

THE TECHNIQUE TO DERIVE THE SURFACE TEMPERATURES AND PRECIPITABLE WATER CONTENT OVER LAND FROM AVHRR/TOVS IR WINDOW MEASUREMENTS

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1. INTRODUCTION

A knowledge of land surface temperatures (LST or T_s) is of significant importance for many applications including numerical weather prediction, climate and environmental studies, agrometeorology. Data on water vapour profiles in the atmosphere or total precipitable water (PW) content are required for assimilation in numerical weather prediction schemes and climate studies. Water vapour content in the atmospheric column is one of parameters affecting on the energetic and hydrological balance in the earth - atmosphere system.

Rather efficient way to monitor the LST and PW content is to use infrared (IR) radiance measurements from meteorological satellites. The measurements of outgoing IR radiances in atmospheric window 10.5-12.5 μm produced by the HIRS/2 (channel 8) and AVHRR (channels 4,5) instruments on board NOAA satellite are commonly used for getting these data. The cloudfree IR brightness temperatures T_r are converted to surface skin brightness temperatures or PW content estimates using so called split window method (SWM). It employs the linear combination (difference) of T_r in AVHRR IR channels 4, 5 (denote as A4, A5) and gives accurate retrieval of sea surface temperature (Emery et al., 1994) and PW content over sea surface (Dalu, 1986).

The largest error source in the application of the SWM for LST estimation is the non-blackness of land surfaces. The accuracy of LST retrievals suffers from inaccurate knowledge of the surface spectral emissivity (SSE). The values of SSE or ϵ_v , where v is wavenumber, are generally different from unity over the range 10.5-12.5 μm (Salisbury, D'Aria, 1992). The measured radiance variations in channels A4,A5 depend on the variations of atmospheric conditions, LST and SSE (Becker&Li, 1990a; Sobrino et al, 1991). To get accurate LST estimates it is necessary to take into account both the atmospheric attenuation and SSE variations effect but the number of unknowns exceeds the number of independent measurements (Li&Becker, 1993). To overcome this problem we propose to use as complementary information the measurements in IR window channel 8 of HIRS/2 instrument (H8, 11 μm) matched with AVHRR data and the simple relationship between ϵ_v in bands A4,A5,H8 (Uspensky, 1992; Uspensky&Scherbina, 1993). The suggested method develops the approach of (Becker&Li, 1990b) and is based on the analysis of non linear combinations of measurements in channels A4,A5,H8 for SSE derivation and on the application of local SWM for T_s estimation.

The problem of PW estimation over land surface from IR window measurements meets similar difficulties. The brightness temperatures difference $\Delta T_r = T_r(A4) - T_r(A5)$ used in the versions of SWM is the function of the atmospheric profiles of humidity and temperature and the channel emissivities. Both effects are coupled so that is not possible to separate them with AVHRR data only. Whereas for sea surface the difference ΔT_r can be used for the PW estimating, for land surface an additional information is required to separate the atmospheric and emissivity effects. It leads also to modification of the SWM. The extension to SWM for retrieving PW over land has been proposed in (Kleespiess&McMillin, 1990; Jedlovec, 1990). It requires a minimum of a priori information but uses the assumption of emissivity invariance. To overcome this restriction the using of combined AVHRR / HIRS data has been proposed. Our approach employs matched

measurements in the channels A4, A5, H8 for the estimation of the SSE, LST and successive PW derivation by means of local SWM.

The structure of the paper is as follows. The next two sections contain a short description of proposed technique for the estimation of SSE, LST and PW. Thereupon the application of this technique to actual satellite data is demonstrated.

2. SSE AND LST DERIVATION ALGORITHMS

In this section we formulate the procedure for estimation of the SSE and LST from combined measurements in channels A4, A5, H8, see (Uspensky&Scherbina, 1993) for more details. In order to separate the problems of ϵ_v , Ts estimating we define similarly to (Becker&Li, 1990b) the special nonlinear combinations of A4, A5, H8 channel radiances which are independent on the Ts. The analysis of these combinations or indices named TISI (Temperature Independent Spectral Indice) together with ancillary information on SSE behavior in A4, A5, H8 channel bands provides the derivation of ϵ_i , where $i= 1,2,3$ relates to channels A4, A5, H8 respectively. Then the version of local SWM technique is applied for Ts retrieval.

Thus the proposed SSE, LST retrieval technique consists of several stages:

Stage 1 - the derivation of TISI. The values of ground radiances $R_i = \epsilon_i * B_i[Ts]$ or channel radiances at ground level $J_{i,s} = R_i + (1 - \epsilon_i) * J_{i,a}^{\downarrow}$ are required for the TISI construction. Here $B_i[Ts]$ is the Planck function and $J_{i,a}^{\downarrow}$ is downwelling atmospheric radiance in channel i . The values of $J_{i,s}$ can be derived from radiative transfer equation $J_i = J_{i,s} * \tau_{i,s} + J_{i,a}^{\uparrow}$, where J_i is the channel measured radiance, $\tau_{i,s}$ is the total atmospheric transmittance function and $J_{i,a}^{\uparrow}$ is the upwelling atmospheric radiance. The results of objective analysis containing vertical temperature and humidity profiles $T^a(p)$, $q^a(p)$ in regular grid points are used for the calculation of $J_{i,s}$. Note that it is possible to use other approximate atmospheric models (climatic atmospheres) for estimating $J_{i,s}$ in sounding points, see (Li&Becker, 1993). We construct then TISI for two channels i and j by rationing the powers of radiances R_i , R_j or $J_{i,s}$, $J_{j,s}$: $w(i,j) = M(i,j) * R_i^{b(i)} / R_j^{b(j)} \cong M(i,j) * J_{i,s}^{b(i)} / J_{j,s}^{b(j)}$ where $M(i,j) = a(j)^{b(i)} / a(i)^{b(i)}$, $b(i)=1$, $b(j) = n(i)/n(j) \cong n(i,j)$; $a(i)$, $n(i)$ are the coefficients in channel Planck radiance approximation $B_i[Ts] = a(i) * Ts^{n(i)}$, see (Uspensky, 1992; Uspensky&Scherbina, 1993). The values of TISI do not depend on Ts since $w(i,j) = \epsilon_i / \epsilon_j^{n(i,j)}$ and can be used to determine SSE.

Stage 2 - the derivation of SSE. Experimental data from (Salisbury, D'Aria, 1992) generalized by Yu. Timofeev and shown partly at fig.1 demonstrate that the values of mean SSE in 10.5-12.5 μm region decrease monotonically with increasing the wave number for different types of land cover. Taking into account this fact and the form of normalized response functions for channels A4, A5, H8 within the band 10.5-12.5 μm (fig.1) it is possible to assume with a good approximation the validity of following relationship: $\epsilon_3 = 0.5 * (\epsilon_1 + \epsilon_2)$. This formula and the definition of the indices $w(1,2)$, $w(3,1)$, $w(3,2)$ (while neglecting the terms $J_{i,a}^{\downarrow}$) lead to the nonlinear equation for unknown ϵ_2 :

$$2 * w(3,2) * \epsilon_2^{n(3,2)} - w(1,2) * \epsilon_2^{n(1,2)} = \epsilon_2.$$

This equation has more complicated form if the terms $J_{i,a}^{\downarrow}$ are not neglected. The numerical solution of these equations can be found applying the Newtonian iteration algorithm (Uspensky, 1992; Uspensky&Scherbina, 1993).

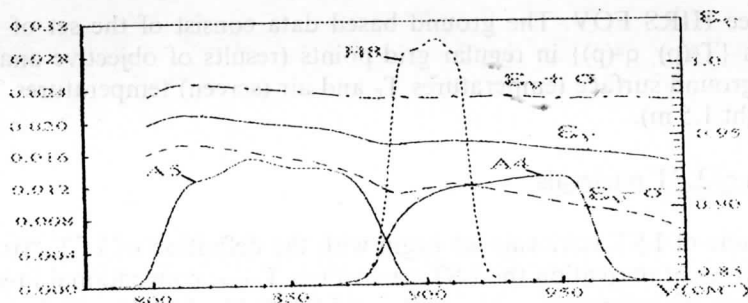


Fig.1. Filter normalized response of NOAA-11 AVHRR and HIRS/2 channels
 A4, A5, H8 and curves of mean emissivities ϵ_v , $\epsilon_v \pm \sigma$, σ - standard deviation.

Stage 3 - the derivation of LST. Once the ϵ_i are derived for channels A4, A5, we can apply one of the versions of local SWM for T_s retrieval. In this study the SWM formulae from (Becker&Li, 1990a; Sobrino et al., 1991; Uspensky&Scherbina, 1993) were utilized.

3. PW ESTIMATION ALGORITHM

The feasibility of deriving the PW content over sea from cloud free IR measurements in 10.5-12.5 μm band and some retrieval schemes have been considered since the beginning of 1980th, see for example (Aoki&Inoue, 1982; Dalu, 1986; Sutovsky et al., 1987; Schlüssel, 1989). Overview of some methods for retrieval PW over sea surface is given in (Schmetz&VandeBerg, 1991). Our studies of this item are overviewed in (Uspensky&Soloviev, 1994; Uspensky&Scherbina, 1996).

The background of application of the SWM for the PW retrieval over sea is well known formula (Dalu, 1986) : $T_{r,1}-T_{r,2}=\Delta T_r = (\tau_{1,s}-\tau_{2,s})*(T_s-T_a)\approx A*PW$. Here T_a is mean radiative temperature of the atmosphere, indices 1,2 relate to channels A4, A5 respectively. This formula leads to the following linear regression relationship between ΔT_r and PW: $PW=C1*\Delta T_r+C2$. Here $C1,C2$ are regression coefficients. The claimed accuracy for this approach (typical version of the SWM) is about 0.5 cm.

The situation is more complicated with PW retrieval over land surface. The simple extension of SWM doesn't work due to reasons mentioned in the introduction. The new approach for the PW derivation (Uspensky&Scherbina, 1996) develops the technique described above. It is also based on the synergistic use of AVHRR/HIRS data. If we define brightness temperatures at ground level $T_{gr,i}$ from formula $B_i[T_{gr,i}]= J_{i,s} \approx R_i$ than the following equation can be obtained from radiative transfer equation: $\Delta T_r = (\tau_{1,s}-\tau_{2,s})*(T_{gr,1} - T_a)+ \tau_{2,s}*(T_{gr,1} - T_{gr,2})$. Basing on this expression the following two versions of linear regression formulae can be suggested:

$PW=C1*\Delta T_r+C2*(T_{gr,1} - T_{gr,2})+C3$ or $PW= C1*\Delta T_r+ C2*(1- \epsilon_1)+C3*(\epsilon_1-\epsilon_2)+C4$. Their implementation assumes the knowledge of SSE and LST in sounding points. This fact together with the technique of SSE, LST estimation enables to propose the following strategy of PW retrieval over land. At first we employ the SSE and LST derivation algorithms (section 2, stages 1-3). Then we proceed to the final objective using one of suggested regression formulae for the estimation of PW content.

4 REAL DATA TEST

The test of ϵ_v , T_s and PW retrieval algorithms is to apply it to actual satellite data and to verify it with ground truth. The special data set of collocated and synchronized satellite and ground based observations has been compiled over region 52-63 °N, 30-41°E of Central European part of Russia for April-August periods of 1993-1995 and then was used to test the proposed technique. The satellite data set contains NOAA-11 day time images of AVHRR (channels A4,A5) and HIRS/2 data (channel 8). The AVHRR and HIRS/2 data matching is accomplished

for each cloudfree HIRS FOV. The ground based data consist of the set of temperature and humidity profiles $\{T^a(p), q^a(p)\}$ in regular grid points (results of objective analysis) and in-situ observations of ground surface temperatures T_g and air (screen) temperatures T_a just above the surface (at a height 1.5 m).

4.1 Validation of LST retrievals

To verify the results of LST retrievals we begin with the definition of LST "true" values. There are following sources of derivation the LST true values $T_{g,true}$: conventional in-situ observations, ground radiometric measurements and results of LST field objective analysis. Due to strong heterogeneity of LST field and local overheating effects it is difficult to obtain from routinely available in-situ observations the true temperature $T_{g,true}$ relevant for AVHRR or HIRS pixels. In order to derive the LST true values in sounding points as a standard for comparison with T_s we use the following linear combination of T_g, T_a : $T_{g,true} = \gamma * T_g + (1-\gamma) * T_a, 0 < \gamma < 1$.

The appropriate value of γ was determined through minimization of the RMS difference between measured (J) and calculated (J') radiances in sounding points. The calculations of "theoretical" channel radiances J' or Tr' use model from (Weinreb&Hill, 1980), the correlative data on $T_s, T^a(p), q^a(p)$ and "typical" values of ϵ_i in the range 0.95-1.0. As a result of such calculations for several dates the value $\gamma=1/3$ was defined. It should be noted that the data on vegetation indices derived from the AVHRR measurements in channels 1,2 can be treated for derivation of $T_{g,true}$.

As a typical example the application of proposed technique to one data set (26.04.94) was considered. For this date the 50 retrievals have been made in which the following necessary conditions took place: absence of clouds; $J_1 < J_3 < J_2$. As the first step the theoretical radiances J' were calculated for $\epsilon_i \equiv 0.99$ and then were compared with respective J_i values. According to preliminary estimates the proposed technique gives the underestimated values of SSE (in the range 0.65-0.8) for big values of residuals $\Delta J_i = |J_i' - J_i|$ ($> 7 \text{ mW/m}^2 \text{ cm}^{-1} \text{ str}$). It is difficult to interpret such underestimated values of ϵ_i in terms of apriory data on SSE (see fig.1), since the ϵ_i vary over a range 0.87-1.0 for different types of land surface.

The SSE, LST retrievals and following calculation of theoretical radiances J_i'' for $\epsilon_i = \hat{\epsilon}_i, T_s = \hat{T}_s$ should cause the decrease of residuals ΔJ_i . The comparison of RMS differences (D) between J_i' and J_i' (initial), or J_i and J_i'' (final) given below demonstrate this effect.

	D(initial)	D(final)
A4	4.75	1.93
A5	4.69	1.74
H8	4.90	1.91

The results of ϵ_i, T_s retrieval and collocated ground based data are given in table 1.

Table 1

 Satellite retrievals $\hat{\epsilon}_1, \hat{\epsilon}_2, \hat{T}_s$ and ground based data $T_g, T_{g,true}$

$\hat{\epsilon}_1$	$\hat{\epsilon}_2$	\hat{T}_s	T_g	$T_{g,true}$
.97	1.00	292.2	294.0	291.1
1.00	1.00	290.8	294.0	291.7
.95	.96	288.2	293.0	290.3
.92	.91	291.1	293.0	291.4
.91	.93	291.5	305.0	295.7
.93	.94	291.9	292.0	291.0
.93	.93	289.9	292.0	291.3
.96	.97	288.7	290.0	289.3
.95	.98	292.1	290.0	289.3
.89	.90	291.5	295.0	292.8
1.00	1.00	290.3	295.0	292.7
.93	.95	284.6	291.0	289.7
.94	.95	292.9	296.0	291.3
.94	.93	285.4	298.0	291.5

The maximum distance between positions of satellite soundings and related in-situ observations or ground truth data is 0.5' (latitude), 0.7' (longitude). The maximum time difference is 1 hour. As it can be seen from table 1 the big departures between satellite estimates T_s and in-situ data T_g relate to local overheating effects detected by in-situ pointwise observations. This effect is noticeably reduced when the ground truth standard $T_{g,true}$ is used for comparison with T_s .

The assessment of T_s retrieval quality has been performed for several dates. The basic statistics, i.e. the mean biases (b) and RMS errors (rmse) are given here for two samples:

b= -1.38 °C, rmse=2.7 °C; N=50; 26.04.94;

b= -1.17 °C, rmse=2.6 °C; N=54; 24.04.94.

4.2 Validation of PW estimates

Now we turn to the results of PW estimates verification. In the real data test the regression coefficients for formulas from section 3 were calculated using the learning sample of collocated satellite and ground based observations. Ground based observations were extracted from the same special data set as for LST validation. The technique of collocated radiances J' derivation (which are used instead of measured values) is described above. The assessment of PW retrieval quality has been performed for the same two dates. The basic statistics, i.e. the mean biases (b) and RMS errors are given here for joined sample (two dates, N=30):

b= -0.28 cm, rmse=0.46 cm.

The mean value of true PW content equals 2.04 cm for this sample.

5. CONCLUSIONS

To sum up the results of study we can conclude:

1. The efficient technique for LST and SSE retrieval from matched AVHRR/HIRS data has been developed. It provides reliable estimates for LST. The comparison with specially constructed LST true values gives the rmse in the range 2.0-3.0 °C.
2. The special ground-based measurements of SSE are required to assess the "physical" reliability of satellite estimates ϵ_i .
3. The proposed technique uses the matched AVHRR and HIRS measurements with different spatial resolution. This fact and strong heterogeneity of LST, SSE fields force to define efficient values of T_s, ϵ_i at various scales and to study the relationship between pointwise and averaged values. The definition of T_s, ϵ_i is made in this paper for HIRS/2 pixel (17-20 km) following (Li&Becker, 1993).

4. The technique for PW estimation over land surface from matched AVHRR/HIRS data has been developed. The comparison with PW true values (results of objective analysis of humidity fields) gives RMS errors in the range 0.3-0.6 cm for different dates and situations.
5. It is necessary to develop the procedure of humidity vertical profile refinement on the base of PW estimates.
6. The further improvements of LST, PW retrieval algorithms are required to make them more robust.

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**TECHNICAL PROCEEDINGS OF
THE NINTH INTERNATIONAL TOVS STUDY CONFERENCE**

Igls, Austria

20-26 February 1997

Edited by

J R Eyre

Meteorological Office, Bracknell, U.K.

Published by

European Centre for Medium-range Weather Forecasts
Shinfield Park, Reading, RG2 9AX, U.K.

May 1997