Temperature-dependent daily variability of precipitable water in special sensor microwave/imager observations

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Disciplines
Atmospheric Sciences | Climate | Meteorology

Comments
Temperature-dependent daily variability of precipitable water in special sensor microwave/imager observations

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Abstract. We use retrievals of atmospheric precipitable water from satellite microwave observations and analyses of near-surface temperature to examine the relationship between these two fields on daily and longer timescales. The retrieval technique producing the data used here is most effective over the open ocean, so the analysis focuses on the southern hemisphere's extratropics, which have an extensive ocean surface. For both the total and the eddy precipitable water fields, there is a close correspondence between local variations in the precipitable water and near-surface temperature. The correspondence appears particularly strong for synoptic and planetary scale transient eddies. More specifically, the results support a typical modeling assumption that transient eddy moisture fields are proportional to transient eddy temperature fields under the assumption of constant relative humidity.

1. Introduction

An important contributor to the atmospheric branch of the extratropical water cycle is the transport of water vapor by atmospheric eddies. This transport also plays an important role in the Earth's energy balance: it is a medium for the poleward movement of heat, it helps determine the distribution of water vapor, the predominant greenhouse gas, and it influences the distribution of clouds. Despite water vapor's role in energy and water balances, its spatial and temporal characteristics are poorly understood because it is difficult to observe well. However, recent advances in space-based observing systems and retrieval techniques promise to substantially reduce these difficulties. One example is the measurements of vertically integrated water vapor, or precipitable water (PW), that can be retrieved from microwave observations by the special sensor microwave/imager (SSM/I) flown on satellites of the Defense Meteorological Satellite Program. Here we use daily precipitable water retrieved from SSM/I observations by Greenwald et al. [1993] to examine the link between water vapor variability and extratropical eddy dynamics. We place special emphasis on the joint variability of moisture and temperature fields, since the latter may be expected to place a substantial constraint on the former.

Our focus is on water vapor variability in the extratropics of southern hemisphere. The southern extratropics are largely ocean covered and thus provide an extensive area amenable to microwave moisture retrievals. Furthermore, the southern extratropics are a region of especially vigorous water cycling. A clue to this perspective is Figure 1, which shows the temporal standard deviation of PW divided by its time average for the water vapor data examined here (described in more detail in section 2). Two especially noteworthy features of Figure 1 are that the largest relative variability of precipitable water occurs in the middle latitudes and relatively strong variability occurs almost uniformly across the southern extratropics. These features are closely linked to southern hemisphere storm tracks [Trenberth, 1991]. The first feature suggests a highly active branch of the water cycle here, with a strong role for transport dynamics in this region because of strong horizontal gradients in water vapor. The second feature implies a significant role for transient eddy dynamics in the water cycle, which might be expected because standing wave dynamics are weaker in this region.

Eddy dynamics in the southern extratropics compare quite closely with idealized models of extratropical waves based on wave zonal-flow interaction through baroclinic instability [Randel and Stanford, 1985a, b], suggesting a possible understanding of the moisture dynamics based on a substantial body of theory. More specifically, moisture transport parameterizations for the extratropics have been advanced [Mullan, 1979; Stone and Yao, 1990] that are based on baroclinic instability theory coupled with an assumption that eddy moisture amounts are strongly governed by eddy temperature fluctuations. Daily PW observations provide an opportunity to test this assumption. The daily PW observations also help us understand the nature of PW fluctuations in relation to temperature variability.

The plan of this paper is as follows. The data sources and their strengths and limitations are described in the next section. The analysis models used here are described in section 3. In section 4 we compare characteristics of the temporal variability of precipitable water and temperature in the lower atmosphere. Section 4 also gives a comparison of spatial characteristics, and Section 5 summarizes conclusions and discusses implications of the results.

2. Data

2.1. SSM/I Precipitable Water

The SSM/I is a passive microwave radiometer that was launched in a Sun-synchronous orbit in July 1987. Measurements of upwelling radiation are made at 19.35, 22.235, 37.0, and 85.5 GHz. At 19.35, 37.0, and 85.5 GHz, measurements are made of both the vertical and horizontal polarizations, whereas at 22.235 GHz, only the vertical polarization has been measured. Tjemkes et al. [1991] have derived a physical method for retrieving precipitable water using polarization differences at
their method is a susceptibility to contamination by atmospheric liquid water. For the extratropics, such contamination would probably be of minor importance. However, Greenwald et al. [1993] have extended the method of Tjemkes et al. [1991] to include simultaneous retrieval of cloud liquid water, using the 37.0-GHz measurements. PW retrievals by Greenwald et al. [1993] may still be contaminated by precipitating water, so they have included in their method an identification of satellite pixels that may have precipitation in the field of view. These pixels are removed from the data set.

Comparisons of PW retrievals with quasi-coincident rawindsonde data by Tjemkes et al. [1991] show an rms difference between the two data sets of about 5.5 kg m\(^{-2}\). This result includes a systematic excess in the retrievals of about 3 kg m\(^{-2}\) that is especially apparent for PW values less than 20 kg m\(^{-2}\). The nonsystematic error in the comparison is 4.6 kg m\(^{-2}\). Some of the difference is, of course, the result of errors in the microwave observations and retrieval scheme, but the rawindsonde measurements also include errors, which depend on the hygrometer used. A somewhat conservative error estimate is 10% [cf. Larsen et al., 1993]. For an approximate mean extratropical PW of 15 kg m\(^{-2}\), this yields an error of 1.5 kg m\(^{-2}\), which suggests that the bulk of the error should be attributed to the microwave observations and retrieval scheme. Further differences may also arise because the rawindsonde point measurements and the SSM/I pixel-area measurements are not precisely coincident, but the size of this error is difficult to estimate. Subsequent removal of liquid water contamination by Greenwald et al. [1993] should reduce the error estimates reported by Tjemkes et al. [1991], although the greatest source of error appears to be the sensitivity of the method to estimates of surface microwave emission. Tjemkes et al. [1991] and Greenwald et al. [1993] also give comparisons of their methods with those proposed by others for retrieving atmospheric water from SSM/I measurements.

The PW retrievals analyzed here were computed and col-

![Figure 1. Temporal standard deviation of daily precipitable water (PW) divided by seasonal average precipitable water for (a) June-August 1988 (JJA) and (b) December 1988-February 1989 (DJF).](image)
lected into 1° × 1° latitude-longitude boxes under the direction of Graeme Stephens at Colorado State University. This study uses daily data archives produced for the periods June–August 1988 (JJJA) and December 1988–February 1989 (DJF). The daily value is an average of all measurements collected in a grid box between 0 and 24 hours Greenwich mean time for a given day; we assume that the measurement so obtained is a representative value for the day. Data voids occur over land, where uncertainties in surface emissivity prevent reliable retrievals, over sea ice, where typical PW is expected to be smaller than the accuracy of the retrieval method, and over ocean sectors not viewed by the radiometer on a given day. The ocean data voids occur primarily in the latitude band 15°–35° in both hemispheres.

2.2. ECMWF Analyses

Temperature data used here are extracted from the twice-daily, global analyses produced by the European Centre for Medium Range Weather Forecasts (ECMWF) on a 2.5° × 2.5° latitude-longitude grid. The data cover the same periods as the SSM/I retrievals. Trenberth and Olson [1988] have compared ECMWF analyses with those produced by the U.S. National Meteorological Center for the earlier period 1980–1986. Results there indicate that the temperature data should represent well the southern hemisphere’s extratropical temperature variability produced by large-scale transient eddies. Hurrell and Trenberth [1992], however, have found that the temporal variability of monthly mean 1000 mbar temperatures derived from ECMWF analyses does not correlate as well as might be expected with the temporal variability of analyzed sea-surface temperatures (SSTs). Our analyses do not rely on the temporal variability of monthly means. Also, the temporal variability of monthly mean temperatures is small, less than 1°C over most of the oceans, and it is much smaller than the range of temperatures used in the analyses here. However, from our analysis, one might be suspicious in general of ECMWF 1000 mbar temperatures in the southern hemisphere extratropics, so we have performed two comparisons that are appropriate for the analyses undertaken here of ECMWF 1000 mbar temperatures versus other temperature estimates.

First, we have compared monthly average, ECMWF 1000-mbar temperatures with colocated SSTs produced by the Climate Analysis Center (CAC) [Reynolds, 1988; Reynolds and Marsico, 1993] of the U.S. National Meteorological Center. The comparison is for the latitudes 30°S–60°S during the two data periods for which we analyze the retrieved precipitable water. The comparison includes only points with SST ≥ 273 K to avoid locations that might have substantial ice cover. Differences between the two fields are summarized in Table 1. A part of the differences in Table 1 occurs because the two fields are not physically the same, and, indeed, the largest differences between the two occur in latitudes 30°S–45°S (not shown), where climatological 1000-mbar heights are higher above the surface than in latitudes farther south [e.g., Oort, 1983]. Even if we view the differences as error in the ECMWF 1000-mbar temperature, the biases and standard deviations in Table 1 are both relatively small compared to the range of temperatures used here in monthly analyses (e.g., Figure 2).

We have also compared twice-daily ECMWF 1000-mbar temperatures with daily and twice-daily 1000-mbar temperatures determined from rawinsonde ascents from islands in the southern hemisphere extratropics, for periods overlapping or preceding our precipitable-water retrieval periods (Table 2).

<table>
<thead>
<tr>
<th>Table 1. Differences Between Monthly Average, ECMWF 1000-mbar Temperatures ($T_{EC}$), and Colocated CAC SST for Latitudes 30°S–60°S</th>
</tr>
</thead>
<tbody>
<tr>
<td>Month</td>
</tr>
<tr>
<td>-------------------</td>
</tr>
<tr>
<td>June-Aug. 1988</td>
</tr>
<tr>
<td>Dec. 1988-Feb. 1989</td>
</tr>
</tbody>
</table>

Abbreviations are ECMWF, European Centre for Medium Range Weather Forecasts; CAC, Climate Analysis Center; SST, sea-surface temperature; sdev, standard deviation.

These island stations were undoubtedly used in the ECMWF analyses and so are not independent from the analyses. As a consequence, errors in the ECMWF analyses may be smaller near the island stations than in regions devoid of all observations. However, the biases and standard deviations are again much smaller than the ranges of daily temperatures appearing in the observational data sets or in our analyses (e.g., Figures 3 and 5). The two comparisons suggest that errors in ECMWF analyses are not so large that they will obscure relationships between precipitable water and 1000-mbar temperature being examined here.

The ECMWF analyses also contain water vapor data. The accuracy of moisture data in these analyses may be too low over observation-sparse regions of the southern hemisphere, such as the oceans [Trenberth and Olson, 1988; Starr and Melfi, 1991], to adequately represent the synoptic variability of extratropical moisture in the southern hemisphere. Liu et al. [1992] have compared monthly PW data computed from ECMWF analyses with corresponding monthly PW values retrieved from SSM/I measurements at 22.235 and 37.0 GHz. Their comparison includes the months October 1987 and January, April, and July 1988 and so overlaps the period of our analysis. The ECMWF fields tend to have weaker gradients and tend to overestimate moisture amounts in dry air masses. For daily data the disparity between the two PW fields could be larger. Also, the vertical resolution of the available ECMWF analyses for the study periods includes data at only 1000 mbar and 850 mbar, which is relatively coarse vertical resolution for the portion of the atmosphere where water vapor undergoes its largest absolute changes with height. Finally, it is advantageous in our opinion to use a water vapor estimate from an independent retrieval. For all these reasons we do not include the ECMWF moisture analyses in this study.

3. Analysis Models

On monthly timescales, precipitable water over the ocean displays a close relationship with sea-surface temperature [Stephens, 1990; Stephens et al., 1993]. However, this result might be expected because near-surface atmospheric temperatures place a significant constraint on atmospheric humidity through the Clausius-Clapeyron relationship and because these temperatures should be strongly correlated with sea-surface temperature on monthly timescales through surface fluxes of sensible heat and radiation. On shorter timescales the coupling between SST and temperatures in the lower atmosphere may not be as strong, so one would expect this relationship to deteriorate. Furthermore, control of PW by the Clausius-Clapeyron relation implies that relative humidity is fairly constant, a restriction suggested in seasonal data [Telegadas and London,
Table 2. Comparison of 1000-mbar Temperatures From Island Rawinsonde Stations ($T_{ob}$) and ECMWF Analyses ($T_{EC}$) Interpolated Bilinearly to the Observation Site

<table>
<thead>
<tr>
<th>Site and Period</th>
<th>Bias ($T_{ob} - T_{EC}$), °C</th>
<th>Sdev ($T_{ob} - T_{EC}$), °C</th>
<th>No. Observations</th>
<th>Range ($T_{ob}$), °C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Marion (46°S, 38°E)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>JJA 1987</td>
<td>-0.7</td>
<td>1.9</td>
<td>119</td>
<td>10</td>
</tr>
<tr>
<td>DJF 1987–1988</td>
<td>+1.1</td>
<td>1.8</td>
<td>105</td>
<td>13</td>
</tr>
<tr>
<td>JJA 1988</td>
<td>-0.3</td>
<td>2.0</td>
<td>99</td>
<td>12</td>
</tr>
<tr>
<td>Dec. 1988</td>
<td>+1.6</td>
<td>2.1</td>
<td>38</td>
<td>9</td>
</tr>
<tr>
<td>Gough (40°S, 10°W)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>JJA 1987</td>
<td>-0.5</td>
<td>1.6</td>
<td>143</td>
<td>14</td>
</tr>
<tr>
<td>DJF 1987–1988</td>
<td>+0.5</td>
<td>1.6</td>
<td>161</td>
<td>12</td>
</tr>
<tr>
<td>JJA 1988</td>
<td>-0.1</td>
<td>1.7</td>
<td>159</td>
<td>11</td>
</tr>
<tr>
<td>Dec. 1988</td>
<td>+0.2</td>
<td>2.1</td>
<td>60</td>
<td>13</td>
</tr>
<tr>
<td>Macquarie (54°S, 159°E)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>JJA 1987</td>
<td>-0.8</td>
<td>1.4</td>
<td>117</td>
<td>8</td>
</tr>
<tr>
<td>DJF 1987–1988</td>
<td>+0.8</td>
<td>1.2</td>
<td>84</td>
<td>7</td>
</tr>
<tr>
<td>Lord Howe (31°S, 159°E)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>JJA 1987</td>
<td>+0.7</td>
<td>1.0</td>
<td>88</td>
<td>7</td>
</tr>
<tr>
<td>May 1988</td>
<td>+0.3</td>
<td>0.6</td>
<td>29</td>
<td>5</td>
</tr>
<tr>
<td>Norfolk (29°S, 168°E)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>JJA 1987</td>
<td>+1.3</td>
<td>1.0</td>
<td>85</td>
<td>6</td>
</tr>
<tr>
<td>May 1988</td>
<td>+0.4</td>
<td>1.1</td>
<td>26</td>
<td>4</td>
</tr>
<tr>
<td>Easter (27°S, 109°W)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>JJA 1987</td>
<td>+0.4</td>
<td>2.3</td>
<td>51</td>
<td>10</td>
</tr>
</tbody>
</table>

Also shown are the number of observations and the range of observed temperatures contributing to each site and period's statistics.

1954; Peixoto and Oort, 1992], but a restriction which may also deteriorate on shorter timescales.

Here we examine how closely daily PW varies with lower atmosphere temperature under the assumption that relative humidity is constant on daily timescales. More specifically, we assume that

$$\text{PW} = \text{PW}_{\text{r}}(T_r) = \int q_{\text{r}}(T_r, z) \rho(z) \, dz,$$

(1)

where

$$q_{\text{r}}(T_r) = r q_{\text{sat}}(T_r) e^{-z/H_q};$$

(2)

$r$ is relative humidity, $q_{\text{sat}}$ is the saturation specific humidity for a near-surface temperature $T_r$, $H_q$ is a humidity scale height, $\rho$ is density, and $z$ is height above the surface. For $T_r$, we use the 1000-mbar temperature in the ECMWF analyses and compute $q_{\text{sat}}$ using the approximate Clausius-Clapeyron relation

$$q_{\text{sat}} = 0.622 \left( \frac{6.11 \text{ mb}}{1000 \text{ mb}} \right) \exp \left\{ \gamma_{\text{r}} \left( \frac{1}{273 \text{ K}} - \frac{1}{T_r} \right) \right\},$$

(3)

where $\gamma_{\text{r}} = 5411 \text{ K}$. We also assume that density follows a scale height relationship

$$\rho(z) = \rho_0 e^{-z/H_p}.$$  

(4)

Then,

$$\text{PW}_{\text{r}} = r \rho_0 H_q q_{\text{sat}}(T_r),$$

(5)

where

$$\frac{1}{H} = \frac{1}{H_q} + \frac{1}{H_p},$$

(6)

In applying (5) to our precipitable water and temperature data we use $H_q = 2.5 \text{ km}$ during DJF, $H_q = 2.1 \text{ km}$ during JJA, and $H_p = 8 \text{ km}$ in both seasons. The $H_q$ values are derived from seasonal and zonal average specific humidity values reported by Oort [1983] at 1000 mb and 700 mb for 35°S–55°S. In each season, $H_q$ varies in latitude by less than 3% about its mean. $H$ in (6) is insensitive to reasonable choices of $H_p$. We assume $\rho_0 = 1.25 \text{ kg m}^{-2}$ in our analyses. Oort's [1983] data for 1000-mbar temperature and geopotential height show that $\rho_0$ varies by less than 4% about this value. We treat $r$ in (5) as an unknown to be obtained by a least squares fit of (1) to the data.

As discussed earlier, parameterizations for extratropical, eddy moisture transport have been advanced that assume that eddy moisture amounts are governed by the eddy temperature field. For these parameterizations,

$$q^* = \left[ r \frac{\partial q_{\text{sat}}([T])}{\partial T} \right] T^*$$

(7)

where ([ )] denotes the zonal average and ([ )]$^*$ the departure from the zonal average. This relationship can be derived by assuming constant relative humidity and retaining the largest derivative in a first-order Taylor series expansion of the Clausius-Clapeyron relationship. A similar derivation for $\text{PW}_{\text{r}}$ yields

$$(\text{PW}_{\text{r}})^* = r \rho_0 H \frac{\partial q_{\text{sat}}([T])}{\partial T} (T^*)$$

(8)

$$= \gamma_{\text{r}} [\text{PW}_{\text{r}}] (T^*)^2. \quad (9)$$

We thus attempt to fit the eddy relation

$$(\text{PW})^* = (\text{PW}_{\text{r}})^*,$$

(10)

where here the parameter $r$ is chosen by a least squares fit of (10) to the data. We further distinguish between standing eddy (SE) fields, given by the seasonal average and denoted by ($$)^*$, and transient eddy (TE) fields, given by the departure
from the seasonal average and denoted by \( (\text{T})' \). Thus we also attempt to fit the relations

\[
(\text{PW})' = (\text{PW}_c)' \quad (11)
\]

and

\[
(\text{PW})^* = (\text{PW}_c)^* \quad (12)
\]

where (11) and (12) use \( (\text{T})^* \) and \( (\text{T})' \), respectively.

Precise comparison of temperature and PW data is inhibited by the mismatch of observation times and observation grids in the two data sets. The PW data set gives daily values. We assume that a representative daily temperature \( T_{dy} \) at any ECMWF ocean gridpoint is given by the sum

\[
T_{dy} = \{T(0Z) + 2T(12Z) + T(24Z)\}/4 \quad (13)
\]

The SSM/I PW we associate with this temperature is an average of the 1°-grid data in a 2° x 2° grid box surrounding the ECMWF data point. We skip any ECMWF data point for which PW data is missing in the 2° x 2° grid box.

4. Results

4.1. Total Fields

The retrieval versus rawindsonde data comparison by Tjemkes et al. [1991] found a systematic excess of 3 kg m\(^{-2}\) in the PW retrievals compared to rawindsonde PW. Guided by this result, for our analyses of the total PW field (eddy + zonal average) we have subtracted 3 kg m\(^{-2}\) from all PW values. In doing so we are assuming that the bias found by Tjemkes et al. is real and equally applicable to all latitudes. Implications of this adjustment are discussed later. Note that this adjustment is irrelevant for later analyses in which the zonal average is subtracted from the data.

Figure 2 shows monthly average, adjusted PW versus 1000-mbar \( T_{dy} \) for extratropical latitudes in the southern hemisphere. The monthly average relationship between PW and 1000-mbar temperature is similar to that depicted by Stephens [1990] and Stephens et al. [1993] for PW versus SST: PW increases with temperature for the simple reason that warmer air can hold more water vapor. Figure 2 can also be viewed as a depiction of PW versus latitude because in the SH extratropics, monthly 1000 mbar temperature over the oceans has a largely zonal distribution.

Figure 2 also shows the curve \( (\text{PW}_c(T_{dy})) \) given by using monthly temperature data in (5). The best fit of the monthly average data between 30 S and 60 S for both seasons occurs for \( r \approx 70\% \) (Table 3), which is consistent with the climatological, zonal and seasonal average relative humidity in the southern hemisphere's lower troposphere reported by Peixoto and Oort [1992]. Peixoto and Oort's data give larger relative humidity in JJA, whereas the fits here give larger relative humidity in DJF. However, the precise value of \( r \) can be affected by any uncertainty in the value of \( H \) and \( \rho_0 \) used in (5). The \( (\text{PW}_c) \) curve reinforces the conclusion that near-surface temperature exerts strong control over monthly PW, in part because of the concentration of atmospheric humidity to the lower troposphere.

We also constructed fits of \( (\text{PW}_c) \) to the PW(T) distribution using daily and 5-day average data. Five days represents an intermediate average over just a few synoptic timescales (and is also the approximate geometric mean of 30- and 1-day periods). For the daily data the spread of values about the \( (\text{PW}_c) \) curve is much larger (Figure 3). For the daily and 5-day average data, best fits occurred for nearly the same values of relative humidity as given by the monthly average data (Table 3). Consistent with Figures 2 and 3 the rms error of the fit increases as shorter and shorter timescales of variability are retained in the data. For daily data

<table>
<thead>
<tr>
<th>Season</th>
<th>Average Period, days</th>
<th>( r, % )</th>
<th>rms(r), kg m(^{-2})</th>
</tr>
</thead>
<tbody>
<tr>
<td>JJA</td>
<td>30</td>
<td>71</td>
<td>1.1</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>70</td>
<td>2.3</td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>70</td>
<td>3.7</td>
</tr>
<tr>
<td>DJF</td>
<td>30</td>
<td>75</td>
<td>1.9</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>74</td>
<td>3.5</td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>75</td>
<td>5.5</td>
</tr>
</tbody>
</table>

PW is precipitable water.

Table 3. Best Fit Values of \( r \) and the rms Error of the Fit, \( \text{rms}(r) \), to (5) in Each Season Examined, Using Temperature and PW Estimates for Latitudes 30°S–60°S and Selected Averaging Periods.
the rms error is about the same as the nonsystematic error of the retrieved PW values estimated by Tjemkes et al. [1991]. While the rms error is smaller in DJF than JJA is not clear, but for both seasons it appears that the accuracy of the fit is affected as much, if not more, by the accuracy of the PW retrievals than the underlying model used in the analysis.

Differences between PW and the actual distribution of PW may appear deceptively large in Figure 3, since Figure 3 does not show clearly the distribution of PW for a given temperature. Such distributions appear in Figure 4 for selected $T_{dy}$. The best fit PW value for each temperature is relatively close to the histogram class with highest frequency. Also, the distributions are fairly narrow with a tendency to be skewed toward values greater than PW. Saturation provides an upper bound on the PW values that can occur for a given temperature, which constrains the spread of the histogram at the high end of the range. Much, if not all, of the spread of PW values in Figure 4 to model relative humidities greater than 100% appears to be attributable to the nonsystematic error in the retrieval scheme. The lower bound on PW, however, would be PW = 0, but for all histograms, very few PW observations occur for very low relative humidities. This behavior likely is a result of the PW observations being limited to ocean areas, where the underlying water reservoir prevents atmospheric relative humidity from becoming very low. The figures suggest that in fact, the ocean prevents near-surface relative humidity from falling below 50% except rarely.

### 4.2. Eddy Fields

The fit of the daily PW data to the PW curve suggests that daily temperature fluctuations govern strongly daily PW. However, the apparent accuracy of the fit could be a consequence of the tendency for zonal average $T$ to decrease with latitude, with a corresponding constraint on PW. Accordingly, we have computed $(\text{PW}_{\text{eddy}})^*$ and, by fitting (10), $(\text{PW}_{\text{eddy}})^*$. Results of the fit appear in Table 4. The best fit $r$ values for the total eddy field are similar to those computed for the total (zonal average + eddy) PW data. Note, however, that the RMS error of the fit is not much smaller than the RMS deviation of the data from its mean value of 0, suggesting some caution in interpreting the goodness of the fit, especially for precise values of $r$.

Equation (8) implies that $(\text{PW}_{\text{eddy}})^*$ should be more sensitive to $(T)^*$ at low latitudes, where $[T]$ is warmer, than at high latitudes. The fit (10) implies similar sensitivity for $(\text{PW})^*$. This behavior appears in Figure 5, which shows $(\text{PW})^*$ and $(\text{PW}_{\text{eddy}})^*$ for representative latitudes in both seasons. As expected by (8) the slope of the line given by $(\text{PW}_{\text{eddy}})^*$ versus $(T)^*$ decreases with increasing latitude. Also shown in Figure 5 is the least squares fit of a straight line to the $(\text{PW})^*$ versus $(T)^*$ relationship, done separately for each latitude and season. For all cases shown, line given by $(\text{PW}_{\text{eddy}})^*$ versus $(T)^*$ matches quite well the linear fit to $(\text{PW})^*$ versus $(T)^*$, supporting the fit to the data of the model given by (10), especially since the independent linear fits also display decreasing slope with latitude. Plots similar to Figure 5 for the transient eddy and standing eddy fields (not shown) depict the same set of relationships between precipitable water, temperature, and latitude.

Table 4 also shows the results of performing fits for the standing eddy and transient eddy fields, using (11) and (12), respectively. These two cases produce a wider range of best fit values for $r$. The results suggest the possibility that compared to the standing eddy field, the transient eddy moisture field responds more strongly to fluctuations in its corresponding temperature field. Note also that although the magnitude of the standing eddy PW field is smaller than the transient eddy PW, its magnitude is not negligible as is the case for some other standing eddy fields in the southern extratropics, such as dynamic transports [e.g., Peixoto and Oort, 1992]. The reason for this is that PW is concentrated in the lower atmosphere, where its distribution will include an imprint of the slowly changing sea-surface temperature distribution.
4.3. Spatial Structure

The correspondence between the PW and temperature fields suggests a common spatial structure for the two, at least on the largest scales of variability. This behavior is examined here by comparing spectra of PW and $T$ versus zonal wavenumber. For both fields we have computed spectra (periodograms) for each day included in our PW data set. For PW the retrievals along a latitude circle contain gaps due to the data voids over land and the oceanic points not viewed by the satellite on a given day. PW spectra were thus computed using a method described by Press et al. [1992] that accounts for uneven sampling of data. Temperature data suffered no gaps in longitude, so that temperature spectra were computed using a standard fast fourier transform. For temperature we reduced the possibility of spectral leakage by applying a split cosine bell taper to the first and last 10% of data along a latitude circle starting and ending at 180° longitude. For the separate temperature and PW fields, daily spectra in the same season were then averaged together. This procedure was performed at 5° intervals from 30°S to 60°S. Seasonally averaged spectra from all these latitudes were then averaged together to yield time and latitude averaged spectra for the zonal wavenumber dependence of PW and temperature. A 3-point running average filter was also applied to the spectra.

Confidence intervals at the 95% level were computed for both the PW and temperature spectra using a standard $\chi^2$ approximation modified to account for the influence of the data taper and the 3-point running average [e.g., Bloomfield, 1976]. Time-lagged and latitude-lagged autocorrelations of the

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**Table 4. Best Fit Values of $r$ and the rms Error of the Fit to (10), (11), and (12) for Total, Standing, and Transient Eddy Fields, Respectively, in Each Season Examined, Using Temperature and PW Estimates for 30°S–60°S**

<table>
<thead>
<tr>
<th>Season</th>
<th>Field</th>
<th>$r$, %</th>
<th>rms ($r$), kg m$^{-2}$</th>
<th>rms (0), kg m$^{-2}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>JJA</td>
<td>total</td>
<td>71</td>
<td>3.7</td>
<td>4.1</td>
</tr>
<tr>
<td></td>
<td>SE</td>
<td>45</td>
<td>1.0</td>
<td>1.2</td>
</tr>
<tr>
<td></td>
<td>TE</td>
<td>91</td>
<td>3.5</td>
<td>4.0</td>
</tr>
<tr>
<td>DJF</td>
<td>total</td>
<td>76</td>
<td>5.3</td>
<td>5.9</td>
</tr>
<tr>
<td></td>
<td>SE</td>
<td>64</td>
<td>1.4</td>
<td>2.1</td>
</tr>
<tr>
<td></td>
<td>TE</td>
<td>89</td>
<td>5.0</td>
<td>5.5</td>
</tr>
</tbody>
</table>

Also shown is the rms departure of each eddy PW field from its mean, rms(0). SE is standing eddy; TE is transient eddy.
Figure 5. (PW)* and (PWcc)* versus (T)* for (a) 30øS, JJA, (b) 60øS, JJA, (c) 30øS, DJF, and (d) 60øS, DJF. As in Figure 3, only 1/30 of the data is plotted. Also shown is a least squares fit of a straight line to the plotted (PW)* data, done separately for each panel.

PW data (not shown) show that the PW fields become essentially uncorrelated after one day and that latitudes 5ø apart are also uncorrelated. For both fields, confidence intervals were computed assuming that the number of independent samples is one half the product of number of daily spectra for each latitude times the number of latitudes.

Spectra for PW and temperature for both transient eddy and total eddy appear in Figures 6 and 7, respectively. For the purpose of comparing wavenumber dependence, all spectra in a season have been normalized by their respective amplitudes at the wavenumber of maximum TE amplitude. For transient eddies the DJF spectra of PW' and T' show a very similar distribution of spatial variance with wavenumber. Roughly the same behavior appears in the JJA spectra, though the T' variance spectrum is skewed somewhat toward lower wavenumbers relative to the PW' spectrum. Beyond the range of wavenumbers depicted in Figure 6, the PW' and T' spectra diverge. On log-log axes, PW' variance decreases with wavenumber with a slope of -1.7, whereas T' variance decreases with a slope of -2.5. Thus the close relationship between PW' and T' expressed in Table 4 appears to be confined to synoptic and planetary scale waves, which, however, are the waves of largest amplitude.

The shortest wavenumbers analyzed here have wavelengths of approximately 300 km and so extend into the range of mesoscale spectra discussed by Lilly [1983] and Nastrom and Gage [1985], among others. The -5/3 slope of the PW' variance at this end of the spectrum is consistent with their analyses. Because water vapor is highly stratified, its turbulence on these scales should be essentially two-dimensional, and a reverse cascade of spectral variance by quasi-two-dimensional turbulence could produce this slope [Gage, 1979; Lilly, 1983]. An analysis of Nimbus 7 water-vapor retrievals by Manney and Stanford [1990] indicates that thunderstorms and frontal zones could provide the source of spectral variance powering this cascade. Why this slope should extend to much larger wavelengths than observed by Nastrom and Gage [1985] for wind and potential temperature spectra is not clear, though guided by Lilly's [1983] exploration of the effects of stratification on turbulence spectra, one might speculate that the strong stratification of atmospheric water vapor may promote this behavior.

Spectra of the total eddy fields appearing in Figure 7 show less of a correspondence between moisture and temperature. The differences are due to a substantial standing eddy component that appears much more strongly in the eddy temperature field than in the eddy moisture field. As noted above, the standing eddy component comes from the close link between 1000-mbar temperature and sea-surface temperature. The link with standing eddy PW does not appear to be as strong. Compared to the results for transient eddies, this behavior suggests that on timescales longer than a few days, the eddy moisture
field tends to be governed as much if not more by processes other than atmospheric eddy dynamics. For example, if $PW = 15 \text{ kg m}^{-2}$, then a typical midlatitude surface evaporation $LE$ of $100 \text{ W m}^{-2}$ yields a turnover time of $PW/LE = 5.4$ days, longer than a midlatitude synoptic scale time of approximately 2 days but much shorter than a season.

5. Summary

We have examined the relationship between daily precipitable water and 1000-mbar temperature in the southern hemisphere’s extratropics. For both the total and the eddy $PW$ fields, there is a close correspondence between local fluctuations in $PW$ and in $T(1000 \text{ mbar})$. The correspondence appears particularly strong for synoptic and planetary scale transient eddies. The results support a typical modeling assumption that transient eddy moisture fields are proportional to transient eddy temperature fields under the assumption of constant relative humidity, though they also suggest that the proportionality factor $r$ for transient eddy departures from the zonal average may be larger than the climatological near-surface relative humidity.

A limitation of the results here is the estimated random error of the PW retrievals, which appears to limit the accuracy of the fitting expressions (10), (11), and (12). This also limits the applicability of our results in high latitudes, where the magnitude of the error becomes comparable to the eddy moisture field itself. The accuracy of the temperature analyses may also affect the fitting of expressions (10)–(12). Perhaps a more serious consideration for modeling purposes, however, is that this study has been confined to atmospheric moisture over the oceans. The northern hemisphere extratropics have substantially greater land cover, which might not supply moisture as readily to the atmosphere as the oceans. A new, daily PW data set being developed [Vonder Haar et al., 1994] that blends radiosonde and infrared and microwave retrievals may be a means for overcoming this limitation.

Our fits of the total PW data, using (5), were shown after an estimated systematic error of $3 \text{ kg m}^{-2}$ was subtracted from the data. It has been suggested (D. Jackson, private communication, 1994) that the systematic error reported by Tjemkes et al. [1991] was largely removed by the correction for liquid water contamination described by Greenwald et al. [1993], so that it was not necessary here. If we do not subtract this error from the PW retrievals, then the best fit for the total PW field occurs...
for $r \sim 90\%$, which is considerably larger than near-surface relative humidities reported by Peixoto and Oort [1992]. Arguably, by adjusting the PW retrievals we are using rawindsonde data to force an agreement with rawindsonde data. However, if the best fit were to occur for $r = 90\%$, then the vertical arrows in Figure 4 would correspond to $90\%$ relative humidity, and there would be a considerably larger population of data points in Figure 4 residing above the $100\%$ level. It would be much harder to explain these large $r$ value points as a consequence of the systematic error in the data.

On the basis of the review of rawindsonde accuracies by Larsen et al. [1993], it seems unlikely that the rawindsonde measurements would have such a large error that they would on average report $75\%$ relative humidity when it actually was $90\%$. There are also possible errors in assigning appropriate values to $\rho_o$ and $H$ in (5) and in assuming that the 1000-mbar temperatures are representative of surface air temperatures. Observed latitudinal variations of $H$, $\rho_o$, and surface pressure suggest that these factors would contribute to an error in $r$ estimates of only a few percentage points. If the appropriate temperature in (5) is actually warmer than the ECMWF 1000-mbar temperatures, then one could obtain a lower $r$. If we were to increase temperatures uniformly by 3.25°C without reducing PW by $3 \text{ kg m}^{-2}$, then we would obtain $r = 0.72$. Reference to Table 1, however, indicates that in making this adjustment, the effective temperature would be below the surface at many latitudes. Perhaps a more serious issue is that the rawindsonde climatology may be biased toward observations over land, whereas the PW retrievals used here of course contain only observations over the ocean, so that a comparison with Peixoto and Oort’s [1992] data might be inappropriate. However, because their data set does include ocean-based observations and because the southern hemisphere midlatitudes are largely ocean covered (so that land values might be strongly governed by nearby ocean humidity fields), the agreement between the best fit $r$ obtained using the adjusted data and the relative humidity given by Peixoto and Oort would appear to be a further confirmation of a systematic error in the retrieved PW used here.

Acknowledgments. The authors thank G. Stephens and colleagues for supplying the PW data used here, D. Jackson for answering our many questions about the data, J. Breid for statistics consultation, and the reviewers for constructive comments. This research was supported by NASA grant NAGW-2993 and NSF grant ATM-912352. The ECMWF and CAC temperature analyses and the rawindsonde observations were obtained from archives maintained by the National Center for Atmospheric Research.

References


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(Received October 31, 1994; revised July 13, 1995; accepted August 7, 1995.)