L. Remarks on developments underway

L-1. Code parallelization

Code parallelization of the model to handle the distributed memory parallel computers has begun, in collaboration with the Numerical Prediction Division of JMA and the Research Organization for Information Science and Technology (RIST ; http://www.tokyo.rist.or.jp/). This program is related to the "*Earth Simulator Project*", planned by the Science and Technology Agency of Japan and is being conducted by the Earth Simulator Research and Development Center (ESRDC ; http://www.gaia.jaeri.go.jp/). A ultra parallel computer with vector processors will be constructed for this project, and will theoretically attain 40 TFLOPS in FY2001. The purpose of the project is to clarify and predict the global climate changes, reproducing a "virtual earth" in the ultra computer. One of the targets is establishment of "1 km meteorology" using cloud-resolving simulations for a several-thousand kilometer square area. A prototype parallel version of MRI/NPD-NHM was developed for this purpose (Saito *et al.,* 1999 ; 2000) and its expansion, "JMA-NHM," has been under development (Muroi *et al.,* 2000 ; see L-2). An MPI (Message Passing Interface) is employed for the communications library.

An elliptic pressure tendency equation (D3-1-1) exists in an HI-VI scheme, and is solved by the dimension reduction method in MRI/NPD-NHM, as described in D-3. However, a simple application of the direct method to the distributed memory parallel environment requires the "all to all" communication between the parallel nodes. To avoid this problem, we divide the model domain in the y-direction, and employ a pre-process just before the Fourier transform (operation of inverse matrix of D3-3-2) in the y-direction, where the matrix of the finite discretization form of the pressure equation is re-arranged.

Figure L-1-2 shows the vertically accumulated water content at 1000 JST, 22 January 1997, simulated by the parallelized nonhydrostatic model (HI-VI version of JMA-NHM). The case is the same as in H-4-2, but the nonhydrostatic model is nested with the 9 hour forecast of RSM, the initial time for which is 2100 JST, 21 January 1997. Four nodes of the HITAC SR8000 of MRI were employed as a test case in this simulation, wherein the model domain was enlarged to $(2160\ \text{km})^2$ but the horizontal resolution and the number of the vertical levels were were reduced to 3 km and 20 levels, respectively. The cloud microphysics were simplified to the warm rain process. We used a Mercator map projection with a standard latitude of 36 degrees north, and the computed LWP was remapped to the " longitude-latitude grid " for visualization to compare with the visible satellite image of the day (Fig. L-1-1).

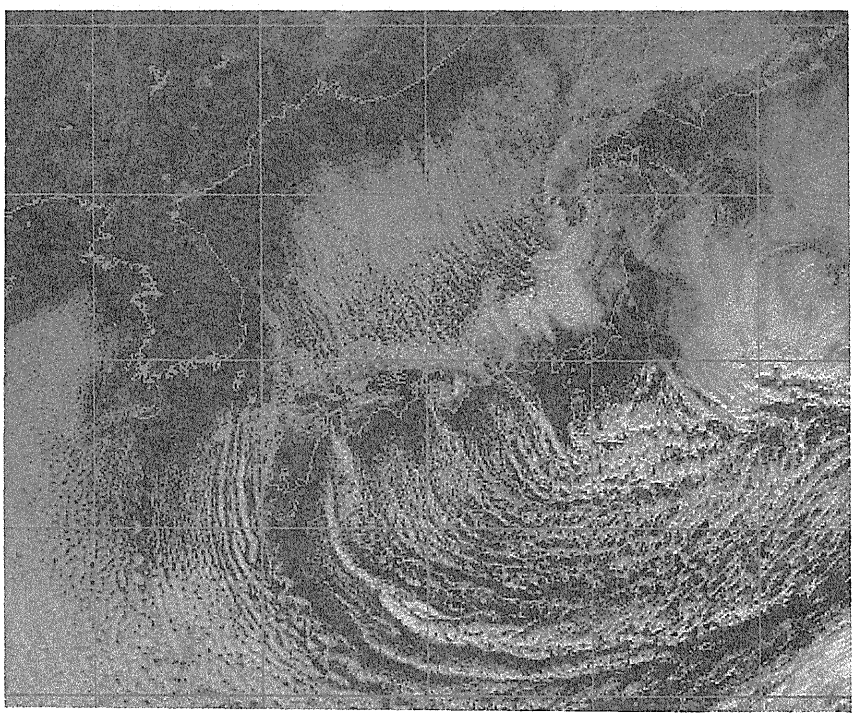

Fig. L-1-1 Visible satellite image at 0200 UTC 1997 JAN 22.

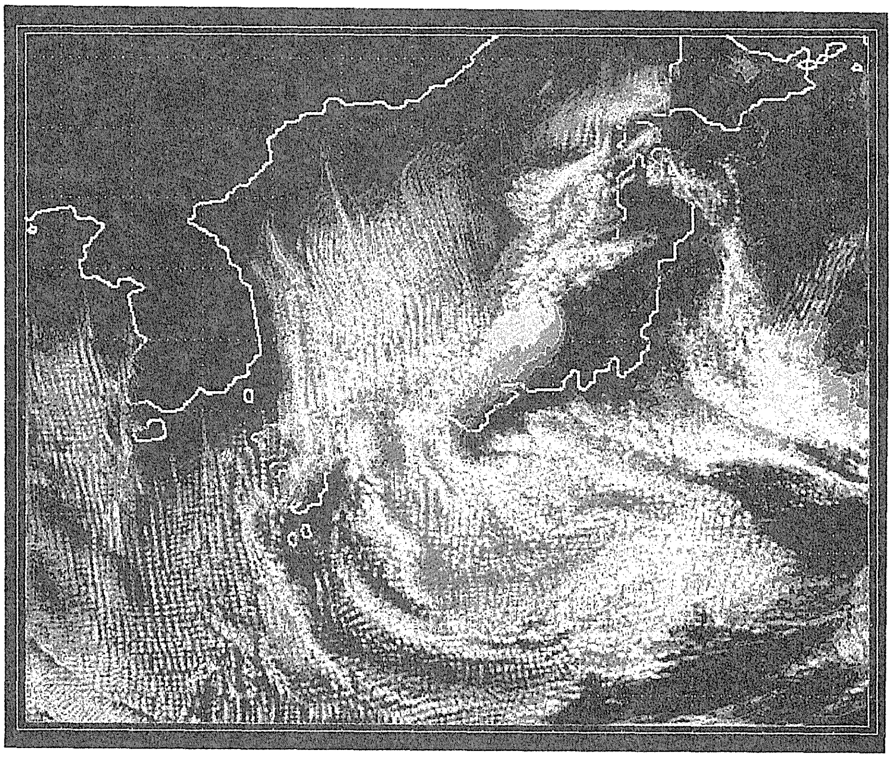

Fig. L-1-2 Accumulated water content of 0100 UTC 1997 JAN 22 simulated by the parallelized nonhydrostatic model. Contours of 0.05, 0.2, 0.5 and 1.0 Kgm^{-2} are depicted. Areas above 0.2 Kgm^{-2} are shaded. After Saito *et al.* (2001b).

L-2. Development for an operational NWP model at JMA

The rapid increase of computer power in recent decades will makes it possible to operate a nonhydrostatic model for numerical weather prediction (NWP) ; and many operational centers are presently developing their nonhydrostatic models. A joint program with the Numerical Prediction Division (NPD) of JMA has been underway since February 1999 (Muroi *et al.,* 1999 ; 2000). A One goal of this program is to develop a unified nonhydrostatic model (MRI/NPD-NHM) for both for research and operational purposes.

A hydrostatic regional spectral model (RSM) is operated at JMA to support short-range forecasts. The horizontal resolution of the model is about 20 km. In 2001, JMA has started operation of a 10 km mesh regional model for to preventing natural disasters ; however, though it is still a hydrostatic model. Demands for more accurate weather information is still increaseing. Improvement of the precipitation amount forecast is one of the biggest primary targets of mesoscale predictions over Japan. Current existing operational model doesn't predict severe rainfall well. Nonhydrostatic models with microphysical processes are highly recommended for a higher-resolution NWP model.

NPD previously developed its a nonhydrostatic model previously (Muroi, 1998 ; 1999a). But MRI and NPD consent an agreement to develop a unified nonhydrostatic model in February 1999, and started a joint program for the development of a next-generation numerical prediction model.

The major primary mission of this project is to optimize the source code and revise the physical processes and pre-post procedures, which will to be suitable for an operational suite. Implementation of an HE-VI scheme is one of the major issues of in this project. In MRI-NHM, semi-implicit (HI-VI) time integration is originally applied. But the HE-VI scheme would be suitable for a higher and wider resolution model on the a distributed memory parallel machine. Theoretically, a semi-implicit scheme requires all-to-all communication in each time step. A split-explicit scheme, however, needs communications only with the neighbors of each node. So it is worthwhile to try a split-explicit scheme on a parallel machine. The detailed specification of the scheme is described in C-3-2.

We conducted a test to examine the efficiency of the HE-VI scheme on HITAC SR2201. The grid numbers of this test is $114\times114\times38$, and the horizontal resolution is 10 km, and the forecast period is 12 hours. The elapsed times of simulation in the base HE-VI and HI-VI cases are

HE-VI scheme : 260 minutes,

HI-VI scheme : 420 minutes,

when 4 processors are used. All other processes, except for the time integration methods, are the same and the cloud microphysics were simplified to the warm rain process. This result indicates that the HE-VI scheme is suitable for a parallel machine.

Development of a data assimilation system, the initialization procedure, and the economic microphysical processes would be other issues of in this project.

A standard coding rule will be required to establish fruitful collaboration between many researchers to develop a unified model. A prototype of this programming rule has been built and refinement of all the source code of the unified model according to this rule will be conducted.

L-3. A spherical coordinate version for a global nonhydrostatic model.

Development of a spherical, curvilinear orthogonal coordinate version of MRI/NPD-NHM is underway. In the new model, we introduce two map factors, m_1 and m_2, along the x- and y- (longitudinal and latitudinal) directions instead of the single map factor m in the conformal projection. The curvature terms (C1-3-15) and (C1-3-16) become

$$Crv_1 = m_1 m_2 v \{ v\frac{\partial}{\partial x}(\frac{1}{m_2}) - u\frac{\partial}{\partial y}(\frac{1}{m_1}) \} - \frac{uw}{a}, \quad \text{(L-3-1)}$$

$$Crv_2 = m_1 m_2 u \{ v\frac{\partial}{\partial x}(\frac{1}{m_2}) - u\frac{\partial}{\partial y}(\frac{1}{m_1}) \} - \frac{vw}{a}, \quad \text{(L-3-2)}$$

In a longitude-latitude grid, if we take

$$m_1 = \frac{1}{a\cos\varphi},\ m_2 = \frac{1}{a}, \quad \text{(L-3-3)}$$

$$w = a\cos\varphi\frac{d\lambda}{dt},\ v = a\frac{d\varphi}{dt}, \quad \text{(L-3-4)}$$

basic equations (C1-3-9)-(C1-3-11) are reduced to the following conventional momentum equations in spherical coordinates.

$$\frac{du}{dt} - \frac{uv\tan\varphi}{a} + \frac{uw}{a} + \frac{1}{\rho}\frac{\partial p}{a\cos\varphi\partial\lambda}$$
$$= 2\Omega v\sin\varphi - 2\Omega w\cos\varphi + DIF.u, \quad \text{(L-3-5)}$$

$$\frac{dv}{dt} + \frac{u^2\tan\varphi}{a} + \frac{vw}{a} + \frac{1}{\rho}\frac{\partial p}{a\partial\varphi} = -2\Omega u\sin\varphi + DIF.v, \quad \text{(L-3-6)}$$

$$\frac{dw}{dt} - \frac{u^2+v^2}{a} + \frac{1}{\rho}\frac{\partial p}{\partial z} + g = 2\Omega u\cos\varphi + DIF.w, \quad \text{(L-3-7)}$$

In the new model, we use the Cylindrical Equidistant projection,

$$m_1 = \frac{\cos\varphi_0}{\cos\varphi},\ m_2 = 1, \quad \text{(L-3-8)}$$

whose map factors become unity at the standard latitude φ_0, and the basic equations are rewritten into the flux form in terrain-following coordinates.

Figure L-3-2 shows an example of 18- and 36-hour forecasts of the sea-level pressure predicted by the new model nested with the global analysis data of JMA (GNANL ; 1.25×1.25 degrees, pressure plain, 17 levels). The horizontal resolution of the nonhydrostatic model is 1.45×1.45 degrees. Vertically, 38 layers are employed, and vertical resolution at the lowest level is 40 m, where the horizontal wind is computed at 20 m level above the ground surface. The domain covers from 80 degrees north to 80 degrees south and from 5 degrees east to 7 degrees west, which corresponds to about 95% of the global surface. For simplicity, a dry model is used, and the lowest level temperature in GANAL is used for the initial value of the ground and sea-surface temperatures. The surface pressure pattern of the model generally follows the global analysis well at the corresponding valid times (figures not shown).

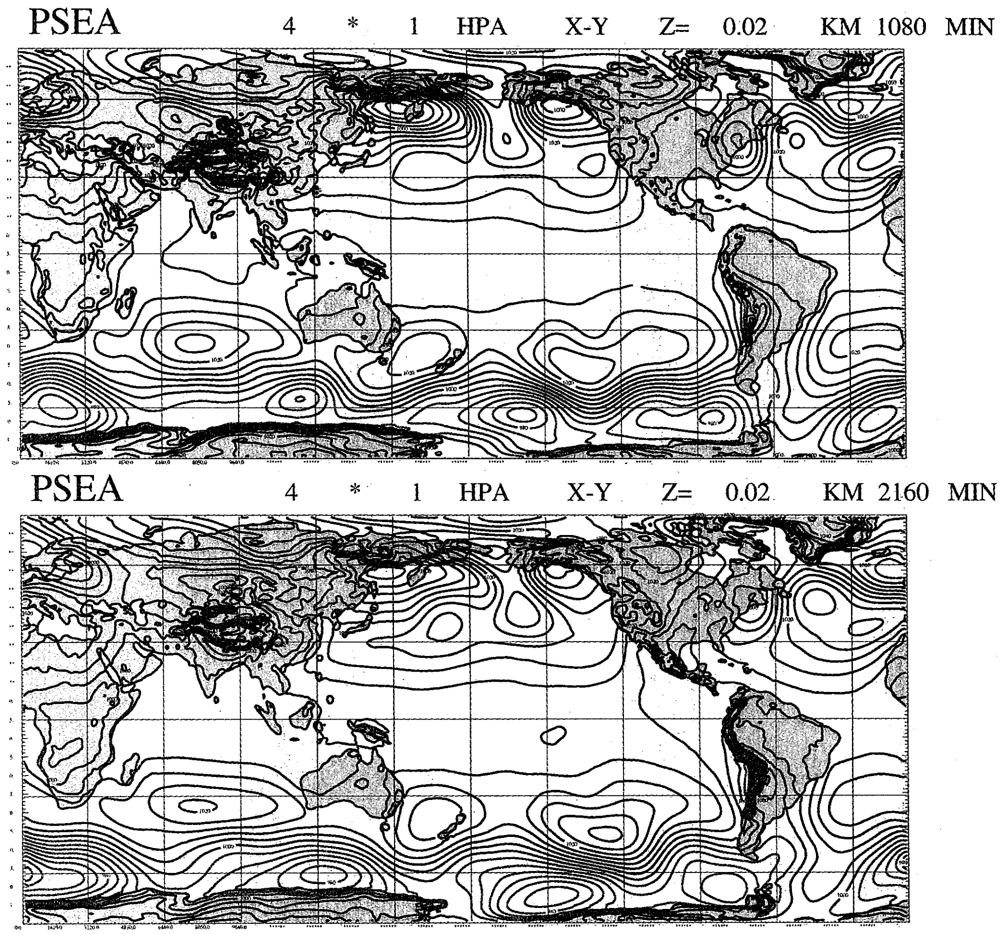

Fig. L-3-2 Sea-level pressure at $t=18$ and 36 hours predicted by the nonhydrostatic model. Contour interval is 4 hPa. Model initial time is 2400 UTC 1 March 1999. After Saito (2001).