Water Transport by Thin Moist Layers in Project STORM Soundings

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ABSTRACT

A previous examination of water vapor layers in Project STORM-FEST is extended to include Project STORM-WAVE rawinsonde observations and assess the contribution of layers in these two datasets to atmospheric water transport. The observations indicate that the contribution of these layers to water transport climatology is only a few percent. However the analysis also shows that episodes occur fairly frequently where these layers contribute 20% or more of the horizontal transport. Instances when the layer's moisture is an important part of the water transport tend to occur for relatively dry soundings. Numerical models that fail to resolve the layers during these episodes may thus miss condensation events leading to cloud formation and precipitation, and also give overly smooth vertical profiles of radiative heating and cooling. The layers thus appear to be important for numerical weather prediction.

1. Introduction

Iselin and Gutowski (1997, hereinafter IG) found thin layers of atmospheric water vapor in over half of the soundings they examined from the Storm-scale Operational and Research Meteorology-Fronts Experiment Systems Test (STORM-FEST; Cunning and Williams 1993). Although the observing period for STORM-FEST was limited to six weeks, the results are consistent with other evidence for layering of atmospheric water vapor (e.g., Newell et al. 1996, 1999). However, IG did not examine the role of the observed layers in the water cycle. The purpose of this note is to show the contribution these layers make to water transport in STORM-FEST soundings. In addition, we broaden the analysis of IG by including soundings from a follow-on campaign, the Project STORM Weather Assimilation and Verification Experiment (STORM-WAVE; USWRP 1995).

Layers in IG were defined to be structures in rawinsonde soundings in which relative humidity within a window no more than 200 hPa deep decreased by at least 40% above and below a local relative humidity maximum (RH_{max}). Under this definition, layers were found in STORM-FEST soundings throughout the troposphere, with an average thickness of 120 hPa and an average RH_{max} level at approximately 550 hPa. Composites of soundings with layers falling in selected pressure ranges showed that the layers tended to be bounded above by a region of relatively high static stability and below by a region of relatively low static stability. Also, the layers tended to be moist intrusions in soundings that were otherwise dry compared to the STORM-FEST average.

These features suggest that the layers might play an important role in horizontal transport that would not be resolved in observational archives at standard pressure levels or in models with coarse vertical resolution in the middle troposphere. We retain IG's definition and compare here moisture transports when layers are included in or excised from STORM-FEST and STORM-WAVE soundings.

2. Data

a. Project STORM-FEST

The United States Weather Research Program (USWRP) conducted Project STORM-FEST to study winter storms in the central United States. The program flew rawinsondes of two types from fixed-location stations: standard National Weather Service (NWS) sta-

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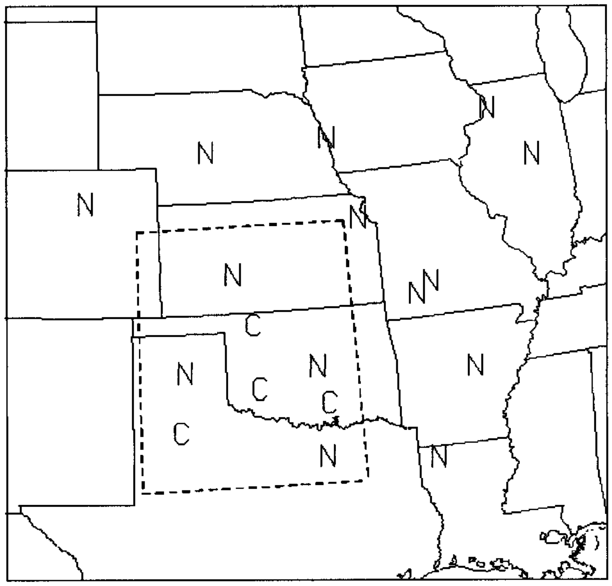

FIG. 1. Distribution of NWS (N) and fixed CLASS (C) STORM-WAVE stations used here. Mobile CLASS stations roamed within the dashed box.

tions and special Cross-chain Loran Atmospheric Sounding Stations (CLASS) established for STORM-FEST. We used a STORM-FEST subset of 11 NWS and 12 CLASS stations distributed across the U.S. central plains (Fig. 1 of IG). Stations took standard atmospheric soundings at 0000 and 1200 UTC from 1 February to 15 March 1992. Additional launches occurred during intensive observation periods (IOPs) that had rawinsondes released as frequently as every 3 h. Iselin and Gutowski (1997) found little difference between analyses with and without the additional soundings and so ignored IOP soundings in most analyses to maintain a more uniform temporal sample. We followed IG and thus also used soundings only at 0000 and 1200 UTC.

b. *Project STORM-WAVE*

The USWRP also conducted Project STORM-WAVE to study spring and early summer storm systems in the U.S. central plains. As with STORM-FEST, STORM-WAVE used both NWS stations and CLASS stations. For this study, a new set of CLASS stations was established. Four were at fixed locations, and five were mobile, moving according to STORM-WAVE criteria. We used 14 NWS stations and the nine CLASS stations. Figure 1 shows locations of the fixed stations and a box outlining the region of mobile station deployment. The project ran from 1 April 1995 to 30 June 1995, taking soundings at standard times as well as nonstandard times. As with the STORM-FEST data, we used NWS soundings only at 0000 and 1200 UTC in our analyses. We treated CLASS soundings differently, because they were usually flown at 1-h intervals during daytime. We thus used all STORM-WAVE CLASS soundings, but analyzed them separately since they had different temporal sampling.

c. *Characteristics of the data*

The USWRP interpolated both datasets to high resolution: 10 hPa for the STORM-FEST data archive and 5 hPa for the STORM-WAVE archive. The USWRP checked each datum manually as they interpolated in order to ensure quality. They flagged data as 1) good, 2) questionable, 3) physically unreasonable, 4) missing, 5) estimated (STORM-WAVE only), or 6) unchecked. For the purposes of this study, we used only data marked as good. Although this resulted in many rejected soundings, the sampling remained fairly uniform in time, so we assume we retained a representative sample of the observing region's environment.

Accuracy limitations of both NWS and CLASS sensors can influence results. NWS rawinsondes used a VIZ carbon hygristor, whereas CLASS rawinsondes used a Vaisala humicap. Iselin and Gutowski (1997) give a detailed discussion of error characteristics of each. Briefly, inherent biases in the VIZ sensor cause NWS rawinsondes to respond slowly to humidity changes at low temperature and, consequently, yield reduced moist-layer detection at higher (colder) levels of the atmosphere. The Vaisala humicap, on the other hand, tends to respond sluggishly to moisture changes at high humidity, resulting in reduced moist-layer detection at lower (high relative humidity) levels of the atmosphere. Thus, we segregate CLASS and NWS soundings in our analyses because they also have different biases in addition to the different sampling frequency in STORM-WAVE CLASS.

For STORM-WAVE, the four fixed-location CLASS locations were either in Oklahoma or northern Texas. Three of these mobile stations were controlled by the National Severe Storms Lab (NSSL) in Norman, Oklahoma. The NSSL often launched these soundings in the vicinity of strong thunderstorms. Partly as a consequence of this procedure, the data from these soundings were often given quality flags worse than ''good'' and so were rarely used in our analyses.

3. Methods

a. *Horizontal transport and precipitable water computations*

The horizontal moisture transport in a sounding between pressure levels p_1 and p_2 is (cf. Peixoto and Oort 1992)

$$\mathbf{Q} = \int_{p_1}^{p_2} q\mathbf{V}\,\frac{dp}{g} = Q_\lambda\hat{\mathbf{i}} + Q_\phi\hat{\mathbf{j}}, \qquad (1)$$

where q is specific humidity, $\mathbf{V}$ is horizontal wind, g is gravitational acceleration, $\hat{\mathbf{i}}$ is the longitudinal (λ) unit vector, and $\hat{\mathbf{j}}$ is the latitudinal (ϕ) unit vector. Our analysis also uses a sounding's precipitable water:

$$P = \int_{p_1}^{p_2} q \frac{dp}{g}. \quad (2)$$

We computed vertical moisture integrals by summing over 10- (STORM-FEST) or 5-hPa (STORM-WAVE) intervals, using a midpoint rule and calculating q from the sounding's temperature and relative humidity. We used two sets of integration limits, p_1 and p_2. One choice was the whole sounding, so long as it was of sufficient depth, as discussed below. This choice, however, meant that $\mathbf{Q}$ and P integrals were not computed uniformly, as integral limits would vary with station elevation and time. A second choice, used for most analyses, was to use the same p_1 and p_2 for all soundings, restricting integration to the portion of the troposphere where IG found the most layers, 400–800 hPa. Qualitative differences in results using either choice are small, so we report here analyses using only 400–800-hPa data.

b. Quality control

In order to ensure that we analyzed only the highest quality data, quality flags for pressure, horizontal wind, temperature, and relative humidity all had to be category one (good) at each level from 400 to 800 hPa for the sounding to be analyzed. We made an exception if data at no more than two adjacent levels failed to meet the quality criteria, in which case vertical linear interpolation in log(pressure) between levels with acceptable observations was used to replace low quality data.

The strictness of this criterion caused rejection of numerous soundings in both datasets when analyzing water vapor transport. When analyzing characteristics of STORM-WAVE layers to compare with IG results, we followed IG and used a more relaxed requirement that the sounding simply had to have good quality at the levels containing the layer.

Despite the sounding rejections, our transport analysis used 1991 soundings, with the more regular NWS soundings accounting for over 75% of the total. The soundings retained were distributed fairly evenly throughout the observing periods, so that we assume they give a representative sampling of water vapor behavior during the two experiments. Temperature and precipitation in the central United States for each observing period showed both positive and negative anomalies relative to climatology, with magnitudes up to 4.5°C in temperature and 7 cm month^{-1} in precipitation. Over most of the region, anomalies were much smaller than these extremes. In addition, central U.S. synoptic weather patterns on 500-hPa and surface pressure maps during STORM-FEST and STORM-WAVE were judged on the basis of our synoptic experience to be fairly typical for their respective periods. Thus, although the combined datasets cover only 4.5 months, results here appear representative of late winter and spring conditions in the central United States.

TABLE 1. Percentage of soundings that contained at least one layer.

Instrument	STORM-FEST (%)	STORM-WAVE (%)
NWS	53	57
CLASS	76	64

c. Layer removal

Since our primary goal is to assess the importance of moist layers in atmospheric water transport, we need to compare transports with and without the layers. To remove layers, we interpolated relative humidity linearly in log(pressure) between sounding values at the top and bottom of a layer. The top and bottom of the layer were the points in the dataset where relative humidity first fell to at least 40% less than RH_{max} when moving up and down away from the local maximum. Other fields were not interpolated as analysis did not show momentum or temperature layers coinciding with the moist layers. Thus, the interpolation removed a layer without affecting the dynamics of the sounding. Any changes in moisture transport resulted from removing the moisture layer, not from changes in the wind field. Note also that layer removal did not eliminate all moisture in the layer, it simply reset relative humidity to what might be considered a background value, closer to the humidity field just outside the layer. Transport and precipitable water with no layers present are designated $\mathbf{Q}_{NL}$ and P_{NL} respectively.

4. Results

a. Thin, moist layers in STORM-WAVE

We analyzed STORM-WAVE soundings for layers in the same manner followed by IG for STORM-FEST. Table 1 shows that the percentage of soundings containing at least one layer was roughly the same for each instrument type during the two observing periods. The distribution of layers versus RH_{max} was also about the same (Fig. 2), though STORM-WAVE soundings had more layers at small RH_{max} than STORM-FEST soundings. As discussed by IG, differences between results for the two sensor types appear to be a consequence of each sensor's bias characteristics. In both datasets, layers were distributed throughout the troposphere with a slight tendency to concentrate toward the middle. Thus, the layer distribution versus height displayed in IG was qualitatively the same for STORM-WAVE layers (not shown). The average pressure level of relative humidity maximum was in the range 500–600 hPa for each instrument and observing period. Layers were also approximately the same thickness on average: 120 hPa for STORM-FEST and 104 hPa for STORM-WAVE. Finally, analyses of STORM-WAVE NWS soundings for

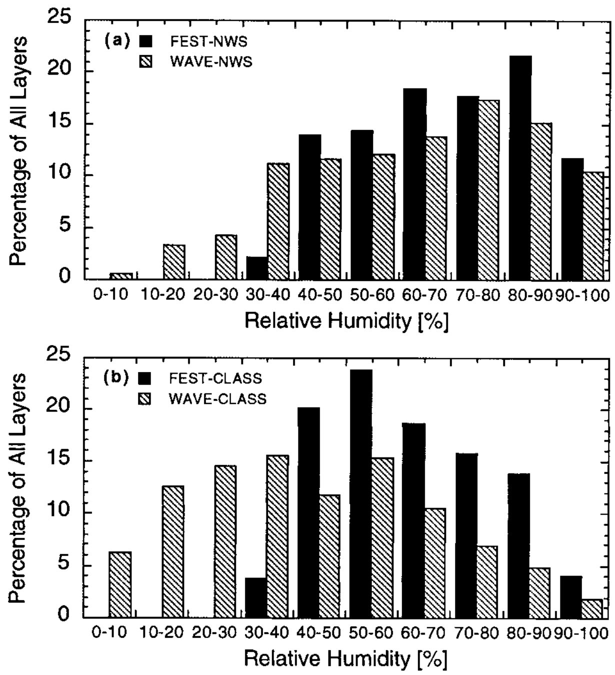

FIG. 2. Distribution of moist layers vs RH_{max} for each observing period: (a) NWS and (b) CLASS.

0000 or 1200 UTC alone showed no discernable diurnal cycle, consistent with IG's STORM-FEST analysis.

Differences between the two observing periods could result for a number of reasons. The sampling periods covered different parts of the annual cycle, with STORM-WAVE occurring in generally warmer weather. The station distributions were not the same, especially for the CLASS instruments. STORM-WAVE CLASS soundings were concentrated in Oklahoma and Texas and thus covered a smaller region than STORM-FEST CLASS soundings. Differences may also be due to interannual variability in atmospheric moisture. The observing periods are too short to warrant further detailed analysis of the differences. More important, differences between STORM-FEST and STORM-WAVE results for each instrument are typically smaller than differences between instrument types, indicating fairly consistent layer characteristics between the two observing periods.

b. Water vapor transport

Our primary interest here is the contribution water vapor layers make to overall moisture transport. We assessed this by computing transports before and after layer removal. Again, we focus on the 400–800-hPa analysis because it is more uniform across all soundings used than our full sounding computations.

Table 2 shows percentage changes in **Q** and *P* under layer removal for each observing period and instrument, along with the total number of soundings used. The percent change in the magnitude of **Q** is computed from $(|\overline{\mathbf{Q}}| - |\overline{\mathbf{Q}}|_{NL})/|\overline{\mathbf{Q}}|$, where the overbar represents the average over all qualifying soundings, whether or not they originally include a layer. The change in *P* uses the same computational form. The contribution of the water vapor layers to the overall water transport is only about 5%–6%. The layers were defined a priori to be relatively thin, and most layers occur in the middle troposphere, which is generally cooler and drier than air closer to the surface. Thus, the modest percentage is not surprising, as the layer's local maximum in relative humidity is not likely to produce a large increment to a sounding's vertically integrated transport. Also, the percentage change in **Q** is approximately the same as the percentage change in *P*. The vertical structure of the wind field thus plays little direct role in determining the importance of water vapor layers to the soundings' horizontal moisture transports.

Iselin and Gutowski (1997) showed that the composite layer in STORM-FEST was a moist intrusion in a relatively dry atmosphere. This suggests that moist layers might be more important during drier episodes. The dry soundings column in Table 2 gives the percent change in average **Q** magnitude when only soundings with $P <$ median(P) are used. The contribution of moist layers is roughly 50% larger, but overall still modest. The layers' added moisture gives a somewhat larger contribution when focusing only on soundings that do have layers (Table 2, layered sounding column), but the contribution is still fairly modest.

The contribution of moist layers to water transport is not uniform across all soundings, however. Figure 3 shows the percent change in |**Q**| caused by layer removal in each sounding, plotted as a function of *P*. Many soundings have changes larger than 20%, some have changes over 40%. Consistent with Table 2, most of the large changes occur in the drier soundings. The contribution of thin moist layers to water vapor transport is thus episodic, and on occasion can be a large portion of a sounding's transport. For over 20% of the soundings with layers in each of the FEST/WAVE and NWS/

TABLE 2. Effect of layer removal on 400–800-hPa soundings.

Period, instrument	Total no.	Percent change: *P*	|**Q**|	|**Q**| (dry soundings)	|**Q**| (layered soundings)
FEST, NWS	776	−5.8	−5.9	−7.0	−13.5
FEST, CLASS	274	−4.2	−4.7	−7.8	−10.1
WAVE, NWS	766	−5.6	−5.3	−7.6	−11.5
WAVE, CLASS	175	−5.9	−6.2	−9.2	−10.2

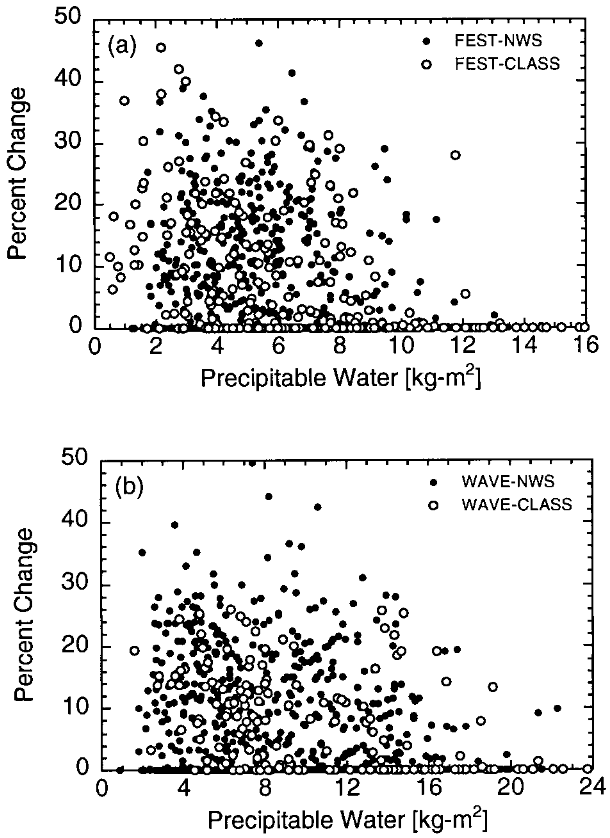

FIG. 3. Percent change in |**Q**| as a function of *P* when moist layers are excised in (a) STORM-FEST and (b) STORM-WAVE soundings. Note different horizontal scales for each observing period.

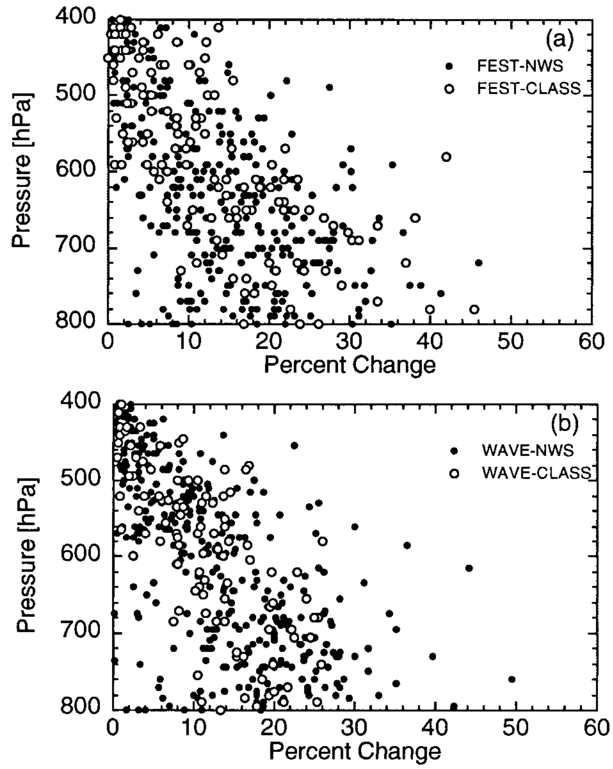

FIG. 4. Pressure at RH_{max} of a sounding's first layer above the surface vs percent change in |**Q**|. (Most layered soundings have only one layer.)

CLASS combinations, the layer's added moisture is more than 20% of the overall transport. The largest changes tend to occur when the layer is closer to the surface (Fig. 4). This is not surprising as atmospheric saturation specific humidity, and thus potential moisture in a layer, tends to be larger closer to the surface. The behavior also occurs because there is a tendency for soundings with smaller precipitable water to have layers closer to the surface (not shown).

5. Discussion

Results in IG suggest that thin moist layers in the atmosphere might play an important role in the atmosphere's water cycle. Our examination of Project STORM-FEST and STORM-WAVE observations indicates that the climatological contribution to water transport of the moisture above background level in these layers is only a few percent. However the analysis also shows that episodes occur fairly frequently where this water constitutes 20% or more of the horizontal transport. Sensor errors likely result in undetected layers (IG) so estimates of layers' contribution to overall transport may have a low bias. However, most serious errors appear to occur at humidity extremes, so we expect this bias to be small for the 400–800-hPa window targeted here.

The question arises as to what effect these layers may have on regional water balance. The length of record and the area covered by the stations may be too small for accurate computation of water vapor convergence (Rasmusson 1977). With this caveat in mind, we computed water vapor convergence with layers included and excised. The influence of the layers on convergence (not shown) appears to be comparable in magnitude and character (e.g., episodic) to their influence on transport.

The present analysis (as well as IG) does not address layer generation. An analysis of layers using multiple chemical species by Newell et al. (1999) has indicated layer sources in the stratosphere and atmospheric boundary layer, with propagation into the troposphere linked to events such as stratospheric intrusion and convection. Lack of a discernible diurnal cycle in our results suggests little ongoing coupling to a diurnally evolving planetary boundary layer, though it does not eliminate the boundary layer as part of a generation mechanism (such as convection rooted in the boundary layer). As noted earlier, we found no tendency for momentum layers to coincide with the moisture layers, thus eliminating internal jets as significant contributors to layer generation and maintenance in these observations, but not differential shear. We have looked within the STORM-

FEST and STORM-WAVE datasets for tendencies for the layer occurrence to cluster in time around specific synoptic events. No such clustering has emerged in our analysis, though the layers detected here may of course originate outside the observing region.

Iselin and Gutowski (1997) observed that the layers tend to be moist intrusions in relatively dry soundings, and indeed instances when the layer's moisture is an important part of the water transport tend to occur for smaller precipitable water (Fig. 3). Numerical models that fail to resolve the layers during these episodes may thus miss condensation events leading to cloud formation and precipitation. Also, as noted by Newell et al. (1999), the models could also give overly smooth vertical profiles of radiative heating and cooling. The layers thus appear to be important for numerical weather prediction.

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