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MM5 nesting techniques : a winter storm application

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**MM5 Nesting Techniques:
A Winter Storm Application**

**A Thesis Presented to
The Faculty of the Department of Meteorology
San Jose State University**

**In Partial Fulfillment
Of the Requirements for the Degree
Master of Science**

**By
Cristina Lozej
December 1998**

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Abstract

MM5 Nesting Techniques: A Winter Storm Application

By Cristina Lozej

This study compares nesting techniques within the NCAR/Pennsylvania State University Fifth-Generation Mesoscale Model (MM5). The interaction between grids can be handled either allowing (2-way nesting) or not allowing (1-way nesting) feedback from the fine to the coarse domain. Three nesting techniques have been compared: 2-way, standard 1-way, and continuous 1-way. This latter method, tested in this study for the first time, differs from the standard one in that it allows for more frequent boundary conditions. MM5 was run in a triple nested configuration to simulate a winter wave cyclone. MM5 captured the general storm evolution, but inaccurate initial conditions caused a simulated upper level flow too zonal and precipitation rates less intense than observed. Continuous 1-way produced more total rain than the other methods, and its overall performance was similar, if not better than 2-way (traditionally considered more accurate), but with lower CPU requirements and only one job submittal.

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1. Introduction

a. Nesting techniques

Mesoscale phenomena, such as frontogenesis or topographically induced flow, cannot be reproduced by numerical models unless their horizontal grid size Δx is sufficiently small to resolve all forcing mechanisms. Diminishment of Δx until it reaches a value for which maximum vertical velocity over the domain does not change is the proposed criterion to identify the physically appropriate maximum horizontal grid size in Lyons *et al.* (1995). In case of cloud resolving models, other parameters, such as vertical mass or cloud liquid water fluxes, should be chosen in addition to vertical velocity (Rafkin 1998). Higher resolution, however, substantially increases CPU time requirements because:

- the time step of integration Δt must be reduced, and thus more iterations are necessary (as Δt is limited by shorter topographically induced gravity waves)
- more grid points are needed to cover the domain.

To minimize these problems, “nesting” is used to increase the spatial (and therefore temporal) resolution in domain regions where smaller scale phenomena might occur. Nesting indicates that a higher resolution domain (or “inner” domain, hereafter referred to as FM, for fine mesh) is inserted into a coarser mesh (CM), referred to as the “mother” or “outer” domain. The number of nested domains can be greater than two, e.g., the Fifth-Generation Mesoscale Model (MM5) allows up to nine domains (Grell *et al.* 1994). Although nesting saves CPU time, the issue arises of how to handle interactions between the FM and CM. Two basic strategies exist: 1-way or 2-way nesting.

In the 1-way approach, meteorological calculations are first performed for the CM, and then results are fed into the FM through its lateral boundaries.

Since the CM has larger grid spacings and time steps than the FM, interpolations in both time and space are required to produce values for FM points at appropriate time intervals (Fig. 1). Note that the symbol X represents a CM cell center (“cross” point), whereas O is a corner point (“dot” point); corresponding FM points are indicated by x and o , respectively. In this case, since three inner grid intervals exist between each X , the nesting ratio n equals three. With horizontal grid spacings indicated as Δx_C and Δx_F for the CM and FM, respectively, $\Delta x_C = n \cdot \Delta x_F$ and $\Delta t_C = n \cdot \Delta t_F$. At boundaries between the two domains (heavy gray lines) interpolation is necessary to provide FM values from CM values. While the simplest interpolation is linear, sophisticated (e.g., polynomial) approaches involve more than boundary points (Phillips and Shukla 1973; Kurihara *et al.* 1979). For example, the “shape preserving” spatial interpolation scheme in MM5 is fourth order accurate and involves the outermost two FM rows and columns (Grell *et al.* 1994).

The basic assumption of 1-way nesting is that small-scale phenomena resolved by the FM do not significantly influence the CM, and thus only interactions from CM to FM are allowed. Two-way interchanges between different domains, however, can be important in cases like baroclinic instability or gravity wave breaking. Another problem associated with 1-way nesting is that troughs, ridges, and disturbances may move with different speeds in each mesh, producing solutions that “diverge” from one another. This creates discontinuities and distortions along FM boundaries in particular (Phillips and Shukla 1973, Kurihara *et al.* 1979).

Two-way nesting represents an alternate strategy to model interactions between the CM and FM. The main difference from the 1-way approach is that 2-way interaction is reciprocal and simultaneous, i.e., not only does the CM feed the FM via its boundaries (as in 1-way nesting), but feedback from the FM to the

CM also exists. This concept is called “dynamic interaction” (Kurihara *et al.* 1979).

The main steps in 2-way interaction are:

Step 1: Values calculated in CM for X- and O-points (Fig. 1) at each Δt_c

Step 2: Spatial and temporal interpolations (as in 1-way nesting) performed to obtain values at x- and o-points on FM boundary at each Δt_f

Step 3: Values calculated in entire FM area at each x- and o-point at each Δt_f

Step 4: At every $n * \Delta t_f$, values over entire FM fed back to CM, which requires interpolation to obtain new values for X- and O-points from values at x- and o-points

Step 5: Process repeated from Step 1 until end of simulation.

Note that in 2-way nesting, the feedback from CM to FM involves only FM boundary values (or perhaps a few additional rows and columns). Feedback from FM to CM, however, involves the entire overlapping area, in which CM fields are replaced by combinations of FM values. In fact, if Step 4 is carried out without smoothing or averaging (i.e., CM values simply replaced by corresponding FM values), feedback from the FM introduces smaller scale waves into the CM that might produce aliasing and/or make the CM solution noisy. Averaging techniques thus include simple averaging (Zhang *et al.*, 1986) and smoothing/desmoothing (Grell *et al.*, 1994). Since 2-way interaction is simultaneous, solution divergence does not occur.

The main disadvantages, however, of 2-way nesting include:

- larger (about 10%) CPU requirements, since double interpolation is required at each Δt_c
- once CM values are overwritten, CM fields in the overlapping area are no longer a solution to CM equations, and induced perturbations can produce

gravity waves in the CM. Thus 2-way advantages are more apparent on the FM than on the CM.

b. MM5 history

Since 1993, when the first MM5 paper was published, a tendency has developed toward its use with higher resolutions and more nested domains. Until 1995, simulations used either no nesting or only one nested domain, with innermost domain resolutions between 25 and 10 km. Recent applications, however, use double or triple nested domains, inner grid resolutions as fine as 3 km, and either 1-way or 2-way nesting techniques. Table 1 is a summary of winter storm applications of MM4 or MM5 that details model options selected in these studies, i.e., nesting type, horizontal resolution, cumulus parameterization (CP) scheme, and explicit precipitation scheme.

MM5 was first described and tested by Dudhia (1993); its main new feature was its non-hydrostatic framework. Several ideal cases (e.g., steady, dry, unsheared flow over a hill in a constant stability environment) and one real storm were simulated. The real case, oceanic cyclogenesis on 13-14 February 1982 over the North Atlantic, was first simulated with a 20 km non-nested grid, 15 vertical levels, high resolution PBL, and Grell convection scheme [one-cloud version of the Arakawa and Schubert (1974) scheme with parameterized downdrafts]. A second experiment with higher horizontal resolution was also performed with 1-way nesting, in which the 20 km mesh provided (by simple interpolation) initial and (one hour interval) boundary conditions (BCs) for a 6.7 km FM domain.

MM5 reproduced both the ideal and real experiments, but nesting appeared to provide additional mesoscale features, such as cold frontal structure. Non-hydrostatic effects were not significant in the North Atlantic case (even on the 6.7

km grid), but for more buoyant convective cases, additional divergence from hydrostatic solutions were predicted to occur.

Reed *et al.* (1994) simulated the evolution of the 4-5 January 1989 extratropical cyclone over the Atlantic. They used MM5 with a double nested configuration, an inner domain that moved to follow the storm front, and a resolution of 60 - 20 km. Deepening and frontal intensification occurred in only six hours (as observed), storm positions and central pressures were close to observed values, but precipitation patterns were not shown.

Several non-nested (Zou *et al.* 1995; Kuo *et al.* 1996a, Zou and Kuo 1996) and double nested simulations (Kuo *et al.* 1996b, Steenburg and Mass 1996, Braun and Houze 1997, Bresch *et al.* 1997, Gallus and Bresch 1997, Marwitz *et al.* 1997) with MM5 followed. The discussion below, however, focuses on triple nested applications.

The first MM5 triple nested application was carried out by Davis (1995), with resolutions of 60 - 20 - 6.7 km, to study the evolution of the mesoscale cold surge (i.e., a transient, frontlike phenomenon occurring in regions of high terrain) observed on 11-12 March 1993 over northeastern Colorado. Simulations were performed using the 2-way approach and Four Dimensional Data Assimilation (4DDA) only on the 60 km grid prior to the start of the forecast. Results sustained the hypothesis that the surge was a transient response to flow impulsively passing over weakly heated terrain. Previous 20 km grid runs had only marginally resolved the surge, but reduction to 6.7 km grid spacing showed how topography and latent heat enhanced updrafts at the leading edge of the surge. Precipitation was again not presented.

Of the six MM5 studies with triple nested domains (Table 1), four have used 2-way nesting, one used 1-way nesting, and one did not provide this infor-

mation. Each focused on a specific aspect of MM5 formulation, and all 2-way nesting papers presented only innermost domain results.

Only one of the six (Liu *et al.* 1997) was carried out for a tropical area, in which hurricane Andrew was studied using 2-way nesting with resolutions of 54 - 18 - 6 km and an innermost domain that moved with the hurricane core. The explicit cloud microphysics scheme was a modified version of the Tao and Simpson (1993) scheme, which contains prognostic equations for cloud water, rainwater, and graupel, and which allows for production of supercooled water. MM5 reproduced the deepening rate of central pressure ($> 1.5 \text{ mb h}^{-1}$), surface wind increase, vertical thermal structure, and spiral rainbands. The predicted eyewall, however, was nearly double in width and drier than observed, and MM5 failed to reproduce the intense squall line along Florida. Deficiencies were attributed to both imperfect initial conditions (too few observations over tropical oceans) and a too coarse resolution (6 km).

The importance of PBL processes in the evolution of a mid-latitude cold front over the Central U.S. was explored by Chen *et al.* (1997). Its rainband was characterized by frontal merging and contraction that produced severe line-convection with a gravity current-like structure along its leading edge. While the nesting scheme type was not specified, resolutions were 45 - 15 - 5 km, and 4DDA was used only for PBL winds. While surface analyses and satellite imagery showed a single convection line, MM5 predictions showed two separated lines that merged. Predicted rainfall rates showed accurate temporal and spatial patterns, but maximum rates were underestimated by as much as 10 mm h^{-1} . This was not attributed to nesting technique, but to inaccuracies in the Grell CP scheme for precipitation events on scales finer than the FM grid size.

Moist physics sensitivity tests and spectral analyses by Powers (1997) emphasized the importance of CP and horizontal resolution in the correct simula-

tion of an episode of explosive cyclogenesis over the Central U.S. in December 1987. The nesting scheme was 2-way, and resolutions were 30 - 10 - 3.3 km. MM5 again correctly reproduced the precipitation pattern, but again underestimated maximum rainfall values (2-3 cm predicted vs. >4 cm observed).

Direct measurements of momentum, sensible heat, and latent heat fluxes were used by Oncley and Dudhia (1995) to simulate a 1992 winter storm centered in eastern Kansas. Domain sizes were 60 - 20 - 6.7 km, and the grid interaction was 2-way. MM5 showed a sensitivity to roughness length and moisture availability values used in calculation of the three fluxes, e.g., errors in air temperature (6 K) and specific humidity (8 g kg^{-1}) occurred if default values were used instead of measured ones.

Similar sensitivity experiments were carried out with the 2-way approach by Chien *et al.* (1997) in an investigation of interactions of a frontal system with the complex topography of the Cascades Mountains on the Western U.S. coast. With resolutions of 45 - 15 - 5 km, and 4DDA for the innermost domain, they found that surface fluxes dominate both the thermal trough production and the marine push. Topography only modifies trough structure and intensifies the front in the mountain lee. Again, no precipitation values were presented.

The only 1-way nesting study in Table 1 is that of Colle and Mass (1996), i.e., a simulation of low-level southwesterly flow in December 1993 over the Olympic and Coastal Mountains of Washington and Oregon. They used resolutions of 27 - 9 - 3 km and the Grell CP scheme (except for the innermost domain, where precipitation was resolved explicitly via a modified version of the Hsie scheme that included a mixed liquid-ice phase). MM5 realistically simulated the surface low and pressure patterns around the mountains (in particular, the asymmetry between the lee trough and windward ridge). It also performed well with precipitation, as 3-h rainfall totals were generally within 1 mm of observa-

tions. An exception occurred on the southern side of the Olympics, where amounts were less than observed by about 3 mm.

Aspects of MM5 performance explored in these previous studies include cumulus parameterization schemes, 4DDA, and higher resolution. Higher resolution benefits can be obtained in two ways: diminish Δx over the entire domain or reduce Δx in only a limited area, i.e., nest a higher resolution domain in a coarser resolution mesh. The latter has been preferred because of its lower impact on CPU requirements. Nesting is performed by either allowing or not allowing feedback from the nested grid to the coarser domain, i.e. 2-way or 1-way nesting, respectively. Although 2-way nesting should theoretically produce more accurate results (Phillips and Shukla 1973, Kurihara *et al.* 1979, Clark and Farley 1984), no such evidence could be found in MM5 simulations in the literature, i.e., no comparisons of results from both nesting approaches were found. Thus, the current research will focus on the use of both nesting techniques within MM5 for a winter precipitation event along the California coast.

2. MM5

The Fifth-Generation Mesoscale Model (MM5) is designed to simulate or predict regional-scale to mesoscale atmospheric phenomena. It was originally developed at the Department of Meteorology at the Pennsylvania State University (PSU) in 1971 (Anthes and Warner 1978; Anthes *et al.* 1987). Since its general release in 1982, it has been improved and extended by PSU, the National Center for Atmospheric Research (NCAR), and other users. Furthermore, auxiliary programs have been created to preprocess its input and to postprocess its output.

a. Formulation

The mesoscale model and its auxiliary programs (four preprocessors and one postprocessor) are usually referred to as the MM5 Modeling System (Fig. 3). The following description focuses on Release 2.5 (June 1997) of MM5 Version 2. While all preprocessors were originally designed to run only on NCAR Crays, MM5 and GRAPH have always been available in both Cray and workstation versions; a workstation version of INTERP has been recently released by NCAR.

The first preprocessor (TERRAIN) produces gridded fields of terrain elevation and landuse for each domain. Topography and landuse data are available in the NCAR archive on a latitude-longitude mesh with resolutions of one degree; 30, 10, or 5 minutes; or 30 seconds. These data are interpolated by TERRAIN to desired grids, using either Mercator, Lambert conformal, or polar stereographic projection. Originally written in 1977, TERRAIN has been revised and improved several times (Guo and Chen 1994). The final version has the following characteristics:

- dynamic memory allocation
- compilation not required if no code modifications made
- multiple nested domains
- 1-way nesting with any nesting ratio; 2-way with nesting ratio of three
- adjustment of terrain and landuse along nest boundaries.

DATAGRID generates first guess meteorological fields on desired mesoscale grids from large scale meteorological model analyses or forecasts (Manning and Haagenson, 1992). Coarse resolution global fields are first retrieved from one of four sources: global model analyses from NCEP, the National Center for Environmental Prediction (Appendix B); global model analyses from the European Center for Medium-range Forecast (ECMWF); ECMWF global model analy-

ses for the Tropical Ocean and Global Atmosphere Program (ECMWF/TOGA); or real-time global NCEP Medium Range Forecast model (MRF) forecasts. All have 2.5° latitude-longitude resolution, except the last, which has 2.5° latitude and 5.0° longitude resolutions. Historical global model analyses are available directly in the NCAR Mass Storage System (MSS), whereas real-time MRF forecasts are available from Unidata.

The second task of DATAGRID is horizontal interpolation of input model analyses (or forecasts) to the selected MM5 grids. Terrestrial fields (latitude, longitude, Coriolis parameter, and map scale factor) are first diagnosed for all MM5 grid points, and then large scale meteorological fields are interpolated to all grid points by use of 16-point, two-dimensional overlapping-parabolic interpolation (Manning and Haagenson, 1992). DATAGRID interpolations are performed for the mandatory pressure levels: 1000, 850, 700, 500, 400, 300, 250, 200, 150, 100, 70, 50, 30, and 10 mb.

Since interpolation cannot add missing mesoscale details, interpolated data should be enhanced with real-time or historical observations from National Weather Service (NWS) surface and rawinsonde stations. This enhancement is performed by program RAWINS (Manning and Haagenson, 1992), which uses a Cressman-type objective analysis scheme (Benjamin and Seaman, 1985). It first creates first guess fields at non-mandatory pressure levels by vertical interpolation from the mandatory ones, and then it improves these fields by nudging toward observations. RAWINS also performs data checks to remove suspect NWS observations, and allows for insertion of local data and for subjective correction of suspect local observations.

Next, INTERP performs a vertical interpolation from pressure levels to the σ -coordinate system levels of MM5 (discussed below), after the number and value of the vertical σ -levels are input. INTERP can be used to create MM5 input

files (“front-end” job) or to convert MM5 output files from σ -surfaces back to pressure surfaces (“back-end” job).

Detailed descriptions of MM5 appear in Gill (1992), Grell *et al.* (1994) and Haagenson *et al.* (1994). Only general features are now described, with emphasis on nesting options.

MM5 can be run from the global scale down to the cloud scale, in either 2-way or 1-way nesting modes; it allows up to nine nested domains, moving grids, and different starting/ending times for each domain. Furthermore, MM5 is fully compressible and has the following options:

- dynamic: hydrostatic or non-hydrostatic
- cumulus parameterization: Anthes-Kuo, Grell, Kain-Fritsch, Fritsch-Chappell, Betts-Miller, or Arakawa-Schubert
- resolvable-scale microphysics: removal of supersaturation, Hsie warm rain, Dudhia simple ice, Reisner mixed-phase, Reisner mixed-phase with graupel, or NASA/Goddard microphysics with hail/graupel
- PBL: bulk formulation, Blackadar, Burk-Thompson (Mellor-Yamada 1.5-order/level-2.5), or MRF
- radiation: simple cooling, Dudhia long- and short-wave radiation, or NCAR/CCM2.

MM5 also allows 4DDA, where specific terms, linearly proportional (Newtonian) to the difference between calculated and external values for every grid point, are added to the equations (Stauffer and Seaman, 1994). Model solutions are thus “nudged” toward external values, i.e., either gridded analysis values (analysis nudging) or local observations (observational nudging).

MM5 can be parallelized (for faster execution) on either shared-memory machines [Cray (EL, J90, YMP), HP-SPP2000, SGI, SUN and DEC Alpha], distributed-memory machines [IBM RISC 6000 cluster (SCD/NCAR)], or massively

parallel machines [Intel Touchstone DELTA, Intel Paragon, IBM Scalable Power-parallel system, and IBM RS/6000 workstation cluster].

Finally, MM5 is free and well documented. Technical notes are available at NCAR and on the Internet at <<http://www.mmm.ucar.edu/mm5/mm5-home.html>>.

b. Coordinates

The MM5 vertical σ -coordinate is defined as:

$$\sigma = \frac{P_0 - P_T}{P_S - P_T}, \quad (1)$$

where all symbols are defined in Appendix A. Note that $p_0(z)$, p_T , and $p_s(x,y)$ refer to a reference state, assumed hydrostatic and constant with time. Since p_0 , p_s , and p_T are assumed constant in time, σ -surfaces are also fixed in time. Values of σ range from zero at the model top to unity at the surface. The lowest σ -level closely follows terrain, while subsequent levels flatten with altitude up to the completely flat top level (Fig. 2). Thus, the σ -system is “terrain influenced” and not “terrain following” (Schayes *et al.* 1996).

The invariant reference state temperature profile is specified by:

$$T_0 = T_{s0} + A * \ln\left(\frac{P_0}{P_{00}}\right), \quad (2)$$

where three constants need to be defined. Sea-level pressure p_{00} is set to 10^5 Pa. The constant reference temperature at pressure p_{00} (i.e., T_{s0}) is frequently set to 270, 280, 290, 300 K in polar, midlatitude winter, midlatitude summer, and tropical conditions, respectively. The temperature difference between p_{00} and p_{00}/e (i.e., A) is usually taken as 50 K, but should be extracted from typical domain soundings. Reference pressure p_0 as a function of z can be calculated using the hypsometric relation and (2), as described in Appendix C.

Pressure perturbation from p_0 , indicated as p' , is calculated by MM5 at each grid point on the σ -surfaces. The pressure at each point is therefore:

$$p(x,y,\sigma,t) = [p_s(x,y) - p_T] \cdot \sigma + p_T + p'(x,y,\sigma,t). \quad (3)$$

MM5 has an Arakawa type-B staggered horizontal grid (Arakawa and Lamb, 1977). Thus in Fig. 1 eastward (u) and northward (v) wind velocity components are defined at O-points (cell corners), whereas all other variables are located at X-points (cell center).

c. Nesting

Three nesting options are available in MM5 (Table 2): 2-way, standard 1-way, continuous 1-way. Descriptions of each follows.

2-way

At the initial time, the value of each variable at each grid point of both meshes must be provided. The following are then performed:

1. Integrate for one time step on CM. To avoid computational instability, the Δt_C value in seconds should be smaller than three times the horizontal resolution in km, as recommended in the MM5 Tutorial Notes available at <http://www.mmm.ucar.edu/mm5/mm5-home.html>.
2. Interpolate to FM boundaries using a fourth order accurate scheme derived from monotone advection algorithms applied to the two outermost rows and columns of FM (Grell, *et al.* 1994, Smolarkiewicz and Grell 1992). These BCs are valid for the first CM time step (the third FM time step), as the FM time step is $\Delta t_F = 1/3 \Delta t_C$, since n must be 3 in MM5 2-way applications. To provide BCs for FM at each Δt_F , linear time interpolation is performed. Notice that CM provides values for FM boundaries only, and CM values calculated for the area that overlaps the FM are not used.
3. Run MM5 on FM for each Δt_F .

4. At $t = 3 \cdot \Delta t_F = \Delta t_C$, FM values are fed back into CM. Note that while CM input for FM comes only via its boundaries, FM feedback to CM occurs over the entire overlapping area. Thus old CM values are completely replaced by new (correctly averaged) FM values. Several averaging options are available in MM5:

- a. No-averaging nor smoothing: old CM values simply replaced by new values calculated at corresponding FM grid points. The CM solution thus appears noisy because it is contaminated with smaller scale FM information.
- b. Weighted averaging: CM grid point values obtained by averaging eight FM surrounding points plus central point, i.e., a “nine-point method.” This method, first used in Zhang *et al.* (1986), does not remove all small scale noise, becomes complicated with several meshes, and imposes severe restrictions on terrain. The following is used to calculate smoothed value $\underline{\alpha}(i,j)$ at CM grid point (i,j) from surrounding FM values:

$$\begin{aligned} \underline{\alpha}(i,j) = & \alpha(i,j) + \frac{\nu}{2}(1-\nu)[\alpha(i+1,j) + \alpha(i-1,j) + \alpha(i,j-1) + \alpha(i,j+1)] + \\ & \frac{\nu^2}{4}[\alpha(i+1,j+1) + \alpha(i+1,j-1) + \alpha(i-1,j-1) + \alpha(i-1,j+1) - 4\alpha(i,j)]. \end{aligned} \quad (4)$$

- c. Smoother/desmoother: two-step filter that removes $2\Delta x$ waves and damps short waves, leaving long waves mostly unaffected. Fields are first strongly smoothed via (4) with $\nu = 0.5$. A second step restores long wave amplitudes, via $\nu = -0.52$.

Note that with all three methods the new CM values do not anymore represent solutions to CM equations. The new values, however, should better represent atmosphere behavior in the overlapping CM and FM area because they have been calculated on the higher resolution domain.

5. Repeat steps 2 through 4 until end of simulation.

Standard 1-way

While in 2-way nesting CM values are fed into the FM at each time step, in MM5 standard 1-way nesting this can not happen because the two meshes are run sequentially, i.e., FM is run only after the CM run is completed. MM5 is first run for the CM for the entire simulation period, and results stored at fixed time steps, typically one hour. These hourly values then provide the lateral BCs for the FM. Since the FM requires BCs at each Δt_f , time interpolation is required to obtain them from hourly CM values. They are obtained by running INTERP as a “non-standard back-end job”. The “standard back-end job” converts MM5 output from σ to pressure coordinates, whereas the non-standard back-end job:

- a. spatially interpolates CM values to the FM grid for the initial time step (with fourth order accurate monotone advection scheme);
- b. provides values for FM boundaries by spatial interpolation at an arbitrarily specified time period (usually one hour).

Steps a and b thus provide initial conditions (IC) and BC files for the FM by interpolation from CM values, with no feedback from the FM to the CM. A problem arises as FM terrain height and landuse values are directly interpolated from CM values. An option is available in INTERP to incorporate higher resolution terrain and landuse information into the FM via an additional external file, created by TERRAIN. Three job submittals are thus necessary to run MM5 traditional 1-way nesting: MM5 for the CM, INTERP to create IC and BC files for the FM, and MM5 for the FM.

Continuous 1-way

Continuous 1-way nesting possesses several potential improvements over traditional 1-way nesting. First, as the two meshes are run simultaneously, the CM provides BCs for the FM at each Δt_c , instead of at only each hour. It thus al-

lows the FM to account for CM variations on a time scale finer than one hour. Furthermore, only one job submittal is required to run both meshes, an operational advantage. Continuous 1-way nesting can be achieved by running the two meshes as in the 2-way nesting mode, but by setting a switch to block feedback from the FM to the CM.

d. Input and Output

The IC file for each mesh (Table 3) includes fields for each grid point (dot or cross) for each σ -level. Note that all 3-D variables in MM5 are multiplied by:

$$p^* = p_s - p_T,$$

and therefore units are multiplied by kPa.

In non-nested simulations (and for the CM with either 1-way or 2-way nesting), the IC file is generated by interpolation of a large-scale model analysis to the MM5 grid (standard initialization). With nested domains, it is also possible to initialize by simple interpolation from CM to FM values. Advantages and disadvantages exist for each choice. With the interpolation option, the FM may be started any time during the simulation and can move. With the standard initialization it is possible to include higher resolution information, but the FM must be started at the same time as the CM and cannot move. For terrain and landuse only, however, it is possible to add higher resolution data even with the interpolation option.

For each domain, a BC file is necessary (Table 4). Values must be provided for the last five grid points of all four lateral boundaries. The required temporal frequency for BC values varies, depending on domain and nesting option. For the outermost domain, the frequency is typically 12 hours with any nesting scheme, as large-scale model analyses are only provided at 0000 and 1200 UTC. For nested domains, the frequency is typically one hour for the traditional

1-way nesting, but Δt_c for either the 2-way or continuous 1-way methods. MM5 produces an output file for each domain that contains the fields described in Table 5.

3. Simulations

a. March 1996 Storm

The weather system that affected the U. S. West Coast, in particular the San Francisco Bay Area, during 11-13 March 1996 is hereafter referred to as the "March 1996 Storm." This synoptic description is based on three data sources: NWS weather maps and satellite images; ETA model analyses and forecasts (Appendix D); and precipitation observations from over 90 meteorological stations in Central California.

On 11 March at 0000 UTC, the synoptic pattern on the 500 mb ETA analysis (Fig. 4) was dominated by a trough (axis approximately 1000 km off the coast) that produced west-southwesterly flow over California and by its closed parent low (512 dam minimum height) over Alaska (north of figure). The north to south oriented vorticity lobe is coincident with the area of the polar jet maximum wind speed (not shown).

The cloud mass off the coast in the corresponding GOES IR satellite image (Fig. 5) indicates the presence of a wave cyclone in association with the above mentioned trough. The narrow cloud streak on the southern edge (arrow) corresponds to the southern edge of the polar jet. Downwind of the vorticity lobe maximum ($>24 \times 10^{-5} \text{ s}^{-1}$), a developing comma cloud is found northeast of the cloud streak. On the corresponding 300 mb NWS chart (Fig. 6), the trough has produced southwesterly flow over California. The polar jet (maximum speed

110 kts or 57 m s^{-1}) is oriented northwest to southeast, while the sub-tropical jet flow (maximum speed 90 kts) is west to east.

The corresponding surface weather system at 0000 UTC (Fig. 7) is characterized by an additional weak trough along the northern California coast, a weak occluded front further west off the coast, and the Pacific high off Baja. The weak occluded front corresponds to the leading edge of the above mentioned comma cloud. Rapidly moving eastward, it reached the Central California coast by 0600 UTC.

At 1200 UTC at 300 mb (not shown), the polar jet maximum has moved southeastward, has lower maximum speed (90 kts), and has brought a cold pool of air ($<-55^\circ\text{C}$ or 218 K) off of northern California. The cold pool (-27°C) is also present at 500 mb (Fig. 8), together with a now negatively tilted trough (564 dam line over San Francisco). The associated flow has become more southerly along the Oregon and Washington coasts, and the Alaska low has filled to 520 dam.

The ETA analysis for this hour (Fig. 9) also now shows the same negatively tilted trough. A new short wave has moved rapidly southeast into the area and produced a second vorticity maximum ($24 \times 10^{-5} \text{ s}^{-1}$), whereas the previous vorticity maximum is now located $\sim 400 \text{ km}$ west of San Francisco Bay. Light precipitation ahead of this maximum yielded 24-hr totals from 0.1" to 0.3" (or 0.25 to 0.8 cm) in the Bay Area to 0.55" in the Santa Cruz mountains.

The two vorticity maxima can also be identified in the IR image (Fig. 10), where the first one is located approximately 500 km west of the San Francisco Bay (west of cumulus type cloud area). The second maximum, which produces the highest precipitation in the Bay Area 24 hours later, is located north of the bright elongated cloud band (western edge of figure). Surface features can be also identified in the figure, e.g., the north-south occluded front along the eastern edge of the cloud-free area off the Northern California coast, the west-east trough

along the northern edge of the same cloud-free area, and the spiral cloud area at the low pressure center at the Mendocino coast. These features appear in the same locations in the corresponding surface analysis (Fig. 11), with the low center having a pressure of 1013 mb.

By 1800 UTC the central low weakened (1016 mb) and reached northern California, while the cold front moved inland beyond San Francisco (Fig. 12) and produced 3-hr rainfall totals up to 0.25" in the North Bay and 0.50" in the Santa Cruz mountains. This frontal passage will be referred to as the 'first' frontal passage.

Six hours later, 12 March at 0000 UTC, the ETA 500 mb analysis (Fig. 13) shows that the first vorticity maximum dissipated over the Sierra, while the second one intensified to $27 \times 10^{-5} \text{ s}^{-1}$. The trough has moved towards the coast, intensified into a closed low, and has a less pronounced negative tilt and almost westerly winds. At the surface (Fig. 14), the cold front has weakened and moved rapidly southeastward to the Mexican border. A new system, associated with the secondary vorticity maximum at 500 mb, is approaching the Central California coast from the northwest as a developing cold front (northwestern corner of figure).

At 1200 UTC the upper level low first reached San Francisco Bay (Fig. 15) and deepened (550 dam), producing a stronger vorticity maximum ($>36 \times 10^{-5} \text{ s}^{-1}$) and heavy precipitation. The corresponding IR image (Fig. 16) shows the main characteristics of this storm, i.e., limited in areal extent, centered over the San Francisco Bay Area, and convective in nature.

At the surface at this time (Fig. 17) the cold front approached the coast, with the low (1009 mb) positioned over San Francisco. The frontal passage produced a second precipitation event over the San Francisco Bay Area, with 3-hr rainfall rates from 0.25-0.50" in the East Bay to 0.50-0.75" in the Santa Cruz

mountains, and thus it will hereafter be referred to as the 'second' front. The 24-hr totals from both precipitation events totaled up to 1.70" in the San Francisco Bay and 2.48" in the Santa Cruz mountains.

At 1200 UTC on 12 March, the surface low is still located east (although with reduced displacement) of the upper level low, indicative of a storm in a baroclinic development phase. The positive tilt of the 500 mb height contours, however, indicates barotropic energy removal from the disturbance to the jet. The system is therefore expected to intensify at a slower rate for only a little while longer, before entering a decaying phase.

The high resolution visible satellite image 3.5 hours later at 1530 UTC (Fig. 18) shows that the surface low was only 50 km wide. Such a phenomenon is difficult to simulate in detail, even with a 9 km resolution (10 Δx segments recommended).

On the 13th at 0000 UTC, the remaining 500 mb vorticity maximum moved southeast and weakened, the upper level low reached its minimum height (548 dam), and the trough became more positively tilted (not shown). At 250 mb, ETA showed indications of decay, as the trough (now narrow) is now more positively tilted. The surface front (now occluded) has moved eastward and weakened (Fig. 19), as indicated by its decreased organization and by the cloud bands that spiral around its low center (north of the Los Angeles basin). After frontal passage, winds along the Central California coast shifted westerly and rainfall maxima occurred in the southern Sierra Nevada mountains (0.1-0.4" in 24 hours).

At 1200 UTC on this day, the upper level trough at 500 mb moved southeast; height contours were parallel to the coast (no tilt), and the vorticity maximum weakened over the southern Sierras (Fig. 20). The synoptic pattern was now characterized by a ridge off the coast, with northerly winds at 500 mb

(maximum speed about 75 kts) off the Oregon coast. The polar jet axis was oriented northeast-southwest, with maximum speeds of 100 kts (Fig. 21). At the surface, the remnants of the March 1996 storm appeared as an weakened occluded front that has moved further east, passing over the Sierra mountains and out of the area of interest.

b. MM5 settings

To simulate the March 1996 storm, a triple nested configuration was chosen (Fig. 22). The outermost domain, hereafter referred to as 'Domain 1', has horizontal resolution of 27 km and dimensions 120 x 57, where the two values indicate the number of grid points in the west-east and south-north directions, respectively. Domain 1 is centered at 39.0° N and 131.0° W degrees to early capture the weather system evolution over the ocean. Domain 2, the intermediate mesh, is designed to include the entire California area and to resolve the storm interactions with topography. With a grid length of 9 km, it has dimensions of 112 x 106. The innermost grid, Domain 3, is centered over the San Francisco Bay Area, where the surface low pressure center was located on 12 March at 1200 UTC, when it reached its maximum intensity (Fig. 16). Domain 3 has approximately the same extension as the low center, and its horizontal resolution of 3 km, with 52 x 40 grid points, should allow for the simulation of the March 1996 storm smaller scale details. All domains have 19 half-sigma levels in the vertical, increasing resolution in the lower layers, and p_r set to 100 mb.

All initialization data were obtained from the NCAR MSS. Terrain elevation data sources, resolution, and coverage for each domain are listed in Table 6, while Fig. 23 - 25 show terrain elevation contours for each of the three domains. Landuse data for all three domains (13 categories), obtained from PSU/NCAR, have a resolution of 10 minutes (or 18.5 km), unfortunately larger than the Do-

main 2 grid spacing. NCEP global analyses (resolution of $2.5 \times 2.5^\circ$) were selected to provide initial and boundary values at each vertical level every 12 hours (Table 7). To improve these low resolution analyses, upper air and surface observations from 12 NWS stations were assimilated, but only the Oakland site is located within Domain 3.

The selected CP scheme was Grell (1993), a modified version of the Arakawa and Schubert (1974) scheme, recommended by MM5 developers for scales between 10 and 30 km. It was therefore applied to Domains 1 and 2 only, whereas in Domain 3 all precipitation is resolved explicitly. The CP cloud spectrum is simplified to one non-entraining cloud (updraft and downdraft couplet), whose size is predicted following Fritsch and Chappel (1980). Thus the dynamic control determines the amount and location of convection, and not the cloud spectrum. The subgrid buoyant energy closure is the quasi-equilibrium assumption of Arakawa and Schubert (1974). Since entrainment is not considered, all parameters dependent on entrainment or detrainment are zero and the normalized mass flux is constant with height. Subgrid precipitation efficiency is assumed a function of the mean wind shear in the lower troposphere following Wang and Seaman (1997) and effects of convective scale downdrafts are parameterized.

The explicit (non-convective or resolvable scale) precipitation scheme was chosen to have full microphysics but not excessive CPU requirements. The Dudhia simple ice scheme (Dudhia 1989; Grell *et al.* 1994) was therefore selected, since it allows for cloud and rain water prediction. Ice phase processes are included without additional memory requirements.

As the March 1996 storm was dominated by synoptic features and not by mesoscale circulations, a revised version of the Blackadar PBL scheme was chosen (Blackadar 1976; Blackadar 1979; Zhang and Anthes 1982; Grell *et al.* 1994)

over the more sophisticated Burk-Thompson scheme. Furthermore, this latter scheme introduces an extra predicted variable, i.e., turbulent kinetic energy, increasing memory requirements. The Blackadar scheme considers two PBL regimes (nocturnal and convective) and four turbulence types (decaying, mechanical, unstable forced, and unstable free).

The atmospheric radiation scheme used in this study, the cloud-radiation scheme (Dudhia 1989; Grell *et al.* 1994), is sophisticated enough to account for long- and short-wave interactions with clouds. It provides atmospheric temperature tendencies as well as surface radiative fluxes.

The simple “force-restore” scheme (Deardorff 1978) is used to predict surface temperature. It allows a lower layer (whose top represents the depth to which diurnal variations occur) with fixed temperature, while surface temperature is obtained via a simplified surface energy budget. Soil moisture is not predicted but depends on landuse category only.

c. Results

The effects of the three nesting techniques on results from three simulations of the March 1996 storm were studied. Each run started on 11 March at 1200 UTC:

- RUN1: 2-way nesting, 36-hr simulation, ending 13 March at 0000 UTC
- RUN2: standard 1-way nesting, 12-hr simulation, ending 12 March at 0000 UTC
- RUN3: continuous 1-way nesting, 36-hr simulation, ending 13 March at 0000 UTC.

Note that RUN2 was carried on for only 12 hours, due to its high storage requirements. Refer to Fig. 24 for location names in the following description.

1) RUN1: 2-way

The initial 500 mb height field from the NCEP/MM5 analysis for Domain 1 is shown along with the concurrent ETA analysis in Fig. 26. Although the general pattern is similar (trough with negative tilt), subtle differences exist, e.g., the ETA trough is extended more southeastward, whereas the NCEP/MM5 flow is more zonal. The two short waves discussed above cannot easily be seen in this figure, but show up clearly as vorticity maxima ('X's in Fig. 27). However, the first short wave, i.e., one closest to the coast, is weaker and not as well defined in the NCEP/MM5 initial field as in the ETA analysis (Fig. 27 vs Fig. 9). Furthermore, the NCEP/MM5 combined vorticity lobe is not extended as far south as in ETA.

The MM5 500 mb 12-hr forecast for 12 March at 1200 UTC (Fig. 28) shows general agreement with the concurrent ETA analysis (Fig. 29), i.e., trough axis aligned north-south and low center located off the northern California coast. The minimum MM5 height of 552 dam is, however, slightly less deep than the ETA value (550 dam) and the MM5 low center is located east of the ETA center (200 vs 400 km offshore), as expected from the more zonal NCEP/MM5 ICs. MM5 winds are westerly over the San Francisco Bay Area at approximately 45-50 kts, as in ETA. Isotherms are parallel to height contours for both models, except for the cold narrow tongue (-27°C) that reaches the California-Oregon border in ETA, but not in MM5. Note the effects of topography: since this is a 2-way nested run, the effects of the Domain 2 high resolution terrain appear in Domain 1 as small perturbations in the isotherms in correspondence with valleys and mountains.

Topographic effects are more evident in the concurrent MM5 vorticity field (Fig. 30), where two main features can again be seen. The small vorticity maximum ($30 \times 10^{-5} \text{ s}^{-1}$) over the Central Valley, which corresponds to the first de-

caying system, has details well resolved by MM5, but not by ETA. The second stronger vorticity maximum ($35 \times 10^{-5} \text{ s}^{-1}$) is located and orientated approximately as in the ETA results (Fig. 13), even if its magnitude is overestimated ($28 \times 10^{-5} \text{ s}^{-1}$ in ETA vs $36 \times 10^{-5} \text{ s}^{-1}$ in MM5); this center will later trigger development of the second front. While MM5 vorticity isolines around the western vorticity maximum are oriented almost parallel to the height contours, ETA results show significant positive vorticity advection (PVA) southward ahead of the low center. It is therefore expected that MM5 will not translate the low as southward as observed, but will produce a weaker storm with a more zonal flow and more rapid translation.

The MM5 500 mb 24-hr forecast for 12 March at 1200 UTC (Fig. 31) confirms this expectation. The low is erroneously located inland at a site northeast of the San Francisco Bay Area with a minimum value of 552 dam, whereas ETA (Fig. 32) shows the low correctly located further south and west (at the Central California coastline) and with a lower minimum value of 550 dam. Furthermore, ETA correctly produces south-southwesterly winds along the San Francisco coast, instead of the west-northwesterly winds forecasted by MM5. Finally, the MM5 low center never hits Domain 3, but unfortunately passes approximately 200 km too far north (Fig. 33).

This northeastward displacement is also visible in Fig. 34, where the observed low is located in the cloud-free area just off San Francisco Bay, but MM5 500 mb overlaid heights show it inland approximately over Sacramento. The MM5 vorticity field illustrates the same displacement and intensity problems (Fig. 35), with its maximum further inland and weaker ($30 \times 10^{-5} \text{ s}^{-1}$) than in the ETA field ($37 \times 10^{-5} \text{ s}^{-1}$) of Fig. 15.

The MM5 36-hr forecast at 500 mb for 13 March at 0000 UTC (Fig. 36) now shows a generally correct pattern, with mainly northerly flow along the northern

coast, speeds of approximately 40 kts, and a trough axis now positively tilted. The MM5 low center, however, is smaller and not closed; it is also still located east of its position in ETA (Fig. 37), shallower (550 vs 548 dam in ETA) and colder (-27°C vs -24°C in ETA). The eastward displacement of the low center is now only 100 km, because the MM5 low continued to move more rapidly (now in a north to south direction) than did the ETA (still in the northwest to southeast direction).

In summary, the MM5 forecasted movement of the upper level low was both too rapid and too northward. This can be attributed to the above mentioned "subtle differences" in the ICs (Fig. 26), which show that the MM5 flow was initially too zonal and thus lacking PVA. As a consequence, the MM5 storm center passed north of Domain 3 at 500 mb (Fig. 33).

Differences in the ICs are even more evident at the surface (Fig. 38): the ETA sea level trough is approximately 300 km off the coast, whereas the corresponding NCEP/MM5 trough is too weak to discern. Furthermore, the surface low approximately 800 km off Oregon is less extended and deeper (1012 mb) in ETA than in NCEP/MM5 (1014 mb).

The NWS surface analysis (Fig. 12) for 11 March at 1800 UTC shows that the first front, corresponding to the above mentioned surface trough, passed through the San Francisco Bay Area and its low split into two. The first low is still off the California coast while the second one is at the Oregon-California border. The concurrent ETA analysis (Fig. 39) shows the two separated low centers, whereas MM5 produces only one extended area of low pressure. ETA also clearly shows the trough along the Central California coast, but this trough is much weaker in the MM5 sea level pressure field for Domain 1.

To better identify this surface trough, it is worthwhile to look at the MM5 higher resolution results for Domain 2 for the same time (Fig. 40). Three wind

regimes can be seen: generally westerly flow over the ocean, distortions due to interactions with topography in Central California (e.g., channeling in the Central Valley), and an almost chaotic pattern over the Sierra. Simulated sea level isobars show several weak troughs in the general area of the observed surface trough; however, the first inland trough seems to better represent the observed one, due to the wind shift and minimum speed along it.

The most western observed low reached the coast on the 12th at 0600 UTC, as shown by the ETA almost closed 1020 mb isobar in Fig. 41. MM5, however, has moved the disturbance further onshore, as shown by the 1016 mb isobar. Note the ridge development in ETA in the northern part of the domain: the ridge axis tilts eastward causing intense warm air advection towards the Oregon coast, therefore intensifying the low closure process. As the MM5 Domain 1 does not extend far enough north to capture entirely the ridge tilting, this effect should be introduced into the domain via its BCs. No such tilt, however, is shown in the northern part of Domain 1, where values are not calculated by MM5 but are interpolated to the MM5 grid from the NCEP analysis.

Six hours later, at 1200 UTC on 12 March, when the observed front hits land and the surface low is approximately over the San Francisco Bay Area (Fig. 17), no such pattern is seen in the MM5 results (Fig. 42). In fact, ETA shows the closed surface low (1011 mb), whereas MM5 does not reproduce any closed features, but only north-south oriented isobars. In particular over the San Francisco Bay area, observations show easterly wind at the surface (Fig. 17), whereas MM5 (Domain 2) produces west-northwesterly flow (Fig. 43).

As an overall evaluation of Domain 1 and 2 results at the surface, MM5 simulated the first frontal passage, but made it weaker than observed. It failed completely in the simulation of the second more intense front; as a consequence, the low pressure center never passed through Domain 3. The reason for this is

again found in the inaccurate ICs. As shown in Fig. 38, relative to ETA, the MM5 initial sea level flow was generally more zonal and the first trough was less narrow and less deep, thus producing a weaker initial front. The second low, that spawned the second intense front, was too weak in the NCEP/MM5 ICs, and therefore MM5 never produced that front.

The more than 50 NWS stations located in Domain 2 report rainfall rates every hour, as well as 24-, 12-, 6-, and 3-hr total precipitation amounts. Due to the difficulty of contouring point precipitation observations in complex terrain, observed values are represented by dots placed at the corresponding station locations. Dot radii are proportional to observed rainfall rates and dot colors match the MM5 scale for calculated precipitation. The (smallest) red dot represents zero precipitation.

The first frontal passage at 1800 UTC on 11 March caused moderate [0.1-0.25" in three hours] precipitation over the San Francisco Bay Area and intense rates [0.25-0.75" in three hours] over the Santa Cruz mountains (Fig. 44c), where precipitation is enhanced due to orography (Archer 1998), and no precipitation south of Monterey Bay. MM5 produced light precipitation everywhere in the northern part of Domain 2 (Fig. 44a), with two areas of intense rainfall [0.25-0.50" in three hours] northeast and west of San Francisco Bay. However, it misses completely the intense precipitation event over the Santa Cruz mountains, since the complex topography in this area cannot be perfectly reconstructed with a 9 km resolution. MM5 also erroneously produced rain in the Central Valley, but correctly produced no precipitation in the San Jose area and generally south of Monterey.

Note that MM5 precipitation results in the area of Domain 2 corresponding to Domain 3 should be looked at carefully. In fact, since no CP scheme is active on Domain 3, calculated convective precipitation is zero everywhere in this

area. With 2-way nesting, all calculated values for any field are fed back from Domain 3 to Domain 2; for convective rain in particular, calculated values are zeros and therefore in Domain 2 an artificial rectangular area of zero convective rain is visible in the overlap area of Domain 3 (Fig. 45). Furthermore, since Domain 3 receives BCs from Domain 2 for each variable, including convective precipitation, the two outermost rows and columns of Domain 3 convective precipitation can contain non-zero values. These are both easily correctable flaws in MM5 code.

Since no CP scheme is active on Domain 3, only explicit precipitation will be shown hereafter. MM5 generally performed well on 11 March at 1800 UTC (Fig. 46a), predicting zero precipitation in the Point Reyes, San Francisco, East Bay and San Jose areas, and moderate rain in the North Bay and Los Gatos areas, as observed. Note that the intense precipitation area over the Santa Cruz mountains (Fig. 46c) is outside of Domain 3.

On 12 March at 0000 UTC, 12 hours before the second frontal passage, no precipitation was reported in Domain 2 along the coast and further inland for approximately 150 km (Fig. 47, left panel), whereas moderate to intense rainfall rates were observed in its eastern part (Sierra Nevada). Note the bogus datum reported at the Golden Gate station. MM5 (Fig. 47, right panel) slightly overpredicts precipitation in the East Bay and San Jose areas, and along the southern coast, producing light (instead of zero) rain; performs well in the Yosemite area, producing intense rain; and overpredicts in the Sacramento area, showing intense precipitation where none occurred.

Due to the lack of the second frontal passage in the MM5 results, its simulated precipitation patterns generally do not agree with observations for 12 March at 1200 UTC (Fig. 48a,c). The high precipitation rates observed in the North Bay, San Jose, Santa Cruz mountains, and Big Sur areas are completely

missing in MM5 results. However, in Domain 3 MM5 produces the correct amounts of rain in the San Francisco, San Leandro, and Big Basin areas (Fig. 49a,c).

Although the timing of this precipitation peak is correctly simulated over Domain 3 by MM5, its cause was not the surface front, completely lacking in MM5, but associated upper level dynamics. Furthermore, the observed west-southwesterly surface winds over the Monterey Bay (Fig. 17) were perpendicular to the coastal mountains, therefore enhancing precipitation, whereas MM5 produced northwesterlies for the same time (Fig. 43). The MM5 precipitation was thus mainly due to the short wave passage, but its associated upper level trough was not deep enough to reach the surface.

2) RUN2: standard 1-way

RUN2, the standard 1-way run, was carried out for only 12 hours due to the high storage requirements of saving many 1-hour output fields. Since the differences between nesting techniques can be seen only in the nested area, the following discussion will focus only on the eastern part of Domain 1.

A comparison of 500 mb results for 2-way and standard 1-way nesting for 11 March at 1800 UTC is shown in Fig. 50 a and c, respectively. The general flow pattern is the same for both runs, but the influence of topography in the higher resolution Domain 2 can be seen in the more “noisy” height and temperature fields over the mountains for the 2-way run. No significant differences can be detected at the surface between the 2-way (Fig. 40) and standard 1-way (Fig. 51) results.

At 500 mb on 12 March at 0000 UTC (Fig. 52a,c), differences can be noticed in addition to the fact that the 2-way height and temperature contours look noisier. In RUN2, the trough extended slightly further south than in RUN1 (e.g.,

the 558 dam line now reaches the southern San Francisco Bay), but height contours are still too zonal and more progressive than observed. The two wind fields are, however, almost identical.

Precipitation patterns on 11 March at 1800 UTC for Domain 2 are shown in Fig. 44; note again that 2-way values for the area corresponding to Domain 3 should not be considered due to the above mentioned contamination. Two areas of precipitation can be seen. The first one, just off the coast, is located further south in RUN2 (d) than in RUN1 (a), indicating a storm movement slightly more progressive to the south and rapid with standard 1-way. In the second area, northeast of Domain 3, both nesting techniques overpredict rainfall rates, but 2-way is somewhat worse, producing over 0.25" instead of zero as observed. In the San Francisco Bay Area (Fig. 46), the area of high precipitation is further southeast in RUN2 (d) than in RUN1 (a), again confirming that the first frontal passage is slightly anticipated with standard 1-way. Overall, RUN1 produces better precipitation results than RUN2 for this time.

3) RUN3: continuous 1-way

RUN3, the continuous 1-way run, was carried out for 36 hours with outputs every three hours, as for RUN1. Since no examples of applications with continuous 1-way was found in the literature, these results may represent the first test for this method. The expectation is that continuous 1-way should be similar to standard 1-way nesting, since both methods do not allow feedback from the FM to the CM. However, given the more accurate BCs in continuous 1-way, some improvements are expected with respect to standard 1-way nesting.

At 500 mb on 11 March at 1800 UTC (Fig. 50b,c) and 12 March at 0000 UTC (Fig. 53b,c), RUN3 produces exactly the same results as RUN2 for Domain 1. This shows that continuous 1-way is a real 1-way method, and thus that no

differences from standard 1-way results should be detected for the outermost domain. More differences should be expected in the inner domains. In fact, for Domain 2 in general the two 1-way nesting techniques produce similar results, but with some subtle differences. At 500 mb on 12 March at 0000 UTC (Fig. 53), for example, the wind and height fields are almost identical, but temperature contours show differences over Central Valley and eastern Sierra; the same applies for Domain 3 (Fig. 54).

More differences, however, can be detected in predicted precipitation rates, as 3-hr rainfall is not an instantaneous field but reflects the cumulative effects of slightly different dynamic fields during the prior three hours. For example, at 1800 UTC on the first day (Fig. 44), RUN3 (b) produces more rain than RUN2 (d) along the coast south of Point Reyes for Domain 2 (0.10-0.25" vs 0.01-0.10" in three hours). For Domain 3, with standard 1-way nesting the band of highest precipitation is located further south than observed (Fig. 46d) on 11 March at 1800 UTC, whereas with the continuous 1-way technique the band is correctly located in the North Bay (Fig. 46b). Precipitation values are in general closer to observed values with continuous 1-way than with 2-way nesting (Fig. 46a); as an example, no rain was simulated in the East Bay with RUN1.

Overall, two conclusions can be drawn based on the first 12 hours of simulation:

- continuous 1-way appears to be a valid alternative to standard 1-way, as it produces results generally similar to standard 1-way, but more accurate due to its more frequent BC updates
- for precipitation during the first frontal passage, comparisons of 2-way, standard 1-way, and continuous 1-way nesting showed that the latter produced the best results for Domain 3.

Since standard 1-way nesting was used only for 12 hours, the following 24 hours of simulations will focus on differences between 2-way and continuous 1-way nesting.

At the time of the second frontal passage, i.e., 1200 UTC on 12 March, the upper level height, wind, and temperature fields for 2-way and continuous 1-way nesting are shown in Fig. 55. The 2-way nesting (left panel) causes the closed low to be less deep (552 dam for the RUN1 center low vs 551 dam for RUN3) and less extended than with 1-way (right panel). Both techniques placed the center low in the wrong location, further north and east than observed (Fig. 32). With continuous 1-way, the cool pool (temperature $< -25^{\circ}\text{C}$) is pushed further east, closer to the ETA results than 2-way. Its center low has a value of 551 dam, only 1 dam higher than observed (2-way value is 552 mb). More details, however, in the height and temperature fields can be detected in the RUN1 results for Domain 1, due to the feedback of topography effects in the overlap nested areas.

At 850 mb, the differences between ETA, RUN1, and RUN3 can be noticed for Domain 2 in Fig. 56. Neither of the two nesting techniques correctly reproduces the closed low centered over the San Francisco Bay Area. Second, they give the same results over the ocean (virtually coincident lines), but not over land, particularly in the northern Sacramento Valley, where small differences are seen.

For precipitation, the second frontal passage at 1200 UTC on 12 March is not reproduced even with the 1-way nesting. For Domain 2 (Fig. 48), RUN1 (a) produces a rain band oriented west to east in an area southeast of the San Francisco Bay, where no observational sites exist to verify it. Furthermore, in the Santa Cruz mountains no rain is forecast whereas observations (c) show values as high as one inch in the three hour period. RUN3 (b) produces a feature similar to

the above mentioned rain band, but it places it further south, to a point east of the north edge of Monterey Bay, allowing for the production of higher precipitation in the eastern Santa Cruz mountains, as observed. Along the coast south of the Monterey Bay, where rainfall rates of over 0.75" in three hours are observed, both nesting techniques produce areas of less intense precipitation (up to 0.25" in three hours) and too offshore than observed.

In Domain 3 for the same time (Fig. 49), both nesting techniques produce a rain band oriented northwest to southeast, but in RUN3 (b) it is located further southeast as 1-way appears again to move the system slightly faster than 2-way (a). This is probably due to a "slowing/dissipating" effect of the mountains for 2-way nesting. Results generally agree with observations, but again precipitation in reality was mainly caused by the frontal passage whereas in MM5 it is due to mainly to the associated upper level dynamics.

The amount of total rain over Domain 3 during each three-hour interval for the three nesting techniques is shown in Fig. 57. Calculations were performed for domain internal points only, i.e., excluding the outer two rows and columns, where the BC effects would deteriorate precipitation results. First, it appears that an initial spin up of approximately four hours is necessary to produce detectable rainfall with all nesting techniques. Second, continuous 1-way produces overall more precipitation than the other two methods, which represents a potential advantage, as in general mesoscale models tend to underpredict rainfall rates.

4. Conclusion

The Fifth-Generation Mesoscale Model (MM5), developed in 1982 by NCAR and Pennsylvania State University, has been successfully used in the past to simulate and/or predict regional to mesoscale atmospheric systems. Non-

hydrostatic, fully compressible, and flexible in its options for cumulus parameterization, explicit microphysics, PBL, radiation, and surface temperature schemes, MM5 allows both 1-way or 2-way interactions between a coarse and a nested domain. Since explicit comparison of results obtained with different nesting methods has not been performed in the past, three nesting techniques have been compared in this study: 2-way, standard 1-way, and continuous 1-way. The latter method, tested in this study for the first time, differs from the standard 1-way in that it allows for more frequent boundary conditions (every coarse domain time interval instead of every hour).

To perform this comparison, MM5 was run in a triple nested configuration (27 - 9 - 3 km) to simulate the 11-13 March 1996 storm, a winter wave cyclone that affected the West Coast of the U.S., and in particular California. Two precipitation events associated with the storm occurred over the San Francisco Bay Area. The first one, at 1800 UTC on the first day, was associated with a weak occluded front and produced 3-hr rainfall totals up to 0.25" in the North Bay and 0.50" in the Santa Cruz mountains. The second event occurred at 1200 UTC on the second day, when an upper level vorticity maximum reached the Central California coast and its corresponding surface low was located over the San Francisco Bay; 3-hr rainfall rates were higher than in the first event, varying between 0.25" in the South Bay, 0.50" in the San Jose area, and 0.75" in the Santa Cruz mountains.

None of the three methods correctly simulated the storm evolution in all its phases. For the first frontal passage, all methods correctly simulated the position and timing of the surface trough, but generally underestimated precipitation rates, particularly in the Santa Cruz mountains. In subsequent hours, the simulated upper level flow became more zonal than observed, causing the 500 mb low pressure center to move too rapidly eastward and not far enough south. As a

consequence, the simulated system missed the third (inner) domain, centered over the San Francisco Bay Area, and neither the closed low nor its easterly flow developed at the surface at 1200 UTC on the second day. MM5 did simulate precipitation in the third domain at that time, but it was not as intense as observed and was due to upper level dynamics that did not produce the second surface frontal passage.

The reason for these discrepancies can be found in the MM5 initial conditions. The initial upper level flow was somewhat too zonal and lacking in PVA, and therefore the entire simulated system developed too far north and moved too rapidly eastward. Initial conditions are not an important factor in systems mainly driven by mesoscale features, such as sea breezes or circulations induced by topography, but they need to be accurate for storms driven by synoptic scale forcing.

Thermodynamic fields produced with the three nesting techniques were similar, yet not identical. For example, 2-way temperature and height fields in the coarser grids were noisier over terrain than in corresponding 1-way fields, due to feedback from the more detailed nested domains. The general evolution of the system is similar with all three techniques, but with continuous 1-way the 500 mb low was slightly further south and deeper than with 2-way, and thus closer to the observed behavior. Small differences in simulated thermodynamic fields, however, led to major differences in derived fields, such as precipitation.

Based on comparisons between observed and simulated precipitation fields obtained with the three nesting techniques, in general it is not possible to claim that one method was best, since the storm location was not correctly captured with any of the three methods. However, 2-way nesting in MM5 showed two disadvantages: higher CPU requirements and contaminated convective precipitation fields when the nested domain has no cumulus parameterization

scheme. Continuous 1-way produces more total rain than any other method, a promising result since atmospheric models generally tend to underestimate rainfall over complex terrain (Chen *et al.* 1997; Powers 1997; Archer 1998). Furthermore, its overall performance was similar, if not better than 2-way (e.g., in the deepening of the 500 mb trough and in the location of precipitation maxima on March 12th). This was achieved with a lower CPU requirement than 2-way and with only one job submittal (instead of one plus twice the number of domains, as in the standard 1-way method).

To determine whether continuous 1-way is a better nesting technique than 2-way for precipitation prediction, it is first necessary to correctly capture all phases of a storm evolution. For this, additional simulations are necessary, and the following efforts are recommended:

1. Initial and boundary conditions: should correctly include all storm features, e.g., extension and tilt of the upper level and surface troughs, and location and intensity of vorticity maxima. The NCEP global analyses used in this study, with their coarse resolution ($2.5 \times 2.5^\circ$ latitude-longitude), are thus not recommended for synoptically driven storms, for which the higher resolution (48 km) ETA model seems a better choice.
2. Cumulus parameterization scheme: should be chosen carefully, based on grid resolution and storm characteristics (i.e., intensity of grid-scale forcing and convective instability). The current Domain 2 resolution (9 km) was mid-way between scales for which cumulus parameterization is necessary (~ 30 km) and scales for which all precipitation can be explicitly resolved (~ 5 km). It was thus decided to use a cumulus scheme, and the Grell scheme was selected, based on results from previous studies (Colle and Mass 1995). Use of any cumulus parameterization scheme with such a fine resolution, however,

may not be appropriate (Molinari and Dudek 1992), and therefore comparative runs without cumulus parameterization in Domain 2 is recommended.

3. PBL and surface temperature schemes: more sophisticated options than Blackadar for PBL (e.g., Burk-Thompson) and force-restore for surface temperature (e.g., multi-layer soil) should be selected.

Qualitative analyses should be first performed on MM5 results obtained with different nesting techniques to verify that general storm features (e.g., low center location and deepening, frontal evolution, and precipitation rates) have been correctly simulated. Only then, can quantitative evaluations of the different nesting techniques be carried out, based on:

- comparisons of observed vs predicted precipitation rates for representative sites as a function of time
- statistical analyses to decompose the total error into its component bias and noise.

Additional recommendations concerning MM5 model formulation also arise from this study. First, since the MM5 domain top is a rigid surface with constant pressure, the only way presently to introduce large scale effects into the domains is through its lateral boundary conditions. A variable upper boundary condition would allow for better representation of synoptic scale forcing and therefore better reconstructions of synoptically driven events. Furthermore, two easily correctable contaminations appears in the 2-way feedback from a nested domain with no cumulus parameterization scheme to a coarse domain with active cumulus parameterization scheme:

- the coarse domain convective precipitation is zeroed in the area corresponding to the nested domain. This does not affect model performance for other variables, since precipitation is a diagnostic and not a prognostic variable, but

causes an unrealistic rectangular hole over the nested grid area in the coarse domain convective rain field

- since the fine mesh receives boundary conditions from the coarse grid for each variable, including convective precipitation, the two outermost rows and columns of the fine grid can contain non-zero convective precipitation values.

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Appendix A: List of symbols and acronyms

Symbols

A	Constant temperature difference between p_{00} and p_{00}/e , usually 50 K
$H(i,j)$	Terrain elevation at grid point (i,j)
i	Index for south-north direction
j	Index for west-east direction
n	Nesting ratio
$p_0(z)$	Reference state pressure
p_{00}	Constant reference state sea-level pressure, usually 10^5 Pa
$p_s(x,y)$	Surface pressure of reference state
p_τ	Top pressure of reference state
$p^*(x,y)$	$p_s - p_\tau$
R	Universal gas constant
$T_0(z)$	Reference state temperature
T_{s0}	Reference temperature at p_{00}
u	west-east wind velocity component
v	south-north wind velocity component
w	Vertical wind velocity component
z_0	Roughness length
$\alpha(i,j)$	Any variable at grid point i,j
Δx	Horizontal grid size
Δt	Time step
Δt_c	Time step for the coarse mesh
Δt_f	Time step for the fine mesh
ν	Smoothing coefficient; $0 < \nu < 1$

σ Sigma vertical coordinate

Acronyms

ASOS	Automated Surface Observation System
DMA	Defense Mapping Agency
GDC	Geophysical Data Center
GSM	Global Spectral Model
NCAR	National Center for Atmospheric Research
NCEP	National Center for Environmental Prediction
PW	Precipitable Water
QPF	Quantitative Precipitation Forecast

Appendix B: NCEP GDAS Analyses

The NCEP Global Tropospheric Analyses are provided since 1 July 1976 on two grids, one for each hemisphere, both having 2.5° latitude-longitude resolution. The Hough analysis method was then used to force a relationship between geopotential heights and winds which causes the zonal mean meridional wind at every level to be zero (Trenberth and Olson, 1988). The Global Data Assimilation System (GDAS) was started on 22 September 1978, using the optimal interpolation (OI) analysis method (9 layer). The quality of stratospheric global analyses were then very poor until May 1980, when the GDAS was switched to a 12 layer model (R24). In May 1986, GDAS started using the Medium Range Forecast (MRF) model, with 18 layers and R40 resolution. In August 1987 the vertical resolution in the MRF was raised from R40 to T80.

NCEP Analyses include (Table 7): surface temperature, geopotential height, temperature, and wind (u and v components) at 1000mb, 850mb, 700mb, 500mb, 400mb, 300mb, 250mb, 200mb, 150mb, 100mb, 70mb, and 50mb. Prior to 22 February 1981, the land temperature analyses were derived from the model surface energy budget, then they were extrapolated from the lowest model layers.

Appendix C: MM5 σ -coordinate system

The basic assumption is that the reference state is hydrostatic, therefore p_0 is only a function of z . To derive an explicit expression for $p_0(z)$, the following form of the hydrostatic equation can be used:

$$d(\ln p) = -\frac{g}{RT} dz, \quad (4)$$

where the only unknown is temperature. But temperature is given, for the reference state, by (1), which can be inserted into (4) to obtain:

$$-\frac{R}{g} \left[T_0 + A \ln \left(\frac{P}{P_{\infty}} \right) \right] d \left(\ln \frac{P}{P_{\infty}} \right) = dz. \quad (5)$$

The integration of (5) from sea level to a generic elevation z leads to:

$$p_0(z) = p_{\infty} \exp \left[-\frac{T_0}{A} + \sqrt{\left(\frac{T_0}{A} \right)^2 - \frac{2g}{A \times R} z} \right]. \quad (6)$$

Given a grid point (i,j) on a σ -surface, simply defined by one value of σ , one can calculate the corresponding reference state pressure p_0 from (1). Solving then (6) with respect to z it is possible to obtain the elevation of the σ -surface for that point:

$$z = -\frac{R}{g} \left[T_0 \ln \left(\frac{P}{P_{\infty}} \right) + \frac{A}{2} \ln^2 \left(\frac{P}{P_{\infty}} \right) \right]. \quad (7)$$

Note that each MM5 grid point, laying on these σ -surfaces, is fixed in space, i.e., it stays at the same constant elevation throughout the simulation, given by (7), but its pressure value changes with time according to (3). Furthermore, replacing z with terrain elevation $H(i,j)$ in (6), it is possible to obtain an expression for the surface reference state pressure p_s . Being (6) non-linear in $H(i,j)$, the first σ -level ($\sigma=1$) follows terrain closely but not exactly.

Appendix D: ETA model

Even though there are several versions of the ETA model, what is used in this study is the 48 km resolution 'Early ETA', so called because it starts the data assimilation 12 hours before starting the real forecast. It is run at the NCEP Environmental Modeling Center, Mesoscale Modeling Branch, and it receives its BCs from the Aviation (AVN) run of the Global Spectral Model (GSM). What makes the ETA the preferred tool for model result comparison is its data assimilation system. First, a first guess field is provided by the Global Data Assimilation System (GDAS) 12 hours before the real start of the forecast, using a spectral-to-grid transformation. Then, the ETA Data Assimilation System (EDAS) is used to assimilate observations every three hours during the 12 hour preforecast period. The peculiarity of the EDAS is that it produces ICs with the exact same resolution as the ETA model; an Optimum Interpolation scheme (Black 1994) is used to incorporate high frequency wind profiler and ASOS data. The ICs provided by the EDAS lead to reduced precipitation spin-up in the early part of the ETA forecast (Archer 1998). These ICs, available at 0000 UTC and 1200 UTC, are believed to be a trustful representation of the atmosphere behavior at those times and therefore they are used in this study for describing the March 1996 storm and for comparison with MM5 results.

Table 1. MM5 applications

Reference		Application		Evaluation		Modeling		Verification		3-Step	
Dudhia (1993)	Winter cyclogenesis	North Atlantic	1-way	20	GR	?					
Grell (1993)	Squall line (PRE-STORM)	Central U.S.	2-way	75	AK	-DU					
Kuo <i>et al.</i> (1993)	Squall line (SESAME)	South-Central U.S.	none	40	KU	?					
Lakhtakia and Warner (1994)	Typical surface hydrological cycles	Southern U.S.	none	?	?	?					
Molders <i>et al.</i> (1994)	Heavy rainfall event	Europe	none	80	KA	WR, -DU					
Reed <i>et al.</i> (1994)	Extratropical cyclone evolution (ERICA IOP)	Western U.S.	?	60	GR	DU					
Sousonis and Fritsch (1994)	Cold air outbreak	Great Lakes	?	90	AK	?					
				30	KF	?					

Table 1. MM5 applications (continued)

Reference	Phenomenon (weather event)	Location	Modeling	Resolution (km)	GP Station	Other Station
Colle and Mass (1995)	Cold surges	East of Rocky Mountains	?	?	?	?
Cortinas and Stensrud (1995)	Severe weather outbreak	U.S. and Gulf of Mexico	2-way	75	AK	-WR
				25	KF	-WR
Davis (1995)	Cold surge	Central U.S.	2-way	60	?	DU
				20	?	DU (?)
				6.7	?	DU (?)
Lipton <i>et al.</i> (1995)	Convective cloud development (CaPE)	Florida	2-way	30	KU	?
				10	KU	?
Oncley and Dudhia (1995)	Winter storm (WISP)	Colorado	1-way	20	GR	DU
				5	GR	DU
	Winter storm (STORM-FEST)	Kansas	2-way	60	GR	DU
Zou <i>et al.</i> (1995)	Blizzard event (STORM-FEST)	Colorado	none	20	GR	DU
				6.67	none	DU
				40,20	none	none

Table 1. MM5 applications (continued)

Author	Phenomenon (Model)	Location	Neurps	Resolution (km)	Grid	Other
Colle and Mass (1996)	Low level SW flow (COAST)	Olympic Mountains	1-way	27	GR	RE
				9	GR	RE
				3	none	RE
Kuo <i>et al.</i> (1996a)	Explosive marine cyclogenesis (ERICA)	Gulf of Mexico	?	60	KU, BM, GR, KF	RE, SS, WR, DU, GO
				20		
Kuo <i>et al.</i> (1996b)	Cyclogenesis (SESAME)	South-Central U.S.	none	40	KU	?
Rotunno and Bao (1996)	Cyclogenesis (ERICA)	South-Central U.S.	?	?	?	?
Steenburg and Mass (1996)	Coastal orographic effects on wave cyclon	North-Western U.S. Coast	1-way	27	GR	DU
				9	GR (?)	DU
Zou and Kuo (1996)	Heavy rainfall event (SESAME)	South-Central U.S.	none	40	KU, GR	?

Table 1. MM5 applications (continued)

Author	Phenomenon (Parameter)	Location	Model	Resolution (km)	Topography (m)	Code
Braun and Houze (1997)	Squall line and rear inflow development (PRE-STORM)	Central U.S.	2-way	60	AK	-DU
				20	KF	-DU
Bresch <i>et al.</i> (1997)	Polar low development	Bering Sea	?	20	KF	RE
				6.67	KF?	RE
Chen <i>et al.</i> (1997)	Cold-frontal convective rainband and gravity current	Central Eastern U.S.	?	45	GR	DU
				15	GR	DU
				5	none	DU
Chien <i>et al.</i> (1997)	Marine push event	Western North America	2-way	45	GR	DU
				15	GR	DU
				5	GR(?)	DU
Gallus and Bresch (1997)	Small scale low pressure system with snowfall	Midwest U.S.	2-way	81	KF	DU
				27	KF	DU
			2-way	60	GR	DU
				20	GR	DU

Table 1. MM5 applications (continued)

Author(s)	Application	Location	Modeling	Modeling	Modeling
Liu <i>et al.</i> (1997)	Hurricane Andrew	Western Atlantic and Gulf of Mexico	2-way	54	BM
				18	BM
				6	none
Marwitz <i>et al.</i> (1997)	Supercooled drizzle in strong frontal zone	Central U.S.	?	75	KF
				25	KF
Powers (1997)	Mesoscale gravity waves during cyclogenesis	Central U.S.	2-way	30	GR,KU,KF
				10	GR,KU,KF
				3.3	none
Wang and Seaman (1997)	Winter cyclogenesis; summer convection	North America	1-way	36	AK, BM, GR, KF
				12	DU

Cumulus Parameterization (CP) Schemes:

GR = Grell

AK = Anthes-Kuo

KF = Kain-Fritsch

KU = Kuo

BM = Betts-Miller

Explicit Schemes:

SS = Simple Supersaturation

WR = Warm Rain

DU = Dudhia's simple ice

RE = Reisner

GO = Goddard

Note: Question mark indicates information not provided in original paper

Table 2. MM5 nesting schemes

Characteristic	Nesting scheme		
	Standard 1-way	Continuous 1-way	2-way
Forcing from CM to FM	<ul style="list-style-type: none"> • only at FM boundaries • every hour 	<ul style="list-style-type: none"> • only at FM boundaries • each Δt_c 	<ul style="list-style-type: none"> • only at FM boundaries • each Δt_c
Feedback from FM to CM	None	None	over entire FM area
Job submittals	Three	One	One

Table 3. MM5 input fields (order as in input file)

Field name	Units	Grid location (Cross/Dot)
3-D fields:		
u	kPa m s ⁻¹	d
v	kPa m s ⁻¹	d
w	kPa m s ⁻¹	c
Pressure Perturbation	kPa Pa	c
Mixing Ratio	kPa kg kg ⁻¹	c
Temperature	kPa K	c
2-D fields:		
p*	kPa	c
Coriolis Parameter	s ⁻¹	d
Map-scale Factor @ cross points	none	c
Map-scale Factor @ dot points	none	d
Latitude @ cross points	°N	c
Longitude @ cross points	°E	c
Latitude @ dot points	°N	d
Longitude @ dot points	°E	d
Ground Temperature	K	c
Terrain Elevation	m	c
Land Use	categories	c
Snow Cover	Yes/No	c

Note: 3-D fields multiplied by kPa.

Table 4. MM5 boundary fields (order as in BC file)

Field name	Units	Grid location (Cross/Dot)
u	kPa m s ⁻¹	d
v	kPa m s ⁻¹	d
Temperature	kPa K	c
Mixing Ratio	kPa kg kg ⁻¹	c
Pressure Perturbation	kPa Pa	c
w	kPa m s ⁻¹	c
Cloud Water	kPa kg kg ⁻¹	c
Rain Water	kPa kg kg ⁻¹	c
Ice Water	kPa kg kg ⁻¹	c
Snow Water	kPa kg kg ⁻¹	c
Graupel	kPa kg kg ⁻¹	c
Number Concentration of Ice	kPa no. m ⁻³	c

Note: all fields multiplied by kPa.

Table 5. MM5 output fields (order as in output file)

Field name	Units	Grid location (Cross/Dot)
3-D fields:		
u	kPa m s ⁻¹	d
v	kPa m s ⁻¹	d
Temperature	kPa K	c
Mixing Ratio	kPa kg kg ⁻¹	c
Cloud Water	kPa kg kg ⁻¹	c
Rain Water	kPa kg kg ⁻¹	c
Ice Water	kPa kg kg ⁻¹	c
Snow Water	kPa kg kg ⁻¹	c
Graupel	kPa kg kg ⁻¹	c
Number Concentration of Ice	kPa no. m ⁻³	c
w	kPa m s ⁻¹	c
Pressure Perturbation	kPa Pa	c
2-D fields:		
P*	kPa	c
Ground Temperature	K	c
Accumulated Non-convective Rain	cm	c
Accumulated Convective Rain	cm	c
Terrain Elevation	m	c
Map-scale Factor @ cross points	none	c
Map-scale Factor @ dot points	none	d
Coriolis Parameter	s ⁻¹	d
Infinite Reservoir Temperature	K	c
Latitude @ cross points	°N	c
Longitude @ cross points	°E	c
Land Use	categories	c
Snow Cover	Yes/No	c

Note: 3-D fields multiplied by kPa.

Table 6. Terrain elevation source data

	Domain		
	1	2	3
Resolution	10'	5'	30"
Coverage	global	global	51-23 °N;130-60°W
Source	GDC	GDC	DMA

Table 7. NCEP input data availability

Level (mb)	Snow cover	Sea-sfc Temp (K)	Sea-level Pressure (mb)	Virtual Temp (K)	Geop Height (m)	u (m s ⁻¹)	v (m s ⁻¹)	RH (%)
Surface	X	X	X	X				
1000				X	X	X	X	X
850				X	X	X	X	X
700				X	X	X	X	X
500				X	X	X	X	X
400				X	X	X	X	X
300				X	X	X	X	X
250				X	X	X	X	set to 10
200				X	X	X	X	set to 10
150				X	X	X	X	set to 10
100				X	X	X	X	set to 10
70				X	X	X	X	set to 10
50				X	X	X	X	set to 10

Figure 1

Figure 2

Figure 3

ETA 980311/0000V000 500 MB HEIGHTS, ABS VORTICITY

Figure 4

Figure 5

Figure 7

Figure 8

ETA 960311/1200V000 500 MB HEIGHTS, ABS VORTICITY

Figure 9

Figure 10

Figure 11

Figure 12

ETA 980312/0000V000 500 MB HGHTS, WINDS & TEMPERATURES

Figure 13

Figure 14

ETA 980312/1200V000 500 MB HEIGHTS, ABS VORTICITY

Figure 15

Figure 16

Figure 17

Figure 18

Figure 19

ETA 960313/1200V000 500 MB HEIGHTS, ABS VORTICITY
Figure 20

Eta 980313/1200V000 250 MB HEIGHTS, ISOTACHS AND WIND (KTS)

Figure 21

Figure 22

Figure 23

Figure 24

Figure 25

MON Mar 11 1996 1200V000Z MM1 (500) Geopotential Height
MON Mar 11 1996 1200V000Z Eta (500) Geopotential Height

Figure 26

MON Mar 11 1996 1200V000Z MM1 (500) Absolute Vorticity
Figure 27

Figure 28

ETA 960312/0000V000 500 MB HGHTS, WINDS & TEMPC

Figure 29

Figure 31

ETA 960312/1200V000 500 MB HGHTS, WINDS & TEMPERATURES

Figure 32

TUE Mar 12 1996 1200V024Z MML (500) Geopotential Height
TUE Mar 12 1996 1200V000Z Eta (500) Geopotential Height

Figure 33

Figure 34

TUE Mar 12 1996 1200V024Z MM1 (500) Absolute Vorticity

Figure 35

Figure 36

ETA 860313/0000V000 500 MB HIGHTS, WINDS & TEMPERATURES

Figure 37

MON Mar 11 1996 1200V000Z MSL (0) Sea Level Pressure
 MON Mar 11 1996 1200V000Z Eta (500) Mean Sea Level Pressure

Figure 38

MON Mar 11 1996 1800V006Z MML (0) Sea Level Pressure
MON Mar 11 1996 1800V006Z Eta (500) Mean Sea Level Pressure

Figure 39

Figure 40

TUE Mar 12 1996 0600V018Z MHI (0) Sea Level Pressure
 TUE Mar 12 1996 0600V036Z Eta (500) Mean Sea Level Pressure

Figure 41

TUE Mar 12 1996 1200V024Z MM1 (0) Sea Level Pressure
 TUE Mar 12 1996 1200V024Z MM1 (0) Mean Sea Level Pressure

Figure 42

Figure 43

Figure 44

Figure 45

Figure 46

Figure 47

Figure 48

Figure 49

Figure 51

Figure 52

Figure 53

Figure 54

Figure 55

TUE Mar 12 1996 1200V000Z Eta (850) Geopotential Height
TUE Mar 12 1996 1200V024Z MM2 (850) Geopotential Height
TUE Mar 12 1996 1200V024Z MM1 (850) Geopotential Height

Figure 56

Mass of precipitation over domain

Figure 57

IMAGE EVALUATION TEST TARGET (QA-3)

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