A Moisture Analysis Procedure Utilizing Surface and Satellite Data

STEPHEN W. WOLCOTT AND THOMAS T. WARNER

Department of Meteorology, The Pennsylvania State University, University Park 16802

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ABSTRACT

Because mesoscale models frequently incorporate grid mesh sizes that can resolve moisture patterns on a finer scale than is discernable from the radiosonde observation network, a moisture analysis procedure has been developed that uses satellite, precipitation and surface specific humidity data to augment the standard radiosonde observations (RAOB) of moisture. Four analyses were produced; one used only RAOB data, one used RAOB data supplemented only by information obtained from the surface observations of specific humidity, one used RAOB data supplemented only by satellite and precipitation data and one included all the sources of data. Mesoscale forecasts using the Penn State University Mesoscale Model were performed to determine the effect of the high-resolution moisture analyses on the forecast of precipitation. For the particular data set used, the supplementary satellite and rainfall data improved the precipitation forecast more than did the use of the surface humidity data. The satellite and rainfall data, which are used to impose a relative humidity constraint on the initial moisture fields, allowed the model to produce rain rates during the first 4 h of the forecast that were 100% larger, and more realistic than the rain rates that were produced when these data were not included.

1. Introduction

The demand for improved moisture analyses has increased with the advent of short-range, mesoscale numerical modeling. Atkins (1974) and Perkey (1976) have demonstrated the sensitivity of precipitation forecasts to initial moisture conditions. Modifications to the moisture field resulted in different rainfall rates during the early portion of the forecast periods. Incorrect forecasts of precipitation and model cloud development also will affect circulation patterns because of their relationships to latent and radiational heating (Kreitzberg, 1976).

Because mesoscale models frequently incorporate grid mesh sizes that can resolve moisture patterns on a finer scale than is discernable from the radiosonde observation (RAOB) network, we have developed a moisture analysis procedure that uses satellite, precipitation and surface specific humidity data to augment the standard RAOB’s of moisture. Mesoscale forecasts using the Penn State University Mesoscale Model (Anthes and Warner, 1978) were performed to determine the effect of the high-resolution moisture analysis on the forecast of precipitation.

2. The moisture analysis procedure

The analysis procedure uses four types of moisture data; radiosonde, infrared satellite, surface specific humidity and precipitation. The RAOB’s serve as the primary source of synoptic scale information whereas the other sources add mesoscale detail to the analysis. The precipitation data and satellite-determined cloud data provide the basis for a relative humidity constraint with the potential for providing high-resolution information whereas the surface specific humidity analysis introduces fine-scale information on low-level moisture patterns. The three components of the analysis procedure will be discussed individually.

a. The analysis of radiosonde moisture data

The radiosonde moisture analysis procedure uses a successive approximation technique (SAT) originally proposed by Berghóthrsson and Deos (1955). The SAT was first used in an operational mode by the Joint Numerical Weather Prediction Unit at the National Meteorological Center (Cressman, 1959) and by the Swedish Air Force Weather Bureau. Although its use is no longer as extensive, the SAT remains an inexpensive, fast, and fairly accurate objective analysis technique. The SAT used in this study differs from the one originally proposed by Cressman in that an elliptical instead of a circular weighting function can be used to determine the influence of the observations on the grid-point values. Although computationally efficient, the circular weighting function does not consider the autocorrelations among the data themselves. Specific humidity, like many other meteorological variables, is best correlated with itself in a direction perpendicular to the gradient. Each ellipse is aligned with
its major axis perpendicular to the gradient and with its centroid at an observation point. The gradients are determined from centered, finite-difference calculations made at the grid point closest to a given observation. An added option includes increasing the eccentricity of the ellipse with each pass of the data. As the length of the radius of influence is decreased after each successive pass, the ellipse becomes more elongated. This feature allows the gradient to have a greater influence as the elliptical area diminishes. This SAT also can generate its own first-guess or background field, based on the actual observations, in the event that no such field is available from other sources.

b. Incorporation of surface specific humidity data

Techniques for relating surface observations of moisture to the atmospheric moisture aloft have been evaluated by Reitan (1963), Bolsenga (1965), Smith (1966), Schwarz (1968) and Reber and Swope (1972). The correlation procedures have been somewhat successful, but the degree of their success has depended on the geographic location, the extent of vertical mixing near the ground and the amount of time averaging applied to the moisture observations.

The analysis procedure implemented in this study uses surface specific humidity data to infer specific humidity aloft at the model levels by the use of first-order linear regression equations. Current RAOB data are first used to develop the regression relationship between surface specific humidities and those at the lowest model level. A correlation coefficient, appropriate for that level, is then determined from the RAOB specific humidities observed at the lowest model level and the specific humidities predicted by the regression equation for that level. If the correlation coefficient is greater than a prescribed value, a specific surface humidity field is objectively analyzed by the SAT procedure using both radiosonde surface specific humidities and first-order surface station observations. The SAT generates its own background field in this case. The regression equation is then applied to each grid point of the analyzed surface field to determine a specific humidity field at the lowest model level. The result is then used as a background field for an objective analysis technique described below, which incorporates radiosonde observations for this level. Finally, the same procedure is repeated for successively higher model levels until the correlation coefficient becomes less than the prescribed value.

This analysis technique, which is similar to one tested by Atkins (1974), replaces the simple SAT analysis procedure (Section 2a) when the surface data are to be incorporated at a given level. The technique is analogous to the SAT with a few exceptions; 1) the first-guess or background field values, which are based on the surface observations as described above, have their own weight in the analysis process and 2) the influence functions for the assimilation of the RAOB data are dependent on the magnitude of the background-field gradient as well as its direction. The equation used for the analysis of q at point \( ij \) is

\[
q_{ij} = \frac{\sum_{k=1}^{n} (W_k q_k + W_b r q_{b,j})}{\sum_{k=1}^{n} (W_k + W_b r)}
\]

(1)

where \( W_k \) is the weight of observation \( k \), \( n \) is the number of specific humidity observations possessing a weight greater than zero, \( W_b \) is the background weight, \( q_{b,j} \) is the background specific humidity, \( q_k \) is an observation of specific humidity and \( r \) is the abovementioned correlation coefficient. The contribution of the background field thus depends on the reliability of the estimates of \( q_b \) at this level. The observation weight is defined by

\[
W_k = \left( \frac{R^2 + d^2}{R^2 - d^2 + 3.0|\nabla q_{b,j} \cdot \hat{r}|} \right)^{-1}
\]

(2)

where \( \hat{r} \) is the position vector between grid point \( (i,j) \) and the \( nth \) observation, \( R \) is the radius of influence and \( d \) is the distance between the observation and grid point. This observation weighting function has much the same effect as the elliptical weighting function used in the SAT procedure. It is designed primarily to take advantage of the spatial correlations exhibited by specific humidity in a direction perpendicular to the gradient. The additional feature of using the strength of the gradient to vary the shape of the isolines of constant weight is used to take greater advantage of the autocorrelation effect.

The original background field is incorporated only for the first pass of the data, while a second pass uses the result of the first analysis for its background field. During both scans, the correlation coefficient \( r \) is multiplied by the background weight \( W_b \). \( W_b \) is set equal to one for the first pass and to two for the second.

c. Utilization of present weather observations and infrared satellite photographs

The moisture analysis procedure here uses satellite data in the form of infrared satellite photographs to determine total cloud volume. The infrared photographs consist of various shades of gray, ranging from black to white, corresponding to different temperature intervals (segment numbers). The temperature intervals colder than –32.2°C are enhanced, i.e., the outline is well defined and the
gray shade is uniform. Because it would be difficult to apply a temperature range in the moisture analysis procedure, the interval is averaged such that a single temperature corresponds to a given segment number. The cloud-top temperatures are then compared to the temperature analyses at all numerical model levels and regions of 100% relative humidity can be determined with relatively little ambiguity. The satellite data are applied in two different ways depending upon the present weather observations. If precipitation has been observed at the location of a particular grid point, the relative humidity is assumed to be 100% from the model's lowest level up to an upper cutoff level. The relative humidity constraint ceases to be applied at the first model level with a temperature colder than the average temperature of the segment number of that grid point. For instance, let a grid point have a segment number equal to 4. The corresponding temperature of $-36.7^\circ$C would lie between a model level A (say, $-40.0^\circ$C) and a model level B (say, $-30.0^\circ$C), where level A is higher than level B. The uppermost extent of the cloud volume would be assigned to the warmer level B. If precipitation was not occurring at that grid point, this level would be the only level at which saturation would be assumed. Perrie's (1950) summary of the characteristics of clouds indicates that an average cloud thickness is adequately represented by an individual model layer in the version of the model used, where the average thickness of a layer was $\sim 2$ km.

The specific humidity of the grid points unaffected by the satellite data is determined by either the modified Atkins technique, where statistically appropriate, or the SAT procedure. When the SAT technique is used, RAOB data determined to be in the cloud volume are not used. Instead, only those data outside the cloud volume are used to modify the grid points outside the cloud volume. This approach keeps moist RAOB's that occur inside a cloud volume from modifying grid points outside the cloud volume, which should remain relatively dry. The result is the creation of a strong moisture gradient at the cloud volume boundary. This procedure is not necessary for the modified Atkins technique, since the combination of the background field and the RAOB data provide a data set that is dense enough to define sharp gradients.

Two cross-section analyses illustrate how the procedure works. Fig. 1a depicts a hypothetical situation that might exist if one were to examine the cloud structure along a cross section through a cold front. Preceeding the front are high, thin cirrus clouds. An anvil shaped cumulonimbus is associated with the frontal boundary. The trailing cool dry air is interspersed with fair weather cumuli and middle level altocumuli. Fig. 1b illustrates how this would appear to the numerical model after analysis. The 100% relative humidity constraint would extend to the lowest model level (level 6 in this case) for the portion of the cumulonimbus where precipitation was occurring. The altocumulus and the stratocumulus behind the front and the cirrus ahead of the front would be accurately portrayed. The small cumulus cloud preceding the cold front and portions of the cumulonimbus where precipitation was not observed do not lie within the model cloud volume.

3. Evaluation of the moisture analysis procedure

Ideally, the analyses produced by the humidity initialization procedure should be verified against a high-density data set. However, because these data are not currently available, other means, such as the verification of forecasts, must be used to test the worth of the initialization procedure. Specific humidity analyses produced by four different analysis procedures were used to define initial data for the Pennsylvania State University mesoscale model. Model forecasts were then compared to determine which moisture analysis procedure allowed the most accurate precipitation forecast.

Moisture analyses were produced for 1200 GMT 19 November 1975. At this time a cold front extended from southwest Texas to northern Wisconsin, joining a stationary front which dipped gradually southeastward until reaching the Atlantic Ocean at the New Jersey coast (Fig. 2). A moist, stagnant high, with a central pressure of 1026 mb, which had persisted during the past week, was situated over West Virginia. On the other side of the fronts, a cold surface high, with a central pressure of 1043 mb, was
had both the first- and second-order station data been available, some hourly rain gauge data were used as supplementary observations of precipitation.

Moisture analyses were performed on the model computation surfaces. The vertical coordinate $\sigma$ is defined in terms of pressure by

$$\sigma = \frac{p - p_1}{p^* - p_1},$$

where $p$ is pressure, $p_1$ is the pressure at the model's top (250 mb), and $p^*$ is the surface pressure. Table 1 gives the model sigma-level values, their approximate pressures for an average surface pressure, and the reference number used for each level.

Four different procedures were used to obtain analyses at the sigma levels. They used various combinations of radiosonde, surface and satellite data. The control procedure used only a SAT analysis of radiosonde data. Procedure 1 is the synthesis of all the techniques discussed in Section 2 and represents the "complete" analysis procedure. Surface, radiosonde, and satellite data are all used. The critical correlation coefficient required for the statistical data to be applied at a sigma level was 0.90. Sigma level 6, with a correlation of 0.96, was the only level where this criterion was met and the regression equation used. Procedure 2 was identical to procedure 1 except that the analysis at level 6 did not include the statistically inferred surface data. Procedure 3 used the statistically inferred surface data and the radiosonde data but did not include the satellite data. The control and other procedures are summarized in Table 2.

The relative humidities, based on the specific humidity analyses, for levels 6 and 2 are presented in Figs. 4 and 5, respectively. Figs. 4e and 5c are analyses of the regions where 100% relative humidity was determined to exist by the satellite and

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**FIG. 2.** The sea level pressure and frontal boundaries for 1200 GMT 19 November 1975.

**FIG. 3.** The subjectively enhanced infrared satellite photograph for 1145 GMT 19 November 1975. The segment numbers are shown. The border surrounding the enhanced cloud data is that of the computational domain.
rainfall data. The most obvious difference between the control analysis and those from procedures 1 and 2 for level 6 is in the location and size of the area of 100% relative humidity. These moist regions are a direct result of the relative humidity constraints, associated with the present weather observations and the satellite-determined cloud volume. The saturated regions in northeast and southeast United States are somewhat smaller in size in analysis 1 than in analysis 2 because surface data have produced a drying effect. The control analysis and analysis 2 differ slightly in regions where no cloud or precipitation was observed because the SAT analysis weighting function was circular in the control and elliptical in the other procedures. Analysis 3 closely resembles the control analysis for this sigma level. The differences relate to the moistening and drying effects of the surface data.

The effects on the analysis of the satellite-determined cloud volume, are even more noticeable for sigma level 2. Analyses 1 and 2 (Fig. 5) demonstrate probable realistic relative humidity gradients. At this level, the humidity is apt to be relatively low outside the cloud, while of course being saturated inside. Even though analyses 1 and 2 are considerably more moist than the control, large differences in the relative humidity patterns are possible at this level without having serious effects on the precipitation forecasts. At this level, analysis 3 (not shown) only differs from the control because of the difference in the shape of the influence function used.

It is important to note that the saturated conditions at the grid points within the cloud volume are incorporated directly into the final analyses. Because no attempt is made to smooth the humidity at the boundary between these grid points and those determined from other objective techniques, strong gradients are apt to exist. Analyses 1 and 2 provide evidence of these gradients.

Figs. 6a and 6b are the specific humidity fields, as determined by analysis procedure 1, for the numerical model, sigma levels 3 and 6. The specific humidity for level 6 is closely related to the surface frontal pattern. Moist air extends northward along the cold front with a few isolated, very moist pockets in eastern Kansas and Wisconsin. The air behind the advancing cold front is relatively dry. The specific humidity analysis for sigma-level 3 shows a strong resemblance to the satellite-determined cloud pattern. The specific humidities in these cloudy regions are higher than in the surrounding area. The strong gradients that existed for relative humidity, also naturally exist for specific humidity.

4. Forecast results

a. The forecast model and initialization procedure

The hydrostatic primitive equation model developed by Anthes and Warner (1978) employs equations for the horizontal wind components, a thermodynamic equation, and continuity equations for mass and water vapor. Temperature, winds and specific humidity are defined at the six sigma levels mentioned in Table 1. The vertical fluxes of the wind, temperature and specific humidity as well as \( \dot{\sigma}(d\sigma/ dt) \) are located at intermediate sigma levels. Temperature, geopotential, omega, and specific humidity are located at grid points which lie midway between, and offset by 45° horizontally from, the wind component grid points. For this study, the wind

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component grid was $30 \times 35$ and the specific humidity grid was $29 \times 34$ with the distance between grid points in both instances equal to 120 km. The time differencing scheme used was that of Brown and Campana (1978) which is explicit but which allows a time step approximately twice as large as the one permitted by the normal centered-in-time procedure. Both convective and nonconvective precipitation are accounted for, where the existence of convective precipitation is determined from the vertically integrated large-scale moisture convergence. Details of the moisture cycle are available in Anthes and Warner (1978) and Anthes (1977).

The initialization procedure for all variables, except specific humidity, was developed by Warner et al. (1978) and Tarbell et al. (1981). The winds for the mandatory pressure levels are first subjectively analyzed and the streamfunction is then obtained after the vorticity field has been calculated. The streamfunction provides the nondivergent wind components. The observed precipitation during a period centered on the initialization time is used to derive vertical velocities using an omega equation containing a diabetic heating term. The omega values together with the continuity equation in pressure coordinates yield the velocity potential. The velocity

Fig. 4. Sigma-level 6 relative humidity analyses. The contour interval is 25% and the shaded areas are regions of 100% relative humidity. The control analysis is shown in (a), analysis 1 in (b), analysis 2 in (c), analysis 3 in (d) and the approximate area determined to be saturated according to rainfall and satellite data in (e).
potential provides the divergent wind components which are used with the nondivergent wind components in the balance equation expressed in sigma coordinates to calculate the geopotentials at sigma levels. The balanced temperatures are then derived from the hydrostatic equation. The sum of the divergent and nondivergent wind components defines the initial winds for the model. Details about the divergent initialization procedure are available in Tarbell et al. (1981).

The mesoscale model requires that the wind components, temperature, specific humidity and surface pressure be defined at the lateral boundaries for the entire forecast period. A linear interpolation is made during the model integration between the observed lateral boundary values at the beginning and ending times of the simulation.

b. The results of the forecasts

The moisture analysis procedures were tested by verifying numerical precipitation predictions that
used the control moisture analysis and the three other moisture analyses to provide initial conditions on specific humidity. Except for the different initial moisture fields, the conditions of the simulations are identical.

The forecasts were compared in terms of the accumulated precipitation during the 12 h period from 1200 GMT 19 November to 0000 GMT 20 November 1975. The predicted and observed 3 h accumulated precipitation totals are shown in Fig. 7. In forecasts 1 and 2, a secondary precipitation maximum was predicted in western Oklahoma, near the observed secondary maximum located in the Texas Panhandle. This feature was not predicted by either the control forecast or forecast 3. Credit for the higher forecast precipitation amounts in forecasts 1 and 2 must be given to the relative humidity constraint imposed by the satellite determined cloud volume and the precipitation observations. For example, Fig. 4 shows that analysis procedures 1 and 2 produce saturated conditions at level 6 in the eastern Texas Panhandle and western Oklahoma. Without the colocation of saturated conditions and the model’s initial upward motion field corresponding to the di-
5. Summary

Four moisture analysis procedures were evaluated in terms of their ability to provide model initial conditions on specific humidity that produce realistic precipitation predictions. Two techniques for augmenting radiosonde observations with high-resolution information on the moisture field were used. First, infrared satellite photograph information and surface observed “present weather” data were used to impose a three-dimensional constraint on the relative humidity. Second, specific humidity data from the surface observation network were used to develop the humidity analysis at the lowest model layer. All forecasts produced rainfall amounts considerably smaller than those observed even though the positioning of the rain events was good. The most realistic rainfall amounts were produced by the model when the saturation constraint was imposed by the use of satellite and surface observed “present weather” data. The rain rates during the first 4 h of these forecast were 100% larger and more realistic than the rain rates produced when these data were not used. The fine-scale structure to the moisture field at the lowest model level, provided by surface-based specific humidity data, did not significantly affect the precipitation prediction. However, in the absence of initial precipitation on which to base the relative humidity constraint and in situations characterized by smaller-scale precipitation events and moisture structure such as might be associated with a developing squall line, the use of these surface humidity observations might produce a more dramatic impact on the accuracy of a forecast. Also, it is important to note that a strong synergistic effect exists between the initial latent heat release in the model and the divergence field that exists in the model initial conditions. If the regions of observed precipitation are not saturated in the initial moisture analysis, the upward motion associated with the initialized divergence field will not be sustained by latent heat release and the divergence will be dissipated by gravity-inertia waves. Thus the model will not correctly predict the precipitation event, at least early in the forecast. If, on the other hand, no realistic divergence is included in the initial wind field, the model will not produce correct precipitation early in the forecast anyhow. It is therefore probable that the extent of the positive influence of the satellite and surface present weather data, at least during the early hours of the forecast, was related to the existence of the relatively sophisticated divergent wind initialization.

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REFERENCES


