Journal of Computational Physics 228 (2009) 1294–1311

Contents lists available at ScienceDirect

Journal of Computational Physics

journal homepage: www.elsevier.com/locate/jcp

Vertically nested nonhydrostatic model for multiscale resolution of flows in the upper troposphere and lower stratosphere

Alex Mahalov *, Mohamed Moustaoui

Center for Environmental Fluid Dynamics, Department of Mechanical and Aerospace Engineering, Department of Mathematics and Statistics, Arizona State University, Tempe, AZ 85287-1804, USA

ARTICLE INFO

Article history:
Received 10 April 2008
Received in revised form 2 October 2008
Accepted 13 October 2008
Available online 7 November 2008

PACS:
65M06
65M12
76E06
76R10
76U05
86A10

Keywords:
Nonhydrostatic atmospheric model
Vertical nesting
Multiscale flows in the upper troposphere and lower stratosphere

ABSTRACT

Vertical nesting with refined gridding in coupled mesoscale weather research and forecasting (WRF)/microscale models are presented with a particular emphasis on improved vertical resolution in the upper troposphere and lower stratosphere (UTLS). The finest mesoscale nest is coupled with a sequence of microscale nests with finer resolution in both the horizontal and the vertical. The fully three-dimensional, compressible nonhydrostatic Navier–Stokes equations are solved using a time-split method with a refined grid in the vertical, and improved resolution in the UTLS region. For nesting, both lateral and vertical boundary conditions are treated via implicit relaxation in buffer zones where all fields are relaxed to those obtained from the finest mesoscale nest. Computational results are presented demonstrating the ability of microscale nests to resolve multiscale physics of strongly nonlinear interactions and laminated structures observed in the Terrain-induced rotor experiment (T-REX) campaign of field measurements. Very high resolution real case nested simulations are conducted. The microscale nests fully resolve localized shear layers and sharp gradients of vertical velocity and potential temperature near the tropopause and in the lower stratosphere.

1. Introduction

Significant advances in computation of atmospheric flows have been achieved during the last decades. The dramatic increase in computer power has facilitated developments of nonhydrostatic mesoscale numerical weather prediction (NWP) codes that have capabilities to resolve small-scale atmospheric processes. This was achieved by implementation of nesting techniques with multiple domains resolving horizontal scales ranging from few to hundreds kilometers, and by the improvement of sub-grid scale parameterizations. Among these models, the advanced research version of the weather research and forecasting model (WRF–ARW) is a next generation mesoscale NWP model [1]. It is the first fully compressible conservative-form nonhydrostatic atmospheric model suitable for both research and weather prediction applications. The WRF–ARW model represents the latest developments following a particular modeling approach that uses time-splitting techniques to efficiently integrate the fully compressible nonhydrostatic equations of motion. The integration scheme uses a time-split method to circumvent the acoustic-mode time step restriction, where the meteorologically significant modes are integrated

* Corresponding author.
E-mail addresses: mahalov@asu.edu (A. Mahalov), mousta66@pearson.la.asu.edu (M. Moustaoui).

0021-9991/$ - see front matter © 2008 Elsevier Inc. All rights reserved.
doi:10.1016/j.jcp.2008.10.030

by using a third-order Runge–Kutta (RK) scheme. The spatial discretization typically uses a fifth-order differences for advection, and the vertical coordinate is based on Terrain following hydrostatic pressure coordinate.

There are two main techniques that are used in atmospheric and oceanic models to improve resolution over limited areas. In dynamically adaptive methods, the spatial resolution is constantly changing with time by coarsening or refining the grid spacing depending on local conditions [19,20]. The adaptive methods are not well established in the atmospheric modeling systems for several reasons [21]: (i) adaptive techniques can incur massive overhead due to indirect data addressing and additional efforts for grid handling which increase the cost of real time forecasting; (ii) physical parameterizations of sub-grid processes are usually optimized for a specific grid resolution, making it difficult to use dynamically and temporally refined or coarsened grids. The other method uses nesting to improve spatial resolution over a limited area. Nesting are widely used in atmospheric (i.e. MM5 [22], WRF [1], COAMPS [23]) and oceanic (i.e. ROMS [24]) models. Large domain models with coarse resolution are used to predict large-scale dynamics, while limited area models with boundary conditions interpolated from coarse grids are used over small domains with finer resolution. The improvement allowed by nesting techniques is that small-scale processes which are not resolved in a coarse grid model, and therefore need to be represented by using sub-grid-scale parameterizations, may be explicitly resolved in the nested model.

One of the main difficulties faced in atmospheric as well as oceanic nested modeling is the specification of the lateral boundary conditions. Usually, the prognostic fields at the lateral boundaries of the nested grid are specified from the large domain. These fields have coarse resolution, and are interpolated in space and time to the nested grid. The inconsistencies between the limited and the large domain solutions create spurious reflections that may propagate and affect the solution in the interior of the nested domain. Several approaches are used to handle the lateral boundary conditions. The flow relaxation scheme [4,5] is the most frequently used for atmospheric mesoscale forecasting models over a limited domain. Lateral open boundary conditions are often used in limited area ocean modeling. These conditions include radiation condition, combined radiation and prescribed condition depending on the inflow and outflow regime at the boundary, and a scale selective approach. A review of these methods is given in [25].

Nesting options are implemented in WRF–ARW. Nevertheless, as in many nonhydrostatic mesoscale atmospheric models, nesting is allowed only in the horizontal direction and all nests use the same grid distribution in the vertical. For real applications, NWP models still use a limited number of grid points in the vertical that is typically well below 100. Usually, grid stretching is implemented to increase the vertical resolution in the boundary layer and lower levels at the expense of the upper troposphere and lower stratosphere (UTLS). The extended region consisting of the bulk of the troposphere and the lower stratosphere represents a significant challenge for numerical prediction. The collusion between the stratification and shear in the UTLS region leads to many complex multiscale physics phenomena, including the formation of vertically thin, laminated structures [15,13]. The lack of vertical resolution in the UTLS region may present a severe limitation in resolving small-vertical-scale processes such as clear air turbulence patches and thin adiabatic layers characterized by sharp vertical gradients at the edges. They are observed in the UTLS region during extreme events such as wave breaking, overshooting moist convection, shear-instabilities near jet streams and gravity wave-critical level interactions [17,16]. These small scale upper level processes are particularly sensitive to the vertical resolution, implying that the vertical grid spacing typically used in operational models is likely insufficient to resolve these vertical scales. NWP systems employ a range of parameterizations to model the effects of unresolved sub-grid processes on the large-scale dynamics. Resolving explicitly these small-scale processes requires computations using fine mesh in both the vertical and the horizontal to encompass all pertinent multiscale phenomena in the UTLS region. This, coupled with sharp velocity and temperature gradient profiles, presents significant challenges for nesting.

In this paper, we treat the computational aspects of physical problems with a particular emphasis on improved vertical resolution of atmospheric flows near the tropopause and in the lower stratosphere. We present for the first time high resolution coupled WRF–ARW/microscale system, where the microscale domains are nested both in the horizontal and the vertical, and where all microscale fields are relaxed towards the WRF finest nest. We present a new relaxation method based on the flow relaxation scheme, where the relaxation is implemented as an implicit correction in the acoustic time step, and we show examples demonstrating that this method is very effective and robust. Computational results in real atmospheric conditions are presented demonstrating the ability of microscale nests to resolve multiscale physics of strongly nonlinear laminated structures observed in the UTLS region. The paper is organized as follows: the model formulation and the computational approach are presented in Section 2. The performance of the model is shown in Section 3. The ability of microscale nests to resolve laminated structures observed in the UTLS region is demonstrated in Section 4, where our computational methodology is applied to the field data obtained during the Terrain-induced rotor experiment (T-REX). Finally summary and conclusion are given in Section 5.

2. Model formulation and computational approach

Our coupled WRF with microscale vertical nesting model simulations are produced by conducting mesoscale simulations with several nests interacting in a two way mode, with a finest WRF nest that uses a horizontal grid spacing of 1 km. The number of vertical sigma pressure levels used for these nests is 150, and they are adjusted to achieve an improved resolution near the tropopause and in the lower stratosphere. The pressure at the top is $p_{top} = 10$ mb, and the vertical resolution is about $\delta z = 150$ m in the UTLS region. WRF simulations are initialized with high resolution global data, that is the European