3. Methodology of TERRAIN

The purpose of TERRAIN is to create the terrain height and land-use files on the mesoscale model grids from the regular latitude-longitude interval source terrain height and land-use characteristics data. To accomplish this goal, the following five procedures are used in TERRAIN for each desired model domain:

1. Calculate the latitudes and longitudes of the model domain grid points on the specified map projection.
2. Determine the area that covers the model domain (search area) and read in the source data within the search area.
3. Interpolate or objectively analyze the source terrain data to the model grids. Create the terrain height file for each model domains.
4. Interpolate the source land-use data to the model grids. Create the land-use file for each model domain.
5. Reset the terrain height and land-use data along the nest boundaries. Replace the terrain height of the overlapping grid points with its highest nest level terrain height.

In the following sections we describe in detail the methods used to complete the above procedure.

3.1 Map projections

Three types of map projections are supported by TERRAIN: Lambert conformal, polar stereographic, and Mercator. The Lambert conformal projection is usually used in the mid-latitude region; the polar stereographic projection is used in the higher latitudes; and the Mercator projection is used in the equatorial region. TERRAIN allows the users to specify their own true latitudes for Lambert conformal and Polar stereographic projections (defined through the terrain namelist variables, TRUELAT1 and TRUELAT2). At present, TERRAIN does not allow the users to specify their true latitude for the

Mercator projection. For the Mercator projection, the true latitude is always set at the equator.

When the type of projection, true latitudes (ϕ_1, ϕ_2), central latitude (ϕ_c), and longitude (λ_c) of the coarse domain and the relationship between the coarse and nested domains are specified, the latitudes and longitudes (ϕ, λ) of the grid points or the grid indices (I, J) of any domain given by latitude and longitude can be calculated from the equations described in the following section. Since the PSU/NCAR mesoscale modeling system uses the staggered "Arakawa B grid" (Arakawa and Lamb, 1977) and the terrain height and land-use are defined at the cross points, the I and J referred to here are the indices of the cross points. The model grid indices I and J are always increased from south to north and from west to east. This means the Y-direction of the model domain always points to the north even if the domain is located in the southern hemisphere.

3.1.1 Mercator projection

• *Calculate ϕ, λ from I, J:*

For Mercator map projection, the grid point latitude is defined as

$$\phi = 2 \times conv \times tan^{-1} \left[exp \left(\frac{Y_c + (I - I_c) \times ds}{C_2} \right) \right] - 90 \qquad (3.1.1)$$

and the grid point longitude is defined as

$$\lambda = \lambda_c + conv \times \frac{(J - J_c) \times ds}{C_2} \qquad (3.1.2)$$

where

$$conv = 57.29578$$

$$C_2 = A \times cos(\phi_1)$$

$$Y_c = C_2 \times ln \left(\frac{1 + sin(\phi_c)}{cos(\phi_c)} \right)$$

where

$$A = 6370km$$

$$\phi_1 = 0$$

In equations (3.1.1) and (3.1.2), I and J represent the model grid indices. The variable Y_c is the distance from the pole to the center of the coarse domain. The variable A is the earth's radius, ds is the grid distance of the given domain, $conv$ is a constant used to convert degrees to radian, ϕ_1 is the true latitude (which is always 0 for the Mercator projection in TERRAIN), and ϕ_c and λ_c are the center latitude and longitude of the coarse domain. The variables I_c and J_c are the grid indices of a given domain that mark the coarse domain center. They can be obtained from the relationship between the coarse domain and the given domain.

$$I_c = (I_{c0} - I_x) \times ratio + 0.5$$

$$J_c = (J_{c0} - J_x) \times ratio + 0.5$$

where $ratio$ is the ratio of the grid size of the coarse to the given domain. I_x and J_x are the coarse domain grid indices that mark the lower left corner of the given domain in the coarse domain. I_{c0} and J_{c0} are the grid indices of the coarse domain center point. Note that here I_{c0}, J_{c0}, I_x, and J_x are the coarse domain dot point grid indices, and

$$I_{c0} = \frac{(IMX + 1)}{2}$$

$$J_{c0} = \frac{(JMX + 1)}{2}$$

where IMX and JMX are the coarse domain dimensions.

• *Calculate* I, J *from* ϕ, λ*:*

To calculate the domain grid indices I and J at the given latitude and longitude ϕ and λ, use equations (3.1.3) and (3.1.4).

$$I = (I_{c0} + \frac{(Y - Y_c)}{ds_0} - I_x) \times ratio + 0.5 \tag{3.1.3}$$

$$J = (J_{c0} + \frac{X}{ds_0} - J_x) \times ratio + 0.5 \tag{3.1.4}$$

where

$$Y = C_2 \times ln\left(\frac{1+sin(\phi)}{cos(\phi)}\right),$$

$$X = C_2 \times \frac{(\lambda - \lambda_c)}{conv},$$

and ds_0 is the coarse domain grid distance.

3.1.2 Lambert Conformal projection

• *Calculate ϕ, λ from I, J:*

For the Lambert conformal map projection, the model grid point latitude and longitude are defined as

if $\phi_c > 0$:

$$\phi = 90 - 2 \times conv \times tan^{-1}\left[tan(\frac{\psi_1}{2}) \times \left(\frac{R \times \kappa}{A \times sin(\psi_1)}\right)^{\frac{1}{\kappa}}\right] \tag{3.1.5a}$$

$$\lambda = \begin{cases} \lambda' + 360 & \lambda' < -180 \\ \lambda' & -180 \le \lambda' \le 180 \\ \lambda' - 360 & \lambda' > 180 \end{cases} \tag{3.1.6a}$$

$$\lambda' = \lambda_c + \frac{conv}{\kappa} \times tan^{-1}\left(\frac{X}{Y}\right)$$

if $\phi_c < 0$:

$$\phi = -90 - 2 \times conv \times tan^{-1}\left[tan(\frac{\psi_1}{2}) \times \left(\frac{-R \times \kappa}{A \times sin(\psi_1)}\right)^{\frac{1}{\kappa}}\right] \tag{3.1.5b}$$

$$\lambda = \begin{cases} \lambda' + 360 & \lambda' < -180 \\ \lambda' & -180 \le \lambda' \le 180 \\ \lambda' - 360 & \lambda' > 180 \end{cases} \tag{3.1.6b}$$

$$\lambda' = \lambda_c + \frac{conv}{\kappa} \times tan^{-1}\left(\frac{X}{-Y}\right)$$

where the X, Y, and R are defined as

$$X = (J - J_c) \times ds$$

$$Y = (I - I_c) \times ds + Y_c$$

$$R = (X^2 + Y^2)^{1/2}$$

where,

if $\phi_c > 0$:

$$Y_c = -\frac{A}{\kappa} \times sin(\psi_1) \times \left[\frac{tan((90 - \phi_c)/conv/2)}{tan(\psi_1/2)}\right]^{\kappa}$$

if $\phi_c < 0$:

$$Y_c = -\frac{A}{\kappa} \times sin(\psi_1) \times \left[\frac{tan((-90 - \phi_c)/conv/2)}{tan(\psi_1/2)}\right]^{\kappa}$$

The variable ψ_1 is the co-latitude and κ is the cone constant. Both of them can be obtained from the true latitudes ϕ_1 and ϕ_2.

if $\phi_c > 0$:

$$\psi_1 = (\frac{\pi}{2} - \frac{|\phi_1|}{conv})$$

if $\phi_c < 0$:

$$\psi_1 = -(\frac{\pi}{2} - \frac{|\phi_1|}{conv})$$

κ is defined as

$$\kappa = \frac{log_{10}\left(cos(\phi_1/conv)\right) - log_{10}\left(cos(\phi_2/conv)\right)}{log_{10}\left(tan((45 - \frac{|\phi_1|}{2})/conv)\right) - log_{10}\left(tan((45 - \frac{|\phi_2|}{2})/conv)\right)}.$$

• *Calculate I, J from ϕ, λ:*

The domain grid indices I and J at a given latitude and longitude (ϕ and λ) for the Lambert conformal map projection are defined as

$$I = (I_{c0} - (\frac{Y_c}{ds_0} + \frac{R_s}{ds_0} \times cos\left(\kappa \times \frac{(\lambda - \lambda_c)}{conv}\right)) - I_x) \times ratio + 0.5 \tag{3.1.7}$$

if $\phi_c > 0$:

$$J = (J_{c0} + \frac{R_s}{ds_0} \times sin\left(\kappa \times \frac{(\lambda - \lambda_c)}{conv}\right) - J_x) \times ratio + 0.5 \tag{3.1.8a}$$

if $\phi_c < 0$:

$$J = (J_{c0} - \frac{R_s}{ds_0} \times sin\left(\kappa \times \frac{(\lambda - \lambda_c)}{conv}\right) - J_x) \times ratio + 0.5 \tag{3.1.8b}$$

where

if $\phi_c > 0$:

$$R_s = \frac{A}{\kappa} \times sin(\psi_1) \times \left[\frac{tan((90 - \phi)/conv/2)}{tan(\psi_1/2)}\right]^{\kappa}$$

if $\phi_c < 0$:

$$R_s = \frac{A}{\kappa} \times sin(\psi_1) \times \left[\frac{tan((-90 - \phi)/conv/2)}{tan(\psi_1/2)}\right]^{\kappa}$$

3.1.3 Polar Stereographic projection

The polar stereographic projection can have either the pole points inside or outside the domain. However, if the pole points are inside any given domain, the user can only use the polar stereographic map projection.

• *Calculate ϕ, λ from I, J:*

The equation used to calculate the latitude ϕ from the model grid indices I and J for the polar stereographic map projection is defined as if $\phi_c > 0$:

$$\phi = 90 - 2 \times conv \times tan^{-1}\left[\frac{R/A}{1 + cos(\psi_1)}\right], \qquad (3.1.9a)$$

if $\phi_c < 0$:

$$\phi = -90 - 2 \times conv \times tan^{-1}\left[\frac{R/A}{1 + cos(\psi_1)}\right], \qquad (3.1.9b)$$

The longitude λ can be obtained from equation (3.1.6). However, $\kappa = 1.0$ and the variable Y_c in equation (3.1.6) for the polar stereographic projection is defined as

if $\phi_c > 0$:

$$Y_c = -A \times sin(\frac{90 - \phi_c}{conv}) \times \frac{1 + cos(\psi_1)}{1 + cos((90 - \phi_c)/conv)}.$$

if $\phi_c < 0$:

$$Y_c = -A \times sin(\frac{-90 - \phi_c}{conv}) \times \frac{1 + cos(\psi_1)}{1 + cos((-90 - \phi_c)/conv)}.$$

If the pole is inside the domain, at some grid points (where $I = I_c$) whose north-south distance (in Y-direction) to the pole is zero, the λ' for these points with $Y = 0$ becomes

$$\lambda' = \begin{cases} \lambda_c + 90 & X \geq 0 \\ \lambda_c - 90 & X < 0 \end{cases} \qquad (3.1.10)$$

• *Calculate I, J from ϕ, λ:*

The equations used to calculate the domain grid indices I and J given the latitude and longitude (ϕ and λ) for the polar stereographic projection are exactly the same as those of (3.1.7) and (3.1.8) for the Lambert conformal projection. However, κ is set to be 1.0 and R_s is defined as

if $\phi_c > 0$:

$$R_s = A \times sin(\frac{90-\phi}{conv}) \times \frac{1+cos(\psi_1)}{1+cos((90-\phi)/conv)}$$

if $\phi_c < 0$:

$$R_s = A \times sin(\frac{-90-\phi}{conv}) \times \frac{1+cos(\psi_1)}{1+cos((-90-\phi)/conv)}$$

In summary, when the map parameters, the projection , ϕ_1, ϕ_2, ϕ_c, λ_c, IMX, JMX, ds_0, I_x, J_x, $ratio$, and ds are given, ϕ and λ can be calculated from I, J and vice versa.

The latitude range (ϕ) for equations (3.1.1), (3.1.2), (3.1.5), (3.1.6), and (3.1.9) is from –90 South to 90 North. The negative latitude indicates the southern hemisphere. The longitude range (λ) for equations (3.1.4), (3.1.6), and (3.1.10) is from –180 West to 180 East. The negative longitude indicates the western hemisphere. All the equations described in this section are used in subroutines SETUP, RFLP, LATLON, and XYOBSLL.

3.2 Search area

To use the source terrain and land-use data efficiently, it is necessary to allow only a subset of the source data which covers the desired mesoscale domain to be stored in the computer core memory. Thus, TERRAIN needs to compute the minimum area in the source data that is a little bigger than the desired model domain, hereafter referred to as the search area. For Mercator and Lambert conformal map projections, the pole is always outside the domain. It is relatively easy to find the search area. The search area can be obtained from the domain grid point latitudes and longitudes and the domain position relative to the user-defined central latitude and longitude (ϕ_c and λ_c). However, it is more complicated to compute the search area if the polar stereographic projection is used and the pole is inside the coarse domain. The approaches to determine the search area, which is defined by the minimum and maximum latitude and longitude (ϕ_{min}, ϕ_{max}, λ_{min}, and λ_{max} respectively) for the coarse and nest domains, are discussed in detail in this section.

3.2.1 General situation

In the MM5 system, each domain is defined as a rectangular box. If using the Mercator, Lambert conformal, or polar stereographic map projections with pole outside the coarse domain (the rule to determine poles inside or outside domains is given in section 3.2.3), there are only three types of domain setup relative to the position of the user-defined central longitude λ_c (index $J = J_{c0}$) for coarse domain and any nest domains.

1) the central longitude is inside the domain, $XW_n \leq J_{c0} \leq XE_n$;

2) the domain is located west of the central longitude, $XE_n \leq J_{c0}$; and

3) the domain is located east of the central longitude, $XW_n \geq J_{c0}$.

Based on the mother domain indices (I_x, J_x) that define the nest domain point (1,1), the mother and nest domain grid distance DIS_m and DIS_n, and the nest domain dimensions IXN and JXN, the four coarse domain indices XW_n (west), XE_n (east), XS_n (south), and XN_n (north) that define the nest domain boundary points are

$$XDIS = (I_x - 1) * DIS_m$$

$$YDIS = (J_x - 1) * DIS_m$$

$$XW_n = YDIS/DIS_c + YOFF + 1$$

$$XE_n = XW_n + (JXN - 1) * DIS_n/DIS_c$$

$$XS_n = XDIS/DIS_c + XOFF + 1$$

$$XN_n = XS_n + (IXN - 1) * DIS_n/DIS_c$$

where $XDIS$ and $YDIS$ are the distance of the nest domain point (1,1) to its mother domain point (1,1). If the nest domain's nest level is greater than 1 (the coarse domain is defined as nest level 0), the final $XDIS$ and $YDIS$ used to compute the coarse domain indices XW_n and XS_n are the summation of all the $XIDS$ and $YDIS$ calculated for each mother-daughter domain pair. The DIS_c is the coarse domain grid distance. If the coarse domain is expanded, XOFF and YOFF are the expanded grid points.

For the coarse domain, the central longitude is always inside the domain. Nest domains may or may not have the central longitude inside the domains.

In order to help users understand the searching methods, the domain example given here is a coarse domain with center longitude and latitude of 180°E and 40°N or 180°E and 40°S. It has two nest domains: domain 2 located west of the 180°E line, and domain 3 located east of the 180°E line (Fig. 3.1).

1) Central longitude is inside the domain ($XW_n \leq J_{c0} \leq XE_n$ or coarse domain):

In the northern hemisphere ($\phi_c > 0$), this type of domain setup has the longitude lines tilted toward the northeast for grid points west of the central longitude and toward the northwest for grid points east of the central longitude (Fig. 3.2a). In the southern hemisphere ($\phi_c < 0$) it is vice versa (Fig. 3.2b). Therefore, if $\phi_c > 0$, the minimum longitude of the domain is always located at the domain point $(IX, 1)$ and the maximum longitude is located at the domain point (IX, JX). If $\phi_c < 0$, the minimum longitude is located at the domain point (1,1) and the maximum longitude is located at the domain point $(1, JX)$. As for the minimum and maximum latitude, if $\phi_c > 0$, the minimum latitude is the minimum latitude of point (1,1) and $(1, JX)$ and the maximum latitude must be located on the northern boundary ($I = IX$). For $\phi_c < 0$, the minimum latitude must be located on the southern boundary ($I = 1$) and the maximum latitude is the maximum latitude of point $(IX, 1)$ and (IX, JX).

if $\phi_c > 0$:

$$\phi_{min} = MIN(\phi(1,1), \phi(1, JX)) - d'$$

$$\phi_{max} = MAX(\phi(IX,1), \phi(IX,2), ..., \phi(IX, JX)) + d'$$

$$\lambda_{min} = \lambda(IX, 1) - d'$$

$$\lambda_{max} = \lambda(IX, JX) + d'$$

if $\phi_c < 0$:

$$\phi_{min} = MIN(\phi(1,1), \phi(1,2), ..., \phi(1, JX)) + d'$$

$$\phi_{max} = MAX(\phi(IX,1), \phi(IX,JX)) - d'$$

$$\lambda_{min} = \lambda(1,1) - d'$$

$$\lambda_{max} = \lambda(1,JX) + d'$$

where IX and JX are the coarse or nest domain dimensions. d' is an increment used to expand the search area a little bigger than the domain. The current values of d' are 2.5° for the source data with 1-degree or 30-minute resolution and 1° for the source data with 10-minute, 5-minute and 30-second resolution.

2) Domain located west of the central longitude ($XE_n \leq J_{c0}$):

If the nest domain is located west of the central longitude, the longitude lines within the nest domain are always tilted toward the northeast in the northern hemisphere and toward the northwest in the southern hemisphere. Therefore, if $\phi_c > 0$, the minimum longitude is located at the nest domain point $(IXN,1)$ and the maximum longitude is located at the nest domain point $(1,JXN)$ (Fig. 3.2c). If $\phi_c < 0$, then the minimum longitude is located at the nest domain point (1,1) and the maximum longitude is located at the nest domain point (IXN,JXN) (Fig. 3.2d). For $\phi_c > 0$, the minimum and maximum latitudes are located at nest domain points (1,1) and (IXN,JXN), and for $\phi_c < 0$, they are located at $(1,JXN)$ and $(IXN,1)$ positions.

if $\phi_c > 0$:

$$\phi_{min} = \phi(1,1) - d'$$

$$\phi_{max} = \phi(IXN,JXN) + d'$$

$$\lambda_{min} = \lambda(IXN,1) - d'$$

$$\lambda_{max} = \lambda(1,JXN) + d'$$

if $\phi_c < 0$:

$$\phi_{min} = \phi(1,JXN) - d'$$

$$\phi_{max} = \phi(IXN,1) + d'$$

$$\lambda_{min} = \lambda(1,1) - d'$$

$$\lambda_{max} = \lambda(IXN, JXN) + d'$$

where IXN, JXN are the dimensions of the nest domains.

3) Domain located east of the central longitude ($XW_n \geq J_{c0}$):

For this type of nest domain setup, the longitude lines are always tilted toward the northwest in the northern hemisphere and toward the northeast in the southern hemisphere. Therefore, when $\phi_c > 0$, the minimum longitude is located at the nest domain point (1,1) and the maximum longitude is located at point (IXN, JXN) as shown in Fig. 3.2e. When $\phi_c < 0$, the minimum longitude is located at the nest domain point $(IXN, 1)$ and the maximum longitude is located at point $(1, JXN)$ (Fig. 3.2f). The minimum and maximum latitudes when $\phi_c > 0$ are located at points $(1, JXN)$ and $(IXN, 1)$ respectively. When $\phi_c < 0$, they are located at grid points (1,1) and (IXN, JXN) respectively.

if $\phi_c > 0$:

$$\phi_{min} = \phi(1, JXN) - d'$$

$$\phi_{max} = \phi(IXN, 1) + d'$$

$$\lambda_{min} = \lambda(1,1) - d'$$

$$\lambda_{max} = \lambda(IXN, JXN) + d'$$

if $\phi_c < 0$:

$$\phi_{min} = \phi(1,1) - d'$$

$$\phi_{max} = \phi(IXN, JXN) + d'$$

$$\lambda_{min} = \lambda(IXN, 1) - d'$$

$$\lambda_{max} = \lambda(1, JXN) + d'$$

3.2.2 Domains across date line

The date line is a discontinuous line of longitude (λ). When the domains are across the date line, the minimum longitude λ_{min} is greater than the maximum longitude λ_{max}. In this case, the λ_{min} is converted to a negative value by subtracting 360, i.e.

$$\lambda_{min} = \lambda_{min} - 360,$$

so that the λ_{min} is always less than λ_{max}, and also $\lambda_{min} < -180$.

For any domain, $\lambda_{min} < -180$ always means that "*the domain is across the date line.*" If $\lambda_{min} < -180$, the same kind of longitude conversion must be made on the grid points whose $\lambda > \lambda_{max}$ prior to the check of whether the data are within the search area during the process of reading in the source data.

3.2.3 North or south poles are inside the domains

This situation can occur only when the polar stereographic map projection is used. To determine whether the north or south poles are inside the coarse domain, TERRAIN calculates an angle which is defined by the two longitude lines from the north pole to the two upper corners of the coarse domain if $\phi_c > 0$, or from the south pole to the two lower corners of the coarse domain if $\phi_c < 0$. The angle is counted counter-clockwise from the east to the west longitude lines (Fig. 3.3a and 3.3b for $\phi_c > 0$ and Fig. 3.3c and 3.3d for $\phi_c < 0$). α is defined as

if $\phi_c > 0$:

$$\alpha = \begin{cases} -\lambda(IX,JX) + \lambda(IX,1) & \lambda(IX,JX) < \lambda(IX,1) \\ 360 - \lambda(IX,JX) + \lambda(IX,1) & \lambda(IX,JX) \geq \lambda(IX,1) \end{cases}$$

The pole is inside the domain when $\alpha \leq 180$ and outside the domain when $\alpha > 180$.

if $\phi_c < 0$:

$$\alpha = \begin{cases} -\lambda(1,1) + \lambda(1,JX) & \lambda(1,1) < \lambda(1,JX) \\ 360 - \lambda(1,1) + \lambda(1,jx) & \lambda(1,1) \geq \lambda(1,JX), \end{cases}$$

The pole is inside the domains when $\alpha \geq 180$ and outside the domain when $\alpha < 180$.

If the pole is inside the coarse domain, the minimum and maximum latitude and longitude are defined as

if $\phi_c > 0$:

$$\phi_{min} = MIN(\phi(1,1), \phi(1,JX), \phi(IX,JX), \phi(IX,1)) - d'$$

$$\phi_{max} = 90$$

$$\lambda_{min} = -180$$

$$\lambda_{max} = 180$$

if $\phi_c < 0$:

$$\phi_{min} = -90$$

$$\phi_{max} = MAX(\phi(1,1), \phi(1,JX), \phi(IX,JX), \phi(IX,1)) + d'$$

$$\lambda_{min} = -180$$

$$\lambda_{max} = 180$$

Even when the pole is inside the coarse domain, the nest domains may or may not contain the pole. TERRAIN uses two criteria to determine whether the pole is also inside any nest domains. They are the product of the longitudes of any two consecutive nest boundaries' grid points and their absolute difference.

The combination of these two criteria can determine how many times the nest boundaries are across the date line and the 0-degree longitude line. The pole is inside the nest domain only if the nest boundaries are across the date and 0-degree longitude lines. Since the longitudes of the model domain grid point range between 0° to 180°E and –180°W to 0°, when the nest boundaries are across the 180°, –180°, and 0° lines, the longitude product of the two grid points will be less than zero. To further decide whether the nest boundaries are across the date line or the 0-degree longitude line, TERRAIN computes the absolute longitude differences between the two consecutive boundary grid points. If the boundary is across the date line, then the absolute longitude difference between the two consecutive grid points that are located on either side of the date line will be greater than 180° (since their longitudes are close to 180° but with a different sign). On the other hand, if the boundary is across the 0-degree line, then the absolute longitude difference between the two consecutive grid points that are located on either side of the 0-degree longitude line will be less than 180°(since they are close to the 0-degree longitude line and less than 90° or –90°). The mathematic forms of this method can be expressed as follows:

1) Calculate the longitude product of the consecutive points along the nest boundaries. When the product is less than 0, save the value of its absolute longitude difference at these points.

   southern boundary ($J = 1, JXN - 1$):

$$if(\lambda(1,J) * \lambda(1,J+1) < 0.0)$$

$$\gamma = |\lambda(1,J) - \lambda(1,J+1)|$$

   eastern boundary ($I = 1, IXN - 1$):

$$if(\lambda(I,JXN) * \lambda(I+1,JXN) < 0.0)$$

$$\gamma = |\lambda(I,JXN) - \lambda(I+1,JXN)|$$

   northern boundary ($J = JXN, 2, -1$):

$$if(\lambda(IXN,J) * \lambda(IXN,J+1) < 0.0)$$

$$\gamma = |\lambda(IXN,J) - \lambda(IXN,J+1)|$$

western boundary ($I = IXN, 2, -1$):

$$if(\lambda(I,1) * \lambda(I+1,1) < 0.0)$$

$$\gamma = |\lambda(I,1) - \lambda(I+1,1)|$$

2) Compute the number of times (N) that the value of γ is greater than 200 for all four nest domain boundaries. Here 200 is an arbitrary value chosen by TERRAIN which is slightly greater than 180.

There are only three possible values for variable N. They are 0, 1, and 2. Again, to help users understand the method, a four-domain example is given (Fig. 3.4). The coarse domain (domain 1) contains the north pole. If N is equal to zero, the pole is outside the domain (domain 2 in Fig. 3.4). To get the nest domain minimum and maximum latitudes and longitudes, search through all nest domain grid point latitudes and longitudes. If N is equal to one, the pole is inside the domain (domain 4 in Fig. 3.4). The nest domain minimum and maximum latitude and longitude are defined as the pole is inside the coarse domain. If N is equal to 2, the pole is outside the nest domain and the nest domain is across the date line (domain 3 in Fig. 3.4). Since the domain is across the date line, the grid point longitudes can be positive or negative. In order to sort out the minimum and maximum longitude of the nest domain, TERRAIN first converts the longitudes of nest domain grid points to between $-360°$ to $0°$ and finds the minimum and maximum longitudes. After the minimum and maximum longitudes and latitudes have been decided, the value of d' is included to determine the final search area.

The methods to find the search area described in this section are used in subroutines MXMNLL and NESTLL.

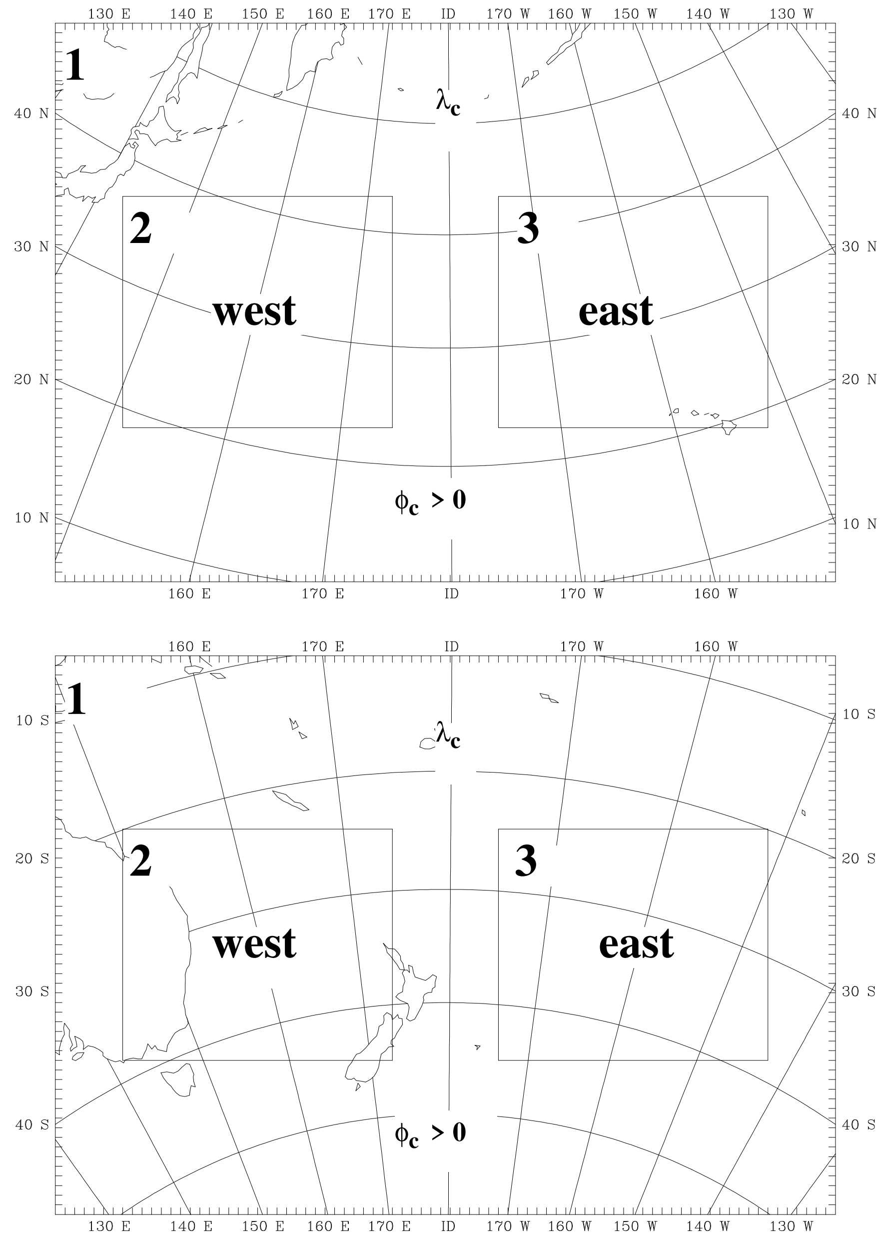

Figure 3.1 Example of 3 domains for northern (upper) and southern (lower) hemispheres. Domain 1 is a coarse domain with $\phi_c=\pm40^o$, $\lambda c=\pm180^o$, and domain 2 is west of the λc; domain 3 is east of the λc.

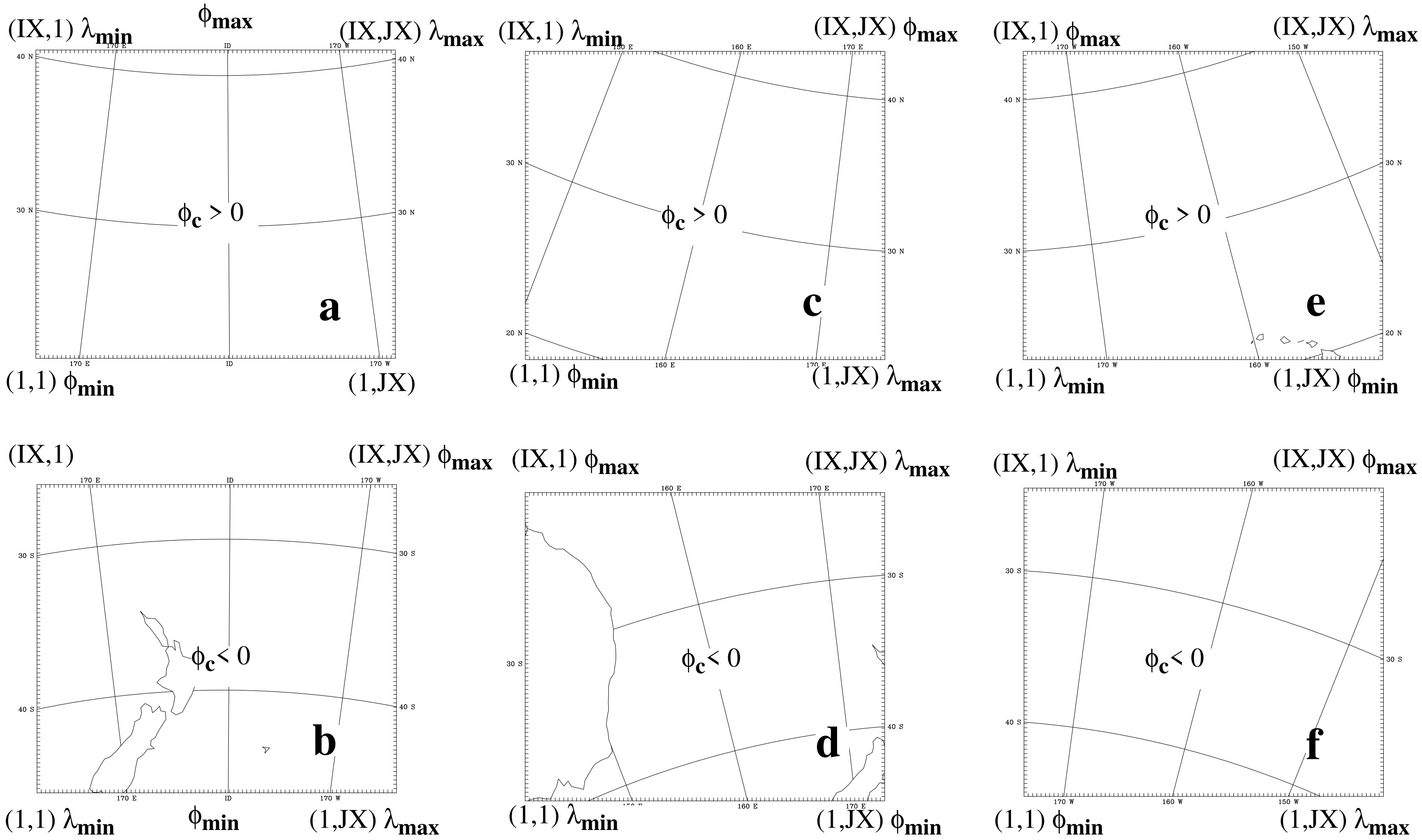

Figure 3.2 Maximum and minimum latitude and longitude for a) central longitude is inside the domain for $\phi_c > 0$, and b) for $\phi_c < 0$; c) domain located west of the central longitude for $\phi_c > 0$, and d) for $\phi_c < 0$, e) domain located east of the central longitude for $\phi_c > 0$, and f) for $\phi_c < 0$.

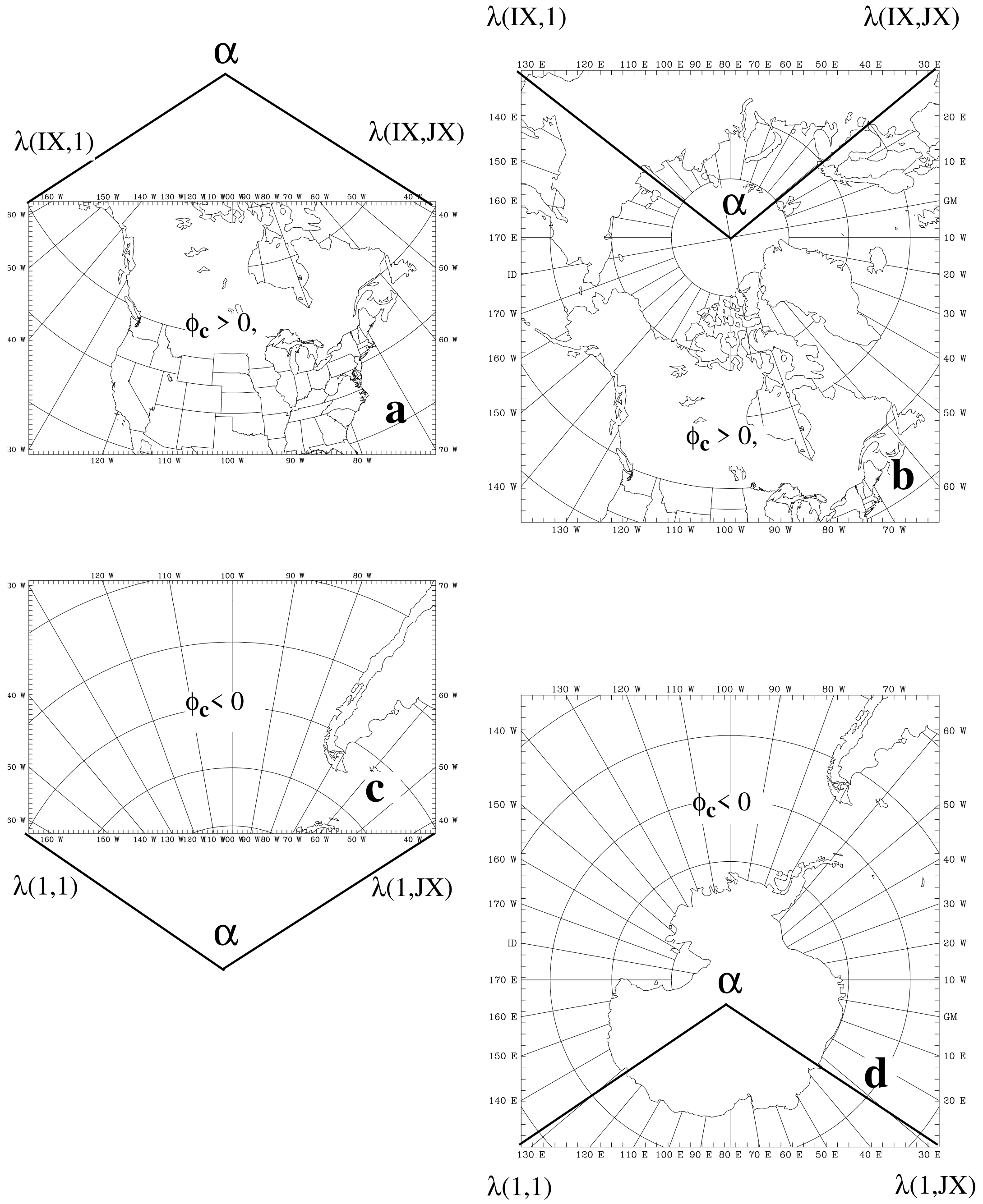

Figure 3.3 Angle α determines the pole location for a) $\alpha > 180$, pole is outside the domain for $\phi_{\mathbf{c}} > 0$ and b) $\alpha < 180$, the pole is inside the domain for $\phi_{\mathbf{c}} > 0$; c) $\alpha < 180$, the pole is outside the domain for $\phi_{\mathbf{c}} < 0$, and d) $\alpha > 180$, the pole is inside the domain for $\phi_{\mathbf{c}} < 0$.

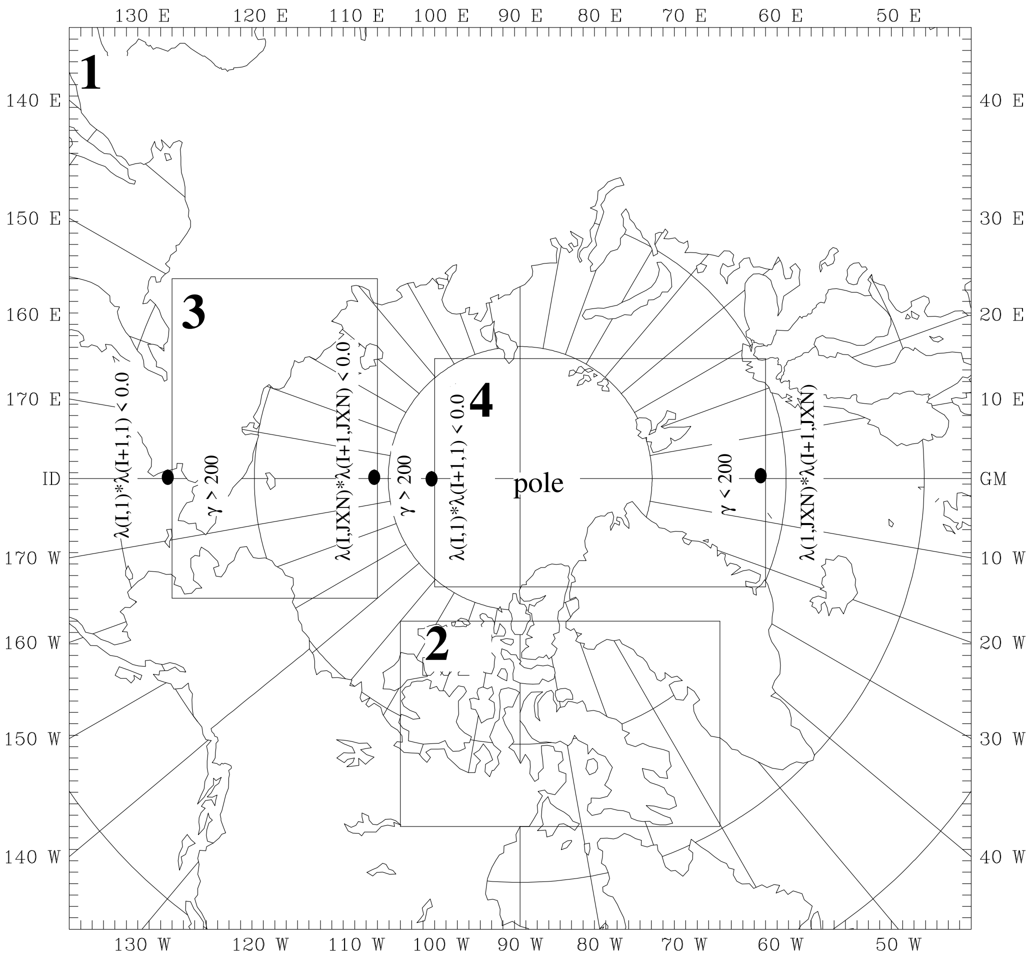

Figure 3.4 Example of 4 domains using the polar stereographic projection. Domain 1 is the coarse domain with the pole inside; domain 2 is the general situation; domain 3 is across the date line; and domain 4 contains the north pole

3.3 Create the terrain height on the mesoscale grids

There are two methods to create the terrain height on the mesoscale model grids: overlapping parabolic interpolation and Cressman-type objective analysis. These two methods are often used in other parts of the modeling system. Manning and Haagensen (1992) have a detailed description of these two methods. The attempt here is to point out how the TERRAIN program creates the terrain height on the mesoscale grids using these two methods.

3.3.1 Overlapping parabolic interpolation

When this method is used, the mesoscale grid point's terrain height can be obtained by using a 16-point, two-dimensional overlapping parabolic fit method on the source data (see Functions BINT and ONED in section 5.3 for details). Since the source data are defined on the latitude and longitude grids with regular intervals, the minimum latitude and longitude of the source data within the search area may be different than the minimum latitude and longitude of the search area. The minimum longitude and latitude of the source data are first initialized to a value 2 degrees greater than the minimum latitude and longitude of the search area (see section 3.1). As the TERRAIN program reads in the source data, it then compares with the initial minimum values and finds the minimum latitude and longitude (ϕ_{gmin} and λ_{gmin}) of the source data within the search area. The minimum latitude and longitude of the source data are the first point (1,1) of the 2-D array (ht_s) used to obtain the terrain height on the mesoscale grids. The I and J indices of this (latitude-longitude) array are defined as

$$I = \frac{(\phi - \phi_{gmin})}{reso} + 1$$
$$J = \frac{(\lambda - \lambda_{gmin})}{reso} + 1$$

where ϕ and λ are the latitudes and longitudes of the source terrain data within the search area. $reso$ is the resolution of the source data in degrees.

To use the overlapping parabolic interpolation, one needs to know the I and J indices of this 2-D (latitude-longitude) array that define the mesoscale grids. Therefore, the indices of the mesoscale grid point (I_m and J_m), given their latitude and longitude values (ϕ_m and λ_m), can be found with the above formula by replacing ϕ and λ with ϕ_m and λ_m. Note that I_m and J_m are real numbers. If the domain is across the date line and λ_m is greater than the maximum longitude of the search area λ_{max}, the conversion of λ_m similar to section 3.2.2 must be made prior to the calculation of I_m and J_m.

if

$$\lambda_m > \lambda_{max} \quad and \quad \lambda_{gmin} < -180$$

then

$$\lambda_m = \lambda_m - 360$$

In order to preserve the coastline as accurately as possible, two special measures are taken. The negative terrain height from the source data is set to a small negative value of -10^{-50}, and if the source terrain height data closest to the mesoscale grid are less than 0.001, a negative value of -0.00001 terrain height is assigned to that mesoscale grid point. The subroutines RDLDTR, CRTER, INTERP and the functions BINT and ONED are used to create the terrain height field using the interpolation method.

3.3.2. Cressman-type objective analysis

A Cressman-type objective analysis is used to produce terrain height at the mesoscale grid points by treating the source terrain data $ht_s(\phi, \lambda)$ as the observations. This method requires the calculations to be performed on the mesoscale grids. First, convert the latitudes and longitudes (ϕ and λ) of the source data to the mesoscale grid indices (I_{obs} and J_{obs}). With the user-specified radius of influence R, only one scan is performed with the standard Cressman-type weighting function.

$$W_s = \begin{cases} (R^2 - r_s^2)/(R^2 + r_s^2) & r_s \le R \\ 0 & r_s > R \end{cases}$$

where $r_s^2 = (I - (I_{obs}))^2 + (J - (J_{obs}))^2$. The units of R is in grid distance, and I and J are the indices of the mesoscale grid points.

The terrain height on the mesoscale grids is defined as

$$HT(I,J) = \frac{\sum_{s=1}^{SN} W_s \times ht_s}{\sum_{s=1}^{SN} W_s}$$

where ht_s is the "observed" height and SN represents the total number of "stations" whose W_s is positive (within the region of influence). Whenever the height is more than 40000 meters, or for 30-second terrain height data the height is less than -1218 meters, it is considered as bad or missing data and is discarded by the program. Since the 30-second terrain height data cover only part of North America, the program assumes a grid point without observed data is an ocean grid point and assigns the value of -0.00001 to the $HT(I,J)$.

To preserve the coastline, the source terrain height with the maximum W_s for each of the mesoscale grid points are saved in an array HT_{sv} during the objective analysis process. The value of $HT_{sv}(I,J)$ is used to replace the value of $HT(I,J)$ if $HT_{sv}(I,J) \leq 0.001$. Also any negative $HT(I,J)$ are set to be -10^{-50}.

When using the objective analysis method to create the terrain height files, the user needs to specify the proper data resolution and radius of influence to get the best results. If the user uses low-resolution data with a small radius of influence, then there could be no observed data available within the region of influence for some grids, and the program will stop. If data resolution is too high or the radius of influence is too large, the final terrain height fields may be too smooth to use. The subroutines RDLDTR, CRTER, XYOBSLL, and ANAL2 are used for the Cressman-type objective analysis.

3.4 Create the land use on the mesoscale grids

As mentioned in chapter 2, the source land-use data has 13 land-use categories and each of the categories are represented by percentages (from 0% to 100%). However, the MM5 model requires that only one land-use category be assigned to a grid point (from 1 to 13, Table 2.2). Therefore, the following procedures are used to determine the dominant land-use at a grid point.

1. Obtain the percentages of each of the 13 land-use categories, $xln(id), id = 1, 2, ..., 13$, at the mesoscale grid point (I, J) by using the overlapping parabolic interpolation method on the source land-use data.

2. Determine the highest percentage from these 13 values of percentages, i.e.,

$$xln(id_{max}) = \begin{cases} MAX(xln(1), ..., xln(7), ..., xln(13)) & xln(7) \geq 50 \\ MAX(xln(1), ..., xln(6), xln(8), ..., xln(13)) & xln(7) < 50 \end{cases}$$

3. The land-use category at point (I, J) is the land-use category with the highest percentage.

$$lnd(I, J) = id_{max}$$

Note that for the grid boxes with less than 50% water (category 7), a land category is assumed even if water is the largest single category.

Users not satisfied with the final land-use data results may use the fudge function in the TERRAIN job script to fudge the grid points' land-use type. The maximum fudge points allowed by the program is set at 100. The subroutines RDLDTR, CRLND, FUDGER and functions BINT, ONED are used to create the land-use field.

After the terrain height and land-use fields are created, the following five steps are performed in sequence to get the final fields.

1. The terrain height fields are smoothed to remove the shorter waves. The user has the choice of using either the smoother-desmoother or the 1-2-1 smoother. Table 3.1 shows the response function of these two smoothers. In general, the 1-2-1 smoother smooths out more wave energy than the smoother-desmoother, especially for the 3 and 4 ΔX waves. The formulas of smoother-desmoother is defined as

$$\alpha^{'}(I,J) = \alpha(I,J) + smcf * [0.5 * (\alpha(I,J+1) + \alpha(I,J-1)) - \alpha(I,J)] \qquad (3.4.1)$$

$$\alpha^{*}(I,J) = \alpha^{'}(I,J) + smcf * [0.5 * (\alpha^{'}(I+1,J) + \alpha^{'}(I-1,J)) - \alpha^{'}(I,J)] \qquad (3.4.2)$$

where α is any variable to smooth and α^* is the smoothed variable. when the coefficient $smcf > 0$, (3.4.1) and (3.4.2) act on the field α as smoother, and $smcf < 0$, they become the desmoother to recover part of energy on the waves with wavelength more than $2\Delta X$. The smoother-desmoother algorithm is first applied the equation (3.4.1) in the J-direction and (3.4.2) in the I-direction with $smcf = 0.50$, then repeated to use (3.4.1) and (3.4.2) with $smcf = -0.52$.

The 1-2-1 smoother algorithm requires the application of equations (3.4.1) and (3.4.2) only with $smcf = 0.50$ as smoother, no desmoother is applied on the field α. There is no any energy recovery on the waves with wavelength more than $2\Delta X$.

2. If the land-use category is water and the terrain height is less than or equal to –1 meters, set the terrain height to -0.001 meters.

3. If the mesoscale domain covers the Great Lakes over the U.S., correct the terrain heights over the Great Lakes.

4. If the terrain height is between 0 and –1 meters, set the land-use category to water to preserve the coastline.

5. If the terrain fudge option is selected in the TERRAIN job script, assign the terrain heights to be -0.001 over the user-specified region if the land-use category is water. This option is designed for situations where there are islands off the continent with a narrow water area between them. If the domain grid spacings are large, the interpolation schemes may generate fictitious land bridges between the continent and the islands. Since this option can change the terrain height for any inland lakes, when the user defines this area, there should be no lakes within the specified domain.

6. Force a zero terrain gradient around the outer 2 rows and columns of the terrain field for the coarse domain.

The above methods are used in subroutines TERDVR, SMTH121, SMTHTR, LAKES, and BNDRY.

Table 3.1 Response Function of the Two-Dimensional Smoother
The table shows energy remaining after "n" passes

(a) Smoother-desmoother

Wavelength(ΔX)	1 Pass	2 Passes	3 Passes
2.0	.000	.000	.000
4.0	.760	.578	.064
6.0	.945	.893	.568
8.0	.984	.968	.851
10.0	.994	.988	.942
12.0	.998	.996	.980

(b) 1-2-1 Smoother

Wavelength(ΔX)	1 Pass	2 Passes	3 Passes
2.0	.000	.000	.000
4.0	.500	.250	.000
6.0	.750	.563	.056
8.0	.854	.729	.206
10.0	.905	.819	.369
12.0	.933	.871	.500

3.5 Adjustment between domains

For multiple-nest-level and multiple-nest-domain applications of the MM5 system, it is important to have a consistent terrain height and land-use category along the nest domain boundaries. If the users apply the MM5 model in the two-way nested mode, then the interior nest grid points that are overlapping with the grid points from the other model domains should have the same value of terrain height and the same land-use category. Therefore, if more than one domain is desired, the TERRAIN program needs to adjust the terrain height and land-use for each domain after these two fields have been created on the mesoscale grids (see sections 3.3 and 3.4).

3.5.1 Reset the nested domain boundary values

Because the lateral boundary condition of a nested domain is provided by its mother domain, the terrain height and land-use on the nest domain boundaries must be replaced and blended in with the values from its mother domain. This procedure is divided in the following three steps.

1. Interpolate the mother domain's terrain height field to the nest domain grid points. If the nest type is two-way, use the interpolation scheme based on a positive defined advection scheme (Smolarkiewicz and Grell, 1992). If the nest type is one-way, use the overlapping parabolic interpolation.

2. Replace the terrain heights on the outer nl rows and columns of the nest domain with the interpolated terrain heights from its mother domain. For rows and columns $nl+1$ to $nl+3$, replace the nest domain terrain heights with the blended terrain heights. The blended terrain heights are a combination of the original nest domain terrain heights and its interpolated terrain heights from the mother domain. Therefore, the blended terrain heights are defined as

$$HT(n) = F(n) * HT_{ori}(n) + (1 - F(n)) * HT_{int}(n),$$

where

$$F(n) = 0.25 * (nl - n + 4),$$

and $nl = 4$ for 1-way, or $nl = 3$ for 2-way nested application. $F(n)$ is the blend-in factor and n is the index of the rows and columns with the values from $nl+1$ to $nl+3$. HT_{int} is the interpolated value from the mother domain, HT_{ori} is the original value, and HT is the blended value.

3. For the two-way nest type, the nest ratio between the mother and the nest domains is always 3. However, for the one-way nest type, the nest ratio can be any number. Therefore, in order to have consistent land-use categories along the nest domain boundaries, for nest ratio N, the program replaces the land-use categories on the outer N rows and columns of the nest domain with the values of its mother domain grid points that define the nest domain boundaries.

3.5.2. Replacement of overlapping grid points

For the one-way nest type, it is not necessary to have the same terrain height for the interior grid points of different domains that overlap with each other. However, for the two-way nest type, the results from the nest domain will feed back to its mother domain. Therefore, the terrain height at the overlapping points must have the same values so that the surface pressure field is consistent between the domains.

The procedure to replace the terrain height of the overlapping grid points needs to start at the highest nest level domain and proceed down to the coarse domain. This means the coarse domain terrain height on the overlapping grid points should have the same values as the highest nest level domain terrain height. After the adjustment of the terrain heights is completed, the land-use category must be reset to 7 (water) if the terrain height is less than 0.0 and greater than -1 meters to assure the consistency between the terrain and land use.