AN ADAPTIVE STRATEGY FOR CLOUD FILTERING IN HIRS/2 CHANNELS

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ABSTRACT

Measured HIRS/2 infrared radiances exhibit very different field dynamics as a consequence of spatial variability of atmosphere and earth surface spectral properties related in particular to cloud distribution and land orography. Cloud filtering for HIRS/2 channels requires different approaches depending on what (i.e. high or low) channels are considered and on the involved area (i.e. land or sea).

In this paper we propose an adaptive filtering strategy in order to reduce errors on clear radiances estimation in cloudy locations. Synthetic brightness temperatures computed by ECMWF operational analysis have been used for HIRS/2 channels 4, 7 and 13. Measured HIRS/2 radiances, together with co-located AVHRR data, have been used to analyze HIRS/2 channel 8. Cloud filtering has been performed, by varying interpolation radius, and restored fields compared with the available reference fields for several satellite passes. Completely restored fields with r.m.s. less than 0.3 °K have been obtained in channel 4 interpolating at large range. Quite half of the scene has been restored in channels 7 and 13 with r.m.s still less than 1 °K. In channel 8, interpolation up to 300 km around each cloudy FOV, produced an r.m.s. smaller than 1°K on the sea and not greater than 1.5°K on the land. Operational cloud masks obtained by processing real data have been used for HIRS/2 channels 4, 7 and 13. Co-located AVHRR data have been analyzed to determine cloud content inside each HIRS/2 FOV for channel 8. Results obtained by cloud contaminated radiances, instead of completely clear, are also discussed.

1. INTRODUCTION

Several schemes have been proposed to compute clear-sky brightness temperatures from cloud-affected measurements. The quality of retrieved products is so poor that its
usefulness in NWP is still under discussion (e.g. Rizzi et al., 1994). The majority of these schemes obtains clear radiances at cloudy Fields of View (FOVs) by interpolating (or, generally speaking, by using) radiances measured in the immediately close clear FOVs. Available clear FOVs are usually not sufficient (and used in a so short range around cloudy locations) so that ancillary data (e.g. MSU) become necessary in a second step to produce a clear radiance field without gaps. Mainly in this phase gross errors are introduced with destructive effects on the quality of the retrieved product.

Comparing the mean error associated with the clear-sky radiances obtained in the first step with the one obtained at the end of the second step, when the complete field has been restored, we can observe a strong increase in the uncertainty specially for low HIRS/2 channels and over land locations. As an example in Table 1 is shown the variance in terms of Brightness Temperatures (BT) obtained on the restored field at the end of the first step (with only part of the scene restored) with the one associated at the complete restoration of the scene by using MSU data. The quoted number are referred to the results obtained over the sea in HIRS/2 channel 8 by using the MR59 cloud clearing scheme (see later) on two satellite passes over the North Europe. This quality degradation due to the introduction of ancillary data at the second step is generally so large to justify more prudence before to heavily introducing them in a cloud-clearing scheme. However, this choice must be the extrema ratio after that other, less expensive ways have been explored. By the other side, measured HIRS/2 infrared radiances exhibit very different field dynamics as a consequence of spatial variability of atmosphere and earth surface spectral properties related in particular to clouds distribution at different levels and to land orography. Looking only at clear HIRS/2 soundings it is possible to see that as one moves from high level to low level channels the average deviation from the mean BT on the field moves from values smaller than \(1^\circ\) K (as in the HIRS/2 channel 4 around 400mb) to values greater than \(5^\circ\)K (as in the HIRS/2 window channel 8 over land). As an example the measured values of standard deviation of BTs in clear HIRS/2 FOVs are reported in Table 2 for channel 4, 7, 13 and 8 for some satellite passes used during this work. Note as, also on the sea, in the window channel 8, the field dynamics is quite flat.

In this paper we propose an adaptive filtering strategy in order to reduce errors on clear radiances estimation in cloudy locations. Synthetic brightness temperatures computed by ECMWF operational analysis have been used for HIRS/2 channels 4,7 and 13 for two satellite passes. Measured HIRS/2 radiances, together with co-located AVHRR data, have been used to analyze HIRS/2 channel 8 for seven satellite passes. Cloud filtering has been performed by using the gaussian interpolation method described in Amato et al.,1991 and Cuomo et al.,1993. This method permits, by a simple way, to change the interpolation radius (i. e. the maximum distance between the cloudy location to be interpolated and the
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clear ones to be used in the interpolation process) by moving only one tuning parameter.
It is the first step of the MR59 cloud-clearing scheme (see for example Cuomo et al., 1993)
successfully validated at the ECMWF during the Cloud Clearing Comparison Exercise
some years ago (Rizzi et al., 1992, 1994).

No ancillary data have been used. The interpolation procedure has been ran for
different values of the interpolation radius, and restored fields compared with the available
reference fields for several satellite passes. Two reference brightness temperature fields
were considered:
the ones coming from ECMWF operational analyses;
the ones coming from co-located clear AVHRR radiances inside partly cloudy
HIRS/2 soundings (HIRS/2 channel 8 only).

In the first case an operational product (UKMO) has been used to identify clouds-free
Fields of View (FOVs). In the second case a product based on co-located AVHRR data
(CMS-Lannion) was applied.

Comparing the errors obtained on the restored area and the fractions of area re-
stored at different interpolation radii, strong indications toward a different filtering strategy,
 adaptable to channel (energy peak level) heights and surface variability, have been
found.
Results obtained by using also cloud contaminated radiances, instead of completely
clear, are also discussed in the case of HIRS/2 channel 8.

2. HIGH CHANNELS

For this analysis we used, as test fields, the synthetic clear-column radiances obtained
for two satellite passes, for HIRS/2 channels 4, 7, 8, and 13, from operational analyses
produced by the ECMWF. HIRS/2 channel 4 peaks at 400 hPa and of the four selected
channels is the one less affected by clouds although it is still sensitive to high clouds.
Both channels 7 and 13 look near the surface (900 hPa and 1000 hPa, respectively) but
have central wavelengths in different spectral ranges (nominally 748 and 2190 cm⁻¹)
and are characterized by different principal absorbing constituents (CO₂/H₂O and N₂O,
respectively). HIRS/2 channel 8 is a window and, therefore, it is very sensitive to clouds
and orography. Operational UKMO cloud masks have been used to identify cloudy location
to be treated as unknown locations in the interpolation process. A gaussian interpolation,
the first step of MR59 cloud-clearing scheme, was performed by varying the interpolation
radius between 40 km (the spacing between adjacent HIRS/2 spots) and 322 km. It never
uses clear data over land to interpolate on cloudy location over sea and vice versa. At
each run the fraction of the rebuilt area Aₜ and the r.m.s. on cloudy locations have been
computed by comparison with synthetic brightness temperatures.
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<table>
<thead>
<tr>
<th>²σ (°K²) OVER SEA</th>
<th>PASS A</th>
<th>PASS D</th>
</tr>
</thead>
<tbody>
<tr>
<td>MR95 ONLY INTERP.</td>
<td>0.30</td>
<td>0.28</td>
</tr>
<tr>
<td>COMPLETE MR95 SCHEME (MSU INCLUDED)</td>
<td>2.50</td>
<td>2.81</td>
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TABLE 1. ΔT variance at the end of the interpolation step only and after complete filtering with ancillary MSU data included.

<table>
<thead>
<tr>
<th>σ (°K)</th>
<th>SATELLITE</th>
<th>PASSES</th>
</tr>
</thead>
<tbody>
<tr>
<td>HIRS/2 CHANNELS</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>A</td>
<td>0.78</td>
</tr>
<tr>
<td></td>
<td>D</td>
<td>0.30</td>
</tr>
<tr>
<td>7</td>
<td></td>
<td>2.54</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1.23</td>
</tr>
<tr>
<td>13</td>
<td></td>
<td>3.38</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1.78</td>
</tr>
<tr>
<td>σ (°K)</td>
<td>G</td>
<td>B</td>
</tr>
<tr>
<td>8 (SEA)</td>
<td>1.39</td>
<td>1.63</td>
</tr>
<tr>
<td>8 (LAND)</td>
<td>4.64</td>
<td>4.00</td>
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</table>

TABLE 2. HIRS/2 measured BTs field dynamics (standard deviation over clear FOVs).

<table>
<thead>
<tr>
<th>PASS</th>
<th>DATE (Y/M/D)</th>
<th>GMT (H:M:S)</th>
<th>HIRS/2 LINES</th>
<th>CLEAR SPOTS FROM CLOUD MASKS</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>AVHRR BASED</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Ce=100 Ce=75 Ce=50 Ce=100</td>
</tr>
<tr>
<td>A</td>
<td>11/02/89</td>
<td>02:48</td>
<td>95 102</td>
<td>171 439 587 774</td>
</tr>
<tr>
<td>B</td>
<td>17/12/91</td>
<td>13:21</td>
<td>100</td>
<td>205 436 582</td>
</tr>
<tr>
<td>C</td>
<td>17/12/91</td>
<td>15:03</td>
<td>100</td>
<td>132 294 426</td>
</tr>
<tr>
<td>D</td>
<td>12/02/89</td>
<td>02:37</td>
<td>60 72</td>
<td>266 552 677 624</td>
</tr>
<tr>
<td>F</td>
<td>06/05/92</td>
<td>15:41</td>
<td>100</td>
<td>341 422 577</td>
</tr>
<tr>
<td>G</td>
<td>07/05/92</td>
<td>13:47</td>
<td>100</td>
<td>569 936 1170</td>
</tr>
<tr>
<td>H</td>
<td>07/05/92</td>
<td>15:29</td>
<td>100</td>
<td>341 604 798</td>
</tr>
<tr>
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<td>13:35</td>
<td>100</td>
<td>484 788 979</td>
</tr>
<tr>
<td>L</td>
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<td>01:53</td>
<td>93</td>
<td>246 864 1144</td>
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</table>

TABLE 3. Used satellite passes.

Fig.1 Measured rms after gaussian interpolation by using different interpolation radii. Results obtained for different HIRS/2 channels. Left: Pass A. Right: Pass D

Fig.2 Fraction of the scene that has been rebuilt by interpolating at different distances compared with the corresponding rms. Results obtained for different HIRS/2 channels. are presented with the symbols of Fig.1. Left: Pass A. Right: Pass D

Fig.3 As in Fig.1 but only for the HIRS/2 channel 8. Left: Results over sea-locations. Right: Results over land locations (no clear data were found for pass D over land)
Figure 1 and 2 show the results we obtained for the channels and passes investigated. From Figure 1 it is possible to see that for all the channels the r.m.s. remains well below 1°K also if interpolation radii greater than 1 are used. For channel 13 and more for channel 7 it is quite evident that interpolating at least up to 120 km is still possible with a final r.m.s. not exceeding 1°K. In channel 4 the final r.m.s. seems to stay below 1°K (but also below the average field dynamics) practically at any interpolation radius up to 320km and more.

Figure 2 immediately says us that fractions of scene between 30% and 40% in channels 7 and 13, not more than 25-30% in channel 8, but also more than 70% in channel 4, will be rebuilt with an r.m.s. still below 1°K by using extended interpolation radii.

By looking at Figure 3 where results obtained in channel 8 are separated for land and sea locations, it is to note that the most important contribution to the final r.m.s. in channel 8 comes from land locations. Over the land (only pass A had completely clear FOVs and was processed) at interpolation radii greater than 160 km the r.m.s. start to decrease mainly because of the increased statistics of interpolated locations.

Over the sea the interpolation can be done at large interpolation radii still saving the final r.m.s under 1°K.

3. SURFACE

The analysis on channel 8 has been performed by using 7 different satellite passes over Europe (the complete list is in table 3). In this case real, limb-corrected, HIRS/2 sounding were used. Co-located AVHRR data have been used to produce cloud contamination masks at the HIRS/2 resolution by computing a clear qualifier \( C_c \) as the percentage of clear AVHRR FOVs inside each co-located HIRS/2 FOV. A linear regression relation

\[
\hat{T}_s^H = a + b \cdot \hat{T}_s^A
\]  

(similar to the one established in Lloyd et al.,1985) was derived between the BTs in HIRS/2 channel 8 and AVHRR derived average skin temperature inside each co-located spot. The coefficients were computed by using only HIRS/2 soundings completely clouds-free.

Different coefficients were computed for each scene and for land, coast and sea locations. The regression relations (1) were then used in order to estimate the HIRS/2 BTs in channel 8 at partly cloudy HIRS/2 FOVs in which AVHRR data still permitted us to obtain skin temperatures. The BT obtained by this way in partly cloudy HIRS/2 spots were used as reference field to validate the cloud-cleared products obtained interpolating with different interpolation radii.

The gaussian interpolation was performed by varying the interpolation radius and accepting as clear-free sounding FOVs affected by clouds for different amounts. Based on
Fig. 4 AVHRR-based cloud masks with a clear qualifier Cc=100 (completely clear FOVs)
the AVHRR cloud contamination masks we considered "clear" the HIRS/2 FOVs having at least a \((C_c \text{ equal to }) 100\%, 90\% \text{ and } 75\% \text{ of clouds-free AVHRR spots inside the co-located HIRS/2 FOV} \) (see Figure 4).

For each run the fraction of the rebuilt area \(A_S\) has been computed. The r.m.s. on cloudy locations have been computed, wherever possible, by comparison with the BTs obtained by the regression relation (1). Figure 5 shows the results we obtained over the sea. By looking to the left side it is possible to see that, for all passes is confirmed the possibility to extend more and more the interpolation radius without rise the r.m.s. level of 1°K. It is also interesting to note that the use of cloud-affected soundings become more and more convenient as far as larger interpolation radii are used and an increased number of "clear" locations comes to compensate degradation of "clear" data quality. A look at the right side of Figure 5 says us that, quite for all passes, the same fraction of rebuilt area is obtained with a lower r.m.s. by using cloud contaminated radiances as "clear" locations in the interpolation scheme. Fractions of sea areas from 40\% up to 60\% have been rebuilt with r.m.s. still under 1°K only extending the interpolation radius. Must be noted (look at the inversions belong the horizontal axis) that in more than one occasion, the increasing of the interpolation radius (increased statistics) produces a reduction in the r.m.s. value.

In Figure 6 results obtained over land show as the trade-off between the increased statistics offered by a degraded cloud mask and the use of a reduced number of "clear" locations of higher quality strongly depends from specific features related on the spatial variability over each scene. Some time (passes I and L) cloud mask degradation offer the best results some time (passes C, F, G and H) it is better to use only completely clear data, in another case (pass B) the two strategies seem quite equivalent. Quality of the interpolation is generally poor as the r.m.s. (see on the left side of Figure 6) only in few cases stay under 2°K and with fractions of rebuilt area \(A_S\) over 30\% (right side of Figure 6). Compared with the results obtained over the sea it is more evident as (and for all passes) the same fraction of rebuilt area is obtained, with a lower r.m.s., at lower values of clear qualifier \(C_c\). In some case, with the same r.m.s., degrading cloud mask produces a terrific increment in the \(A_S\) value. This could depend also from cloud mask quality that, due to the spatial variability, can be more and more selective but nevertheless generally poor over land.

If results obtained on the sea seem to strongly support interpolation at larger distances, over the land it seems that the number and spatial distribution of clear HIRS/2 soundings is heavily not sufficient to accurately describe field dynamics over land.

In Figure 7 we show the result we obtained, for pass D, after introducing as new clear HIRS/2 sounding, the ones we obtained from the regression relation (1). By this way the number of known grid points, in the interpolation scheme, had a substantial increase

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Fig. 5 Cloud clearing performances in the HIRS/2 channel 8 (window) for seven satellite passes and only sea locations. Left side: measured rms after gaussian interpolation by using different interpolation radii. Right side: Fraction of the scene that has been rebuilt by interpolating at different distances compared with the corresponding rms. Results obtained with clear qualifier Cc=75, 90 and 100 are showed with different symbols.
from about 300 to more than 1200 points across the scene. The used BTs field is the one already used in Section 2 (coming from ECMWF operational analyses) and it was used also as reference field. The used cloud mask is, in this case, the one based on co-located AVHRR data with a clear qualifier \( C_c = 100 \). In the graph, the used interpolation radius increases from a value of about 40 km on the right part of the curve up to assume a value of 322 km moving toward the left side (r.m.s. values decreasing) of the picture. Only for this pass, between the two ones available, the AVHRR based cloud mask found completely clear spots on the land so only in this case was possible to compute the coefficients for the regression relation (1) and perform this test.

Due to the relative closeness of clear spots (and the smallness of the land area investigated) the increasing of interpolation radius seems to have quite no effect on the \( A_S \) parameter that is, in any case at the 70% value with an r.m.s lower than 0.35°K. Compared with the results obtained by using only HIRS/2 data the improvement is really relevant and, if confirmed over an extended data set, could suggest a really promising strategy for land clear-sky radiances determination.

4. ADAPTIVE STRATEGIES AND NEW INSTRUMENTS DESIGN

The analysis we performed suggests that reliable (final r.m.s less than 1° K), high channels or over sea, HIRS/2 clear-sky radiances, can be obtained by an appropriate (gaussian from MR59 in this context) interpolation algorithm using, as known grid points, clear-soundings up to 300 km (and more) around each unknown (cloudy) location. Strong improvements we found (but only one satellite pass was processed) by interpolating cloudy locations over land after the introduction of ancillary clear-sky radiances coming from AVHRR data. The fraction of the cloud-cleared scene is enormously increased already at the interpolation step strongly reducing the relative impact of other, low quality, ancillary data sources that, for the higher channels could be even completely avoided.

So, due to different field dynamics in HIRS/2 channels, different strategies can be suggested for future cloud-clearing schemes. For higher HIRS/2 channels the interpolation can be extended at very high interpolation radii (300 km and more for channel 4 as well for channel 8 over the sea). Extended interpolation radii can be used also for lower channels (at least 120 km for channel 7 and 13) with cloud cleared areas up to a 40%.

In channel 8, over land locations, some improvements in the retrieved area is still achievable by including cloud contaminated radiances (up to \( C_c = 75 \)) in the set of "clear" soundings but, a strong errors reduction is found only when AVHRR derived clear-sky radiances are introduced.

From a different point of view these results seems to introduces some new arguments into the current debate on new instruments design.
**Fig. 6** As Fig. 5 but now for land locations

**Fig. 7** Improved performances after the introduction of AVHRR derived clear radiances. (only pass D)
In fact performances of atmospheric sounders mainly depend on
a) spectral resolution
b) spatial resolution and sample spacing

Spectral resolution mainly affects the quality of vertical profiles. Both spatial resolution and instrument sample spacing affect clouds handling and by this way quality (and extension) of reconstruction in the horizontal field. So to improve reconstruction quality our needs are toward higher spectral resolution for channels peaking throughout the atmospheric layers, toward higher spatial resolution for window channels to be used for cloud detection and surface analysis.

By the other hand clouds-free areas tend to clusterize at every scale (see for example Zhu et al., 1992, Serio et al., 1995) so that, by reducing FOV size, more (Cuomo et al., 1992, Smith et al. 1993) and more uniformly distributed (Derrien, 1992, Cuomo et al., 1993b) clear soundings, can be found. Due to clouds-free area distribution across the scene sample spacing reduction will be quite equivalent to FOV size reduction in order to improve the relative number of clear soundings but less efficient if more uniform clear sounding distribution is concerned (Cuomo et al., 1993b).

As we have just seen the horizontal field dynamics in atmosphere is enough flat that high quality cloud-cleared BTs fields can be achieved also interpolating at distances that are higher of the actual HIRS/2 sample spacing. So to increase both, spectral resolution and number of clouds-free soundings under practical constraints (e.g. instrumental NEΔT), FOV size, instead than sample spacing, reduction could be pursued.

Furthermore the problems encountered performing cloud-clearing in the HIRS/2 channel 8 over land locations, specially because of the related high field dynamics, indicate that higher spatial resolution soundings (in term of FOV size and sampling density), must be included, not only in the cloud detection process but also directly in the retrieval of surface parameters at the HIRS/2 spatial resolution.

5. CONCLUSIONS

The results of this work seem to suggest the use of a more adaptive strategy in cloud-clearing schemes applied to HIRS/2 infrared radiances.

An extension of the interpolating radii must be considered in the interpolation step before introducing (if still necessary) low quality ancillary data (e.g. MSU), both when high channels or at sea surface, HIRS/2 soundings are involved. In these cases fractions of the scene between 40% and 80% can be cloud-cleared with a final r.m.s. still below 1°K. Due to the high field dynamics in the window channel 8 over land locations, clear soundings statistics can be favorably increased by introducing ancillary data coming from co-located infrared AVHRR soundings in partly cloudy HIRS/2 spots. The number and
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quality of this ancillary data was so high, in the case we analyzed, that a fraction of about 80% of land area was cloud cleared with an r.m.s. below 0.4°K. Finally results we obtained seem to confirm that quality of cloud clearing products in the out-windows channels and over sea locations depends more on instrument FOV size than on sampling density. Both of them being, instead, essential requirements when land locations are concerned.

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