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The National Meteorological Center's Operational Seven Layer Model on a Northern Hemisphere Cartesian 190.5 km Grid

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I. Introduction

On 6 June 1966, the National Meteorological Center (NMC) introduced a six-layer primitive equation model on a 381-km Northern Hemisphere grid into its routine forecasting operations. Since that time, numerous evolutionary and revolutionary changes to the model have occurred--this essay is a compendium of the major changes made over the past 12 years. For a description of the model as it was in 1966, see Shuman and Hovermale 1968.

II. Model Design and Domain of Integration

The basic differential equations, their finite difference analogues, and the horizontal and vertical coordinate systems have not changed in any fundamental way. There are, however, alterations in detail, some of which are of considerable impact.

The first of these relates to the vertical structure. The original model had six layers (boundary, three tropospheric, two stratospheric layers) and a cap (a seventh layer) of constant potential temperature and no meteorological import. The revised model has seven meteorological layers--the new one is a third stratospheric layer--and no constant potential temperature cap. Fig. 1 shows the new layer structure and indicates some of the important boundary conditions: $\dot{\sigma}$ (vertical velocity)

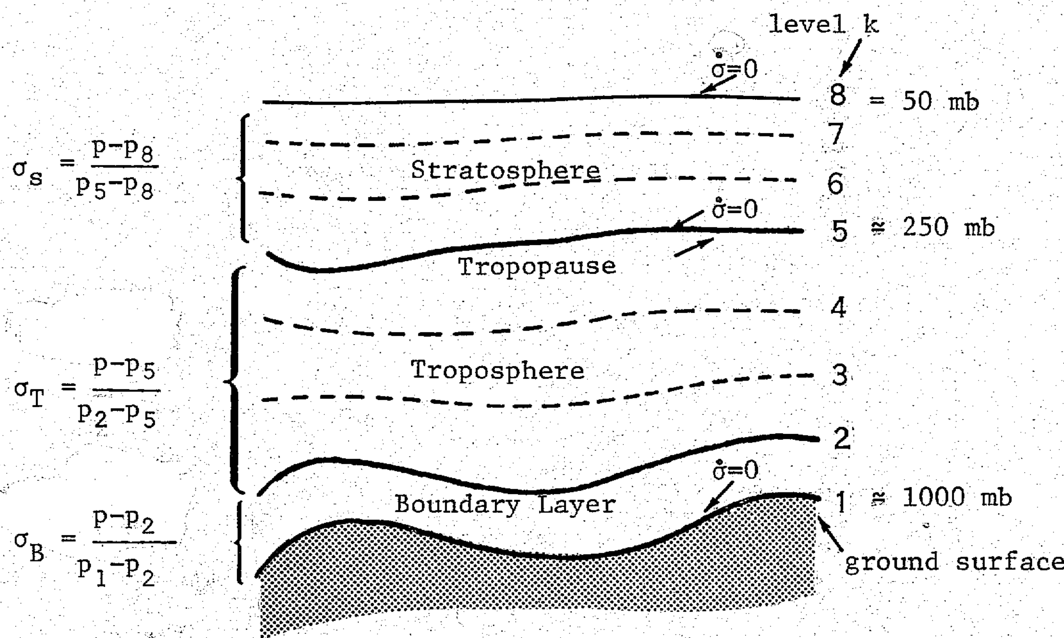

Fig. 1. 7-Layer Model, Vertical Structure.

identically zero at the ground ($\sigma_B = 1$), at the tropopause ($\sigma_T = 0$), and at the top ($\sigma_S = 0$). The top of the model is now a 50-mb surface constant in both space and time. The figure also indicates the definition of the σ-coordinate for the three σ-domains of the model: the boundary layer, in which $p_1 - p_2 = 50$ mb for all time and space; the three-layer troposphere, and three-layer stratosphere. As before, the forecast variables are: u, v, and θ in each of the layers; p_σ, the domain pressure thickness in the troposphere and stratosphere (the boundary layer p_σ, 50 mb is unchanging), and moisture variables. The model no longer forecasts a single integrated moisture parameter, but carries moisture information in each of its three lowest layers--this is detailed below.

The second substantial alteration relates to the horizontal domain of integration. The original model ran on a 53 x 57 point cartesian grid centered on the North Pole. The grid spacing was 381 km (½ inch) at 60°N on a 1:30 million polar stereographic projection true at 60°N (one "bedient," to give the long definition of the grid spacing a unit name). Two changes were made over the years: The first expanded the grid to 65 x 65 points and brought the entire hemisphere within the domain of integration--the pole is at point (33,33) and the equatorial circle is inscribed by the square grid; the second and far more significant change reduced the grid spacing to one-half a bedient, 190.5 km at 60°N, etc. The model now runs on a 129 x 129 point grid, with the pole at (65,65); this doubling of the resolution (with a consequent reduction of truncation error) has brought many benefits, but at some cost.

The benefits, which were observed in a series of comparative tests, were in general overall improvements in the forecasts: The phase errors of troughs and ridges were reduced, the location and central pressures of highs and lows became closer to the verifying positions and values, some very nonmeteorological wind pattern forecasts were completely corrected, and high-level temperature biases were all but eliminated (this was more a function of the additional stratospheric layer than the increased resolution); all of these improvements in subjectively observable phenomena were reflected in improvements in various objective verification statistics and scores. A somewhat disappointing result was that the precipitation forecasts showed no particular improvement with the increased resolution--perhaps models of still finer resolution are needed to capture the rain correctly.

The cost for the increased resolution was, of course, an increased running time on the computer; had the increase been by a full factor of eight (four times as many points times twice as many time steps, the latter to maintain linear stability), it would have been prohibitive in an operational framework. The necessity to cut the time step in half, however, was obviated by a time averaging device applied to the pressure gradient force terms of the equations, (Brown and Campana, 1977). Thus, the 10-minute time step could be retained even though the grid spacing was reduced. The six-layer one-bedient mesh model required some 8 minutes of computer time for a 24-hour forecast, the seven-layer half-bedient mesh model uses 28 minutes for the same length forecast. The elimination of the cap from the six-layer model removed some special calculations and saved some computer time, hence a run time increase factor of 3.5 rather than 4.

III. Physical Parameterizations

A number of alterations and augmentations to parameterizations of nonhydrodynamic physical processes have been made. Mainly, these have been in the sections on radiative and other heating terms, and precipitation modeling.

A. Radiation

The Shuman and Hovermale paper describes some of the radiation parameterization, in particular the cooling of the lowest layer under conditions of clear skies, nighttime, and snow-covered ground. The cooling rate is now 3.84^{o}C/day under those conditions. In addition, an extremely simplified estimate of long-wave cooling of the atmosphere, a constant cooling rate of 1.44^{o}C/day, is applied to the temperature forecasts in all layers above the highest of any layer containing "clouds." "Clouds," in turn, are defined as existing in any of the three lowest moisture-bearing layers with a relative humidity greater than 60% of the model's saturation criterion. See the precipitation section below for a discussion of what "saturation criterion" means.

In conjunction with the simplified long-wave cooling, a somewhat more realistic calculation of solar heating of the atmosphere was incorporated into the model. The heating is calculated from absorption of the solar beam by water vapor only, plus a rough approximation of the effect of the sun heating the earth's surface, in turn heating the boundary layer of the model. This can best be described in terms of the disposition of the photons in a beam of sunlight. The solar zenith angle is calculated hourly for each grid point and the sun is given an assumed solar constant of 1.86 ly/cm^2 (2.0 ly/cm^2 less 7% to account for Raleigh scattering from the beam before it reaches the lower troposphere). Given the moisture content of each of the three lowest layers and the cosine of the zenith angle, the optical path length for each layer can easily be computed. Then, using a linear approximation to the curves given in Manabe and Wetherald (1967), the amount of energy absorbed from the beam, as it passes through a layer of known path length, can be found. The quantity of energy absorbed is converted to an increase of temperature for the layer and that increase is a contribution to the full temperature tendency equation. No account is taken of possible cloudiness in layers even though the presence of a cloudy layer would make <u>beam</u> absorption calculations slightly in error.

When the sunbeam reaches the ground, account is taken of the clouds (if any) in computing the boundary layer warming effects. First, the total amount of energy absorbed by water vapor is subtracted from the original beam. Then the beam is further depleted by a factor (1 - cloud albedo) where the cloud albedo term (value between 0 and 1) is the largest albedo of any clouds encountered in the three moist layers. The current assumptions are: If clouds exist (60% humidity or greater) in the boundary layer, the albedo is 1; if in the lowest tropospheric layer the albedo there is 0.75; if in the mid-tropospheric layer, 0.5. After depletion by absorption and possibly by reflection, the beam reaches the ground and is further reflected according to the albedo assumed for the surface. Any remaining energy is passed directly to the boundary layer as an additional heating term. The ground albedo has a value of 1 over snow or open water, i.e., total reflection or total absorption and, therefore, there is no solar energy to heat the boundary layer. Over land, the albedo is 0.9, stating that 10% of the variously depleted solar beam goes to heat the air. An albedo of 0.9 is, of course, highly nonmeteorological; it can best be thought of as an "effective heating albedo," parameterizing numerous surface effects which have a net effect of heating the air.

The heating of the boundary layer over warm ocean water remains the same as in the original description, except that monthly climatological sea temperatures are used in lieu of analyzed temperatures.

B. Moisture and Precipitation Forecasts

As has been alluded to above, the forecast of moisture has been changed from a forecast of total precipitable water advected by a vertically integrated wind to a layer-by-layer forecast of precipitable water.

The forecast equation for the W value of each layer is

$$\frac{\partial}{\partial t} W + \nabla \cdot W\vec{V} + \left(\frac{q\, p_\sigma}{g}\,\dot{\sigma}\right)_k - \left(\frac{q\, p_\sigma}{g}\,\dot{\sigma}\right)_{k-1} = 0$$

The evaluation of the vertical advection terms at σ-levels k and k-1 is accomplished by

1) defining a layer mean value of

$$q/g = \frac{W}{p_\sigma \Delta\sigma} \quad ,$$

where W is the layer's value of the precipitable water, q is specific humidity, and $\Delta\sigma$ is the value of the sigma coordinate difference across the layer; then

2) assuming a linear, with p, variation of q between two adjacent layers to give an appropriate value at the σ-surface between those layers.

Once a forecast for W has been obtained, it is compared with the saturation value of precipitable water, W_s, and then any excess (supersaturation) is allowed to fall out as rain, with an appropriate latent heat contribution to the temperature change in the supersaturated layer. Full 100% saturation is not required--the W_s, actually used for the comparison, has been reduced to 90% of its original value, in effect asserting that an entire layer need not be saturated for rain to fall from that layer. A value of W that exceeds 90% of W_s, the saturation criterion, then forms rain; otherwise, nothing happens. When rain is forecast in the amount of $W-0.9W_s$, the value of W for that layer is set back to $0.9W_s$: The supersaturation doesn't persist unless it is again forecast in the next time step.

The rain does not fall undisturbed. If the rain falls into a layer with a forecast W less than the saturation criterion, enough water (if there is enough) to bring W up to $0.9W_s$ is evaporated. This will consume latent heat (cooling the layer) and the remaining rain, if any, proceeds to the next layer where the process may repeat. The rain reaching the bottom of the boundary layer constitutes the end produce of this portion of the forecast model, but it is not the only source of precipitation in the forecast.

The 7-layer model parameterizes convective (i.e., small scale) precipitation in addition to the sort of rain that the saturation calculation will detect. The scheme is to search the grid points for conditional instability such that if a parcel were lifted from a layer along its dry and moist adiabats to the layer above, it would then be warmer than the layer above. If such a condition is found, an additional amount of rain (proportional to the temperature excess of the lifted parcel) would be added to the precipitation forecast for that particular grid point. This convective rain, because it is computed from a highly parameterized system, does not add latent heat to the model. There is only a slight adjustment to the pair of layers involved--a warming of the upper and cooling of the lower--such that the instability is neutralized.

The only source of moisture from the model is over open water--the relative humidity in the lowest layer is not allowed to become less than 30% of the saturation criteria at any time. If such is forecast, the value of W is simply increased accordingly.