HIRS/2-LIKE TOTAL WATER VAPOR COLUMNAR CONTENT MEASUREMENTS FROM AVHRR

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1. INTRODUCTION

Many algorithms have been proposed in order to measure total water vapor columnar content (precipitable water $PW$ in the following) at the global scale from satellite-borne multi spectral sounders. Accuracies from 0.145 to 0.17 cm have been obtained by using SSM/I over sea (see for example Schulz et al. 1993, Schluessel et al. 1990), between 0.3 and 1 cm by using VAS (Chester et al., 1987), AVHRR and HIRS/2 (see for example Schluessel, 1989 and references therein). Multi channel regressions have been used in order to predict $PW$ from measured radiances with coefficients computed by using some radiative transfer model (in order to produce synthetic satellite radiances) together with atmospheric profiles measured by radiosonde. Global, regional or local coefficients are then produced depending on how much atmospheric profiles are considered to be representative of global or local features. It is important to note as the reliability of algorithms drawn for the global scale could have strong degradation when the same algorithms are forced to depict phenomena whose spatial dynamics is typically high at wavelengths lower than mesoscale (see for example Jedlovec, 1990 and Klespies et al., 1990). This is particularly evident in the case of atmospheric water vapor, which high space-time variability has been observed both by active (lidar) and passive ground-based techniques (e.g. Cuomo et al. 1995a, 1995b, Rogers et al. 1991). By the other side algorithms addressed to measure $PW$ at the local scale offer accuracies which are usually better (see for example Eck et al., 1994) thanks to the calibration process which permits to define local coefficients related to local features (specially surface parameters). Generally speaking quality of $PW$ retrievals seems to be strongly dependent on instruments design (spectral capability and spatial resolution) as well as on the atmospheric water vapor space-time dynamics and observation conditions (land/sea, day/night, dry/wet atmosphere). Errors are generally higher over land (specially because of infrared emissivity indetermination and/or variability) and at $PW$ values lower than 1 cm (Jedlovec 1990); however larger mesoscale features (wavelengths greater than 100 km), low-level water vapor gradients as well as moisture sources and principal sink regions appear now to be resolvable from satellite observations. All the infrared-based algorithms work only in clear sky conditions (no clouds into the sounder
field of view). Consequently $PW$ is not achievable in cloudy or partly cloudy soundings which often occur in significant portions of a scene. In the case of soundings which are partly cloud contaminated, therefore, the use of independent, contemporary measurements obtained at higher spatial resolution would be useful to reduce the fraction of the scene in which water vapor cannot be retrieved. The merging process is not trivial and could give rise to strong inhomogeneity - mainly due to differences in instrument capabilities (spatial, spectral, temporal resolution and coverage) and retrieval techniques (global/local algorithms and validation data-sets) - which could be enhanced from the intrinsic space-time dynamic of the variable under study.

In this paper we face this problem in the case of precipitable water measurements performed at the global scale by using HIRS/2 and AVHRR based techniques. Higher spatial resolution offered by AVHRR could help in order to obtain PW measurements also in partly cloudy locations where HIRS/2 fails. By the other side HIRS/2 offers higher absolute quality of PW measurements at the global scale. The use of AVHRR in order to obtain HIRS/2-like PW sounding in partly cloudy condition will be discussed and a new merging approach suggested which is supposed to be suitable for extensions to the case of different instruments or different retrieval techniques.

Observed $PW$ spatial variability, related to observation conditions (land/sea, dry/wet atmosphere, sea/night), has been, at first, analyzed by using several satellite passes and co-located radiosonde over Europe. An optimal merging technique able to reproduce HIRS/2-like (no-bias, same error structure) $PW$ retrievals from AVHRR data in partly cloudy HIRS/2 locations, has been then proposed and results compared with coincident radiosonde.

Section 2 describes used data and algorithms. Section 3 describes results of the comparison between HIRS/2 $PW$ retrievals and corresponding AVHRR products averaged inside co-centered circles, of variable radius. The best averaging radius will be determined belong this section after a correlation analysis performed under different observational conditions.

In Section 4 a new merging technique will be proposed and its performances validated by using independent radiosonde retrievals.

Finally, in Section 5, we will draw some preliminary conclusions.

2. DATA SOURCE AND ALGORITHMS

Belong this work HIRS and AVHRR based $PW$ retrievals have been obtained by using algorithms proposed by the authors (Cuomo et al., 1995). Both algorithms are based on a
linear regression like:

\[ PW = a_0 + \sum_{i=1}^{N} a_i T^S_i \]  

(1)

where \( T^S_i \) are brightness temperatures in channel \( i \) for the sounder \( S \) (e.g. \( S = A \) for AVHRR, \( S = H \) for HIRS/2), and \( N \) the number of channels. Coefficients \( \{ a \} \) were computed, for various satellite zenithal view-angles, using 760, globally distributed, radiosonde profiles coming from the standard NOAA data-base and, as RTMs the MODTRAN package for HIRS and Woolf's package (Woolf, 1995) for AVHRR. The error associated with the AVHRR-based algorithms (split-window) was evaluated in 0.45 cm at all satellite zenithal angles. By using HIRS/2 channels 4, 8, 10, 11, 12 and 15 the associated r.m.s. was evaluated in 0.47 cm for NOAA11 satellite instrumental packages. This value will be assumed, in the following, as a reference value in order to evaluate the effectiveness of our approach in reproducing HIRS/2-like \( PW \)-fields by using AVHRR in partly cloudy conditions. Six NOAA 11 satellite passes (described in Table 1) were used belong this work together with 130 available, coincident (maximum time-delay 200 min.) radiosonde profiles. AVHRR cloud masks, obtained following Derrien et al. (1993), have been used in order to identify cloud-free locations and to measure cloud-contamination inside each co-located HIRS/2 spot. The clear qualifier \( C_q \) (defined as the percentage of cloud-free AVHRR soundings within each co-located HIRS/2 footprint) has been used in order to classify HIRS/2 soundings depending on their cloud-contamination.

3. DETERMINATION OF THE BEST AVERAGING RADIUS FOR AVHRR

As HIRS/2 and AVHRR have different FOV's size and spatial dynamics of \( PW \) can be high enough to exhibit field-structure even within HIRS/2 spots, one preliminary test has been performed in order to establish at which spatial resolution AVHRR-based \( PW \) product is better correlated with the corresponding, HIRS/2-based product. Both, AVHRR and HIRS/2, \( PW \) retrievals are available in cloud-free conditions. So we began by comparing co-located AVHRR-based \( PW \) retrievals, obtained as average within circles of variable radius (between 1 and 40 AVHRR pixels), with corresponding HIRS/2-based retrievals obtained in cloud-free conditions. Used radii (in AVHRR pixels) were \( r = 1, 2, 3, 4, 6, 8, 12, 20, 25, 30, 35, 40 \). For each selected \( r \), \( PW \) values were computed and compared with corresponding HIRS/2-based retrievals by using only cloud-free locations over all satellite passes. Standard correlation analysis was performed and the correlation coefficient \( R \) between HIRS/2 and AVHRR-based \( PW \) retrievals was computed for each selected \( r \). \( R \) values were also computed using only day-time or night-time scenes (three for both categories) and separately for land and sea locations. Results are shown in Figures 1 and 2 where \( R \) values are plotted against the merging parameter \( r \). By comparison,
HIRS/2 has FOVs of 17.4 km (nadir-view) at best and spacing between instantaneous FOVs (IFOV) of about 42 km (nadir-view and along-track scanning). So, on the r axis, HIRS/2 ground resolution, roughly corresponds to $r = 8$ and inter-sounding spacing to $r = 20$. In this way, $r = 40$ would roughly correspond to the area covered by four HIRS/2 soundings. Figure 1 shows as correlation coefficient $R$ has a similar behavior, for night and day-time passes. $R$ is higher than 0.65 when the value of $r$ is between 1 and 40 and higher than 0.8 for $4 < r \leq 8$. For $r < 4$, night-time retrievals give worse $R$ values even if still better than 0.75. Day time retrievals have quite stationary values with $R > 0.8$ for $r \leq 8$ so that a choice of the merging parameter $r = 8$ appears a good choice for both cases. At $r = 8$, a standard deviation $\sigma = 0.36cm$ was found for day-time passes, $\sigma = 0.34cm$ for night-time passes.

Figure 2 shows results obtained over sea (six passes) and over land (four passes only had cloud-free soundings over land). Correlation over sea locations shows a weak dependence on spatial resolution. $R$ is higher than 0.7 when the value of $r$ is between 1 and 40 and higher than 0.75 for $r \leq 8$. Over land the correlation is quite high ($R = 0.85$) at $r \leq 8$ and decreases as higher values of $r$ are reached. At $r > 18$, $R$ values become lower than corresponding values found for sea locations.

<table>
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<th>GMT</th>
<th>SCAN LINES</th>
</tr>
</thead>
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<td>01962</td>
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<tr>
<td>N1</td>
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<td>01969</td>
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<td>03:07:33</td>
<td>4881</td>
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Table 1. NOAA11 satellite passes identification.

Fig.1. Correlation analysis between HIRS/2 and AVHRR-based PW retrievals: correlation coefficient $R$ is plotted against the merging parameter $r$ separately, for day-time and night-time passes. Only cloud-free spots ($Cq=100$) are considered over all passes.

Fig. 2. As in Figure 1 but here results are separated for sea and land locations.
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These results well meet expected behavior of PW-field with spatial dynamics higher over land than over sea. Flat dynamics, associated with sea locations, makes correlation between AVHRR and HIRS/2 observations not strongly dependent on the size of the area where AVHRR retrievals are averaged. On the contrary, high PW variability over land, requires spatial constraints to be respected in order to obtain that, averaged AVHRR retrievals well represent the same situation measured by HIRS/2. As a result, a merging parameter of $r = 8$ seems to represent the best correlation between HIRS/2 and AVHRR-based PW retrievals, even if, for sea situations, different values of the radius $r$ appear able to give similar results. For $r = 8$, a standard deviation $\sigma = 0.36\,cm$ was found for sea locations, $\sigma = 0.37\,cm$ for land.

4. IN PLACE MERGING

In the previous section we have seen as PW retrievals, obtained from AVHRR and HIRS/2, are highly correlated with a maximum of correlation when a merging parameter $r \approx 8$ (in AVHRR pixels units) is used as averaging radius for AVHRR-based PW product. Figures 3 show, for $r = 8$, comparisons between AVHRR and HIRS/2 PW retrievals as obtained under different observation conditions. A best fit line is drawn between HIRS/2 (with $C_q = 100$) and AVHRR (with $r = 8$) based PW retrievals. Its equation is:

$$PW^H = A + B(PW^A)$$  \hspace{1cm} (2)

where superscripts $H$ and $A$ stand for HIRS/2 and AVHRR-based PW products. Values of $A$, $B$, and $R$, as well as standard deviation $\sigma$ and bias corresponding to the performed analysis are reported in Table 2. From Table 2 it is possible to see as associated dispersion ranges from $0.34$ cm (for night-time conditions) to $0.37$ cm (for land locations) with correlation coefficient $R$ ranging from 0.77 (sea locations) to 0.86 (land locations). Bias is generally high (between 0.60 for day-time set and 0.88 for land locations). Must be noted that dispersions are smaller than errors ($0.45$ cm for AVHRR, $0.47$ cm for HIRS/2-based PW retrievals) intrinsically associated with the used retrieval techniques. So, in principle, coefficients of (2) could be computed once for all by using a global collection of cloud-free HIRS/2 and co-located AVHRR soundings. By this way an expression as:

$$PW^S = A + B(PW^A)$$  \hspace{1cm} (3)

could be used to predict HIRS/2 PW retrievals ($PW^S$) in partly cloudy location ($C_q \leq 100$) where $PW^A$ values, thanks to the higher spatial resolution of AVHRR, are however available.

By the other side must be also noted as:
Fig. 3. HIRS/2-based PW retrievals over cloud-free (Cq=100) spots against co-located, AVHRR-based PW retrievals averaged at \( r=8 \). The corresponding correlation coefficient is indicated in parenthesis. a) three day-time passes (R=0.82); b) three night-time passes (R=0.81); c) only SEA locations over all passes (R=0.77); d) only LAND locations over all passes (R=0.86).

<table>
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<th>OBSERVATION CONDITIONS</th>
<th>A (cm)</th>
<th>B</th>
<th>( \sigma ) (cm)</th>
<th>bias (cm)</th>
<th>r.m.s.</th>
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<td>0.80</td>
<td>0.88</td>
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<tr>
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<td>0.82</td>
<td>0.89</td>
</tr>
<tr>
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<td>0.6</td>
<td>0.36</td>
<td>0.82</td>
<td>0.90</td>
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Table 2. Correlation analysis at \( r=8 \): results over all passes (see text)

<table>
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<tr>
<th>PASSES</th>
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<th>Q</th>
</tr>
</thead>
<tbody>
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<td></td>
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<td>B</td>
<td>R</td>
</tr>
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<td>0.91</td>
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</tr>
<tr>
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<td>1.08</td>
<td>0.83</td>
</tr>
<tr>
<td>N1</td>
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<td>0.79</td>
<td>0.90</td>
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<tr>
<td>N2</td>
<td>-2.59</td>
<td>1.68</td>
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<tr>
<td>N3</td>
<td>0.19</td>
<td>0.61</td>
<td>0.64</td>
</tr>
</tbody>
</table>

Table 3. Correlation analysis at \( r=8 \): results for each pass (see text)
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1) even in presence of strong correlations, strong biases are present and AVHRR over-estimates corresponding HIRS/2-based PW retrievals with relative differences up to 100% as far sea locations or night-time observations are concerned (see figures 3b and 3c).

2) coefficients $A$ and $B$ of equation (2) strongly depends on the selected observation conditions as it is possible to see from Table 2.

This situation is furthermore confirmed also from a scene by scene approach as it is possible to see from Table 3 which reports results obtained performing the same correlation analysis separately for each scene and for land and sea locations.

It is finally evident that if it is possible to find high correlation (with low dispersion) between HIRS/2 PW measurements and corresponding AVHRR-based products the form of this correlation is very sensitive to very local features. Results obtained on a scene by scene basis are much more significant if we consider that all the scene we used regard the same season (winter) and the same geographical area (Europe). From this it is easy to predict that higher and higher biases could be introduced from an attempting to use a global approach (i.e. coefficients of equation (2) and (3) established on a global basis by using, as usual, a collection of summer/winter, tropical/polar, etc., situations). A local more than a global approach seems to be mandatory in this case. Consequently, an in place technique has been developed in order to estimate HIRS/2 PW retrievals in partly cloudy spots by exploiting higher spatial resolution offered by AVHRR.

For each satellite scene, this technique will be based on the following steps:
- compute AVHRR-based cloud-mask
- co-locate HIRS/2 and AVHRR soundings and compute $C_q$ at each HIRS/2 spot
- use the chosen algorithm (as in equation (1) with $S = H$) in order to compute $PW^H$ at each HIRS/2 location where $C_q = 100$
- use the chosen algorithm (as in equation (1) with $S = A$) in order to compute $PW^A$ from co-located AVHRR soundings and average inside a circle of radius $r = 8$ (AVHRR pixels) around the center of the corresponding HIRS/2 spot.
- calculate linear regression (2) using separately land and sea locations
- use expressions (3), separately for land and sea, to predict HIRS/2-like $(PW^S)$ retrievals at each (partly cloudy) location where $PW^A$ values are available.

This technique was successfully applied to the selected satellite passes.

In the last column of Table 3, note the ratio:

$$Q = \frac{N(PW^H) + N(PW^S)}{N(PW^H)}$$

between the number of HIRS/2 locations where PW measurements were achieved using also AVHRR merging, and the number of locations (completely cloud-free) where
Fig. 4. HIRS/2-like PW measurements obtained from AVHRR against coincident radiosonde retrievals for all passes.

Fig. 5. Pass D2: Interpolated PW field obtained after in place merging of HIRS/2 and AVHRR-based PW retrievals (see text).
5. CONCLUSIONS

Different techniques devoted to measuring the same parameter can be merged in order to exploit different instrumental capabilities. Quality of merging products appears to be strongly dependent on the selected merging parameters (e.g. desired final spatial resolution), reliability of retrieval techniques and observation conditions. In this paper we have focused on these problems in the special case of AVHRR and HIRS/2 merging applied to the retrieval of precipitable water at the global scale. In partly cloudy conditions HIRS/2-based algorithms usually fail whereas coincident AVHRR clear-soundings can be found and therefore exploited to fill gaps into the HIRS/2-based retrieval field. So AVHRR higher spatial resolution can be exploited in order to extend the capability of HIRS/2-based techniques (more suitable for applications to the global scale) in order to retrieve total atmospheric water vapor content (PW) also in partly cloudy conditions. This means not only to largely extent the number of PW retrievals across a scene but also to obtain a more uniform distribution of them which can greatly help in the following interpolation steps (Cuomo et al. 1993). The main target of this work was the definition of a merging technique able to correctly introduce AVHRR-based information into an HIRS/2-based PW retrieval field. The proposed approach avoids to merge independent measurements as they are and forces one instruments (AVHRR) to reproduce results which could be achievable by the other (HIRS/2-like) at higher spatial resolutions. This approach comes from recognizing the higher reliability, at the global scale, of HIRS/2-based PW retrievals and exploiting the observed correlation (local) with corresponding averaged AVHRR-based products. Effects of atmospheric water vapor space-time dynamics have been considered and investigated by comparing HIRS/2-based PW retrievals with coincident measurements obtained by averaging AVHRR-based PW retrievals into different fractions of the corresponding (co-located) HIRS/2 footprint. Comparison was performed using only cloud-free locations across six satellite passes over Europe. At each cloud-free location, AVHRR PW retrievals were averaged inside circles of variable radius (r from 1 to 40 AVHRR pixels) to simulate PW retrievals at spatial resolutions ranging from 3 to 90 km. Correlations with corresponding HIRS/2-based products have been discussed to infer optimal averaging radius r depending on the observation conditions (day/night, land/sea). The analysis showed a linear correlation, between HIRS/2 and AVHRR-based retrievals, generally higher around r = 8 AVHRR pixels, under different observation conditions. High correlation (R \approx 0.8) and low dispersion (standard deviation between 0.35 cm and 0.37 cm) were found in all conditions with regression coefficients highly variable depending on the selected scene and observation conditions. So, an in place technique has been suggested in order to predict HIRS/2-like PW values in partly cloudy spots by exploiting higher spatial resolution offered by AVHRR. Linear regression coefficients have been computed separately.
for each scene, for land and sea locations, using only cloud-free locations. On the basis
of these coefficients, HIRS/2-like PW retrievals have been calculated, in partly cloudy
locations, using the established in place correlation and AVHRR PW products obtained
with \( r = 8 \). Results over several satellite passes have been analyzed in terms of restitution-
capability of a PW field from a richer (i.e. extended to include partly cloudy HIRS/2
spots) and homogeneous (HIRS/2-like), data-set. Comparison with PW retrievals from
coincident radiosonde demonstrates that our technique preserves the final r.m.s. under
the limit intrinsically associated to HIRS/2-based algorithms without introducing additional
bias. AVHRR-based, HIRS/2-like, PW retrievals obtained in partly cloudy HIRS/2 spots,
permits to largely extend (up to 10 times and more) the area where PW retrievals can be
obtained. The most relevant advantage offered by the proposed merging approach is the
possibility of taking into account local features (on a scene by scene basis) by using only
satellite data at hands and without biases typically associated with algorithms depicted
for global applications. It is opinion (and scheduled work) of authors that the proposed
approach could be suitable for products coming from other retrieval techniques and/or
instruments.

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