A Comparison of the First-Guess Dependence of Precipitable Water Estimates from Three Techniques Using GOES Data

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ABSTRACT

This paper evaluates and intercompares three existing algorithms for calculating precipitable water (PW) using infrared radiances from the *GOES-7* VISSR (Visible and Infrared Spin Scan Radiometer) Atmospheric Sounder (VAS). The study exclusively uses simulated, rather than observed, VAS radiances in all retrievals. The National Environmental Satellite, Data, and Information Service simultaneous physical algorithm utilizes data from all 12 VAS channels and produces a vertical profile of temperature and dewpoint from which PW can be calculated. The Chesters technique and Jedlovec's physical split-window technique retrieve PW from radiances in the two split window channels without first computing a dewpoint profile. All three algorithms also can be used with *GOES-8* and *GOES-9* data.

These algorithms have not been intercompared previously. Each is applied on case days having wide variations in temperature and moisture. The algorithms are supplied with first-guess information of varying accuracy to assess their sensitivity to the guess data. The performance of the techniques relative to one another is described, including important similarities and differences among them.

Results show that all three algorithms perform well within most temperature and moisture regimes. Each retrieves PW that is generally an improvement upon the first guess and is more accurate than PW predicted by surface temperature alone. However, each algorithm is somewhat dependent upon the first guess. Warm-biased first-guess surface temperatures are generally associated with moist-biased PW retrievals, while cold-biased first-guess surface temperatures are generally associated with dry-biased retrievals. The first-guess surface temperature errors reflect the presence, in either the first-guess or observed temperature profiles, of low-level inversions that cause the PW retrieval errors. Retrievals made where the observed contribution of low-level moisture to total column PW is small are usually moist biased, while those where the low-level contribution is large are usually dry biased. Both of these relationships exist irrespective of the sign of the first-guess PW error.

1. Introduction

Describing the variability of water vapor is crucial to many applications in atmospheric science. Precipitable water (PW) is a parameter often used for this purpose. Although it does not describe vertical moisture structure, PW does identify horizontal gradients of column-integrated water vapor content. Recent research has striven to develop methods for estimating PW using remote sensing techniques. The goal is to improve upon the temporal and spatial resolution of moisture data from the conventional radiosonde network.

Precipitable water retrieval techniques utilize a variety of data sources, including surface-based solar (Thome et al. 1992) and microwave (Birkenheuer 1991; Rogers and Schwartz 1991) radiometers, as well as polar-orbiting satellite sensors such as the Special Sensor Microwave/Imager (Alishouse et al. 1990) and the TIROS (Television Infrared Observation Satellite) Operational Vertical Sounder (TOVS) (McGuirk et al. 1994). Some comparisons between these retrieval methods have been conducted. Le Marshall (1988) compared various physical and statistical techniques used to retrieve PW from TOVS data. Recently, Reagan et al. (1995) compared columnar water vapor retrievals obtained with solar and microwave radiometers.

Several techniques for estimating PW use infrared radiances measured by sensors onboard the Geostationary Operational Environmental Satellites (GOES). Most utilize data from two adjacent channels in the infrared split-window region near 10–12 μm. The Chesters technique (Chesters et al. 1983, 1987), developed for the VISSR (Visible and Infrared Spin Scan Radiometer) Atmospheric Sounder (VAS) on *GOES-7*, is a statistical approach based on a single-layer radiative transfer model. Jedlovec's (1987) physical split-window (PSW) technique utilizes the constraints of the radiative transfer equation. It was applied to VAS split-window data by Guillory et al. (1993). Precipitable water also can be retrieved by vertically integrating mixing ratio profiles obtained from the operational National Environmental

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Satellite, Data, and Information Service (NESDIS) simultaneous physical algorithm (Hayden 1988). This algorithm is more complex than the VAS split-window techniques since it utilizes data from all 12 radiometric channels.

The Chesters technique, Jedlovec's PSW technique, and the NESDIS simultaneous physical algorithm differ significantly in approach. Each can provide a different result when applied to the same atmospheric column. However, a comprehensive intercomparison of these three methods has not been previously reported. This paper evaluates and intercompares the ability of the techniques to accurately estimate PW from *GOES-7* VAS radiances. We applied each technique to a similar set of conditions to determine the strengths and weaknesses of each and to identify those conditions that produce the most accurate or inaccurate retrievals. Simulated VAS radiances that are calculated from radiosonde soundings were used exclusively. This research builds upon initial results presented by Knabb and Fuelberg (1994) and summarized by Knabb and Fuelberg (1996). Since each technique being investigated is also applicable to *GOES-8* and *GOES-9* data in much the same form, our results for *GOES-7* are relevant for future use.

2. Comparative descriptions of the techniques

Input for the Chesters technique (Chesters et al. 1983, 1987) includes observed split-window channel brightness temperatures along with calculated differential absorption coefficients and the effective radiating temperature of the single atmospheric layer upon which the technique is based. The layer temperature and absorption coefficients are obtained by regression on training data consisting of collocated PWs and brightness temperatures. Inserting observed brightness temperatures into the resulting equation produces the retrieved PW.

The PSW technique (Jedlovec 1987; Guillory et al. 1993) retrieves PW from the difference between observed and first-guess split-window channel brightness temperatures. Specifically, retrieved PW is a perturbation from the PW computed from the first-guess brightness temperatures. A perturbation form of the radiative transfer equation is used. Guillory et al. (1993) described this procedure in detail. Surface skin temperature is retrieved by the PSW algorithm to a high degree of accuracy for use in the PW calculation. The PSW technique is physically based and does not rely on statistical procedures to relate PW to other quantities.

The NESDIS simultaneous physical algorithm (Hayden 1988) retrieves a full vertical profile of temperature and mixing ratio. Precipitable water is obtained from the mixing ratios. The algorithm utilizes data from all 12 VAS channels in a matrix inversion procedure to solve a set of radiative transfer equations. It requires first-guess skin temperature, as well as temperature and moisture profiles, from which first-guess brightness temperatures are computed. Similar to the PSW technique, the retrieved temperature and moisture profiles are perturbations from the first guess. Thus, the PSW and NESDIS algorithms both have physical foundations on the radiative transfer equation, and both require individual first-guess profiles at each retrieval location. We examined PWs from the NESDIS algorithm to determine whether the additional information that it incorporates (i.e., more channels and the retrieval of a full moisture profile) provides advantages over the two simpler split-window procedures.

Precipitable water estimates from each of the three techniques depend somewhat on the first-guess data that are provided. Soundings retrieved with the NESDIS algorithm are often not improvements on their guess profiles (Fuelberg and Olson 1991). Jedlovec and Carlson (1994) noted that PW estimates from the PSW technique are influenced by the first-guess temperatures. Although not directly dependent on an individual first-guess sounding, PWs from the Chesters technique are influenced by the characteristics of the training data used to develop the necesary regression equation (Baker et al. 1993). A major goal of the current research is to examine first-guess dependencies in greater detail.

3. Methodology and data

Our methodology made exclusive use of simulated, rather than actual observed, VAS radiances. These simulated radiances were calculated from radiosonde-derived temperature and dewpoint soundings using the technique of McMillin et al. (1979). This one radiative transfer code was used for all simulations involving the three retrieval techniques. The simulations provided collocated PWs and VAS brightness temperatures at each retrieval location and for the first-guess data (described later in this section). Each simulation utilized a surface skin temperature equal to the observed surface shelter temperature, and emissivity was set to unity. Application of the algorithms using simulated radiances, computed from radiosonde soundings having known PW, is advantageous since the retrieved and observed PWs are at exactly the same locations.

Fifteen case days during June through October of 1979 were examined. The January–May and November–December periods were not considered, due to numerous cloudy soundings and small values of PW. Such conditions did not yield a sufficient sample of retrieval locations to fairly evaluate the performance of the techniques. Three consecutive days from each month were chosen: 20–22 June, 4–6 July, 17–19 August, 25–27 September, and 15–17 October. Characteristics of the soundings and the availability of first-guess data (described below) were then used to select specific retrieval sites for the study. A total of 84 retrieval sites (observed ‘‘ground truth’’) were chosen. All of these soundings are from 0000 UTC and are located at 20 different radiosonde stations across North America. Additional soundings at surrounding locations and times that had

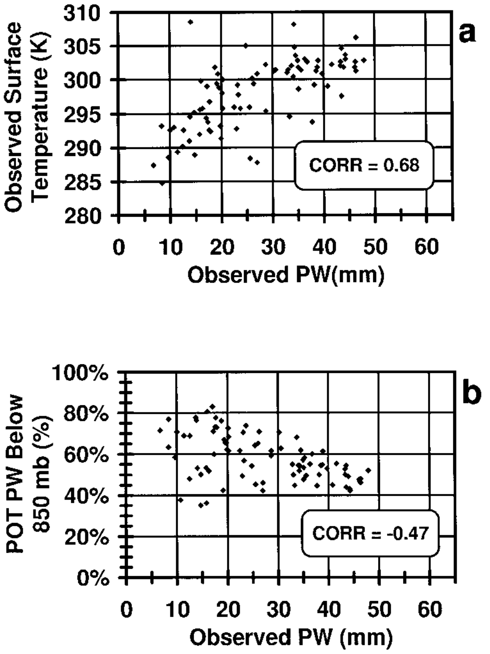

FIG. 1. Scatter diagrams of PW (mm) versus (a) surface temperature (K) and (b) POT PW in the surface–850-mb layer. Values are from RAOB profiles at 0000 UTC at all 84 retrieval locations during June–October 1979. CORR is the linear correlation coefficient.

similar characteristics to those at retrieval sites were selected for use as first-guess data (described below).

The 84 retrieval sites represent a wide range of temperature and moisture conditions. Their PW and surface temperature values range from warm and moist to cool and dry (Fig. 1a). All infrared techniques for moisture retrieval use channel brightness temperatures that depend strongly upon the surface temperature and boundary layer temperature. The techniques are inherently limited by the difficulty in separating upwelling surface radiation from that due to boundary layer water vapor. The high correlation (0.68, Fig. 1a) between PW and the surface temperature (which is very similar to the boundary layer temperature) suggests that the infrared retrieval techniques will have some success in estimating PW. The results presented later will indicate how well each technique improves upon this correlation between observed PW and surface temperature. Our observations include columns with equal PW but with varying vertical distributions of that moisture (Fig. 1b). This is particularly evident at locations having small PW. A later section will describe the effects of vertical moisture distribution on PW retrievals.

Each radiosonde sounding that was selected had the following characteristics: 1) at least 20 levels reporting both temperature and dewpoint, 2) a temperature profile extending from the surface to at least 100 mb, 3) a dewpoint profile extending to at least 350 mb, 4) a station pressure of at least 1000 mb, 5) no level reporting a dewpoint depression of less than 1 K (to minimize the influence of clouds), and 6) no level having obviously erroneous data. These characteristics ensured that columns from which PW was computed had equal vertical extent and data quality, thus eliminating unwanted variability from the PW comparison. Each sounding was then interpolated, linearly by the logarithm of pressure, to the 40 pressure levels needed by the forward radiative transfer model that was used to simulate the VAS brightness temperatures. It should be emphasized that all input soundings were interpolated to these same 40 levels *prior* to the simulations. Furthermore, ground-truth PW in the 1000–350-mb layer (e.g., Fig. 1) was computed from the mixing ratio profile of these interpolated soundings. This ensured that the observed PW was computed from the identical sounding used in the simulation. Without this consistency, a direct comparison between observed and retrieved PW would not be valid.

Previous uses of the PW algorithms have utilized first-guess data from a variety of different sources. The NESDIS implementation of the simultaneous physical algorithm uses first-guess sounding profiles from a numerical meteorological model, which are then enhanced by surface observations or satellite-derived sea surface temperatures (Hayden and Schmit 1994). The PSW technique has been applied mostly in a research mode where a single guess profile is used at multiple retrieval sites. This guess profile is the average of the observed and model-produced profiles (Guillory et al. 1993; Jedlovec et al. 1994; Jedlovec and Carlson 1994). Both the NESDIS and PSW algorithms utilize a guess profile for each retrieval. The Chesters technique is somewhat different in that it requires a training dataset of soundings that represent a wide range of PW values.

The first-guess data for our intercomparison served the needs of all three techniques and provided each with the same amount of available information. A separate set of first-guess data was utilized on each of the 15 case days. Each of these sets consisted of soundings from 12 and 24 h prior to the 0000 UTC retrieval time—that is, 0000 and 1200 UTC on the previous day. These soundings were utilized differently by each technique. Specifically, for the NESDIS and PSW techniques, each retrieval location was provided with its own first-guess profile, which was obtained by averaging the soundings from 12 and 24 h prior to the retrieval time at that site (retrieval location). Retrievals were not made at locations where profiles from the two previous times were not available at that same location. In contrast, the Chesters technique used a regression relationship determined from the entire set (described above) of first-guess data for each day. Its training data consisted of PWs and corresponding simulated VAS split-window channel brightness temperatures computed from all soundings in the set for that day. Thus, first-guess soundings provided to the PSW and NESDIS techniques were extracted from the same set of first-guess data utilized by the Chesters technique.

Figure 2 shows that both accurate and inaccurate first-

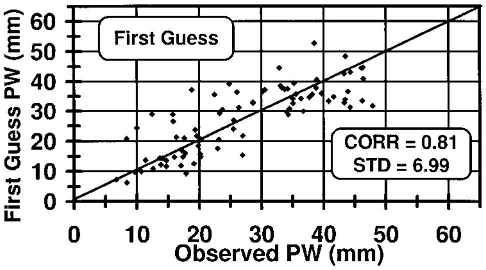

FIG. 2. Scatter diagram of observed versus first-guess PW (mm) provided to the NESDIS and PSW techniques at the 84 retrieval locations. The solid line drawn through the points denotes equality between the quantities. CORR is the linear correlation coefficient, and STD is the standard deviation of differences.

guess soundings were provided to the PSW and NESDIS techniques. Since these soundings were also a large part of the training dataset used with the Chesters technique, it also was provided with first-guess data having variable accuracy. More accurate first guesses could have been obtained from other data sources (e.g., output from the Nested Grid Model or hourly surface observations), and these are used operationally with the NESDIS algorithm. However, since this study intercompares retrieval response to various conditions and does not directly assess expected operational performance, the scatter in Fig. 2 is desirable. The results presented in the next section reveal sensitivities of the retrievals to both accurate and inaccurate first-guess data and are thus relevant to many future research and operational applications of the three techniques.

4. Intercomparison of retrieval results

a. Retrieved versus observed PW

Figure 3 compares retrieved PWs from each technique to collocated observed PWs at all 84 locations during the 15 case days. Linear correlation coefficients (CORR) between retrievals and the ground truth are high, ranging from 0.81 (the Chesters technique) to 0.92 (the PSW technique). However, each scheme produces some inaccurate PWs, as indicated by the scatter in the diagrams and the standard deviations of differences (STD). The PSW technique has the largest CORR (0.92) and the smallest STD (4.97 mm). PSW retrievals explain 85% of the variance in the observed PWs, compared to only 66% explained by the first guess. All three techniques yield CORRs that equal or exceed the correlation between the first-guess and observed PWs (0.81, Fig. 2), suggesting that each generally improves upon the first guess. This improvement on the first-guess data is expected of well-designed PW retrieval algorithms. Furthermore, these CORRs are greater than that between observed PW and observed surface temperature (0.68, Fig. 1a), showing that even moderately accurate first-guess data yield retrievals that are improvements over those that would be predicted by surface temperature alone.

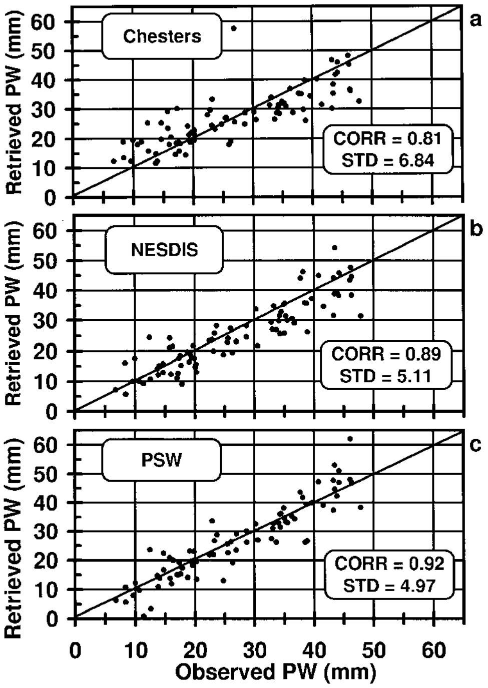

FIG. 3. Scatter diagrams of observed versus retrieved PW (mm) using the (a) Chesters, (b) NESDIS, and (c) PSW techniques at the 84 retrieval locations. The solid lines through the points denote equality between the quantities. CORR is the linear correlation coefficient, and STD is the standard deviation of differences.

Retrievals from the Chesters technique (Fig. 3a) exhibit a slight differential bias—that is, moist-biased retrievals where observed PW is small and dry-biased retrievals where observed PW is large. A similar differential bias was identified by Baker et al. (1993). PWs from the NESDIS technique (Fig. 3b) tend to lie below the line of equality, indicating a slight overall dry retrieval bias; this bias is discussed in more detail later. The PSW technique (Fig. 3c) shows little bias, with only slightly more retrievals below the line of equality than above. Of course, neither technique necessarily produces the most accurate result at any single location, and the small sample size of 84 retrievals may not accurately represent general conditions. The following sections provide additional details about the relative performance of the algorithms under the various conditions present on the 15 case days.

b. Relationships between first-guess, retrieved, and observed PW

This section compares retrieval errors (retrieved PW minus observed PW) to first-guess errors (first-guess PW minus observed PW). Figure 4 contains results for all 84 retrievals (the ALL group), plus results divided into four groups of 21 retrievals each, based on the

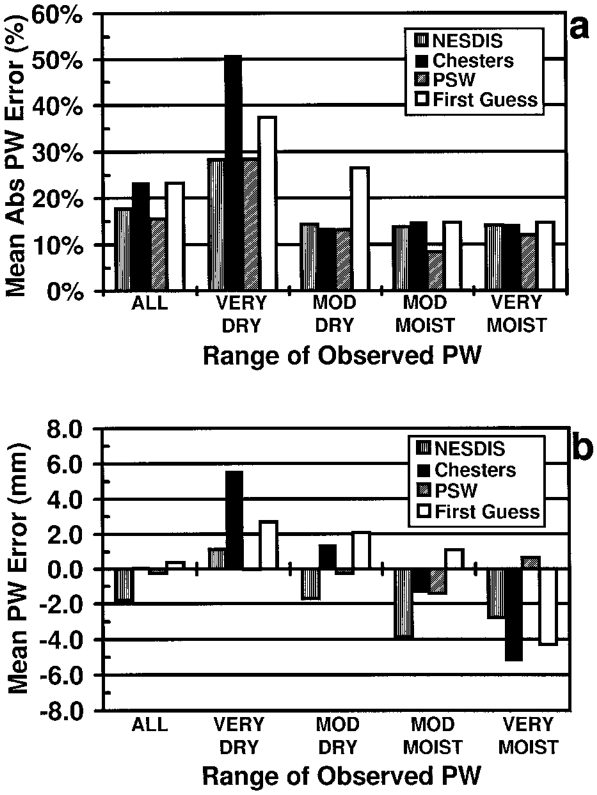

FIG. 4. Intercomparison of PW retrieval errors (retrieved PW minus observed PW) averaged within groups having varying amounts of observed PW. Mean first-guess PW errors (first-guess PW minus observed PW) are shown along with mean retrieval errors for the Chesters, NESDIS, and PSW techniques. The ALL group includes all 84 retrieval locations. The VERY DRY category includes locations with the 21 smallest observed PWs, MOD DRY has the 21 next driest locations, etc. (a) Mean absolute PW errors expressed as a percentage of the observed total column PW. (b) Mean PW errors (mm) that are averages of actual differences in PW.

magnitude of observed PW (ground truth) at each retrieval site. The VERY DRY group contains the 21 retrievals with the smallest observed PWs (average near 13 mm), the MOD DRY group has the 21 next largest observed PWs (average near 21 mm), and these are followed by the MOD MOIST (average near 32 mm) and VERY MOIST (average PW near 42 mm) groups. The mean errors in Fig. 4 are computed by averaging separately within each group. Recall that the Chesters technique does not use individual first-guess soundings, but uses regression on training data composed of many first-guess soundings. Thus, it is valid to compare mean first-guess errors for the Chesters technique to mean errors of the individual first-guess PWs used for the NESDIS and PSW techniques. Figure 4a contains mean absolute retrieval errors computed as a percentage of observed total PW. Results for the ALL group and the four subgroups indicate that each technique usually improves upon the first-guess error—that is, mean absolute retrieval errors are smaller than mean absolute first-guess errors. This suggests the ability to provide successful retrievals even when the first-guess is relatively poor (discussed later in this section). The VERY DRY group contains larger percentage errors because the retrieval errors are greater relative to the smaller total PW values. The results for each group show that the PSW technique, on average, has smaller absolute retrieval errors than do the other two techniques.

Figure 4b was constructed in the same manner as Fig. 4a, except that actual retrieval errors (not percentage errors) were averaged. This depiction reveals in more detail the biases seen in Fig. 3, showing that the retrieval errors for each technique are not distributed about the same mean. The ALL group shows that the NESDIS-retrieved PWs average 1.8 mm smaller than observed values. The Chesters and PSW techniques exhibit much smaller biases. Progressing from the VERY DRY to the VERY MOIST groups, mean retrieval errors generally shift from a moist (positive) to a dry (negative) bias. This is most evident for the Chesters technique and least evident for the PSW technique. Mean first-guess errors exhibit a similar change in bias—that is, providing overestimates in the driest categories and underestimates in the most humid categories.

Both the first-guess data and the Chesters retrievals have difficulty identifying the moist or dry extremes (Fig. 4b). They are more reliable for moderate values of PW. The physical nature of the NESDIS and PSW techniques allows them to adjust for first-guess PW errors at the individual retrieval sites. Thus, very dry or very moist PWs can be retrieved more accurately than with the Chesters technique.

The NESDIS and PSW retrievals are susceptible to large first-guess PW errors (Fig. 5). NESDIS retrieval errors (panel a) are more correlated with the first-guess PW errors (CORR $= 0.48$) than are PSW errors (panel b, CORR $= -0.11$). Both techniques produce some retrieval errors in excess of 5 mm and a few exceeding 10 mm (in absolute value). Figure 6 indicates the degree to which retrievals are improvements on the first guess. Retrieval improvement is defined as the absolute value of the retrieval error minus the absolute value of the first-guess error, where positive values indicate improvement on the guess and negative values indicate a retrieval worse than the first guess. The PSW technique (Fig. 6b) improves upon the first guess 68% of the time, compared to 50% for the NESDIS technique (Fig 6a). These results for the NESDIS technique are consistent with those of Fuelberg and Olson (1991), who found that the algorithm improved upon first-guess temperature and dewpoint profiles approximately half of the time. In the current case, both algorithms usually improve upon large first-guess errors, but many small first-guess errors (less than 5 mm) are made even worse. Reasons for this poor performance are discussed in sections 4c and 4d.

Figure 7 indicates the extent to which each technique improves upon the first guess, using a methodology similar to that of Fig. 4. The ALL group again represents

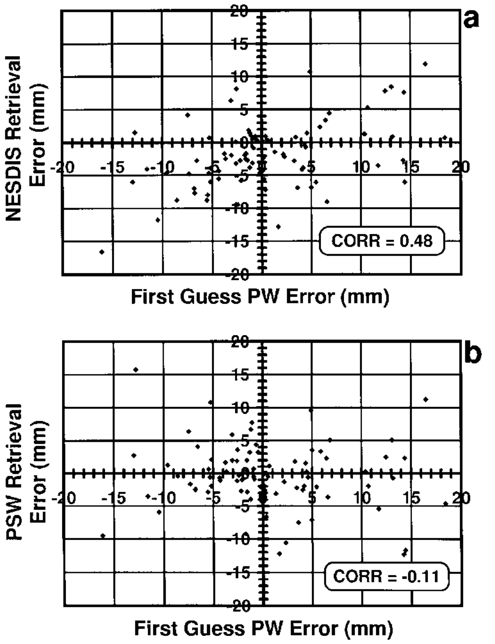

FIG. 5. Scatter diagrams of first-guess PW errors versus retrieval errors (mm) for the (a) NESDIS and (b) PSW techniques at the 84 retrieval locations. CORR is the linear correlation coefficient.

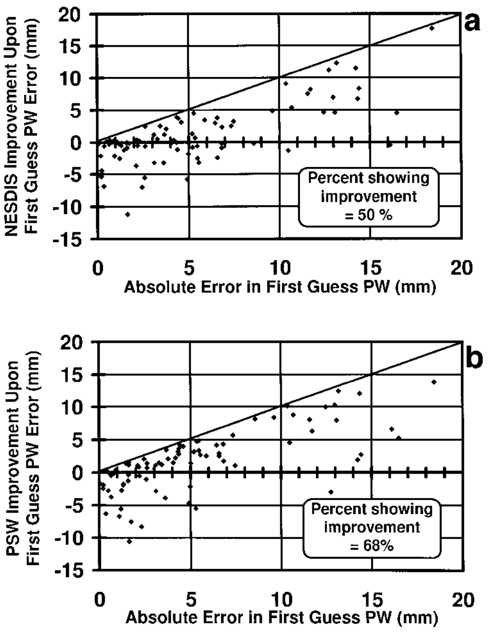

FIG. 6. Scatter diagrams of absolute error in first-guess PW (mm) versus improvement upon first-guess PW (mm) for the (a) NESDIS and (b) PSW techniques at all 84 retrieval locations. Improvement is defined as the absolute first-guess error minus the absolute retrieval error. Positive improvement indicates that retrieved PW is closer to the observed PW than is the first-guess PW. The solid line drawn at the upper extent of the data points in both diagrams denotes the maximum possible improvement, in which case retrieved PW equals observed PW.

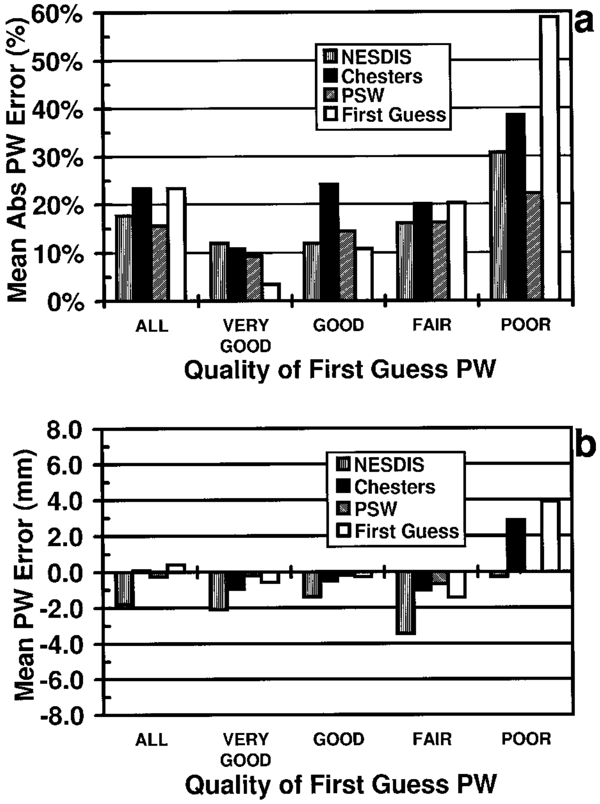

FIG. 7. As in Fig. 4 but for groups of retrievals with varying amounts of absolute error in first-guess PW. The VERY GOOD group includes locations with the 21 smallest first-guess PW errors, the GOOD group contains the 21 next smallest, etc.

results averaged over all 84 locations. However, the four subgroups (VERY GOOD, GOOD, FAIR, and POOR) denote increasing absolute error in first-guess PW—that is, a decrease in the accuracy of the first-guess PW. Figure 7a shows that mean absolute retrieval errors for each technique exceed mean absolute first-guess errors when those guesses are VERY GOOD (mean absolute first-guess error near 3%) or GOOD (mean absolute first-guess error near 11%). Thus, when provided with a relatively accurate first guess, each technique generally retrieves a less accurate PW. However, each technique substantially corrects for POOR first guesses, which have a mean absolute error of 58% (the rightmost bar in Fig. 7a) and exceed the observed PW by an average of nearly 4 mm (Fig. 7b). For example, the PSW retrievals based on POOR first guesses have a mean absolute error of only 22% (Fig. 7a), with a near-zero average of actual retrieval errors (Fig. 7b). When VERY GOOD, GOOD, and FAIR first guesses are used, retrievals from each technique exhibit a bias with the same sign as the first-guess errors (Fig. 7b). Specifically, the first guesses are slightly dry biased, as are the retrievals from each technique. These results indicate a significant first-guess dependence that is common to all three techniques, supporting the findings from Fig. 6. They also show that the Chesters technique, just like the PSW and NESDIS techniques, often fails to improve upon reasonably accurate first-guess information. Later sections explain some of the reasons for these findings.

None of the three techniques always produces a retrieval that is accurate or is even an improvement upon the first guess. This is the case mainly because factors other than PW affect the VAS brightness temperatures. These factors include variations in surface skin temperature, ambient temperatures at the various levels, and the vertical distribution of water vapor. The NESDIS and PSW techniques often respond to these variations since retrieval adjustment (retrieved PW minus first-guess PW) is due to differences between observed and first-guess brightness temperatures. The Chesters technique utilizes observed brightness temperatures in a regression equation where they are compared to an effective atmospheric temperature. Thus, these retrievals also depend on differences between the observed brightness temperatures and the first-guess brightness temperatures used to develop the regression. When factors other than PW affect brightness temperature differences, all three techniques still attribute these differences entirely to PW. As a result, incorrect adjustments can be made to the first-guess PW. The next two sections describe in greater detail the influence of the above-mentioned factors on the 84 retrievals in this study.

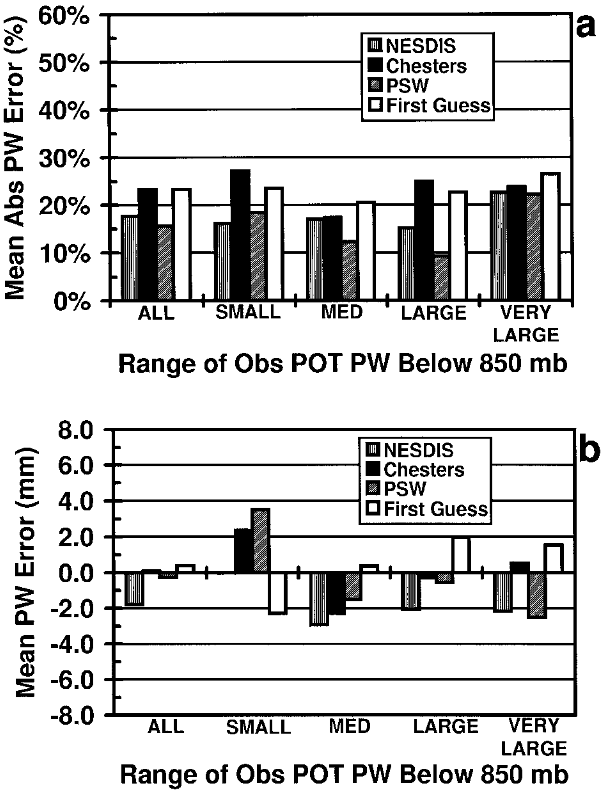

FIG. 8. As in Fig. 4 but for groups of retrievals with varying amounts of POT PW in the surface–850-mb layer. The SMALL group includes locations with the 21 smallest amounts of POT PW in this layer, the MED group has the 21 next smallest, etc.

c. Retrieval dependence on vertical moisture structure

Atmospheric columns having the same PW can have different vertical distributions of that water vapor. In the current study, for example, between 35% and 85% of the moisture in columns having PW near 15 mm resides between the surface and 850 mb (Fig. 1b). The VAS channels that are sensitive to water vapor, including the split-window channels, respond to this variability in a way that may be misinterpreted by the retrieval algorithms.

Figure 8 presents PW errors as a function of vertical moisture distribution. The methodology is similar to that used earlier in Figs. 4 and 7. The SMALL group contains the 21 ground-truth soundings having the smallest percentage of total (POT) PW between the surface and 850 mb (an average of 44%). In other words, the moisture in these soundings is least concentrated near the surface. The MED, LARGE, and VERY LARGE groups represent increasing POT PW in the surface–850-mb layer. The POT PWs in these groups are 53%, 61%, and 73%, respectively. The combined set of 84 retrievals represented by the ALL group has an average POT PW below 850 mb of 58%.

Mean absolute retrieval errors (Fig. 8a) are generally slightly greater at the extremes of observed POT PW—that is, in the SMALL and VERY LARGE groups. The techniques perform better when the vertical moisture distribution at the retrieval site is more uniform (as in the MED and LARGE groups). These changes in retrieval accuracy occur mainly because most of the first-guess soundings, created by averaging the 0000 and 1200 UTC soundings, do not have extreme POT PWs. Instead, they more accurately represent the vertical moisture distribution of retrievals in the MED and LARGE groups. Actual retrieval errors (Fig. 8b) are generally opposite in sign to the corresponding first-guess errors, indicating frequent overadjustment. This is particularly true for the PSW technique when the observed POT PW is SMALL or VERY LARGE. The NESDIS technique is less susceptible to extremes in vertical moisture structure, perhaps due to its use of additional VAS channels that sample more vertical layers. Since the Chesters technique does not utilize individual first guesses at each retrieval site, it also is less responsive than the PSW technique to differences in vertical structure between the first-guess and observed moisture profiles.

The difference between the observed and first-guess vertical moisture distributions strongly affects the PSW retrievals because it directly influences the split-window channel brightness temperatures. With all other factors constant, both channel temperatures will decrease in response to an upward shift in the altitude of moisture (assuming constant PW). This occurs because radiation

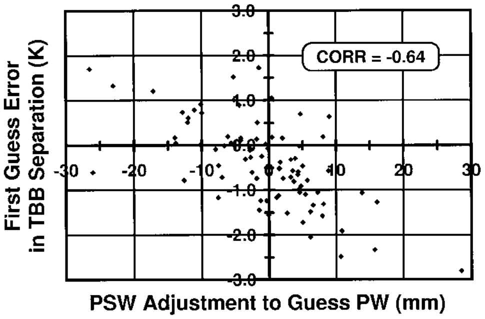

FIG. 9. Scatter diagram of the adjustment made to first-guess PW by the PSW technique (mm) versus the first-guess error in the separation between the split-window channel temperatures (K) at the 84 retrieval locations. CORR is the linear correlation coefficient between the quantities.

emanating from the surface encounters the same absorption at higher altitudes. As a result, the channel weighting functions peak at higher altitudes—that is, where tropospheric temperatures are usually cooler. Since the brightness temperatures are directly related to the ambient temperatures at the levels of these peaks, they are also cooler. Further, since the 12-μm channel is more sensitive to moisture than its 11-μm counterpart, the 12-μm channel brightness temperature decreases more rapidly with an upward moisture shift. Thus, the difference between the split-window channel brightness temperatures becomes larger when moisture is concentrated at higher altitudes. For the purpose of discussion, we will denote this difference as the split-window channel temperature "separation." It is not an error, but simply the amount by which the temperatures in the two channels differ for any single VAS observation.

An analysis of first-guess errors (first guess minus observed ground truth) in the split-window channel temperature separation (Fig. 9) indicates that they are negatively correlated (CORR $= -0.64$) with the PSW technique's adjustment to first-guess PW (retrieved minus first-guess PW). Negative (positive) first-guess errors in separation are correlated with positive (negative) adjustments to the first-guess PW. Recall that larger (smaller) separations occur when moisture is concentrated at higher (lower) altitudes. Thus, it follows that if the observed moisture is concentrated at higher (lower) altitudes, the PW retrieval will be a positive (negative) adjustment to the first guess. This occurs in the groups having SMALL (VERY LARGE) POT PW below 850 mb, where observed moisture is concentrated at higher (lower) altitudes (Fig. 8b). PSW-retrieved PWs in the SMALL (VERY LARGE) group generally are greater (less) than the first-guess PWs—that is, there is a positive (negative) adjustment. In fact, overadjustment occurs—that is, the sign of the retrieved PW error is opposite that of the first-guess PW error—in both the SMALL and VERY LARGE groups. Clearly, the first-guess error in vertical moisture distribution is a major factor affecting the ability of the PSW technique to accurately retrieve PW.

Similar reasoning applies to the NESDIS and Chesters techniques. These algorithms also overadjust the first-guess PW error in the SMALL and VERY LARGE groups (Fig. 8b). Knabb et al. (1994) describe another split-window-based PW retrieval technique, developed by Jedlovec (1990) but not applicable to VAS data, which responds similarly to variations in the vertical moisture distribution.

d. Retrieval dependence on temperature

We investigated the influence on PW retrievals by temperatures aloft and at the surface. One should recall from section 3 that our surface skin temperatures were equal to surface shelter temperatures, hereafter referred to as surface temperatures. Temperature variations in the middle and upper troposphere are not described here since their influence on the retrievals was found to be much less than that due to surface and low-altitude temperatures. Most VAS channels respond to changes in surface and low-altitude temperatures, especially those channels whose weighting functions peak near the surface (e.g., the split-window channels). Consequently, differences between observed and first-guess temperatures are related to differences between observed and first-guess VAS brightness temperatures. This causes adjustments to first-guess PW.

This section considers the combined influences of errors in the first-guess PW and surface temperature. Although the influences of surface temperature alone were examined, that experiment did not offer significant additional information compared to the effects of varying observed PW (Fig. 4). This is due to the relatively strong positive correlation (CORR $= 0.68$) between PW and skin temperature (Fig. 1a). For simplicity, the results that follow examine the effects of surface temperature on retrievals to infer the effects of low-altitude temperatures.

Figure 10 shows how the accuracy of first-guess PW and surface temperature is related to PW retrieval error. We subdivided the 84 retrievals into four groups based on simple criteria. The WARM AND DRY group contains nine retrievals whose first-guess surface temperatures are warmer than, and the first-guess PWs smaller than, the observed ground truth. Of the 75 remaining retrieval locations, 27 are in the COOL AND MOIST group (where first-guess surface temperature is too cold and the first-guess PW too moist), 11 in the WARM AND MOIST group, and 37 in the COOL AND DRY group.

The three retrieval techniques have a common weakness. Specifically, Fig. 10b shows a strong tendency to overcorrect first-guess PW errors in the WARM AND DRY and COOL AND MOIST groups. That is, the signs of PW retrieval errors tend to be opposite those of first-guess PW errors. Conversely, PW retrieval errors gen-

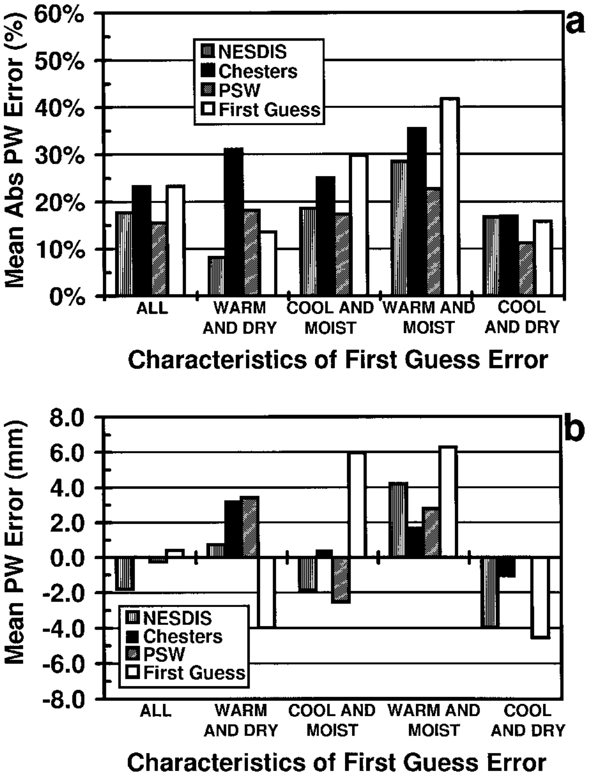

FIG. 10. As in Fig. 4 but for groups of retrieval locations with varying conditions of first-guess error in PW and surface temperature. The WARM AND DRY group contains those retrievals with a warm (positive) first-guess temperature error and a dry (negative) first-guess PW error, etc.

erally have the same sign as first-guess PW errors in the WARM AND MOIST and COOL AND DRY groups. The retrieval biases in Fig. 10b are clearly not due to the sign of the first-guess PW errors. Specifically, moist-biased retrievals occur when the first-guess surface temperature is too warm, and dry-biased retrievals occur when it is too cold. These retrieval biases occur irrespective of the sign of the first-guess PW error. The lack of a strong relationship in the mean absolute PW errors (Fig. 10a) suggests that surface temperature errors are not strongly associated with the magnitude of retrieval errors, but mainly their signs.

Errors in first-guess surface temperature do not directly cause the retrieval biases in Fig. 10b. Instead, they are due to differences between first-guess and observed profiles of low-level temperatures. At most of the retrieval sites where there is a significant first-guess surface temperature error, there is also a low-level temperature inversion in the radiosonde observation that is not in the first-guess profile, or vice versa. A first-guess surface temperature that is too warm generally indicates the presence of an inversion in the radiosonde data at the retrieval site. Conversely, a first-guess surface temperature that is too cold generally indicates an inversion in the first-guess profile. The latter scenario is more common in our study than the former since our 0000 UTC retrievals incorporated first-guess data from 0000 and 1200 UTC on the previous day. The 1200 UTC soundings introduced low-level inversions, and cold-biased surface temperatures, into many of the first-guess profiles. Since VAS channel brightness temperatures are sensitive to low-level temperatures, these inversions induce PW retrieval errors that are not due to errors in the first-guess PW. This will occur even if an accurate first-guess surface skin temperature is used, as with the PSW technique, which retrieves skin temperature for use in the PW calculation. To summarize, a first-guess error in the low-level vertical temperature structure will generally cause an error in the sign of the PW retrieval error.

The inversions cause overadjustments in the WARM AND DRY and COOL AND MOIST groups because variations in low-level temperature, like variations in vertical moisture structure, affect channel weighting functions and the resulting adjustments to first-guess PWs. For example, assume that the first-guess surface temperature is too cold and that a low-altitude temperature inversion exists in the first-guess profile, but not in the profile at the retrieval location. Also assume that the first-guess PW is moist biased and the retrieval falls into the COOL AND MOIST category described in Fig. 10b. Then, the first-guess split-window channel brightness temperatures will be too cold, and the separation between first-guess split-window channel brightness temperatures will be larger than the observed separation. Finally, recall from Fig. 9, using the PSW technique as the example, that this scenario induces a negative adjustment to the first-guess PW, as depicted in the COOL AND MOIST group in Fig. 10b. This also occurs with the NESDIS technique, even though it uses all 12 VAS channels, because the split-window channels dominate the others in retrieving water vapor near the surface, and this dominates the calculation of PW. Although the Chesters technique does not explicitly adjust a first-guess PW value, its regression relationship consistently produces a smaller retrieved PW with warmer observed channel temperatures. This happens in areas with cold-biased first-guess surface temperatures. When these results are combined with those regarding vertical moisture distribution (section 4c), it is clear that all three techniques often overadjust for the first-guess PW.

5. Conclusions

Three different methods for retrieving PW from VAS radiance data have been evaluated and intercompared in a case study scenario. The 15 case study days in June through October 1979 included a variety of conditions to test the performance of the techniques. The exclusive use of simulated VAS data allowed a direct comparison between retrieved PWs and the ground truth from which they were derived. Our results show that retrievals from all three techniques exhibit a high correlation with observed PWs. They generally provide retrieved PW that improves upon the first guess. This is especially the case for the NESDIS and PSW techniques, which often produce a successful retrieval even when provided with a relatively poor first guess. All three techniques generally yield retrievals that are improvements over those that would be predicted by surface temperature alone.

Overall, the PSW technique exhibited the greatest correlation with observed PWs, and it was least susceptible to systematic bias. The Chesters technique frequently overestimated PW in very dry regions and underestimated PW in very moist regions. The NESDIS technique exhibited a slight dry bias at most retrieval locations. This bias may have occurred because the majority of the first guesses were cold biased.

The results of this study are based on a wide range of atmospheric conditions, but not a large sample. Additionally, our retrievals were made only at 0000 UTC, and the relative performance of the techniques may differ at other times of the day. Thus, the results may not represent general conditions. Our results emphasize the performance of the techniques relative to one another and with respect to first-guess data having variable accuracy. This contrasts with an operational setting, where great effort is used to obtain very accurate first guesses. Variably accurate first-guess data were purposefully utilized in our study to examine sensitivities of retrievals to the guess data.

All of the techniques were dependent on the first-guess data. The sign of the first-guess surface temperature error, indicating low-level temperature inversions in either the first-guess or observed temperature profiles, was related to the sign of the PW retrieval error. First-guess profiles that were warm (cold) biased in terms of surface temperature were generally associated with moist- (dry) biased PW retrievals. This appears to occur irrespective of the sign of the first-guess PW error. Thus, differences between first-guess and retrieved low-level vertical temperature profiles are responsible for overadjustments to the first-guess PW error. Variations in vertical moisture structure produce an additional source of retrieval uncertainty, especially for the PSW technique. The PSW technique's overadjustment to first-guess PW appears to be common both in areas of very small or large contributions by low-level moisture to total column PW. The Chesters and NESDIS algorithms seem less susceptible to this error.

Although this research utilized *GOES-7* VAS, similar results are expected for *GOES-8* and *GOES-9* since procedures utilized by each technique are not significantly different for this new instrument. *GOES-8* and *GOES-9* have several improvements over *GOES-7*, such as smaller noise values, greater bit depth, finer horizontal resolution, and separate imaging and sounding instruments. These improvements may yield more accurate PW retrievals. Suggs and Jedlovec (1996) indicate that PSW retrievals from *GOES-8* better characterize PW gradients and are less sensitive to the first-guess than corresponding retrievals from *GOES-7*. Improvements to NESDIS moisture retrievals are also observed with *GOES-8* (Rao et al. 1996).

This study has presented results of applying three infrared PW retrieval techniques to the same set of conditions. Our goal was to intercompare the techniques in a fair and comprehensive manner. The selected conditions exhibited significant variability, but were based on criteria that preserved the fair comparison. Further studies should evaluate whether the performance of these three techniques is common, or even predictable, under a wider range of conditions. Such determinations are necessary to properly interpret the retrievals in future operational and research applications.

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