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Objective Humidity Analysis on
Isentropic Surfaces for a Limited Area

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1. Introduction

An isentropic analysis package has been developed at the National Meteorological Center (NMC), in conjunction with the development of a Movable Fine-Mesh Model for a limited area. The MFM model is designed to predict the movement and development of hurricanes and tropical storms, as well as those of extratropical systems that are confined in a limited area. Within the isentropic analysis package, special attention is devoted to the analysis of moisture in order to achieve the following: a) better vertical resolution of the moisture field by incorporating radiosonde data at significant levels as well as those at standard levels; b) a much more detailed analysis of the moisture field in the planetary boundary layer; c) the use of cloud and weather observations at surface stations to infer moisture data in the lower troposphere in areas where radiosonde data are unavailable. This paper documents the scheme of moisture analysis in the isentropic analysis package.

2. Highlights of the Analysis Scheme

Some highlights of the moisture analysis scheme are listed as follows:

a. Analysis is performed on isentropic (constant potential temperature, θ) surfaces. There are 15-30 levels in the vertical, with $\Delta\theta = 4 - 2°K$. θ at the lowest level varies with seasons. (Lowest in winter, highest in summer.)

b. There are 783 (27 x 29) grid points on each isentropic surface. It's a subset of the NMC coarse mesh grid. The total area covered approximates that covered by the LFM grid.

c. Location of grid is variable. Both vertical and horizontal spacings and grid location can be changed by input cards.

d. Use Cressman scheme of analysis with multiple scans. Utilize radiosonde data at both mandatory and significant pressure levels. Surface data are used in the analysis.

e. Perform various checks on radiosonde and surface data. Interpolate for needed data that are missing. Discard data that are "bad."

3. Procedure

In addition to moisture, other variables of height (z), temperature (T), second derivative of Montgomery stream function $(\partial^2 M/\partial^2 z)$, and wind components (u and v) are also analyzed in the isentropic analysis package. In the order of analysis procedure, the fields of z, T, and $\partial^2 M/\partial^2 z$ are analyzed before that of moisture. The moisture analysis may be carried out before or after the wind analysis, since there is no interaction between the moisture field and the wind field.

A simplified flow-diagram showing major steps in the isentropic moisture analysis is presented in Figure 1. These major steps are now explained with more detail.

a. The NMC data carry mean relative humidity (RH) values in three sigma layers in the troposphere: the boundary layer, and two tropospheric layers above that. The mean RH in the third, and last, layer is not carried, but will be set at 40% everywhere in our analysis. While the pressure at the bottom of the four layers is that at the surface (p*), the pressure at the top
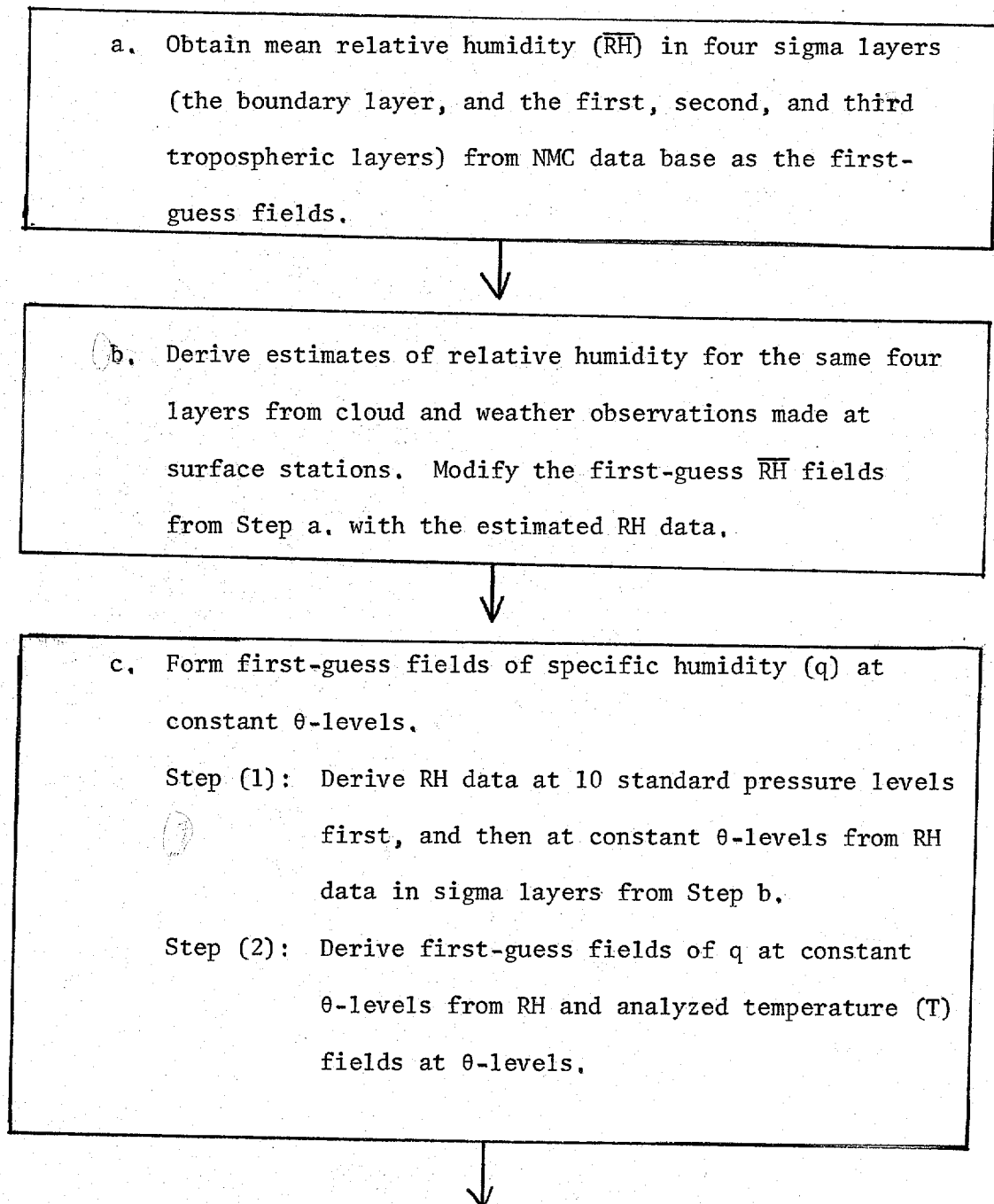
a. Obtain mean relative humidity ($\overline{RH}$) in four sigma layers (the boundary layer, and the first, second, and third tropospheric layers) from NMC data base as the first-guess fields.

b. Derive estimates of relative humidity for the same four layers from cloud and weather observations made at surface stations. Modify the first-guess $\overline{RH}$ fields from Step a. with the estimated RH data.

c. Form first-guess fields of specific humidity (q) at constant θ-levels.

Step (1): Derive RH data at 10 standard pressure levels first, and then at constant θ-levels from RH data in sigma layers from Step b.

Step (2): Derive first-guess fields of q at constant θ-levels from RH and analyzed temperature (T) fields at θ-levels.

Figure 1. Major steps in isentropic moisture analysis.

d. Analyze q fields at constant θ-levels.

e. Perform special moisture analysis in the boundary layer to improve the analysis at low levels.

Step (1): Analyze the specific humidity field at surface (q_0).

Step (2): Analyze the field of $R(\overline{q}/q_0)$.

Step (3): Obtain the field of $\overline{q}$ (the product of analyzed q_0 and analyzed R), the mean specific humidity in the boundary layer.

Step (4): Merge analyzed $\overline{q}$ with analyzed q on θ-levels to improve q analyses at lower levels.

f. Derive q (or RH) fields at constant pressure or sigma levels from q (or RH) at constant θ-levels through vertical interpolation.

Figure 1 (continued).

coincides with that at the tropopause (p^{**}). Figure 2 shows the vertical structure of the 6-layer Primitive Equation (PE) Model and the Limited Area Fine Mesh (LFM) Model currently in use at NMC. Once p^* and p^{**} are specified, p_2, p_3, and p_4 can be calculated as follows:

$$p_2 = p^* - 50 \text{ mb} \tag{1}$$

$$p_3 = p^{**} + (2/3)(p_2 - p^{**}) \tag{2}$$

$$p_4 = p^{**} + (1/3)(p_2 - p^{**}) \tag{3}$$

Mean relative humidity (RH) values for these four layers for the the subset of 27 x 29 grid points are now obtained from the NMC data base.

This step is completed in Subroutine MGES.

b. This step is completed in two stages, which are described below:

(1) Derive estimates of mean relative humidity ($\overline{RH}$) in the four tropospheric layers from cloud and weather observation at surface stations.

The input data used to derive estimates of $\overline{RH}$ are these observations taken at surface stations: present weather, fractions of sky cover by low, middle, and high clouds. From the reported present weather codes relative humidity values (RHWW) are assigned according to Table 1, which is currently in use in the LFM analysis package at NMC.

C C C	0	1	PRESENT WEATHER TABLE (RH) 2	3	4	5	6	7	8	9
0	65.,	65.,	65.,	65.,	65.,	65.,	50.,	50.,	50.,	55.,
1	90.,	90.,	90.,	85.,	90.,	95.,	95.,	95.,	90.,	90.,
2	90.,	90.,	90.,	90.,	90.,	90.,	90.,	90.,	90.,	90.,
3	50.,	50.,	50.,	50.,	50.,	50.,	60.,	60.,	60.,	60.,
4	90.,	90.,	90.,	90.,	90.,	90.,	90.,	90.,	90.,	90.,
5	95.,	99.,	99.,	99.,	99.,	99.,	95.,	99.,	95.,	99.,
6	95.,	99.,	99.,	99.,	99.,	99.,	95.,	99.,	95.,	99.,
7	95.,	99.,	99.,	99.,	99.,	99.,	90.,	90.,	90.,	50.,
8	95.,	99.,	99.,	95.,	99.,	95.,	99.,	95.,	99.,	99.,
9	99.,	95.,	99.,	95.,	99.,	95.,	99.,	99.,	95.,	99./

Table 1. Relative humidity assignments for various present weather codes used in synoptic surface reports.

CONSTANT Θ LAYER

STRATOSPHERE

TROPOPAUSE   p**

Layer 3   p₄

TROPOSPHERE

Layer 2

p₃

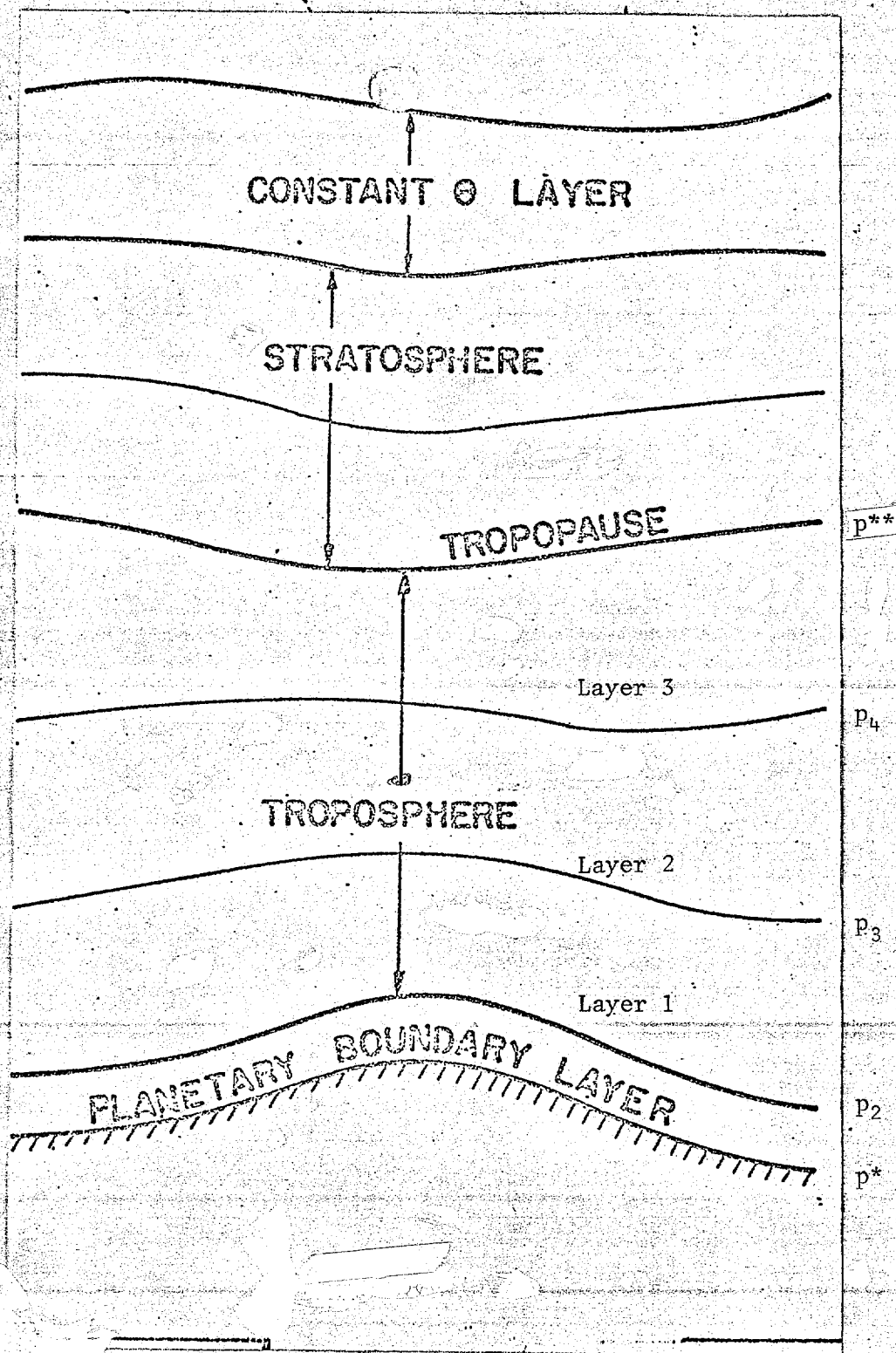Layer 1

PLANETARY BOUNDARY LAYER

p₂

p*

Figure 2. The vertical structure of PE and LFM Models at NMC.

Relative humidity values are assigned according to fractions of sky cover by the following formula:

$$\overline{RH}(\%) = M - A \cos\left(\frac{\pi}{8} \text{ OKTAS}\right) \qquad (4)$$

where OKTAS is sky cover by low, middle, or high clouds in eighths; M and A are constants which have different values for low, middle, and high clouds. The values of M and A are those used in the LFM analysis (Desmarais, 1971). For $\overline{RH}$ in Layer 3 (RH 3) inferred from sky cover by high cloud, M has a value of 55 and A has a value of 10. For $\overline{RH}$ in Layer 2 (RH 2) inferred from middle cloud, M has a value of 60 and A of 15.

When the existence of low cloud is reported, the additional information of height of cloud base is important. If the cloud base height is 2,000 ft. or higher, only $\overline{RH}$ in Layer 1 (RH 1) is inferred from the low cloud amount with M=75, A=15. However, when the cloud base height is less than 2,000 ft, both $\overline{RH}$ in Layer 1 (RH 1) and that in the boundary layer (RH BL) are derived from the low cloud amount through Formula (4). In this case, different values of M and A are used: for RH1, M = 70, A = 10; and for RHBL, M = 79, A = 19.

The temperature, dewpoint temperature and pressure observed at a surface station are used to calculate a surface relative humidity (RHG). The final inferred $\overline{RH}$ in the boundary layer is then the average of RHG, RHWW (RH inferred from the observed present weather) and RHBL (RH inferred from the amount of low cloud with its base height less than 2,000 ft.). The final inferred $\overline{RH}$ in Layer 1 is the average of RHWW and RH1 (RH inferred from the

amount of low cloud, the value of which depends on whether the cloud base is above or below 2,000 ft.). No averaging is carried out in Layers 2 and 3, where the $\overline{RH}$ is just that inferred from middle cloud amount (RH2) in Layer 2, and that from high cloud amount (RH3) in Layer 3.

The derivation of humidity estimates from cloud and weather obser-vations at surface stations is carried out in Subroutine SFCRH.

(2) Modify the first-guess $\overline{RH}$ fields from Step a. with the inferred $\overline{RH}$ data from (1).

The $\overline{RH}$ fields in four layers are now analyzed with the inferred $\overline{RH}$ data from (1), and first-guess fields from Step a. The Cressman method of analysis (1959) with multiple scans is used. A typical analysis would use three scans with scan radii of 2.5, 2.0, and 1.5 grid distances in decreasing order. More detail about the analysis scheme will be discussed under Step d.

The analysis of each layer is done in Subroutine HNALY.

c. The $\overline{RH}$'s in four layers that have been modified by inferred $\overline{RH}$ data now become the input for deriving first-guess fields of specific humidity (q) at constant θ-levels. This is achieved in two steps.

(1) From $\overline{RH}$ in four sigma layers RH values at ten standard pressure levels from 1000 mb to 100 mb are derived through interpolation. RH is assumed to vary linearly with pressure in this vertical interpolation. From that at ten standard pressure levels, RH at constant θ-levels is obtained again by vertical interpolation. Again, the RH is assumed to vary linearly with pressure, which at θ-levels can be calculated with the analyzed temperatures now available.

(2) At constant θ-levels the analyzed temperature field and the computed pressure field together determine the field of saturation specific humidity (q_s). With the interpolated RH field at θ-levels from (1), the field of specific humidity (q) is derived by multiplying RH by q_s. The q-fields thus derived form the first-guess fields of q at θ-levels.

Step c. is completed in Subroutine MGES.

d. Analyze q-fields at constant θ-levels.

(1) Radiosonde data and their treatment

Radiosonde data at stations within the area of interest are used in the analysis of q fields at constant θ-levels. After the data have been read from ADPUPA file, they are subject to a series of checks commonly used in an objective analysis program. Some of the checks are performed to make sure that:

. the data are within the area of interest;

. there are reports at no less than six levels, and no more than 99 levels at each reporting station;

. at each reporting station the reports are arranged in proper order according to the observed pressure at each level, and that no level is duplicated;

. at each level pressure height, temperature, and dewpoint temperature are reported.

When missing data are noted, each situation is handled according to the following:

. when the height value at the very first level is missing, the entire report from that station is discarded;

. when the pressure value at one level is missing, the entire level is discarded;

. when the temperature value at one level is missing, the entire level is discarded with the exception at 1000 mb and 850 mb, where the temperature is obtained through horizontal interpolation of the first-guess field.

. when the dewpoint temperature value at one level is missing, the dewpoint depression at an adjacent level is subtracted from the temperature value at that level to arrive at an approximated dewpoint temperature.

The treated radiosonde data are now used to calculate specific humidity (q) values at all pressure levels at each reporting radiosonde station. These q values are then used to derive q at constant-θ levels, with the assumption that q varies linearly with π, where

$$\pi = \left(\frac{p}{1000}\right)^{R/c_p} \tag{5}$$

R = gas constant, c_p = specific heat of air at constant pressure, p = pressure in mb.

The acquisition, treatment, and interpolation of radiosonde data are performed in the MAIN program.

(2) The analysis method

The analysis method used is essentially that of Cressman (1959) with multiple scans or passes. On each pass, an observation occasions a change or correction to all grid points within a distance R, where R is called the scan radius or radius of influence. To compute this change or

correction, a bilinear interpolation is used first to derive the value of
the first guess at each report position. The difference between the first
guess and the observed value is then spread to each grid point within the
influence area and weighted according to the distance, d, between each grid
point and the report position. The weight, W, is given by the following form:

$$W = \frac{R^2 - d^2}{R^2 + d^2} \tag{6}$$

After all reports within the influence area have been considered,
the sum of the weighted differences at each grid point is divided by the
number of reports, n, influencing that point, i.e.,

$$C_{i,j} = \frac{1}{n} \sum_{k=1}^{n} W_k \left(\phi_{k_{Guess}} - \phi_{k_{Obs}} \right) \tag{7}$$

where $C_{i,j}$ is the change to be added to the first guess at a grid point
i,j to arrive at the analyzed value of variable ϕ. As mentioned before, a
typical analysis of each field uses three scans with scan radii of 2.5, 2.0,
and 1.5 grid distances in decreasing order.

    e. Perform special moisture analysis in the boundary layer.

The conduct of a detailed analysis of moisture in the boundary layer
is based on the premise that such an analysis would help produce better
delineated and more detailed moisture fields at low levels. It is hoped
that these low-level moisture fields with better delineation and more detail
would, in turn, help the prediction model to produce better forecast of
moisture and, more importantly, precipitation.

The boundary layer moisture analysis is designed to make full use of observation data at surface stations, which are several times greater in number than radiosonde observation stations. Following the concept of Inman (1970), the ratio of mean humidity $(\bar{q})$ in the boundary layer to surface humidity (q_o) is objectively analyzed with radiosonde data and spread out to all points in the area of interest. Concurrently, a surface humidity (q_o) field is also analyzed with surface data of greater number to yield q_o at all grid points. The product of the analyzed ratio $(\bar{q}/q_o)$ and the analyzed q_o yields the analyzed field of $\bar{q}$, the mean humidity in the boundary layer.

This carefully analyzed mean humidity in the boundary layer $(\bar{q})$ is then meshed into the humidity fields at levels of constant potential temperature within the boundary layer. A proper weighting of $\bar{q}$ and the specific humidity (q) already existing at levels of constant potential temperature is carried out during this process.

(1) Analyze the specific humidity field at surface, q_o.

The first guess field of RH at 1000 mb derived from Step c. and the first guess field of temperature at 1000 mb are used to calculate a specific humidity field, which is used as the first guess field of surface specific humidity, q_o. From all surface stations in the area of interest, the observed dewpoint temperature and station pressure are used to compute the observed specific humidity used in the analysis. The analysis method is the one described in Step d. (2). The analysis is carried out in Subroutine HNALY.

(2) Analyzed the field of R, the ratio of $\overline{q}/q_0$.

For both the first guess field and observation of R, the numerator $\overline{q}$ is computed first in Subroutine MEANQ. At each grid point (in the case of first guess) or radiosonde station (in the case of observation), $\overline{q}$ is computed as a pressure-weighted mean quantity:

$$\overline{q} = \frac{\int_{p_b}^{p_t} q \, dp}{\int_{p_b}^{p_t} dp} \tag{8}$$

where p is pressure, p_t is pressure at top of the boundary layer, p_b is pressure at bottom of the boundary layer, and q is specific humidity at each pressure level in the boundary layer. The difference between p_t and p_b, or the depth of the boundary layer, is usually taken as 100 mb. The division of the computed $\overline{q}$ by q_0 gives the ratio R.

Subroutine HNALY, in which the field of a single variable is analyzed, is also used to analyze R. The analyzed value of R have an upper limit of 2.0 and a lower limit of 0.5. This range of values is chosen to minimize the impact of unrepresentative value of observed dewpoint temperature at the surface. In reality, however, most of the observed values of R are well within this range.

(3) The analyzed field of $\overline{q}$ is obtained by multiplying the analyzed field of $\overline{R}$ (i.e., $\overline{q}/q_0$) and that of q_0. This is done in the MAIN program.

(4) The analyzed $\bar{q}$ field is then merged with analyzed q at θ-levels to improve q analyses at lower levels. The merging of $\bar{q}$ is carried out in the following manner in Subroutine MERGQ:

In MERGQ the pressure value at each θ-level beginning at the lowest level at each grid point is checked to see if it falls within the 100-mb layer above the surface. Only those θ-levels whose corresponding pressure values are within 100 mbs above the surface are employed in the merging process.

At each grid point, an estimated q value is calculated at each θ level whose pressure value falls within 100 mbs above the surface:

$$q_e = q_o + \frac{\bar{q} - q_o}{p^* - \bar{p}} (p^* - p) \tag{9}$$

where q_e is the estimated q value at θ-level, q_o is the surface specific humidity, $\bar{q}$ is the mean specific humidity in the boundary layer, p^* is the surface pressure, $\bar{p}$ is the pressure value at the midpoint between the surface and the top of the boundary layer, and p is the pressure at θ-level.

This q_e at each θ-level and q_θ at the same level from isentropic analysis are now combined to determine a final value of q at the θ-level:

$$q_f = W q_e + (1 - W) q_\theta \tag{10}$$

where q_f is the final value of q at the θ-level, W is a weighting function. Presently, a parabolic function in the following form is used:

$$W = \left(\frac{p - p}{50 \text{ mb}}\right)^2 \tag{11}$$

f. Derive q (or RH) fields at constant pressure or sigma levels from q (or RH) at constant θ-levels through vertical interpolation.

For the purpose of display or providing initial moisture field to a prediction model, q fields at constant pressure or sigma levels are derived from q fields at constant θ-levels through vertical interpolation. For the sake of accuracy, q fields along with the known temperatures and pressure fields at each θ-level are converted to relative humidity (RH) fields first. The RH and temperature (T) fields are then vertically interpolated, assuming that they vary linearly with the logarithm of pressure. The RH and T fields at constant pressure or sigma levels are then used to yield q fields at these levels.

4. References

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