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CLOUD TOP INFERENCE FOR HYPERSPECTRAL INFRARED RADIANCE ASSIMILATION

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1. INTRODUCTION

Numerical weather prediction (NWP) centers are now actively involved in new avenues of research and development created by the availability of hyperspectral infrared radiances. The main goal is to improve NWP analyses and subsequent forecasts, taking maximum advantage of the rich information content present in these new data. The AIRS instrument (Atmospheric Infrared Radiance Sounder), operational since 2002, provides 2378 channels covering the infrared spectrum at unprecedented spectral resolution. Most of the globe is covered in a period of about 12 h. These data are distributed in real time to several NWP centers in the form of subsets of 281 or 324 channels with one pixel (~14 km field of view) every ~50 km. As a first step toward assimilation, the main task is the monitoring of the data which implies to identify those radiances which are not affected by clouds. This is the object of this paper. The MSC 3D-var system (soon 4D-var) allows the relatively straightforward assimilation of radiances. The current work has views toward the assimilation of cloudy radiances and such research requires as a foundation a good characterization of cloud amount and height.

2. RADIANCE MONIRORING

2.1 *Clear Sky Determination*

The first step consists in determining if the field of view is clear or not. The algorithm to do this relies on a single window channel, here channel 787 (10.9 μm). Since a similar channel is available on most platforms, the clear sky determination is not AIRS specific and previously developed algorithms based on a similar channel can be used. Each pixel is matched with a 6-h background estimate of the atmospheric profile (temperature, humidity, surface skin temperature T_s and surface pressure P_s). The cloud detection algorithm is defined by Garand and Nadon (1998). One of the main criteria relies on the effective height HE defined as that height where the observed brightness temperature BT matches the background atmospheric temperature. HE is required to be less than 730 m in most cases. The algorithm considers possible special cases such as low inversions. Following that step, radiative transfer calculations are made from the background state to compute observed minus calculated BTs O – P) where P stands for "Predicted". The (O – P) distribution has the desirable Gaussian structure in the window channel, except for the tails, notably on the cold side, which are not smooth. An estimate of the skin temperature is obtained by inverting the radiative transfer equation based on the observed BT and using the background atmospheric profile. The difference between T_s (BT) and that from the 6-h forecast (in effect the sea surface analysis over oceans) is computed. Pixels with a T_s difference in excess of 2 K are assumed cloud contaminated over oceans. The threshold is set to 4 K over land.

2.2 *Radiance bias correction*

At the present time, a flat bias correction (single constant) is considered. Rather than simply removing the overall bias in the O-P distribution, we proceed in the following manner: the number of samples NMAX at the peak of the O-P histogram (based on ocean clear cases, globally from 60 S to 60 N) is identified and the bias is computed from bins with a number of samples N superior to NMAX/2, thereby not considering the tails of the distribution. A residual bias is obtained and no attempt is made to remove it. A small residual bias and small overall standard deviation are indicative of a reliable channel. A modest residual bias (< +/- 0.2 K) may be caused by regional model errors. More work is required to establish possible air mass dependent radiative transfer model (RTM) biases. The RTM used is RTTOV (version 7, Matricardi et al., 2001) which is also used at Meteo-France, ECMWF and UK MET Office. This allows a comparison of our respective monitoring statistics on the same basis (only the forecast model differs). Fig. 1 shows the STD and residual biases for a 6-h period (~10,000 samples) for clear skies over oceans. We use the 281 channel set. Problematic channels (from the data or radiative transfer modeling) are immediately apparent, notably the ozone sensitive channels (135-155 covering 9.3 to 9.9 μm) and CO_2 channels 232-236 (near 4.2 μm) and 32-41 (near 15.0 μm). In the latter cases, the CO_2 Jacobian has a complex structure and is not negligible at the radiative transfer model top of 0.1 hPa. To avoid solar effects, only nighttime observations are used for short wave channels 215-281 (3.7-4.6 μm). A large bias is seen in channel 277 (AIRS 2357). Water vapor channels (172-214, 6.2-7.6 μm) are well behaved in terms of bias. The STDs of the order of 2 K are normal given model errors associated to humidity. These results are in line with those obtained at other centers.

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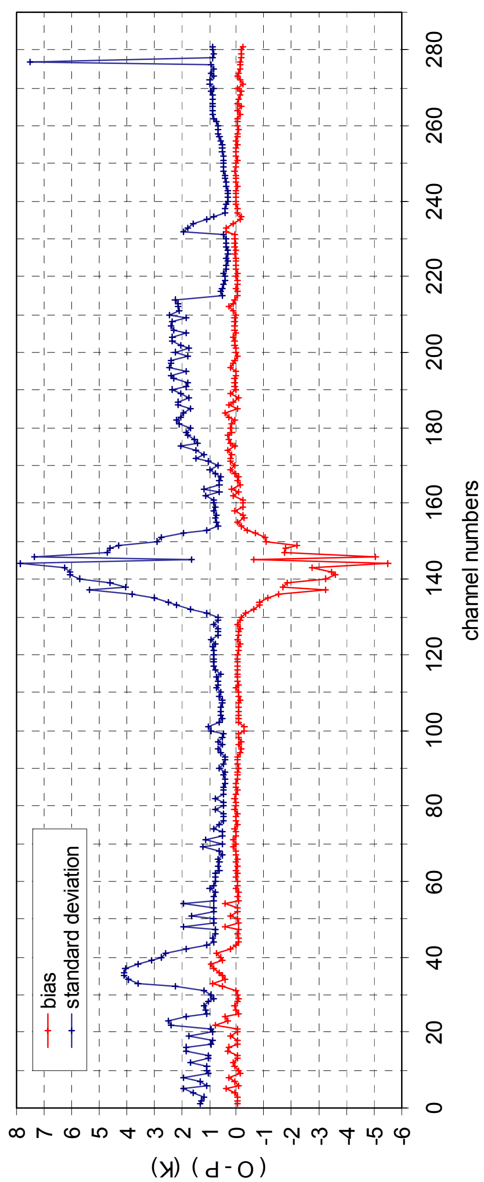

Fig. 1. (O-P) statistics for a 6-h period.

3. CLOUD TOP DETERMINATION

3.1 *Methodology*

The number of clear field of views is limited, representing on a global basis less than 15 % of the cases. It is therefore important to assimilate channels which are not sensitive to clouds. The approach chosen is to infer the cloud top height and then use channels which response (temperature/humidity Jacobian) is not significant at and below the cloud top. A good example is water vapor channels sensitive to humidity and temperature in the layer 200-500 hPa and not sensitive to cloud, temperature or gases at low levels. At MSC, this approach is used to assimilate GOES imager 3 radiances (6.7 μm). Based on a similar approach McNally and Watts (2003) designed a scheme to isolate clear radiances using AIRS data. The technique relies on O-P using most channels, with separation in bands to take into account the spectral variability of cloud emissivity. The cloud top height is not inferred. Our approach which attempts to infer the true cloud top height is conceptually simpler. It is also a necessary step toward the assimilation of cloudy radiances.

A nominal estimate of the cloud height HT is obtained from the effective height HE, previously defined. In the presence of non-black clouds or a partially filled field of view, HE is lower than the true height. The well established method of "CO2 Slicing" (CS, Menzel et al., 1983) can be used to infer the true height in addition to the effective cloud cover Ne which is the product of the cloud fraction times the emissivity. As will be shown, AIRS hyperspectral data provide the means to locally infer the uncertainty associated with the CS estimate, which is very useful. The method is based on the ratio of a pair of channels (a channel "k" paired with a reference channel "ref"), and searches for the pressure level p minimizing the difference:

$$(R_{clr} - R_o)_k / (R_{clr} - R_o)_{ref} - [Ne(R_{clr} - R_p)]_k / [Ne(R_{clr} - R_p)]_{ref} = F(p) \qquad (1)$$

where R_o is the observed radiance, R_{clr} the calculated clear radiance from the background and similarly R_p is the computed radiance from pressure level p. If cloud emissivity is assumed to be the same for the two channels, the ratio Ne_k/Ne_{ref} is unity which allows determination of the cloud pressure level cp. Once this is done, Ne can be found from either channel:

$$Ne = (R_{clr} - R_o) / (R_{clr} - R_{cp}) \qquad (2)$$

Programming the CS technique appears simple. However one soon realizes that there are many instances where the method provides no satisfactory answer. It is not meant to infer low cloud heights or clear skies. It is highly preferable to predetermine clear cases using for example an algorithm as that presented in Section 2.1. It does not work well in a nearly isothermal atmosphere, which is frequent in Arctic regions. Wylie et al. (1994) described other difficult situations such as the presence of multilayered clouds in the field of view. There might be more than one solution to (1). In part, these difficulties are due to the ratio technique. Channels too close in frequency are desirable for the equal emissivity hypothesis, but the method is more unstable with ratios near unity. After careful examination of the profile F(p), what was found to provide a robust estimate is the following:

1) Search for the first zero crossing (change in sign) of F(p). Reject if no zero crossing is found.
2) If the zero crossing occurs between levels J and J+1, then test for absolute values F(J-2) >

F(J-1) > F(J) and similarly that F(J+1) < F(J+2). In other words, a well defined minimum must be found.

3) Interpolate to F(p) = 0 to find the exact cloud pressure cp. Use (2) to get Ne.

There is a clear advantage to select a window channel as reference since such a channel is sensitive to clouds at all heights. On the other hand, a window channel is likely more subject to errors in the estimation of R_{clr}. This is another cause of possible difficulties associated with the method. Channel 528 (12.2 μm) was selected as reference channel. Twelve channels were paired with the reference channel to get as many estimates of HT and Ne: 204, 221, 232, 252, 262, 272, 299, 305, 310, 355, 362, 475. The following considerations played a role in the selection:

1) The range in wavelength is 12.2-14.4 μm. In that range the emissivity of ice clouds is similar (Ebert and Curry, 1992).
2) The monitoring should show reliable statistics as seen in Fig. 1 (Channels 89-122 for the 281 channel numbering).
3) Channels should not be very sensitive to water vapor or ozone.
4) The Jacobians should be well behaved with an isolated maximum as opposed to long stratospheric tails.
5) The use of high peaking channels (above 250 hPa) did not seem to add much. Therefore, these were not used.

3.2 *Results*

The CS technique can yield non physical results such as Ne < 0 or Ne >1. In the case of Ne > 1, HT becomes lower than HE (higher value of cloud top pressure). In those cases, HT is simply set to HE and Ne is set to 1. Values of Ne between 0.2 and 1.0 are considered valid. Values below 0.2 are often not reliable: in that case the inferred cloud top tends to be very high while the true situation may be clear. When Ne < 0, a limited examination of high resolution images seems to indicate that the sky is clear. Here an estimate was retained for Ne > 0.2 along with predetermined clear cases. The mean and variance of Ne and HT among up to 12 estimates were computed. Weighting the estimate of HT according to a criterion like dF(p)/dp did not seem justified. Rather, the variance estimate is used as a measure of uncertainty. Examples of results for HE, HT, Ne, their respective variance as well as the number of reliable estimates out of 12 are shown In Fig. 2 for portions of three consecutive orbits obtained within 2-h of 00 UTC February 3 2004.

The HE figure (2-a) shows a significant perturbation in the north with its typical comma shape. Elsewhere there are seemingly broad areas of clear skies or low clouds. The HT figure (2-b) provides good examples of HE = HT in the middle of fronts, and more interestingly HE < HT on the edge of fronts. The CS technique picks up thin cirrus ahead of perturbations and corrects the HE estimate. Cirrus are also apparent on the NW sector where the CS estimate is much higher (lower pressure) than HE. However the HT variance is relatively high in that sector (Fig. 2-c). Elsewhere, including near fronts, variances well below 50 hPa are the norm, which is excellent. Similarly Fig. 2d shows values of Ne well below unity ahead of fronts. Yet, the variance of Ne (Fig. 2e) remains low, most often < 0.1. The number of estimates (Fig. 2f) is high for high clouds (and predetermined clear) but low or zero in regions of very low clouds. Criteria have to be defined in order not to reject vast areas of low clouds where the estimate based on HE may be quite reliable. Currently, an estimate of HT is obtained for 65 % of the cases globally. Missing cases are linked to low clouds, near isothermal atmospheres and other causes and the distribution of HE for these cases spreads over the entire range.

4. Conclusion

Significant progress has been made at MSC to monitor AIRS hyperspectral radiances in view of assimilating both clear sky radiances and radiances which are not affected by low or mid level clouds. The CS technique was reexamined. The conditions leading to reliable estimates were established. The hyperspectral data opens new avenues to obtain a better estimate of cloud height along with a local estimate of uncertainty. The low variance associated to Ne in most instances is a nencouraging result. Independent validation using for example lidars would be desirable. An ambitious goal for future research is to aim at the assimilation of cloudy radiances, starting with opaque cloud cases.

5. References

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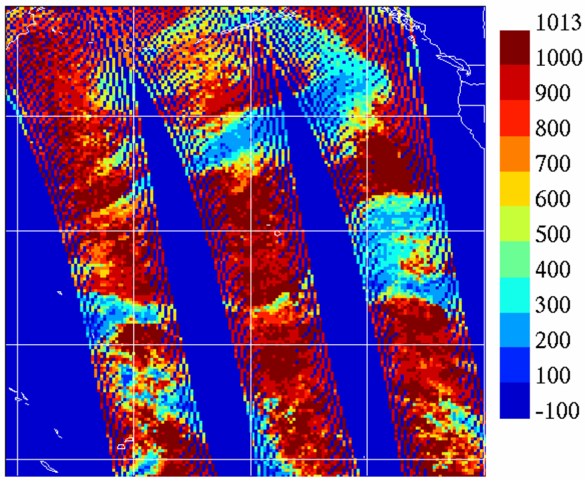

Fig. 2-a Effective height HE (hPa).

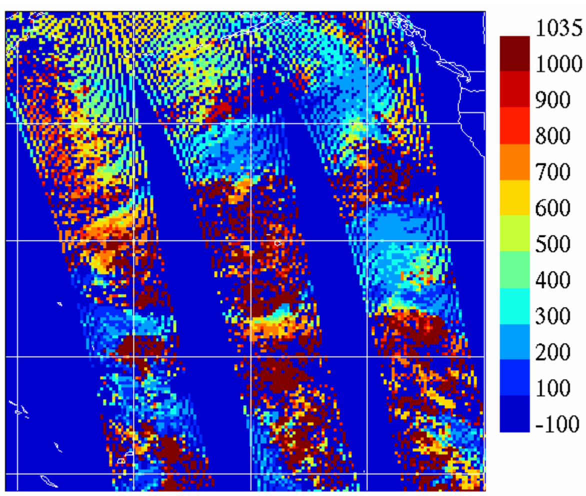

Fig. 2-b Average HT (hPa) from CS technique..

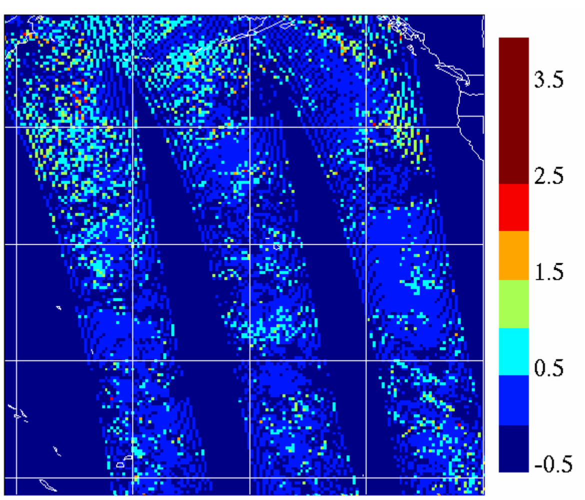

Fig. 2-c. HT Variance (0.5 means 50 hPa).

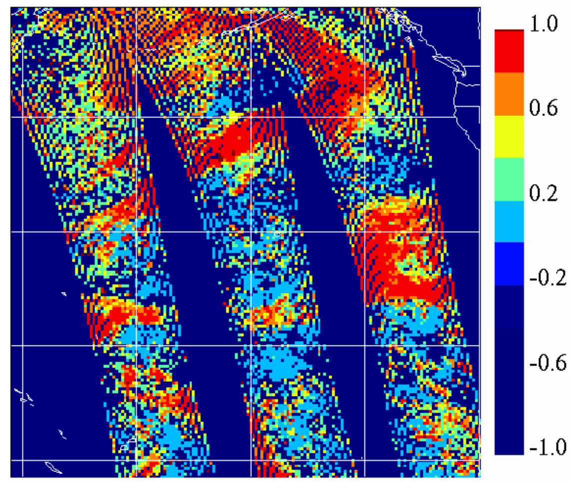

Fig 2-d. Average estimate of Ne.

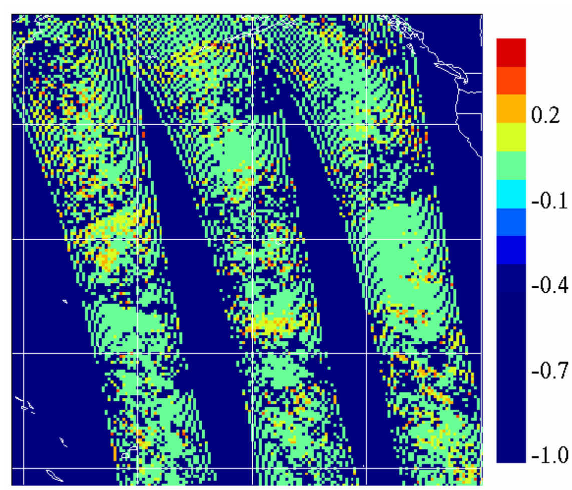

Fig 2-e. Variance of Ne. Green is 0.0 to 0.1.

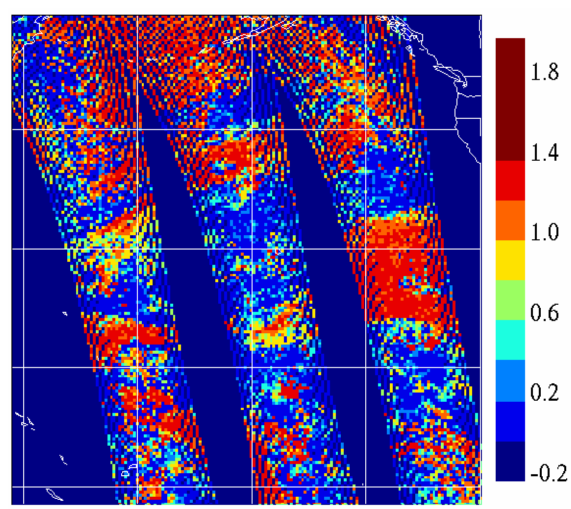

Fig. 2-f Number of reliable estimates (1.0 means 10).