Low-Level Water Vapor Fields from the VISSR Atmospheric Sounder (VAS) “Split Window” Channels

DENNIS CHESTERS AND LOUIS W. UCCELLINI
Goddard Laboratory for Atmospheric Sciences, NASA/Goddard Space Flight Center, Greenbelt, MD 20771

WAYNE D. ROBINSON
Computer Sciences Corporation, Silver Spring, MD 20910, Goddard Laboratory for Atmospheric Sciences, NASA/Goddard Space Flight Center, Greenbelt, MD 20771

(Manuscript received 28 May 1982, in final form 4 February 1983)

ABSTRACT

A simple physical algorithm is developed which calculates the water vapor content of the lower troposphere from the 11 and 12 μm (split window) channels on the VISSR Atmospheric Sounder (VAS) on the Geostationary Operational Environmental Satellites (GOES). The algorithm is applied to a time series of VAS split window radiances observed at 15 km horizontal resolution over eastern North America during a twelve hour period on 13 July 1981. Color coded images of the derived precipitable water (g cm⁻²) fields show vivid water vapor features whose broad structure and evolution are verified by the radiosonde and surface networks. The satellite moisture fields also reveal significant mesoscale features and rapid developments which are not resolved by the conventional networks. The VAS split window clearly differentiates those areas in which water vapor extends over a deep layer and is more able to support convective cells from those areas in which water vapor is confined to a shallow layer and is therefore less able to support convection. The spatial and temporal continuity of the water vapor features indicates very good relative accuracy, and point verification at radiosonde sites indicates fair absolute accuracy. Surface temperature variations are very effectively removed by the algorithm. Consequently, the VAS split window could be used operationally to monitor mesoscale developments in the low-level moisture fields over relatively cloud-free areas of the United States.

1. Introduction

The development of convective storm systems depends upon several critical factors, including the initial distribution of water vapor. While this is an obvious prerequisite for the development of precipitation in general, our ability to accurately forecast convective systems is seriously impaired by our inability to measure the mesoscale water vapor structure using the available radiosonde network (Browning, 1980). In the convective environment, two-thirds of the water vapor variance exists on scales of less than 200 km, while one-third of the variance occurs on this scale for the non-convective environment (Barnes and Lilly, 1975). Recent numerical experiments indicate that the amount of precipitation predicted by a mesoscale model depends significantly upon the detailed water vapor structure (Perkey, 1980). In these simulations, the precipitation amounts computed within squall lines were greatly enhanced when the initial state was specified to contain mesoscale moisture variations. These results suggest that improved mesoscale water vapor observations should have a significant impact upon the analysis and prediction of those processes which lead to the development of convective storm systems.

This paper describes a fast, simple algorithm for determining the detailed mesoscale structure of the low-level precipitable water from the VAS “split window” channels at 11 and 12 μm. The low-level moisture algorithm presented in Section 2 is based on a physical model for radiation transfer through a single thick layer of moist air in the lower troposphere. The two-channel algorithm involves three unknowns: surface temperature, air temperature and integrated water vapor. Consequently, the calculation requires one empirical parameter derived from conventional weather data. We use the “average air (brightness) temperature” for the lower troposphere, whose value is determined at clear radiosonde sites imbedded within the VAS radiance field. The algorithm is refined on simulated VAS data in order to parameterize the average molecular absorption and to establish quality controls for radiometric noise and unresolved clouds. Section 3 demonstrates the low-level moisture algorithm using a case study approach for one day of VAS observations. A color coded image sequence of precipitable water fields over the United States is computed from the split window radiances. Areas are noted where VAS indicates a large water vapor content and/or gradient before the outbreak of convective activity. The error budget for the split window algorithm is analyzed, and the satellite-derived precipitable water estimates are verified by comparison to independent radiosonde reports. Several possible enhancements of the algorithm are outlined, and two schemes for incorporating additional VAS or con-
ventional data fields are tested. Section 4 summarizes the results and discusses some related studies.

2. Model for low-level moisture in the VAS split window

a. Background

The VISSR Atmospheric Sounder (VAS) is the thermal infrared radiometer now operating on the Geostationary Operational Environmental Satellite (GOES). The VAS instrument is an improved version of the previous imager on the GOES, with eleven infrared channels added to the 11 \textmu m window and visible detectors. Radiometric quality has been upgraded to meet remote sounding requirements, with ten bit precision instead of eight, \( \pm 1.5 \) K calibration accuracy instead of \( \pm 3.0 \) K, and six infrared detectors instead of one. The VAS is designed to exploit its geosynchronous station by observing the development of mesoscale temperature and water vapor fields with frequent multi-channel images at 15 km horizontal resolution (nadir view) in the spectral windows and molecular absorption bands of the earth’s thermal infrared spectrum (Suomi et al., 1971). In particular, the pair of channels at 11 and 12 \textmu m are designed to use the differential water vapor absorption across this part of the spectrum in order to estimate the water vapor absorption along the line of sight. The two channels are called a “split window” because they use the difference in brightness at two adjacent bandpasses in order to separate the atmospheric and surface radiance contributions (see Fig. 1). One intuitively expects some simple combination of the VAS split window radiances to measure the water vapor content of the lower troposphere. A two-channel estimate of the integrated water vapor is certainly not as sophisticated as a water vapor profile retrieval which uses all of the VAS channels and human quality control. Rather, the estimate is intended to be a real-time high-resolution mesoscale field which displays the horizontal water vapor distribution with fair absolute and very good relative accuracy.

In the near future, NOAA will operate VAS with minimal impact upon the pre-established community of operational VISSR data users. Even now, the additional infrared detectors make it possible to deliver both the VISSR channels (visible and 11 \textmu m) and two other infrared channels simultaneously, in what is called the “Transparent Multi-Spectral Imaging” (TMSI) mode. Consequently, three VAS infrared channels (6.7, 11 and 12 \textmu m) could be used routinely to monitor mid-level and low-level water vapor fields at mesoscale resolution. These expectations have motivated the development of an algorithm which can automatically produce real-time water vapor fields from these channels alone.

In general, remote water vapor sounding from satellite radiances is more difficult than temperature sounding because:

1) Vertical water vapor structures are usually unresolved by the broad vertical extent of the passive radiometer response functions.

2) Most of the precipitable water along a line of sight is concentrated in the air just above a bright background of highly variable topography, emissivity and skin temperature.

3) The radiance contribution from the atmosphere is a nonlinear combination of both air temperature and water vapor content.

Nevertheless, some quantitative information about the atmospheric water vapor has been retrieved over land from thermal infrared satellite data. Recent case studies of mesoscale water vapor retrievals with the High-Resolution Infrared Sounder (HIRS) over the Texas–Oklahoma area were able to display dryline features down to the 30 km horizontal resolution of that instrument (Hillger and Vonder Haar, 1981). These HIRS analyses could only determine the relative horizontal structure of the water vapor features, and not their absolute magnitudes. Similar error patterns have also been found in the operational satellite temperature soundings: there are larger errors near the surface, biases in areas of unusual topography or clouds, and systematically underestimated horizontal gradients. Such problems have been found both over ocean (Phillips et al., 1979) and over land (Schlatter, 1981). Likewise, simulated case studies of VAS water vapor retrievals within pre-convective environments have shown a pattern of good relative gradient determination, but poor absolute accuracy (Chesters et al., 1982). In particular, the VAS simulations showed a poor linear correlation between the split window brightness difference and the low-level mixing ratio, due to the general difficulties with water vapor retrievals.

The first VAS instrument was launched on GOES-4 in September 1980 and was used operationally at 135\textdegree W from March 1981 until its failure in December 1982. Experience with the first VAS data indi-

![Fig. 1. The VAS water vapor channels are illustrated by (A) a sketch of the earth's radiance spectrum compared to (B) the spectral sensitivities of the filters at 11, 12 and 6.7 \textmu m.](image-url)
cated that the instrument is a relatively stable, somewhat biased radiometer (Chesters et al., 1981; Menzel et al., 1981). Temperature and water vapor profiles have been retrieved by using careful radiometric corrections and a physical retrieval method at hand-picked, clear fields-of-view (Smith et al., 1981). The VAS radiances from GOES-4 have also been used in a regression retrieval scheme to interpolate mesoscale temperature and water vapor fields between radiosonde stations (Chesters et al., 1981). Subsynoptic low-level water vapor features definitely appear in objective analyses of the VAS soundings from both retrieval methods. Mesoscale features derived from VAS cannot be verified with the relatively coarse, infrequent radiosonde network. In this sense, VAS is the only available source of frequent, quantitative, high-resolution atmospheric data for the United States. The data used in this paper are from the second VAS instrument, launched on GOES-5 in May, 1981. The data were acquired during demonstration and testing of the VAS Processor at NASA/GSFC in July 1981 just before GOES-5 was moved in August 1981 from its post-launch station at 85°W to its current operational station at 75°W.

b. The VAS split window

A “split window” requires two channels at adjacent wavelengths in a fairly transparent region of the earth’s atmospheric spectrum. Because the radiances in both channels are subject to nearly the same modifications by surface emittance, aerosols and clouds, the difference in brightness temperature is controlled by the differential molecular absorption. The molecular and surface contributions to the radiance can be separated algebraically, and then the molecular concentration can be determined from calculated values of the absorption cross sections. Naturally, the reliability of this method depends upon several factors, including the accuracy of the radiometer, the field-of-view registration between the channels, the parameterization of molecular absorption cross sections, the criteria for cloud rejection, and the formulation of an algorithm which is robust enough to operate with only two channels and simple quality controls.

The VAS split window covers the 11–13 \( \mu \text{m} \) region of the earth’s radiance spectrum, which is sketched in Fig. 1. The window region is bracketed by the 10 \( \mu \text{m} \) ozone band and the 15 \( \mu \text{m} \) carbon dioxide band, with increasing molecular absorption at the longer wavelengths due to water vapor and carbon dioxide. The differential absorption across the split window was originally proposed as the basis for a correction to the sea surface temperature derived from the VISSR 11 \( \mu \text{m} \) window (Prahabakara et al., 1974). The 11 \( \mu \text{m} \) window has been used to estimate the precipitable water (PW) over tropical oceans by relying upon the stable atmospheric and sea surface conditions to allow the moisture content to be calculated from just one channel (Aoki and Inoue, 1982). Differential absorption by the individual water vapor lines at 9 \( \mu \text{m} \) has been observed by the Infrared Interferometer Spectrometer (IRIS) on Nimbus-4, and the difference has been used to estimate precipitable water over the oceans (Prahabakara et al., 1979). The algorithm presented in this paper uses the 11 and 12 \( \mu \text{m} \) channels to eliminate the background (skin) temperature in order to calculate the water vapor absorption over land as well as water.

The standard radiance weighting functions for the VAS 11, 12 and 6.7 \( \mu \text{m} \) channels are shown in Fig. 2; the shapes of the weighting functions reflect the smooth vertical water vapor profile of the U.S. Standard Atmosphere. The 11 and 12 \( \mu \text{m} \) channels transfer radiance from the entire lower troposphere (600 to 1000 mb), with the radiance exchange concentrated near the boundary layer, where most of the water content exists. The other moisture-sensitive channel is centered on the strong 6.7 \( \mu \text{m} \) water vapor absorption band, which obscures the view of the lower troposphere. Mid-level tropospheric water vapor image fields have been investigated with this bandpass from polar orbit using Nimbus-4 data (Rodgers et al., 1976), and also from geosynchronous orbit using both METEOSAT data (Ramond et al., 1981) and VAS data (Petersen et al., 1982).

c. The single layer model

A single layer radiation model for the low-level water vapor is suited to the limited vertical resolution of the VAS 11 and 12 \( \mu \text{m} \) channels shown in Fig. 2. The main features of the model are: a surface radiating at an effective temperature \( T_{\text{eff}} \), a layer of air radiating at an average temperature \( T_{\text{air}} \), and a satellite-observed brightness temperature \( T_{\text{sat}} \) in bandpass \( \nu \). The water vapor-determined transmittance (\( r_v \)) controls the blend of surface and air brightness in a linearized radiation transfer equation:

![Fig. 2. Radiance weighting functions for the VAS water vapor channels at 11, 12 and 6.7 \( \mu \text{m} \).](image-url)
\[ T_\nu^* = T_{sfc} \tau_\nu + T_{air}(1 - \tau_\nu), \]
\[ \tau_\nu = \frac{T_\nu^* - T_{air}}{T_{sfc} - T_{air}}. \] (1)

In the first form of (1), surface radiance is attenuated by the factor \( \tau_\nu \) and is replaced by the corresponding fraction \( 1 - \tau_\nu \) from the air. The net effect is controlled by both the surface-to-air temperature contrast and the available water vapor. Previous VAS studies (Chesters et al., 1981 and 1982) attempted to use the simple algebraic difference between the split window brightness temperatures \( (T_{12}^* - T_{11}^*) \) as a measure of the water vapor content. However, both theory and practice show that the variability of the underlying surface (skin) temperature undermines this simple water vapor indicator.

In the second form of (1), the transmittance is expressed as the fraction of the surface-to-air temperature contrast which is observed from the satellite. The transmittance ratio between the 11 and 12 \( \mu \)m split window removes the difficult surface term:

\[ \frac{\tau_{12}}{\tau_{11}} = \frac{T_{12}^* - T_{air}}{T_{11}^* - T_{air}}. \] (2)

The steps required for the application of (2) to the VAS split window are: 1) a simple parameterization linking the transmittance ratio to the water vapor content, and 2) an empirical method for determining the air temperature.

d. Parameterizing the transmittance

Transmittance \( \tau(P) \) is the probability of the satellite observing a photon at wavenumber \( P \) after it has passed up through the atmosphere from pressure level \( P \). The total transmittance can be computed exactly from radiosonde temperature and water vapor profiles as the product \( \tau^{\text{dry}} \tau^{\text{wet}} \) between the transmittance through the dry, well-mixed gases (CO\(_2\), NO\(_x\), CH\(_4\), N\(_2\), and O\(_2\)) and the transmittance over the water vapor profile. Exact transmittance calculations must be done laboriously from molecular line-by-line cross sections (McClatchey et al., 1973), including p-type and e-type continuum cross sections (Roberts et al., 1976). For practical use in real-time computations, the transmittance for each channel at every VAS field-of-view is estimated from average values of the wet and dry absorption coefficients for a single layer atmospheric model with weak absorption:

\[ \tau^\text{tot} = \tau^\text{wet} \tau^\text{dry}. \]
\[ \tau^\text{wet} = \exp[-\sec(\theta)(a_{PW} + a'_{PW}^2)] \]
\[ \tau^\text{dry} = \exp[-\sec(\theta)(k_i + k_i'(T_{air} - 280 \text{ K})]}. \] (3)

The water vapor transmittance in (3) is parameterized with absorption cross sections and the precipitable water (PW, measured in g cm\(^{-2}\)) projected on the line-of-sight, using the zenith angle \( \theta \). The water vapor term contains both a linear \( (a_i) \) and a second-order \( (a'_i) \) dependence upon the precipitable water, representing both line-by-line and continuum absorption. The dry absorption coefficient for the well mixed gases is parameterized with both a constant \( (k_i) \) and a first-order \( (k'_i) \) temperature dependence, representing the effect of air temperature upon the CO\(_2\) absorption. The modest effects of the \( a'_i \) and \( k'_i \) terms may be ignored within a single air mass, but the \( a'_i \) term should be included for the moisture range over the United States, and the \( k'_i \) term should be included for the temperature range over the globe.

The absorption parameters \( (a_i, a'_i, k_i, k'_i) \) were determined by least squares fits to exact multi-layer transmittance calculations for a wide ranging (arctic to tropical) set of 32 radiosonde reports, simulated at zenith angles from 0\(^\circ\) to 50\(^\circ\). Average values of the absorption parameters are listed in Table 1 for selected VAS channels. They should apply with acceptable precision to any clear VAS field-of-view. The rms error in the transmittance ratio \( \tau_{12}/\tau_{11} \) was \( \pm 0.035 \) over the global range of simulated conditions. The error in this ratio for the 13 July 1981 VAS data is approximately \( \pm 0.025 \), which corresponds to approximately \( \pm 0.3 \text{ g cm}^{-2} \) uncertainty (less than \( \pm 10\% \)) in the total precipitable water.

The water vapor absorption cross section is approximately twice as great at 12 \( \mu \)m as at 11 \( \mu \)m. The transmittance in the VAS 11 \( \mu \)m channel is typically \( \tau_{11} = 0.60 \), so that the satellite receives roughly 60% of the photons emitted by the surface at 11 \( \mu \)m, and only 36% (i.e., 0.60\(^2\)) at 12 \( \mu \)m. Consequently, the two channels provide a distinct separation of the radiometric affects of surface temperature and water vapor in the lower troposphere. Fig. 3 shows simulated brightness temperatures in the VAS split window channels using (1) and (3) and Table 1 for a range of \( T_{surf} \) (280 to 320 K) and PW (0 to 6 g cm\(^{-2}\)) values, with \( T_{air} \) fixed at 280 K and sec(\( \theta \)) at 1.25. For a completely dry atmosphere (PW = 0 g cm\(^{-2}\)), both channels appear a little cooler than the surface due to the CO\(_2\) absorption. For normal atmospheres (PW = 1 to 4 g cm\(^{-2}\)), the 12 \( \mu \)m channel reveals more of the surface-to-air temperature contrast than the 11 \( \mu \)m channel, providing a good differential sig-

| Table 1. Wet and dry absorption parameters derived from least squares fits to exact calculations for a wide range of transmittance for the VAS windows and lower tropospheric channels. Reflected sunlight can be a substantial factor in the 3.9 \( \mu \)m window. |

<table>
<thead>
<tr>
<th>Channel (( \mu )m)</th>
<th>( \nu ) (cm(^{-1}))</th>
<th>( a ) (g cm(^{-2}))</th>
<th>( a' ) (g cm(^{-2}))</th>
<th>( k ) (K(^{-1}))</th>
<th>( k' ) (K(^{-1}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>11.2</td>
<td>897.40</td>
<td>0.0860</td>
<td>0.001572</td>
<td>0.00107</td>
<td>0.00019</td>
</tr>
<tr>
<td>12.7</td>
<td>789.24</td>
<td>0.2217</td>
<td>0.002098</td>
<td>0.00611</td>
<td>0.00091</td>
</tr>
<tr>
<td>13.3</td>
<td>750.35</td>
<td>0.2734</td>
<td>0.002670</td>
<td>0.7109</td>
<td>0.00727</td>
</tr>
<tr>
<td>3.9</td>
<td>2541.1</td>
<td>0.0200</td>
<td>-0.00059</td>
<td>0.1257</td>
<td>-0.00025</td>
</tr>
<tr>
<td>4.4</td>
<td>2252.6</td>
<td>0.0405</td>
<td>-0.00221</td>
<td>1.3070</td>
<td>0.00252</td>
</tr>
</tbody>
</table>
The radiosonde-based average \( \langle T_{\text{air}} \rangle \) from (5) is used in (4) to make satellite estimates of PW over the rest of the field. The radiation transfer model represented by (4) actually treats the “average air (brightness) temperature” \( \langle T_{\text{air}} \rangle \) as an empirical parameter which accounts for the lower tropospheric radiances in the split window. An even simpler empirical method for estimating \( \langle T_{\text{air}} \rangle \) is manual adjustment so that the satellite-derived precipitable water values nearly match the values expected within the scene. This subjectively derived model can only be estimated from climatological considerations, such as for oceanic fields. More elaborate horizontal models for the air temperature field are investigated in Section 3b.

The sensitivity of satellite-derived precipitable water to the air temperature can be estimated from (4) as the derivative \( d\text{PW}/dT_{\text{air}} \). For typical midsummer conditions of \( T_{\text{ref}} = 300 \) K, \( T_{\text{air}} = 280 \) K, \( \text{PW} = 4 \) g cm\(^{-2}\) and \( \sec(\theta) = 1.25 \), the sensitivity is \( d\text{PW}/dT_{\text{air}} = 0.7 \) g cm\(^{-2}\) K\(^{-1}\). Such sensitivity makes the satellite-derived water vapor fields sensitive to biases. Like previous studies, this report finds evidence for very good determination of the relative water vapor minima, maxima and gradients, but less certain absolute accuracy. Indeed, the parameter \( T_{\text{air}} \) behaves like a scaling factor for PW in (4), and our empirical approach to the air temperature determination is intended to cancel as many biases as possible.

### f. Quality control

Fig. 3 indicates that the VAS water vapor estimate will suffer when there is low contrast between air and surface temperature or when there are large amounts of precipitable water along the line-of-sight. The noise in the VAS split window channels is approximately \( \pm 0.5 \) K (Chesters et al., 1981), so that the water vapor estimates are significantly limited under low contrast conditions. Clouds in the field-of-view also cause the brightness temperatures in the split window channels to decrease and approach one another, so that the precipitable water solution in equation (4) becomes biased and sensitive to noise, due to the small differences with respect to the “air temperature.” Consequently, a series of simple threshold tests is used to identify doubtful fields-of-view:

\[
\begin{align*}
\text{Reject if} & \quad (T_{\text{P}} - T_{\text{air}}) < 1 \text{ K in either channel} \\
& \quad \text{or} \quad (T_{\text{P}} - T_{\text{air}}) < 1 \text{ K} \\
& \quad \text{or} \quad \text{PW} > 6 \text{ or } 10 \text{ g cm}^{-2} \\
\end{align*}
\]

(6)

The first threshold accounts for most of the rejected pixels, which are cold cloud tops. The second thresh-
old rejects low contrast conditions. The third threshold provides some subjective quality control—PW values greater than 6 g cm$^{-2}$ indicate the influence of clouds which are unresolved by the VAS 15 km footprint, warning the user to regard those areas with suspicion.

3. VAS split window observations of low-level water vapor

a. Case study, 13 July 1981

At 1200 GMT on 13 July 1981, a weak surface low was drifting slowly from eastern Colorado toward

---

Fig. 4. NWS maps of conventional surface data are shown at: (A) 1200 GMT 13 July 1981, (B) 1800 GMT 13 July 1981 and (C) 0000 GMT 14 July 1981; the solid lines are isobars (e.g., 16 = 1016 mb) and the dashed lines are isotherms ($^\circ$C). The corresponding radar precipitation maps are shown at: (D) 1135 GMT, (E) 1735 GMT and (F) 2335 GMT on 13 July 1981: maximum tops (dkm) are underlined, and an arrow with a number indicates direction and speed (m s$^{-1}$) for the convective system.
Nebraska, with a cold front extending from Nebraska toward northern Illinois and into the southern Great Lakes region (Fig. 4a). The southeastern United States was dominated by a broad high pressure system centered near the Mississippi and Alabama border. The resultant anticyclonic circulation forced a southerly air flow over a rather broad band west of the Mississippi River. This air was noticeably and uniformly humid with surface dewpoints greater than 20°C over the region from the Gulf of Mexico northward into southern Minnesota, and with dewpoints greater than 24°C located both in southern Illinois and near the Gulf Coast. Precipitation observed by radar (Fig. 4d) was mainly confined to thunderstorms along and to the north of the cold front, extending along a line from South Dakota to the Ohio valley. Weak thunderstorms and showers were also reported in the Texas–Louisiana coastal area.

By 1800 GMT, the southerly air flow and the morning insolation had forced surface temperatures to rise well above 30°C over the central United States, while the dewpoints remained high (Fig. 4b). Two
distinct dewpoint maxima are observed, one directed from the Gulf of Mexico toward eastern Oklahoma and the other extending from Iowa to Ohio. A noticeable gradient in the dewpoints is evident in the area between eastern Colorado and eastern Kansas. The thunderstorms originally in South Dakota had drifted northward and diminished in intensity, while the storms originally in Iowa weakened considerably as they moved into Illinois (Fig. 4e). The convection along the Gulf Coast continued to intensify and numerous rain and thundershowers were reported east of the Mississippi River.

By 0000 GMT on 14 July 1981, two regions persisted where the surface dewpoints exceeded 24°C: in the Gulf States region extending northward to eastern Oklahoma, and immediately along the warm front now observed over Iowa and west central Illinois (Fig. 4c). The dewpoint gradient from eastern Nebraska to Kansas strengthened considerably as drier air moved east-northeast from Colorado into Nebraska. The relative dewpoint minimum in western and central Missouri became more distinct at this time, while the air in the rest of the Mississippi Valley remains almost uniformly moist. Scattered rainshowers developed in the area of Kansas, Oklahoma and Arkansas, and heavier thunderstorms developed from New Mexico to western Nebraska, while the band of thunderstorms continued along the Texas–Gulf Coast region (Fig. 4f). In Iowa, intense thunderstorms with tops approaching 18000 m developed south of the frontal zone and were accompanied by weaker cells in extreme eastern Nebraska.

Our application of the VAS split window will focus upon the changes in the water vapor field in the middle portion of the United States, where scattered rain showers developed in Oklahoma and intense thunderstorms went through various stages of development in Iowa and Illinois.

b. Satellite imagery

Satellite images help one to understand and evaluate the low-level water vapor algorithm. Fig. 5 contains four satellite images of the United States at midmorning on 13 July 1981:

1) Fig. 5a is an operational visible VISSR image taken from SMS-3 at 1430 GMT. At 1 km resolution, it shows that the central United States is relatively cloud free, demonstrating that unresolved clouds are not a serious hazard at this time to processing the VAS thermal infrared data at 15 km resolution. Visible imagery was not available at 1200 GMT, due to the low sun angle at that time, so we must assume that similar cloud conditions existed during the preceding VAS and radiosonde observations. Visible imagery taken after 1500 GMT shows the development of broken clouds over much of the east-central United States, along with the development of overcast conditions in the regions of precipitation found in Figs. 4e and f.

2) Fig. 5b is the VAS 11 μm infrared image taken from GOES-5 at 1500 GMT. For inter-channel comparisons, the radiances have been converted to brightness temperature over a range from 200 to 320 K, with a color coded spectrum assigned in 10 K steps. Each color is shaded internally to display detailed gradients more clearly. A typical clear pixel in the central United States has \( T_{\text{IR}} \) between 290 and 300 K, color coded red. At 1500 GMT, one can see a 10 K gradient between the high plains and the central river valleys, but little contrast between the land and water areas. By 2100 GMT, the VAS 11 μm images of the central United States were observed to brighten by another 10 K, while the clear oceanic areas remained about the same. This is a substantial dynamic range of underlying surface temperatures to remove from the split window water vapor estimates. The cloudy areas in Fig. 5b are radiometrically colder, from 220 to 280 K, and are colored with yellows, greens, blues and whites. Some of the radiosonde sites which were judged to be cloud free at 1200 GMT are indicated with their station names on this 1500 GMT image.

3) Fig. 5c is the corresponding VAS 12 μm image at 1500 GMT. Since the water vapor attenuation is greater at 12 μm, the brightness temperatures are 5 to 10 K less than found in the 11 μm image shown in Fig. 5b. The central plains show \( T_{\text{IR}} \) between 280 and 290 K, shifted by almost one 10 K color coded step (from red to orange) with respect to Fig. 5b, while the unattenuated cloud top temperatures remain the same.

4) Fig. 5d is the corresponding VAS 6.7 μm brightness temperature image at 1500 GMT. As expected from the radiance weighting function in Fig. 2, this mid-level moisture-imaging channel is radiometrically independent of the split window channels. The surface and lower tropospheric features are totally hidden by the mid-tropospheric water vapor, and only the tops of the higher clouds appear as “landmarks” which can be found in the other panels of Fig. 5. Mid-level water vapor patterns appear as cold, relatively wet areas (colored dark green, near 240 K) mixed with warm, relatively dry areas (colored light
green and yellow, near 250 K). The warmest streaks are interpreted as relatively transparent "dry slots" in the upper air, often associated with upper-level jets (Ramond et al., 1981). A more detailed analysis of the mid-level water vapor patterns inferred from the VAS 6.7 μm channel as well as animated overlays of the mid- and lower-level moisture images have been reported elsewhere for this case (Petersen et al., 1982). The 5 to 10 K difference between $T^*_p$ and $T^*_s$ in Figs. 5b and c is used as the satellite "signal" for precipitable water estimates.

c. The empirical air temperature estimate

True PW values were calculated from the 1200 GMT radiosonde data at 28 clear, collocated fields-of-view. Observations are defined as "collocated" if they occur within 75 km and 1 h of each other, and as "clear" if they pass the quality control tests listed in Section 2f. The corresponding values of $T_{air}$ were determined by substituting the true PW values into (5). The average value of the "air temperature" $\langle T_{air} \rangle = 283.2 ± 1.6$ K was adopted because the radiosonde-based values of $T_{air}$ showed no systematic variations within the 1200 GMT field. For this midsummer case, $\langle T_{air} \rangle$ was approximately equal to the radiosonde temperatures reported at 700 mb. Because $T_{air}$ characterizes the entire lower troposphere, its value should be little affected by diurnal heating within the planetary boundary layer. Consequently, the value of $\langle T_{air} \rangle$ from the 1200 GMT radiosondes was extended to the VAS split window fields throughout the day, up to and including the subsequent radiosonde launch at 0000 GMT.

Of course, a single value for the air temperature cannot apply over a large or complex domain. For instance, the mean value $\langle T_{air} \rangle$ from the central United States produces overestimates of the precipitable water in the distinctly colder air mass over the Great Lakes region and underestimates in the sub tropics. Indeed, the threshold tests prescribed by (6) reject the substantially colder air mass in Canada (note the low 11 μm brightness temperatures in Figs. 5b and c) and even some of the cold waters in the Great Lakes themselves. Some alternative approaches to the problem of applying ancillary data to the split window algorithm are discussed in Section 3h.

d. Color coded images of low-level water vapor

Fig. 6 is a series of five color coded images of the low-level water vapor derived from the VAS split window. The algorithm in (4) was applied to every pixel which was not rejected by the quality controls in (6). The images were taken at approximately three hour intervals from 1200 GMT on 13 July to 0000 GMT on 14 July 1981 (the last image was actually started one hour early, at 2300 GMT). The PW range is from 0 to 10 g cm$^{-2}$, with a change of hue on the color coded spectrum every 1 g cm$^{-2}$. Each hue is internally shaded to display detailed PW variations. Fields-of-view which were rejected by the quality control thresholds are colored black, and most of them obviously correspond to the cold cloud tops seen in Fig. 5. Drier pixels are colored red, normal pixels are colored orange and yellow, wetter pixels are colored light green, and excessively wet pixels are colored dark green and blue.

For quality assurance, a histogram has been made of the precipitable water distribution of the processed pixels within each frame of Fig. 6. The number of pixels with PW between 0 and 10 g cm$^{-2}$ are counted within 0.125 g cm$^{-2}$ bins. The pixels with PW greater than 6 g cm$^{-2}$ are contaminated by unresolved clouds. While they account for about 20% of the processed fields-of-view, they are clearly grouped into cloudlike patterns within the Gulf of Mexico and along the edges of the recognizable cloud masses. The histogram statistics remain nearly stationary over the 12 h observing period, supporting the assumption that the average 1200 GMT air brightness temperature applies consistently throughout the day. There is a small shift towards lower PW values by midday, which is consistent with both the increasing number of dry pixels in the High Plains, and with a small actual increase in $T_{air}$ due to daytime heating.

e. Qualitative verification of the moisture patterns

The low-level water vapor patterns in Fig. 6 show vivid features evolving during the observing period. The spatial and temporal continuity of the features is convincing qualitative evidence of the relative accuracy of the algorithm. The following subsections examine the spatial and temporal self-consistency of the VAS results and compare the satellite-derived images to conventionally observed water vapor fields, relating the corresponding features down to the resolution limits of the synoptic and mesoscale networks.

1) Self-consistency in the satellite images

The temporal continuity of the water vapor images in Fig. 6 is excellent over the 12 h observing period. The algorithm has eliminated all traces of the un-
derlying 20 K range in skin temperatures observed in the 11 μm radiances during the day. For instance, the relatively cloud-free area in the northwestern Gulf of Mexico serves as a "secondary standard" for the satellite-derived low-level water vapor, which monitors the temporal stability of the algorithm within a region of steady atmospheric and surface conditions. Likewise, the dry area in Nebraska monitors the temporal stability of the satellite-derived low-level water vapor within a region of steady atmospheric conditions but rapidly varying surface temperature. In fact, the excellent continuity of the low-level water vapor fields from the split window has been demonstrated with VAS data taken at 15 minute intervals on 13 July 1981, and animated fields of the moisture developments in the central United States have been produced with 15 km horizontal resolution (Petersen et al., 1982).

A full spatial spectrum of horizontal moisture variations is evident in Fig. 6. The amplitude of the variations is rather mild on the synoptic scale (due to the extension of the average air temperature from the central United States to Mexico and Canada), large on the meso-α scale, and moderate on the meso-β scale, with very little pixel-to-pixel variation which is not associated with cloud cover. The correctness of the spatial features can be judged objectively by comparison to conventional moisture data.

2) SYNOPTIC-SCALE COMPARISONS

Fig. 7 shows a Barnes objective analysis of the radiosonde-based precipitable water values at 0000 GMT on 14 July 1981, using a spatial weighting parameter consistent with the average radiosonde station spacing of 390 km (Koch et al., 1983). Broad gradients occur across the central Great Plains and across the stationary front in the northern United States. The analysis indicates a relative maximum over Iowa and a relative minimum from southern Illinois to northern Georgia. Note that the conventional synoptic water vapor values are actually unknown over significant regions, such as central Iowa and Missouri, due to the absence of radiosonde sites. The synoptic scale features in the VAS-based precipitable water image (Fig. 6e) correspond very well to the radiosonde analysis (Fig. 7), with VAS values absent where clouds or the colder air mass in Canada preclude computations. The moisture maximum over Iowa, the moisture gradient from Nebraska to northern Texas and the moisture minimum from southern Illinois to northern Georgia are all measured directly by the VAS split window. Moreover, some subsynoptic features, such as the relative moisture minimum across central Missouri, appear in the VAS image but are not found in the radiosonde analysis. This is due to the limited horizontal resolution of the radiosonde network, so that further confirmation of the VAS-derived water vapor patterns rests upon comparison to the denser space-time observations provided by the conventional surface (airways) network.

The main VAS water vapor features in Fig. 6 correspond to the broad dewpoint patterns in the conventional surface analyses in Fig. 4. For instance, the moist cloudy area in Arkansas drifts slowly into Oklahoma with the low-level flow, and develops convective elements by 2100 GMT. The surface dewpoint maximum in the Gulf States is somewhat masked by clouds in the satellite precipitable water images, but its location does correspond with the maximum surface dewpoints in southeastern Oklahoma at 1800 GMT. Likewise, the moisture gradient from Nebraska to Kansas (surface dewpoints from 10 to 20°C in Fig. 4a) is detected by the VAS split window (precipitable water from 2 to 5 g cm⁻² in Fig. 6a). This gradient strengthens in both analyses over the 12 h observing period, as a markedly dry feature moves northeastward across Nebraska and enlarges to the south of a developing low pressure area. In fact, all of the synoptic scale VAS-derived space-time moisture features over the central United States are confirmed at the lower resolution of the conventional analyses. The moisture features which are normally unobserved in the conventionally data-void areas, such as the Gulf of Mexico and the Atlantic Ocean, are subjectively verified by the continuity of their development.

3) MESOSCALE COMPARISONS

On the mesoscale, the VAS split window images in Fig. 6 display vivid structures and significant changes within the synoptic features. For instance,
the satellite-derived water vapor images depict the evolution of the broad moisture maximum over Arkansas and Kansas into two separate moisture bands within which convective clouds ultimately develop. By 0000 GMT, the precipitation pattern, which includes two separate bands of light to moderate rain and thundershowers in the Oklahoma region (Fig. 4f), reflects the distinct VAS-determined low-level pre-convective moisture pattern (Fig. 6e). Likewise, Iowa was the scene of interesting changes during the 12 h period. After the morning thunderstorms dissipated over eastern Iowa, a water vapor maximum remains in clear air at 2100 GMT (Fig. 6d). By 0000 GMT, new thunderstorms develop in southern and eastern Iowa, within a local water vapor maximum and along a water vapor gradient, respectively (see Figs. 4f and 6c). The storms along the water vapor gradient in southern Iowa are located 150 km behind the warm frontal zone, which remains in northern Iowa during this period (Fig. 4e). Another interesting example of mesoscale variability is found within the stable dry features in Nebraska and in Georgia. The single dry zone originally in southwest Nebraska slowly propagates northeastward between 1500 and 1800 GMT and then is rapidly enlarged by the development of a second dry zone in northeastern Nebraska between 2100 and 2300 GMT (Figs. 6c, d and e). Thus, the increase in the conventional surface dewpoint gradient across eastern Nebraska (Fig. 4b and c) appears to be the result not only of the advection of dry air originally in western Nebraska but also of the rapid formation of a second dry region, perhaps due to the downward transport of mid-tropospheric air. Likewise, a distinctly dry zone grows rapidly in northern Georgia, west-northwest of several developing convective cells in South Carolina. A corresponding moisture minimum is found in the 0000 GMT radiosonde analysis (Fig. 7) and in the surface data (Fig. 4c) for this region, where surface dewpoints drop to 20°C in Georgia while reports from the surrounding areas approach 24°C. The radiosonde soundings at Athens, Georgia, (Figs. 8a and b) reveal a distinct drying in the lower and middle troposphere between 1200 GMT on 13 July and 0000 GMT on 14 July 1981, which confirms the split window observations (Figs. 6a and e).

Fig. 6 reveals a wealth of high-resolution details and rapid changes within the VAS-derived low-level moisture fields which cannot be fully confirmed by the conventional radiosonde or surface networks. The changing mesoscale moisture fields in the Iowa region provide an excellent example of the limitations of using conventional analyses for verification of satellite data. There are no radiosonde stations in the entire state of Iowa to corroborate the VAS-observed precipitable water in the lower troposphere. The hourly surface data also lacks the vertical information necessary to verify integrated water vapor content. In particular, the conventional surface stations within Iowa and central Illinois report dewpoints approaching 24°C in a band extending immediately south of the warm front (Fig. 4c), where the satellite measurements of precipitable water are also large. However, the surface dewpoints are relatively uniform throughout Iowa, Illinois and Missouri, while the VAS precipitable water field (Fig. 6d) exhibits a narrow band of significantly drier air which extends from central Nebraska through northern Missouri, and into a distinct minimum in south-central Illinois. The radiosonde soundings from Salem, Illinois, at 1200 GMT on 13 July and 0000 GMT on 14 July 1981 (Figs. 8c and d) verify that significant drying has occurred within several layers below 600 mb in south-central Illinois, even though the surface dewpoint readings remain nearly constant. The drying is also verified numerically by the spot values of precipitable water computed at the collocated VAS and radiosonde observations (listed on Figs. 8c and d). Therefore, the VAS split window can differentiate those areas in which the water vapor extends over a deep layer and is more able to support convective cells from those areas in which the water vapor significantly decreases immediately above the earth's surface and is therefore less able to support convection.

Another example of the mesoscale limitations of conventional surface analyses is found by comparing the smooth surface dewpoint gradient extending from Nebraska to Oklahoma with the complex VAS moisture patterns in the same region. The VAS integrated water vapor images show a separate band of moisture and showers from north Texas to central Kansas at 0000 GMT (Fig. 6e) which are located to the west of the dewpoint gradient analyzed from the surface data (Fig. 4c). Apparently, moist air from the east is overrunning a shallow dry layer which still envelopes the surface-level stations in central Oklahoma and Kansas. This interpretation is supported by the 0000 GMT radiosonde reports from Dodge City, Kansas, Oklahoma City, Oklahoma and Little Rock, Arkansas (Figs. 9a, b and c, respectively). The boundary layer values at the three sites reflect the west-to-east dewpoint gradients analyzed at the earth's surface (Fig. 4c). However, the Dodge City and Oklahoma City soundings indicate a deeper moisture layer extending up toward 600 and 500 mb, respectively, than is evident in Arkansas where the moisture is capped near the 700 mb level. Thus, the total amount of moisture within the lower 300 to 400 mb of the troposphere remained greater than 4.0 g cm⁻² in central Oklahoma, as measured both by VAS and by the radiosondes (Fig. 9b), even though the surface dewpoint analysis (Fig. 4c) shows that a significant moisture gradient existed within the boundary layer over the southeastern part of Oklahoma. As in Iowa, convective clouds and rain developed within the VAS-determined water vapor maximum. Hence, the VAS split window is a much better indicator of the true mesoscale location and horizontal distribution of the
total low-level moisture than is the conventional surface network.

f. Quantitative verification of the moisture values

The conventional radiosonde network is the only available source of “ground truth” data for quantitative verification of the satellite values of the vertically integrated water vapor content. The 1200 GMT radiosonde reports on 13 July 1981 were already used to establish the average air temperature, so that they do not provide a completely independent measure of the accuracy. The open circles in Fig. 10 compare the satellite-derived precipitable water to the radiosonde-derived values at 1200 GMT, showing an rms difference of \( \pm 1.01 \) g cm\(^{-2}\).

The 0000 GMT 14 July 1981 radiosonde reports provide a completely independent quantitative measure of the accuracy, twelve hours after the determination of the air (brightness) temperature. At this later time, 35 sites were accepted by the algorithm’s threshold tests. The filled circles in Fig. 10 compare the satellite-derived precipitable water to the radiosonde values at 0000 GMT. Table 2 lists the impor-
tant statistics for the VAS minus radiosonde precipitable water differences from the dependent (1200 GMT) and independent (0000 GMT) datasets which are plotted in Fig. 10. The rms error for this independent set is $\pm 1.07 \text{ g cm}^{-2}$ over a range of 1.7 to 5.5 g cm$^{-2}$. The mean error for the 0000 GMT verification sites was $-0.40 \text{ g cm}^{-2}$, which could be explained by an actual increase in the average air temperature by $+0.6 \text{ K}$ during the twelve daylight hours following the 1200 GMT determination of $\langle T_{\text{air}} \rangle$. Some of the test sites were reporting scattered or broken clouds at 0000 GMT. Apparently, the threshold tests on the split window do not remove all cloud contamination from the water vapor estimate.

### g. Error analysis

The qualitative verification provided by the spatial and temporal continuity of the low-level water vapor fields indicates good relative accuracy at high horizontal resolution. The quantitative verification of the satellite-derived precipitable water at “ground truth”

---

**Fig. 9.** Skewed $T$-$\log P$ diagrams of radiosonde reports which verify the precipitable water gradient detected by the VAS split window in the central Great Plains at 0000 GMT on 14 July 1981: (A) Dodge City, Kansas; (B) Oklahoma City, Oklahoma; and (C) North Little Rock, Arkansas.
sites indicates fair absolute accuracy over a large range of water vapor content.

The error budget is dominated by radiometric uncertainties, clouds and model limitations:

1) Radiometric error propagation in Eq. (4) is controlled by $dP/WdT^*$ (approximately 0.7 g cm$^{-2}$ K$^{-1}$). Hence, random noise (approximately $\pm 0.5$ K) contributes $\pm 0.4$ g cm$^{-2}$ to the error budget for this case. Absolute calibration errors should be nearly cancelled by the empirical value of $T_{air}$. In addition, the broad spectral filters at 11 and 12 $\mu$m do not provide as precise a signal of water vapor content as spectroscopically resolved water vapor lines (Prahabakara et al., 1979), so that precipitable water cannot be retrieved as accurately.

2) Unresolved clouds cause systematic errors which are more difficult to quantify. Simulations with cloud cover terms in Eq. (1) indicate that clouds colder than the average air temperature cause precipitable water overestimates in Eq. (4), and warm clouds or fog cause underestimates. Unfortunately, the use of more severe thresholds for the split window would suppress genuine features in the colder areas such as the Great Lakes region.

3) The errors due to simplifications by the linearized single layer model for the lower troposphere are also difficult to quantify. From simulations, the random errors in the absorption coefficient parameterization are estimated to contribute approximately $\pm 0.3$ g cm$^{-2}$. The single-layer model appears to work very well, despite the lack of adjustment for surface topography or for variations in the vertical temperature and moisture profiles. Unfortunately, more complicated models introduce more unknowns to be determined, which usually destabilize the error propagation in an algebraic solution.

4) The systematic errors caused by using a constant value for the "air (brightness) temperature" are scarcely detectable (less than 0.3 g cm$^{-2}$) in the statistical, horizontal and temporal behavior of the precipitable water fields over the central United States in Fig. 6. Section 3h tests the impact of utilizing a field of $T_{air}$ values instead of a constant.

5) Errors due to field-of-view misregistration between the split window channels are important when there are clouds or a complicated background. Cases where the 15 km footprints are known to be misregistered by 7.5 km produce had precipitable water fields, indicating that the cancellation of unresolved horizontal details is very important. The misregistration between different VAS channels observed on the same GOES scan line is estimated to be less than 1 km.

Altogether, the random radiometric and parametric errors contribute approximately $\pm 0.5$ g cm$^{-2}$ uncertainty to the precipitable water estimate for the midsummer conditions in this case study. The remaining uncertainty must be due to more systematic errors.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Clear sites</td>
<td>28</td>
<td>35</td>
</tr>
<tr>
<td>Correlation (r)</td>
<td>0.27</td>
<td>0.43</td>
</tr>
<tr>
<td>Mean error</td>
<td>$-0.02$ g cm$^{-2}$</td>
<td>$-0.40$ g cm$^{-2}$</td>
</tr>
<tr>
<td>RMS error</td>
<td>$\pm 1.01$ g cm$^{-2}$</td>
<td>$\pm 1.07$ g cm$^{-2}$</td>
</tr>
</tbody>
</table>

Using $\langle T_{air} \rangle$ from the 1200 GMT radiosonde sites.

| Clear sites         | 27                            | 33                               |
| Correlation (r)     | 0.53                          | 0.66                             |
| Mean error          | $+0.09$ g cm$^{-2}$            | $+0.04$ g cm$^{-2}$              |
| RMS error           | $\pm 1.21$ g cm$^{-2}$         | $\pm 0.98$ g cm$^{-2}$           |

Using the VAS 13 $\mu$m channel and $\langle \Delta T_{air} \rangle$ from 1200 GMT.

| Clear sites         | 29                            | 26                               |
| Correlation (r)     | 0.57                          | 0.53                             |
| Mean error          | $+0.26$ g cm$^{-2}$            | $+0.11$ g cm$^{-2}$              |
| RMS error           | $\pm 1.21$ g cm$^{-2}$         | $\pm 0.85$ g cm$^{-2}$           |

Using conventional thickness $\Phi$ (700–920 mb) fields.
from misregistration, unresolved clouds, model limitations and air temperature variations.

h. Algorithm enhancements

The “average air temperature” is adopted in Eq. (4) as the simplest means of introducing the ancillary data (a few radiosonde profiles) which is needed to solve two equations [the split window radiance in Eq. (1)] containing three unknowns (the surface brightness, air brightness and water vapor content). However, the satellite-derived water vapor field is inappropriate for regions outside of the air mass which was used to determine \( T_{\text{air}} \). It is difficult to introduce another data field which allows \( T_{\text{air}} \) to be position dependent over a large area without sacrificing the speed and simplicity of the two-channel algorithm. More elaborate schemes also violate our original intention, which was to develop a simple real-time algorithm which can calculate mesoscale low-level moisture fields from the split window radiances with a minimum of ancillary data. Nevertheless, two schemes which utilize ancillary satellite and conventional data fields are examined in the following sections.

1) Utilizing a VAS sounding channel

Table 1 indicates that the VAS temperature sounding channel at 13.3 \( \mu \text{m} \) is close enough to the split window to share a surface emittance which is not contaminated by reflected sunlight. However, the effective “air temperature” is lower at 13 \( \mu \text{m} \) than it is at 11 and 12 \( \mu \text{m} \) because the dry absorption coefficient is an order of magnitude larger. Hence, the third channel introduces a fourth unknown, the difference in the “air temperatures” \( \Delta T_{\text{air}} \). The difference \( \Delta T_{\text{air}} \) is related to the vertical gradients, which are more stable over a large region than \( T_{\text{air}} \) itself. For this case, the average value \( \langle \Delta T_{\text{air}} \rangle = 12.1 \pm 0.7 \text{ K} \) was computed from all three channels at the radiosonde sites which were originally used to determine \( T_{\text{air}} \) in Section 3c. This value is used to solve simultaneously for PW, \( T_{\text{surf}} \) and \( T_{\text{air}} \) from the three-channel versions of Eqs. 1, 3 and 6 at every field-of-view in Fig. 6a. Because the equations must be solved by numerical iteration, it requires more computer time to produce an entire precipitable water field from three VAS channels. The new field (not shown) contains low-level moisture patterns very similar to Fig. 6a. The new field shows reasonable moisture values in the different air masses from central Canada to the Gulf of Mexico, but many fewer fields-of-view to pass the quality control tests in Eq. 6. Table 2 indicates that there is no increase in the accuracy of the VAS precipitable water at either 1200 or 0000 GMT from the three-channel treatment. Except for the expanded regional coverage, this use of the VAS 13 \( \mu \text{m} \) channel to estimate the “air temperature” produces no significant improvement compared to the original two-channel algorithm for this case.

2) Utilizing conventional thickness fields

Because the air temperature controls the thickness of the atmosphere, maps of layer thickness \( \Phi \) can be used to estimate the value of \( T_{\text{air}} \) at every field-of-view within the VAS split window. The 700 to 920 mb thickness at the 1200 GMT radiosonde sites on 13 July 1981 is well correlated \( (r = 0.90) \) with the corresponding “air temperature”:

\[
T_{\text{air}}(\Phi) = [0.12209 \text{ K m}^{-1}] \Phi(700–920 \text{ mb})
\]

An objective analysis of \( \Phi(700–920 \text{ mb}) \) was made from the 1200 GMT reports, and this analysis (not shown) was used to estimate \( T_{\text{air}}(\Phi) \) in Eq. 4. Precipitable water fields were recalculated from the split window radiances for Figs. 6a and 6b. The new PW fields (also not shown) have improved coverage in the cold Canadian air mass, but poorer coverage and accuracy in the High Plains. Table 2 indicates no effect upon the statistical accuracy of PW values calculated from \( T_{\text{air}}(\Phi) \). Except for the expanded regional coverage, this use of conventional data to estimate the “air temperature” provides no significant improvement upon the original split window algorithm for this case.

3) Other potential enhancements

The lack of impact by a single VAS channel or by conventional temperature fields upon the accuracy of the VAS PW values from the 11 and 12 \( \mu \text{m} \) channels suggests that the fixed value of \( \langle T_{\text{air}} \rangle \) is not the major limitation to the application of our algorithm to the split window. Other enhancements of the low-level moisture algorithm should be tested. For instance, the VAS sounding channels provide better quality control over the cloud-contaminated fields-of-view, as well as an independent estimate of the air temperature. Likewise, collocated visible data (available at 1 km resolution and interleaved with the VAS infrared radiances) are being used during daylight hours to avoid clouds which are not resolved with the 15 km footprint of the thermal sensors. Oceanic moisture fields can be processed more accurately with a rearrangement of the algorithm to use the sea surface temperature instead of the average air temperature as ancillary conventional data.

In general, the algorithm presented in this paper will be less effective in dry winter air, in the cloud-and water vapor-obscurt tropics, and in any situation where the surface-to-air temperature contrast is small. Real-time processing with only two VAS channels is not as accurate as multi-channel soundings with human quality control. However, the ease and
speed with which water vapor fields can be computed from the VAS split window alone is a distinct advantage when the forecast is simply based upon pattern recognition of relatively accurate mesoscale details within rapidly evolving moisture fields.

4. Summary and discussion

Fields of low-level atmospheric water vapor are derived from the "split window" 11 and 12 μm infrared channels of the VISSR Atmospheric Sounder (VAS) carried on the GOES-5 satellite. The differential water vapor absorption between the two adjacent bandpasses makes it possible to separate the surface and atmospheric radiance contributions within a field-of-view. The average air brightness temperature, determined at radiosonde sites, allows the further separation of atmospheric emission and absorption terms. A simply parameterized algorithm is developed from a single-layer model for the split window radiances. The vertically integrated water vapor content (measured in g cm\(^{-2}\)) of the lower troposphere is calculated from a time-sequence of 5 VAS split window images taken every 3 hours over the United States on 13 July 1981. Color coded images of the integrated water vapor show vivid subsynoptic and mesoscale details at 15 km horizontal resolution which evolve continuously during the twelve hour period. Precipitable water estimates are verified with independent radiosonde measurements taken twelve hours after the initial air temperature determination, and an accuracy of ±1.0 g cm\(^{-2}\) is established over a range of 1.7 to 5.5 g cm\(^{-2}\). Cloudy fields-of-view are detected as being colder than the air, and are simply rejected from the images. Unresolved clouds are readily identified as cloudlike patterns of excessive water vapor in the images. Spot verification of mesoscale water vapor developments indicate fairly good absolute and very good relative accuracy. The background surface temperature variations are eliminated quite effectively, and the residual errors within an air mass are dominated by noise and unresolved clouds. The VAS split window clearly differentiates those areas in which the water vapor extends over a deep layer and is more able to support convective cells from those areas in which the water vapor is confined to a shallow layer and is therefore less able to support convection. Several areas of enhanced low-level water vapor develop into convective cloud formations. The sequence of low-level water vapor fields in Fig. 6 demonstrates that the VAS instrument can indeed monitor low-level mesoscale moisture variations from geosynchronous station and can fill the space-time gaps in the conventional coverage. The split window observations can be augmented by the use of additional satellite or conventional data fields, although the improvement in regional coverage is scarcely justified by the computational burden imposed by the ancillary data.

This midsummer day of VAS data provides a wealth of information for further studies of satellite sounding techniques and mesoscale meteorology. Vertical water vapor structure has already been animated by overlaying the VAS 6.7 μm channel on the low-level moisture fields derived from the split window, and a preliminary meteorological analysis has been made from mesoscale fields of VAS multi-channel soundings (Petersen et al., 1982). The VAS temperature sounding channels are being tested as an aid to cloud detection and as an alternative source of air temperature data. The split window estimates are being compared to water vapor profile retrievals derived from all the VAS channels plus other conventional data. A detailed meteorological analysis is being made of the VAS-derived mesoscale developments associated with the Iowa thunderstorms. Finally, the influence of VAS-derived water vapor fields upon mesoscale model results will be studied to determine the impact of satellite data upon numerical forecasts.

In summary, these high resolution satellite measurements can draw attention to the evolution of otherwise undetected mesoscale water vapor fields within relatively clear air. Ultimately, the utility of the VAS-derived water vapor patterns will be judged by their impact upon numerical forecast models and by their acceptance as a mesoscale analysis tool, when the VAS moisture channels are distributed as a real-time product of the operational GOES system.

Acknowledgments. This work is funded through the VAS Demonstration Project of NASA's Operational Satellite Improvement Program (OSIP), managed by Mr. James Greaves and Dr. Harry Montgomery of NASA/GSFC. We thank Mr. Anthony Mostek of Computer Sciences Corporation for preparing some of the datasets. We also thank the anonymous reviewers for their comments which helped us to clarify the final version of this manuscript, and for encouraging us to test alternative schemes for estimating the air temperature.

REFERENCES


