THE BASICS of WEATHER MODELS

by

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AWS/XTX

This forecaster memo (FM) summarizes the history and fundamentals of modern numerical weather prediction models for operational weather forecasters. The information is intended to help forecasters understand the models' strengths and weaknesses. It is published with the expectation that an increased understanding of the details of these complex mathematical models will help forecasters make better use of NWP model forecasts. The FM complements information in Chapter 7 of AFP 105-56, Meteorological Techniques. The author would like to thank Lt Col James Davenport, Chief of the Product Improvement Division, HQ Air Weather Service, for suggesting the topic. He would also like to thank Lt Col Edwin Jenkins, Deputy Director of Technology, HQ Air Weather Service, for his assistance in publishing the memo. Thanks also to Mrs Mary Fulton for typing the manuscript.


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INTRODUCTION
Without using mathematics, this memo summarizes the important information weather forecasters need to know to apply numerical weather prediction (NWP) forecasts. We've had to make some tough choices regarding what material to include. We've put the more technically rigorous information in an appendix; readers can review this material as they have time. We've organized the material under three main topics:

- **History of NWP.**
- **Components of an NWP model.**
- **Strengths and weaknesses of NWP models**—what these models can and cannot do.

HISTORY OF NWP
Meteorology has been described as the second most complex science; medicine being the first. Nevertheless, a set of mathematical equations that completely describes the behavior of the atmosphere has been known since early in the nineteenth century. During World War I a British meteorologist-mathematician-statistician by the name of L. F. Richardson attempted to use these equations to predict the future state of the atmosphere based on observations of the atmosphere's initial state. Of course he performed his calculations without the aid of an electronic computer. Although he failed in his effort (his calculations predicted that weather systems would travel in the wrong direction at the speed of sound), his book, *Weather Prediction by Numerical Process*, published in 1922, has provided a valuable introduction to the complexities of NWP for many years. An overview of the physical and mathematical basis of NWP is given in the Appendix to this memo.

The development of electronic computers in the late '40s prompted a revival of interest in NWP and led to the initiation of operational NWP in 1955. It is not surprising that weather forecasters were at first hesitant to put a lot of faith into NWP models, the first of which were very primitive (in the negative sense of the word):

Early models did not use the full set of unmodified equations (or so-called "primitive" equations in the meteorological sense of the word) to predict the behavior of the atmosphere. They prepared forecasts for only one level of the atmosphere (near 500 millibars). As a result, they were not able to predict changes in the intensity (development or decay) of weather systems.

NWP models and electronic computers have changed dramatically since 1955. Experienced weather forecasters have come to appreciate the usefulness of NWP models and now accept them as a most valuable tool in preparing operational forecasts. Some of the improved acceptance of NWP models can perhaps be explained by a growing understanding among weather forecasters that all professional weather forecasts are based on some kind of model. Even totally subjective weather forecasts are based (consciously or unconsciously) on conceptual models of the atmosphere that
enable forecasters to relate operationally-important weather elements and events (e.g., temperature and heavy precipitation) to patterns of (1) highs, lows, and fronts on weather maps, (2) cloud features on a meteorological satellite picture, (3) reflectivity and velocity on a computer display of a Doppler radar; or to all three. Unfortunately, these models (or rules of thumb) are seldom documented. A branch of the science called "Artificial Intelligence" referred to as "Knowledge-Based, Expert Systems" has attempted to preserve the special knowledge contained in these conceptual models in automated computer models, with some success.

COMPONENTS OF AN NWP MODEL
The most important components of an NWP model are familiar to most weather forecasters. They include the following:

Analysis Model. An analysis model translates irregularly-spaced and sometimes sparse weather observations into a data format that is acceptable to the NWP model. Before spectral NWP models were invented, analysis models simply interpolated weather data onto the more or less regular grid points of models. Spectral NWP models use a series of mathematical sine and cosine functions to represent the atmospheric waves that are sampled by the weather observations. The spectral analysis model translates the amplitudes (i.e., strengths) of the various atmosphere waves into a series of amplitudes of the sine and cosine waves. The NWP model predicts the future amplitudes on these sine and cosine waves and then uses other mathematical functions to translate these amplitudes back into weather waves to forecast the future state of the atmosphere.

Initialization Model. The function of this aspect of an NWP model is to translate the analyzed weather data into a physical state that will be accepted by the NWP forecast model. The various atmospheric states represented by good NWP models, like the atmosphere itself, are in a delicate state of balance. Consequently, the initial state of the various atmospheric fields (e.g., temperatures and winds) presented to an NWP model must also be in this delicately balanced state. Indeed, NWP models are so particular about the kind of initial data they will accept that operational NWP models often take several hours of model forecast time to settle down before they begin producing useful weather forecasts. NWP models spend this time translating so-called "noisy" initial data into a balanced state that the model can live with. This period of time is referred to as "model spin up time." It is clear that if you want to use the first few hours of forecasts provided by an NWP model, you'll need to know the model spin up time. The question of what does and does not constitute atmospheric "noise" is a critical issue in operational NWP. We will return to this important question later in the discussion of the strengths and weaknesses of NWP models.

Numerical Components of the Model. The numerical components of an NWP model translate the hydrodynamic equations described in the appendix into a computer code that can be run on a modern electronic computer. Because good NWP models are nearly as complex as the atmosphere itself, the numerical components of NWP models must deal with a bewildering variety of technical issues. Many issues are so complex that the numerical components of NWP models
are usually developed by teams of meteorological and mathematical specialists. Several numerical components of NWP models have great operational significance. These include:

The Vertical and Horizontal Resolution of the Model. NWP models cannot resolve or forecast weather events that have smaller spatial scales than the effective resolution of the horizontal grid (or the "spectral" technique) used by the model. The maximum achievable resolution of NWP models that use grid-points is twice the horizontal distance between model grid points. However, the effective resolution of these models is usually much less than this maximum value. The actual value depends upon several numerical aspects of the model. A good rule of thumb is that operational NWP models can resolve weather events with spatial scales equal to about four times the horizontal resolution of the models (i.e., four times the distance between horizontal grid points for a grid-point NWP model). The table below gives some idea of the spatial scale of some operationally important weather events. For a thunderstorm (20 km), model resolution would have to be 5 km (or 3 miles between grid points) to resolve this size phenomena.

Scale Definitions of Some Important Atmospheric Events

<table>
<thead>
<tr>
<th>Space Scale (km)</th>
<th>Atmospheric Events</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>&gt; 10,000 km</td>
<td>Planetary atmospheric waves</td>
<td>Planetary waves are often apparent on 300-mb polar projection charts</td>
</tr>
<tr>
<td>2,000 to 10,000 km</td>
<td>Upper-atmosphere (UA) cyclone waves</td>
<td>These &quot;short waves&quot; travel through the troughs and ridges of planetary waves</td>
</tr>
<tr>
<td>200 to 2,000 km</td>
<td>Fronts and tropical cyclones</td>
<td>Position and intensity of fronts can often be subjectively inferred from patterns of UA cyclone waves</td>
</tr>
<tr>
<td></td>
<td>Mesoscale convective waves</td>
<td>Often apparent on weather satellite and weather radar imagery</td>
</tr>
<tr>
<td>20 to 200 km</td>
<td>Squall lines, low-level jets, and ocean-land circulations; downslope mountain windstorms, hazardous turbulence, small-scale atmosphere waves (including gravity waves)</td>
<td>Episodes of strong CAT often accompany strong UA fronts</td>
</tr>
</tbody>
</table>
Model Boundary Conditions. Limited-area (or window) models require information about the weather conditions at their lateral boundaries (as well as at their upper and lower boundaries) throughout the time period forecast by the model. Global models, of course, need only upper and lower boundary conditions. Often, the boundary conditions for a window model are prepared by another NWP model. Errors associated with these boundary conditions will propagate into the interior of the model window at the speed of the fastest moving phenomena predicted by the model. This can be a big problem if the model predicts sound waves as well as weather phenomena. Fortunately, sound waves can be fairly easily excluded from NWP model predictions.

Spatial Dimensions of the Model. Operational NWP models are usually three-dimensional. Operationally useful one- and two-dimensional models are also available, but they are more difficult to use. For example, the user of a two-dimensional NWP model must figure out what is going on in the missing third dimension.

Physical Components of the Model. The physical components of an NWP model include all those components of the model that are not addressed by the numerical components of the model. The physical components enable the model to take some account of (parameterize) important physical processes that cannot be explicitly resolved by the model. These often include boundary layer processes such as evaporation cooling of the air from rain-soaked ground or radiation cooling of the ground at night under clear skies. The parameterization of physical processes in NWP models is a tricky business, but the following example may clarify the process. It is possible to make a good estimate of the radiation cooling of the earth's surface by multiplying an estimate of the surface temperature, raised to the fourth power, by a constant number called the Stefan Boltzmann constant. If this rule is included in the code of an NWP model, the model can be said to have parameterized surface radiation cooling. Of course the goodness of this parameterization depends on the accuracy of the surface temperature forecast as well as on the goodness of the parameterization rule itself.

STRENGTHS AND WEAKNESSES OF NWP MODELS, or what NWP models can and cannot do.

As parents of teen age sons and/or daughters know, one person's music is important another person's noise. This is clearly the case in NWP. Virtually all operational NWP models (and many research NWP models) treat atmospheric gravity waves, which appear virtually everywhere in the atmosphere, caused by a combination of gravity and buoyancy forces. Buoyancy forces, of course, are responsible for cumulus clouds.
waves seems to justify treating these waves as noise: synoptic-scale gravity waves simply serve to enhance the frictional drag on the atmosphere. However, there is mounting evidence that smaller-scale gravity waves play a crucial role in many operationally important weather events, including the initiation of severe convective storms. This multiple personality of atmospheric gravity waves can be understood by referring to the table below. As shown, synoptic-scale atmospheric gravity waves travel at nearly the speed of sound. At these speeds, they do not have a chance to interact with the slower-moving, synoptic-scale atmospheric waves. However, small-scale gravity waves travel at speeds that are comparable to the speeds of smaller scale atmospheric waves and sensible weather phenomena (e.g., fronts). The slower speeds give these gravity waves a chance to significantly influence and modify important but smaller-scale weather phenomena.

Atmospheric Phenomena and Atmospheric Gravity Wave Speeds

<table>
<thead>
<tr>
<th>Weather Phenomena</th>
<th>Phenomena Speeds</th>
<th>Gravity Wave Speeds</th>
</tr>
</thead>
<tbody>
<tr>
<td>Planetary Waves</td>
<td>10 m/sec</td>
<td>300 m/sec</td>
</tr>
<tr>
<td>Tropospheric Cyclones</td>
<td>10 m/sec</td>
<td>150 m/sec</td>
</tr>
<tr>
<td>Fronts</td>
<td>20 m/sec</td>
<td>35 m/sec</td>
</tr>
</tbody>
</table>

Atmospheric gravity waves put the designers of high-resolution NWP models in a really difficult position.

- They can choose to eliminate gravity waves during the model initialization (by employing an appropriate model initialization scheme). However, they run the risk of degrading model forecasts of atmospheric weather events associated with gravity waves (at least during the first several hours of the model predictions--later on during the model run the model may generate its own gravity waves).

- They can choose to retain the gravity waves in the model. However, they run the risk of having the model "blow up" because its initial state is too noisy--unfortunately, models have a difficult time distinguishing between the effects of real atmospheric gravity waves from real noise (errors) in NWP analyses due to imperfect analysis schemes and imperfect and sparse weather observations.

- They can choose to employ an initialization scheme that can accommodate the gravity waves and get rid of the real noise in the data. Clearly this is the most desirable choice. Unfortunately, available schemes substantially increase the running time of NWP models.
Appendix

THE PHYSICAL AND MATHEMATICAL FOUNDATIONS FOR NWP

NWP models embody only three physical principles: the conservation of momentum (wind), of mass (air density), and of energy (temperature). These principles can be expressed mathematically in:

- Three equations of air motion, which relate accelerations of the wind in the east, north, and upward directions to forces in those directions. These forces are due to pressure differences between nearby locations in the atmosphere, the rotation of the earth (the coriolis force), and friction.

- An equation of continuity which relates imports (or exports) of air into a volume to the balancing increases (or decreases) of air density in the volume.

- A thermal (air temperature) energy equation, which relates the heat energy added to a parcel of air to:

  -- Increases in the internal energy (temperature) of the air parcel.

  -- Work done by the air parcel expanding against the pressure forces of the air surrounding it.

- An equation of state, which relates the pressure, density, and temperature of the air parcel.

The above set of hydrodynamic equations comprise a complete system of six equations in six unknowns. Meteorologically, these equations provide the basis for NWP. Mathematically, they make up what is called an initial value problem—if one had complete knowledge of the initial state (the initial condition) of the atmosphere at a particular time (which of course is not possible), and if one could find a unique (i.e., single) solution to the hydrodynamic equations for this initial state, this solution would describe the future behavior of the atmosphere for all time—clever, yes? In practice, the equations represent a set of non-linear, partial differential equations for which only approximate, numerical solutions are known. This fact, of course, provides the basis for Numerical Weather Prediction. The NWP problem consists in solving (integrating) this system of equations based on some known initial conditions.
The hydrodynamic equations have been very successful in describing the behavior of many important phenomena—examples include air flow around a wing, the propagation of sound waves in the air, the propagation of ocean waves on the sea surface, and the development of a land-sea breeze on a calm summer afternoon when there is no threat of a frontal passage. These successes have prompted meteorologists and mathematicians to use these equations to predict the general behavior of the atmosphere.

The non-linearity of the hydrodynamic equations has a most important effect on the application of these equations in NWP. Non-linear phenomena are of such great significance that the systematic study of these phenomena has led to the development of an entirely new science called, "Non-linear, Dynamically Systems", or "Chaotic Systems", or simply, "Chaos". It is noteworthy, that the first demonstration of the unique, chaotic behavior of a non-linear, dynamical system (a cumulus cloud) was performed by Edward Lorenz, a meteorologist at MIT. An appreciation of the significance of the non-linear characteristics of atmospheric motions is fundamental to understanding and forecasting the behavior of the atmosphere.

Non-linear equations are easy enough to recognize:

\[ y = 2x + 3 \] is an example of a linear equation.

\[ y = 2x + x^2 + 3 \] is an example of a non-linear equation.

Real-world non-linear events are commonplace. Mortgage interest rates and new housing starts are an example. Lower interest rates prompt increased housing starts which in turn prompt higher interest rates. OK, but what are non-linear atmospheric motions (winds)? We can use our hydrodynamic equations to provide a quick answer to the question. If we let \( V \) represent the motion of the air in our equations (i.e., the velocity, or speed and direction, of the wind) then any term in the equations that contains \( V \) to a power higher than one (e.g., \( V^2 \)) is a term that represents non-linear air motions. Surprisingly, only one term in the hydrodynamic equations is non-linear; this term describes the advection (or transport) of the air by the air itself. Several meteorologists have tried to describe this phenomena in words. The following colorful description has been attributed to L. F. Richardson,

Big Whirls have little Whirls that feed on their Velocity. Little Whirls have smaller Whirls. And so on to Viscosity.
A more precise description was offered by Edward Lorenz of MIT:

*Because the motion of the atmosphere is not uniform, different portions of the advected motion field undergo different displacements and the field (of motion) becomes distorted.*

Both descriptions describe how the air motion influences itself. This feedback of an effect onto its cause is the essence of non-linearity and is the principal cause of the incredible complexity of the atmosphere.

We can appreciate the importance of the non-linearity of atmospheric motions to weather forecasting by looking at two of its practical consequences.

- The most profound effect of non-linearity has to do with the global behavior of the atmosphere. The words attributed to L. F. Richardson above are often used to describe one theory of this behavior of the atmosphere. According to this theory:

  -- The abundance of solar radiation near the equator causes air to rise there in large convective cells and to ascend into the upper troposphere.

  -- Air travels away from the equator in the upper troposphere toward the poles (it has no other place to go).

  -- Air cools in its trajectory to the poles, sinks back into the lower troposphere, and eventually returns south to the equator to complete a global circulation of the atmosphere.

  -- This global circulation (a Big Whirl) then breaks down into Smaller Whirls according to the non-linear process described by Richardson: "Big Whirls (the general circulation) have little Whirls (mid-latitude cyclones) that feed on their Velocity. Little Whirls have smaller Whirls (turbulence), And so on to Viscosity (friction)."

This concept is important because it offers a practical (albeit imperfect) basis for translating NWP forecasts into weather forecasts. This concept is based on assumptions that:

-- Operational NWP models provide good forecasts of the behavior of the big whirls (e.g., 500 mb, synoptic scale wind and temperature patterns).
--Because *little whirls* (mid-latitude cyclones) mainly *feed on the velocity of big whirls* (i.e., are mainly due to the *cascade* of energy, down-scale, from the *big whirls* to *smaller whirls*):

--The behavior of the little whirls and their associated weather cyclones and fronts can be inferred from NWP forecasts of the big whirls using conceptual models developed in Norway and the United States during WWII and the early fifties.

--Forecasts of the weather associated with the cyclones and fronts can be inferred from the same class of conceptual models.

- The second consequence of the non-linearity of atmospheric motions helps explain the fundamental limitations of NWP models in general and the limitations of the latter approach to using operational NWP models to prepare weather forecasts. This effect of the non-linearity of our equations is rooted in the fact that any application of these equations (e.g., to predict the weather) constitutes an *initial value problem*. When the equations are used to predict the weather, they (the equations) assume that the initial values they are given represent the *real initial conditions* of the atmosphere at a particular instant in time. Since weather observations represent an average value over some time period, we must modify our equations to take this fact into account. We can understand how this is done by referring to the following diagram.

As the diagram shows, we may replace the instantaneous Temperature ($T$) at a particular instant by the *sum* of the average $T$ over a time period that includes that instant, and the *difference between the average $T$ and the instantaneous $T$ at that instant* (often called $T$ Prime).

We can use this rule to replace all the occurrences of our original *instantaneous* unknowns with the new unknowns that include the desired *average values* of our unknowns. Our new NWP equations are now ready to accept real data derived from real weather observations.
So what do our new averaged NWP equations look like? At first glance, they look exactly like our original equations--except that the instantaneous unknowns have been replaced with the new average value unknowns. However, upon closer inspection, we find that the equations now contain new terms that contain the products of the primed unknowns introduced above. If we took the trouble to track down where these new terms came from, we would discover (as you might guess) that they are produced by the non-linear terms in our equations. If we would investigate the physical significance of these new terms, we would find that they represent the effects of the non-linear interactions of atmospheric motions. Meteorologists have come to call this phenomena "atmospheric turbulence."

This is the same turbulence that causes evaporation of water in a lake (e.g., dense variety turbulence) and the turbulence that threatens the safety of aircraft (e.g., severe or extreme clear air turbulence). These turbulence processes are also responsible for many operationally significant weather events that are not predicted by operational NWP models. An example is radiation fog (fog caused by radiation cooling of the ground at night). Most of the physical processes responsible for radiation fog can be modeled by the turbulence expressions described above. These processes include the cooling and drying (or moistening) of air near the surface by the turbulent mixing of the air in the boundary layer. It is relatively easy to build a simple forecast model for atmospheric radiation fog by combining a model of radiation cooling of the surface with a model of the above turbulence mixing processes (we have developed a prototype of such a model at HQ AWS/XTX). But if this is the case, why are such models not available to operational weather forecasters? These models are more difficult to use than all-purpose, three-dimensional operational NWP models because they put the weather forecaster in the position of having to decide when it is and when it is not appropriate to use them. Therefore, forecasters must have a really good understanding of the technical capabilities and limitations of this or any model--a tough and time-consuming effort.