# MODEL TYPE

# (Adapted from COMET online NWP modules)

## 1. Introduction

Grid point and spectral models are based on the same set of primitive equations. However, each type formulates and solves the equations differently. The differences in the basic mathematical formulations contribute to different characteristic errors in model guidance.

The differences in the basic mathematical formulations lead to different methods for representing data. Grid point models represent data at discrete, fixed grid points, whereas spectral models use continuous wave functions. Different types and amounts of errors are introduced into the analyses and forecasts due to these differences in data representation.

The characteristics of each model type along with the physical and dynamic approximations in the equations influence the type and scale of features that a model may be able to resolve.

Model type does not necessarily impact the size of a model's domain. Global models have, however, historically been spectral because the wave functions and spherical harmonics in the spectral formulation operate over a spherical domain, a good match for global models. Global models are increasingly becoming grid point as computer resources increase.

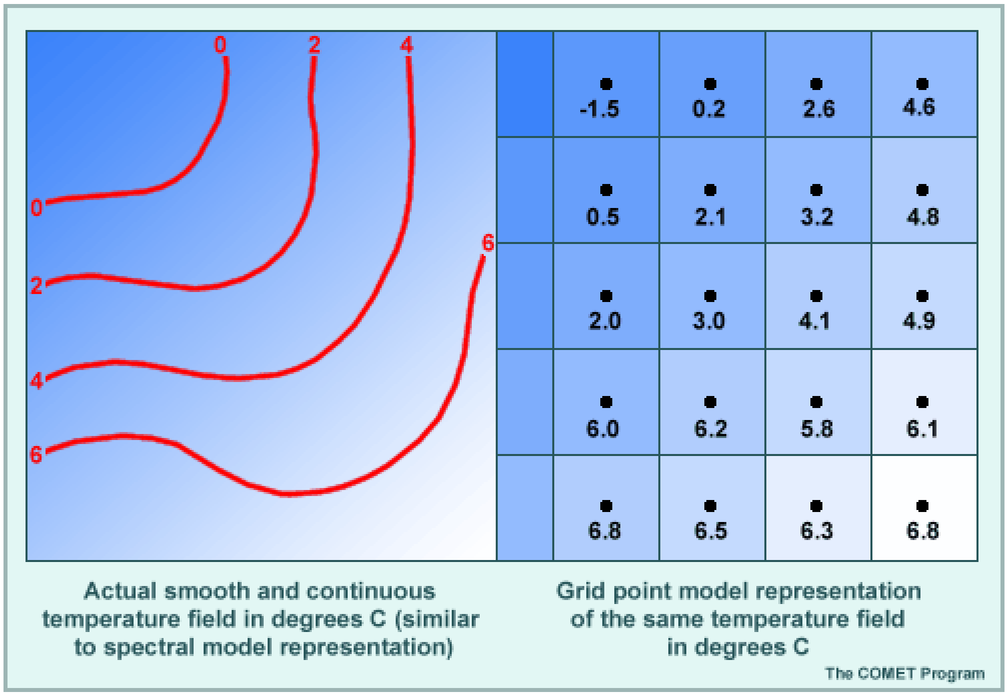
Model type has no direct impact on the choice of horizontal or vertical resolution. Theoretically, grid point and spectral models can be of any resolution, within the limitations of available computing power.

The remainder of this section explores the characteristics and errors associated with grid point and spectral models in more detail.

## 2. Grid Point Models

## 2.1 Data Representation

In the real atmosphere, temperature, pressure, wind, and moisture vary from location to location in a smooth, continuous way. In the graphic below, the continuous temperature field is depicted with the red contours, labeled in degrees Celsius. This is similar to how a spectral model would depict the field.




Grid point models, however, perform their calculations on a fixed array of spatially disconnected **grid points**. The values at the grid points actually represent an area average over a grid box. The continuous temperature field, therefore, must be represented at each grid point as shown by the black numbers in the right panel. The temperature value at the grid point represents the grid box volume average.

Grid point models actually represent the atmosphere in three-dimensional grid cubes, such as the one shown above. The temperature, pressure, and moisture (T, p, and q), shown in the center of the cube, represent the average conditions throughout the cube. Likewise, the east-west winds (u) and the north-south winds (v), located at the sides of the cube, represent the average of the wind components between the center of this cube and the adjacent cubes. Similarly, the vertical motion (w) is represented on the upper and lower faces of the cube. This arrangement of variables within and around the grid cube (called a staggered grid) has advantages when calculating derivatives. It is also physically intuitive; average thermodynamic properties inside the grid cube are represented at the center, while the winds on the faces are associated with fluxes into and out of the cube.

## 2.2 Grid Point Models

As discussed earlier, grid point models must use finite difference techniques to solve the forecast equations. In the simplified moisture forecast equation shown below, time changes in moisture at the center of a grid cube are caused by moisture advection across the cube. This, in turn, depends upon the changes in the moisture between the adjacent cubes and the average wind over the grid cube. The cube drawing graphically illustrates the conceptual moisture equation shown at the bottom.

In the real atmosphere, advection often occurs at very small scales. For example, sea breezes have strong advection but are usually confined to distances of only a few tens of kilometers from shore. In our example, the grid points are spaced about 80 km apart. This lack of resolution introduces errors into the solution of the finite difference equation. The greater the distance between grid points, the less likely the model will be able to detect small-scale variations in the temperature and moisture fields. Deficiencies in the ability of the finite difference approximations to calculate gradients and higher order derivatives exactly are called **truncation errors**.

The top finite difference equation can be converted into the form below it to explicitly show that we are solving for the future value of **q**. This value depends on its current value and the moisture difference between the grid points to the east and west. This is illustrated conceptually in the bottom equation.

While finite difference equations appear complex, they are relatively simple and fast for a computer to evaluate. The grid point model structure is then used so the equations can be solved in a straightforward way for every grid point to produce a weather forecast.

Note that this is the simplest possible finite difference approximation for the original equation. In practice, more complex expressions are used to increase the accuracy of the approximation. Typically, more grid points are also involved in the calculation of each term.

Additionally, note that forecasters often calculate diagnostic quantities from model output as part of the forecasting process. These calculations will not necessarily be the same as those performed by the forecast model itself, since some variables have been averaged during model postprocessing. For instance, a complicated quantity such as potential vorticity, which requires an average of the gradients of winds and temperatures over several grid points, will appear to be smoother in the forecaster's diagnostic than was in fact the case in the forecast model itself.

# 3. Spectral Model

## 3.1 Data representation

Spectral models represent the spatial variations of meteorological variables (such as geopotential heights) as a finite series of waves of differing wavelengths.

In the introduction, we considered the structure of a conceptual two-wave model. Let's now look at a real data set.

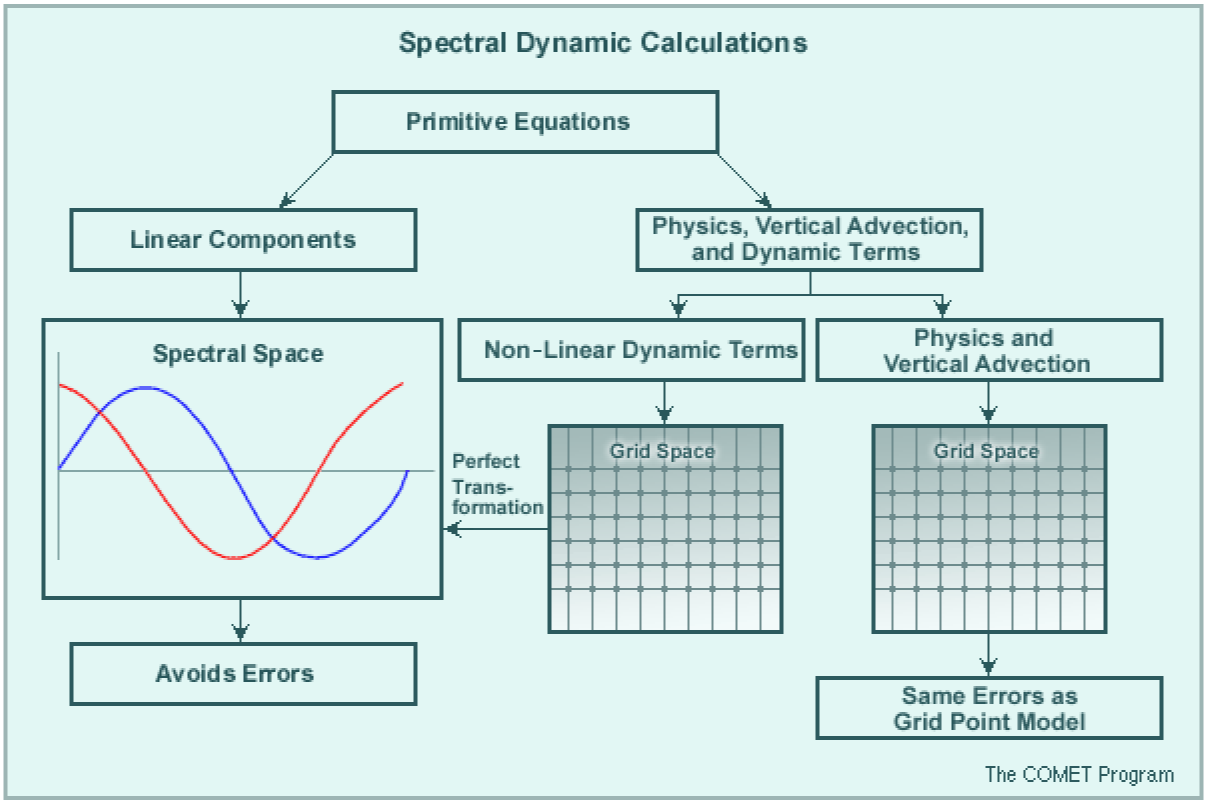
Consider the example of a hemispheric 500-hPa height field in the top portion of the graphic. If the height data are tabulated at 40°N latitude every 10 degrees of longitude (represented at each yellow dot on the chart), there are 36 points around the globe. It takes a minimum of five to seven points to reasonably represent a wave and, in this case, five or six waves can be defined with the data. The locations of the wave troughs are shown in the top part as solid red lines.

When the data are plotted in the graph, the five wave troughs are definable by the blue dots but are unequally spaced. This indicates the presence of more than one wavelength of small-scale variations. In this case, the shorter waves represent the synoptic-scale features, while the longer waves represent planetary features.

## 3.2 Use of Grid Point Methods in Spectral Models

Spectral models use a combination of computational techniques, both spectral and grid point. Parts of the forecast equations use information about the forecast variables and their derivatives obtained entirely from the wave representation. Examples of these linear components include the important pressure gradient and Coriolis forces. Horizontal gradients are precisely calculated from the wave representation, avoiding errors associated with finite differencing.

Other parts of the forecast equations must be calculated on grids, for example, precipitation and radiative processes, vertical advection, and parts of the wind advection terms. Grid point calculation of time tendencies for forecast variables resulting from physical processes introduces truncation errors. These errors are not removed when time tendencies are transformed back to wave representation and noise is introduced in the transformation process.



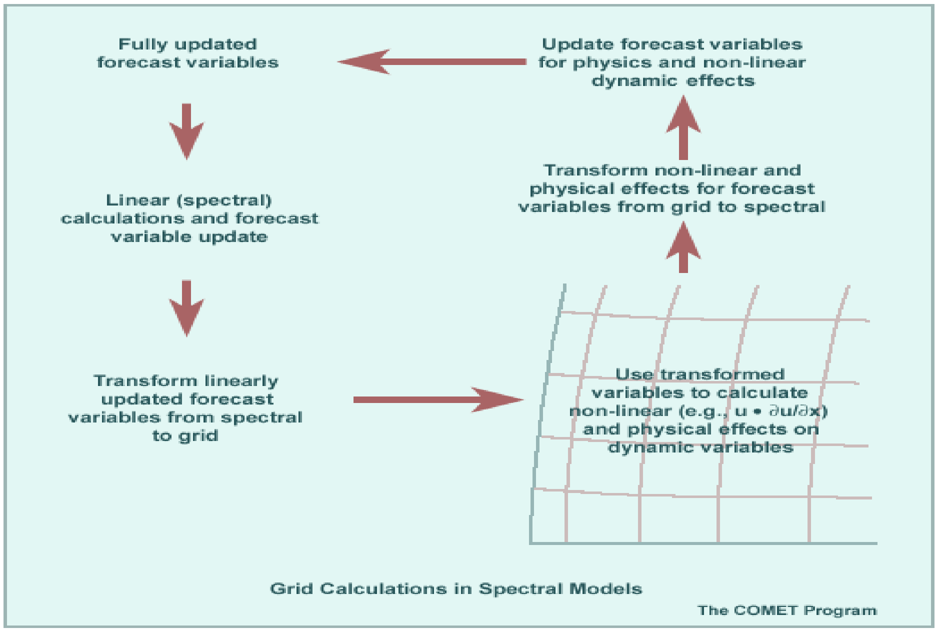

While vertical advections are calculated using finite differencing, which generates truncation errors, horizontal advections, including wind advection, are also calculated on grids. However, special mathematical properties avoid the introduction of error for these terms.

The more accurate computational techniques used in spectral models can be integrated over much longer periods than those used in grid point models without the generation of small-scale noise and provide smoother longer-range forecasts. This is one of the reasons why spectral models are most often used in global medium-range forecasting.

## 3.3 Impacts of Grid Point Physics Calculations in Spectral Models

For the grid point calculations, the values of the forecast variables must be transformed from spectral representation to grid points. The exact location and spacing of the grid points is determined by the model's "resolution" (maximum number of waves). The location and spacing of points is chosen to closely match the model's spectral resolution (maximum wave number) and most accurately calculate the non-linear dynamic terms. However, since model physics are also calculated on this grid, problems can result when the local effects of physics introduce errors during the transformation from grid point back to spectral representation.

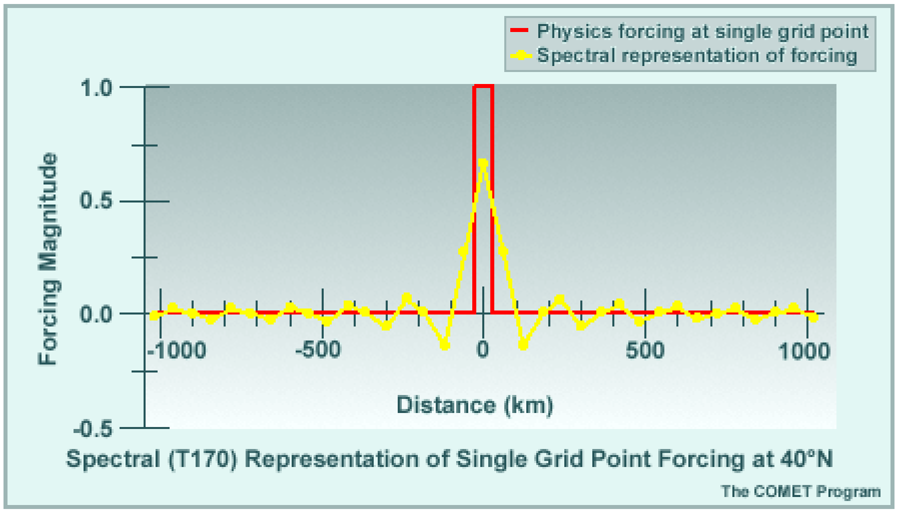
The graphic illustrates the process for calculations done on the grid in spectral models.




Specific impacts of physics grid calculations include the following:

- Grid calculations are subject to the limitations found in grid point models, for example, errors in the calculation of estimated gradients.
- Errors in the time tendency terms for the forecast variables are carried back into spectral space and thus are not removed.
- Since physical processes often do not result in wave-like time tendencies for the forecast variables, a distortion resulting from converting step-like features into waves occurs. A prime example is the time tendency of temperature from latent heat release due to precipitation processes. At the outer edges of a precipitation region, these fields tend to be more 'step-like' than 'wave-like.' When the 'step' in the latent heat release time tendency between grid points is transformed into a spectral representation, the distortion spreads through the model domain (though its amplitude becomes small away from the step location). Spectral models use filtering methods to minimize the effects of these distortions on the forecast variables. Additionally, postprocessing of data includes noise-reducing filtering of the physical fields.
- Patterns produced by physical processes occurring at several adjacent grid points can cause minor oscillations in the spectral representation of the shorter wavelengths. The total effect is on the order of up to a few percent but can extend for a long distance on either side of the source of physical forcing. Thus, intense latent heating causes the model dynamics to respond to small amounts of heating in places where the physics actually has none. Because the oscillations are only a few percent, the effect at any one time is minimal. However, because this occurs throughout the model at different places at all times, it results in spurious background noise at small scales superimposed on the reliable part of the forecast.

This effect can also be seen in the terrain elevation of the AVN model (see the Horizontal Resolution section).

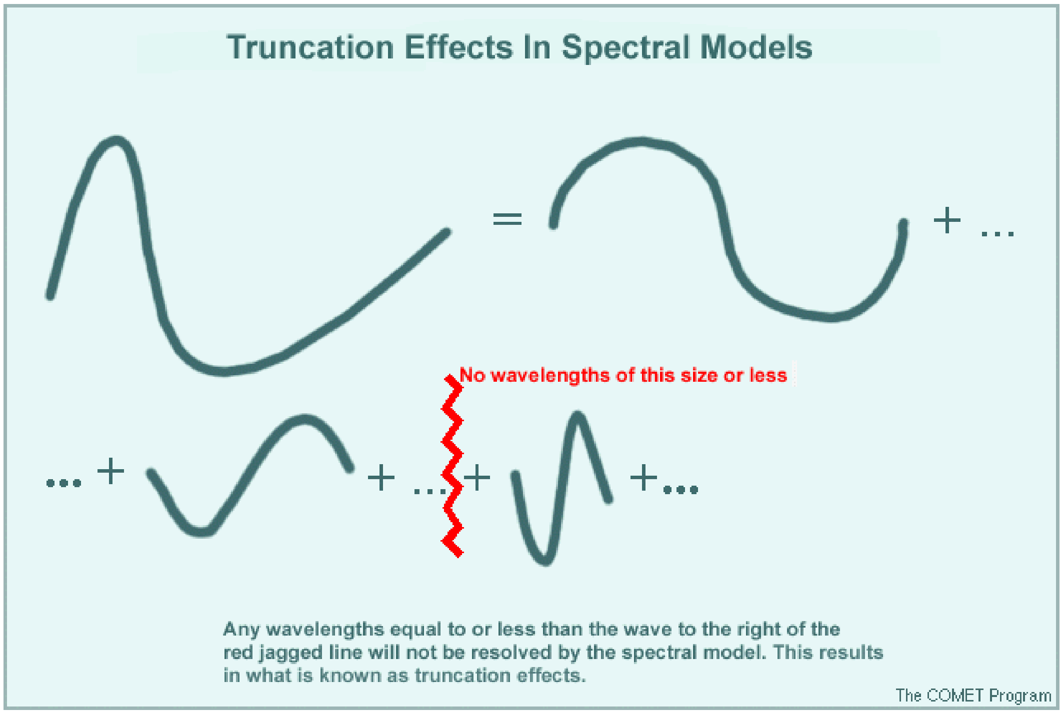



Now suppose that convective precipitation is triggered at a **single** physics grid point. The graphic illustrates how the effects are felt within the model. The red line represents the convective parameterization that causes a forcing of magnitude 1.0 at a single grid point on the physics grid in a spectral model. The yellow line is the spectral representation of this forcing plotted back onto the physics grid. Note that the associated warming retained in the spectral representation is reduced by around 33% at that location and its influence spread throughout a long distance in an unphysical oscillating pattern, as illustrated here. As the maximum number of waves in the spectral model is doubled, the oscillation fades faster so the distance scale would read about half of what is shown. This example is for a spectral model with a maximum wave number of 170 and a location along 40°N.

# 3.4 Spectral: Truncation Effects

What are the effects of truncation in a spectral model? Recall that in a grid point model, truncation error is associated with the finite difference approximations used to evaluate the derivatives of the model forecast equations. One of the nice features of the spectral formulation is that most horizontal derivatives are calculated directly from the waves and are therefore extremely accurate.

This does not mean that spectral models have no truncation effects at all. The degree of truncation for a given spectral model is associated with the scale of the smallest wave represented by the model. A grid point model tries to include all scales but does a poor job of handling waves only a few grid points across. A spectral model represents all of the waves that it resolves perfectly but includes no information on smaller-scale waves. If the number of waves in the model is small (for example, T80), only larger features can be represented and smaller-scale features observed in the atmosphere will be entirely eliminated from the forecast model. Therefore, spectral models with limited numbers of waves can quickly depart from reality in situations involving rapid growth of initially small-scale features.




Several types of wave orientation are possible in spectral models. Triangular (T, as in T170) configuration is the most common in operational models since it has roughly the same resolution in the zonal and meridional directions around the globe.

# 4. Hydrostatic vs. Non-Hydrostatic Models

## 4.1 Hydrostatic Models

Most grid point models and all spectral models in the current operational NWP suites are hydrostatic. That is, they use the hydrostatic primitive equations, which assume a balance between the weight of the atmosphere and the vertical pressure gradient force. This means that no vertical accelerations are calculated explicitly.

The hydrostatic assumption is valid for synoptic- and planetary-scale systems and for some mesoscale phenomena. A most notable exception is deep convection, where buoyancy becomes an important force.

Hydrostatic models account for the **effects** of convection using statistical parameterizations approximating the larger-scale changes in temperature and moisture caused by non-hydrostatic processes.

# 4.2 Non-Hydrostatic Models

Currently, most non-hydrostatic models use grid point formulations. They are generally applied to forecast problems requiring very high horizontal resolution (from tens of meters to a few kilometers) and cover relatively small domains.

Non-hydrostatic models can explicitly forecast the release of buoyancy in the atmosphere and its detailed effects on the development of deep convection. To accomplish this, non-hydrostatic models must include an additional forecast equation that accounts for vertical accelerations and vertical motions directly, rather than determining the vertical motion diagnostically, solely from horizontal divergence. The basic form of the equation is similar to that of the horizontal wind forecast equation. Conceptually, it states

change in vertical motion with respect to time = advection terms - nonhydrostatic vertical pressure gradient force in a grid box + buoyancy as it deviates from the large-scale average - precipitation drag

$$\frac{\partial w}{\partial t} = \text{advection terms} - \frac{1}{\rho_0}\frac{\partial p'}{\partial z} + gB - gq$$

P′ is the pressure departure from the large-scale hydrostatic balance
$\rho_0$ is the density of the environment
g is gravity
B is buoyancy
-gq is precipitation drag

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In addition to changes in the vertical motion due to changes in orographic uplift and descent, changes in vertical motion from one time step to the next in a grid box are caused by

- Advection bringing in air with a different vertical velocity
- Pressure deviations from hydrostatic balance resulting from
    - Changes in horizontal convergence/divergence
    - Phenomena with non-hydrostatic pressure perturbations, such as thunderstorms and mountain waves
- Buoyancy (B): Positive (negative) buoyancy generates a tendency toward upward (downward) motion. Positive buoyancy is caused by
    - Warm temperature anomalies in a grid box compared to its surroundings
    - Higher moisture content in a grid box compared to its surroundings

- Downward drag caused by the weight of liquid or frozen cloud water and precipitation

In addition, to account for vertical motions and buoyancy properly, non-hydrostatic models must include a great deal of detail about cloud and precipitation processes in their temperature and moisture forecast equations. Since hydrostatic models do not have a vertical motion forecast equation, none of these processes can directly affect the vertical motion in their predictions.

One disadvantage of non-hydrostatic models is longer computation time. Since the models must finish running in time for forecasters to use model products, hydrostatic models are more advantageous unless non-hydrostatic phenomena need to be simulated or unless resolution finer than around 10 km is needed.

Non-hydrostatic models run at very high resolution characteristically predict detailed mesoscale structure and associated forecast impacts on surrounding areas. For instance, a prediction of a mesoscale convective system will include a well-defined gust front, downstream thick anvil affecting surface temperature, and trailing mesohigh affecting winds for some distance from the active convection. These details will look like the kinds of features observed in real convective systems, but the forecast of convective initiation is subject to considerable error, possibly throwing off the whole forecast. Generally, mesoscale detail is most reliably predicted when forced by topography or coastlines. Otherwise, the detailed structure gives an idea of what to expect if the weather event causing it develops, but the timing and placement of that event may have considerable error.

# 5. Summary

***GRID POINT MODELS***

- **Characteristics**
  - Data are represented on a fixed set of grid points
  - Resolution is a function of the grid point spacing
  - All calculations are performed at grid points
  - Finite difference approximations are used for solving the derivatives of the model's equations
  - Truncation error is introduced through finite difference approximations of the primitive equations
  - The degree of truncation error is a function of grid spacing and time-step interval
- **Disadvantages**
  - Finite difference approximations of model equations introduce a significant amount of truncation error
  - Small-scale noise accumulates when equations are integrated for long periods
  - The magnitude of computational errors is generally more than in spectral models of comparable resolution

  - Boundary condition errors can propagate into regional models and affect forecast skill
  - Non-hydrostatic versions cover only very small domains and short forecast periods
- **Advantages**
  - Can provide high horizontal resolution for regional and mesoscale applications
  - Do not need to transform physics calculations to and from gridded space
  - As the physics in operational models becomes more complex, grid point models are becoming computationally competitive with spectral models
  - Non-hydrostatic versions can explicitly forecast details of convection, given sufficient resolution and detail in the initial conditions

***SPECTRAL MODELS***

- **Characteristics**
  - Data are represented by wave functions
  - Resolution is a function of the number of waves used in the model
  - Model resolution is limited by the maximum number of waves
  - The linear quantities of the equations of motion can be calculated without introducing computational error
  - Grids are used to perform non-linear and physical calculations
  - Transformations occur between spectral and grid point space
  - Equations can be integrated for large time steps and long periods of time
  - Originally designed for global domains
- **Disadvantages**
  - Transformations between spectral and grid point physics calculations introduce errors in the model solution
  - Generally not designed for higher resolution regional and mesoscale applications
  - Computational savings decrease as the physical realism of the model increases
- **Advantages**
  - The magnitude of computational errors in dynamics calculations is generally less than in grid point models of comparable resolution
  - Can calculate the linear quantities of the equations of motion exactly
  - At horizontal resolutions typically required for global models (late 1990s), require less computing resources than grid point models with equivalent horizontal resolution and physical processes

***HYDROSTATIC MODELS***

- **Characteristics**
  - Use the hydrostatic primitive equations, diagnosing vertical motion from predicted horizontal motions
  - Used for forecasting synoptic-scale phenomena, can forecast some mesoscale phenomena

    - Used in both spectral and grid point models (for instance, the AVN/MRF and Eta)
- **Disadvantages**
    - Cannot predict vertical accelerations
    - Cannot predict details of small-scale processes associated with buoyancy
- **Advantages**
    - Can run fast over limited-area domains, providing forecasts in time for operational use
    - The hydrostatic assumption is valid for many synoptic- and sub-synoptic-scale phenomena

***NON-HYDROSTATIC MODELS***

- **Characteristics**
    - Use the non-hydrostatic primitive equations, directly forecasting vertical motion
    - Used for forecasting small-scale phenomena
    - Predict realistic-looking, detailed mesoscale structure and consistent impact on surrounding weather, resulting in either superior local forecasts or large errors
- **Disadvantages**
    - Take longer to run than hydrostatic models with the same resolution and domain size
    - Used for limited-area applications, so they require boundary conditions (BCs) from another model; if the BCs lack the structure and resolution characteristic of fields developing inside the model domain, they may exert great influence on the forecast
    - May predict realistic-looking phenomena, but the timing and placement may be unreliable
- **Advantages**
    - Calculate vertical motion explicitly
    - Explicitly predict release of buoyancy
    - Account for cloud and precipitation processes and their contribution to vertical motions
    - Capable of predicting convection and mountain waves