Horizontal Resolution (Part 2)

(Adapted from COMET online NWP modules)

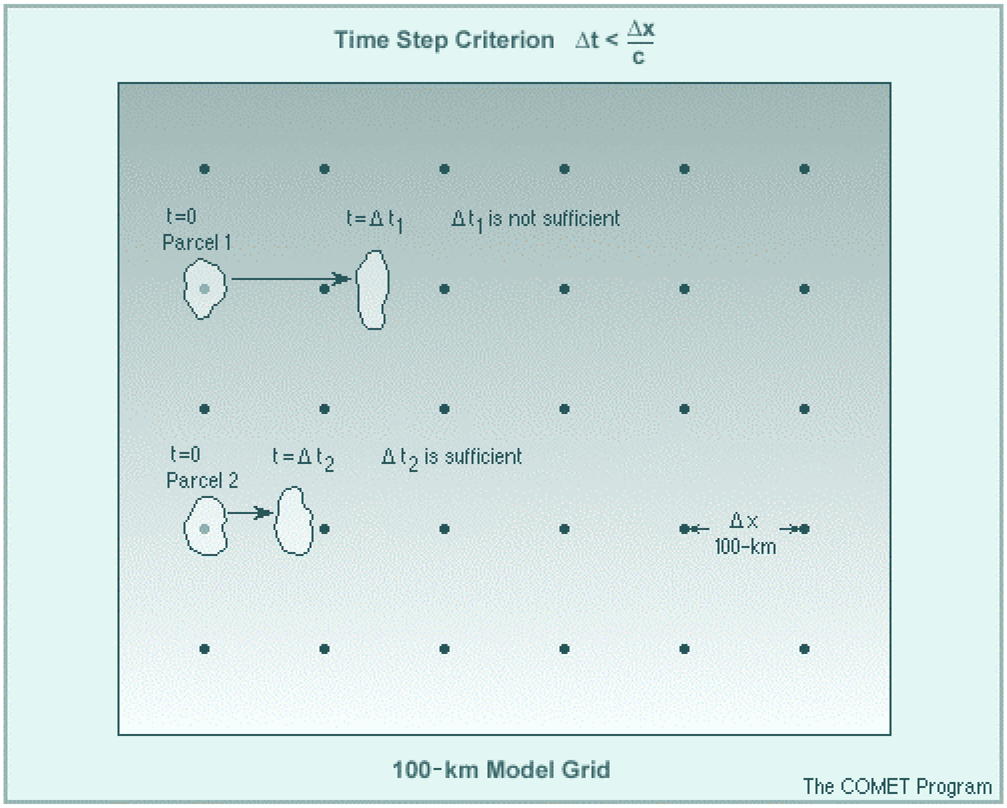
1. Computer Resources vs. Resolution

Since its inception, NWP has pushed the limits of available computing capacity. To complete one forecast, equations need to be solved for many variables and for thousands of grid points up to several thousands of times. For example, in 1999, a 48-hr forecast from the Eta Model (32-km resolution) solves the forecast equations for 3.65 million grid points (223 x 365 for 45 layers) at 1,920 different times (48 hours at a time step of 90 seconds) for each variable! The current Eta model employ a horizontal resolution of 12-km with 60 vertical layers!

Computing resources ultimately limit the resolution of NWP models. The additional computing resources required to run a model at ***half*** its current horizontal resolution increase ***by a factor of eight***, assuming no change to the vertical resolution or domain size.

The relationship governing the length of time between intermediate forecast steps is given in the time step equation at the top of the graphic. The equation states that the time step (Δt) between intermediate forecasts must be less than the time it takes the fastest moving wave in the model (denoted by c) to cross a distance of Δx. ***This constraint has a simple physical basis – one must look at a moving parcel often enough to keep track of its actual path*** (e.g., the CFL stability criteria). The time step equation computes the largest time step interval for a given model resolution. Increasing the resolution requires decreasing the time step interval.

In reality, NWP models generally use much shorter time steps than would be computed by this equation. This is due to instabilities in the numerical methods and the use of physical parameterization schemes that require short time step intervals to adequately simulate smaller-scale processes.



Let's look at an example of a hypothetical model with a Δx of 100 km. You might assume that a time step of an hour or so would be sufficient to forecast synoptic-scale motions. However, the model generates waves with propagating speeds in excess of 100 m/s relative to the winds, which themselves may reach 100 m/s in the jet core. **So we need to consider the wave speed of the fastest wave in the model, at least 200 m/s**. Using this value for c yields the following:

$$\Delta t < \frac{\Delta X}{c} \approx \frac{10^5 \text{ m}}{200 \text{ m/s}} = 500 \text{ sec}$$

c = wave speed

The time step should be less than 500 seconds or approximately eight minutes! That is, the model would have to make about seven interim forecast steps per hour to complete its forecast. If longer time steps were used, large errors could quickly develop in the forecast fields and large amounts of 'noise' would contaminate the model output.

If the resolution were increased to 50 km, there would be four times as many grid points on each horizontal level. The time step would be only **four minutes**, which means that twice as many interim forecast steps would be necessary to produce a forecast of the same length.

$$\text{Solution: } \Delta t < \frac{50000 \text{ m}}{200 \text{ m/s}} = 250 \text{ seconds}$$

Therefore, for every halving of a model's horizontal grid spacing, it takes **eight times** as long to compute a forecast of a given length (for example, [four times as many grid points] x [two times as many time steps]). This assumes that the vertical resolution and horizontal domain remain the same. Applying a commensurate doubling in vertical resolution as well would increase the required computing power by 16 times. To put this into perspective, if a regional model takes one hour to produce a 48-hr forecast and then has its resolution doubled in all directions, it will take 16 hours to produce the same 48-hr forecast!

Operational centers determine the highest model resolution that will allow a model run to be completed within a specific time interval based on both the time that the model guidance must be delivered to the field to meet operational forecast schedules and the speed of their computers. Typically, NWP centers have significantly increased model resolution only after purchasing more powerful computers. However, NWP centers are moving toward an approach of continually upgrading their computing resources (and thus increasing model resolution more frequently) to take better advantage of the almost yearly doubling of computing capabilities.

In addition to resolution, model physics (especially radiation, cloud, and precipitation processes) are computationally intensive, data assimilation even more so. However, a more realistic representation of physical processes and better data assimilation systems can yield significant forecast improvement, forcing modeling centers to compromise between using higher resolution, more advanced data assimilation systems, and better model physics.

2. Feature Resolution

A model's ability to resolve meteorological features on different scales depends upon a number of factors, notably the

- Grid spacing or number of waves (horizontal resolution)
- Available computer resources (which limit the smallest grid spacing or maximum wave number that can be used)
- Model terrain representation
- Amount of truncation error that will occur within a model's primitive equations

Models tend to have the greatest difficulty resolving features influenced or caused by characteristics of the earth's surface that are not adequately represented in the model, such as terrain and coastal interfaces, and with small-scale features, such as MCSs and outflow boundaries.

It typically takes at least five grid points to define a feature in a grid point model. The smallest scale phenomena that can be preserved, even within short-range forecasts, have wavelengths of five to seven grid point spacings. Phenomena that can be preserved in one- to two-day forecasts typically have wavelengths greater than eight to ten grid spaces. Note that even if a feature meets the resolvable size criteria, it may still be inadequately resolved based on its orientation and juxtaposition within the model grid.

Even if a feature is of sufficient size to encompass an area defined by eight or ten grid points, the model often cannot adequately resolve all of the physical and microphysical processes embedded in the feature. The model may initially resolve the feature, but lose it over the forecast period if the physical processes necessary to maintain or develop it cannot be defined.

Convective and other precipitation processes occur on scales much smaller than can be resolved by most operational models. These processes must be parameterized to simulate their **effects** on the larger-scale environment and their impact on longer-range forecasts. Parameterizations are particularly important when the model cannot resolve a feature but may correctly predict the larger-scale atmospheric conditions conducive to its development.

The MCS case is a good example since the model uses a convective parameterization scheme to simulate the effects of convective processes on the larger-scale environment. The scheme may be activated when the model forecasts atmospheric conditions favorable for convection.

Parameterizations are used in many ways in NWP. However, if a model cannot depict a feature or does not forecast conditions right for its development, the appropriate parameterization (convective scheme) will not be invoked.

As Gradient intensity is also limited by model resolution. Since the packing of the temperature gradient right behind a sharp cold front is effectively a small-scale feature, the model can only capture the large-scale pattern around the front. Likewise, a hurricane eyewall (where the strongest winds are forecast) and a critical part of the hurricane vertical circulation (which maintains the storm) cannot be resolved in most operational models, such as the Eta. In such cases, weather features are likely to be detected, although their intensity will probably be too weak, their location misplaced, and forecasts of their evolution inaccurate.

Additionally, feedbacks can occur in features that the model tries to simulate but cannot actually resolve. For instance, heating rates that are representative of convection but occur over a large grid box cause the model surface pressure to fall more than it would if the heating only occurred on the convective scale. This, in turn, causes more low-level convergence, which increases the convective heating rates, causing the pressure to fall further.

3. Summary: Grid Point and Spectral Models

The key points associated with horizontal resolution for both grid point and spectral models are summarized below.

Grid Point Models

- Horizontal resolution is defined as the distance between grid points
- The smallest features that can be forecast in a grid point model should have full wavelengths of five to seven grid points
- Computer resources limit how small a model's grid spacing can be, given the large increase in computing time required to run higher-resolution models
- Grid spacing affects a model's ability to represent terrain, which, in turn, affects how well the model can define terrain-induced or terrain-enhanced meteorological phenomena
- Grid spacing impacts the amount of truncation error (degree of error associated with the computation of model primitive equations), which introduces increasing amounts of error to the primitive equation calculations as they are carried out over time

Spectral Models

- Horizontal resolution is a function of wave number (number of waves used to represent the data)
- Higher numbers (more waves) indicate finer resolution
- The more waves used to represent the data, the more computing power required to carry out the calculations
- Terrain representation and associated weather are improved when the number of waves is increased
- Truncation is a function of the wave number and refers to the minimum wavelength used by the model to represent the data. Smaller wavelengths are truncated and are not used in the calculations

A model's ability to resolve features depends not only on its horizontal resolution, but also on its vertical resolution, number of vertical layers, and the physics package used to define a variety of surface and atmospheric processes. Additionally, limited-area models are strongly constrained by their boundary conditions.