Humidity Profiles over the Ocean

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ABSTRACT

The distribution of water vapor in the atmosphere affects climate change through radiative balance and surface evaporation. The variabilities of atmospheric humidity profile over oceans from daily to interannual time scales were examined using nine years of daily and semidaily radiosonde soundings at Island stations extending from the Arctic to the South Pacific. The relative humidity profiles were found to have considerable temporal and geographic variabilities, contrary to the prevalent assumption. Principal component analysis on the profiles of specific humidity were used to examine the applicability of a relation between the surface-level humidity and the integrated water vapor; this relation has been used to estimate large-scale evaporation from satellite data. The first principal component was found to correlate almost perfectly with the integrated water vapor. The fractional variance represented by this mode increases with increasing period. It reaches approximately 90% at two weeks and decreases sharply, below one week, down to approximately 60% at the daily period. At low frequencies, the integrated water vapor appeared to be an adequate estimator of the humidity profile and the surface-level humidity. At periods shorter than a week, more than one independent estimator is needed. High-frequency surface humidity can be estimated if additional information on the vertical structure of the humidity profile is available or if the integrated water vapor in the boundary layer, instead of the entire atmospheric column, can be measured accurately by spaceborne sensors.

1. Introduction

Water vapor is a greenhouse gas; it plays an important role in the radiative balance of the atmosphere (e.g., Raval and Ramanathan 1989; Linzen 1990). The vertical distribution of water vapor in the atmosphere also affects surface evaporation and latent heat flux (Liu 1988). Using radiosonde soundings, many attempts have been made to describe the variability of the humidity profile and to compile its climatological distribution (e.g., London 1957). The soundings used were largely made over land, although over 70% of the earth’s surface is covered by ocean. The oceans form the largest reservoir of water on earth. With its high specific heat and large thermal inertia, the oceans are also the “flywheel” of the global heat engine. Evaporation and latent heat flux from the oceans are the dominant components of the surface thermal and hydrologic forcings and are important to short-term climate changes. Adequate global measurements of the water vapor over oceans can only be provided by spaceborne sensors. The main objective of this study is to examine the variability of humidity profile with respect to the estimation of evaporation using satellite data.

The distribution of water vapor in the atmosphere is often estimated using temperature soundings with an assumed relative humidity profile. Manabe and Wetherald (1967) were among the first to find it more convenient to use this approach to study atmospheric thermal equilibrium. Spaceborne sensors, such as the TOVS (Tiros-N Operational Vertical Sounders), have provided atmospheric temperature soundings for over a decade. The validity of such a method, however, depends on the assumption that the relative humidity profile normalized by the surface value is invariant with location and season. Variability of the relative humidity distribution over oceans has not been adequately studied.

To derive surface evaporation with the conventional bulk parameterization method, the humidity in the atmospheric surface layer (approximately 50 m thick) is needed (e.g., Frihe and Schmitt 1976; Liu et al. 1979). The vertical resolution of the present atmospheric sounders is not adequate to provide surface-layer temperature and humidity required to compute surface fluxes. The column-integrated water vapor, generally referred to as precipitable water, in three layers of the atmosphere is operationally derived from TOVS observations. However, the infrared sensors in TOVS are not as sensitive to atmospheric moisture over the ocean as are microwave radiometers. At present, only the integrated water vapor in the entire atmospheric column

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is operationally produced from microwave radiometers such as the SSMI (Special Sensor Microwave Imager). Knowledge of the vertical distribution of water vapor and its variability is important to the application of satellite data.

Liu (1984) demonstrated, with one year of radiosonde reports at Bermuda, that there is only one dominant mode of variability in the humidity profile of the atmosphere on monthly time scales. He found high correlation between this mode of variability and the variability of integrated water vapor in the atmospheric column (W) and suggested the possibility of deriving surface-level specific humidity (Q0) from W. A global relation between monthly mean Q0 and W was derived using 17 years of radiosonde reports from 46 midocean meteorological stations (Liu 1986). The Q0 derived from satellite data through this relation was used with surface wind speed and sea surface temperature to compute the evaporation and latent heat flux in the tropical Pacific (Liu 1988). These latent heat flux fields were then combined with surface solar irradiance to study the ocean’s response to the annual and interannual thermal forcing on the ocean (Liu and Gautier 1990). The Q0–W relation by Liu (1986) was evaluated by Hsu and Blanchard (1989) using measurements during 13 field experiments distributed over the global ocean. The results indicated that the relation could be used to describe not only monthly mean but also instantaneous soundings. In a number of recent studies (e.g., Simonot and Gautier 1989; Eymard et al. 1989), the relation was applied to satellite data at temporal scales from one to several days to derive ocean surface latent heat flux with various degrees of success. The validity of the Q0–W relation at these time scales depends on how well it accounts for the high-frequency variability of atmospheric humidity.

The variabilities of vertical profile of specific and relative humidities will be examined. The data will be described in section 2. In section 3, the profile of relative humidity will be compared with specific humidity. The vertical profile of specific humidity and its variability will be examined in section 4. The empirical orthogonal functions (EOF) are the most efficient way of summarizing uncorrelated modes of the variance (Lorenz 1956). An extension of the EOF (also known as principal component) analysis by Liu (1984) and Liu (1990) will be presented in section 5. The optimal time scales for the application of the Q0–W relation will be given in section 6. The physical parameters to be used in the estimation of Q0 are discussed in section 7. The conclusion will be found in section 8.

### Table 1: Power index of mean humidity profile

<table>
<thead>
<tr>
<th>Station</th>
<th>Latitude</th>
<th>Longitude</th>
<th>Soundings used</th>
<th>Number of interpolations</th>
<th>( \lambda )</th>
</tr>
</thead>
<tbody>
<tr>
<td>St. Paul</td>
<td>57.2°N</td>
<td>189.8°E</td>
<td>6568</td>
<td>1144</td>
<td>3.00</td>
</tr>
<tr>
<td>Midway</td>
<td>28.2°N</td>
<td>182.6°E</td>
<td>6549</td>
<td>742</td>
<td>3.33</td>
</tr>
<tr>
<td>Wake</td>
<td>19.3°N</td>
<td>166.7°E</td>
<td>6576</td>
<td>117</td>
<td>3.50</td>
</tr>
<tr>
<td>Majuro</td>
<td>7.1°N</td>
<td>171.4°E</td>
<td>3288</td>
<td>11</td>
<td>2.89</td>
</tr>
<tr>
<td>Pago Pago</td>
<td>14.3°S</td>
<td>189.3°E</td>
<td>6575</td>
<td>169</td>
<td>3.11</td>
</tr>
</tbody>
</table>
values would cause a moist bias, but excluding them would cause a larger bias. Although their distribution is skewed toward high levels, the 19% values in the data examined spread over a large depth; the quantitative effect of including these values in our analysis is difficult to ascertain.

Similar problems have confronted users of the archived U.S. upper-level data. The 19% relative humidity has been used at face value on the assumption that the effect is negligible. Our data show that the precipitable water between 400 and 300 mb is only approximately 1% of the total in the atmospheric column. Without the values of 19% relative humidity, the percentages of sounding reaching above 300-mb levels are reduced to 4%, 48%, 47%, 72%, and 58%, respectively, at the five stations from north to south, requiring considerable extrapolations at the top. Attempted extrapolations with various methods resulted in a large number of unreasonable values of relative humidity (larger than 20% and lower than 0%) in place of the original 19%. The following analysis is based on using all of the 19% values.

Underestimation of relative humidity at near saturation was also known. Golden et al. (1986) indicated that 100% relative humidity was frequently reported as 96%–98% in U.S. radiosondes. Although less dramatic than the cutoff at the dry end, this problem is reflected in the dropoff of relative humidity greater than 96% at St. Paul, Wake, Majuro, and Pago Pago, as shown in Fig. 1. Schwartz (personal communication, 1991) indicated that this distribution feature is unique to the U.S. radiosondes and attributed the reason to the overcorrection of relative humidity by the algorithm implemented in 1980. We do not have any explanation for the exception at Midway where a relatively large number of 100% relative humidity is found in all the years. The result of this problem is the underestimation of the averaged relative humidity, particularly at low levels.

Observations are sampled daily at Majuro (0000 UTC) and semidaily (0000 and 1200 UTC) at all other stations. The humidity soundings also contain short time gaps, and Lagrangian interpolation was also used to produce continuous uniform time series needed for EOF analysis. The number of temporally interpolated soundings and the total number of soundings resulting are also listed in Table 1. At St. Paul and Midway, 8 and 16 profiles are missing at the beginning of the period, respectively. At Midway and Pago Pago, 11 and 1 profiles are missing at the end of the period. Since we did not extrapolate in time, the number of soundings used is less in these stations.

3. Profile of relative humidity

In their radiation study, Manabe and Wetherald (1967) used a linear relation between relative humidity \((R)\) and pressure \(\rho\),
\[ \frac{R}{R_0} = \frac{(p/p_0 - 0.02)}{0.98} \]  

where the subscript denotes values at the surface level. The profiles of mean and standard deviations of \( R \) at five stations are shown in Fig. 2. For all five stations, the 9-year means neither decrease monotonically with pressure nor follow a linear relation, but have maxima just below 900 mb. The maxima of the variance are at higher altitudes. The variances are reduced at all levels in the monthly means.

The application of (1) was largely based on the assumption that \( R \) profiles are not as variable as the specific humidity (\( Q \)) profile. The profiles of the relative variabilities of \( Q \) and \( R \), in form of the ratio of standard deviation to mean, are compared in Fig. 3. At St. Paul, \( R \) has smaller relative magnitude of variability than \( Q \). However, at Wake, Majuro, and Pago Pago, \( Q \) has smaller relative magnitude of variability between 900 and 400 mb. Above 400 mb, the mean \( Q \) is small and the ratio for \( Q \) changes much more rapidly than the ratio for \( R \).

4. Profile of specific humidity

The mean profiles of \( Q \) at the five stations are shown in Fig. 4. The humidity decreases monotonically with pressure. Smith (1966) fitted climatological soundings to a power relation

\[ \frac{Q}{Q_0} = \frac{(p/p_0)^\lambda} \]

and found \( \lambda \) dependent on season and latitude. The values of \( \lambda \) obtained from the 9-year mean profile are listed in Table 1. Equation (2) can be expressed as

\[ Q_0 = AW \]

where

\[ A = g(\lambda + 1)/p_0 \]

and \( g \) is the gravitational acceleration. The value of \( \lambda \) at Majuro is lower than at other stations, indicating less concentration of water vapor in the lower levels. In the western tropical Pacific, where Majuro is located, more water vapor penetrates to high levels due to deep convection. At St. Paul in the Bering Sea, the values of \( \lambda \) during summer are less than those in the rest of the year because of surface saturation, as discussed by Liu (1986). The standard deviation profiles for individual soundings and their monthly means are also shown in Fig. 4. Among the five stations, the largest variance is found at Midway. The maxima of variance of individual profiles are at the surface and at approximately 800 mb, which is likely to be the average position of the top of the atmospheric boundary layer. The amount of variance at the surface relative to the amount at 800 mb decreases toward the equator. The variance for the monthly mean is reduced at all levels but relatively more reduction is found at 800 mb, indicating that the variance at 800 mb has larger high-frequency com-

![Fig. 2. Profiles of mean relative humidity, standard deviation of individual measurements, and standard deviation of the monthly mean, computed from nine years of radiosonde soundings at five stations.](image-url)
Fig. 3. Profiles of the ratio, standard deviation to mean, for relative humidity and specific humidity.

Fig. 4. Same as Fig. 2, except for specific humidity.
ponents. The large variations at the top of the boundary layer may be mostly due to the entrainment of wet and dry air with synoptic systems.

5. Empirical orthogonal function

An EOF analysis was performed to study the amount of variance at various time scales, which can be represented by a statistical estimation in the form of (2). The objective is to decompose the specific humidity at pressure level \( p \) and time \( t \), \( Q(p, t) \), in terms of a set of \( N \) orthonormal functions, \( F_i(p) \), and their corresponding uncorrelated time amplitudes (principal components), \( C_i(t) \), such that

\[
Q'(p, t) = \sum_{i=1}^{N} C_i(t) F_i(p)
\]

where primed quantities represent deviations from the temporal means. The eigenvector computed from the covariance matrix is \( F_i(p) \). The principal components are derived by

\[
C_i(t) = \sum_{j=1}^{N} Q'(p, t) F_i(p).
\]

The total variance of the data is apportioned among the various components. The fraction of total variance explained by the \( i \)th component is equal to

\[
a_i = \alpha_i / \sum_{j=1}^{N} \alpha_j
\]

where \( \alpha \) is the eigenvalue of the covariance matrix of \( Q \). Another useful quantity is the percentage of the variance at level \( p \) represented by the \( i \)th component

\[
b_i(p) = \alpha_i F_i^2(p) / \sum_{j=1}^{N} \alpha_j F_j^2(p).
\]

The eigenvectors are arranged in descending order of \( \alpha \), such that the first eigenvector explains the largest amount of variance. The number of eigenvectors required to explain a given fraction of the total variance is the fewest of any set of orthogonal functions. Many investigators have used EOFs as an a priori method of minimizing the number of estimators in statistical estimation (e.g., Davis 1976; Lorenz 1977).

The first three EOFs \( F_i \alpha_i^{1/2}, i = 1 \) to 3, for each station, are shown in Fig. 5. The percentages of variance \( a_i \) accounted by the first three EOFs are listed in Table 2. Together they account for 78\% (Majuro) to 92\% (St. Paul) of the total variance. As a common characteristic of orthogonality, the EOFs have an increasing number of zero crossings. For each station, the first EOF is entirely positive, implying that the dominant variability is positively correlated in the vertical. Similar to the profile of variance, the magnitude at the surface relative to 800 mb is less in the tropics than at higher latitudes.

**Fig. 5.** The first three EOFs of the specific humidity soundings.
TABLE 2. Percentage variance of individual soundings represented by the first EOFs.

<table>
<thead>
<tr>
<th></th>
<th>First</th>
<th>Second</th>
<th>Third</th>
</tr>
</thead>
<tbody>
<tr>
<td>St. Paul</td>
<td>79.06</td>
<td>8.54</td>
<td>4.01</td>
</tr>
<tr>
<td>Midway</td>
<td>67.16</td>
<td>11.49</td>
<td>6.59</td>
</tr>
<tr>
<td>Wake</td>
<td>62.37</td>
<td>10.99</td>
<td>8.25</td>
</tr>
<tr>
<td>Majuro</td>
<td>57.01</td>
<td>13.79</td>
<td>6.88</td>
</tr>
<tr>
<td>Pago Pago</td>
<td>56.38</td>
<td>13.37</td>
<td>8.20</td>
</tr>
</tbody>
</table>

The first EOF has a peak at levels that probably represent the mean position of the top of the atmospheric boundary layer. This level increases slightly toward the equator from approximately 825 mb at St. Paul to 750 mb at Majuro. It is at this level that the second EOF changes sign. For the second mode, the variability within the boundary layer is opposite in phase with that above the boundary layer. The third EOF consists of three layers: the upper and the surface layer have the same sign but opposite to the middle layer. The magnitude of the middle layer peaks at approximately the same level of the first EOF.

Since the upper levels include more extrapolated and cutoff values of relative humidity, the EOF analysis described was repeated as a check, using soundings up to 500 mb. The shapes of the EOFs are similar to the lower part of those shown in Fig. 5. There is no obvious change in position of the zero crossings. Only the percentage variances represented by the first EOFs increase slightly at all stations.

A single EOF, or one independent estimator, can account for at most 79% of the semiday variance at St. Paul, and 57% of the daily variance at Majuro. More than one independent estimator are needed to represent more of the variance. At low frequencies (annual and interannual), the second and third EOFs are found to have relatively much less variance. Liu (1984) demonstrated with limited data that for monthly mean soundings, the first EOF accounts for approximately 90% of the variance at Bermuda, thus suggesting that a single-parameter statistical estimation in form of (2) may be sufficient for estimation at the monthly time scale.

6. The optimal time scales

In order to examine the variabilities from a day to a month, the 9-year time series are averaged at periods from 1 to 30 days. The shapes of the first three EOFs computed from these average profiles are similar to those shown in Fig. 5, but the relative magnitude of variance represented by the first EOF increases with averaging period. The percentage of total variance represented by the first EOF, $a_1$, and the percentage of variance at the first level represented by the first EOF, $b_1(1000 \text{ mb})$, are computed at each station. Their values are shown in Fig. 6 as functions of the averaging period.

FIG. 6. Percentage variance of specific humidity represented by the first EOF at various averaging periods.
period. There is an inflection point at approximately 10 days. The amount of variance represented by the first EOF decreases rapidly below 7 days. With periods longer than 14 days, the amount of variance represented by the first EOF does not change much, and a single mode of variability dominates. For monthly averages, the values of $a_1$ are 97%, 91%, 92%, 88%, and 89%, respectively. The values of $b_1$ (1000 mb) do not differ much from $a_1$; they are less than $a_1$ at St. Paul, Majuro, and Pago Pago, but higher at Midway and Wake.

The radiosonde results are averaged for two time intervals, 10 days and monthly. From these average soundings $Q_0$ and $W$ were computed and compared with the relation of Liu (1986) in Fig. 7. For the 10-day means, there are 1588 pairs of data and the root-mean-square (rms) deviation from the relation is 1.11 g kg$^{-1}$. For monthly means, the rms deviation for the 530 data pairs is 1.01 g kg$^{-1}$. The difference between these two values is much smaller than the difference between either one and the rms deviation of the daily sounding which is 1.76 g kg$^{-1}$.

7. Physical estimators

The results illuminate two suggestions for improving $Q$ estimation at high frequencies. The first (Liu 1990) is by additional estimators that provide information on the vertical structure of the humidity profile, and the second (Liu, 1980) is to replace the integrated water vapor in the entire atmospheric column with integrated water vapor only in the boundary layer ($W_b$).

a. Vertical structure

Physical interpretations of EOFs are not always evident in EOF analysis. In this case, the EOFs resemble trigonometric functions, with increasing zero crossings; the atmosphere is divided into increasing numbers of

![Graph](image)
layers whose variabilities have opposite correlation with those in the adjacent layers. To account for the larger fraction of the variance, larger numbers of independent modes representing finer vertical structures are needed. The significance of the EOF analysis is the indication that only the first three modes (with three layers) are needed to account for 80%–90% of the variance.

In the first mode, the whole atmosphere varies as a single coherent layer, and $W$ was found to be a good candidate to represent this mode. The derivation of the $Q_0-W$ relation, starting with Liu (1984), was driven by this fact. As an example, the time series of $C_1$ is compared with the time series of $W$ at Majuro in Fig. 8. The component $C_1$ encompasses the whole spectrum of frequency from synoptic to interannual. In Figs. 8a, b, the 9-year time series of the monthly means of $C_1$ and $W$ show almost identical annual cycles and interannual changes. The deficit during the 1982–1983 El Niño and Southern Oscillation (ENSO) episode (Liu 1988) appears both in Figs. 8a and 8b. The daily deviations from the monthly mean in the first year, 1980, are stretched out in Figs. 8c, d to reveal the agreement in synoptic and intraseasonal variations. The temporal variability of the first mode has almost perfect agreement with $W$. The correlation coefficient between $C_1$ and $W$ are shown in Table 3 with a number of data pairs used to form the correlation.

The second mode represents the contrast between the boundary layer and the atmosphere above. The increase in boundary layer humidity due to convergence and uplifting in the atmospheric boundary layer may be accompanied by divergence and descending dry air above the boundary layer during passage of synoptic systems. The identification of an observable to represent this mode is not as clear as the first one. Three parameters that represent vertical structures were examined. The first is the exponent $\lambda$ in Eq. (1), computed from each sounding through regression. The second is the ratio $R_L = W_L/W$, where $W_L$ is the precipitable water below 850 mb. The third is the ratio $R_2 = W_2/W$, where $W_2$ is the water vapor above 750 mb. The correlation coefficient between these three parameters and $C_2$ are also listed in Table 3. The correlations are significant assuming independent samples, but the agreement between $C_2$ and any of the three parameters are not as good as demonstrated between $C_1$ and $W$. Recently, Wagner et al. (1990) also examined the relation between $C_2$ and $R_L$ using seven months of data in the North Atlantic and arrived at similar results. As an example, the monthly means for 9 years and the daily deviations from the monthly mean in the first years of $R_L$ and $C_2$ at Majuro are compared in Fig. 9. At present, none of the three parameters: $R_L$, $R_2$, and $\lambda$, can be obtained from operational satellite data.

b. Boundary layer precipitable water

The high-frequency variance at the top of the boundary layer and the shape of the second EOF suggests some decoupling between distribution of water vapor in the upper levels and in the boundary layer, on synoptic scales. Within the boundary layer, the humidity distribution should be well behaved and is governed by similarity laws (e.g., Brown and Liu 1982). The height of the boundary varies with the passage of synoptic system; it is taken to be 850 mb in this study only as an approximation. The first EOF of the individual humidity soundings up to 850 mb is also entirely positive and accounts for 93%, 85%, 85%, 70%, and 79% of the variance for the five stations (from north to south), respectively.

In Fig. 10, $Q_0$ and $W_L$ at daily and monthly periods are shown with their linear regressions. Only one out of ten daily data is plotted. The linear regression of the daily data, constrained to pass through the origin, is $Q_0 = 0.78 W_L$, where $Q_0$ is in grams per kilogram and $W_L$ is in grams per centimeter squared. The r.m.s deviations from this regression are 0.94 g kg$^{-1}$ for 16 430 daily data and 0.42 g kg$^{-1}$ for 545 monthly data. The validity of a linear relation for the whole range of data in Fig. 10 suggests that the change of slope at high

**Fig. 8.** Time series at Majuro of (a) monthly mean first principal component of specific humidity profiles, (b) monthly mean integrated water vapor of the whole atmospheric column, (c) daily deviations from the monthly mean of the first principal component, and (d) daily deviations from the monthly mean of integrated water vapor of the whole atmospheric column.
humidity shown in Fig. 7 is the result of different water vapor distributions above the boundary layer. It is in agreement with the interpretation by Liu (1986) that the slope in the $Q_0-W$ relation changes because more water vapor penetrates above the boundary layer as a result of deep convection. At present, there is no operational satellite measurement of integrated water vapor in the boundary layer.

8. Discussion and conclusion

Radiosonde soundings at island stations were examined to resolve humidity variability with periods between a day and approximately a decade. Large variability in the relative humidity profile was found, contrary to the prevalent invariant assumption. The statistical technique of empirical orthogonal functions enabled us to summarize the variability of specific humidity profiles into independent modes; these modes were found to have increasing vertical structures with decreasing amount of variance represented. Although the EOF analysis does not explicitly identify the physical parameters as the optimal estimators for these modes, it put accuracy bounds on any statistical estimations at various frequencies. At the daily time scale, only three independent modes are necessary to account for 80% to 90% of the variance; the same amount of fractional variance can be represented by single dominant modes at time scales longer than 2 weeks.

In the first mode, moisture in the whole atmospheric column varies together and its variability correlates almost perfectly with $W$ in the atmosphere. The fractional variance represented by this mode increases with decreasing frequency from approximately 60% at a period of 1 day to approximately 90% for periods longer than 2 weeks. The results indicate that the global relation between $Q_0$ and $W$ derived by Liu (1986) would best be applied to periods longer than 10 days. The fraction of variance represented by the first mode also shows a poleward increase, implying that the $Q_0-W$ relation would work better at higher latitudes. However, during a few months in summer, $Q_0$ over high-latitude oceans is often saturated, with $R_0$ very close to 100% (Liu 1986; Liu and Niih 1990) and cannot adjust to the $Q_0-W$ relation. The estimator $W$ was measured by the SMMR (Scanning Multichannel Microwave Radiometer) on both Seasat and Nimbus-7 and is continuing being monitored by SSMI on the operational spacecraft of DMSP (Defense Meteorological Space Program). The results of this study strengthen the application of this satellite dataset.

For the other independent modes, the atmosphere is divided into layers; the humidity variation in one layer is opposite in phase with the adjacent layers. At the daily period, the second and third EOF together account for approximately 20% of the variance. The second mode has one zero crossing and represents the contrast between variations in the boundary layer and above the boundary layer, as during the passage of synoptic systems. A number of physical parameters are suggested in this study as the estimators for the second mode, but none of them has the high correlation with the second principal component as the correlation between $W$ and the first principal component. None of these parameters is operationally derived from satellite data at present.

Additional estimators could be derived from a combination of the radiance measured by the water vapor channels of future microwave atmospheric sounders whose weighting functions (the contribution of the radiance as a function of height) peak at various levels. Microwave emissions at frequencies near 183 GHz

![Figure 9](image-url)
were found to be sensitive to humidity at various heights in the atmosphere (Schaer and Wilheit 1982), and the channels for measuring at these frequencies will be incorporated in sensors such as AMSU (Advanced Microwave Sounding Unit) and SSMT-2 (Special Sensor Microwave Temperature) to be flown on future NOAA and DMSP polar orbiters. Although the weighting functions of these channels are broad relative to the depth of the troposphere, our EOF analysis indicated that such broad structures may be sufficient in accounting for most of the variance in the humidity profile. The results of our analysis may explain the success of statistical profile retrievals using simulated radiances of just a few channels with broad weighting functions (e.g., Kakar and Lambrighten 1984).

Using the integrated water vapor in the boundary layer would increase the accuracy at all time scales. An algorithm for retrieving such a parameter from satellite data can be developed (P. Schuessel, personal communication) but such effort will be complicated by the variability of boundary layer height. The boundary layer thickness has diurnal and synoptic variabilities and is affected by the presence of clouds. Sea surface temperature, which has been observed by spaceborne sensors for decades, has been used alone or in addition to $W$ as an estimator of $Q_0$ (S. Crewell, personal communication, 1990). However, Liu and Niiler (1990) demonstrated that, in most extratropical oceans, the seasonal variation of $T_s$ and $Q_0$ are out of phase, reflecting the longer memory of seasonal forcing inherent in the ocean compared to the atmosphere. Other suggested estimators, such as wind divergence, have to be scrutinized.

Except for St. Paul, the five stations are located far from continental influence and should be representative of oceanic conditions. The length of data record (nine years) chosen is long enough to include interannual variabilities (including two ENSO episodes), but short enough for the matrix to be accommodated by our computing power. It is not the intention of this study to evaluate the quality of radiosonde soundings; there has been an upsurge in such studies recently (e.g., Finger and Schmidlin 1991; Schwartz 1990). The 19% cutoff values of relative humidity (discussed in section 2), although not ideal, are more informative than miss-
ing data. We found our basic conclusions remain the same when we repeated our EOF analysis only on the lower portion (1000–500 mb) of the soundings, which have less amount of low relative humidity data.

This study is intended only to put an approximate accuracy bound on the $Q_0 - W$ relation at various frequencies and to explore the possibility of improving the statistical estimation; it does not provide the precise errors in estimating $Q_0$. The results at the five stations shown in this report are only examples from data analysis taken at various locations in both Pacific and Atlantic oceans, and at different periods of time (Liu 1984; Liu 1990). The basic results presented, including the relative positions of EOF zero crossings, the dominance of three independent modes at the daily time scale, and the effectiveness of $W$ as an estimator of $Q_0$ at periods longer than 10 days, are not affected by our datasets and the interpolation/extrapolation schemes; they remain the same in all our studies. There are other factors besides $W$ that affect $Q_0$. However, their variabilities are vertically coherent only in limited height and are decoupled from $W$. These factors are likely to be important to $Q_0$ variation only at high frequencies.

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REFERENCES


