Parallelizing a Very-High-Resolution Climate Model Using Clusters of Workstations with PVM and Performance and Load Balance Analyses

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Abstract *Environment and climate change problems are very complicated, and their research and operational prediction heavily depend on powerful computer techniques. Even with today most powerful supercomputer, the climate and environmental models are still limited to very coarse resolution. In this paper, we report our recent effort in parallelizing our very-high-resolution numerical model systems. First, the mathematical equations, algorithms, and numerical schemes are designed and analyzed; then domain decomposition, data decomposition, and functional decomposition schemes are tested in our implementations on clusters of HP workstations and/or DEC Alpha stations with PVM; finally, the performance and load balance are analyzed. Shelterbelts cause significantly inhomogeneous computation distribution on the domain, therefore, common and easiest domain decomposition does not work well on our problem. Special care must be taken to treat computations around shelterbelts. With careful design of algorithms, we found that cheap and still powerful workstations or PCs make it possible to run these models in clusters of workstations or PCs.*

Keywords: cluster computing, climate model, scientific computing, parallel and distributed algorithm, load balance, numerical analyses

1 Introduction

Flows around obstacles or terrain are very complex, especially near porous obstacles like shelterbelts and windbreaks. The importance of natural and man-made shelters in the landscape has been recognized for centuries. Functional effects of shelterbelts are directly related to the effects of shelterbelts on airflow. The primary effect of any shelterbelt or windbreak system is the reduction in wind velocity. Windspeed reduction influences turbulent transport processes and results in a modification of the microclimate in the sheltered zone. The amount of sheltering and the range of the sheltered zone are dependent on the structure of shelterbelt. We have developed a very high resolution numerical model which can treat practical shelterbelt systems [2-5]; with coupled climate models, the problems related to impact assessment, adaptation, and migration of global climate changes and sustainable development can be systematically studied. However, such research and prediction need huge amount of computations. We parallelize our model system on clusters of workstations with PVM[1].

2 Numerical Scheme and Algorithm

2.1 Model Equations

The derivation details of our model equations can be found in our previous paper [2]. Under the Boussinesq approximation, the non-hydrostatic, incompressible atmospheric continuity equation and equations of motion may be written as

$$\frac{\partial u_i}{\partial x_i}=0 \qquad (1)$$

$$\frac{\partial u_i}{\partial t}=-u_j\frac{\partial u_i}{\partial x_j}-\frac{1}{\rho_0}\frac{\partial p}{\partial x_i}-\gamma g_i\theta-\epsilon_{ijk}f_k u_j+\nu\frac{\partial^2 u_i}{\partial x_i^2} \qquad (2)$$

where Einstein summation is used; u_i is the component of windspeed in the i direction, f_k the Coriolis parameter, γ the coefficient of thermal expansion, p the atmospheric pressure perturbation, ρ_0 the air density, θ the potential-temperature departure from its basic state, g_i gravitational acceleration, and ν the molecular viscosity coefficient. We apply Reynold averaging to average above equations and obtain the atmospheric boundary layer mean equations and the Reynold stress equations:

$$\frac{\partial\overline{\langle u_i\rangle}}{\partial x_i}=0 \quad (3)$$

$$\begin{aligned}\frac{\partial\overline{\langle u_i\rangle}}{\partial t}&=-\overline{\langle u_j\rangle}\frac{\partial\overline{\langle u_i\rangle}}{\partial x_j}\\&-\frac{\partial(\overline{\langle u_i\rangle'\langle u_j\rangle'})}{\partial x_j}-\epsilon_{ijk}f_k\overline{\langle u_j\rangle}\\&-\gamma g_i\overline{\langle\theta\rangle}-\frac{1}{\rho_0}\frac{\overline{\partial\langle p\rangle}}{\partial x_i}\\&+\nu\frac{\partial^2\overline{\langle u_i\rangle}}{\partial x_j^2}-\frac{1}{\rho_0}F_i\end{aligned} \quad (4)$$

and

$$\begin{aligned}\frac{\partial\overline{\langle u_i\rangle'\langle u_j\rangle'}}{\partial t}&=-\overline{\langle u_k\rangle}\frac{\partial\overline{\langle u_i\rangle'\langle u_j\rangle'}}{\partial x_k}\\&-\overline{\langle u_i\rangle'\langle u_k\rangle'}\frac{\partial\overline{\langle u_j\rangle}}{\partial x_k}-\overline{\langle u_j\rangle'\langle u_k\rangle'}\frac{\partial\overline{\langle u_i\rangle}}{\partial x_k}\\&-\gamma(g_i\overline{\langle u_i\rangle'\langle\theta\rangle'}+g_j\overline{\langle u_j\rangle'\langle\theta\rangle'})\\&-f_k(\epsilon_{jkq}\overline{\langle u_i\rangle'\langle u_q\rangle'}+\epsilon_{ikq}\overline{\langle u_j\rangle'\langle u_q\rangle'})\\&-\frac{\partial\overline{\langle u_k\rangle'\langle u_i\rangle'\langle u_j\rangle'}}{\partial x_k}\\&-\frac{1}{\rho_0}\left(\frac{\partial\overline{\langle u_i\rangle'\langle p\rangle'}}{\partial x_j}+\frac{\partial\overline{\langle u_j\rangle'\langle p\rangle'}}{\partial x_i}\right)\\&+\frac{1}{\rho_0}\overline{\langle p\rangle'\left(\frac{\partial\langle u_i\rangle'}{\partial x_j}+\frac{\partial\langle u_j\rangle'}{\partial x_i}\right)}\\&+\nu\frac{\partial^2\overline{\langle u_i\rangle'\langle u_j\rangle'}}{\partial x_k^2}-2\nu\overline{\frac{\partial\langle u_i\rangle'}{\partial x_k}\frac{\partial\langle u_j\rangle'}{\partial x_k}}\\&+\frac{1}{\rho_0}\overline{\langle u_i\rangle F_j}+\frac{1}{\rho_0}\overline{\langle u_j\rangle F_i}\end{aligned} \quad (5)$$

where the overline of variables stands for the time average of the variables, and prime stands for fluctuation from the time average. For convenience, we use an angle bracket around a term or variable to indicate the spatial average of the variable. The equations of mean motion have an additional term arising from the form drag. The Reynold stress equations have two additional terms related to this force:

$$\begin{aligned}F_i&=\overline{\frac{1}{V}\iint_S pn_i dS'}\\&-\overline{\frac{\nu}{V}\iint_S\frac{\partial u_i}{\partial\mathbf{n}}dS'}\end{aligned} \quad (6)$$

and the drag force may be expressed by the commonly used formula

$$F_i=\rho_0 CUu_i \quad (7)$$

where C is a drag coefficient for an obstacle element, and U is the mean windspeed defined as

$$U=\sqrt{\overline{\langle u_i\rangle}\ \overline{\langle u_i\rangle}} \quad (8)$$

For the vegetation case, formula (7) can be rewritten as

$$F_i=\rho_0 C_d AUu_i \quad (9)$$

where C_d is a drag coefficient for unit leaf area density, and A is the leaf area density.

The equations can be simplified as

$$\begin{aligned}\frac{\partial u}{\partial t}&=-\frac{1}{\rho_0}\frac{\partial p}{\partial x}-u\frac{\partial u}{\partial x}-w\frac{\partial u}{\partial z}\\&-\frac{\partial\overline{u'^2}}{\partial x}-\frac{\partial\overline{u'w'}}{\partial z}-C_d AUu\end{aligned} \quad (10)$$

$$\begin{aligned}\frac{\partial w}{\partial t}&=-\frac{1}{\rho_0}\frac{\partial p}{\partial z}-u\frac{\partial w}{\partial x}-w\frac{\partial w}{\partial z}\\&-\frac{\partial\overline{u'w'}}{\partial x}-\frac{\partial\overline{w'^2}}{\partial z}-C_d AUw\end{aligned} \quad (11)$$

$$\frac{\partial u}{\partial x}+\frac{\partial w}{\partial z}=0 \quad (12)$$

where u and w are mean windspeed components in x and z direction, u' and w' are their fluctuating values, p is the pressure perturbation, and ρ_0 air density. For convenience we omit the overbar on mean values. C_d is the unit LAI form drag coefficient exerted on airflow by solid elements, and A is the leaf area index of vegetation. U is total mean windspeed, and drag coefficient $C=C_dA$.

In equations (10) and (11), the velocity fluctuation correlations (Reynold stress) terms may be expressed as

$$-\overline{u'_i u'_j}=K_m\left(\frac{\partial u_i}{\partial x_j}+\frac{\partial u_j}{\partial x_i}\right)-\frac{2}{3}E\delta_{ij} \quad (13)$$

$$K_m=c_1 l E^{1/2} \quad (14)$$

where l is the mixing length, K_m is turbulent exchange coefficient, E is turbulent kinetic energy (TKE), and Einstein summation is also used here. With the above simplifications, equation (5) gives the TKE equation as

$$\frac{\partial E}{\partial t}=-u\frac{\partial E}{\partial x}-w\frac{\partial E}{\partial z}+\frac{\partial}{\partial x_i}\left(K_E\frac{\partial E}{\partial x_i}\right)-\overline{u'_i u'_j}\frac{\partial u_i}{\partial x_j}-c_2\frac{E^{3/2}}{l}+C_dAU^3 \quad (15)$$

and the mixing length, l, can be predicted as

$$\frac{\partial El}{\partial t}=-u\frac{\partial El}{\partial x}-w\frac{\partial El}{\partial z}+\frac{\partial}{\partial x_i}\left(K_E\frac{\partial El}{\partial x_i}\right)-c_3 l\overline{u'_i u'_j}\frac{\partial u_i}{\partial x_j}-c_4E^{3/2}\left[1+c_5\left(\frac{l}{kz}\right)^2\right]+C_dAlU^3 \quad (16)$$

2.2 Grids and Domain

In this paper, the model computational domain is from 30 H upstream to 50 H downstream of shelterbelt in the streamwise direction and from the ground surface to 8 H in the vertical direction. We tested different domain decomposition methods: horizontal strips, vertical strips, grids, and uneven divided zones according to estimated amount of computations to adapt the intensive computation around shelterbelts.

2.3 Numerical Techniques

We solve 5 equations: horizontal motion equation (17), nonhydrostatic vertical motion equation (18), continuity equation (19), TKE equation (22) and mixing length prediction equation (23) linked by formulae (20) and (22). We use the finite difference method to discretize these 5 equations into a set of algebraic equations with tri-diagonal matrices, with forward differencing for the time terms, centered differencing for pressure terms, upstream differencing for advection terms, and the modified Crank-Nicolson scheme is used for flux terms. A set of auxiliary velocity fields u^{aux} and w^{aux} are computed. The results are then substituted into primitive equations:

$$u^{n+1}=u^{aux}-\frac{\Delta t}{\rho_0}\frac{\partial p}{\partial x} \quad (17)$$

$$w^{n+1}=w^{aux}-\frac{\Delta t}{\rho_0}\frac{\partial p}{\partial z} \quad (18)$$

where Δt is timestep, u^{n+1} and w^{n+1} are the prediction of u and w at the n+1 timestep. To calculate divergence, we use

$$\frac{\partial u^{n+1}}{\partial x}+\frac{\partial w^{n+1}}{\partial z}=\frac{\partial u^{aux}}{\partial x}+\frac{\partial w^{aux}}{\partial z}-\frac{\Delta t}{\rho_0}\left(\frac{\partial^2}{\partial x^2}+\frac{\partial^2}{\partial z^2}\right)p \quad (19)$$

n+1 timestep values are mass-conserving, so

$$\left(\frac{\partial^2}{\partial x^2}+\frac{\partial^2}{\partial z^2}\right)\frac{p}{\rho_0}=\left(\frac{\partial u^{aux}}{\partial x}+\frac{\partial w^{aux}}{\partial z}\right)/\Delta t \quad (20)$$

This dynamic pressure equation is solved by the SOR method with a relaxation factor of 1.75.

3 Performance and Load Balance

We tested several schemes and listed only part of our results here due to the limitation of length of this paper. Scheme 1 is the even divided grids domain decomposition, as shown in Table 1, the load balance is worsening with increasing nodes, because the intensive computation around shelterbelts exerts much heavier load on some node. We also design a new adaptive domain decomposition algorithm (scheme 8) which migrates computation according to load situation at each node. As shown in Table 2, our new algorithm significantly improves load balance and speed-up ratio.

Table 1: Speed-up ratio and Load Balance for scheme 1 (HP workstations)

Nodes	8	6	4	2
Speed-up	2.13	1.94	1.51	0.92
Balance ratio	0.41	0.56	0.72	0.87

Table 2: Speed-up ratio and Load Balance for scheme 8 (HP workstations)

Nodes	8	6	4	2
Speed-up	4.72	3.66	2.41	0.96
Balance ratio	0.93	0.91	0.89	0.94

We also tested our parallelized model system on DEC Alpha stations. We achieved speed-up ratio of 3.7 on cluster of 5 DEC Alpha stations (Table 3).

Table 3: Scheme 8 on 5 DEC Alpha stations

Speed-up ratio	Load balance ratio
3.70	0.93

4 Conclusions

Cluster computing make it possible to solve complicated scientific problems which required supercomputers before. Workstations or PCs are more readily available to most users in the world (especially in the developing countries) than supercompters. Due to the complexity of scientific computing, load balance is a main issue and it can significantly affect speed up performance. The results show that our adaptive algorithm can handle this problem quite well.

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