On the Potential Change in Surface Water Vapor Deposition over the Continental United States due to Increases in Atmospheric Greenhouse Gases

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ABSTRACT

Characteristics of surface water vapor deposition (WVD) over the continental United States under the present climate and a future climate scenario reflecting the mid-twenty-first-century increased greenhouse gas concentrations were evaluated by using a regional climate model forced by initial and lateral boundary conditions generated by a GCM. Simulated seasonal WVD frequency and daily amounts are presented and elaboration on their relation to potential surface dew/frost is also provided. The climate scenario showed in winter a noticeable decline in WVD frequency over snow-covered areas in the Midwest and over most of the elevated terrain in the western United States, contrasted by an overall increase in the eastern United States. In summer, a decline in frequency was simulated for most of the United States, particularly over the mountains in the west. A spatially mixed trend of change in the frequency was indicated in spring and fall. The trend of change in WVD amount resembled that of the frequency in summer, whereas a largely reversed relation was shown in winter. Quantitatively, changes in frequency and amount of WVD in the range of −30% to +30% generally were indicated for all locations and seasons, except for the western half of the United States, where the change was larger in summer. While areas passing a local statistical test on WVD changes ranged from 11% to 36% of land domain, the WVD differences as a whole field between present climate and future scenarios are significant.

1. Introduction

Changes in relevant forcing mechanisms, due to increased atmospheric greenhouse gas (GHG) concentrations, might affect surface water vapor deposition (WVD) and thus the dew and frost characteristics over the United States. This note attempts to provide a preliminary evaluation of such potential impacts using climate models. The modeling approach employs a relatively fine-grid regional climate model to downscale coarse-grid general circulation model (GCM) output. Thus, it better accounts for features such as land use and topography and their impacts on WVD. The simulated changes in WVD climatologies between the present climate and mid-twenty-first-century climate scenario will be presented.

Many studies have evaluated evapotranspiration features over the continental United States and their potential change under climate variations (e.g., Walter et al. 2004 and references therein) and under an increased GHG scenario (e.g., Pan et al. 2004a; Thompson et al. 2005). However, the reversed situation, surface WVD, which reflects dew or frost formation, has not been addressed. Since dew and frost are commonly observed in various locations over the United States, an initial evaluation of their characteristics under increased
Likewise canopies covered by dew are effective sinks for some atmospheric acidic pollutants through dry deposition, which may cause leaf tissue damage (Wallin 1967). Also, dew affects the activity of insects and application of pesticides. In semiarid locations dew may be important for the water balance of native vegetation (Sharma 1976). Seasonal frost accumulation over snow packs may have some contribution to the amount of snow water equivalent. In contrast, when the snow skin temperature is at 0°C, WVD causes snow-melt through the release of latent heat of condensation. Melting frost over canopies may provide, similarly to dew, a sink for dry deposition of atmospheric pollutants. During summer, WVD over the United States consists only of dew, while in other seasons it consists of dew and frost. Dew formation on a canopy may be caused by the following processes (Monteith 1961): (i) dewfall—the contribution to condensation by downward atmospheric water vapor flux; (ii) distillation—the contribution to condensation over a canopy by upward water vapor flux originating at a wet soil; and (iii) guttation—water exudation from leaf tissues in some vegetation species. Dew may be formed also on bare soil that is sufficiently cool. In the cold season analogous processes to (i) and (ii) may contribute to frost formation over vegetation. However, frost formation is quite common also over cold ground as well as over snow surfaces with skin temperatures <0°C.

Using a regional climate model, as suggested in the present study, enables accounting only for (i) and (ii) above, while (iii) can be practically ignored. Overall, the significance of distillation compared to dewfall tends to be low (Long 1958; Jacobs et al. 1990). The grid resolution of regional climate models covering the United States is typically a few tens of kilometers. Considering the uniform representation of subgrid land use and topography and the imperfect parameterization presently available to resolve stable surface layer fluxes (Mahrt 1998), the computed WVD can provide only gridpoint-averaged bulk characteristics of dew or frost (however, an improved estimation compared with direct prediction of GCMs). In contrast, real-world dew and frost characteristics may significantly vary spatially in response to subgrid changes in the land use and topography and are strongly dependent on the height of the condensate-collecting surface (Newton and Riley 1964; Garratt and Segal 1988). Thus some discrepancies are likely to occur while comparing model gridpoint-averaged WVD with point observations of dew/frost.

Within the context of climate change, various types of forcing responsible for the formation of WVD may be altered. Garratt and Segal (1988) provide a sensitivity scaling analysis for some of these forcing types when dew formation is considered. The primary forcing is the net longwave radiative cooling at the surface. Its contribution to accumulated dew typically decreases with the decrease in background temperature or with the increase in cloud cover. On the other hand, an increase of light surface wind and decrease of relative humidity reduce the accumulated dew. Prediction of future climate response to an increase in atmospheric GHG level using GCMs has indicated, for example, a trend of increasing cloudiness and specific humidity in various locations of the United States (Pan et al. 2004a,b). The trends in these two fields oppose each other considering their effects on dew formation. It is likely that when accounting for all possible processes relevant to WVD formation, the future climate WVD features will show detectable differences compared to those in the present climate.

This note presents seasonal quantification of the WVD frequency and amount for the present climate, followed by an evaluation of their changes under a mid-twenty-first-century enhanced GHG climate scenario (the WVD will be confined to atmospheric contribution). Several implications are outlined in the conclusions section.

2. Methodology

One-way nesting of a regional climate model into a coarse-grid resolution GCM was adopted. The present climate and future enhanced GHG climate scenario simulated by the GCM provided initial and lateral boundary conditions to the regional model. The GCM used in the present study is the Second Hadley Centre Coupled Ocean–Atmosphere GCM (HadCM2) (Johns et al. 1997), which has a grid resolution of 2.5° latitude by 3.75° longitude. The HadCM2 transient scenario climate simulation assumes a 1% per year increase in the emission rates of effective greenhouse gases after 1990. The regional climate model used is the Regional Climate Model version 2 (RegCM2) (Giorgi et al. 1993a,b), with horizontal grid resolution of 52 km. The RegCM2 surface processes are coupled by using the Biosphere–Atmosphere Transfer Scheme (BATS) (Dickinson et al. 1993). The BATS includes surface

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1 It is worth noting that soybean rust fungal disease was detected in fall 2004 in North America, the last major continent invaded by the disease (Stokstad 2004). Dew is a key factor for viability of soybean rust spores (Yang et al. 1991).
layer schemes, representation of interactions with canopy, and prognostic equations for snow and soil physical processes. Some climate evaluation of the RegCM2 prediction skill over the United States relevant to the present climate simulations is reported (e.g., Pan et al. 2004a,b).

Two 10-yr climate simulations over the continental United States were carried out using the RegCM2. The first was forced by initial and lateral boundary conditions produced by the GCM present climate and the second was forced by the GCM-enhanced GHG climate scenario. The 10-yr window selected for the present climate corresponds to the last decade in the twentieth century, whereas that for the enhanced GHG scenario climate corresponds to the 2040s. The lateral boundary conditions of the regional model were updated every 6 hours, using a buffer zone where the model-predicted variables were gradually nudged to the GCM output. Both regional model simulations lasted for 10 years and 3 months, with the first 3 months being discarded from the analysis to reduce spinup effects.

Accumulated water vapor flux at the surface contributed from the atmosphere was computed for eight 3-h periods each day. The surface may consist of bare soil, vegetation, or snow cover. Negative 3-h accumulation implies dominant evapotranspiration in this study and was ignored in the analysis. Positive 3-h accumulation indicates dominant surface WVD and was considered in the model WVD seasonal climatology (the seasons are defined as winter: December–February; spring: March–May; summer: June–August; and fall: September–November). Days in which WVD occurred at least in one 3-h period were included in the frequency analysis. The sum of all daily 3-h computed WVDs provides the daily amount of WVD.

The model WVD values were saved every three hours for the entire 10 years. First the 3-h WVDs were merged into daily values and then combined into seasonal values. Finally the seasonal ensemble mean of 10-yr WVD amounts were averaged over the 10 seasons. Those days without WVD contributions were not considered in the averaging. The WVD frequency is based on daily WVD occurrence during a season, and then its seasonal ensemble was obtained in a similar procedure for the WVD amount.

3. Results

a. Simulated WVD characteristics in the present climate

Figure 1 shows the seasonal frequency of WVD occurrence for the present climate. In winter a relatively high frequency (>14 days month\(^{-1}\)) is simulated in the north-central United States and in extensive mountainous areas in the west. The high frequency was promoted by increased relative humidity as well as snow cover in these regions (Baldwin 1973). In the north-central United States, the increased frequency was likely supported by occasional advection of relatively warm moist air from the southern United States or from local snow-free areas. Cold bare soil surfaces in these locations were also conducive to frequent formation of WVD. The WVD frequency comparatively declined in the High Plains, while it was moderate in the southeastern and eastern United States. Generally a similar spatial distribution of frequency to winter was indicated for the spring, however with a notable decrease in the north-central United States due to the shrinking of snow-covered areas. A noticeable decline in frequency was indicated during summer in the western half of the United States compared with winter. Worth pointing out is the peak frequency in northern Idaho that is consistent with summer dew observations in this location (Lloyd 1961). However, dew observations at Ames, Iowa, (Shaw 1955) and Auburn, Alabama, (Getz 1978) might suggest underpredicted WVD frequency at these locations. Generally the WVD frequencies were somewhat higher in fall than in summer.

Observations of dew/frost over the United States are sparse and are available only at selective sites and sporadic times. Therefore climatology of occurrence frequency for dew/frost over the United States is unavailable. The simulated frequency of WVD implies dew/frost occurrence within the constraints outlined in section 1. However, the following aspects also have to be considered while interpreting the simulated frequencies: (i) The surface characteristics change seasonally and consequently change the intensity of the WVD forcing mechanism. For example, in the Midwest summer the model-prescribed land use consists mostly of crops combined with some portion of bare soil. The bare soil portion of a model grid point effectively contributes to warmer nocturnal surface than the canopy and thus offsets partly the gridpoint-averaged dew contribution compared with that over the vegetated fraction of the grid point. In contrast, in winter the land use is mostly bare ground that, under the prevailing low background temperature, is conducive to strong radiative cooling and an increased frequency of nocturnal WVD. (ii) The nighttime in winter is longer than in summer, thus supporting an increased WVD frequency. Also, winter daytime WVD is prevalent in various locations (and to some extent in spring and fall) where warm advection occurs over cold surfaces, further contributing to increased frequency.
The seasonally averaged WVD daily amounts for the present climate are given in Fig. 2. In winter the WVD amounts were highest in the western and eastern United States (reaching as high as 0.18 mm day\(^{-1}\)), while they were lowest in the midcontinental United States (as low as 0.04 mm day\(^{-1}\)). Relatively warm moist air originating over the water bodies surrounding the United States is likely to be a contributing factor to this spatial frequency distribution pattern. In spring the pattern is similar to winter, except for some WVD amount decline in the western United States. The summer WVD amount showed relatively moderate spatial variability, except for the mountainous areas of the western United States. The fall pattern of the WVD amount largely resembles that of summer.

Typical observed nocturnal dew amounts are <0.3 mm (Wallin 1967; Garratt and Segal 1988; Zangvil 1996). It is suggested that, as a first approximation, the simulated range of WVD amount is in agreement with observations. Over regions with relatively dry soil, where distillation contribution to dew should be negligible and guttation from vegetation is absent or small, dewfall is the dominant process contributing to dew formation. Thus, in such locations the model-simulated WVD reflects mostly dewfall contribution.

Owing to sparse observations of dew/frost or surface vapor flux, it is impossible to quantify WVD bias projected by the regional model for the present climate over the domain of interest. However, a few available observed frequencies of dew during summer tend to suggest that the frequency is underpredicted in the Midwest and the southeastern United States. The evaluation of the biases for the predicted meteorological variables related to dew/frost formation might provide some indirect estimation of the model bias. However, quantification of the contribution of these variables to WVD bias in the model is not feasible due to the incomplete availability of observed data and non-linear effect of those variables. Thus, only a qualitative assessment of the biases is provided here. The WVD amount is related primarily to these surface variables: net longwave radiation, relative humidity, wind speed, and temperature. (Additionally, the distillation contribution to dew is related to soil wetness.) Since effec-

![Fig. 1. Simulated seasonal average frequency of surface WVD occurrence (days month\(^{-1}\)) in the present climate over the continental United States. Contour interval is 2 days month\(^{-1}\).](image-url)
tively no net longwave radiation observations are available, we inferred a negative bias for this variable based on comparison of simulated cloudiness as implied by daytime decrease in simulated incoming solar radiation at the surface (Pan et al. 2004b). Slight overprediction of relative humidity (~5%) is indicated over large areas. Based on Segal et al. (2002) the predicted and observed surface wind speeds tend to be comparable in some main areas relevant to rich summer WVD. The surface temperature is overpredicted in the cold period and underpredicted in the warm period in its impact on WVD (bias of 1–3 K). [Underpredicted soil wetness (~5% lower soil volumetric wetness: Pan et al. 2001a) is indicated in the central United States, reducing the distillation amount.] Based on the aforementioned information and using the scaling diagrams in Garratt and Segal (1988), it can be inferred that WVD frequency and amount in the warm period of the year is likely to be underpredicted, with no clear indication for the cold period of the year. Finally, although we attempted general characterization of the bias, it should be noted that the biases are largely spatially dependent.

b. Simulated changes in WVD characteristics in the mid-twenty-first-century enhanced GHG climate scenario

Figure 3 presents the WVD frequency difference between the climate scenario and the present climate. In winter the frequency in the scenario climate dropped mostly in the areas affected by snow cover in the Midwest and in the elevated terrain in the western United States. This pattern is consistent with the decline in snow cover duration and extent in the scenario climate (Pan et al. 2001b). The rest of the United States was affected mostly by a frequency increase (~2 days month$^{-1}$). In summer most of the United States showed a decrease in WVD frequency. The decrease was typically ~2 days month$^{-1}$ except for the mountains in the northwest where the decrease was as large as 9 days month$^{-1}$. This trend is explained in part by the increased cloudiness in the scenario climate (Pan et al. 2004a,b) and, thus, the reduction of the nocturnal net longwave radiative surface cooling. An interesting feature is the increase in frequency in the central United States.
States in the location indicated by Pan et al. (2004a) to be affected by a relatively mild surface temperature increase ("warming hole") in the climate scenario, primarily due to increased soil moisture. Changes in the frequency range of \( \leq 3 \text{ days month}^{-1} \) are typically obtained in spring and fall. Percentage wise, for all seasons the change in frequency was between \(-30\%\) and \(+30\%\) except for the warming hole zone where the frequency increase reached \(60\%\) in spring and fall and in the western United States where the frequency decrease reached \(90\%\).

Figure 4 presents the difference in the WVD amount between the climate scenario and the present climate. In winter, areas that experienced a frequency decline in the scenario climate showed mostly an increase in WVD amount and vice versa. The range of WVD amount difference was mostly between \(-15\%\) and \(+30\%\). In spring, over large areas, the trends of change in WVD amount and frequency were spatially similar. Increased WVD amount in the scenario climate in snow-covered areas in winter and spring may be attributed in part to an increased impact of warm advection episodes. The WVD amount associated with such episodes can be extremely high, reaching several millimeters per day (Leathers et al. 1998; Wei et al. 2001). The spring WVD amount difference range was commonly between \(-30\%\) and \(+30\%\). In summer, the scenario climate WVD amount decreased in most of the United States, typically by \(10\% - 30\%\) in the eastern half and \(30\% - 90\%\) in the western half. In fall and spring a spatially nonuniform trend of change in the WVD amount was indicated.

c. **Local and field significance tests on the climate change in WVD characteristics**

In the previous section we described the WVD changes in amount and frequency with varying amplitudes across season and regions. Conventional statistical tests such as the \(t\) test and other nonparametric tests are usually applied in a local sense. Like other meteorological variables, however, WVD is a two-dimensional field. Thus we need to test if the change passes a sig-
nificance test at individual grid points in a local sense and if the change passes a field significance test over the simulation domain in a global sense.

1) **LOCAL SIGNIFICANCE TEST**

We assessed the local significance using the two-sample permutation test (von Storch and Zwiers 1999; Wilks 1995, p. 148). The null hypothesis (no difference between the means of the climate scenario and present climate) is built up by repeatedly and randomly re-grouping a pool of 20 WVD values at a grid point into two artificial batches. The test statistic, that is, the mean difference between the two arbitrary groups, is computed for 200 randomly selected permutations. The resulting probability distribution of synthetic differences constitutes the null distribution and is compared with the predicted mean difference between the future climate scenario and present climate. If the predicted difference falls in either 0.025 tail of the probability distribution, then the grid point passes the permutation test at the 0.05 significance level. The percentages of passing grid points are given in Table 1, and the areas failing the local significant test are shaded in Figs. 3 and 4. The locally significant areas in general match regions of greater changes, except a few scattered areas with

![Image](https://example.com/image.png)

**Fig. 4.** The seasonal difference between the scenario and present climates (scenario minus present) in surface WVD ($10^{-2} \text{ mm day}^{-1}$) over the continental United States. Contour interval is 0.005 mm day$^{-1}$ and negative contours are dashed. Shading indicates areas where the changes failed the local significance test (two-sample permutation at 0.05 significance level).

<table>
<thead>
<tr>
<th>Variable</th>
<th>WVD amount</th>
<th>WVD frequency</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Winter</td>
<td>Spring</td>
</tr>
<tr>
<td>Degrees of freedom</td>
<td>46</td>
<td>49</td>
</tr>
<tr>
<td>% of grid points passing required by chance</td>
<td>11.8</td>
<td>11.5</td>
</tr>
<tr>
<td>% of grid points actually passed local tests</td>
<td>30.5</td>
<td>24.1</td>
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small changes as well as small variability. The changes are more significant in winter and spring and less significant in summer and fall. The percentages of passed areas range from 10.8% to 30.5% for WVD amount and 22.1% to 35.7% for WVD frequency. We also ran a test on the WVD changes, and the outcome agreed with the permutation test well, suggesting that the results are robust. This magnitude of significant percentage area and distribution of WVD amount change is similar to that for rainfall reported in Pan et al. (2001b).

2) Field significance test

The field significance test is complicated by spatial correlation that reduces the degrees of freedom (DOF) of the field. Wang and Shen (1999) compared four methods of estimating effective degrees of freedom for spatially correlated meteorological fields and concluded that the Livezey and Chen (1983) method (called the B method) is more robust than the others. Following Livezey and Chen (1983) and Wang and Shen (1999), we performed 3000 Monte Carlo trials at each land grid point. For each trial at every point, the 10-season time series (present climate only) was artificially correlated to 10 independent random numbers ranged [0–1]. The percentage of grid points passing the local significance correlation tests is tabulated for the entire land domain. The largest of the 5% field significance level percentage, which occurs in the right tail of the percentage histogram, dictates the global confidence interval.

The DOFs obtained for the WVD amount are 46, 49, 95, and 38 for winter, spring, summer, and fall, respectively. These values are well within the range of typical surface fields, which vary from ~30 for annual smooth fields (annual surface temperature) to 130 for seasonal noisy fields (e.g., summer precipitation) (Wang and Shen 1999). The DOF for WVD frequency is similar to those obtained for WVD amount except for smaller values in summer.

The DOFs obtained by Monte Carlo trials were used to determine the field significance for the climate change in WVD by using the binomial distribution at 95% confidence at both local and global levels. The percentage of grid points passing the local tests individually for seasonal WVP required for field significance is 11.8%, 11.5%, 9.5%, and 12.8% for winter, spring, summer, and fall, respectively. The model-predicted percentages of locally significant grid points over land are 30.5%, 24.1%, 20.0%, and 10.8% for WVD, respectively. These projected percentages are well above the required binomial distribution that represents the statistically minimum number of points passing the local significance by chance. Thus, the model-projected climate changes in WVD are field significant both in terms of amount and frequency.

The passing of field significance tests by quite a large margin seems reasonable although the areas where changes occur in WVD amount and frequency are relatively small. The model-predicted difference in WVD field should be significant as a whole since the forcing between the 1990s and 2040s are noticeably different.

4. Conclusions and discussion

A regional climate model was used to evaluate the potential change of surface water vapor deposition over the United States in a climate scenario associated with increased atmospheric greenhouse gas concentrations. The regional model lateral boundary conditions were extracted from GCM simulations, facilitating a downscaling approach to obtain WVD characteristics (the WVD was confined to the atmospheric contribution). Constraints on the interpretation of the regional-model-simulated WVD patterns while being compared with a few available site observations of dew/frost have been discussed.

The WVD was evaluated for the entire day (i.e., 24 h), which promotes, during winter, spring, and somewhat in fall, an increased frequency in cold regions where WVD may also occur during daytime over snow or relatively cold ground surfaces. Shrinking of snow-covered areas in the scenario climate in the cold seasons appears to be conducive to a noticeable WVD pattern modification. In summer, a declining trend in WVD frequency and amount was typical in most of the United States, while in the other seasons the trends varied spatially. Changes in frequency and amount of WVD in the range of −30% to +30% were generally indicated for all locations and seasons, except for the western half of the United States where the change was larger in summer. Both local and field significance tests were performed on the WVD changes. The tests indicated that, while areas passing the local statistical test ranged from 11% to 36% of the land domain, the WVD difference as a whole field between present climate and future scenarios is significant.

Several implications of the results are suggested: (i) The trends in WVD frequency and amount in the climate scenario imply a slight decline in summertime plant fungal diseases as well as the dry deposition of pollutants. In other seasons the trend is spatially mixed (note that fungal diseases are relevant only in warm locations). (ii) Some scaling of the cold season WVD contribution to snow packs in the north-central United States or in the western mountains is suggested. Based on the simulated present climate winter pattern in those
locations, it can be suggested that the characteristic winter WVD is \(\sim 0.1 \text{ mm day}^{-1}\) and that of frequency is \(\sim 10 \text{ day month}^{-1}\). Thus the winter characteristic accumulated contribution is \(\sim 3\) mm, which is quite small (accounting also for fall and spring contribution suggests at most doubling of this contribution). The simulated changes in WVD frequency and amount imply a modification of the winter characteristic accumulated WVD contribution in the climate scenario by \(\leq 20\%\). It is worth noting however that, when the snow skin temperature is at 0°C, WVD contributes to snowmelt due to the condensation of vapor on the snow surface. In this case the melted snow water equivalent is \(\sim 7\) times (the ratio of latent heat of vapor condensation to that of ice fusion) larger than the accumulated WVD. (iii) Formation of dew/frost and thus the release of latent heat of condensation are known to offset, to some extent, the nocturnal net longwave radiative cooling at the surface, thus moderating the nocturnal temperature decline. In the climate scenario this temperature restraint is indicated to be reduced somewhat in summer as WVD frequency and amount mostly declined, while acquiring a mixed trend in the other seasons.

Finally, the accuracy of the simulated change in WVD under enhanced atmospheric GHG scenario climate is related primarily to the capability of the GCM to capture realistically the patterns of this climate. Considering the potential biases in the GCM and regional model predictions and additional insight that can be gained by employing downscaling using an ensemble approach and a further refined land surface scheme in the regional model, the results presented in this note should be considered as preliminary.

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