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COMPARISON OF SSM/I AND MODEL ESTIMATES OF INTEGRATED CLOUD WATER DURING WISP94

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1. INTRODUCTION

Ideally, accurate forecasts of aircraft icing could be determined by forecasts of super-cooled liquid water and the size and concentration of cloud droplets. However, numerical models operationally in use at the National Meteorological Center (NMC) have only begun to incorporate explicitly prognosed cloud liquid water. In these early versions, there are a few inherent problems with model-generated cloud liquid water. First, since there are no measurements of this parameter, models cannot begin with an initial analysis field of cloud liquid water. Second, most analyses smooth out the relative humidity horizontally and vertically since they are produced on horizontal scales of approximately 60 km and vertical scales of 500 m or more; some finer scale variations exist. This tends to de-emphasize important regions of high humidity. Last, combining these two factors is the problem of "spin-up". Since cloud water is not an analyzed field, a model must produce its own by increasing the already too-low (analyzed) relative humidity to saturation, then convert it to cloud liquid water, using parameterizations which themselves have limitations.

Validation data for any icing forecast are sparse at best coming mostly from ground-based upward-looking microwave radiometers (which give accurate point or small-area measurements) and experimental aircraft observations. Aircraft pilot reports give qualitative information about icing but cannot be used to quantify cloud liquid water. However, over oceans, the Special Sensor Microwave Imager (SSM/I) aboard the Defense Meteorological Satellite Program (DMSP) spacecraft (overview in Spencer et al. 1989 and Hollinger et al. 1990) gives good estimates of integrated liquid water and excellent estimates of integrated water vapor at a spacing of 25 km. Thus, there exists an opportunity to assess model performance in terms of integrated cloud liquid water and integrated water vapor over large oceanic regions.

This paper presents a comparison over the eastern Pacific Ocean between the SSM/I data described in Section 2 and numerical model output collected during the Winter Icing and Storms Project of 1994 (WISP94). The comparison is performed with explicitly predicted cloud liquid water from two numerical models: 1) NMC's soon-to-be operational mesoscale Eta model, and 2) the fifth-generation PSU/NCAR mesoscale model (MM5). These models and their cloud liquid water parameterizations are described briefly in Section 3. Two parameters are compared: integrated liquid water and integrated water vapor. While integrated liquid water is the more critical parameter, integrated water vapor is more accurately obtained from both the models and the SSM/I and also can provide useful comparisons. A total of ten case days were investigated of which two case days are presented in Section 4. Section 5 presents some preliminary conclusions and addresses ideas for future research.

2. SSM/I DATA

Integrated liquid water [hereafter referred to as ILW) computed from SSM/I data (Petty and Katsaros, 1990) provides reasonable values of cloud water in marine stratus and stratocumulus and can be used to distinguish cloud-covered regions from clear regions. Precipitation heavier than drizzle can contaminate the ILW estimates but can be used to delineate regions of high liquid water.

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Takeda and Liu (1987) found that values greater than about 1 kg·m^{-2} indicate precipitation. Smaller values in post-frontal convective precipitation should also not be used quantitatively because of a bias introduced by spatial averaging.

Integrated water vapor [hereafter referred to as IWV] is spatially much smoother than integrated liquid water. Though an integrated sum, its magnitude is strongly correlated with absolute humidity in the boundary layer. Thus, intercomparisons of IWV essentially evaluate differences in low-level moisture. Furthermore, the temporal evolution of an IWV field is tied to moisture advection in the boundary layer (Lee and Boyle, 1991). Because synoptic-scale cold fronts correspond to large gradients in IWV, the SSM/I integrated vapor parameter can provide a useful indicator of frontal position (Katsaros et al., 1989).

The SSM/I IWV is more robust than ILW, showing only modest degradation in areas of precipitation. Overall, RMS differences between the Petty and Katsaros (1990) algorithm and rawinsondes are about 2 kg·m^{-2}. An unknown fraction of this difference arises from errors in rawinsondes themselves, as well as from spatial and temporal mismatches. In theory, the SSM/I could provide integrated vapor measurements as accurate as rawinsondes.

3. NUMERICAL MODELS

3.1 *Eta Model*

During the WISP94 field program, an experimental version of the Eta model was provided by NMC with horizontal spacing of 40 km. Data were received daily from the 0000 UTC model run with forecasts at 6-hr intervals out to 36 hr. All data were provided on the model's native horizontal and vertical coordinates providing 38 vertical levels. This version of the Eta model also contained cloud liquid water and cloud ice parameterizations as described by Zhao et al. (1991). This parameterization could be considered "semi-explicit" because it includes contributions by both convective (deep convection only) and grid-scale (stratiform type clouds) precipitation parameterizations. For initializations over oceanic regions, the Eta model utilizes the global spectral model analysis fields.

3.2 *MM5 Model*

Also during the WISP94 period, the fifth generation Penn State/NCAR mesoscale model (MM5) provided real-time forecasts. This research mesoscale model contained three nested grids and was run twice daily providing forecasts of 24 hr in length. The coarsest grid had a 60 km grid increment and covered the Continental U.S., southern Canada, northern Mexico and a large part of the eastern third of the Pacific Ocean. The nested grids with 20 and 6.7 km grid increments were centered over the WISP domain of northeastern Colorado and southeastern Wyoming (and don't extend into the Pacific) and are not considered here. MM5 used a sigma-p, terrain-following vertical coordinate and provided 27 vertical levels. MM5 was initialized using its previous 12-hr forecast as a first-guess field. The MM5 model has complex, fully-explicit microphysical parameterizations that produce cloud liquid water, cloud ice, rain, and snow as described by Reisner et al. (1993). The nature of these parameterizations usually require a "spin-up" time of 2-6 hr for microphysical variables.

4. CASE STUDIES

4.1 *9 February 1994*

A DMSP satellite pass at 0137 UTC 9 February 1994 provided the SSM/I integrated liquid water field shown in Fig. 1a as gray-shaded areas. The eastern edge of the data follows the North American coastline, while the western edge is limited by the satellite view, marked by the line from the upper-left to lower-right in the figure. Cloud-free regions are clearly evident off the northern California coast, whereas regions of cloud liquid water exist off the Washington coast. This figure reveals ILW values from 0.17 to 0.75 kg·m^{-2} extending southwest from Vancouver Island (likely associated with a synoptic-scale cold front) and sporadic amounts west of southern California.

Comparing this to the Eta 24-hr forecast valid at 0000 UTC 9 Feb (depicted by the solid contour lines), reveals that the model appears too slow in its prediction of the feature near Vancouver Island. Notice the model's positioning of ILW is north and west of the observed feature. Quantitatively, model-predicted amounts of ILW are in close agreement with a maximum of 0.86 kg·m^{-2} predicted by Eta compared to ~0.80 kg·m^{-2} observed with the SSM/I. The sporadic regions of ILW observed west of southern California do not appear to be handled well by the model forecast. The model tends to smooth-out this feature as evidenced by the large region enclosed by the 0.29 kg·m^{-2} contour.

SSM/I integrated water vapor at 0137 UTC 9 Feb is shown in Fig. 1b and reveals a maximum of IWV extending southwest from Vancouver Island

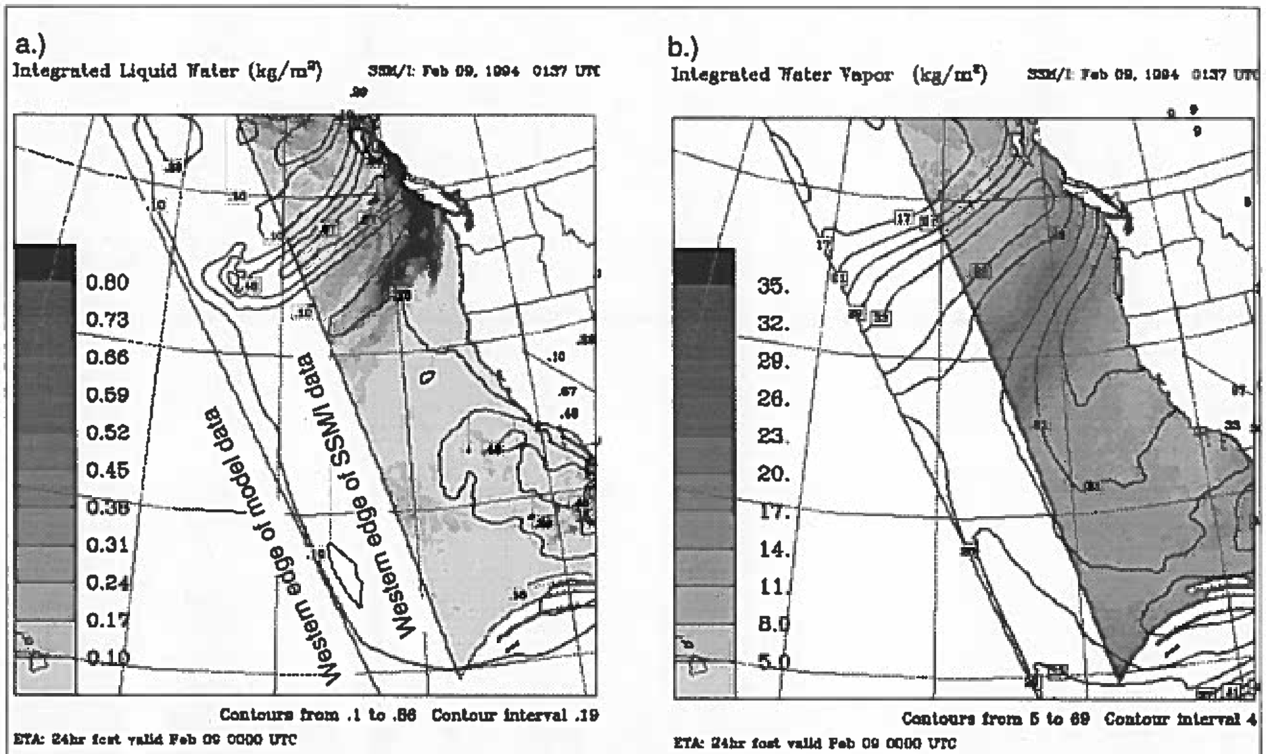

Figure 1: (a) SSM/I Integrated liquid water (kg·m^{-2}) in gray-shades for 0137 UTC 9 February 1994 with an overlay of the Eta model 24-hr forecast of the same field valid at 0000 UTC contoured using sold lines. (b) Same as in part (a) except with Integrated water vapor (kg·m^{-2}).

much like the feature shown for ILW. Extremely dry regions are indicated by the lighter gray-shading off the California coast and west of British Columbia. Comparisons between these observations and the Eta model 24-hr forecast reveal the same deficiency as previously mentioned; because the model-predicted maximum lags behind what the SSM/I shows. Quantitatively, values predicted by the Eta model are 10-15% larger than the observed amounts.

An apparent forecast error in the speed of progression for the weather system near Vancouver Island isn't unreasonable considering this is a 24-hr forecast and likely was initialized poorly due to a lack of observational data over oceans. However, inspection of the 0-hr Eta forecast from the 0000 UTC 9 Feb model run reveals errors in the initialization of the moisture field. Figure 2 shows only the IWV data from the SSM/I and Eta model and shows that the model was poorly initialized near the region of maximum IWV southwest of Vancouver Island. The model *does* tend toward a maximum in this region but does not extend far enough north and east. The observed minimum farther northwest, and to a lesser extent, the mini-

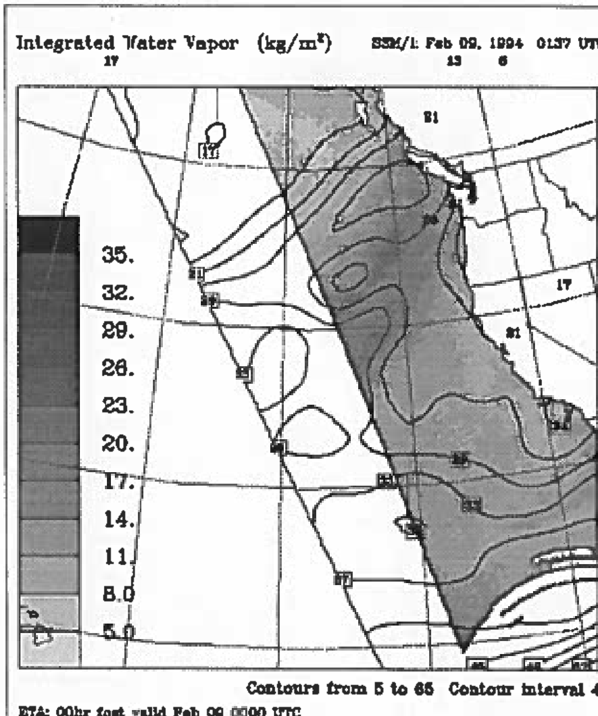

Figure 2: Same as in Fig 1b except using a 0-hr Eta model forecast

mum off the California coast appear to be initialized well by the model. It could be argued that the 24-hr forecast of Figure 1 predicts the patterns better than the next day's 0-hr forecast but is shifted northwest of the correct position. In other words, the shapes of the model-*predicted* features of Fig.1 subjectively compare better to observations than do the model-*analyzed* features of Fig 2. Problems of this nature were confined to oceanic and other data-sparse regions. These problems were not consistently found in all of the other case days investigated.

Results from a 14-hr MM5 model forecast are shown in Fig. 3 and have an error similar to that seen in the 24-hr Eta forecast. Again, the major feature near Vancouver Island is predicted well to the north-west of the observed position. Comparing IWV fields (Fig 3b) reveals a worse prediction by MM5 as evidenced by the northernmost maximum lagging far behind the observed position.

Inspection of the 2-hr forecast by MM5 (not shown) exposed the same problem seen in the 0-hr Eta forecast: model initialization of moisture variables over data-sparse regions. The 2-hr forecast of IWV (from the 12 hr later model run) appeared exactly as Fig. 3 with the primary feature well to the northwest of the observed position. This is directly attributable to the MM5's use of its own previous 12-hr forecast for initialization purposes. Since few observations exist in these regions, the "first-guess" field, provided by the previous model run, immediately introduces a position error relating to this feature. The initial error in the prior forecast was due to errors in the forecast of the global spectral model which is used for "nudging" the boundary conditions of the MM5 model. So a negative feedback mechanism has been created whereby one bad forecast by the parent model (the one supplying forecast boundary conditions) has transcended into successive model runs, causing significant impacts on all forecasts especially near the data-sparse oceans.

4.2 *12 February 1994*

Another satellite pass at 1502 UTC 12 February provided the SSM/I ILW and IWV fields shown in Fig. 4. Multiple maxima of ILW are seen with the largest in a banded structure oriented southwest from British Columbia. Other maxima are located to the south; one broad area along and west of the 130° meridian and two others, oriented east-west, between 20° and 30° N. The 18-hr Eta forecast valid 1800 UTC 12 Feb (3 hr after the

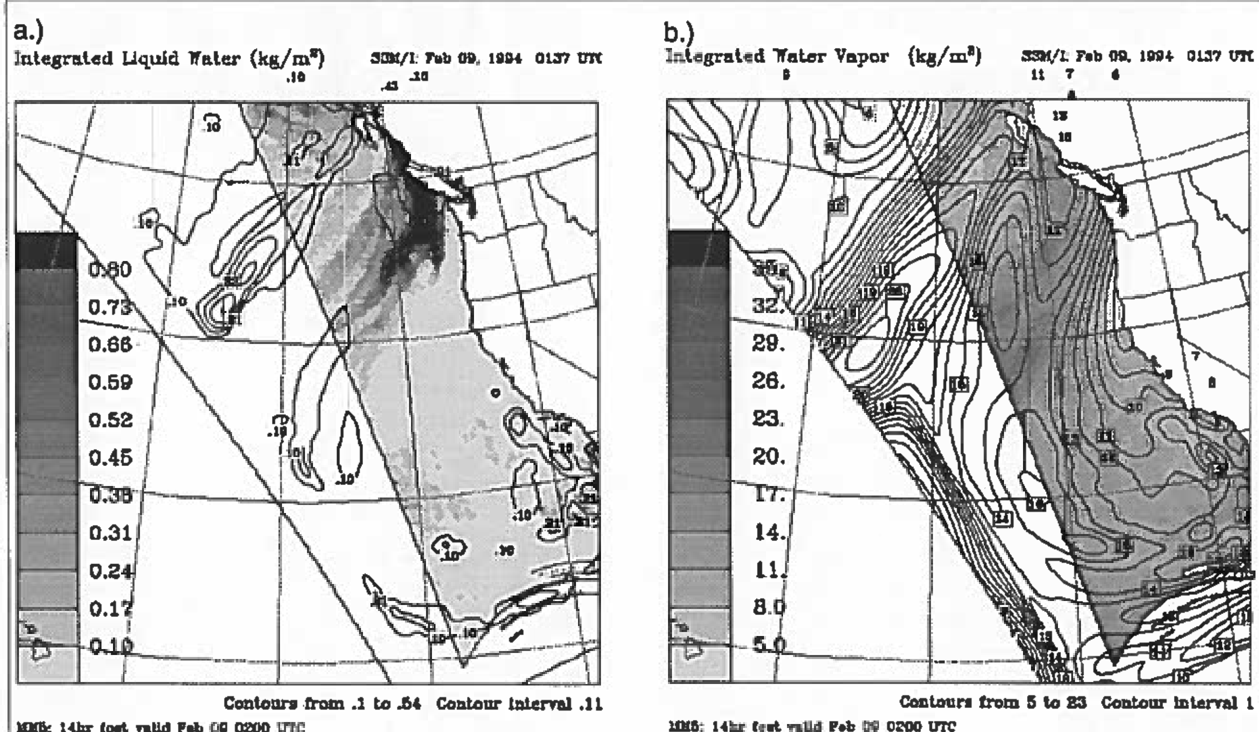

Figure 3: Same as Figure 1 except using a 14-hr MM5 model forecast.

SSM/I data), is contoured over the SSM/I data and compares favorably to the observations. Note that the northernmost primary feature corresponds reasonably well with the predicted ILW. Farther south, along the 130° meridian, the model bears less resemblance to the observations but still retains the southward protrusion of positive ILW. A shortcoming of this forecast lies in the timing of the northernmost feature. Inspection of the 12 and 18-hr forecasts revealed the model was moving the system too slow; the 18-hr forecast should predict this feature farther south and east than the 1502 UTC observations depict. Eta-forecasted IWV reinforces the favorable comparison as shown in Fig 4b. Eta predicts a maximum which corresponds closely with observations and the overall pattern appears to be forecast well.

The 15-hr MM5 forecast is also quite impressive and is shown in Figure 5. The northernmost feature as predicted by the model corresponds closely with observations. Farther south, the model continues to produce an excellent forecast west of 130°. Continuing farther south, the next feature is an east-west oriented band near 30° N. This, too, appears to be well handled by the model, although the correspondence is less striking. Again the IWV field (Fig 5b) reinforces the favorable comparisons noted above with striking resemblance between model forecast and SSM/I observations.

5. DISCUSSION

Comparisons of SSM/I data with model predicted ILW has emphasized the need for improving model initializations of moisture fields. From the case studies presented here, it appears likely that significant improvements to numerical model forecasts can be gained by incorporating satellite data. This is obviously true for 24 hour and longer forecasts but may also be true for short-term forecasting.

Numerical model cloud liquid water parameterizations are beginning to be used operationally and appear to function best in strong, dynamically forced, synoptic-scale situations. Weakly-forced, mesoscale features provide the biggest challenge to liquid water parameterizations.

Future research will investigate the utility of NOAA's AVHRR and new GOES-8 satellite data for use in assessing model performance as well as possible applications to initialize numerical models. Furthermore, applying subtraction algorithms to satellite channels may provide additional information necessary to distinguish cloud water from cloud ice (Lee and Clark, 1995).

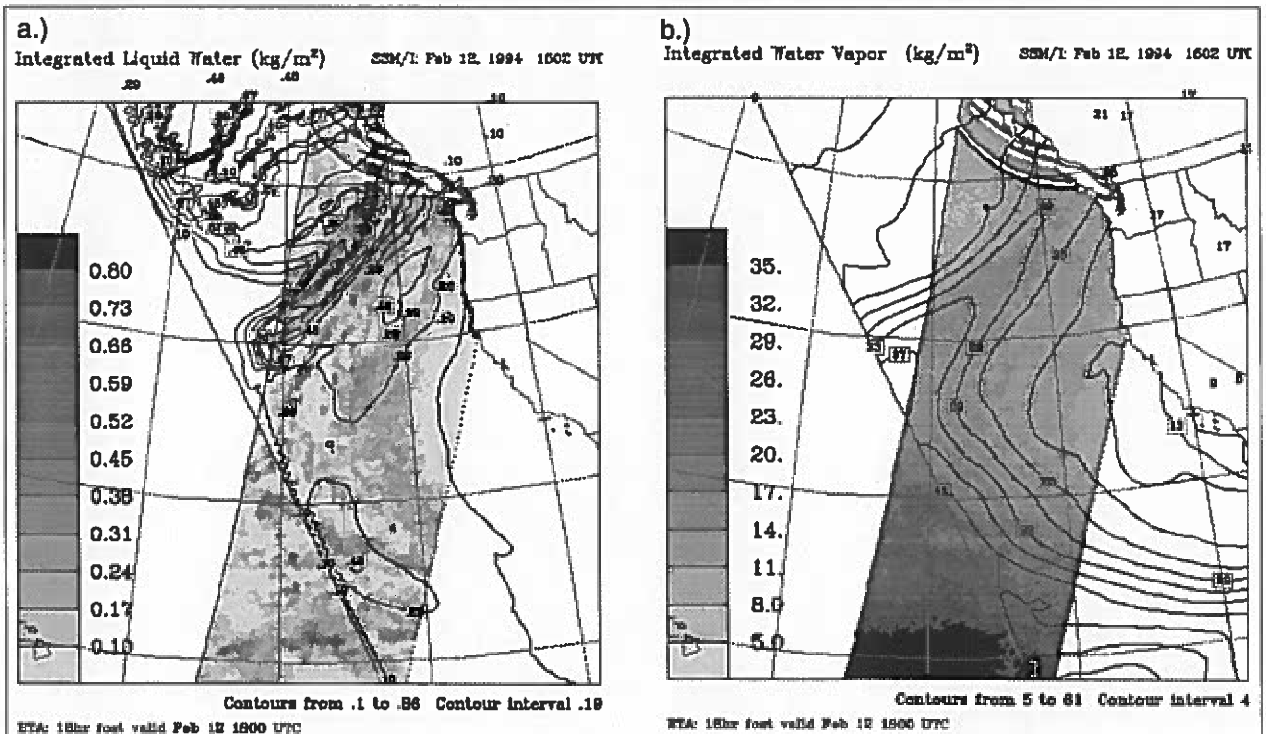

Figure 4: Same as Figure 1 except SSM/I data valid at 1502 UTC 12 Feb and Eta model data from a 18-hr forecast valid at 1800 UTC.

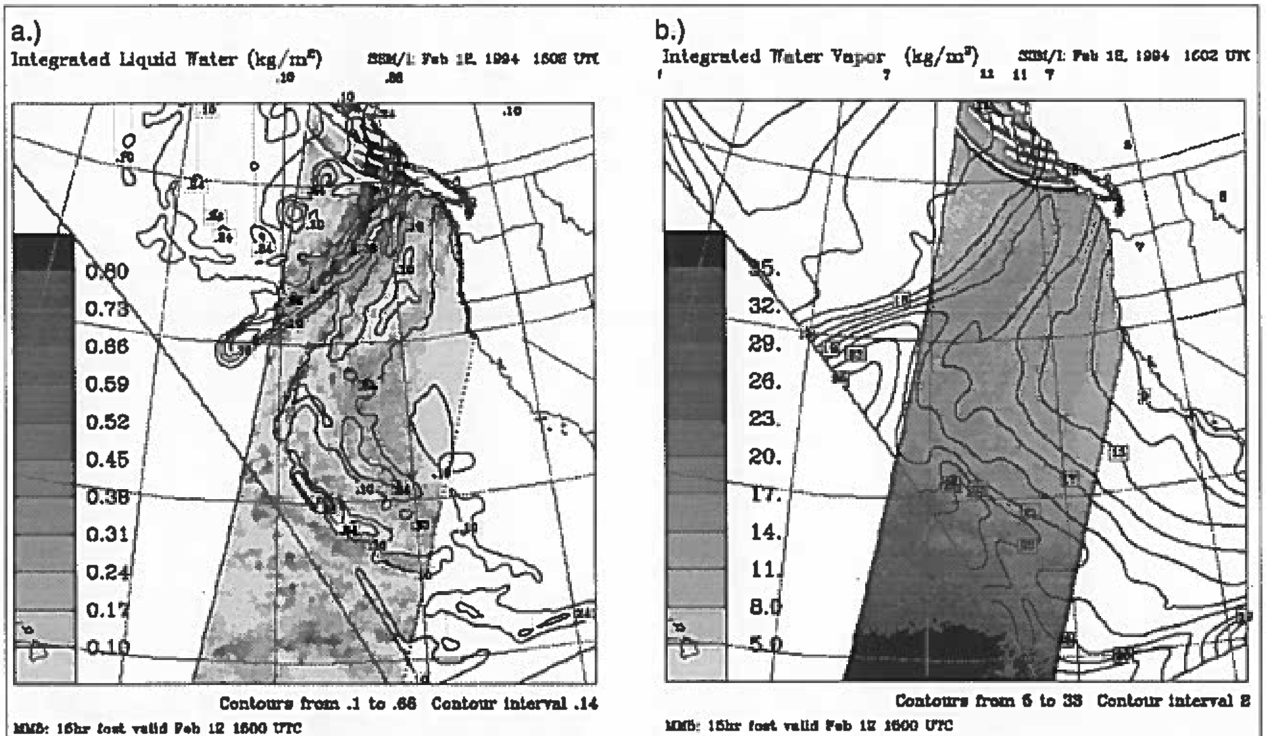

Figure 5: Same as Figure 4 except using a 15-hr MM5 model forecast

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