1 INTRODUCTION

1.1 Introduction to MM5 Modeling System

The Fifth-Generation NCAR / Penn State Mesoscale Model is the latest in a series that developed from a mesoscale model used by Anthes at Penn State in the early '70's that was later documented by Anthes and Warner (1978). Since that time it has undergone many changes designed to broaden its usage. These include (i) a multiple-nest capability, (ii) nonhydrostatic dynamics, and (iii) a four-dimensional data assimilation capability as well as more physics options, and portability to a wider range of computing platforms. These changes have effects on how jobs are set up using the modeling system, so the purpose of this introduction is to acquaint the user with some concepts as used in the MM5 system.

A schematic diagram (Fig. 1.1) is provided showing a flow-chart of the complete modeling system. It is intended to show the order of the programs, flow of the data, and to briefly describe their primary functions. Terrestrial and isobaric meteorological data are horizontally interpolated (programs TERRAIN and REGRID) from a latitude-longitude mesh to a variable high-resolution domain on either a Mercator, Lambert Conformal, or Polar Stereographic projection. Since the interpolation does not provide mesoscale detail, the interpolated data may be enhanced (program RAWINS/little_r) with observations from the standard network of surface and rawinsonde stations using a successive-scan Cressman or multiquadric technique. Program INTERP performs the vertical interpolation from pressure levels to the sigma coordinate system of MM5. Sigma surfaces near the ground closely follow the terrain, and the higher-level sigma surfaces tend to approximate isobaric surfaces. Since the vertical and horizontal resolution and domain size are variable, the modeling package programs employ parameterized dimensions requiring a user-defined amount of core memory. Some peripheral storage devices are also used.

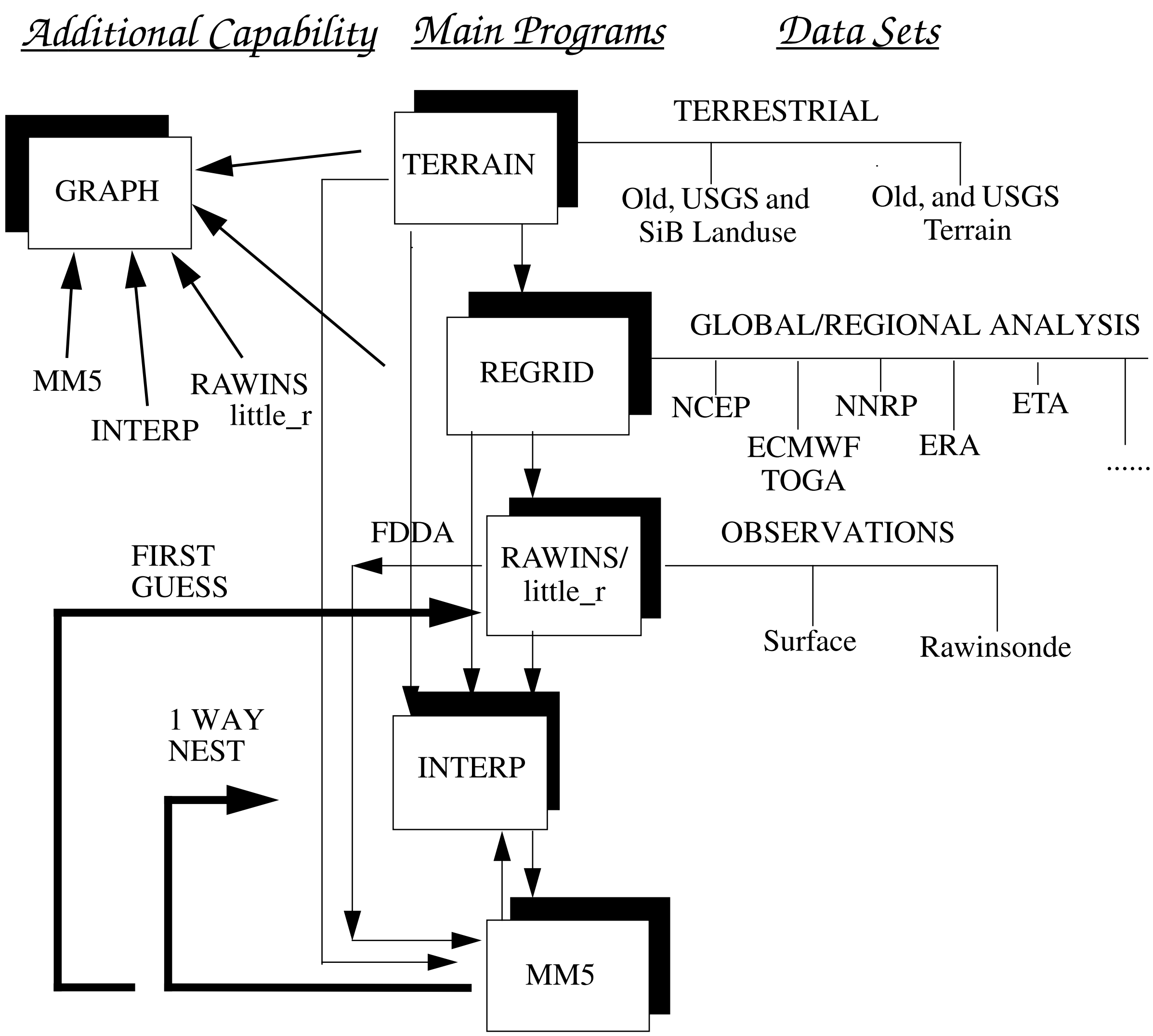

Fig 1.1 The MM5 modeling system flow chart.

1.2 The MM5 Model Horizontal and Vertical Grid

It is useful to first introduce the model's grid configuration. The modeling system usually gets and analyzes its data on pressure surfaces, but these have to be interpolated to the model's vertical coordinate before being input to the model. The vertical coordinate is terrain following (see Fig. 1.2) meaning that the lower grid levels follow the terrain while the upper surface is flat. Intermediate levels progressively flatten as the pressure decreases toward the chosen top pressure. A dimensionless quantity σ is used to define the model levels where

$$\sigma = (p - p_t)/(p_s - p_t) \tag{1.1}$$

p is the pressure, p_t is a specified constant top pressure, p_s is the surface pressure.

As described in a later section, the nonhydrostatic model coordinate uses a reference-state pressure to define the coordinate rather than the actual pressure which is used in the hydrostatic model. It can be seen from the equation and Fig 1.2 that σ is zero at the top and one at the surface, and each model level is defined by a value of σ. The model vertical resolution is defined by a list of values between zero and one that do not necessarily have to be evenly spaced. Commonly the resolution in the boundary layer is much finer than above, and the number of levels may vary from ten to forty, although there is no limit in principle.

The horizontal grid has an Arakawa-Lamb B-staggering of the velocity variables with respect to the scalars. This is shown in Fig 1.3 where it can be seen that the scalars (T, q etc.) are defined at the center of the grid square, while the eastward (u) and northward (v) velocity components are collocated at the corners. The center points of the grid squares will be referred to as cross points, and the corner points are dot points. Hence horizontal velocity is defined at dot points, for example, and when data is input to the model the preprocessors do the necessary interpolations to assure consistency with the grid.

All the above variables are defined in the middle of each model vertical layer, referred to as half-levels and represented by the dashed lines in Fig 1.3. Vertical velocity is carried at the full levels (solid lines). In defining the sigma levels it is the full levels that are listed, including levels at 0 and 1. The number of model layers is therefore always one less than the number of full sigma levels. Note also the I, J, and K index directions in the modeling system.

The finite differencing in the model is, of course, crucially dependent upon the grid staggering wherever gradients or averaging are required to represent terms in the equations, and more details of this can be found in the model description document (Grell et al., 1994).

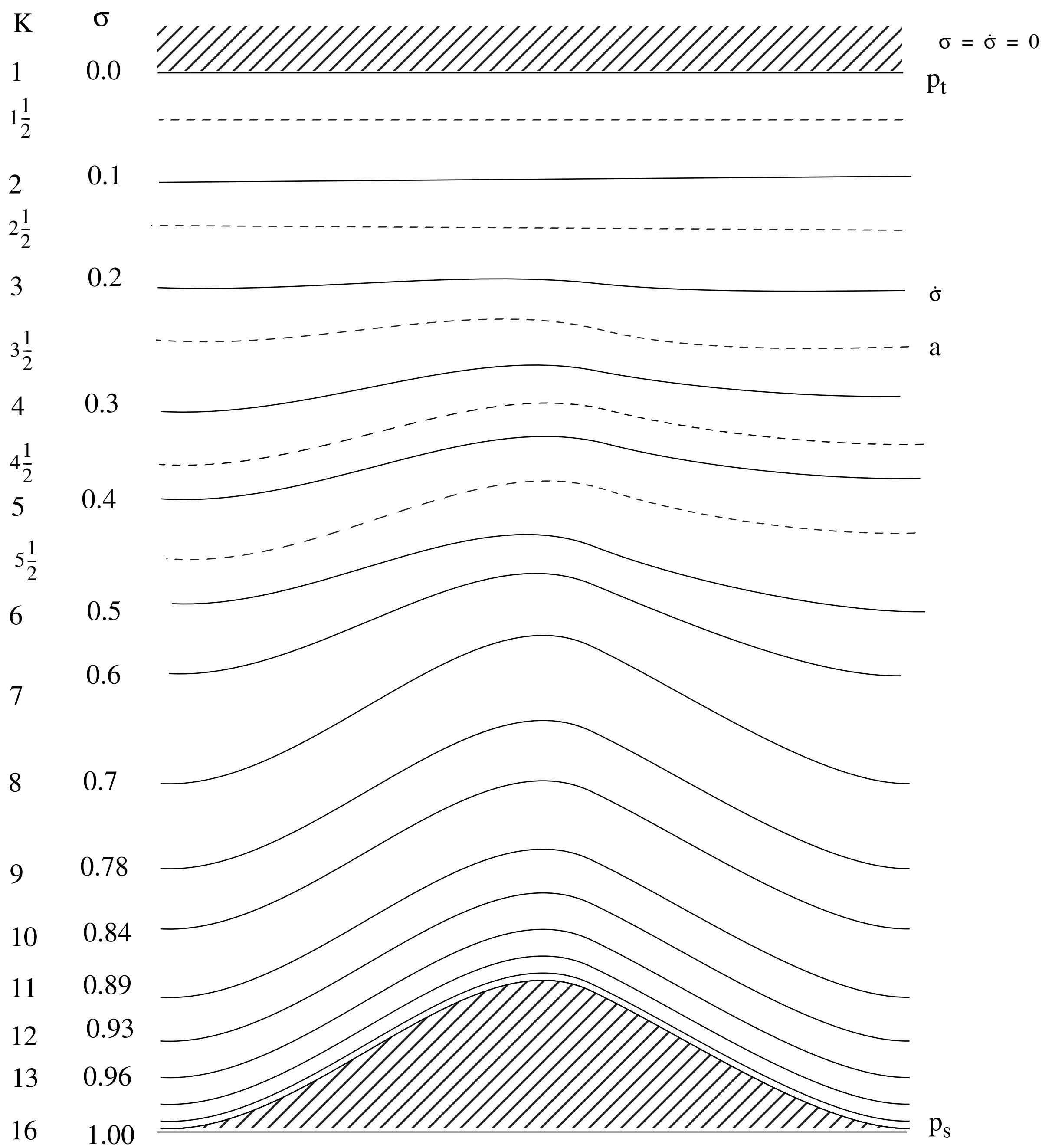

Figure 1.2 Schematic representation of the vertical structure of the model. The example is for 15 vertical layers. Dashed lines denote half-sigma levels, solid lines denote full-sigma levels.

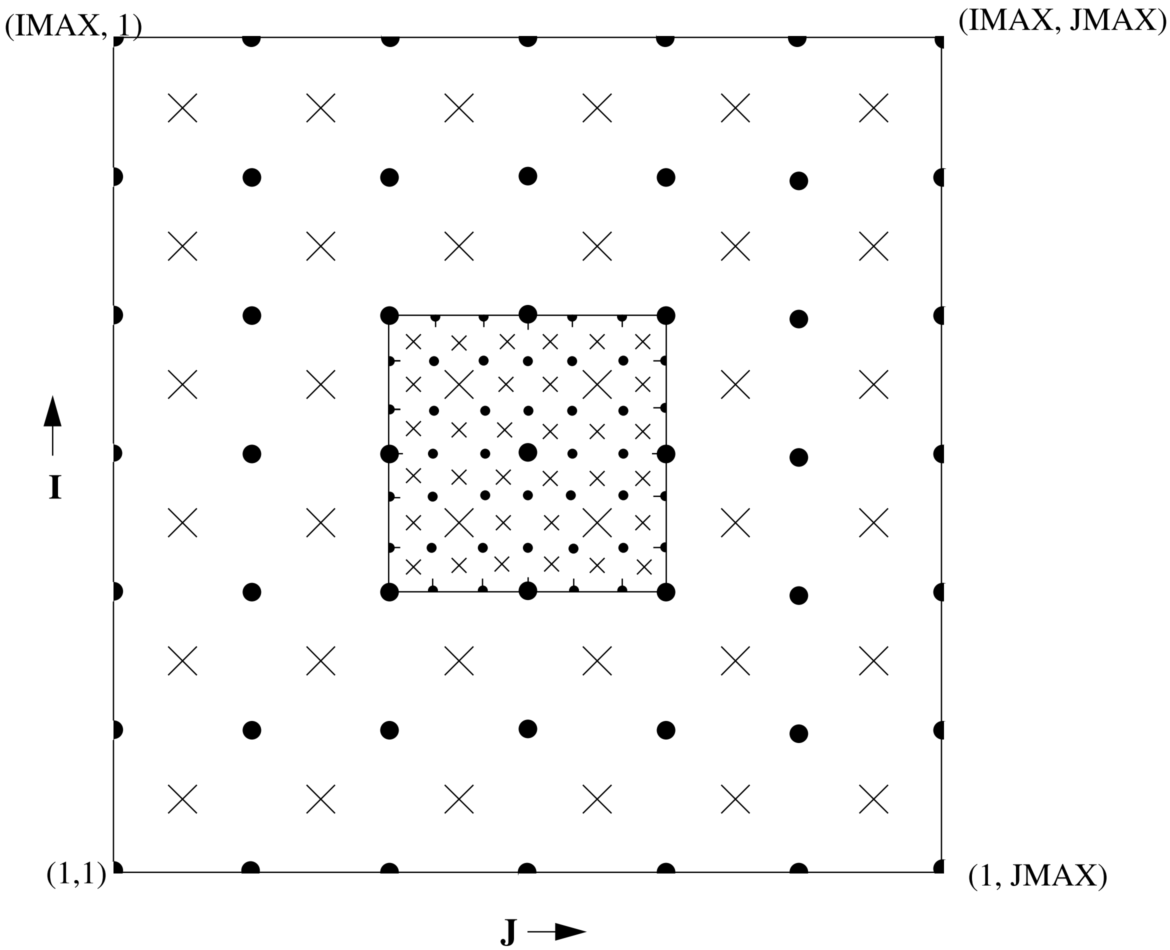

Figure 1.3 Schematic representation showing the horizontal Arakawa B-grid staggering of the dot (●) and cross (x) grid points. The smaller inner box is a representative mesh staggering for a 3:1 coarse-grid distance to fine-grid distance ratio.

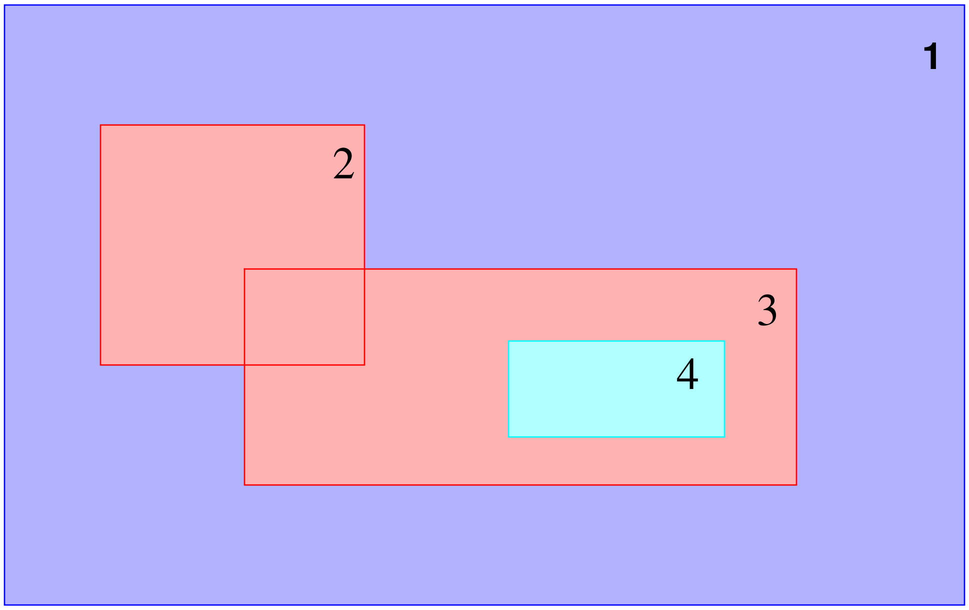

Fig 1.4 Example of a nesting configuration. The shading shows three different levels of nesting.

1.3 Nesting

MM5 contains a capability of multiple nesting with up to nine domains running at the same time and completely interacting. A possible configuration is shown in Fig 1.4. The nesting ratio is always 3:1 for two-way interaction. "Two-way interaction" means that the nest's input from the coarse mesh comes via its boundaries, while the feedback to the coarser mesh occurs over the nest interior.

It can be seen that multiple nests are allowed on a given level of nesting (e.g. domains 2 and 3 in Fig 1.4), and they are also allowed to overlap. Domain 4 is at the third level, meaning that its grid size and time step are nine times less than for domain 1. Each sub-domain has a "Mother domain" in which it is completely embedded, so that for domains 2 and 3 the mother domain is 1, and for 4 it is 3. Nests may be turned on and off at any time in the simulation, noting that whenever a mother nest is terminated all its descendent nests also are turned off. Moving a domain is also possible during a simulation provided that it is not a mother domain to an active nest and provided that it is not the coarsest mesh. Another example of nest configuration can be found in Fig 7.5.

There are three ways of doing two-way nesting (based on a switch called IOVERW). These are

- Nest interpolation (IOVERW=0). The nest is initialized by interpolating coarse-mesh fields. Topography, land-use coastlines only retain the coarse-mesh resolution. This option should be used with moving nests. It requires no additional input files.
- Nest analysis input (IOVERW=1). This requires a model input file to be prepared for the

nest in addition to the coarse mesh. This allows the inclusion of high-resolution topography and initial analyses in the nest. Usually such a nest would have to start up at the same time as the coarse mesh starts.

- Nest terrain input (IOVERW=2). This new option requires just a terrain/land-use input file, and the meteorological fields are interpolated from the coarse mesh and vertically adjusted to the new terrain. Such a nest can be started up at any time in the simulation, but there will be a period over which the model would adjust to the new topography.

One-way nesting is also possible in MM5. Here the model is first run to create an output that is interpolated using any ratio (not restricted to 3:1), and a boundary file is also created once a one-way nested domain location is specified. Typically the boundary file may be hourly (dependent upon the output frequency of the coarse domain), and this data is time-interpolated to supply the nest. Therefore one-way nesting differs from two-way nesting in having no feedback and coarser temporal resolution at the boundaries. The one-way nest may also be initialized with enhanced-resolution data and terrain. It is important that the terrain is consistent with the coarser mesh in the boundary zone, and the TERRAIN preprocessor needs to be run with both domains to ensure this.

1.4 Nonhydrostatic Dynamics Versus Hydrostatic Dynamics

Historically the Penn State/NCAR Mesoscale Model has been hydrostatic because typical horizontal grid sizes in mesoscale models are comparable with or greater than the vertical depth of features of interest. Therefore the hydrostatic approximation holds and the pressure is completely determined by the overlying air's mass. However when the scale of resolved features in the model have aspect ratios nearer unity, or when the horizontal scale becomes shorter than the vertical scale, nonhydrostatic dynamics should not be neglected.

The only additional term in nonhydrostatic dynamics is vertical acceleration that contributes to the vertical pressure gradient so that hydrostatic balance is no longer exact. Pressure perturbations from a reference state (described later) together with vertical momentum become extra three-dimensional predicted variables that have to be initialized. The vertical coordinate, as mentioned above, is also slightly differently defined so initializing the nonhydrostatic model option requires a different input dataset from the hydrostatic and this choice is made in the INTERP deck.

1.5 Reference State in the Nonhydrostatic Model

The reference state is an idealized temperature profile in hydrostatic equilibrium. It is specified by the equation

$$T_0 = T_{s0} + A\log_e(p_0/(p_{00})) \tag{1.2}$$

T_0 (p_0) is specified by 3 constants: p_{00} is sea-level pressure taken to be 10^5 Pa, T_{s0} is the reference temperature at p_{00}, and A is a measure of lapse rate usually taken to be 50 K, representing the temperature difference between p_{00} and p_{00}/e = *36788* Pa. These constants are chosen in the INTERP program. Usually just T_{s0} needs to be selected based on a typical sounding in the domain. The reference profile represents a straight line on a T-log p thermodynamic diagram. The accuracy of the fit is not important, and typically T_{s0} is taken to the nearest 10 K (e.g. 270, 280, 290, 300 in polar, midlatitude winter, midlatitude summer, and tropical conditions, respectively). A closer fit however does reduce the pressure gradient force error associated with sloped coordinate surfaces over terrain, so T_{s0} should be selected by comparison with the lower tropospheric profile.

The surface reference pressure therefore depends entirely upon the terrain height. This can be derived from (1.2) using the hydrostatic relation,

$$Z = -\frac{RA}{2g}\left(\ln\frac{p_0}{p_{00}}\right)^2 - \frac{RT_{s0}}{g}\left(\ln\frac{p_0}{p_{00}}\right) \tag{1.3}$$

and this quadratic can be solved for p_0 (surface) given Z, the terrain elevation. Once this is done, the heights of the model σ levels are found from

$$p_0 = p_{s0}\sigma + p_{top} \tag{1.4}$$

where

$$p_{s0} = p_0(surface) - p_{top} \tag{1.5}$$

and then (1.3) is used to find Z from p_0.

It can be seen that since the reference state is independent of time, the height of a given grid point is constant.

1.6 Four-Dimensional Data Assimilation

In situations where data over an extended time period is to be input to the model, four-dimensional data assimilation (FDDA) is an option that allows this to be done. Essentially FDDA allows the model to be run with forcing terms that “nudge” it towards the observations or an analysis. The benefit of this is that after a period of nudging the model has been fit to some extent to all the data over that time interval while also remaining close to a dynamical balance. This has advantages over just initializing with an analysis at a single synoptic time because adding data over a period effectively increases the data resolution. Observations at a station are carried downstream by the model and may help fill data voids at later times.

The two primary uses for FDDA are dynamical initialization and four-dimensional datasets. Dynamical initialization is where FDDA is used over a pre-forecast period to optimize the initial conditions for a real-time forecast. It has been shown that the added data is beneficial to forecasts compared to a static initialization from an analysis at the initial time. The second application, four-dimensional datasets, is a method of producing dynamically balanced analyses that have a variety of uses from budget to tracer studies. The model maintains realistic continuity in the flow and geostrophic and thermal-wind balances while nudging assimilates data over an extended period.

Two methods of data assimilation exist that depend on whether the data is gridded or individual observations. Gridded data, taking the form of analyses on the model grid, are used to nudge the model point-by-point with a given time constant. This is often most useful on larger scales where an analysis can accurately represent the atmosphere between the observations that go into it. For smaller scales, asynoptic data, or special platforms such as profilers or aircraft, where full analyses cannot be made, individual observations may be used to nudge the model. Here each observation is given a time window and a radius of influence over which it affects the model grid. The weight of the observation at a grid point thus depends upon its spatial and temporal distance from the observation, and several observations may influence a point at a given time.

1.7 Land-Use Categories

The model has the option of three sets of land-use categorizations (Table 4.2) that are assigned along with elevation in the TERRAIN program from archived data. These have 13, 16, or 24 categories (type of vegetation, desert, urban, water, ice, etc.). Each grid cell of the model is assigned one of the categories, and this determines surface properties such as albedo, roughness length, longwave emissivity, heat capacity and moisture availability. Additionally, if a snow cover dataset is available, the surface properties may be modified accordingly. The values in the table are also variable according to summer or winter season (for the northern hemisphere). Note that the values are climatological and may not be optimal for a particular case, especially moisture availability.

A simpler land-use option distinguishes only between land and water, and gives the user control over the values of surface properties for these categories.

1.8 Map Projections and Map-Scale Factors

The modeling system has a choice of several map projections. Lambert Conformal is suitable for mid-latitudes, Polar Stereographic for high latitudes and Mercator for low latitudes. The x and y directions in the model do not correspond to west-east and north-south except for the Mercator projection, and therefore the observed wind generally has to be rotated to the model grid, and the model u and v components need to be rotated before comparison with observations. These transformations are accounted for in the model pre-processors that provide data on the model grid, and post-processors.

The map scale factor, m, is defined by

m = (distance on grid) / (actual distance on earth)

and its value is usually close to one varying with latitude. The projections in the model preserve the shape of small areas, so that dx=dy everywhere, but the grid length varies across the domain to allow a representation of a spherical surface on a plane surface. Map-scale factors need to be accounted for in the model equations wherever horizontal gradients are used.

1.9 Data Required to Run the Modeling System

Since the MM5 modeling system is primarily designed for real-data studies/simulations, it requires the following datasets to run:

- Topography and landuse (in categories);
- Gridded atmospheric data that have at least these variables: wind, temperature, relative humidity and geopotential height; and at these pressure levels: surface, 1000, 850, 700, 500, 400, 300, 250, 200, 150, 100 mb;
- Observation data that contains soundings and surface reports.

Mesouser provides a basic set of topography, landuse and vegetation data that have global coverage but variable resolution. The Data Support Section of Scientific Computing Division at NCAR has an extensive archive of atmospheric data from gridded analyses to observations. For information on how to obtain data from NCAR, please visit URL: *http://www.scd.ucar.edu/dss/index.html.*