Domain and Boundary Conditions

(Adapted from COMET online NWP modules)

1. Introduction

Model domain refers to a model's area of coverage. Limited-area models (LAMs) have horizontal (lateral) and top and bottom (vertical) boundaries, whereas global models, which by nature cover the entire earth, have only vertical boundaries. For limited-area models, larger-domain models supply the data for the lateral boundary conditions.

For all models, accurate information must be provided for all forecast variables and along each model boundary (lateral, top, and bottom) in order to solve the forecast equations. Boundary values can be obtained from a variety of sources, including

- Data assimilation systems
- Forecast values from a current or previous cycle of a large-scale model (as is the case for lateral boundary conditions used in LAMs)
- Some type of climatological or fixed value (for specifying certain surface characteristics, such as soil moisture, sea surface temperature, and vegetation type)

The key issues related to model domain to consider when using model guidance, particularly from limited-area models are:

- The proximity of the local forecast area to the model's boundaries, given the increased likelihood of errors propagating inward from the boundaries during the forecast cycle
- The quality and resolution of the forecast of the larger-domain model used to supply boundary conditions for the limited-area model. Deficiencies in its forecast will influence the smaller-domain model and amplify errors during the forecast period. Common examples include errors in the placement, intensity, and structure of low-pressure systems, fronts, jets, and a variety of other features
- The lower boundary conditions (those that describe many of the physical processes occurring on or near the earth's surface), in particular, how they are prescribed and the accuracy of the parameterizations used to determine them. The accuracy with which the physical processes are depicted is crucial to the forecast of many sensible weather elements, such as temperature, winds, turbulence, and precipitation

The domain of an NWP model can be viewed as a three-dimensional array of cubes similar to that illustrated here. Each cube encompasses a volume of the atmosphere corresponding to a model grid point. Forecast values for the meteorological variables in each cube are derived from the current values within the cube plus those from the surrounding cubes. Because the cubes on the boundaries are not surrounded by other cubes on all sides, the information needed to provide forecast values for the meteorological parameters cannot be determined using only the data contained in the model. The information for the outside boundaries must be supplied from another source.

The remainder of the Domain & Boundary Conditions section discusses these and other issues related to vertical and lateral boundary conditions, including the methods used to incorporate meteorological variables from outside the model domain and the errors introduced into the model domain by boundary conditions.

2. Lateral Boundary Conditions

The methods discussed here apply only to limited-area models and are used to provide needed information about changes to the meteorological forecast variables occurring outside of the model domain.

Ideally, boundary conditions should be based on observed data (as they are in research case studies). However, the best that can be done in weather prediction is to use boundary conditions based on another forecast model.

The quality of limited-area or local model predictions is greatly affected by the quality of predictions produced by the model supplying the lateral boundary conditions. Errors in forecasts from larger-domain models will move into the LAM's forecast domain and can, in some instances, amplify. For example, the NCEP Eta Model is run with boundary conditions from an earlier run of the AVN, so that in westerly flow, systematic errors in the AVN over the Pacific are also present in the western part of Eta forecasts. Likewise, if a LAM is run at a forecast office using boundary conditions from the Eta Model, errors similar to those in the Eta can spread rapidly across the limited domain of the local model forecast.

The lateral boundary conditions largely control the position and evolution of features that cover the entire forecast domain. For example, for a domain covering the 48 states, long-wave patterns are almost entirely determined by the boundary conditions. Weaker impacts are noted on jet streaks and fronts, especially in regions far downwind from the upstream boundary. Similarly, in a high-resolution mesoscale model running over a small section of the country, the placement and timing of synoptic-scale features are determined almost completely by the synoptic-scale model supplying the boundary conditions.

Since the influence of boundary conditions spreads away from (and particularly downstream of) the boundaries and, in some cases, the effects amplify downstream, the area of primary forecast concern should be located as far from the boundaries as possible, especially the upstream boundary. Because some of the boundary influence is carried by the wind, the speed and direction of greatest forecast impact will vary from one flow regime to another. Forecasters should pay attention to how long it takes a trajectory to move from the model boundary to the vicinity of their forecast area.

2.1 One-Way Interaction

Lateral boundary conditions are usually obtained from a previous run of a larger-domain model. For example, a 6- to 54-hr forecast from a global model run at 06 UTC could supply the lateral boundary conditions for a 0- to 48-hr forecast from a regional model starting at 12 UTC. Information flows in **one direction**, from the previously integrated forecast over the larger domain to the smaller-domain model. Therefore, this is called **one-way interaction**.

2.2 Two-Way Interaction

Some limited-area models, including the UW-NMS, ARPS, and MM5, are run with small-area, finer-resolution grids nested inside of coarser-resolution grids within the **same** model. This nesting is necessary because computer memory and speed limitations prohibit fine-resolution grids from covering the entire model domain.

The information for the outermost boundaries of these nested-grid models is still supplied from an outside source, using one-way interaction. However, the interfaces **between the grids inside the nested grid model** are determined from the forecasts within the model itself.

Where the fine grid covers the coarse grid, the forecast variables for the coarse grid are updated based on the fine-grid prediction. The coarse-grid prediction, in turn, affects the fine-grid prediction by supplying boundary conditions on the mesh interface. Since information flows both ways, this is called **two-way interaction**.

2.3 Sources of Error

The following is a list of factors related to boundary conditions that can cause errors in model forecasts.

1. The accuracy of the forecast produced by the model supplying boundary conditions

- **How old the forecast supplying boundary conditions is**
- **Small-scale features and processes missing from the boundary conditions supplied by the larger-domain model**
- **Boundary conditions with insufficient depiction of gradients**

2. Differences in model formulation between the larger-scale and finer-scale models

The physical parameterizations and dynamical formulations of the model providing lateral boundary conditions may be different from the smaller-domain model, which may lead to forecast errors. The following are some of the formulation differences and the forecast errors they can cause.

- **Dynamical inconsistencies within the model based on different vertical coordinates between the two models**
- **Differences in vertical resolution**
- **Differences in topography at the boundary**
- **Different convective parameterizations, which can cause air entering through the boundary to immediately trigger the convective parameterization on the fine-mesh model**
- **Different saturation thresholds for determining the presence of clouds in the models**
- **Cloud water predicted by one model, but not the other**
- **Differences in the representation of physical processes**

2.4 Additional Source of Error

At the interface between grid meshes of differing resolution, atmospheric waves in a numerical model behave much the same way as light waves at the interface between air and water.

The speed of wave propagation in a model varies with the number of points used to represent the wave. A well-resolved wave will be forecast to move at the correct speed, while a poorly-resolved wave will be forecast to move slower than its true speed. This means that a wave passing through a mesh interface can bend, changing its orientation as illustrated in the animation. Additionally, boundary conditions can force the slower wave motion upon the finer-resolution mesh, disrupting the better solution near the boundary. In the worst case, waves can even be reflected at a model or mesh boundary. However, improved numerical methods now reduce or eliminate this behavior.

The following weather features can be affected by refraction or redirection of atmospheric waves at a model's lateral boundaries:

- Precipitation fields

- Temperature fields
- Jet stream pattern
- Vertical motion field
- Intensity and placement of surface lows and fronts

Note that this type of error does not affect waves that are well-resolved on the coarser mesh supplying the boundary conditions (either within the LAM or the larger-domain model).

This type of error will become less significant as global model resolution improves.

3. Upper Boundary Conditions

All forecast models, including global models, require that boundary conditions be specified at the top and bottom of the model domain.

Model tops are placed well above the tropopause. Assumptions must be made as to how the forecast variables will change above the assigned top throughout the forecast period.

Most models employ a rigid upper boundary condition, which means that no vertical motion is allowed through the top of the model. Problems occur when gravity waves (such as those generated by convection in the model or flow over the model topography) reflect off the top of the model. If untreated, these gravity waves can "bounce" around the entire model depth and severely affect vertical motion and precipitation forecasts. Fortunately, special numerical treatments, such as the addition of an "absorbing" or "damping" layer near the model top, have been developed to avoid this problem. These treatments can only be applied when the model top is much higher than any weather features to be forecast, since the forecast for the highest model layers will not be realistic.

4. Lower Boundary Conditions

The lower boundary is defined by the interface of the model's lowest atmospheric level with the model topography or model sea surface. The accuracy with which this boundary condition represents conditions at the earth's surface depends upon the specific surface physics and parameterizations used in the model as well as its source of information for snow cover, soil temperature and moisture, soil type, and vegetation cover.

Vertical motion at the ground is set to zero, except for an upslope or downslope component due to flow along the model topography. Horizontal winds are predicted as an average for the lowest layer rather than at the ground or anemometer level. Near-surface winds are then empirically determined.

Since most models predict near-surface conditions using energy balance principles, errors will be introduced due to inadequate handling of terrain, albedo, the amount of rainwater available for evaporation from the surface, lake and sea temperature, vegetation cover, the method of simulating soil-vegetation-atmosphere interaction, and many other details relating to model representation of physical processes.

5. Operational Impacts

Operational forecast models incorporate as many physically meaningful models of surface processes as possible (given computational constraints) to make accurate forecasts. In 1999, NWP models include coupled atmosphere-land interaction (including soil moisture, vegetation, and snow forecasts). In the future, coupled atmosphere/land models will become even more sophisticated to improve the depiction and forecast of surface conditions, and atmosphere/ocean models will likely be incorporated to allow a real linkage between the atmosphere and underlying water surfaces.

Since models use specified surface characteristics as part of their bottom boundary conditions, errors can be introduced because

1. **The surface may not be depicted with sufficient resolution to capture conditions necessary to produce an accurate forecast**

   For example, inadequate depiction of local terrain features can result in the misplacement or non-existence of air-mass thunderstorms in a certain part of the forecast area, such as near mountain slopes or reservoir edges. Local-scale terrain features can be entirely contained within a grid box or two, resulting in poor forecasts of the phenomena they may force.

2. **Model, rather than observed, atmospheric data are used to determine surface conditions, so that model biases and errors create additional biases and errors in surface conditions**

   For example, forecast precipitation is often used to determine soil moisture. A wet bias in model precipitation would cause a wet bias in soil moisture, leading to a cool temperature bias, excessive evaporation, and low-level moistening. It may also amplify the already existing high precipitation bias as a feedback in the model.

3. **The model specifications do not accurately reflect the actual surface conditions that will affect the local forecast**

   For example, in some models, lake surface temperatures in the U.S. Great Lakes are set to the zonal average of the global sea surface temperature (SST) rather than the actual lake temperature. While the impact is minimal in coarse-resolution models (since they cannot adequately resolve the lakes and their influence on weather), this can significantly impact finer-resolution models.

4. **Processes that impact the model forecast are not properly represented in the model**

   A prime example is atmosphere/ocean interaction. It has been shown that SSTs can have a diurnal cycle of as much as 3°C in near-calm conditions. As of 1999, all NCEP NWP models prescribe that the SSTs remain fixed (retain their initial value) throughout the forecast period. This can cause the models to underestimate daytime ocean-surface evaporation and affect low-level moisture supplies to nearby land areas.

It is extremely important to account for known model guidance deficiencies during the forecast preparation process. Surface processes exert a tremendous influence on sensible weather at the ground and on local variations in the forecast area. Unfortunately, representation of these processes is extremely difficult and contributes strongly to forecast error. However, these errors can often be compensated for by attentive forecasters.

6. Summary

General points

- Model domain refers to a model's area of coverage.
- Global models only use vertical (top and bottom) boundary conditions, since their horizontal domains encompass the entire earth.
- Limited-area models use both vertical and lateral (horizontal) boundary conditions.
- Limited-area models require inputs for the lateral boundary conditions from larger-domain models.
- The influence of lateral boundary conditions can not only spread into the forecast domain approximately with the speed of the wind flowing in through the boundaries, but can also affect forecasts near the boundaries. In some cases, the downstream effects can amplify and move inward faster than the wind speed along the boundaries.
- Top boundary conditions are treated well enough in most models to be of little concern to forecasters, but those setting up local models must make sure that these conditions are configured well to avoid problems in model prediction.
- The lower boundary interfaces with the model representation of surface processes. Failure to realistically represent all relevant physical processes or accurately describe the physical state of the ground generates error in the model forecast.
- Lateral boundary conditions and lower boundary specifications are major sources of model forecast error.

Methods for treating lateral boundary interactions

- **One-way interaction:** Information flows in one direction, from the coarser-mesh, larger domain to the finer-mesh, smaller domain. Computations within the finer-mesh model do not affect the larger domain model.
- **Two-way interaction:** Information flows in both directions in the interior grid interfaces of a nested model. The coarser-grid forecast supplies boundary conditions to the finer-grid forecast, while the finer-grid forecast is used by the coarser grid in determining the forecast variables.

Methods for mitigating errors

- Building features, such as more accurate physics and parameterizations, into the model and improving its ability to represent processes and features that occur at the surface
- Correcting for known model deficiencies in representing the surface condition and physical processes that affect surface conditions
- Using diagnostic tools to assess the accuracy of initial and early forecast model fields near the domain boundaries

Points to keep in mind when reviewing model guidance

- The location of the forecast area in relation to the model's boundaries
- The quality of the forecast of the larger-domain model supplying boundary conditions for the limited-area model
- The lower boundary conditions, in particular, how they are prescribed and the accuracy of the parameterizations used to depict them, if forecast lower boundary conditions are used