# Vertical Coordinates

## (Adapted from COMET online NWP modules)

## 1. Introduction

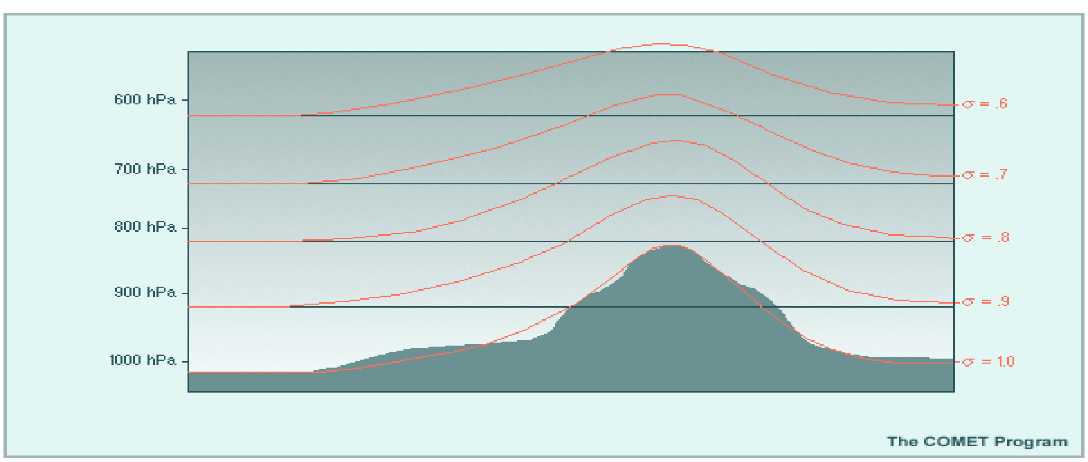
A model's vertical structure is as important in defining the model's behavior as the horizontal configuration and model type. Proper depiction of the vertical structure of the atmosphere requires selection of an appropriate vertical coordinate and sufficient vertical resolution.

Unlike the horizontal structure of models where discrete or continuous (grid point or spectral) configurations can be used, virtually all operational models use discrete vertical structures. As such, they produce forecasts for the average over an atmospheric layer between the vertical-coordinate surfaces, not on the surfaces themselves.

This section addresses the many common vertical coordinate systems that are used in operational models.

## 2. Sigma Vertical Coordinate ($\sigma$)

The equations of motion, which form the basis for all NWP models, have their simplest form in pressure coordinates. Unfortunately, pressure coordinate systems are not particularly suited to solving the forecast equations because, like height surfaces, they can intersect mountains and consequently 'disappear' over parts of the forecast domain. To address the problem of discontinuous forecast surfaces, Phillips (1957) developed a terrain-following coordinate called the sigma ($\sigma$) coordinate, illustrated below. The sigma coordinate or variants are used in the NGM, AVN/MRF, ECMWF, NOGAPS, and UKMET models and appear in some mesoscale models, such as AFWA MM5, COAMPS, and RAMS.



In its simplest form, the sigma coordinate is defined by $\sigma = p/p_s$, where p is the pressure on a forecast level within the model and $p_s$ is the pressure at the earth's surface, not mean sea level pressure. The lowest coordinate surface (usually labeled $\sigma = 1$) follows a smoothed version of the actual terrain. Note that the terrain slopes used in sigma models are always smoothed to some degree. The other sigma surfaces gradually transition from being nearly parallel to the smoothed terrain at the bottom of the model ($\sigma = 1$) to being nearly horizontal to the constant pressure surface at the top of the model ($\sigma = 0$). The top layer of the model is typically placed well above the tropopause, usually between 25 and 1 hPa.

The sigma vertical coordinate can also be formulated with respect to height (z), rather than pressure. While not currently used in operational models, it is used in RAMS. For more information on the sigma-z coordinate, see Pielke and Martin 1981.

## *2.1 Advantages of the Sigma Vertical Coordinate*

**Advantage #1:** Since the sigma coordinate is related to pressure, it produces relatively simple formulations for handling the lower boundary without overly complicating the equations of motion. The simplified formulations are easier to program.

**Advantage #2:** The sigma coordinate conforms to naturally sloping terrain.

The terrain-following nature of the sigma coordinate allows for good depiction of continuous fields, such as temperature advection and winds, especially in areas where terrain varies widely but smoothly. Additionally, the sigma coordinate can predict such phenomena as downslope wind events in the lee of mountain slopes. However, since the coordinate allows for continuous flow over mountains, it can have difficulty forecasting situations where the mountains act as barriers to flow, for example, cold-air damming in the lee of mountains and leeside cyclogenesis.

**Advantage #3:** The terrain-following nature of the sigma coordinate lends itself to increasing vertical resolution near the ground consistently over the full model domain.

The model can better define boundary-layer processes and features that contribute significantly to sensible weather elements, such as diurnal heating, low-level winds, turbulence, low-level moisture, and static stability.

**Advantage #4:** Unlike pressure, height, or isentropic coordinates, the sigma coordinate eliminates the problem of vertical coordinate surfaces intersecting the ground. The other coordinate systems can intersect with the earth's surface in areas of uneven terrain or in areas with strong variation in surface pressure across weather systems.

When a model layer intersects the ground, the wind field (and thus temperature and moisture advection) in the area can be interrupted or blocked, which is physically incorrect. To compensate for this error, sophisticated mathematical techniques must be used in the model.

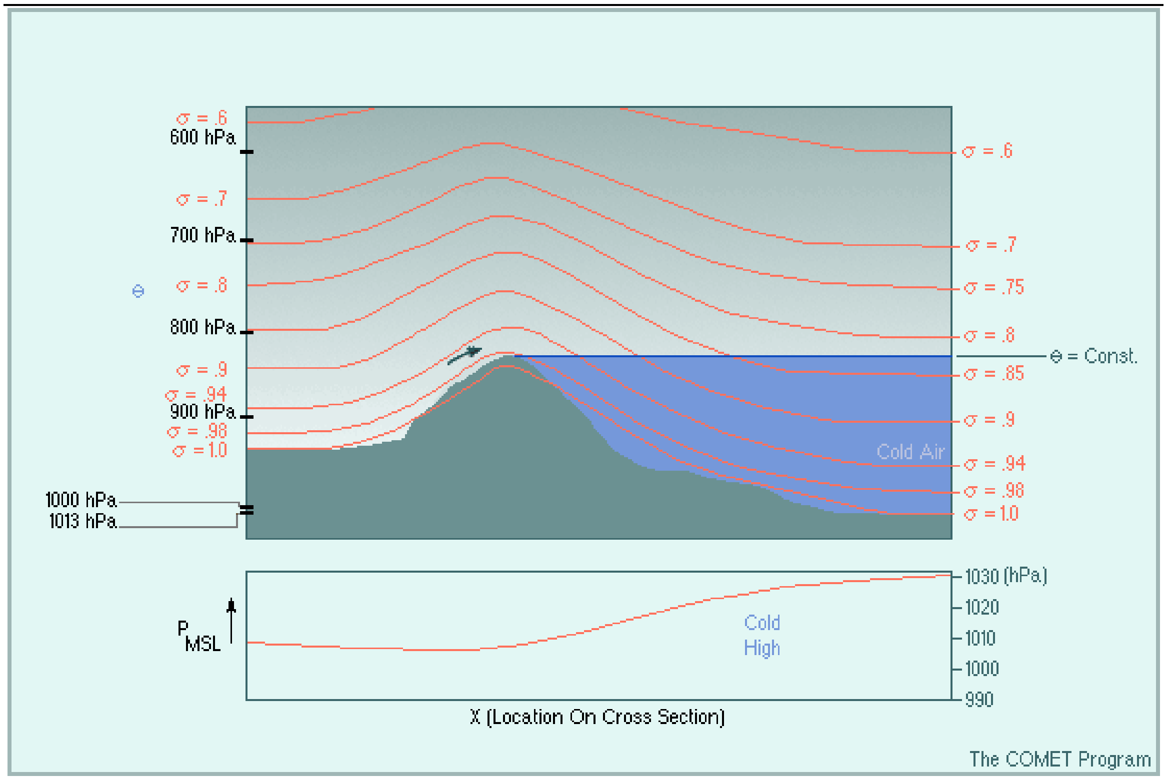
## *2.2 Limitations of the Sigma Vertical Coordinate*

**Limitation #1:** Model wind forecasts depend upon accurate calculation of the pressure gradient force (PGF), which is very simple to calculate in pressure coordinates when the height is known. However, when sigma surfaces slope, the PGF must be expanded from its simple pressure coordinate form to include the effects of the slope. This introduces errors because the lapse rate must be approximated at points that lie between the pressure surfaces where height is observed. This error can become very large in areas with steep mountain slopes. Due to the dependence of the wind forecast equations on the pressure gradient force (see the Model Type section), this can cause substantial errors in wind forecasts and can affect the entire depth of the model, especially in situations where the downslope flow and pressure gradients are large. Click for a detailed explanation and example of the difficulties calculating geostrophic winds in sigma coordinate models.

**Limitation #2:** Because the actual and often abrupt steepness of mountain slopes is smoothed in sigma coordinate models, they often misrepresent the true surface elevation. This can cause forecasts for locations immediately adjacent to mountain ranges to severely misrepresent the surface pressure and thus the temperature and moisture. For example, due to terrain smoothing required in sigma models, an 80-km sigma model could place the elevation of stations adjacent to steep mountain ranges, such as Denver, as much as 500 m too high. This could produce afternoon surface temperature errors of as much as 5°C.

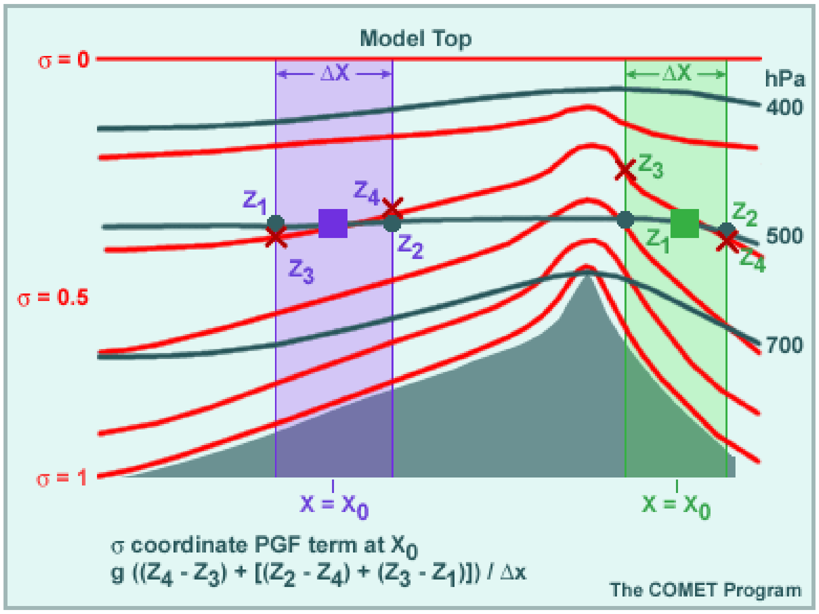
**Limitation #3:** Because of the smoothing required in mountain ranges along oceanic coasts, land points in the model can be forced to extend beyond the true coastline. This affects the Pacific Northwest and Canadian coasts by moving the coastline farther west than in reality, making coastal stations appear to be located further inland than they should be.

**Limitation #4:** Sigma models can have difficulty dealing with weather events in the lee of mountains, for example, cold-air damming and leeside cyclogenesis. In strong cold-air damming events, the inversion (**vertical** temperature gradient) in the real atmosphere above the cold air mass, shown in the right portion of the figure, is transformed in part into a "**horizontal**" temperature gradient along the steeply sloped sigma surfaces. As a result, the model can move the cold air away from the mountains through "horizontal" advection along the sigma surfaces, rather than channeling the flow over the mountains above and parallel to the inversion above the cold air. Likewise, excessive low-level downslope flow can result in exaggerated "vortex-tube stretching" and can produce exaggerated and too-frequent leeside cyclogenesis.



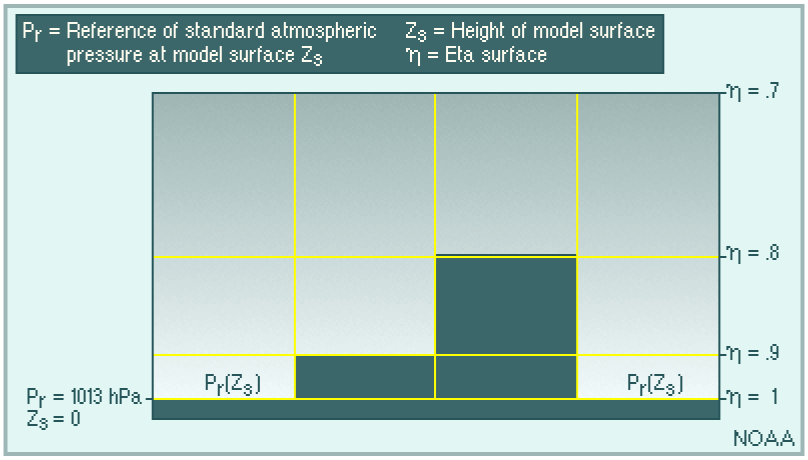

**Additional information: Explanation and example of difficulties calculating geostrophic winds in sigma coordinate models**

Let's look at an example of calculating changes in the east-west wind at the locations of the purple and green squares in the graphic below. To do this, we must first calculate the geostrophic wind. In pressure coordinates, the PGF is calculated using the heights $z_1$ and $z_2$ – it looks directly at the height change in the x direction on the pressure surface. This represents the true east-west pressure gradient felt by the air in this grid box, regardless of the vertical coordinate system used. To calculate a PGF in a sigma model, we must determine an equivalent to the $z_1$ and $z_2$ on the pressure surface. However, because the sigma model produces data only along sigma coordinate surfaces, it has values at $z_3$ and $z_4$. Two additional terms shown in the graphic are needed to convert the heights on the sigma surface to corresponding heights on the pressure surface. This introduces error. To determine the height difference on the sigma surface corresponding to the $z_2$ - $z_1$, we must take the difference between the height difference along the sigma surface ($z_4$ - $z_3$) and the correction term ($z_2$ - $z_4$) + ($z_3$ - $z_1$), both parts of which depend upon the approximated lapse rate between the sigma surfaces. Both of these terms are much larger than the height difference on the pressure surface, and the resulting difference in the terms can lead to significant errors. The larger the slope of the sigma surface, such as in the green area, the larger the possible error in the PGF.




# 3. Eta (or Step) Vertical Coordinate (η)

The eta coordinate (η) was created in the early 1980s in an effort to reduce the errors incurred in calculating the pressure gradient force using sigma coordinate models.




The eta coordinate is, in fact, another form of the sigma coordinate, but uses mean sea level pressure instead of surface pressure as a bottom reference level. As such, eta is defined as

$$\eta_s = (p_r(z_s) - p_t) / (p_r(z=0) - p_t)$$

where

- $p_t$ is pressure at the model top
- $p_r(z=0)$ is the standard atmosphere MSL pressure (1013 hPa)
- $p_r(z_s)$ is the standard atmosphere pressure at the model terrain level $z_s$

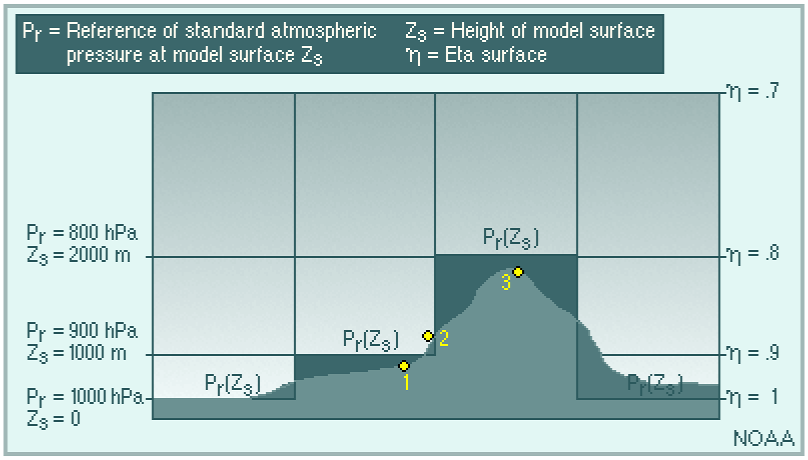
Eta usually is labeled from 0 to 1 from the top of the model domain to mean sea level. Unlike sigma models, where all grid cubes are considered to be above the earth's surface, in eta models, some of the model's grid cubes are located underground in areas where the surface elevation is notably above sea level. This requires special numerical formulations to model flow near the earth's surface.

The difference between the definitions of the sigma and eta coordinate systems allows the bottom atmospheric layer of the model to be represented within each grid box as a flat "step," rather than sloping like sigma in steep terrain. For this reason, the eta coordinate is sometimes referred to as the **step-mountain coordinate**. This configuration eliminates nearly all errors in the PGF calculation and allows models using the eta coordinate to have extreme differences in elevation from one grid point to its neighbor. Eta coordinate models can therefore develop strong vertical motions in areas of steep terrain and thus more accurately represent many of the blocking effects that mountains can have on stable air masses.

Even when the step-like eta is used as the vertical coordinate, model terrain is still much coarser than real terrain, but the topographic gradients are less smoothed than in sigma models. Although this representation of terrain is a source of error in areas strongly affected by small-scale terrain features, it is still necessary to depict the average elevation within the entire grid box area. Representing terrain in this manner impacts the scale of features that can be preserved in the model's forecast, making the forecast representative of the average conditions in the grid box.

### *3.1 Calculating Eta Surfaces*

Let's walk through an example of how to determine which eta level is closest to a station. For simplicity, we will assign the MSL reference pressure to be 1000 hPa.




First, the heights at each model level must be defined. In this example, we have defined a model with 10 eta layers (only 3 shown) distributed evenly with respect to pressure from sea level to the top of the atmosphere. Standard atmosphere pressures are then determined at each of these heights.

At point 1, the actual terrain elevation is 848 m. This is closest to the 1000-m height defined for the first eta level. The standard atmosphere pressure at that height is 900 hPa. What, then, is the eta level closest to this point?

Using the eta equation, $\eta_s = (p_r(z_s) - p_t) / (p_r(z{=}0) - p_t)$,

$\eta$= (900-0) / (1000-0) = .9.

If we go to point 2, the actual terrain height is 1126 m and is also closest to the 1000-m height. Therefore, the eta level closest to this point is again .9.

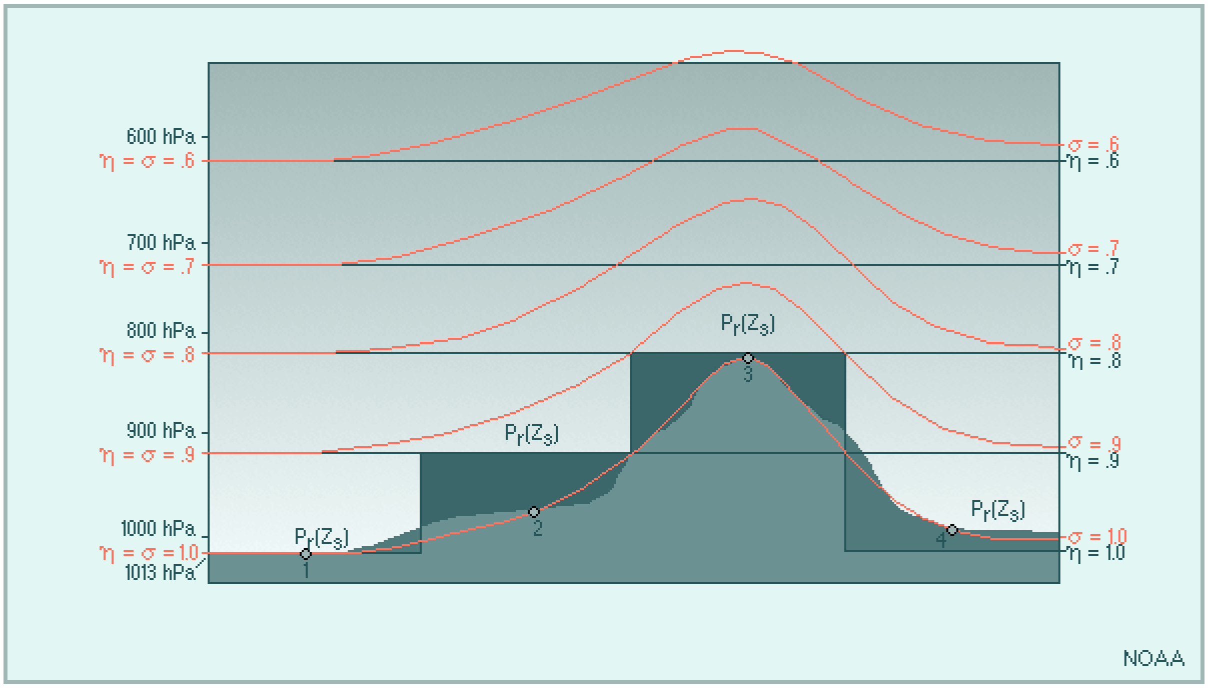
However, if we go up to point 3 (1832 m), the nearest eta surface in the model is at 2000 m. Here the standard atmospheric pressure is 800 hPa. The nearest eta level is therefore

$\eta$= 1 x (800-0 / 1000-0) = .8.

Note that the eta levels are predefined and the model topography is set to the nearest eta surface even if it does not quite match the average or smoothed terrain height in the grid box.

This has been a simplified example. In reality, it is necessary to choose the intervals between eta levels in a way that both depicts the planetary boundary layer (PBL) with sufficient detail and yet represents the average changes in elevation over the entire forecast domain.

### *3.2 Advantages of the Eta Vertical Coordinate*

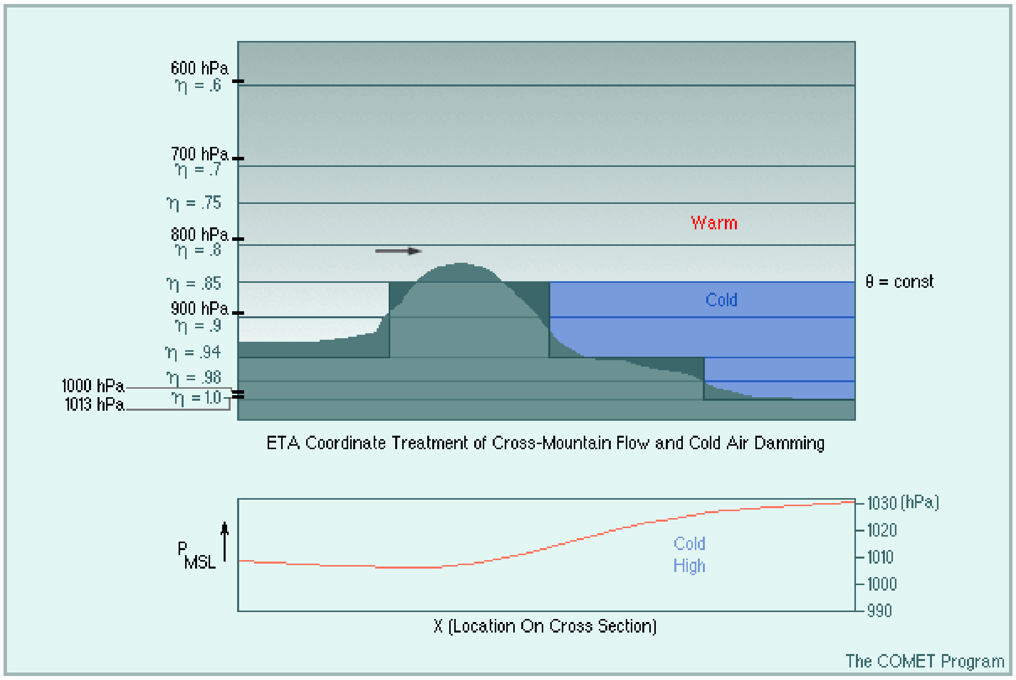



The fact that the eta coordinate is nearly horizontal and allows terrain features, such as mountains, to be depicted as blocks of solid earth in several levels of the model has several important advantages.

- **Advantage #1:** Eta models do not need to perform the vertical interpolations that are necessary to calculate the PGF in sigma models (Mesinger and Janjić 1985). This reduces the error in PGF calculation and improves the forecast of wind and temperature and moisture changes in areas of steeply sloping terrain.

- **Advantage #2:** Although the numerical formulation near the surface is more complex, the low-level convergence in areas of steep terrain are far more representative of real atmospheric conditions than in the simpler formulations in sigma models (Black 1994). The improved forecasts of low-level convergence result in better precipitation forecasts in these areas. The improved predictable flow detail compared to a comparable sigma model more than compensates for the slightly increased computer run time.

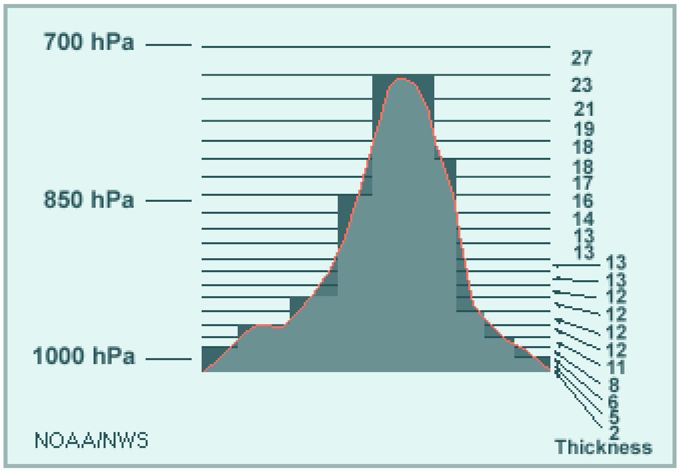
- **Advantage #3:** Compared with sigma models, eta models can often improve forecasts of cold air outbreaks, damming events, and leeside cyclogenesis (Mesinger and Black 1992, Mesinger et al. 1988). For example, in cold-air damming events, the inversion (**vertical** temperature gradient) in the real atmosphere above the cold air mass show7n in the right portion of the figure are preserved almost exactly in an eta model. As a result, there is little or no contribution to erroneous horizontal temperature gradients in the lee of mountains. Therefore, the model channels the flow over the mountains above and parallel to the cold air inversion, rather than producing erroneous downslope flow. Similar processes allow eta models to preserve the integrity of cold air masses and arctic highs moving southward in the lee of mountains. The improvement in the depiction of downslope flow also results in more realistic "vortex-tube stretching" (and thus more accurate increases in vorticity) in leeside cyclogenesis events.




### *3.3 Limitations of the Eta Vertical Coordinate*

While the eta coordinate has many useful advantages for numerical modeling, it also has some limitations.

- **Limitation #1:** The step nature of the eta coordinate makes it difficult to retain detailed vertical structure in the boundary layer over the **entire** model domain, particularly over elevated terrain.



Because the depth of the layers of an eta model usually increase when moving upward in elevation from sea level, the eta coordinate system can have difficulty representing boundary-layer processes over elevated terrain. For example, the depth of the lowest model layer over a mountaintop may be more than ten times than that near mean sea level (2 versus 23 hPa). This is in contrast to sigma models in which the vertical depth of the lowest layers is far more uniform across the full model domain. This increase in model layer depth near the surface can affect the model's ability to forecast surface and boundary-layer processes over high terrain.

In addition, because a relatively large number of the model's layers may be below ground, fewer layers are available for forecasting atmospheric processes over uniform, high plateau regions.

- **Limitation #2:** Eta models do not accurately depict gradually sloping terrain. Since all terrain is represented in discrete steps, gradual slopes that extend over large distances can be concentrated within as few as one step. This unrealistic compression of the slope into a small area can be compensated, in part, by increasing the vertical and/or horizontal resolution.

- **Limitation #3:** Eta models have difficulty predicting extreme downslope wind events.

Staudenmaier and Mittelstadt 1997 documented that the eta coordinate has difficulty representing mountain waves in the lee of mountain barriers. This is due to eta models' tendency to create flow separation above the lee slopes of the stepped model terrain. Their results suggested that this behavior might have been responsible for the weak flow forecast in the lee of the Wasatch Mountains during a strong downslope wind event.

- **Limitation #4:** Eta models must broaden valleys a few grid boxes across or fill them in.

The NCEP Eta Model sets the horizontal wind to zero on the sides of the steps. Thus, a valley two grid-spacings wide has only one row of predicted velocity points, an insufficient number to calculate divergent processes. See the Eta Model Vertical Coordinate section in the Operational Models Matrix (PCU2) for more information.

- **Limitation #5:** Eta coordinates can create spurious waves at step edges.

These spurious waves can be large and important only if the model has horizontal resolution considerably finer than 10 km and if the vertical resolution increment is a large fraction of the actual topographic feature (Gallus and Klemp 1999).

### *3.4 Considerations for Using the Eta Vertical Coordinate*

1. Remember that the **boundary-layer resolution** will not be as detailed over the mountains as over the plains.

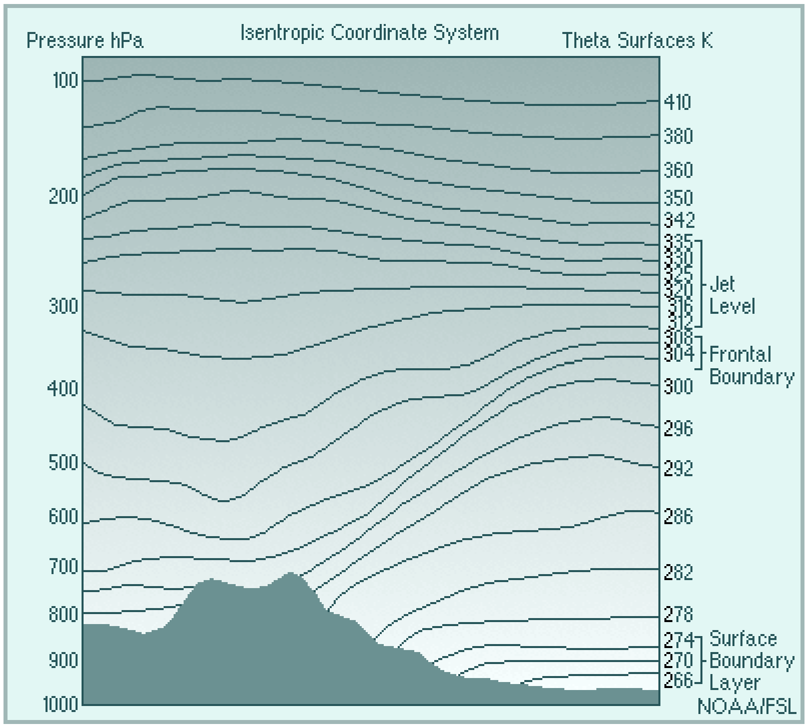
Recall that one disadvantage of the eta coordinate is that the model's lowest atmospheric layers have less vertical resolution at higher than at lower elevations. This may degrade the accuracy of low-level temperature and stability forecasts over elevated terrain. However, this problem can be reduced if more vertical layers are added to keep the resolution equally high to the top of the mountains.

2. You should notice a more accurate forecast of the low-level wind field resulting from the more accurate calculation of the **horizontal pressure gradient** over the sloping terrain.

Since each eta surface is flat rather than sloped like the sigma coordinate over complex terrain, the eta coordinate does a superior job predicting horizontal pressure gradients and thus winds in areas of steeply sloping terrain.

The eta coordinate works better for flow around or over a barrier while the sigma coordinate works better when the flow actually glides along a gentle slope.

# 4. Isentropic (Theta) Vertical Coordinate ($\theta$)




Since flow in the free atmosphere is predominantly isentropic, potential temperature (θ) can be very useful as a vertical coordinate system. However, non-adiabatic processes dominate in the boundary layer and isentropic surfaces intersect the earth's surface. For these reasons, potential temperature alone is not currently used as a vertical coordinate in any operational numerical model system. However, isentropic coordinates do form an essential part of many hybrid vertical coordinate systems.

## *4.1 Advantages*

Isentropic vertical coordinates have many advantages for performing diagnostic studies of weather events, many of which also apply to numerical weather prediction.

- **Advantage #1:** The theta coordinate allows for more vertical resolution in the vicinity of baroclinic regions, such as fronts, and near the tropopause.

Theta increases more rapidly with height in stable layers. The increased resolution in these sloping stable layers (fronts and baroclinic zones) allows more accurate depiction of significant horizontal and vertical wind shears and jet streaks.

- **Advantage #2:** For adiabatic motion, air flows along constant theta (isentropic) surfaces and implicitly includes both horizontal and vertical displacement.

Because most of the three-dimensional flow in the free atmosphere is computed as two-dimensional flow in isentropic models, less vertical finite differencing is required and fewer errors are introduced in advective calculations. This allows the advection of quantities such as water vapor to be portrayed very accurately because air is not being mixed from layers above and below.

- **Advantage #3:** Vertical motion through isentropic surfaces is caused almost exclusively by diabatic heating.

Vertical motion in isentropic models is a result of two processes: adiabatic motion and diabatic forcing. Since isentropic coordinates are a "natural" coordinate system, in which adiabatic flow follows the coordinate surfaces themselves, adiabatic vertical motions are included within the "horizontal" component of the forecast equations. The vertical component of the isentropic forecast equations is related entirely to diabatic processes. By having the total vertical motion related only to these adiabatic and diabatic components, there is a far more direct cause and effect relationship in interpreting the model forecast fields.

- **Advantage #4:** Isentropic coordinate models conserve important dynamical quantities, such as potential vorticity.

The ability of isentropic models to preserve potential vorticity (PV) is superior to any other coordinate systems because

  - PV is very nearly conserved in adiabatic flow in the free atmosphere
  - PV changes are primarily related to diabatic heating and cooling, which is handled more directly in isentropic coordinates

Retention of the dynamically important features assures a far more dynamically consistent forecast that is capable of capturing important development processes.

## *4.2 Limitations*

The primary limitations of isentropic coordinates occur in the boundary layer, where the flow can be strongly non-adiabatic.

- **Limitation #1:** Isentropic surfaces intersect the ground.

Because isentropic surfaces terminate when they intersect the earth's surface and can move up and down through the earth's surface throughout the day, they are not available at all times and locations for making calculations and their behavior cannot be modeled easily. Theta coordinates are usually used in combination with the sigma coordinate near the ground so that at least the first layer of the model follows the surface terrain. Coordinate combinations are discussed in the Hybrid Vertical Coordinates section.

- **Limitation #2:** Isentropic coordinates may not exhibit monotonic behavior with height, especially in the boundary layer.

  Superadiabatic layers can develop anywhere in the atmosphere, but predominantly occur in the boundary layer due to diurnal heating. When they develop, isentropic surfaces then appear more than once in the vertical profile above a point, something that cannot be allowed in a model's vertical coordinate system. Numerical adjustments could be made to restrict the occurrence of unstable layers, but this could **severely** limit the model's ability to predict many weather events.

- **Limitation #3:** Vertical resolution in nearly adiabatic layers is coarse.

  The same quality that leads to enhanced resolution in baroclinic zones conversely means that large adiabatic regions (commonly observed as soundings with a lapse rate nearly the same as the dry adiabaitc lapse rate and important to vertical mixing processes) will have decreased vertical resolution when theta is used as a vertical coordinate. This may lead to problems in adequately resolving the vertical mixing that takes place in these regions.

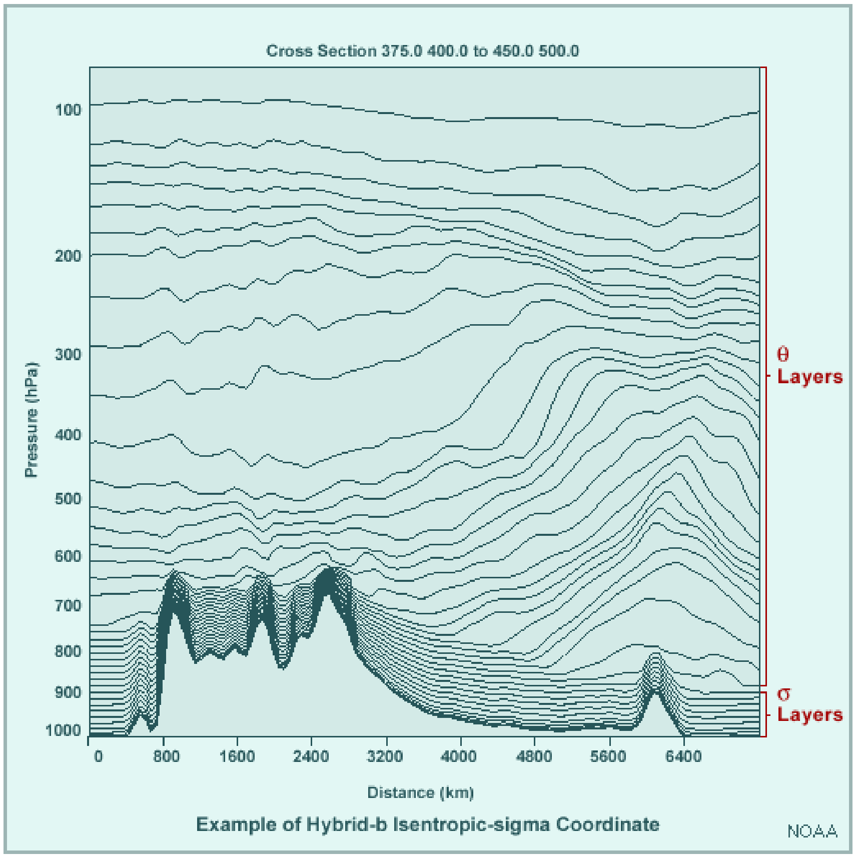
Isentropic surfaces have steep slopes in the vicinity of sharp baroclinic regions, such as fronts. However, steep slopes in isentropic coordinates do not produce the same inaccuracies in the horizontal pressure gradient calculation as in sigma coordinates. This arises from exploiting strong dynamical constraints associated with using a natural coordinate – that is, one dynamically related to the flow. Thus, even in frontal zones where isentropes can have appreciable slope, the prediction of geostrophic wind, and, in turn, ageostrophic wind, does not suffer badly.

# 5. Hybrid Vertical Coordinates

As modeling efforts advance, various combinations of parameters are experimented with as vertical coordinate systems. In 1979, Uccellini et al. introduced important advancements that improved the feasibility of using hybrid isentropic-sigma vertical coordinates. This was refined by Bleck and Boudra 1981 and Bleck and Benjamin 1993 and is currently used in the operational RUC. Currently, the ECMWF uses a $\sigma$-p hybrid coordinate system with sigma surfaces near the ground transitioning to pressure surfaces near the top (Zhu et al. 1992). The NOGAPS Model also uses a hybrid sigma-pressure coordinate, and some mesoscale models can operate with hybrid vertical coordinates as well.

## *5.1 Hybrid Isentropic-Sigma Vertical Coordinate System*

Hybrid isentropic-sigma coordinate models have a combination of sigma layers at the bottom that shift to isentropic layers above. Uniting theta and sigma into one vertical coordinate system combines the terrain-following advantages of sigma and the increased vertical resolution in key baroclinic areas due to the adaptive nature of isentropic surfaces. This is a powerful solution to some of the limitations of using either system independently.




The boundary sigma layer must be sufficiently deep to be able to model diurnal boundary-layer processes, including friction and heating. This typically requires that the sigma boundary layer be approximately 200 hPa deep. If the sigma layer is too shallow, superadiabatic layers can still form or will not be treated properly above the boundary sigma domain.

## *5.2 Advantages*

Using the hybrid isentropic-sigma coordinate system has many advantages.

- **Advantage #1:** This system retains the advantages of isentropic models in the free atmosphere, including better precipitation starting times for isentropic upglide (warm advection) than in sigma-coordinate models.

- **Advantage #2:** This system eliminates the problem of isentropic surfaces intersecting the ground.
- **Advantage #3:** This system represents surface heating and dynamical mixing in the boundary layer well.
- **Advantage #4:** The system allows good surface physics interactions, including surface evaporation and treatment of snow cover.

A hybrid isentropic-sigma vertical coordinate system allows the sigma coordinate to sufficiently model processes in the convectively unstable boundary layer while retaining the advantages of the adaptive nature of theta in the vicinity of baroclinic regions, such as fronts and the tropopause.

Above the boundary layer, where the flow is primarily adiabatic, it has been shown that vertical advection (which usually has somewhat more truncation error than horizontal advection) does much less "work" in these hybrid models than in sigma or eta models. That's because the adiabatic component of the vertical motion on the theta surfaces is captured in flow along the two-dimensional surfaces. This results in improved moisture transport and very little precipitation spin-up problem in the first few hours of the forecast in situations where the dynamical processes forcing the weather events are primarily above the boundary layer. Warm-frontal grid-scale precipitation even later in the forecast period begins on time rather than suffering belated onset as in sigma-coordinate models (Johnson et al. 1993).

## *5.3 Limitations*

- **Limitation #1:** Hybrid isentropic-sigma models no longer preserve adiabatic flow in the boundary layer as easily as pure isentropic models.

  Adiabatic flow cannot be preserved at low levels (where the sigma coordinate is used), even when that might be advantageous. An example is flow over shallow fronts. The sigma coordinate must use vertical finite differencing in vertical advection terms to simulate the flow over the front and ends up numerically mixing out part of the frontal gradient. The problem also applies to moisture gliding over the front in an isentropic layer in nature but in the sigma-coordinate portion of the model.

- **Limitation #2:** The depth of the sigma layers does not match the true depth of the PBL, so processes near the PBL/free atmosphere interface may not be depicted with the best coordinate.

Adiabatic flow immediately above the PBL may not be depicted in isentropic coordinates because it occurs within the model's sigma coordinate vertical domain. An example is the development of the nocturnal low-level jet (LLJ) found in the Great Plains. If the sigma layer is deeper than the thin nocturnal boundary layer, the greater mixing in the sigma layer may reduce the strength of the forecast LLJ and result in errors in its vertical placement. Subsequent development of nocturnal convection, which depends upon the advection of moisture and moisture convergence resulting from the LLJ, may be underpredicted.

Alternatively, the PBL may be so deep that the surface-based mixed layer in nature extends above the model's sigma region. Isentropic coordinates end up being used for the upper part of a well-mixed boundary layer. The weakness of isentropic coordinates in adiabatic regions was discussed previously.

Since the depth of the sigma layer cannot match PBL depth, adiabatic flow events that are above the true PBL but below the top sigma layer may be spread across several isentropic layers.

- **Limitation #3:** It can be difficult to blend coordinate types at their interfaces.

It is imperative that there be full interaction across the interface of the two vertical coordinate domains that realistically portrays atmospheric processes without introducing spurious mass, momentum, or energy sources. This can be difficult to accomplish numerically.

# 6. Special Considerations for Non-Hydrostatic Models

The requirement that non-hydrostatic models solve a prognostic vertical motion equation constrains the choice of vertical coordinate and increases computation time, which competes with horizontal and vertical resolution for limited computational resources. The result is that

- Most non-hydrostatic models use a vertical coordinate based on height. (A few are pressure-based, and none use isentropic coordinates.) Eta and sigma formulations can be used, subject to their usual limitations.

- Most non-hydrostatic forecast models sacrifice vertical resolution in order to run the models in real time at fine horizontal resolution. This is not a serious problem for research studies of deep convection but limits their usefulness for forecasting detailed boundary-layer structure, thin sheets of moisture drawn into sloping baroclinic zones, and detailed structure of the tropopause region and above. This situation should improve as computing power increases.

- The ratio of vertical to horizontal resolution is typically poor. Therefore, the slope of features, such as baroclinic zones, cannot be well represented because the fine horizontal resolution anchors the horizontal location while the vertical location is subject to large finite-difference error. This inconsistency can introduce numerical noise into the forecast and reduces the advantages of non-hydrostatic models in predicting baroclinic systems.

# 7. Summary: Vertical Coordinate Systems

All of the vertical coordinate systems used by NWP models have strengths and weaknesses, both computational and meteorological in nature. To best interpret model output, it is helpful to know which system a model uses and understand the strengths and limitations of each system as applied to various weather phenomena and meteorological settings.

| Vertical Coordinate | Models | Primary Advantage | Primary Limitation |
|---|---|---|---|
| Eta ($\eta$) | Eta | Allows for large local differences in terrain from one grid point to another | May not represent the boundary layer with sufficient resolution over elevated terrain |
| Generic hybrid | ECMWF, NOGAPS | Combines strengths of several coordinate systems | Difficult to properly interface across coordinate domains |
| Isentropic-sigma hybrid ($\theta$) | RUC | Naturally increases resolution in baroclinic regions, such as fronts and tropopause | Incompletely depicts important low-level adiabatic flow |
| Sigma ($\sigma$) | AVN/MRF, NGM, MM5, RAMS | Surfaces are terrain-following and therefore resolve the boundary layer well | May not correctly portray weather events in lee of mountains |

The following table summarizes how well each coordinate meets the criteria for serving as a vertical coordinate.

| Criteria | Sigma | Eta | Isentropic | Hybrid Isentropic-Sigma |
|---|---|---|---|---|
| Exhibits monotonic behavior | Yes | Yes | May not | Yes |
| Preserves conservative atmospheric properties and processes | Fairly well | Fairly well | Very well | Well |
| Accurately portrays pressure gradient force | No | Yes | Mostly | Mostly |