FILTERING OUT CLOUDS OVER BRAZIL USING SATELLITE DATA

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ABSTRACT. The main purpose of this study is to evaluate a technique for filtering out clouds in order to obtain vertical temperature and moisture profiles over Brazil using Advanced TROS Operational Vertical Sounder (ATOS). The evaluation consists of a sequence of tests using Advanced Very High Resolution Radiometer (AVHRR) infrared images and the Mask AVHRR for Inversion ATOS (MAIA) algorithm. Two distinct versions of this algorithm were used, namely, filtered (F) and climatological (C). Precipitable water (PW) and surface temperature data as forecasted by a global numerical weather prediction model were used in the former case, whereas a climatological value of PW was estimated using Advanced Microwave Sensor Unit (AMSU) data over ocean areas. The results show that MAIA does evidence coherence between the areas classified as cloudy and those ones sorted as cloudy according to a visual subjective comparison of images. The two versions of the cloud mask algorithm yielded similar results that fly over the southwest Atlantic Ocean. However, over cloud-free areas it was observed a small increase in areas given as clear when the F-version was used. Furthermore, it was also observed that the cloud mask is highly sensitive to changes in the first guess vertical values based on the brightness temperature standard deviation in oceanic areas.

Keywords: satellite sounding; cloud mask; infrared.

RESUMO. Este trabalho apresenta resultados de uma técnica de filtragem de nuvens para obtenção de perfil vertical de temperatura e umidade via Advanced TROS Operational Vertical Sounder (ATOS). As análises basearam-se em uma sequência de testes com imagens infravermelhas do observador Advanced Very High Resolution Radiometer (AVHRR) sobre o Brasil e o uso do algoritmo Mask AVHRR for Inversion ATOS (MAIA). Duas versões distintas deste último foram avaliadas: a versão filtrada (F) e climatológica (C). No primeiro caso, o valor da água precipitada (AP) e temperatura da superfície foram provenientes de um modelo global de previsão numérica de tempo, enquanto, no segundo experimento, utilizaram-se os dados de um "áreas climatológicas" fornecido por um próprio modelo. Em ambos os casos, o foco foi o estudo do uso dos resultados do Advanced Microwave Sensor Unit (AMSU), os resultados obtidos mostraram que o MAIA apresenta coerência entre as áreas classificadas como nuvem ou não indicadas como nuvem matizada, segundo um critério de comparação visual das imagens. De modo geral, as duas versões do algoritmo de máscara de nuvens produziram resultados semelhantes, sobretudo sobre o oceano Atlântico. Sobre o continente, verificou-se um pequeno aumento na área de cobertura iniciada conforme a nova que se usou a versão "F". Além disso, verificou-se que o resultado final da máscara de nuvens sofre bastante influência de alterações no valor do limite de detecção na tabela de desvio padrão de temperatura de brilho sobre o oceano.

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INTRODUCTION

One of the difficulties in retrieving temperature and moisture profiles in the atmosphere is the presence of clouds (Smith et al., 1986, Lavrani et al., 1997; Chaboureau et al., 1999, Cavalcato et al., 1999). This is particularly true in the tropics where cloud cover is relatively high. The ATOV system on board of NOAA satellites has a large potential to improve the quality of the soundings in these regions because it uses a large number of channels operating in the microwave spectral region (Smith, 1991).

Despite the technological advances in sensor development, it is deemed imperative that new techniques and models be created aiming at more accurate moisture and temperature profiles. For instance, the impact of cloudiness and precipitation (English et al., 1999, Subhani et al., 1999a, b, Carvalho, 2002) on the brightness temperature, as observed in high resolution channels is considerable, therefore, more exploited models for cloud/precipitation detection should be used. However, to explore its entire usefulness in improving the quality of the soundings is a necessary and crucial, and difficult use of such models. Smith et al. (1993) proposed the use of the Advanced Very High Resolution Radiometer (AVHRR) system in remote soundings, due to its high spatial resolution, which helps obtaining a better distinction between cloud coverage and surface temperature. Yaqub et al. (1998) studied the impact of AVHRR on International TOVS Processing Package (ITPP) data. ITPP is used to obtain vertical temperature and moisture profiles over Brazil. He showed that improved estimates are obtained when AVHRR images are used to filter out clouds. The mentioned studies also indicated that the use of AVHRR images, in conjunction with High Resolution Infrared Radiation Sounder (HIRS) channels, allows for superior detection and classification of clouds. However, this approach is far from being ideal and in some situations yields erroneous cloud classification.

Cloudiness over the Earth does not show a homogeneous pattern but is characterized by a large space and time variability. Therefore, a detailed analysis of the products provided by cloud masks is necessary to ensure their use by the inversion methods and, at the same time, identify possible failures and limitations of this technique. Thus, the main objective of this work is to evaluate a methodology that enables the use of ancillary information such as precipitable water, surface temperature and climatological data to filter out clouds using the Mask AVHRR for Inversion ATOV (MAIA) (Lavran et al., 1999). Since these data are usually available at operational weather forecast centers, their potential to improve cloud mask techniques and, subsequently, the retrieval of vertical temperature and moisture profiles cannot be overlooked.

One of the difficulties in the validation process of cloud detection algorithms is the establishment of an objective comparison criterion since most of cloud related information stems from satellites and are subjected to the same errors and inaccuracy. In this study, a subjective analysis was chosen instead, where the validation process is made via visual comparison between the cloud mask MAIA generated data and satellite images from the AVHRR sensor in its full resolution. It is worth mentioning that this approach has been successfully used in middle latitudes but its application in the tropics, where cloud coverage is much larger, still calls for some refinements.

METHODS AND MATERIALS

Satellite Data

NOAA - 15 satellite images in High Resolution Picture Transmission (HRPT) format received by the National Institute for Space Research (INPE) - ground station (23.1°S, 45.88°W) were used in the present study. The AAPP-2.0 model (AAPP Documentation, 1999) was used to transform HRPT data archives into brightness temperatures. Full resolution (approximately 1 km) AVHRR satellite images were also used for the days 23/02/2000 at 10:02 UTC and 02/03/2000 at 22:26 UTC. Although this study comprised the analysis of a number of images, it was deemed appropriate to discuss only the two representative situations of the austral summer.

Cloud Masks

The decrease in brightness temperature values in the presence of high and medium level clouds covering a pixel is quite large and can easily be evidenced by using simple quality control tests on the results of the inversion methods. However, when either the area covered by clouds is just one small fraction of the pixel or low level clouds are present, the measured brightness temperatures are quite close to those that would be obtained under clear sky conditions. This impacts the identification of clouds in the pixel and constitutes a serious problem for inversion methods.

The main function of the used model MAIA is to identify and quantify cloud coverage within each pixel using HIRS's field of view (FOV) as infinitesimal for temperature and moisture profiles retrievals in the atmosphere. This is quite useful information regarding the choice of the most adequate channels to be used in the inversion process (Carvalho, 2002). For example, if a pixel is classified as cloudy, the largest portion of the infrared channel must be left out in the inversion process, thus avoiding the erroneous processing of this information. However, the inversion...
process does not require a detailed identification or a classification of different cloud types existing in the image.

The MAIA algorithm involves a sequence of tests that are applied to all AVHRR pixels mapped within the FOV HIRS for various channels combinations. The test series and their corresponding limits applied to each pixel depend on several factors such as surface type (land, ocean or snow/ice), zenith angle (which determines the day period as day-time, night-time or twilight) and the presence or not of sunglint. The tests may be performed using either one channel (monospectral) or a channel combination (multispectral tests). One pixel is classified as cloudy if one of the tests is not satisfied (MAIA Documentation 1999). The main tests used in this study are:

T1) The 1.12 μm channel brightness temperature (AVHRR channel 4) is compared against the observed temperature: if \( T_{1.12} - T_{\text{obs}} > \text{threshold} \), the pixel is sorted out as cloudy. This test permits the identification (with high accuracy) of medium and high-level clouds, but it has a small efficiency regarding low-level clouds because the temperatures of the tops of these clouds and the surface temperatures are smaller than the previously defined threshold.

T2) Estimates of night-time temperature differences between 3.7 μm and 12.0 μm (\( T_{3.7} - T_{12} \)). This procedure is used to detect semi-transparent clouds with ice crystals and snow pixels with cold clouds. Its efficiency is based on the premise that the contribution to the soil (relatively warm) brightness temperature is larger at 3.7 μm than at 12.0 μm because the cloud ice transmittance is smaller and also due to the high non-linearity of the Planck function at 3.7 μm. This difference is a function of the cloud height, depth (for cirrus clouds) and cloudiness.

T3) The difference in brightness temperatures at 11 μm and 3.7 μm (\( T_{11} - T_{3.7} \)) is analysed during night-time hours. This test is used to detect low-level clouds composed of water droplets and its efficiency is warranted by the spectral variability of the emissivity of clouds with respect to liquid water, which is smaller at 3.7 μm than at 11 μm (Eyre et al., 1984). This difference in brightness temperature is larger for clouds with maritime water droplets since continental and oceanic surfaces (except sandy deserts) have similar brightness temperature in the two channels. This test depends on the PW amount and is applied only for night-time hours because the 3.7 μm channel is contaminated by solar radiation during day-time.

T4) The local spatial variability (standard deviation) of the 11.2 μm brightness temperature is analysed in order to detect small cumulus and cirrus clouds.

T5) Cirrus clouds are searched using the difference in brightness temperature at 11.0 μm and 12.0 μm (\( T_{11} - T_{12} \)). The brightness temperature difference of these channels is larger in the presence of cirrus clouds relatively to cloud-free regions due to different behaviour of the emissivity of the two targets (Earth’s surface and clouds).

T6-T7) The detection of low-level clouds is made using the 0.63 μm visible channel (A1) or the 0.9 μm near infrared channel (A2). These tests take advantage of the larger reflectance observed over areas contaminated by clouds relative to cloud-free regions (over continents and oceans as well). A1 is used over land while A2 over the oceans, because the latter has less scattering effect than the visible channel.

Most of the results obtained with the described tests are to some extension sensitive to climatic conditions of the region. Therefore, in order to have more accurate results, it becomes necessary to adjust the threshold values and the tests to the prevailing climatic conditions. MAIA model, in its original version, here namely climatological version (C), used the same parameters for the test independently of the region being observed. The other versions, namely forcast version (F) uses distinct set of parameters, suitable for given climatic conditions, was used in MAIA’s second version (MAIA-2.0). The latter contains a dynamic adaptation based on the response of multispectral tests to different PW. The use of this variable and surface temperature requires some auxiliary data, which can be supplied by either numerical weather prediction (NWP) models, climatology or calculated by specific algorithms. This version of MAIA. In the current study, the PW over ocean was estimated using microwave AMSU-A sensor following Grody et al. (1999). Over land, an atlas of monthly mean PW was available, but superior estimates were used with NWP outputs. The latter consists presents a disadvantage in the sense that it is necessary to have the forecast archives in due time to initialize the model. There was also a monthly climatological atlas for the surface temperature, although it introduces large errors over continental regions. When NWP data are not available, the tests based on the radiometric temperature at 11 μm yielded better results.

Tables 1 and 2 show test sequences used by the cloud identification algorithm for two different satellite orbits representing day-time and night conditions, respectively. It is noticeable that
the sequence and test types depend on the surface type. Other tests and sequences (not shown) are also used in dawn hours and special reflection situations. Initially, a sea ice and snow (over continent) detection algorithms should be applied before any cloud detection test is employed, although for most of the cases consid-
ered in this study this procedure was not necessary. The need (or not) of using a 3.7μm channel is based on the following bright-
ness temperature threshold: If T< 3.7μm ≥ 180 K then use 3.7μm.

Table 1 - Types of cloud identification tests during day time period.

<table>
<thead>
<tr>
<th>Land</th>
<th>Atlantic Ocean</th>
<th>Shoreline*</th>
</tr>
</thead>
<tbody>
<tr>
<td>T1</td>
<td>T2</td>
<td>T1</td>
</tr>
<tr>
<td>T2</td>
<td>T3</td>
<td>T2</td>
</tr>
<tr>
<td>T1</td>
<td>T3</td>
<td>T1</td>
</tr>
</tbody>
</table>

*The identification of the pixels surface coverage (land, ocean) is determined by a test using AVHRR channels 1 and 2.

Table 2 - Types of cloud identification tests during night time period.

<table>
<thead>
<tr>
<th>Land</th>
<th>Atlantic Ocean</th>
<th>Shoreline*</th>
</tr>
</thead>
<tbody>
<tr>
<td>T1</td>
<td>T2</td>
<td>T1</td>
</tr>
<tr>
<td>T2</td>
<td>T3</td>
<td>T2</td>
</tr>
<tr>
<td>T1</td>
<td>T3</td>
<td>T1</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Width of 3.7μm channel</th>
<th>Width of 3.7μm channel</th>
<th>Without 3.7μm channel</th>
<th>Without 3.7μm channel</th>
</tr>
</thead>
<tbody>
<tr>
<td>T1</td>
<td>T2</td>
<td>T1</td>
<td>T1</td>
</tr>
<tr>
<td>T2</td>
<td>T3</td>
<td>T2</td>
<td>T2</td>
</tr>
<tr>
<td>T1</td>
<td>T3</td>
<td>T1</td>
<td>T1</td>
</tr>
</tbody>
</table>

RESULTS

Figures 1a-b show the cloud coverage fraction from the NOAA-15 image on March 02, 2000 (night time) using the cloud mask algorithm. The pixels associated with cloud free sky are shown in red and those associated with overcast sky in blue. The com-
parison between the cloud mask algorithms (Figures 1a-b) and the corresponding 12.0μm infrared cloud cover image (Figure 2) showed a good agreement. The areas identified as cloud free by the cloud masks corresponded very well to those with high bright-
ness temperature values in the 12.0μm image. On the other hand, the areas considered cloudy corresponded to the relatively low brightness temperature values.

Figures 3a-b show the cloud masks for the February 23, day-
time image, and Figure 4a, the corresponding infrared image. In this case, the visible image (Figure 4b) may be used to help the validation process for the cloud mask once the albedo values, as-
sociated with different types of targets in the image, are known. Clouds normally have higher reflectivity indices, relatively to the typical Earth's surface albedos and, therefore, areas with high al-
bedo values must be associated with pixels total or partially con-
taminated by clouds. On the other hand, areas with low albedo values are associated with pixels related to short wave radiation reflected by the surface, that is, cloud free regions. It is worth mentioning that for some targets such as snow or sand covered (deserts) areas, the albedo is also very high and caution should be taken to avoid erroneously interpret them as clouds. In general, a good agreement was observed between the cloud masks and the infrared and visible images.

For the two cases analyzed, the comparison between the re-
sults obtained by the two versions of MM5 model indicated that regions identified as cloud free are practically the same in both versions and the differences between them are small, with the F version being slightly more inflexible; as a consequence, a large number of pixels were considered cloudy. This feature can also be observed in Figures 1c and 3c, that show the differences between F and C data versions, respectively for February 22 and March 02, 2000. Both versions show similar results over ocean areas, but they appear to overestimate cloud pixels, that is, some clear pixels may be being classified as cloud pixels.

Tables 3 and 4 show the fraction of pixels considered cloudy in each test used for cloud identification for the two cases previ-
ously discussed. Only AVHRR pixels located within the bounds of an ellipse formed by the HIRS/3H1 pixels were taken into ac-
count in the calculations. A noticeable fraction difference in the pixel considered cloudy by the two versions was observed over land.

The use of forecast surface temperature allows for a more rea-
listic threshold for the 3.7μm brightness temperature, above which a pixel is considered cloud. However, this threshold va-
ue should be as small as possible, but large enough to take into account factors such as forecast errors, differences between the air temperature near the surface and surface radiometric tempera-
ture, radiative cooling (night-time) or heating (day-time), surface emissivity, time differences between AVHRR observations and fo-
recast times. In this study, for comparison purposes between C and F data versions, a threshold of 1K and 0K were adopted for the night and day time passages, respectively. It was also noti-
ced that, when the forecast surface temperature version was used,

Ref: Pontes-Martins et al., 2009.
Figure 1 - Fraction (%) of cloud coverage within HIRS FOV from NOAA-15 image at March 03, 2001 at 22:26 UTC: (a) Version 1, (b) Version 2 and (c) F - C.

Figure 1 - Fracção (%) de cobertura de nuvens dentro do FOV do HIRS da imagem da satélite NOAA-15, dia 03 de março de 2001 às 22:26 UTC: (a) versão 1, (b) versão 2 e (c) F - C.
a larger number of pixels was classified as cloudy over land according to T7 (not shown). However, over ocean areas the use of pixel-based surface temperature did not influence the percent of pixels considered cloudy, or in other words, a climatological atlas of sea surface temperature could be alternatively be used. This is probably due to the smaller variability of the sea surface temperature, relatively to continental surfaces. Regarding other tests, the only difference between F and C data versions was in the amount of precipitation water. The use of climatological PW may yield larger errors mainly in the regions where the moisture content in general is highly variable. On the other hand, the tests showed little sensitivity regarding the PW fields, except for T5, which presented a large-percentage reduction in cloudy pixels in the F-data version. The results remained unchanged over ocean areas because the PW variable was the same in both versions.

It was also verified that the climatology test for the temperature threshold (test T1) was the most reliable in identifying pixels set aside as cloudy according to MAIA algorithm, although a considerable portion of these pixels was also identified by the other tests. Regarding the night-time orbits, in addition to the threshold test T7, other tests (which classify a large number of pixels) were deemed important, such as test T4 (spatial coherence technique) and 2 (T4, T2, or T3). On the other hand, regarding the day-time passages, the most significant tests were T4 and T7 (not shown). Test T5 that per se classified a large amount of cloudy pixels hardly affected the final result of the cloud masks, that is, it was practically redundant for the analyzed cases.

Test T4, as mentioned before, is based on the calculation of the brightness temperature standard deviation using pixels within a 3 x 3 pixel “box.” A threshold of 25 K is used as the maximum value allowed for the standard deviation in order to classify a pixel as cloud free. However, a more detailed analysis of the results for ocean areas showed that this value is not adequate for the region under consideration and that higher values, about 35 K, could be used without compromising the reliability of the algorithm (preventing that cloud pixels be classified as cloud free ones). Figures 5 and 6 show the standard deviation average values for each HRSS pixel.

Figure 2 - Brightness temperature (K) derived from 12 µm AVHRR channel, on March 02, 2000 at 22:26 UTC.

Figure 3 - Brightness temperature (K) derived from channel 3 and 4 (11 µm) - AVHRR channel 3 and 4, March 02, 2000 at 22:26 UTC.
Figure 3 – As in Figure 1, except for February 23, 2000 and 10/21 Utc.

Figure 3 – Igual a Figura 1 excepto para 23 de Fevereiro de 2000 a 10/21 UTC.
Franca and Cracknell (1966) in their study on the Brazilian Northeast used for the standard deviation method a value of 0.4K below which the pixel was classified as cloud free. This value was tested for the above-presented cases and the results are shown in Figures 7a and 8a. When the "STDDEV" version of the cloud mask is checked against the forecast data version (Figures 7a and 8a), it is clear that the number of pixels given as cloudy is significantly reduced. This can also be seen in the graph that depicts the difference between the two versions (Figures 7b and 8b). The percentage reduction in cloud pixels over the Atlantic Ocean occurred practically all over the image, with values ranging from 0 to 40%. Table 5 shows the pixel count with respect to the total image pixel that were considered cloud-free according to test T4 and the final percent of these pixels (after the application of the sequence of tests) for the forecast data version as well for the version that utilizes the value of 0.4K for the standard deviation. In both cases a considerable reduction in cloud pixels was evident according to T4, which ended up also influencing the final cloud mask results.

CONCLUDING REMARKS
The results of this study show that the application of the cloud mask algorithm MAA over Brazil showed that both versions of the algorithm (forecast and climatological data) produced similar results for the region under consideration, mainly over the ocean.

Brasília, novembro de 2004, 10/10/2004
Table 4 - A type of test for day 3/30/2000 and 10:30 UTC.

<table>
<thead>
<tr>
<th></th>
<th>C version</th>
<th></th>
<th>F version</th>
<th></th>
<th>G3DEV version</th>
</tr>
</thead>
<tbody>
<tr>
<td>Test 1</td>
<td>0.331</td>
<td>0.170</td>
<td>0.468</td>
<td>0.336</td>
<td>0.186</td>
</tr>
<tr>
<td>Test 2</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
</tr>
<tr>
<td>Test 3</td>
<td>0.003</td>
<td>0.001</td>
<td>0.004</td>
<td>0.003</td>
<td>0.001</td>
</tr>
<tr>
<td>Test 4</td>
<td>0.591</td>
<td>0.000</td>
<td>0.591</td>
<td>0.000</td>
<td>0.000</td>
</tr>
<tr>
<td>Test 5</td>
<td>0.048</td>
<td>0.009</td>
<td>0.033</td>
<td>0.048</td>
<td>0.003</td>
</tr>
<tr>
<td>Test 6</td>
<td>0.312</td>
<td>0.000</td>
<td>0.295</td>
<td>0.312</td>
<td>0.008</td>
</tr>
<tr>
<td>Test 7</td>
<td>0.000</td>
<td>0.432</td>
<td>0.205</td>
<td>0.000</td>
<td>0.435</td>
</tr>
<tr>
<td>Test 8</td>
<td>0.079</td>
<td>0.000</td>
<td>0.021</td>
<td>0.079</td>
<td>0.000</td>
</tr>
</tbody>
</table>

Pixel total: 202x700

Figure 5 - Standard deviation of the test for day 3/30/2000 and 10:30 UTC.

Figure 6 - Estimation of the standard deviation for pixels of the test for day 3/30/2000 and 10:30 UTC.

where they were identical, suggesting that the utilization of forecast data is not an impairment to a satisfactory classification using the cloud mask technique. However, this technique is sensitive to the value used in calculating the standard deviation for the brightness temperature over the ocean, where a more appropriate value of 0.4 K is suggested. It is important to mention that the comparison problem, using outputs of cloud mask algorithm, is very difficult because some types of clouds may be not apparent in certain
Figure 6 - Standard deviation estimate (test T4) for each area with a 3 x 3 grid from NOAA 15 image on February 23, 2000 at 10:02 UTC.

Figure 6 - Identical to Figure 5, except for the day 29 of February of 2000 at 10:02 UTC.

Table 5 - Percent of pixels (from analysis of test) that were considered to be free according to test T4 and the standard deviation of the pixels that were evaluated using the F and STDEV versions.

<table>
<thead>
<tr>
<th>Analysed Cases</th>
<th>F Version</th>
<th>STDEV Version</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Free Cloud Pixels</td>
<td>Free Cloud Pixels</td>
</tr>
<tr>
<td></td>
<td>(Test T4)</td>
<td>(Total)</td>
</tr>
<tr>
<td>02/03/2000</td>
<td>30.2%</td>
<td>17.6%</td>
</tr>
<tr>
<td>23/02/2000</td>
<td>40.9%</td>
<td>37.4%</td>
</tr>
</tbody>
</table>

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Figure 7 – Fraction (%) of cloud cover age with HIRS (red) and of view from NOAA-15 Image of February 23, 2000 at 16:00 UTC. (a) using 8 version data with a new threshold for 14; (b) F-STEM.

Figure 7 – Fração de cobertura de nuvem (vermelha) do sensor HIRS processada a partir de imagem do satélite NOAA-15, dia 23/02/2000 às 16:00 UTC, (a) utilizando dados de Previsão com um novo limiar para 14; (b) diferença entre as versões Previsão e STEM.

Figure 8 – As in Figure 7, but for March 01, 2000 at 22:24 UTC.

Figure 8 – Iguais à Figura 7, exceto para dia 01 de Março de 2000 às 22:24 UTC.
channels and the associated image may not reveal where these clouds are present. Also, the current analyses focused only typical auroral summer cases. Thus, the obtained results are not definitive and complete.

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