Cloud filter for CO retrieval from IMG infrared spectra using ECMWF temperatures and POLDER cloud data

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Abstract. Infrared atmospheric measurements provided by space nadir looking remote sensors are affected by the presence of clouds. To obtain cloud-free CO global distributions from the radiance spectra measured by the IMG instrument, we have developed a simple method of spectra selection using skin temperatures provided by the ECMWF model. Information on the cloud cover was provided by the cloud data of the POLDER instrument which flew aboard the same platform as IMG. We show that a filter based on skin temperature, with thresholds of 8 K over sea and 15.3 K over land, allows to remove most of the cloudy cases.

Introduction

Ultraviolet and infrared atmospheric measurements provided by spaceborne remote sensors in the nadir geometry are affected by the presence of clouds [*Koelemeijer and Stammes*, 1999; *Reichle et al.*, 1999; *Joiner and Rokke*, 2000]. In the infrared spectral range, clouds scatter, absorb, and reemit the radiation emitted from the surface and throughout the Earth's atmosphere, and hence affect the spectra recorded by an instrument at the top of the atmosphere. The presence of clouds is usually detected using the infrared atmospheric windows, between 8 and 12 μm (833-1250 cm^{-1}) [*McMillin and Dean*, 1982; *Smith et al.*, 1993; *Amato et al.*, 1999; *Serio et al.*, 2000].

The Interferometric Monitor for Greenhouse Gases (IMG) instrument is a nadir looking Fourier transform spectrometer which measured the Earth-atmosphere system radiation in the thermal infrared spectral range, between 600 and 3030 cm^{-1} (3.3-16.7 μm), aboard the Japanese ADvanced Earth Observing System (ADEOS) platform [*Kobayashi et al.*, 1999]. It was designed to retrieve temperature vertical profiles and concentrations of trace gases in the atmosphere. Previous studies have shown that CO measurements from IMG spectra were contaminated by the presence of clouds during the signal acquisition [*Clerbaux et al.*, 1999; *Hadji-Lazaro et al.*, 1999]. Ancillary data should have contained information on the presence of clouds but the wrong working of the operational cloud filter wrecked this information [*IMG Project Technical Report*, 1999].

The IMG instrument used three detectors to cover the total spectral range, providing three separated bands corresponding to three squares of 8 km sides on the Earth surface separated by 4 km each. To retrieve CO total columns, we work with spectral channels selected between 2000 and 2200 cm^{-1}, which are not located in the infrared atmospheric windows [*Clerbaux et al.*, 1998]. The footprints of the detectors fields of view being separated by 12 km, cloud information for spectra recorded around 1000 cm^{-1} may not be helpful to analyze spectra around 2000 cm^{-1}.

To improve the quality of the CO global distribution provided by the IMG data, we have developed a simple cloud filter method for the IMG spectra in the 2000-2200 cm^{-1} spectral range. It is based on the estimation of radiative temperatures, brightness temperatures calculated with emissivities not equal to the unity, at three spectral channels and on their comparison with the radiative surface temperature provided by the European Centre for Medium-Range Weather Forecasts (ECMWF) model. Information on the cloud cover is provided by the POLarization and Directionality of the Earth's Reflectances (POLDER) instrument, flying on the same platform as IMG [*Buriez et al.*, 1997].

Data description

The IMG instrument recorded the Earth-atmosphere system radiance with a spectral resolution better than 0.1 cm^{-1}. Spectra are calculated with a sampling rate less than 0.05 cm^{-1}. In the present study, we have used the unapodized IMG spectra. As the instrument used the Earth surface thermal emission as source, it measured radiation during night and day.

The POLDER instrument measured (over elementary pixels of about 6 by 7 km at nadir) the solar radiation reflected by the Earth-atmosphere system in 8 spectral channels, some of which polarized, with up to 14 different viewing directions. Therefore, the POLDER data are available during the day only. These data allow the study of: the atmospheric aerosol distributions, the cloud and land surface properties, the vegetation cover, the total integrated water vapor content, the ocean color, and the Earth radiation budget (ERB) [*Deschamps et al.*, 1994]. In the present study, we have used the POLDER operational "ERB, water vapor,

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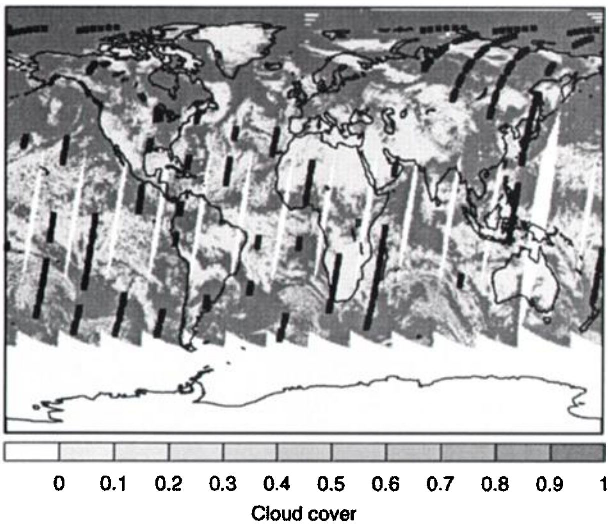

Figure 1. Cloud cover, expressed as the fraction of the POLDER super-pixel occupied by clouds, measured on June 16th, 1997. The black bars correspond to the IMG measurements during the same day.

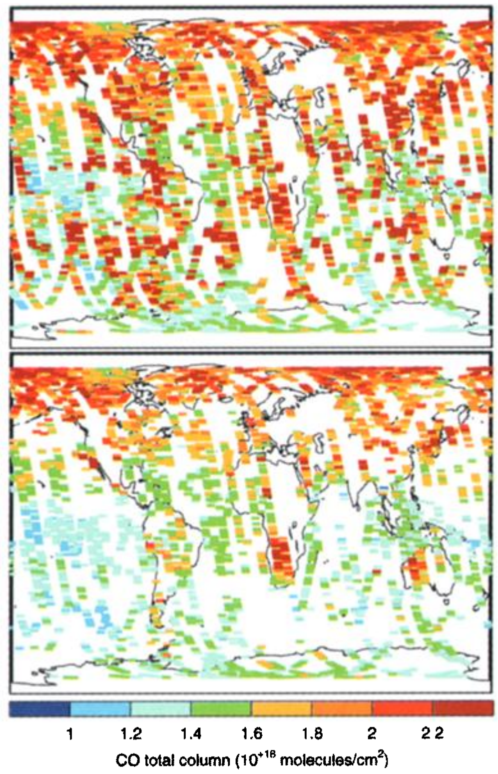

Figure 3. Initial (top) and cloud-cleared (bottom) CO global distributions (total columns in molecules cm^{-2}) as retrieved from IMG data for the period between June 16 and 19, 1997. The colored bars correspond to the CO total column values.

and clouds" products, which provide the cloud cover and its properties as the optical thickness and the apparent and Rayleigh pressures which indicate the cloud altitude [*Parol et al.*, 1999]. For technical reasons, the results provided for the cloud properties are their values averaged over a "super-pixel" of 9 by 9 elementary pixels and their standard deviations [*Buriez et al.*, 1997]. The cloud cover is expressed as the fraction of the super-pixel affected by clouds. In Figure 1, we present POLDER cloud cover measurements with colocated IMG measurements for June 16th, 1997. In the following, we use all the common IMG-POLDER available data during four days between June 16 and 19, 1997.

To compare the radiative temperatures calculated from the IMG spectra, we worked with skin temperatures extracted from the ECMWF Advanced Operational Analysis Data Sets. This temperature is that of the Earth's surface emission. Over ocean, the skin temperature is the sea surface one. It is estimated by the ECMWF model from assimilated data and it presents a standard deviation lower than 1 K [*Reynolds and Smith*, 1994]. Over land, the skin temperature is calculated by a land surface parameterization scheme, included in the ECMWF model, taking into account the effect of a vegetation or litter layer on top of the soil [*Viterbo et al.*, 1999]. There is no direct validation of this temperature by lack of data. A comparison between the brightness temperatures measured by the TIROS (Television InfraRed Observation Satellite) Operational Vertical Sounder (TOVS) instrument and those simulated by a radiative transfer code in the same spectral channels from the skin and atmospheric temperatures of the ECMWF analyses gives the following results for clear sky conditions: a difference of the order of 10 K during the day and of 3K during the night [*P. Viterbo, private communication*]. As the POLDER measurements are available only during the day, a standard deviation of 10 K for the land skin temperatures was considered. We have colocated the ECMWF skin temperatures with the IMG measurements by multi-linear interpolation in time and space.

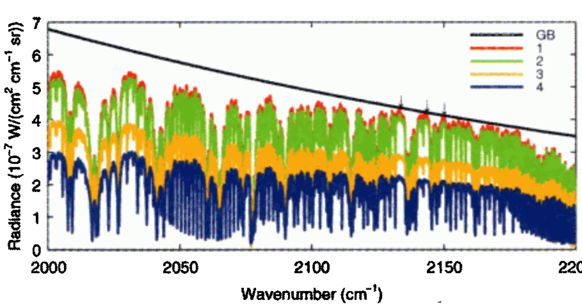

Figure 2. Four consecutive radiance spectra (W/(cm^{2}cm^{-1}sr)), in the 2000-2200 cm^{-1} spectral range, recorded by the IMG instrument over the Pacific Ocean on June 16, 1997. These spectra are compared with the radiance distribution of a gray body (GB) at a temperature of 302.2 K with an emissivity of 0.9788. The POLDER cloud covers corresponding with the IMG spectra are 0.025 (1), 0.255 (2), 0.975 (3), and 1 (4). The three spectral channels used in the selection method are pointed out by three arrows.

Method

We have selected three spectral channels between 2000 and 2200 cm^{-1} where we assume that the atmosphere is relatively transparent: 2133.28, 2143.00, and 2150.11 cm^{-1}.

At these wavenumbers, simulations with a line-by-line radiative transfer model (LBLRTM) [*Clough and Iacono*, 1995] using different standard atmospheres give maximum values of transmission higher than 80% for a tropical atmosphere and higher than 95% for a subarctic winter one. The atmospheric radiative contribution is neglected at the three spectral channels and the IMG instrument records the radiation of the Earth surface considered as a gray body with a ε emissivity at a T_{rad} radiative temperature.

From radiances measured at the three selected spectral channels, we calculated T_{rad}^i (i=1, 2, and 3), three values of the radiative surface temperature using the Planck's law. An emissivity of 0.9788 was set over sea [*Wilber et al.*, 1999], whereas a mean value of 0.9677 was used over land. The latter value was obtained using the land emissivity values, ranging from 0.8353 to 1 according to the surface type, weighted by the soil occurrence provided by *Wilber et al.* [1999]. The estimated uncertainty on the T_{rad}^i radiative temperatures associated with the uncertainty on the emissivity value is 0.7 and 1.2 K for cases over sea and land, respectively.

The calculated T_{rad}^i temperatures are compared with the skin temperature extracted from the ECMWF analyses. We introduce Δ_i (i=1, 2, and 3) the differences between the T_S ECMWF skin temperature and the T_{rad}^i radiative temperatures as $\Delta_i = T_S - T_{rad}^i$ such that considering the ECMWF and radiative temperatures as independent variables, their uncertainties result in Δ_i uncertainties of 1.3 and 10.1 K for cases over sea and land, respectively.

Figure 2 shows four IMG spectra between 2000 and 2200 cm^{-1} compared with the radiance distribution of a gray body with an emissivity of 0.9788 at a temperature of 302.2 K, the ECMWF skin temperature colocated with the IMG spectra. The POLDER cloud fractions corresponding to these spectra are 0.025, 0.255, 0.975, and 1, respectively. In this example, we see that the more the cloud cover increases the more the spectrum deviates from the gray body radiance distribution. The three arrows point out the three spectral channels used for this study.

To select clear spectra, we determine thresholds on the Δ_i differences above which corresponding spectra are considered as perturbed and the atmosphere as cloudy. In the set of common IMG-POLDER data for cloud covers between 0 and 0.1 (at most 10% of the POLDER super-pixel are cloudy and the IMG pixel has a low probability to be cloudy), the maxima of Δ_i values are 6.7 and 5.2 K for sea and land cases respectively. By adding to these maxima the uncertainty on the Δ_i differences, we define the final threshold values: 8 K for sea cases and 15.3 K for land cases.

Results and discussion

Efficiency of the cloud detection

The selection method was applied to the IMG data for the period between June 16 and 19, 1997 (6198 spectra). For each day, about 60% of the IMG spectra are considered as clear. Among them, we find obviously all the daytime IMG measurements associated with POLDER cloud covers lower than 0.1, and about 94, 75.5, 55 and 24% of the daytime IMG data for cloud covers between 0.1 and 0.5, 0.5 and 0.7, 0.7 and 0.9, and higher than 0.9 respectively.

A detailed study was undertaken on the cases associated with POLDER cloud covers between 0.1 and 1 considered as clear by the selection, knowing that the size difference between the IMG pixel (8 by 8 km) and the POLDER super-pixel (~ 50 by 50 km at the equator) may result in ambiguities. If a POLDER super-pixel is partly cloudy, we have no information on the cloud cover in the associated IMG pixels. For cloud covers higher than 0.1, the situations considered as clear by the selection are those where the IMG infrared spectrum is not significantly affected by the presence of clouds, and hence a cloud detected by the POLDER operational algorithm is not detected by our cloud filter method. All these cases were identified as either low altitude or thin clouds in the POLDER data.

When clouds are close to the Earth surface, the difference between the cloud top and skin temperatures could be of the order of the uncertainty of the skin temperature taken into account in the thresholds of our filter method. Clouds with low associated optical thickness are too transparent to perturb significantly the radiation recorded by the IMG instrument. Because of the size difference between the IMG pixel and the POLDER super-pixel, for some super-pixels presenting high standard deviations for the apparent and/or Rayleigh pressures and/or the optical thickness, the IMG pixel can also be situated in an area of clouds thin and/or low enough not to be detected by the IMG spectra selection method.

The rates of IMG spectra considered as clear by our selection method are in good agreement with those obtained from the POLDER data, taking into account that the POLDER algorithm aims to detect any cloud when our filter allows low or thin clouds which hardly affect the IMG measurements and hence the CO retrieval.

Improvement of the CO total column retrieval

To show the efficiency of the method described in this paper, we compare in Figure 3 the CO global distributions retrieved before and after the cloud filtering of the IMG data available for the period between June 16 and 19, 1997. The CO total columns are provided by an inversion algorithm based on the neural network techniques [*Hadji-Lazaro et al.*, 1999].

The first map shows the CO total columns retrieved from the whole of the IMG data for the four days. The missing data are due to a preliminary selection of the spectra operated by the IMG Data and Information System (IMGDIS) to remove those associated with troubles during instrumental calibration. We find in the retrieved CO global distribution main known features: higher columns in the Northern Hemisphere polluted regions and over biomass burning regions, lower values in oceanic regions of the Southern Hemisphere. However, unexpected high CO total columns are observed in areas where concentrations are commonly low.

In the second map, we present the global distribution of CO total column retrieved after cloud filtering for the same period. The spectra selection has cleaned the CO global distribution by eliminating the anomalies. We checked that the threshold values are fitted correctly to remove cases which damage the quality of the CO total column retrieval. The results are satisfying and the cloud-cleared distribution can then be assimilated in a three-dimensional chemical-transport model to study the budget of the carbon monoxide at the global scale [*Clerbaux et al.*, 2000]. The selection method is easy to adapt to another spectral range, to retrieve ozone concentration from IMG data for example.

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References

Amato, U., V. Cuomo, I. De Feis, F. Romano, C. Serio, and H. Kobayashi, Inverting for geophysical parameters from IMG radiances, *IEEE Trans. Geosci. Remote Sens., 37,* 1620-1632, 1999.

Buriez, J. C., C. Vanbauce, F. Parol, P. Goloub, M. Herman, B. Bonnel, Y. Fouquart, P. Couvert, and G. Sèze, Cloud detection and derivation of cloud properties from POLDER, *Int. J. Remote Sens., 18,* 2785-2813, 1997.

Clerbaux, C., P. Chazette, J. Hadji-Lazaro, G. Mégie, J.-F. Müller, and S. A. Clough, Remote sensing of CO, CH_4, and O_3 using a spaceborne nadir-viewing interferometer, *J. Geophys. Res., 103,* 18,999-19,013, 1998.

Clerbaux, C., J. Hadji-Lazaro, S. Payan, C. Camy-Peyret, and G. Mégie, Retrieval of CO columns from IMG/ADEOS spectra, *IEEE Trans. Geosci. Remote Sens., 37,* 1657-1661, 1999.

Clerbaux, C., J. Hadji-Lazaro, D. Hauglustaine, G. Mégie, B. Khattatov, and J.-F. Lamarque, Assimilation of carbon monoxide measured from satellite in a three-dimensional chemistry-transport model, in press, *J. Geophys. Res.,* 2000.

Clough, S. A., and M. J. Iacono, Line-by-line calculation of atmospheric fluxes and cooling rates: 2. Application to carbon dioxide, ozone, methane, nitrous oxide and halocarbons, *J. Geophys. Res., 100,* 16,519-16,535, 1995.

Deschamps, P.-Y., F.-M. Bréon, M. Leroy, A. Podaire, A. Bricaud, J.-C. Buriez, and G. Sèze, The POLDER mission: Instrument characteristics and scientific objectives, *IEEE Trans. Geosci. Remote Sens., 32,* 598-615, 1994.

Hadji-Lazaro, J., C. Clerbaux, and S. Thiria, An inversion algorithm using neural networks to retrieve atmospheric CO total columns from high-resolution nadir radiances, *J. Geophys. Res., 104,* 23,841-23,854, 1999.

IMG Mission Operation & Verification Committee, Interferometric Monitor for Greenhouse Gases (IMG) Project Technical Report, edited by H. Kobayashi, 45 pp., CRIEPI, Tokyo, 1999.

Joiner, J., and L. Rokke, Variational cloud-clearing with TOVS data, *Quart. J. Roy. Meteorol. Soc., 126,* 725-748, 2000.

Kobayashi, H., A. Shimota, C. Yoshigahara, I. Yoshida, Y. Uehara, and K. Kondo, Satellite-borne high-resolution FTIR for lower atmosphere sounding and its evaluation, *IEEE Trans. Geosci. Remote Sens., 37,* 1496-1507, 1999.

Koelemeijer, R. B. A., and P. Stammes, Effects of clouds on ozone column retrieval from GOME UV measurements, *J. Geophys. Res., 104,* 8281-8294, 1999.

McMillin, L. M., and C. Dean, Evaluation of a new operational technique for producing clear radiances, *J. Appl. Meteorol., 21,* 1005-1014, 1982.

Parol, F., J.-C. Buriez, C. Vanbauce, P. Couvert, G. Sèze, P. Goloub, and S. Cheinet, First results of the POLDER "Earth Radiation Budget and Clouds" operational algorithm, *IEEE Trans. Geosci. Remote Sens., 37,* 1597-1612, 1999.

Reichle Jr., H. G., et al., Space shuttle based global CO measurements during April and October 1994, MAPS instrument, data reduction, and data validation, *J. Geophys. Res., 104,* 21,443-21,454, 1999.

Reynolds, R. W., and T. M. Smith, Improved global sea surface temperature analyses using optimum interpolation, *J. Clim., 7,* 929-948, 1994.

Serio, C., A. M. Lubrano, F. Romano, and H. Shimoda, Cloud detection over sea surface by use of autocorrelation functions of upwelling infrared spectra in the 800-900-cm^{-1} window region, *Appl. Opt., 39,* 3565-3572, 2000.

Smith, W. L., X. Lin Ma, S. A. Ackerman, H. E. Revercomb, and R. O. Knuteson, Remote sensing cloud properties from high spectral resolution infrared observations, *J. Atmos. Sci., 50,* 1708-1720, 1993.

Viterbo, P., A. Beljaars, J.-F. Mahfouf, and J. Teixeira, The representation of soil moisture freezing and its impact on the stable boundary layer, *Quart. J. Roy. Meteorol. Soc., 125,* 2401-2426, 1999.

Wilber, A. C., D. P. Kratz, and S. K. Gupta, Surface emissivity maps for use in satellite retrievals of longwave radiation, *Tech. Publ. NASA/TP-1999-209362,* 35 pp., Nat. Aeron. and Space Adm., 1999.

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