30 km	100 km	N/A	5%	1%	3 h
Long-wave cloud emissivity	30 km	100 km	N/A	3%	0.5%	3 h
BASIC (also available from METOP)						
Cloud imagery	3 km	10 km	N/A	N/A	N/A	3 h
Cloud type	30 km	100 km	N/A	3 classes	15 classes	3 h
Cloud top height	30 km	100 km	N/A	1 km	0.2 km	3 h
Cloud top temperature	30 km	100 km	N/A	1 K	0.2 K	3 h
SUPPORT TO BASIC						
Temperature profile	30 km	100 km	3 km	3 K	0.5 K	3 h
Relative humidity profile	30 km	100 km	3 km	10%	5%	3 h
Ozone total column	30 km	100 km	N/A	30 DU	5 DU	3 h
ASSUMED TO BE AVAILABLE						
(Accurate) Temperature profile	30 km	100 km	1 km	1 K	0.2 K	3 h
(Accurate) Relative umidity profile	30 km	100 km	1 km	10%	2%	3 h
Solar irradiance at TOA	N/A	N/A	N/A	0.5 W m^{-2}	0.1 W m^{-2}	3 h

Because of the monitoring objective of the mission, which implies compliance with long-term sustainability requirements, only passive instruments have been proposed to ensure a swath of at least 1400 km for a global coverage each one or two days (depending on the spectral band used to retrieve the product) and to achieve long life-time requirement.

Six instruments, all conical scanning, have been defined for the mission purpose: four optical instruments integrated in a single payload, a MW (Micro-Wave) radiometer and one in the Sub-mm region. The key aspect of the CLOUDS mission, in fact, is the exploitation of a widest range of the electromagnetic spectrum (*i.e.* the range of wavelengths spans from 0.34 μm to 4.3 cm) to collect as many "signatures" as possible of the different parameters to be measured.

About the orbit, a synergy with EPS/METOP is envisaged, in ensuring that CLOUDS information can be embedded on the basic meteorological fields, specially accurate temperature and water vapour profiles.

3. – The model

The radiative transfer model used for the sensitivity study is the one developed by Chou and Suarez [9,10]. For the sake of completeness, we shortly review the main features of this model.

The model is a broad-band one and it is based on the parameterisation of processes that occur in the atmosphere in the infrared and solar spectral regions. It takes into account the effects of the main absorbers of the thermal radiation such as water vapour, carbon dioxide and ozone and, also, other trace gases such as N_2O, CH_4 and CFCs are considered. The model inputs are pressure, temperature, ozone and water vapour profiles, minor gas content, cloud ice content, cloud optical thickness and cloud particle size. The scheme computes very accurately the fluxes (upward and downward) from the Earth's surface up to 0.01 hPa and cooling rates from the surface up to 20 hPa.

The infrared spectrum is divided into 10 bands from 0 cm^{-1} to 3000 cm^{-1} ($> 3\ \mu$m), while the solar spectrum is divided into 11 bands from 1000 cm^{-1} to 57140 cm^{-1} (0.175–10 μm). This division allows to group together different absorbers with similar radiative properties, therefore, simplifying the fluxes computation.

The solar part of the model has a similar structure of the infrared one. In particular, in this spectral region the effects of absorption by H_2O, O_3, O_2 and CO_2 are considered, as well as the Rayleigh scattering. An accurate description of these methods can be found in Chou and Suarez [9, 10].

The model considers an atmospheric column divided into several layers (whose number is specified by the user) and for each layer also aerosols and clouds may be taken into account. One possibility to characterise clouds is that of specifying the physical thickness, the fractional cover, the drop size, the physical state of drops (water or ice) and the water/ice content. The cloud ice/water content C is directly related to the cloud optical thickness by the equation

$$\tau = \beta\, C\, z\,, \tag{1}$$

where z is the geometric thickness of cloud, τ the optical thickness and β the extinction coefficient that is a function of the wavenumber and the effective particle radius.

A cloud that partially fills a layer is usually smeared over the entire layer, and the optical thickness is adjusted by a factor that depends on the fractional cloud cover [12,13].

In the model also cloud scattering is considered. The theoretical treatment is based on Chou *et al.* [14,15] and the scattering function f is computed according to the method of Fu *et al.* [16, 17].

4. – Method

In this section we present a method which is able to capture whether the accuracy of the measurements by the CLOUDS instruments package is sufficiently good that a further refinement of them would lead only to a marginal improvement, at least of what concern the performance of the radiative model. The method is designed for the cases of measurements related to the cloud parameters listed in table I.

The clouds effect on the net radiative balance of the Earth at the top of the atmosphere may be estimated by computing the net Cloud Radiative Forcing, hereafter CRF (how clouds modify the net radiation). CRF is given by

$$CRF = (F_{\mathrm{SOL}} - F_{\mathrm{IR}})_{\mathrm{c}} - (F_{\mathrm{SOL}} - F_{\mathrm{IR}})_0 \,, \tag{2}$$

where the subscripts "c" and "0" denote cloudy and clear sky condition, respectively, while F_{SOL} and F_{IR} are the solar and the infrared flux at the top of the atmosphere [4].

In the present sensitivity study we compute the CRF for a mid-latitude summer atmosphere setting in a fixed configuration some external parameters of the model. Then we change the values of the parameters within the range corresponding to the r.m.s. listed in table I. Thus the difference between the two simulations (hereafter DCRF) gives information about the sensitivity of the model to the accuracy provided by CLOUDS measurement. In our notation

$$DCRF = CRF_{\mathrm{p}} - CRF \,, \tag{3}$$

where the subscript "p" stays for "perturbed" cloud radiative forcing.

We set a threshold value of 5 W m^{-2} on DCRF to discriminate among the results. DCRF value less than this threshold denotes poor sensitivity of the model to the errors of the satellite measurements and vice versa. This particular threshold has been chosen because the greenhouse forcing is thought to be in the order of 4 Wm^{-2} at the top of the atmosphere if an instantaneous CO_2 doubling occurs.

The parameters analysed in this study are limited to the first nine in table I.

5. – Results

We show the main results by plotting the DCRF for each of the considered parameter. Values of DCRF less than 5 Wm^{-2} are in blue colour, otherwise other gradations refer to higher values, meaning that more accurate measurements are required.

5·1. *Cloud water gross profile.* – The cloud water gross profile parameter (*i.e.* the water content in gm^{-3} in a given vertical layer of the atmosphere) is supposed to be given at the accuracy of 30% , for any particle size. Here, we investigate the accuracy of the assumed vertical resolution of the satellite measurements, which is 3 km.

For this purpose, suppose that the column of the atmosphere is filled with three clouds at different heights: a low cloud at 616 hPa, a middle cloud at 360 hPa and a high cloud at 208 hPa (see fig. 1). Each cloud has a given optical thickness (*i.e.* cloud water content) and a physical thickness of 280 m, which is the height of one vertical level in the model. By considering this "basic" configuration we compute the CRF. Then, we perform other 4 simulations varying the clouds physical thickness from 560 m to 1400 m (in our notation from two to five cloud levels each 280 m thick) and leaving unchanged the cloud optical thickness. The DCRF is then computed by subtracting the CRF for clouds more than one level thick from the CRF for the basic configuration. The resulting DCRF as a function of the particle size in μm and the cloud levels are shown in fig. 2a, b, c for the optical thickness 4, 10 and 15, respectively.

The figures show that the DCRF is less than 5 Wm^{-2} for clouds with any particles size (from 10 to 150 μm), physical thickness roughly less than 840 m (*i.e.* three levels thick). Moreover, only thick clouds (greater than 840 m) having large particles size give a DCRF less than the threshold. When we increase the cloud optical thickness (from 4 to 15) we have the DCRF below the threshold for clouds having at most 3.5 levels

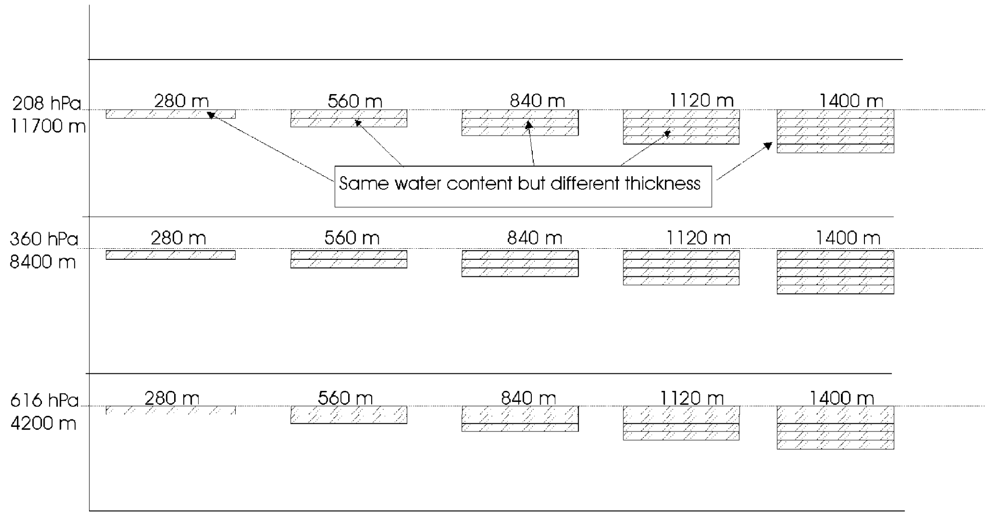

Fig. 1. – Scheme used to investigate the accuracy of the required vertical resolution of the satellite measurements. The column of the atmosphere is filled with three clouds at different heights: a low cloud at 616 hPa, a middle cloud at 360 hPa and a high cloud at 280 hPa. Each cloud has a given optical thickness and a physical thickness of 280 m (the three clouds on the left of the figure). Other 4 simulations are computed by varying the clouds physical thickness from 560 m to 1400 m (in the figure from two to five cloud levels each 280 m thick) and leaving unchanged the cloud optical thickness.

and large particle sizes. Thus, we may argue that, for realistic values of cloud physical thickness, the vertical resolution of the satellite is sufficiently defined to get a significative model response. It must be noted that in the tropical atmosphere it is possible to have convective clouds with a physical thickness that can exceed the satellite resolution. For this kind of clouds, which are mostly homogeneous, it is useful to have measurements of the cloud water total column rather than the vertical water gross profile.

5˙2. *Cloud ice gross profile*. – The sensitivity of the model to the vertical resolution of cloud ice gross profile is computed with the same method above. Results are shown in figs. 3a, b, c for the optical thickness equal to 4, 10 and 15, respectively. It must be noted that they are very close to the ones shown for the cloud water gross profile. The figures suggest that the measurement resolution for cloud ice profile is more geared towards the model response than the cloud water profile is. Probably this is due to the different parameterisation of the radiative processes that involve water particles than the ones concerning the cloud ice particles [10].

5˙3. *Cloud water total column*. – The accuracy of cloud water total column measurements may be studied by computing the cloud forcing for given values of the water content (in our case by considering the corresponding cloud optical thickness) and adding them 5 gm^{-2} (*i.e.* the r.m.s. value defined in the mission requirements). The evaluation of DCRF as a function of the particles size is computed for different clouds (low, middle and high cloud). In fig. 4 we show the results obtained for the case of a middle cloud (500–600 hPa). Results for high and low clouds have been not shown since they behave similarly to the case just above. An inspection of the figure suggests that when large

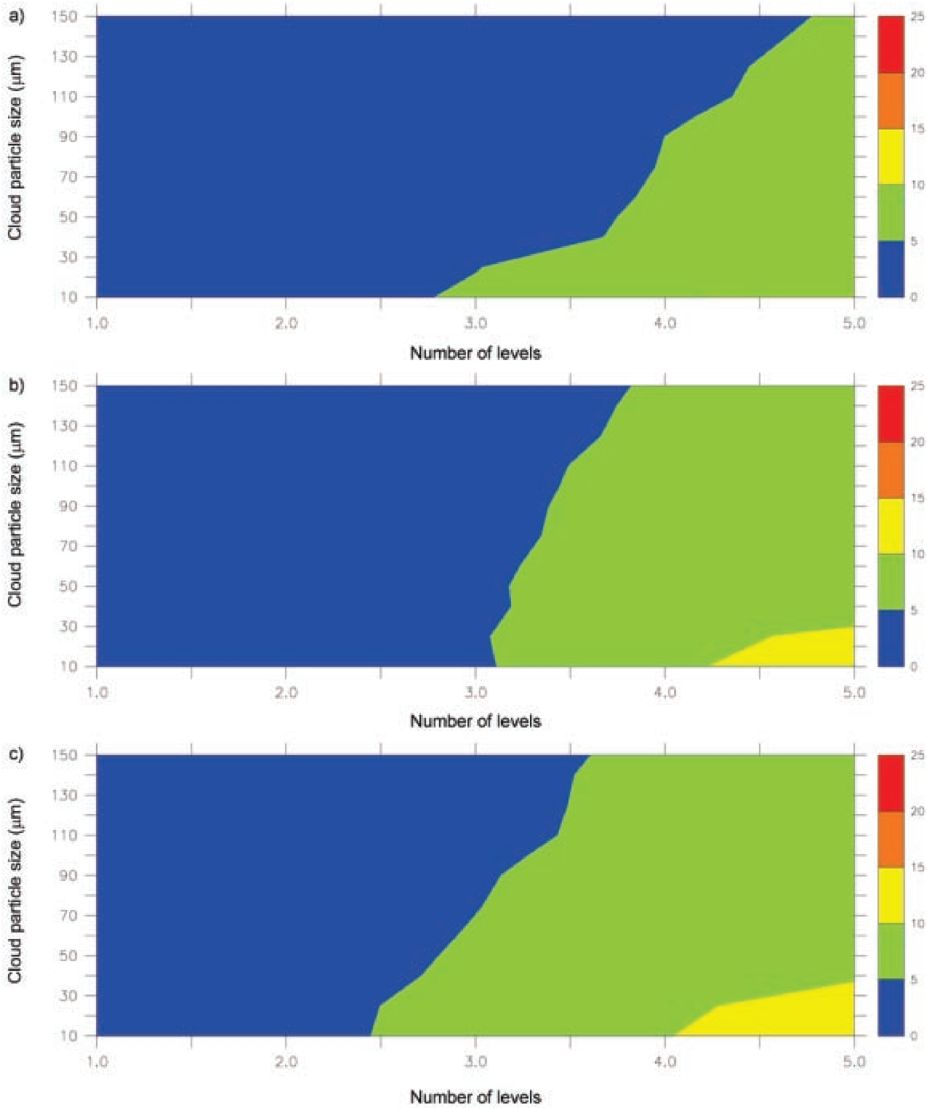

Fig. 2. – Differences between the cloud forcing computed with clouds that fill more than one level and that one with clouds that fill only one level as a function of the particle size (μm) and the number of cloud levels (dimensionless) for the optical thickness equal to 4 (a), 10 (b) and 15 (c). DCRF is in W m^{-2} and one cloud level is equal to 280 m.

drops (roughly particle size greater than 80 μm) are considered the measurements are enough accurate to leave unchanged the model response. For smaller drops, instead, more accuracy is required.

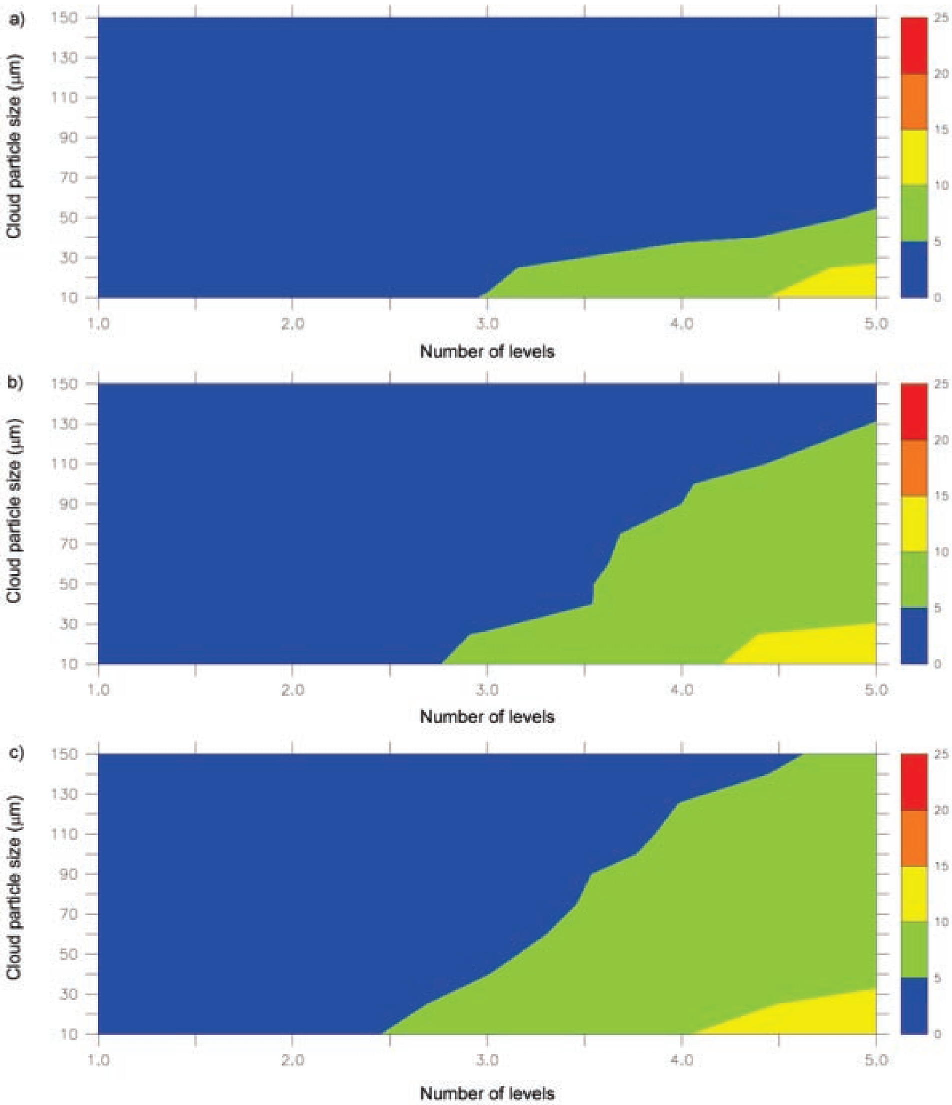

Fig. 3. – As in figs. 2a, b, c but for cloud ice gross profile perturbations.

5˙4. *Cloud ice total column.* – The DCRF is computed by perturbing the cloud ice content of 0.5 gm^{-2} and following the same method adopted for the study of cloud water total column. In fig. 5 the DCRF for a middle cloud as a function of particles size in micrometer and the cloud optical thickness is presented. The result suggests that the required accuracy is achieved, excluding the case where the particle size is less than 20 μm.

5˙5. *Cloud optical thickness.* – The CLOUDS mission requirements set the optical thickness accuracy to the value of 30%. We use this value to compute the DCRF as a function of the cloud cover and the cloud optical thickness.

The range of the optical thickness is chosen according to the observed annual zonal

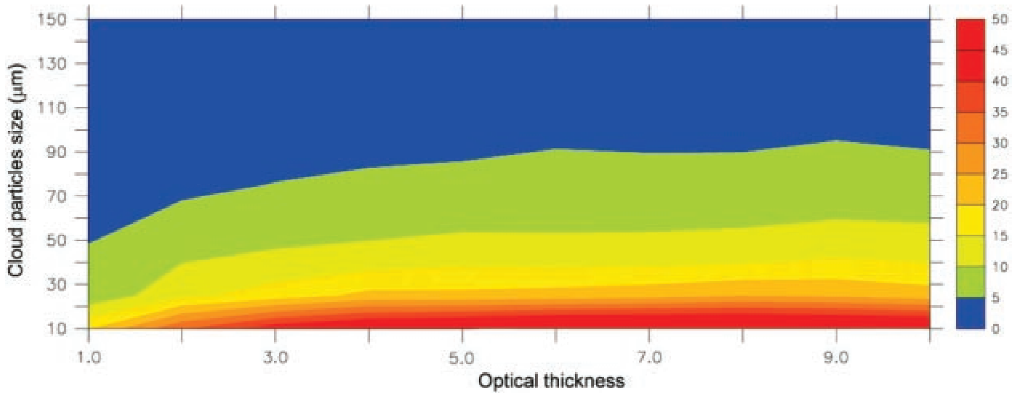

Fig. 4. – DCRF for cloud water total column variations as a function of the cloud particle size (μm) and the optical thickness (dimensionless) when a middle cloud is considered (500–600 hPa).

mean of this parameter in middle latitudes as suggested by Rossow and Schiffer [18] (the optical thickness ranges between 0 and 14).

To consider as many cases as possible, and yet retaining conciseness, clouds at different heights (low, middle and high) and with different particle sizes are considered. The results for middle clouds and for 10, 50 and 100 μm particles size are shown in figs. 6a, b, c, respectively. By increasing the particle size the model is less sensitive to changes of the cloud optical thickness (see the increasing of the blue area in the figures). Generally, the results are below 5 Wm^{-2} for low optical thickness and low cloud cover. Moreover, other results, here not shown, suggest that the model is less sensitive to the parameter perturbations when high clouds are considered. Instead, the effect for low or middle clouds seems to be highly sensitive to this parameter.

5˙6. *Cloud cover*. – In these simulations the geophysical parameter under study is the cloud cover and its accuracy is required to be 5%. The DCRF results, for a middle cloud,

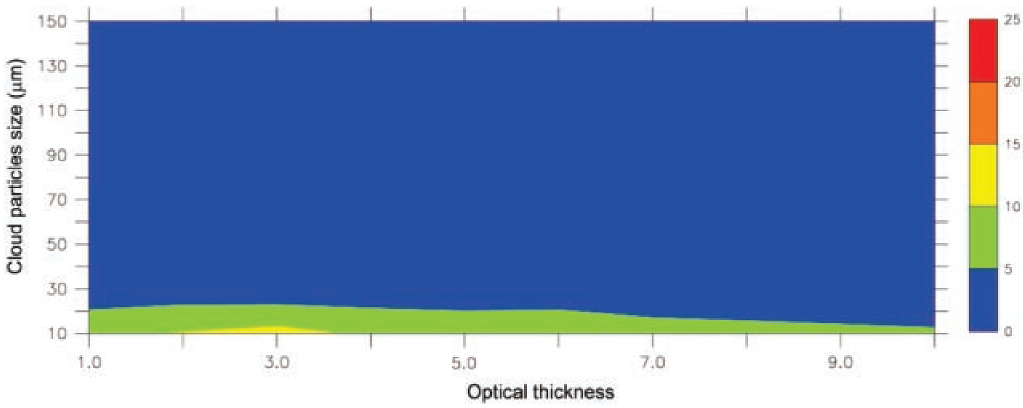

Fig. 5. – As in fig. 4 but for cloud ice total column perturbations.

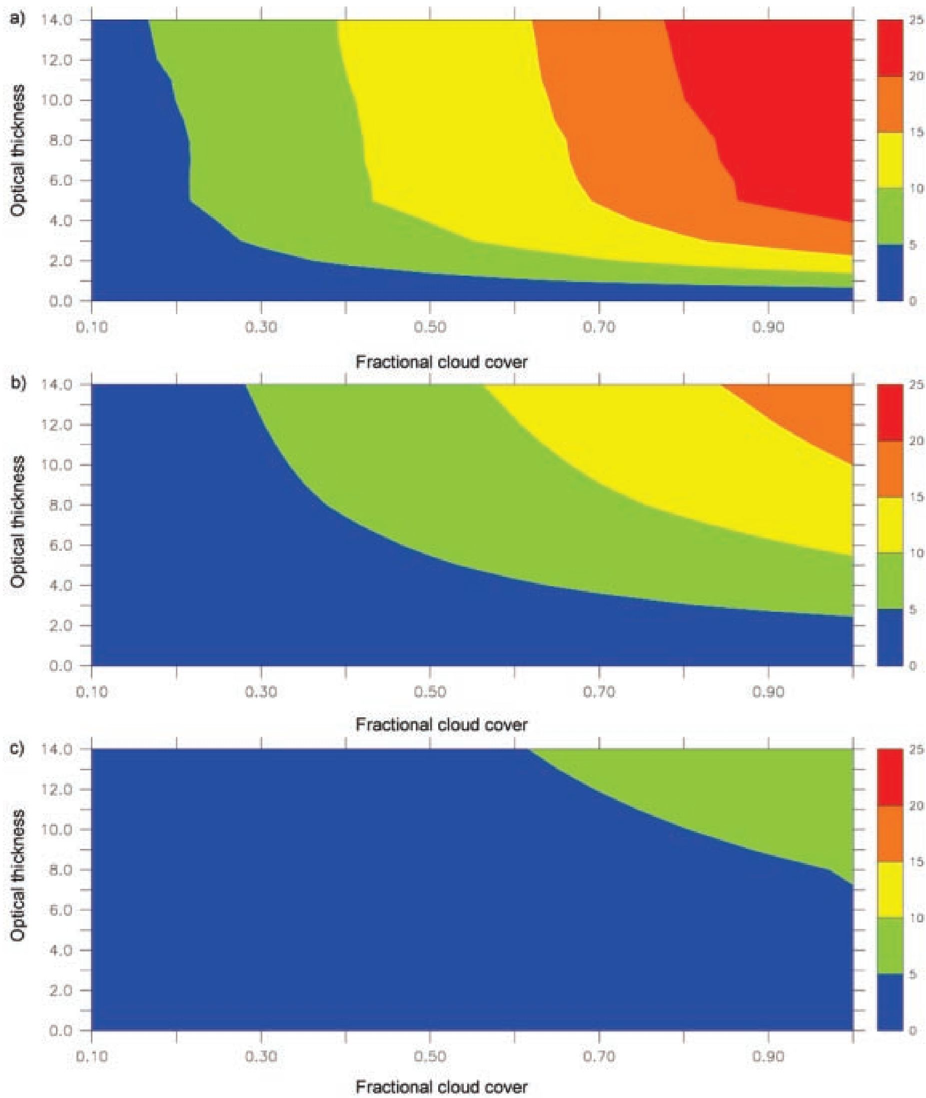

Fig. 6. – DCRF for cloud optical thickness perturbations as a function of the optical thickness (dimensionless) and the fractional cloud cover (dimensionless) for a middle cloud and for particle size of 10 μm (a), 50 μm (b) and 100 μm (c).

as a function of the cloud cover and the cloud optical thickness, are shown in figs. 7a, b, c for particle size of 10, 50 and 100 μm, respectively. By increasing the particles size we have a larger range of the parameters giving favourable results to the perturbations of the cloud fractional cover (see the increasing of the blue area in the figures). Generally, high cloud cover and high optical thickness require more accurate measurements.

5˙7. *Cloud drop size*. – Here we analyse the sensitivity of the model to changes of cloud drop size of 5 μm, according to the accuracy of the satellite measurements. The

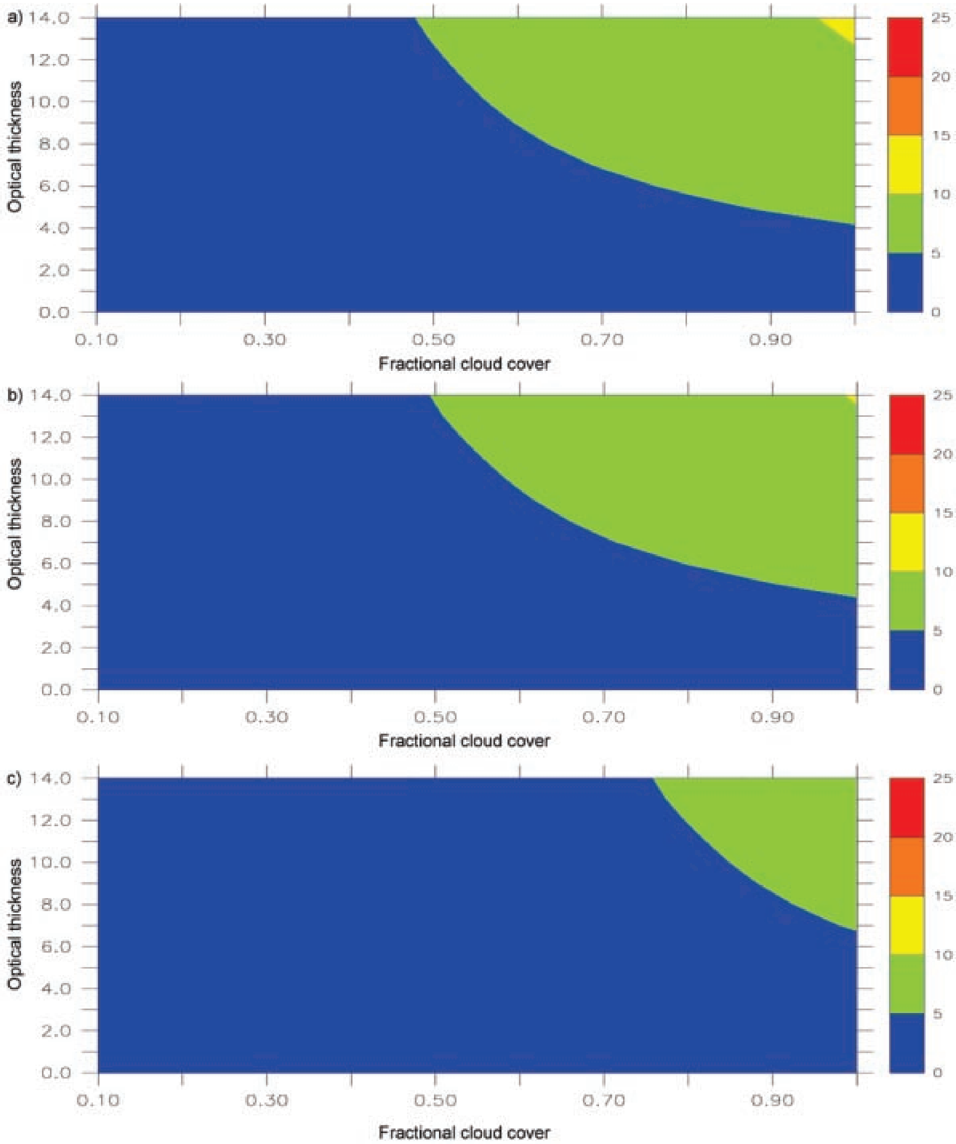

Fig. 7. – As in figs. 6a, b, c but for cloud cover perturbations.

DCRF for a middle cloud as a function of the optical thickness and drop size is shown in fig. 8. The result shows that the model is very sensitive to variations of cloud drop size: only for a small range of the parameters (particle size greater than 50 μm and low values of the optical thickness) the DCRF is less than the threshold value.

For an easier reading of the whole computations we have summarised the main results in table II.

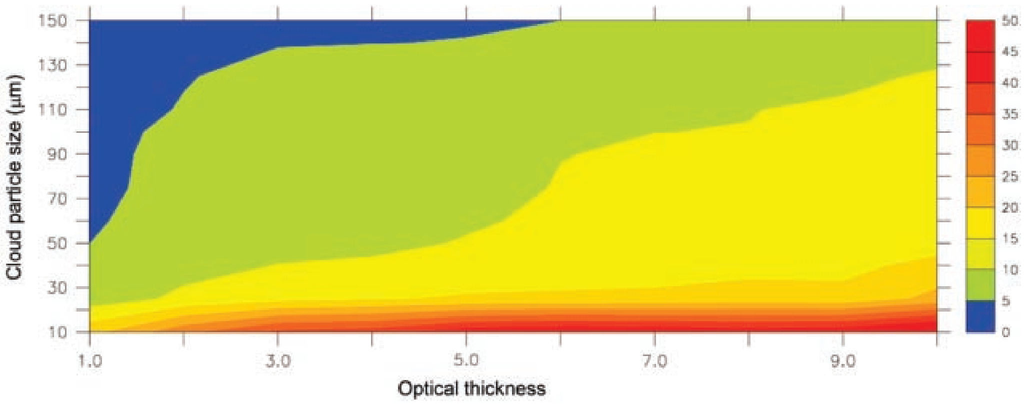

Fig. 8. – DCRF for a middle cloud as a function of the optical thickness (dimensionless) and the drop size (μm). The perturbed parameter is cloud drop size.

TABLE II. – *Summary of the main results obtained from the sensitivity study. For each studied geophysical parameter the compliance with the mission requirements (second column), the criticality (third column) and the reference figures (fourth column) are listed.*

Geophysical parameter	Compliance	Criticality	Reference
Cloud water gross profile	Good for realistic clouds, *i.e.* cloud physical thickness less than 840 m.	Thick clouds having high optical thickness.	fig. 2a, b, c
Cloud ice gross profile	Better than the cloud water gross profile.	As in the previous case.	fig. 3a, b, c
Cloud water total column	Good for drop size > 80 μm.	Poor for small drops size.	fig. 4
Cloud ice total column	Good for most particles size.	Poor for particles size < 20 μm.	fig. 5
Cloud optical thickness	Good for low optical thickness and low cloud cover.	Poor for high optical thickness and high cloud cover, especially for smaller particles size (< 50 μm).	fig. 6a, b, c
Cloud cover	Good for low optical thickness and low cloud cover.	Poor for high optical thickness and high cloud cover.	fig. 7a, b, c
Cloud drop size	Good for cloud drops size > 50 μm and very low optical thickness.	Poor for drops size < 50 μm and high optical thickness.	fig. 8

6. – Conclusions

Summing-up, the following main results may be listed:

- The satellite vertical resolution for water and ice gross profile may be considered sufficiently high. The model shows little differences (less than 5 W m^{-2}) in the case of realistic clouds (however, for thicker clouds the DCRF does not exceed 10–15 W m^{-2}).
- For liquid water total column, the model shows high sensitivity for particles $< 80\ \mu$m and it would require more accurate measurements in this range.
- For cloud ice total column, problems rise only for particles $< 20\ \mu$m.
- For clouds having high optical thickness and high cloud cover, the model would require better resolution than the one CLOUDS provided. Moreover, we get better results when large particles size are considered (roughly $> 50\ \mu$m).
- Concerning cloud drop size, the accuracy of CLOUDS measurements seems to be not adequate (with exception in a small range of the parameters, *i.e.* low optical thickness and high particles size).

Overall, several conclusions can be drawn. The model is less sensitive to the errors in the measurements when cloud particles have an effective radius roughly bigger than 50 μm or more. Performances are better suited for ice particles rather than for liquid water drops. For the latter item the results suggest further investigations to understand whether the sensitivity of the model is due to the different parameterisation of the cloud ice particles with respect to water drops. The analysis should be repeated by using other radiative models where different cloud parameterisations are implemented and tested as we have done in the present paper.

The insufficient accuracy of the measurements revealed for cloud drop size is probably due to the established value of 5 μm for the r.m.s. This means that for small particles we have a large percentage error (*i.e.* for particles of 5 μm the percentage error is 100%), while for large drops it is smaller (for example, for particles of 80 μm the percentage error is 6.25%). A way to circumvent this problem may be to set a percentage error also for cloud drop size, as in the case of the cloud cover or the optical thickness.

Additional work should be done to extend the sensitivity study here presented to the remaining parameters listed in table I, specially the ones involving aerosols, precipitation and the outgoing radiation at TOA.

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REFERENCES

[1] Hunt B. G., *Q. J. R. Meteorol. Soc.*, **104** (1978) 91.
[2] Hunt G. E., Ramanathan V. and Chervin R. M., *Q. J. R. Meteorol. Soc.*, **106** (1980) 213.

[3] Wang J. and Rossow W. B., *J. Climate*, **11** (1998) 3010.
[4] Weare B. C., *Clim. Dyn.*, **17** (2001) 143.
[5] Stephens G. L., Vane D. G. and Walter S. J., *World Clim. Res. Prog.*, **110** (2000) WMO/TD-NO. 993.
[6] Cess R. D., Potter G. L., Blanchet J. P., Boer G. J., Ghan S. J., Kiehl J. T., Liang S. B. A., Mitchell J. F. B., Randall D. A., Riches M. R., Roeckner E., Schlese U., Slingo A., Taylor K. E., Washington W. M., Wetherald R. T. and Yagai I., *Science*, **245** (1989) 513.
[7] Senior C. A. and Mitchell J. F. B., *J. Climate*, **6** (1993) 393.
[8] Kidder S. Q. and Vonder Haar T. H., *Satellite Meteorology. An Introduction* (Academic Press) 1995.
[9] Chou M.-D. and Suarez M. J., *NASA Tech. Memo.* 104606, **3** (1994).
[10] Chou M.-D. and Suarez M. J., *NASA Tech. Memo.* 104606, **15** (1999).
[11] Bizzarri B., Desbois M., Stanfuss C., Harries J., Murray J., Russell J., Naud C., Gasiewski A., Künzi K., Heygster G., Miao J., Mugnai A., Gobbi G. P., Liberti G. L., Dietrich S., Slingo A., Sutera A., Bordi I., Tibaldi S., Alberoni P. P. and Rizzi R., *Scientific background for CLOUDS - a Cloud and Radiation monitoring satellite* in *Proceedings of the EOS/SPIE Symposium on Remote Sensing, Sept. 25-29, 2000, Barcelona, Spain, SPIE*, **4168** (2000) 39; Bizzarri B., Spera P., Maggi E., Coppo P., Bonsignori R., Zimmermann P., Rose T., Grant N. and Vial L., *Instruments and system for CLOUDS - a Cloud and Radiation monitoring satellite*, in *Proceedings of the EOS/SPIE Symposium on Remote Sensing, Sept. 25-29, 2000, Barcelona, Spain, SPIE*, **4169** (2000) 279.
[12] Harshvardhan and Randall D. A., *Mon. Wea. Rev.*, **113** (1985) 1832.
[13] Cahalan R. F., Ridgway W., Wiscombe W. J., Bell T. L. and Snider J. B., *J. Atmos. Sci.*, **51** (1994) 2434.
[14] Chou M.-D., Suarez M. J., Ho C.-H., Yan M. M.-H. and Lee K. T., *J. Climate*, **11** (1998) 202.
[15] Chou M.-D., Lee K.-T., Tsay S.-C. and Fu Q., *J. Climate*, **12** (1999) 159.
[16] Fu Q. and Liou K.-N., *J. Atmos. Sci.*, **50** (1993) 2008.
[17] Fu Q., Liou K.-N., Cribb M. C., Charlock T. P. and Grossman A., *J. Atmos. Sci.*, **54** (1997) 2799.
[18] Rossow W. B. and Schiffer R. A., *Bull. Am. Meteorol. Soc.*, **80** (1999) 2261.