A. Preface

This technical report describes a multipurpose nonhydrostatic atmospheric model developed by the Forecast Research Department of the Meteorological Research Institute and the Numerical Prediction Division of the Japan Meteorological Agency. This work was accomplished as a first step in the collaboration between MRI and NPD to develop a unified mesoscale model.

In MRI, " Nonhydrostatic model developed at the Forecast Research Department of MRI (Ikawa and Saito, 1991)" was published in the MRI Technical Report. Ikawa and Saito's (1991) model was developed as a research tool and used for simulations of mountain flow (Saito, 1993 ; Saito et al., 1994) and orographic snowfall (Saito et al., 1996). The model was modified to a nesting model to realistically simulate mesoscale phenomena (Saito and Ikawa, 1992 ; Saito, 1994a). For its basic equations, fully compressible equations including a map factor (Saito and Kato, 1996 ; Saito, 1997) replaced anelastic equations, where the linearlization using the reference atmosphere was removed. The semi-implicit time integration scheme (HI-VI scheme) was employed. Furthermore, the Box-Lagrangian rain drop scheme (Kato, 1995), the moist convective adjustment (Kato and Saito, 1995), the prediction of ground temperature (Kato, 1996), the modified centered difference advection scheme (Kato, 1998), two atmospheric radiation schemes (Kato, 1999 ; Eito et al., 1999), *etc.,* were also incorporated into the model. These modifications extended the model to a full-scale mesoscale model called " MRI-NHM (Saito and Kato, 1999)" that has been used for several studies in MRI (*e.g.,* Fujibe et al., 1999 ; Seko et al., 1999 ; Yoshizaki et al., 2000).

In NPD, a spectral nonhydrostatic model was developed by Goda and Kurihara (1991). Development of another fully compressible grid model was begun in 1997, and its numerics were reported by Muroi (1998). The split-explicit time integration scheme (HE-VI scheme) was employed, considering the computational efficiency in the next generation computing facilities. Muroi (1999a) experimented a nested run with 10 km horizontal resolution by the NPD nonhydrostatic model, supposing future numerical prediction in JMA.

Collaboration between MRI and NPD should be promoted to prepare for the rapid change of computer environments and to accelerate nonhydrostatic modeling for both research and operational objectives (Muroi, 1999b). From this viewpoint, the two modeling centers agreed to unify the two mesoscale models, and joint work was started in February 1999. As the first step, the HE-VI time integration scheme was incorporated into MRI-NHM by Muroi et al. (1999), and the first version of the unified model, " MRI/NPD-NHM," was completed in July 1999. Further collaboration on this prototypical model is currently under way to develop the next generation system (Muroi et al., 2000). Under these circumstances, the model described in this technical report is the final version of MRI-NHM and, simultaneously, the first version of the MRI/NPD community model, which is the starting point of mutual modeling work at MRI and NPD.

Many aspects of our model must be revised, including code parallelization to accommodate distributed memory parallel computers and optimization as an operational model, which are urgently needed. The code should be refined using FORTRAN 90 based on new programming standards. Several points must also be improved in the dynamic frame, boundary conditions and physical processes. Some revisions of the above points have already been started, as mentioned in Chapter L. In addition, a number of university scientists are currently expressing interest in participating in our modeling work. We hope that this model will be used more widely in the Japanese research community and that new reports on further upgraded models will be published in the future.

A large number of scientists have contributed to developing this model. We thank the staff of MRI and NPD for supporting our modeling work. Specifically, M. Yoshizaki, Head of the First Laboratory of the Forecast Research Department of MRI, gave us invaluable comments and continuous encouragement. We also thank R. Hasegawa, H. Koga, S. Otsuka, S. Yoshizumi, H. Kondo, T. Maruyama, M. Wada, H. Nakamura, K. Aonashi, H. Seko, K. Kurihara, T. Tamiya, F. Fujibe, H. Kanehisa, M. Ueno, A. Murata, W. Mashiko, N. Seino, A. Yamamoto and M. Murakami of MRI for their help and discussions. We also express our appreciation to N. Sato, T. Iwasaki, T. Tsuyuki, M. Nakamura, M. Nagata, H. Gouda and K. Yamada of NPD for their help and courtesy in referring to the NPD operational models. Some source codes of this nonhydrostatic model were developed with reference to the program of JSM. We express our deepest respect for the achievements of the late Dr. M. Ikawa, who passed away in 1991 after dedicating half his life to developing a nonhydrostatic model in MRI.

The organization of this report is as follows. Chapter B presents an overview of the model. Chapter C gives the governing equations and pressure equations. Chapter D describes their finite discretization form and relevant pressure equation solver. Chapters E and F introduce the initiation procedures and boundary conditions. Chapter G explains newly incorporated physical processes after Ikawa and Saito (1991) and diffusion processes. Chapter H presents examples of numerical simulation. Chapters I and J describe the model code structure and relevant utilities. Chapter K is the user's guide to running the model. In Chapter L, we briefly refer to current and future programs for code parallelization and joint programs of MRI and NPD to develop a regional model of JMA for numerical prediction. A spherical curvilinear orthogonal coordinate version under development to realize a global nonhydrostatic model in the future is also briefly introduced.

Sections C-2-4, C-3-4, D-2-3, G-1-2, G-1-3, G-1-4, G-2-2, G-5-1, H-3, J-3-2 and K-5-2 were mainly written by T. Kato; sections G-5-2 and H-4, by H. Eito; and sections C-3-2 and L-2, by C. Muroi. Section I-2 was written by all authors. Other sections were mainly written by K. Saito.

Finally, we would like to extend our gratitude to the anonymous reviewers, whose valuable comments improved the manuscript significantly.

B. Overview of the model

The MRI/NPD unified nonhydrostatic model is a multipurpose mesoscale model being developed by the Forecast Research Department of the Meteorological Research Institute and the Numerical Prediction Division of the Japan Meteorological Agency for both research and operational forecasting. Fully compressible equations with conformal mapping or anelastic approximation (AE) can be selected as the basic equations. The fully compressible model doesn't contain approximations, such as the linearlization using the reference atmosphere and/or omitting the diabatic heating term in the pressure equation. In addition to the semi-implicit scheme (HI-VI scheme) employed in MRI-NHM, the split-explicit scheme (HE-VI scheme) developed at NPD has been incorporated into the model for the computational scheme. Accordingly, three dynamic cores (HI-VI, HE-VI and AE) are available and can be selected by a mode switch.