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"Third ICTP/WMO International Workshop on Tropical Limited Area Modelling"
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"Regional Modelling: Operational Research & Development"

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Regional Modeling
(operational research and development)

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10:00 - 11:00 Thu. 24 October 1996

<< Tropical LAM Workshop in Trieste, Italy >>

Contents

A Recent progresses in regional modeling at JMA

1. Introduction

Efforts have been devoted to developments of various aspects of operational modeling at JMA. Here we summarize recent progresses made in regional numerical weather predictions.

On the occasion of the installation of the new computer system COSMETS including a supercomputer HITAC S-3800/480 March 1, 1996, the Japan Meteorological Agency (JMA) started operation of advanced numerical analysis and prediction models to meet requirements for enhanced meteorological services. All the analysis and prediction models have been refined:

- All the analysis models are now employing three-dimensional Optimal Interpolation (3D-OI) scheme on prediction model levels.
- Global Sea Surface Temperature (SST) analysis is performed at 1 x 1 deg resolutions everyday, used both in global and regional prediction models.
- All the prediction models have enhanced their resolutions both in the horizontal and in the vertical.
- All the prediction models have changed their physics (cumulus parameterization).

Expecting the improvement of accuracies of predictions, the models have extended their prediction hours:

Global Spectral Model (GSM)

72/192 hours from 0000/1200 UTC

↓

84/192 hours from 0000/1200 UTC

Rlobal Spectral Model (RSM)

24-48 hours from 0000/1200 UTC

↓

51 hours from 0000/1200 UTC

TYphoon prediction Model (TYM)

60 hours from 0000/1200 UTC

↓
78 hours from 0600/1800 UTC

2. Prediction models

<Dynamics>

- Resolutions -

To reduce the error associated with approximations of time and space differencings, resolutions of the prediction models are increased:

GSM

T106 (~ 110 km)／21 levels → T213 (~ 55 km)／30 levels

RSM

(Asia) 75 km／16 levels →
(Japan)30 km／23 levels → (East Asia) 20 km／36 level (257×217)

TYM

50km／ 8levels → 40km／15levels (163×163)

- Hybrid sigma-pressure vertical coordinate -

To reduce the error in the calculation of horizontal pressure gradient force over the mountains, the hybrid sigma-pressure coordinate system is used in both global and regional models.

- Water loading effect -

Kato and Saito (1995) demonstrated that at the horizontal resolution around 20 km the effect of water loading is much larger than that of the hydrostatic approximation in the simulation of convective precipitation in convectively unstable conditions (Fig. 1). The water loading effect, therefore, is incorporated into the regional models RSM and TYM. It works to supress spurious growth of small-scale disturbances, such as 'grid-point storms', leading to reduction of extrema in vertical velocity and precipitation fields.

<Physics>

- Cumulus parameterization -

In replacement of the Kuo scheme (Kuo, 1974) (GSM) and the moist convective adjustment scheme (Manabe and Strickler, 1964; Gadd and Keers, 1970) (RSM, TYM), a more sophisticated scheme: the Arakawa-Schubert scheme (Arakawa and Schubert, 1974; Moothi and Suarz, 1992; Randall and Pan, 1993), which has a clear physical base in the modeling of convection, has been introduced into all the prediction models (GSM, RSM, TYM). The scheme has proven to produce much better tropical cyclone track predictions than the other schemes, as shown in Figs. 2 and 3.

3. Analysis and physical initialization

<Models>

- Resolutions -

As in the prediction models, all the analysis models have introduced three-dimensional Optimal Interpolation (3D-OI) scheme on prediction model levels and increased their resolutions both in the horizontal and in the vertical.

- Moisture analysis using satellite data -

JMA developed in late 1980s a moisture estimation method using satellite-measured cloud information. The method is called 'T_{BB} moisture bogusing' and has been working well in the moisture analysis, especially in tropical oceans where few sonde observations are available.

Before applying the method to daily analysis of moisture field, we have made statistics of relative humidity observations by sonde, stratifying them according to satellite-measured cloud information and surface observations of precipitation and cloud base height. Specifically, first, all moisture observations by sonde are categorized with respect to total cloud amount (0, 1-20, 21-70, 71-99, 100%), cloud top height in pressure (< 300, 301-400, 401-500, 501-700, 701-850, 850 hPa <), standard deviation of T_{BB} (0.0-2.9, 3.0 ℃ <), weather (rain, rain in the previous 3h or nearby, high cloud base, unidentifiable) and latitudinal belt (tropics with latitude < 23.5, mid latitudes > 23.5). Then mean and standard deviation are calculated for each category and the former is used as the representative vertical profile of relative humidity and the latter as the statistics error of estimation. One example for a category with cloud amount of 71-99%, cloud top height of 501-700 hPa, standard deviation of T_{BB} < 3.0 ℃, weather of rain in the tropics is shown in Fig. 4.

By preparing these data as a table, we can estimate vertical profiles of moisture from satellite-measured cloud information and surface observations of precipitation and cloud base height. The method has proven effective in reducing analysis errors of mousture in the tropics. An example of the analyzed moisture field is given in Fig. 5.

- Physical initialization -

JMA developed a simple physical initialization scheme using radar-surface combined rainfall analysis field for a regional model and has been using it for years. Now the scheme is experiencing modifications to fit the new cumulus parameterization scheme incorporated in the prediction models.

The basic idea is to make the prediction model produce analyzed amount of precipitation at the very beginning of the time integration by modifying moisture and divergent component of wind. To attain the goal, we have to solve the cumulus parameterization algorithm inversely and apply the non-linear normal-mode initialization to the initial field.

The flow of the processes in the case of the moist conective adjustment scheme (see Fig. 6) is:

- Modify the moisture field, so that the adjustment marginally triggers convection, according to the lapse rate.
- Convert the Radar-AMeDAS (RAM) ※ analyzed precipitation into the vertical

(column) integral of diabatic heating.

- Define the cloud top level with satellite T_{BB} data and the cloud base level with the level of lifting condensation.
- Distribute the diabatic heating to each model level assuming a parabolic profile.
- Adjust the divergent component of wind with the diabatic non-linear normal-mode initialization scheme using the diabatic heating as the forcing in the thermodynamic equation.

The physical initialization scheme has worked to reduce the spin-up error in precipitation prediction to a large extent (Fig. 7, Fig. 8).

The scheme can be modified to use not only combined radar-surface precipitation analysis but also satellite-estimated precipitation (Fig. 9).

※ Radar-AMeDAS precipitation analysis (RAM)

The system combines precipitations observed by radars and surface rain gages. Actually radar rainfall rates are calibrated with surface raingage data used as the ground truth. Since both measurements have different properties, their combination can take advantages of both merits of the two measurements:

Radar	high resolution	but	low accuracy of measurement
Surface rain gage			
	low resolution	but	high accuracy of measurement
Combination	high resolution	and	high accuracy of measurement.

In Japan more than 1300 surface rain gages are deployed with average spacing of 17 km and 19 conventional radars are covering almost the whole country. An example of the analysis is given in Fig. 10.

B Tropical cyclone prediction at JMA

For tropical cyclone forecasts, the new Global Spectral Model (GSM) (Table 1a) with horizontal resolution of T213 and 30 vertical layers makes 84-hour and 192-hour predictions at 0000 and 1200UTC, respectively, while the new TYphoon prediction Model (TYM) (Table 1b) with horizontal resolution of 40 km and 15 vertical layers runs for up to two target typhoons in the western North Pacific to make 78-hour predictions at 0600 and 1800UTC.

Typhoon positions and intensities predicted by the old TYM had been disseminated twice a day to the national meteorological / hydrological organizations of the ESCAP/WMO Typhoon Committee. The RSMC Tokyo Typhoon Center enhanced its guidance products for forecast of typhoons, FXPQ20, 21 RJTD, to four times a day and up to 84 hours and 78 hours with the new GSM and TYM, respectively, March 1, 1996. The center has a plan to extend its official typhoon forecast from 48 hours up to 72 hours soon after it confirms in an extensive validation statistics that the new models provide typhoon predictions with enough accuracy.

2 Validation statistics of tropical cyclone predictions by new models

<track prediction>

Statistics for several cases during an examination period in 1995 (Fig. 11) shows that the new GSM can reduce typhoon position error in prediction by 15% (T+24h), 36% (T+48h) and 33% (T+72h) while TYM can do modestly by 9% (T+36h) and 15% (T+60h), although the test was performed using global analyses made by the old-version model for their initial fields. Year-to-year statistics including a preliminary validation for early typhoons in 1996 (Fig. 12) shows again a marked decrease of typhoon position error in GSM and a modest one in TYM, resulting in competing precisions between the two models in typhoon track prediction.

The old JMA numerical models had suffered northward drifting biases in their typhoon track predictions, especially for typhoons in their pre-recurvature stage in low latitudes. The new models are free from such a bias in typhoon track prediction, even though they develop slight 'slow biases' (Fig. 13). Sensitivity study has revealed that the incorporated mass-flux-type cumulus parameterization scheme (Arakawa-Schubert scheme) has a large impact on typhoon track, contributing to the reduction of systematic bias in track prediction.

<intensity prediction>

Intensity forecast of tropical cyclones is believed to be a much more difficult job than their track forecast. An error statistics for intensity prediction of typhoons by the new models (Fig. 14) indicates that it is actually a tough work. The TYphoon prediction Model (TYM), which has a higher horizontal resolution of 40 km, has time-independent positive biases of 5 - 8 hPa and RMSEs (root mean square errors) of 10 - 20 hPa in central pressure throughout the forecast hours. The latter, however, are smaller than those for the persistency method after T+24 h. This encouragingly demonstrates that the prediction by the model carries useful information on intensity of tropical cyclones.

Feasibility of intensity prediction of tropical cyclones will be pursued in a framework of the mesoscale model intercomparison project COMPARE under WMO-CAS/JSC-WGNE, choosing a supertyphoon during the SPECTRUM/TCM-90 period as its target tropical cyclone. JMA is taking a lead in making the experimental plan, preparing and distributing reanalysis data, doing a validation study and holding a workshop.

3 Summary and discussion

By introducing advanced new models, tropical cyclone predictions have been much improved. The serious northward drifting bias has disappeared, leaving slight 'slow bias', leading to reductions of mean central position errors. Intensity prediction of tropical cyclones has become an increasingly feasible target for numerical predictions, although there still exist large errors.

To further improve tropical cyclone prediction, there are several development fields we should devote our efforts to:

- Enhancement of resolutions of numerical models

Since intensity prediction has proved to have a hopeful outlook as shown above, we should put some portion of acquired excess of computer resources into the enhancement of resolutions of prediction models. If we get a computer with a speed 16 times as fast as that of the current one, we can double the resolution of the model horizontally and vertically without increasing running time of the model. In regard to the TYphoon prediction Model (TYM), the horizontal resolution can be 20 km, nearly the same as that of the NCEP Hurricane Model (Kurihara *et al.*, 1993; Kurihara *et al.*, 1995), which is believed to be currently the most advanced one in the world. A model with this high resolution can resolve fine structure of tropical cyclone to a good extent and is expected to contribute to reducing central pressure error in tropical cyclone intensity prediction.

- Asymmetric tropical cyclone bogusing

JMA introduced asymmetric typhoon bogusing in its global and regional objective analyses in August 1994, which has reduced track prediction error (Fig. 15). Meanwhile, TYM still uses its own axi-symmetric typhoon bogusing. To reduce track prediction error, we should develop an appropriate asymmetric typhoon bogusing scheme and incorporate it into the model.

- Better analysis and bogusing in upper levels

Upper tropospheric potential vorticity anomalies have been shown to exert influence on tropical cyclones (e.g., Wu and Emanuel, 1993; Wu and Kurihara, 1996). However, observations are sparse in the oceanic tropics, especially in upper levels. We need to assimilate as many effective data as possible into the model. Detailed cloud drift winds may be one kind of such data.

- Ocean-atmosphere interactions

Numerous studies have shown that there exist various types of interaction between ocean and atmosphere. Those include processes causing sea-surface temperature drops on the passage of an intense tropical cyclone (Bender *et al.*, 1993). Such processes should be calculated in the prediction models to obtain more realistic simulation of tropical cyclones. Since we are increasing the number of degrees of freedom of the prediction model when incorporating these processes into it, we need to watch if the model does not develop a serious systematic error (climatic drift).

- Ensemble forecasts

As the length of prediction increases, the model atmosphere has a higher probability for chaotic features to develop owing to non-linear effects. In this situation, ensemble forecasts may emerge as a useful technique in reducing prediction errors, although reliable techniques have not yet been developed of constructing initial perturbations which produce an ensemble of forecasts with enough spread.

References

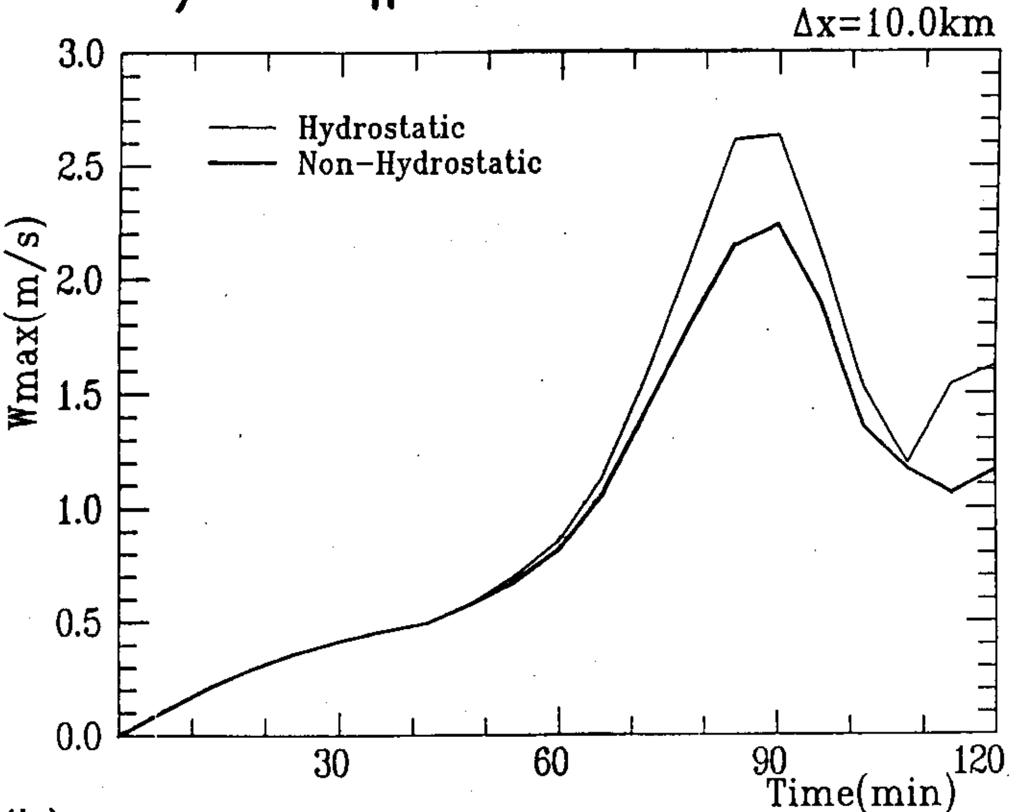
Arakawa, A., and W. H. Schubert, 1974: Interaction of a cumulus cloud ensemble with

the large-scale environment. Part I. *J. Atmos. Sci.*, 31 , 674-701.
Bender, M. A., I. Ginis, and Y. Kurihara, 1993: Numerical simulation of tropical cyclone-ocean interaction with a high-resolution coupled model. *J. Geophy. Res.*, 98 , D12, 23245-23263.
Gadd, A., and J. Keers, 1970: Surface exchanges of sensible heat in a 10-level model atmosphere. *Quart. J. Roy. Meteor. Soc.*, 96 , 297-308.
Kato, T., and K. Saito, 1995: Hydrostatic and non-hydrostatic simulations of moist convection: Applicability of the hydrostatic approximation to a high-resolution model, *J. Meter. Soc. Japan*, 73 , 59-77.
Kuo, H. L., 1974: Further studies of the influence of cumulus convection on large scale flow. *J. Atmos. Sci.*, 31 , 1232-1240.
Kurihara, Y, M. A. Bender, and R. J. Ross, 1993: An initialization scheme of hurricane models by vortex specification. *Mon. Wea. Rev.*, 121 , 2030-2045.
Kurihara, Y, M. A. Bender, R. E. Tuleya, and R. J. Ross, 1995: Improvement in the GFDL hurricane prediction system. *Mon. Wea. Rev.*, 123 , 2791-2801.
Manabe, S., and R. Strickler, 1964: Thermal equilibrium of the atmosphere with a convective adjustment. *J. Atmos. Sci.*, 21 , 361-385.
Moothi, S, and M. J. Suarez, 1992: Relaxed Arakawa-Schubert: A parameterization of moist convection for general circulation models. *Mon. Wea. Rev.* , 120 , 978-1002.
Randall, D, and D.-M. Pan, 1993: Implementation of the Arakawa-Schubert cumulus parameterization with a prognostic closure. Meteorological Monograph / The representation of cumulus convection in numerical models. 46 , 137-144.
Wu, C.-C., and K. A. Emanuel, 1993: Interaction of a baroclinic vortex with background shear: Application to hurricane movement. *J. Atmos. Sci.*, 50 , 62-76.
Wu, C.-C., and Y. Kurihara, 1996: A numerical study of the feedback mechanisms of hurricane-environment interaction of hurricane movement from the potential vorticity perspective. *J. Atmos. Sci.*, 53 , 2264-2282.

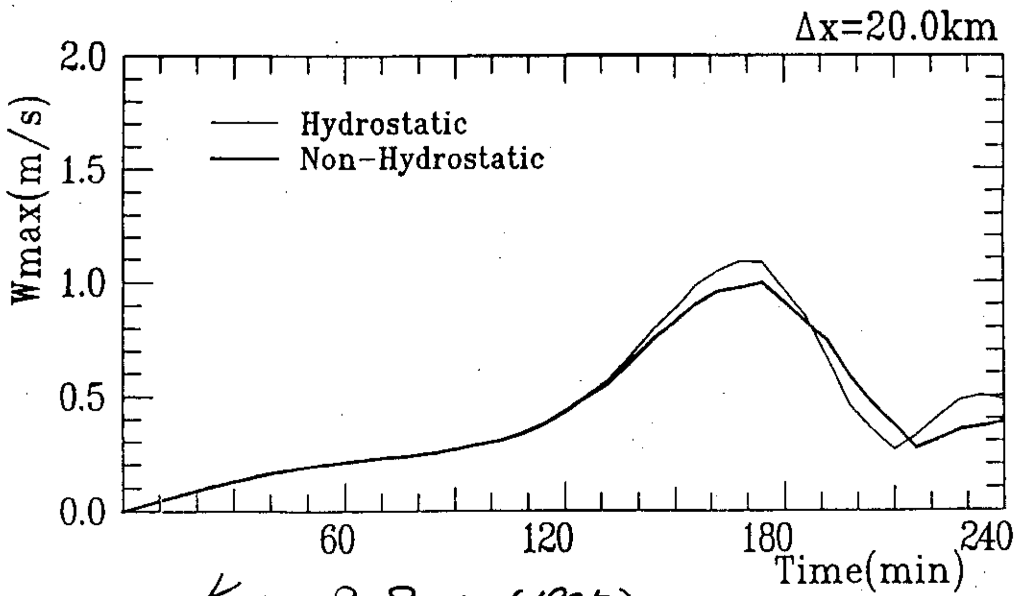
$$\frac{dw}{dt} = -g - \frac{1}{\rho}\frac{\partial p}{\partial z} + \text{Diff.}$$

$\frac{dw}{dt} \approx 0$ — hydrostatic approx. ...... valid when $\left(\frac{H}{L}\right)^2 \ll 1$

Fig.1 (a)



(b)



Kato & Saito (1995)

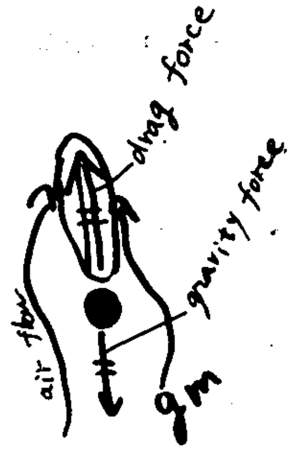
"water loading" effect

$$\frac{\partial p}{\partial z} = -\rho g - (\text{drag force})$$

$$\text{drag force} = \rho_r g$$

$$\frac{\partial p}{\partial z} = -\rho_d(1-0.608 q_v + q_r) g$$

$$\frac{\partial \phi}{\partial \ln p} = -\frac{g}{R T_d (1+0.608 q_v - q_r)}$$



falling raindrop at a constant speed

diagnozed from precip

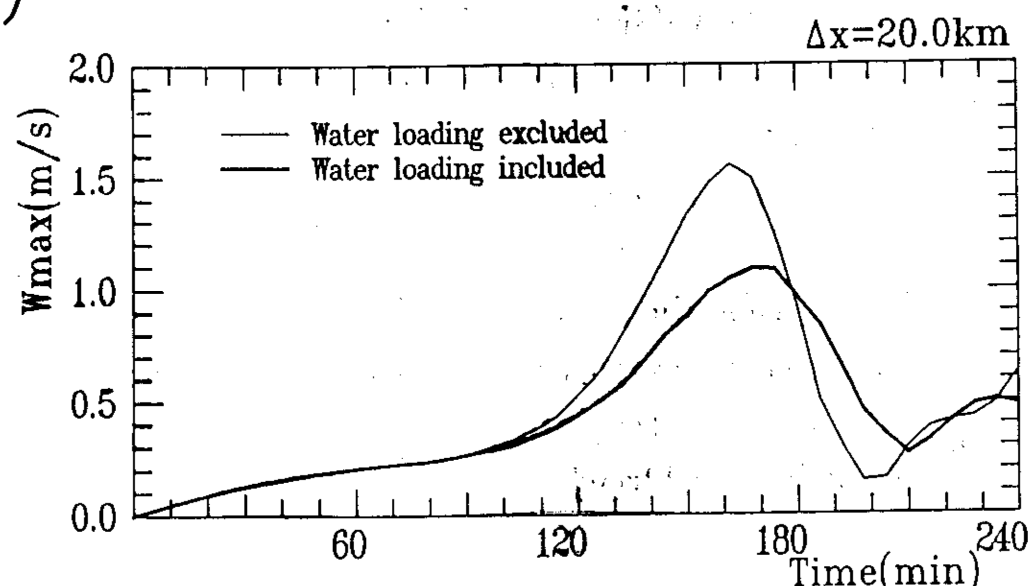
prognostic variable

$$\rho = \rho_d (1-0.608 q_v + q_r)$$

$$\rho = \frac{P}{RT}$$

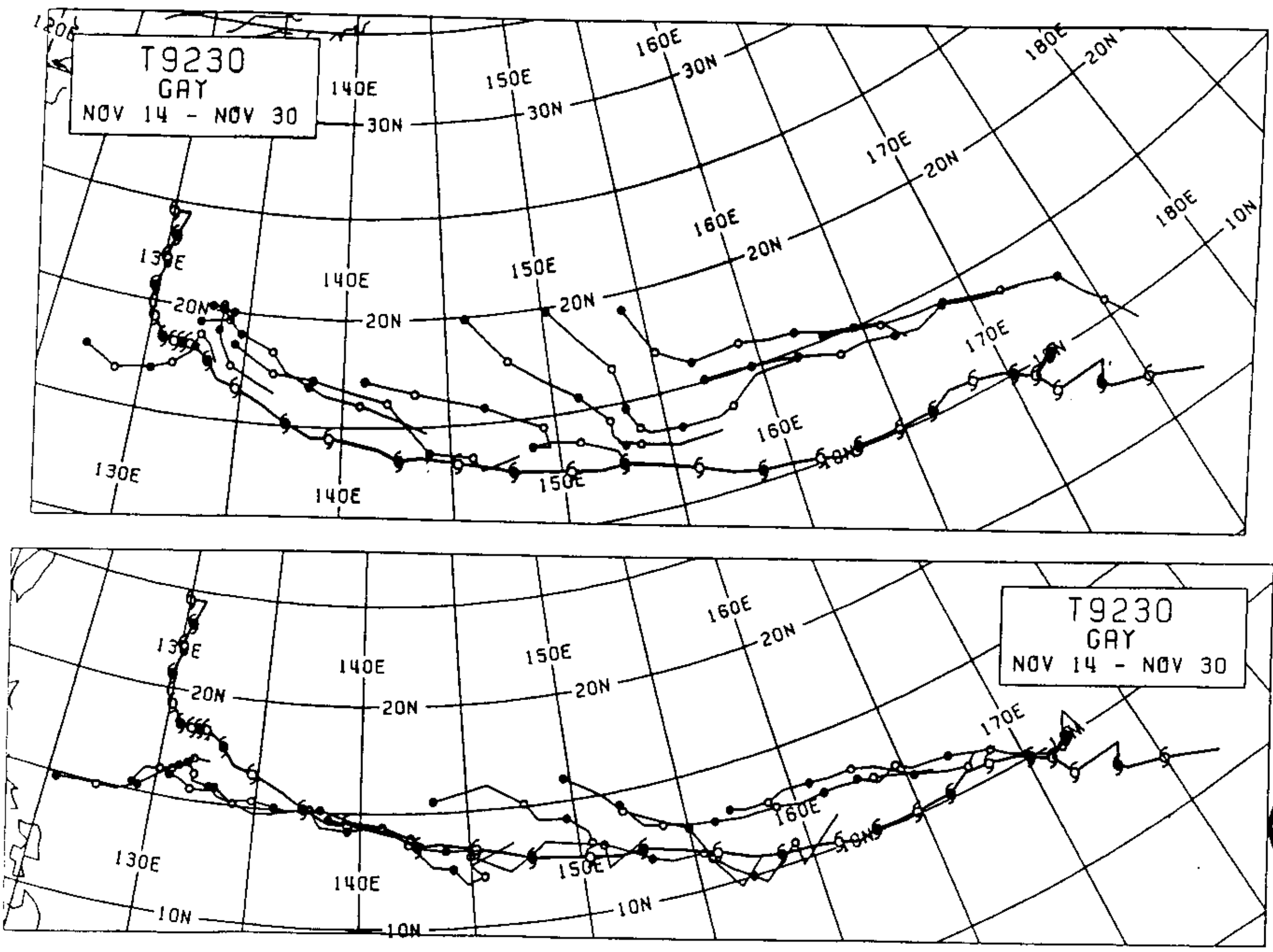
$$T = T_d (1+0.608 q_v - q_r)$$

(C)



Kato & Saito (1995)

	Hydrostatic	non-Hydrostatic
ΔX = 40 km	O	O
ΔX = 20 km	O if water loading included	O
ΔX = 10 km	?	O



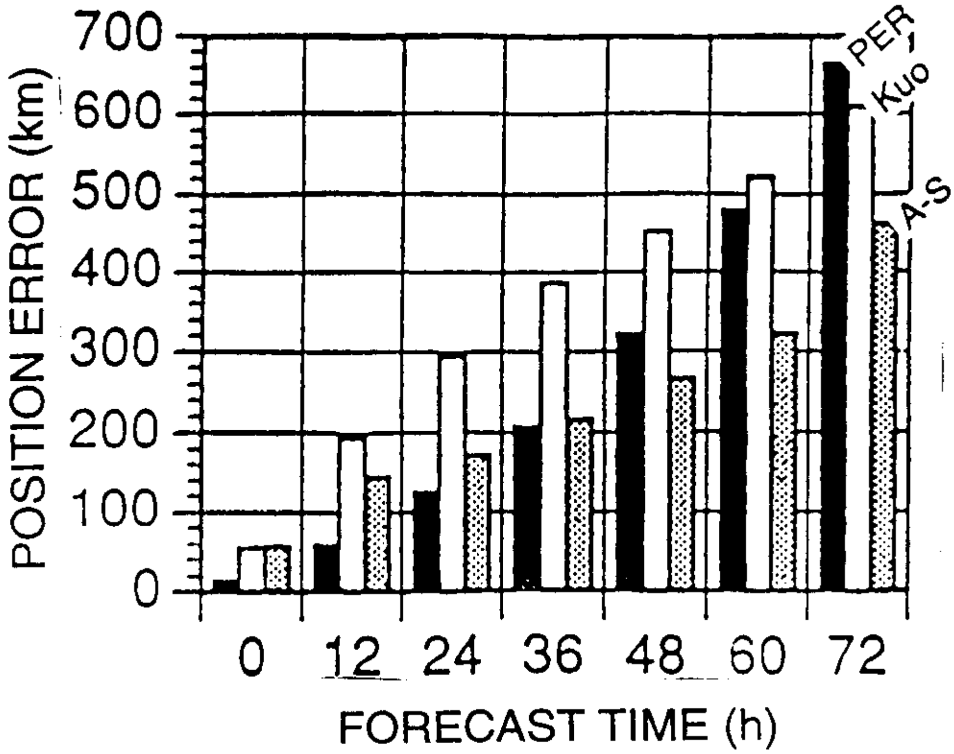
Experiment using T106 GSM

Kuo

A.-S. (mass-flux scheme)

Fig. 2

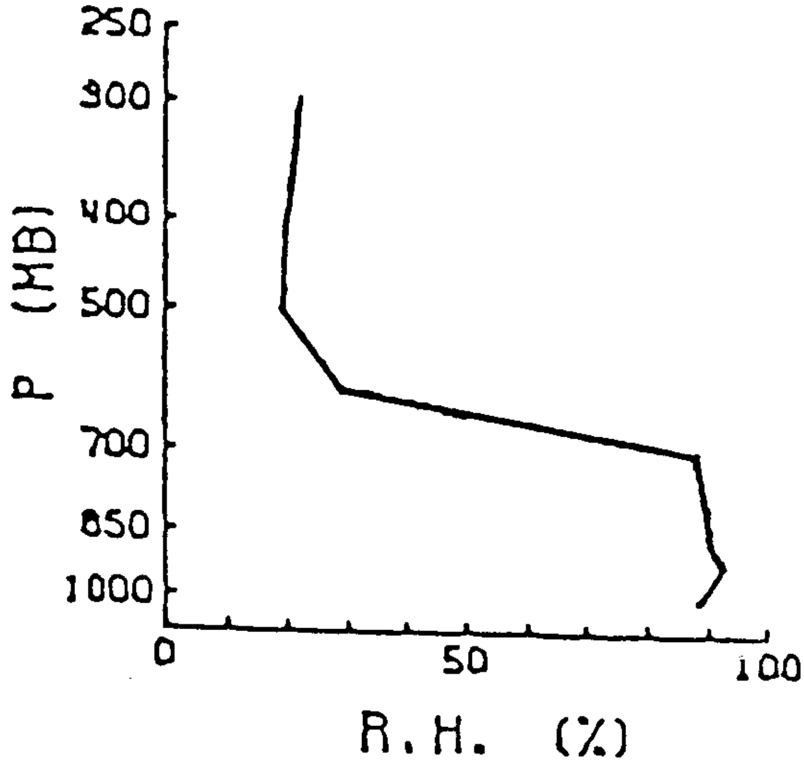
Impact
of
Arakawa-Schubert cumulus parameterization



(average of 21 cases)

PER: Persistency Method
Kuo: Kuo scheme (current GSM)
A-S: A-S scheme (new GSM)

Fig. 3



12 TR RR-71×ST-700

Fig. 4

Moisture Analysis at 700 hPa (r.h., %) Satellite Image in TBB

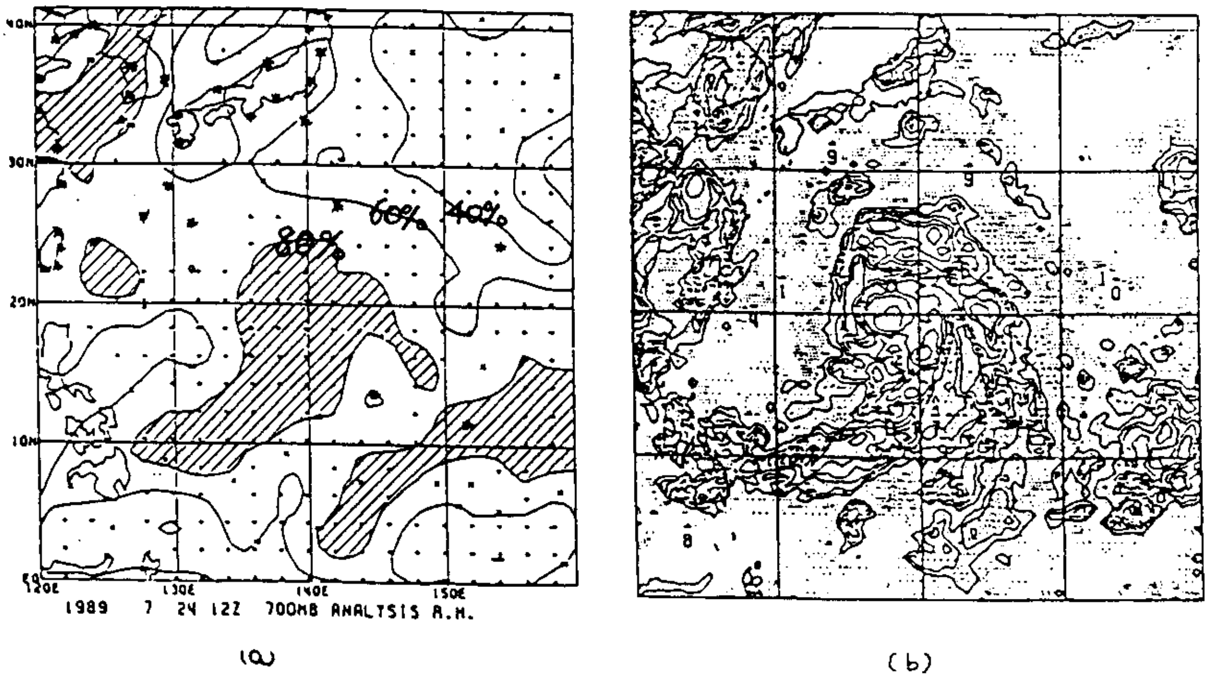
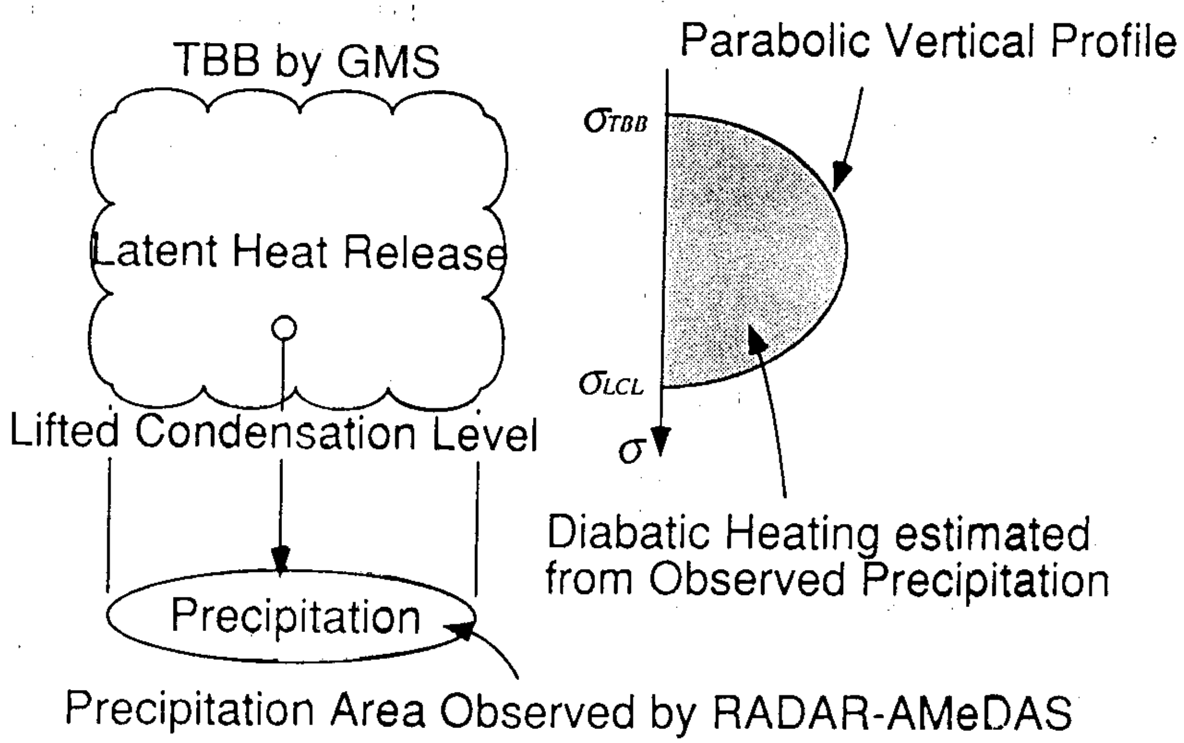


図3.8　1989年7月24日12UTCの日本南方海上の700 hPaレベルの湿度の解析値(a)とその時刻のGMSの雲イメージ(b)。解析図のコンターは20%間隔。80%以上のところは陰影がついている。*はラジオゾンデデータ，×，+がGMS湿度データである。

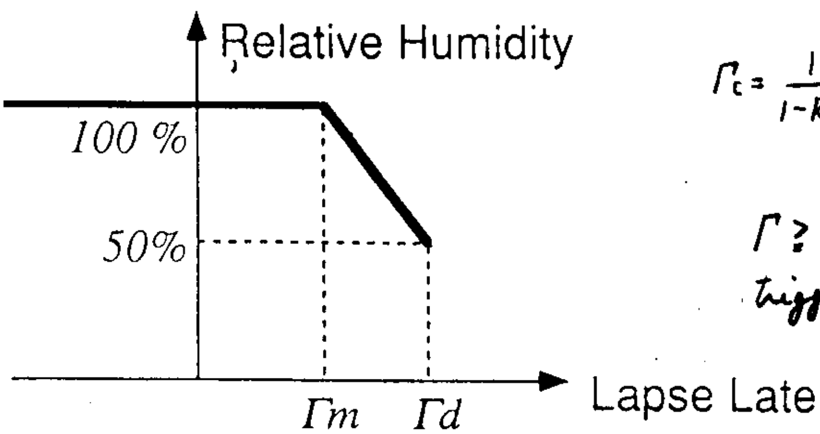
Fig. 5

NMI with Observed Heating



Precipitation rate ≥ 1 mm / hour
Cloud Amount by GMS ≥ 80 %

Physical initialization of Relative Humidity with R-A



$$\Gamma_c = \frac{1}{1-RH_c}\left[\Gamma_d(1-RH)+\Gamma_m(RH-RH_c)\right]$$

$RH_c = 0.5$ (50 %)

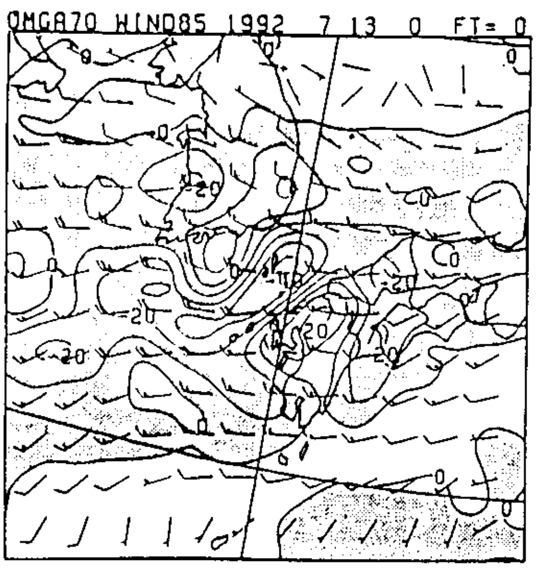
$\Gamma \geq \Gamma_c$, $RH > RH_c$

trigger convection

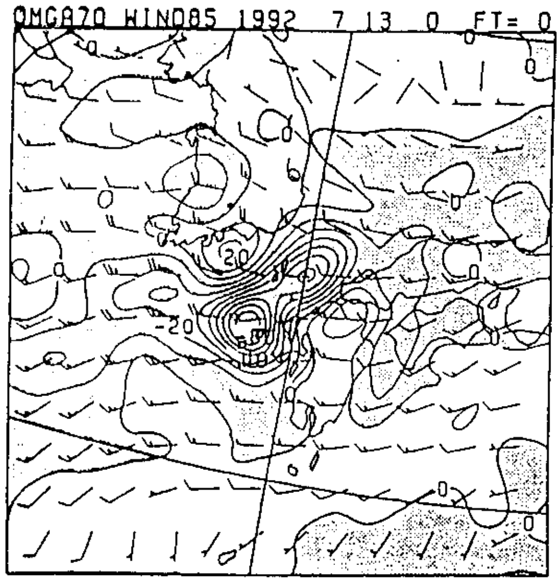
$\Gamma \rightarrow \Gamma_c$

Fig. 6

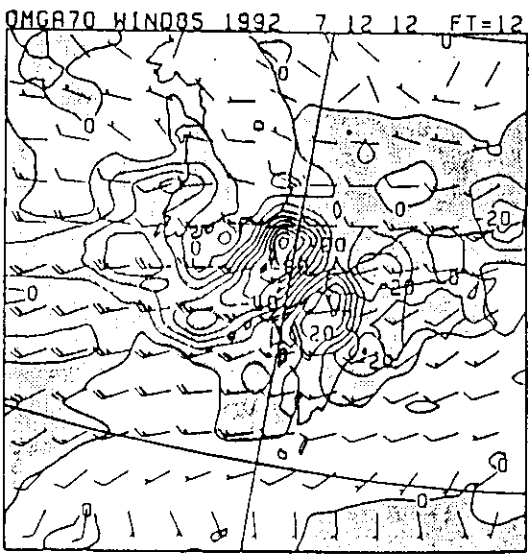
92年7月13日00Ｚの 700hPa 鉛直流と 850hPa 風
初期値化に用いたレーダーアメダスデータ



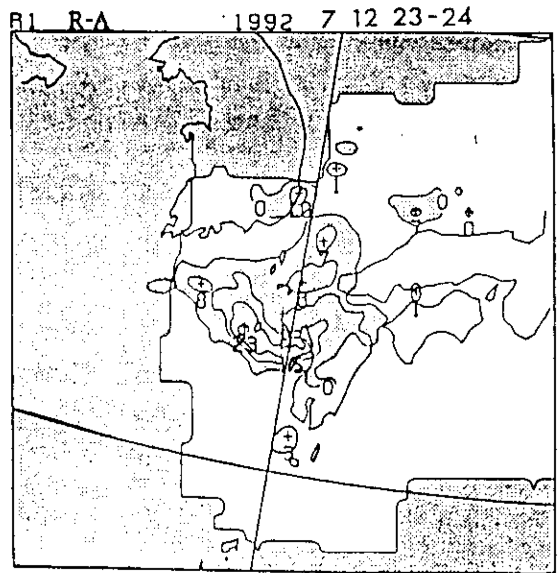
7月13日00Ｚイニシャル　初期値
レーダーアメダスを使わない初期値化
Initialized without RAM Precip.



7月13日00Ｚイニシャル　初期値
レーダーアメダスを使った初期値化
Initialized with RAM Precip.



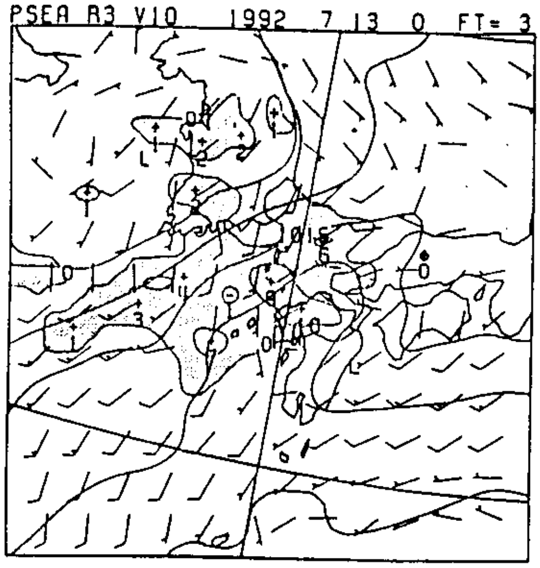
7月12日12Ｚイニシャル　12時間予報
レーダーアメダスを使わない初期値化



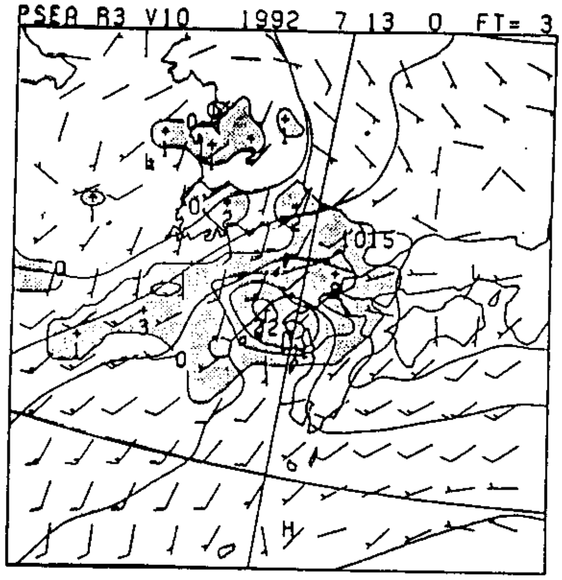
RAM Precip.
レーダーアメダス雨量合成値
7月13日00Ｚ前１時間

Fig. 7a

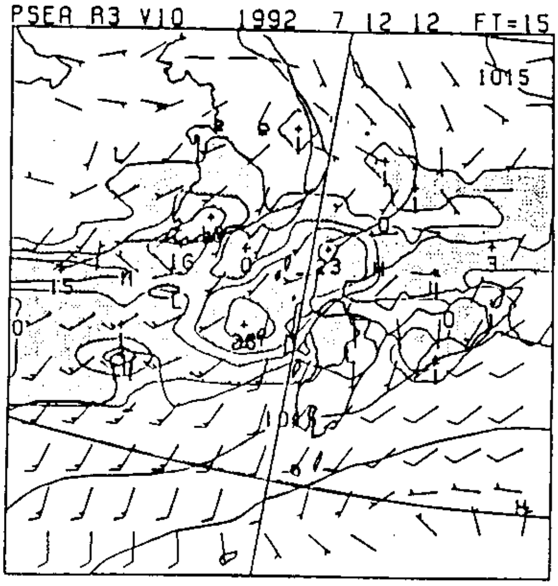
92年7月13日03Ｚの海面気圧、地上風と00Ｚ～03Ｚの雨



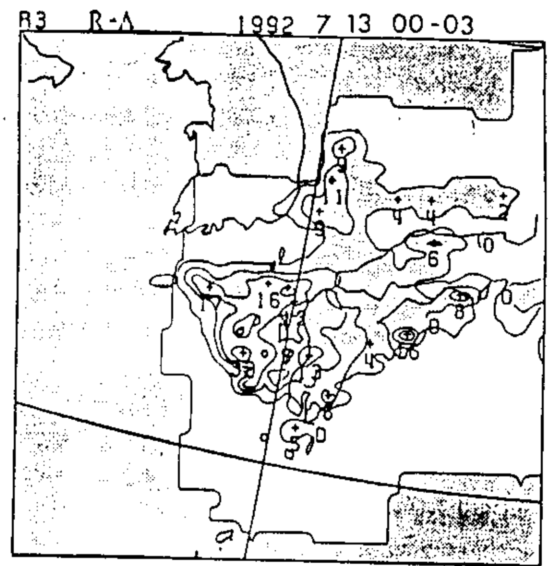
7月13日00Ｚイニシャル　3時間予報
レーダーアメダスを使わない初期値化
from Initialization w. o. RAM



7月13日00Ｚイニシャル　3時間予報
レーダーアメダスを使った初期値化
from Initialization w.t. RAM



7月12日12Ｚイニシャル　15時間予報
レーダーアメダスを使わない初期値化



RAM Precip
レーダーアメダス雨量合成値
at 00-03 UTC
13 July 1992

≪ for Verification ≫

Fig. 7b

Treat Score $\equiv \frac{A}{A+B+C}$

analysis \ fcst	Yes	No
Yes	A	B
No	C	D

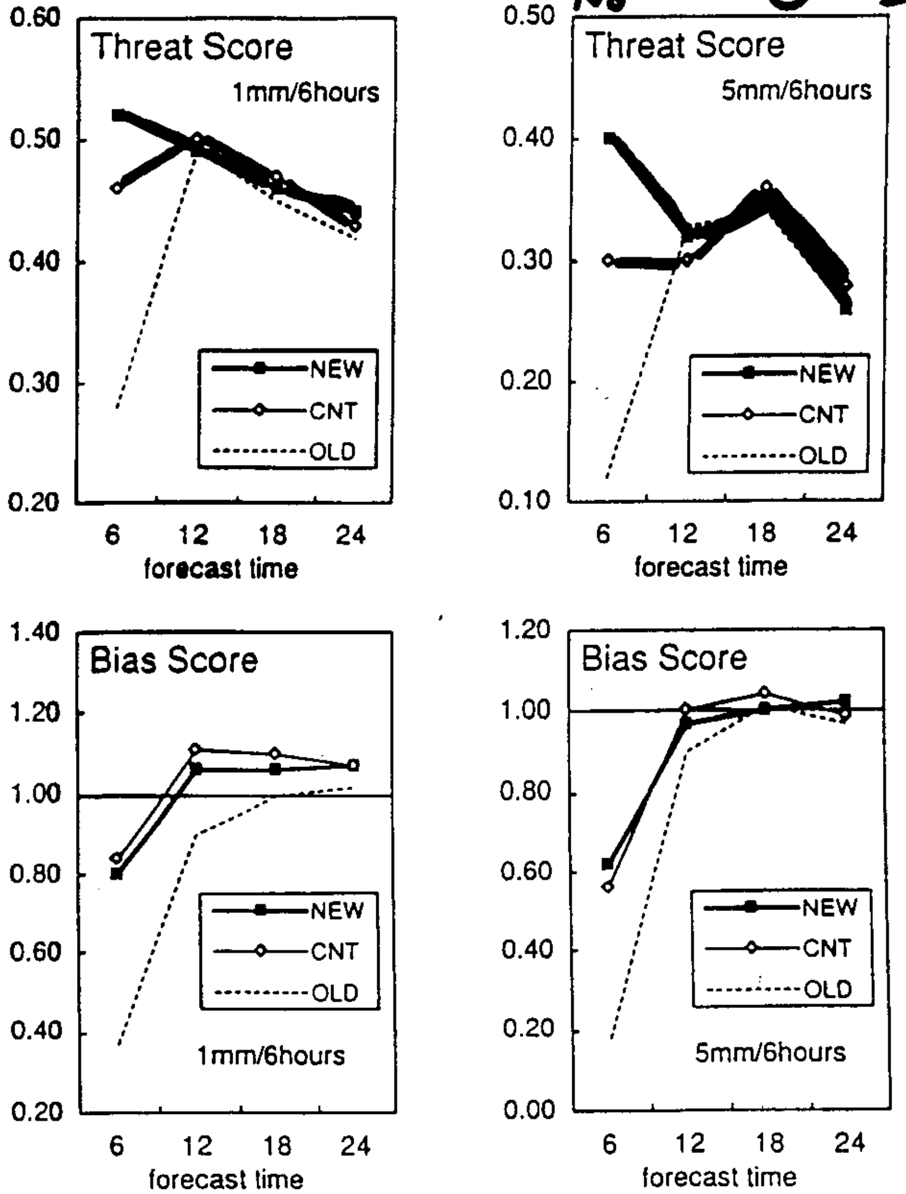
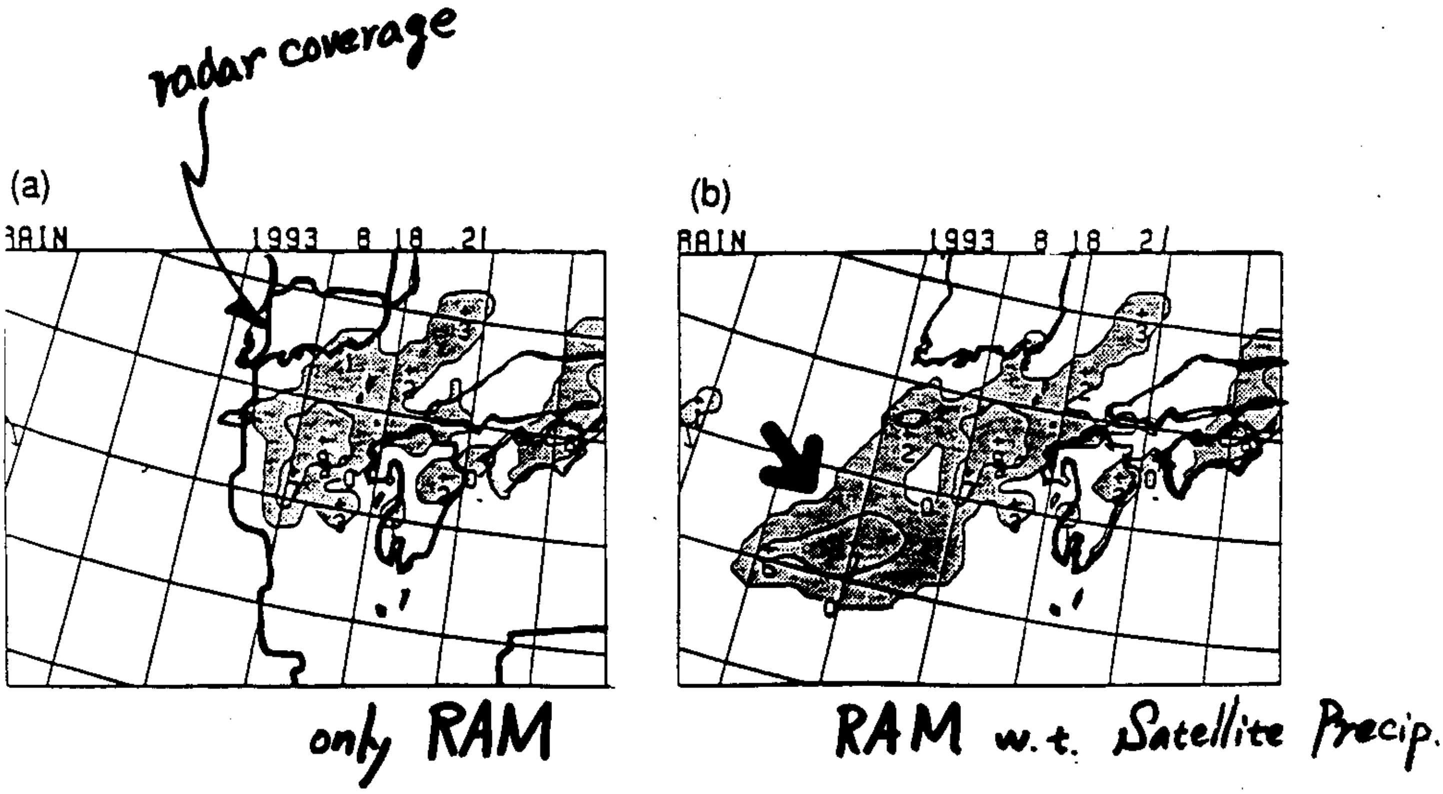


図3．5．1　新しい初期値化スキームを使った予報の統計的検証結果。アメダス・データに対する6時間降水量のスレット・スコアとバイアス・スコアを示す。しきい値は1mmと5mmの二種類。検証期間は91年6月20日～7月5日。NEWが今回の初期値化。CNTは従来の断熱NMIと客観解析でのレーダ・アメダス同化による予報(JSM 9203)、OLDは解析予報サイクル導入以前のルーチンJSMの予報(JSM 8803)。

Fig. 8



第４－６図　(a)　レーダ・アメダス解析雨量（mm/hour）18日21時
(b)　衛星雲データから推定された降水量を解析雨量(a)と結合した降水分布（mm/hour）18日21時

Fig. 9

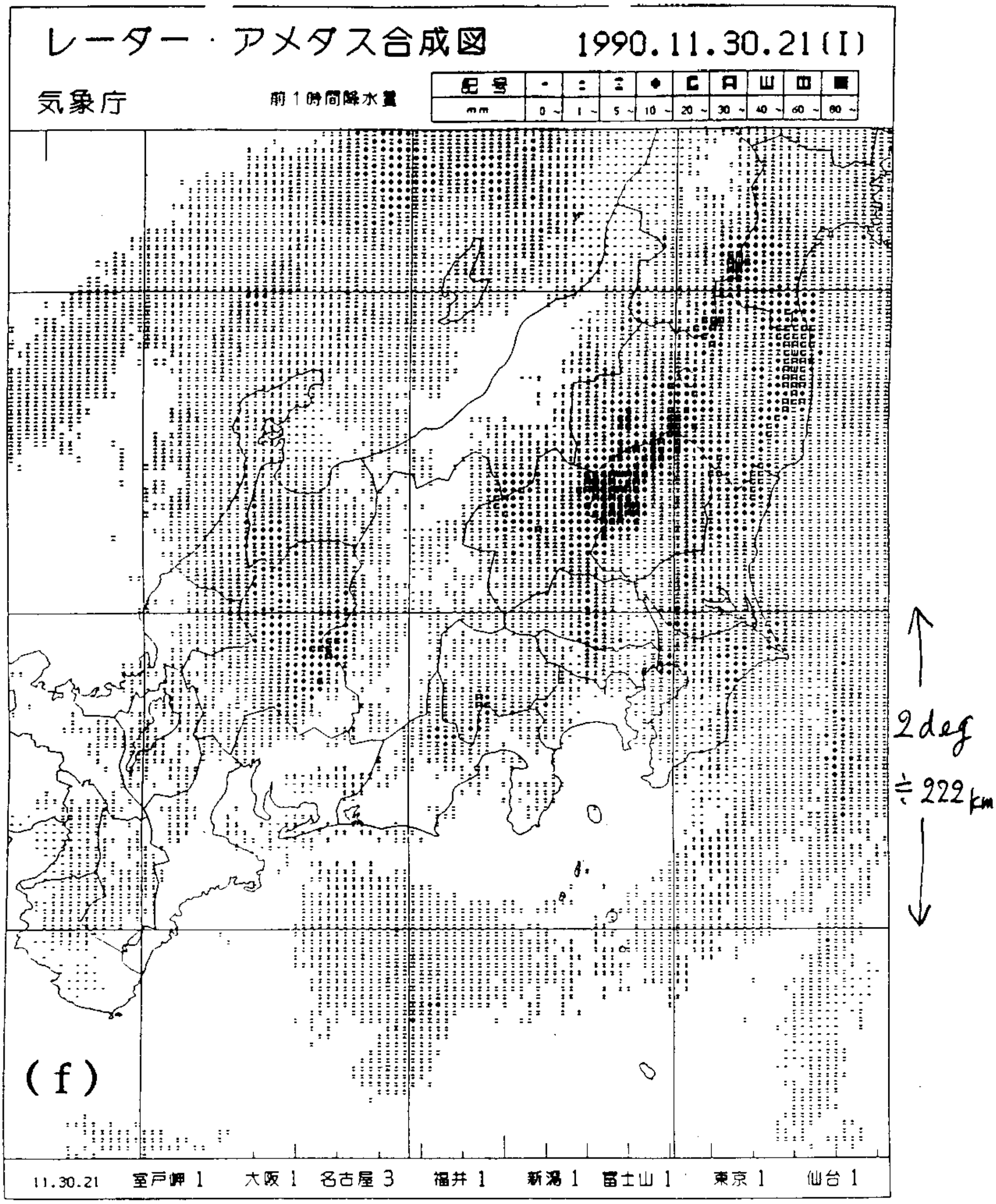


Fig. 9. (f) Radar-AMeDAS precipitation chart at the same time obtained by composing fields of Radar-AMeDAS precipitation by radar, disseminated through facsimile.

Japanese words in the top title are denote, from the upper left side to the lower right side, "Radar-AMeDAS precipitation chart", "Japan Meteorological Agency", "one hour precipitation amount", and the legend. In the bottom area under the chart, place names of observation sites are written in Japanese followed by numerics 0 to 3 which indicate the conditions of operation of the radar. The number 1

Fig 10

Table 1a Specifications for the Global Spectral Model GSM

	old Global Model (GSM8911-T106L21)	new Global Model. (GSM9603-T213L30L)
Integration ahead	72 hours (00 UTC), 192 hours (12 UTC)	84 hours (00 UTC), 192 hours (12 UTC)
Resolution		
Horizontal		
grid interval	approx. 110 km	approx. 55 km
number of grid pints	320*160	640*320
max. wave number	106 with triangular truncation	213 with triangular truncation
Vertical		
number of levels	21	30
coordinate	η (σ − p hybrid)	η (σ − p hybrid)
top	10 hPa	10 hPa
Initial field		
Analysis	mandatory pressure levels, 1.875 deg. lat/long grid 2 dimensional optimum interpolation + asymmetric typhoon bogus	model η levels model Gaussian grid 3 dimensional optimum interpolation + asymmetric typhoon bogus
Initialization	non-linear normal mode full vertical modes	non-linear normal mode up to fifth vertical mode with inclement method
Dynamical process	hydrostatic approximation	hydrostatic approximation
Time integration	Eulericean time integration	Eulerian time integration
Discretization		
horizontal:	spectral	spectral
vertical:	finite-difference	finite-difference
Physical process		
Cumulus convection	Kuo scheme	Arakawa-Schubert scheme
Boundary layer	level-2 closure scheme	level-2 closure scheme
Land surface	Simplified Biospheric (SiB) model	Simplified Biospheric (SiB) model with improvement of initialization of hydrological processes
Radiation	short- and long-wave radiations	short- and long-wave radiations under improvement of cloud radiation

Table 1b Specifications for the TYphoon Model (TYM)

	old TYM	new TYM
Resolution		
Horizontal		
grid interval	50 km (at typhoon center)	40 km (at typhoon center)
number of grid points	109*109	163*163
max. wave number	70*70	106*106
Vertical	8 levels	15 levels
Coordinate		
Map projection	Mercator (Lambert): when typhoon center is south (north) of 20°N at initial time	
Vertical	σ	hybrid ($\sigma - p$):η
Prognostic variables	U, V, T_v, q, ln(Ps)	(cloud amount, water content to be added)
Domain	approx. 5400km x 5400km	approx. 6480km x 6480km
Integration ahead	60 hours from 00,12 UTC	78 hours from 06,18 UTC
Initial field		
Analysis	1.875°-resolution Global Objective Analysis field (mandatory pressure levels) + asymmetric typhoon bogus	model Gaussian grid (~ 0.5625°) Global Objective Analysis field (model hybrid ($\sigma - p$):η levels) + asymmetric typhoon bogus
Initialization	NNMI (non-linear normal-mode initialization)	NNMI + physical initialization using precipitation field analyzed with radar, surface rain gage, and satellite data
Initialization of typhoon(s)	transplantation of modeled typhoon(s) + symmetric adjustment of initial movement velocity	transplantation of modeled typhoon(s) symmetric none
Boundary conditions		
lateral	predictions by GSM starting at T-12h	predictions by GSM starting at T-6h
upper	no vertical velocity ($\dot{\sigma} = 0$) at the top	no vertical velocity ($\dot{\eta} = 0$) at the top with some sponge layers to avoid reflection of gravity waves
Dynamical process	hydrostatic approximation, Eulerian time integration	
Discretization	horizontal: double-Fourier spectral vertical: finite-difference	
Water loading:	not included	included

Physical process		
Cumulus convection		
	moist convective adjustment	Arakawa-Schubert scheme
Radiation	not included	same as current GSM
Boundary layer	simple K-theory with bulk method for surface fluxes	Level-2 closure
Surface	analyzed SST/ no heat flux over land	analyzed SST/ heat budget for multi-layer soil-temperature prediction

Typhoon position error statistics for GSM (top, for 21 cases) and TYM (bottom, for 25 cases).

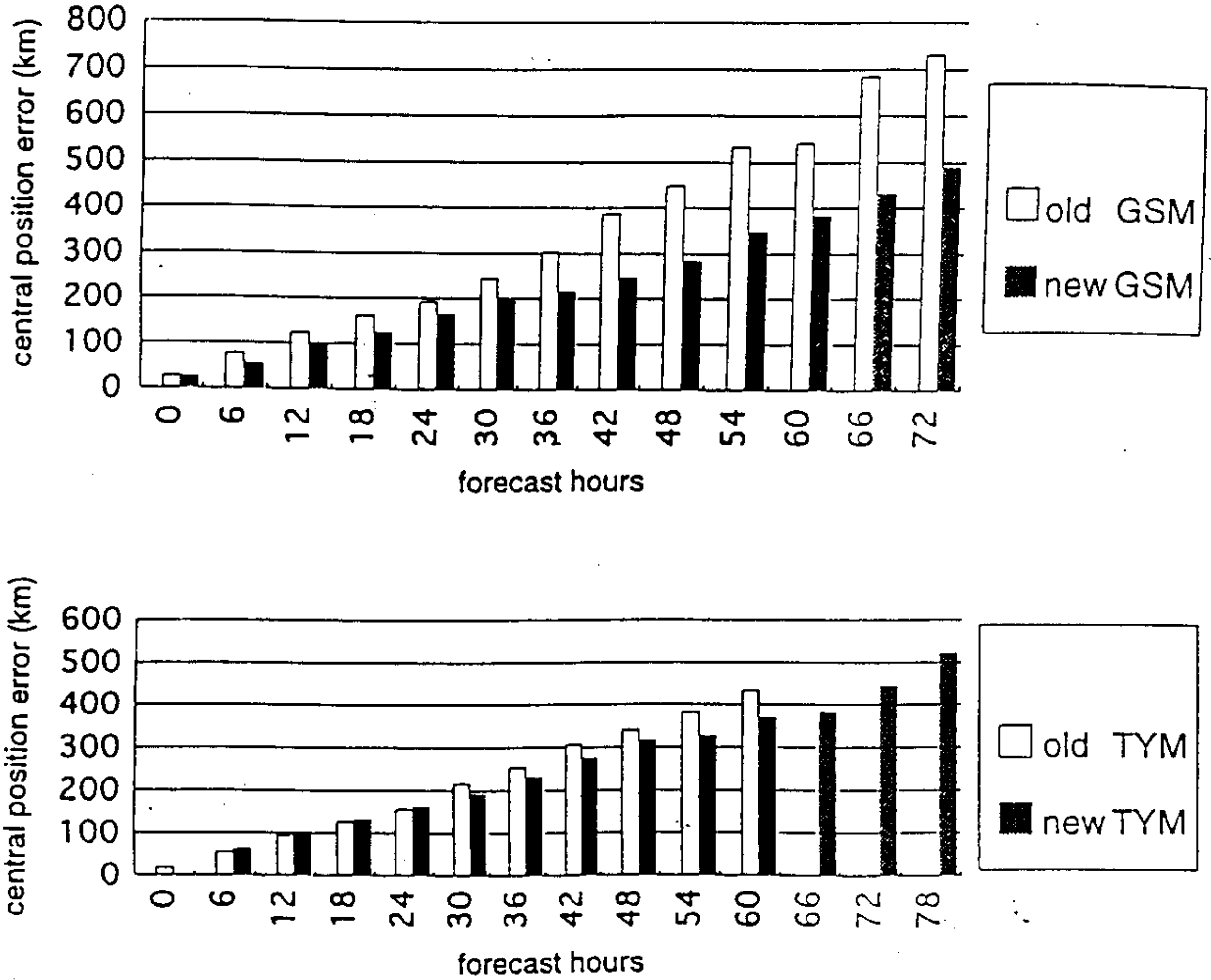
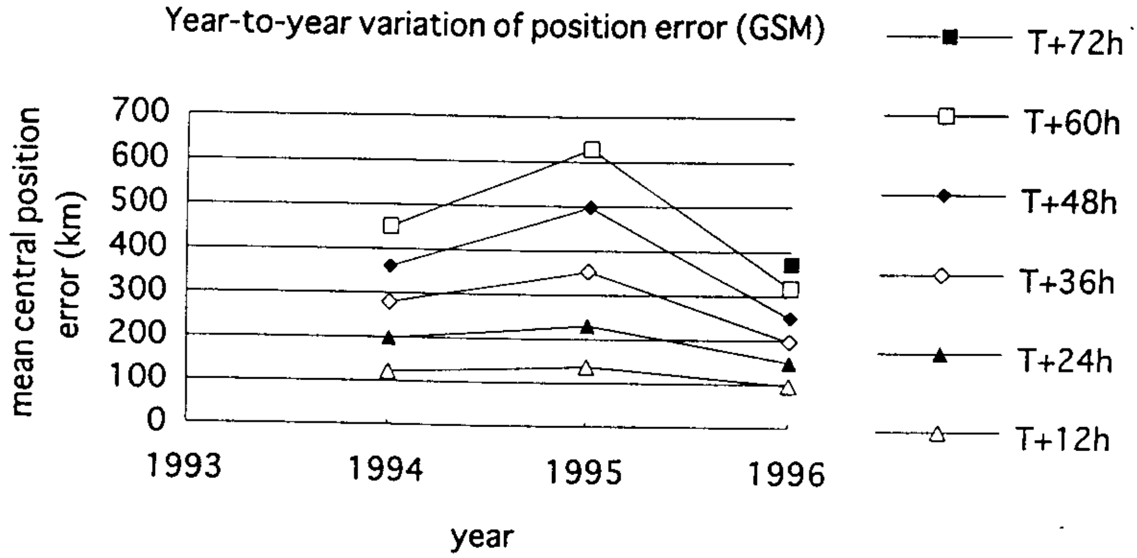


Fig. 11


Year-to-year variation of position error (GSM)
mean central position error (km)
700
600
500
400
300
200
100
0
1993
1994
1995
1996
year
T+72h
T+60h
T+48h
T+36h
T+24h
T+12h

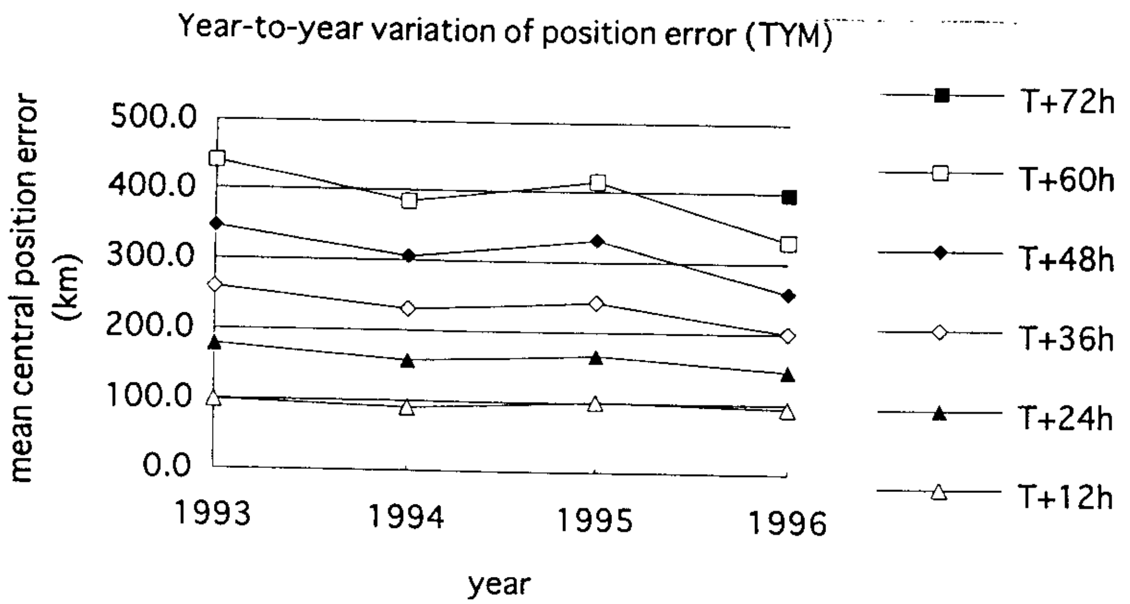

Year-to-year variation of position error (TYM)
mean central position error (km)
500.0
400.0
300.0
200.0
100.0
0.0
1993
1994
1995
1996
year
T+72h
T+60h
T+48h
T+36h
T+24h
T+12h

Fig. 12

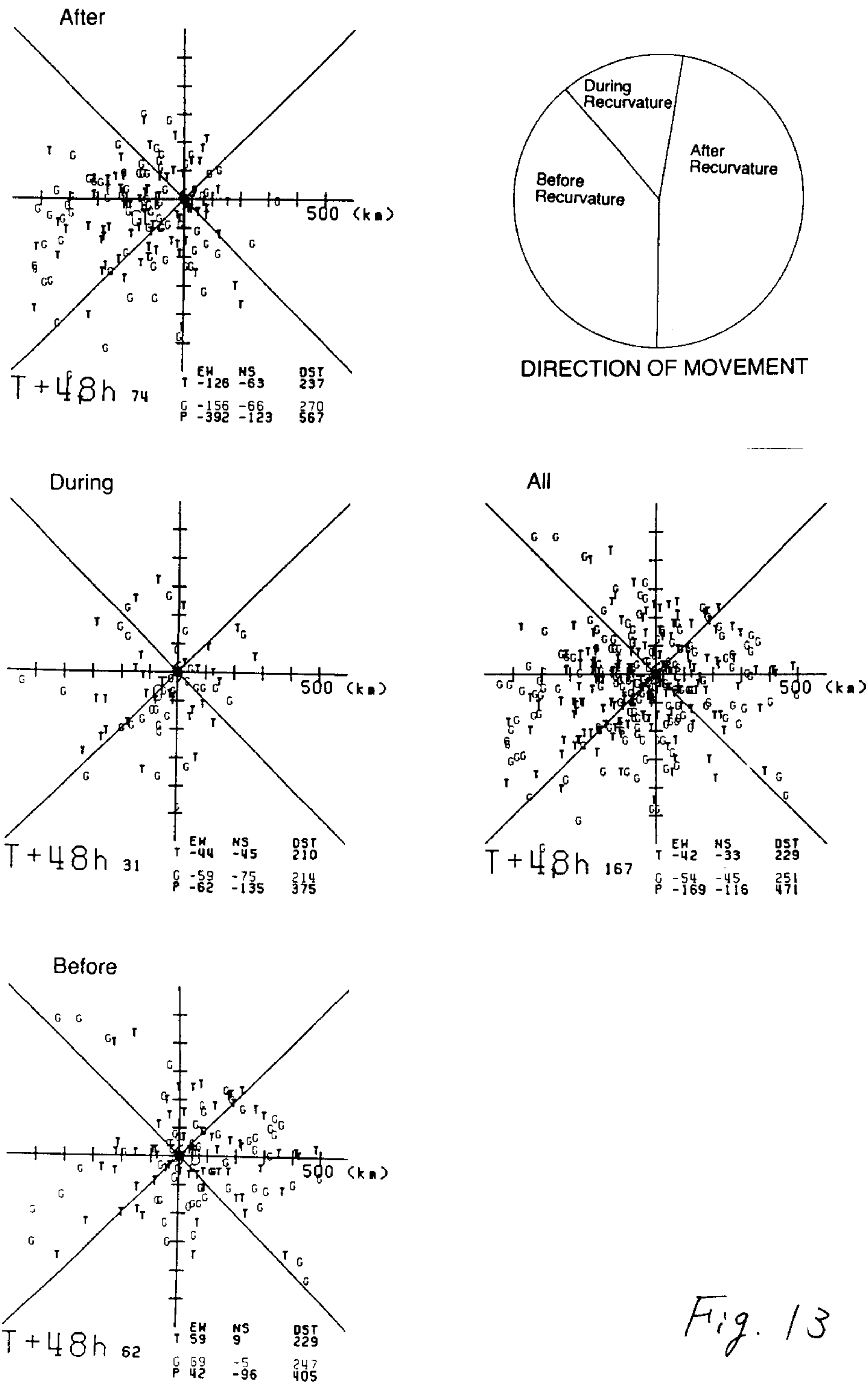
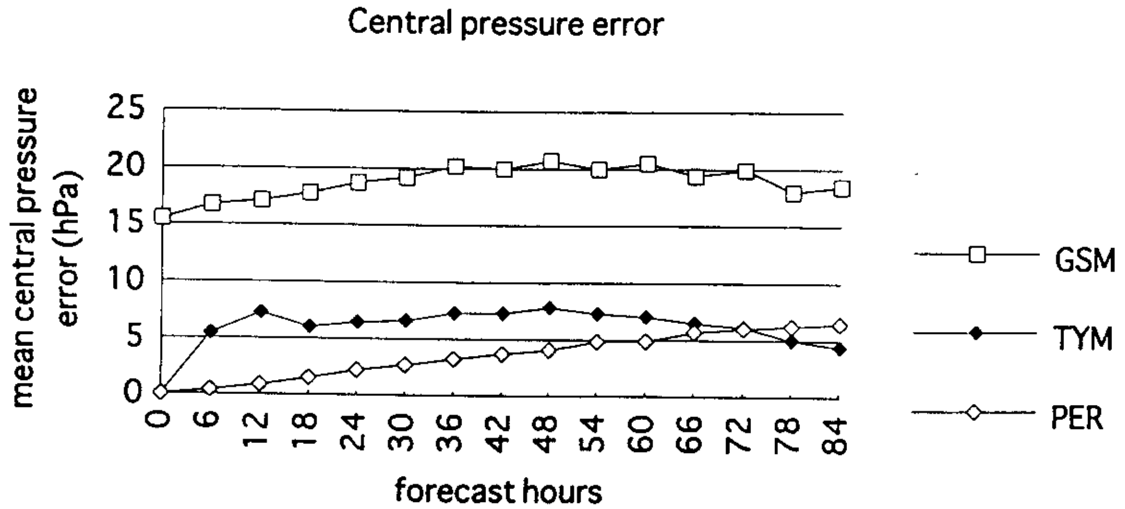
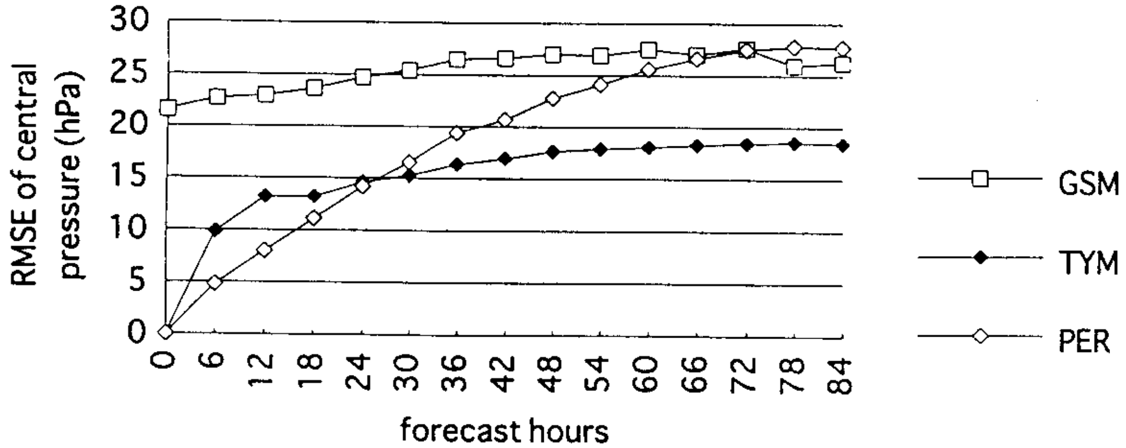

After
500 (km)
T+48h 74
EW NS DST
T -126 -63 237
G -156 -66 270
P -392 -123 567
During Recurvature
After Recurvature
Before Recurvature
DIRECTION OF MOVEMENT
During
500 (km)
T+48h 31
EW NS DST
T -44 -45 210
G -59 -75 214
P -62 -135 375
All
500 (km)
T+48h 167
EW NS DST
T -42 -33 229
G -54 -45 251
P -169 -116 471
Before
500 (km)
T+48h 62
EW NS DST
T 59 9 229
G 69 -5 247
P 42 -96 405

Fig. 13



Central pressure error
mean central pressure error (hPa)
25
20
15
10
5
0
0 6 12 18 24 30 36 42 48 54 60 66 72 78 84
forecast hours
GSM
TYM
PER

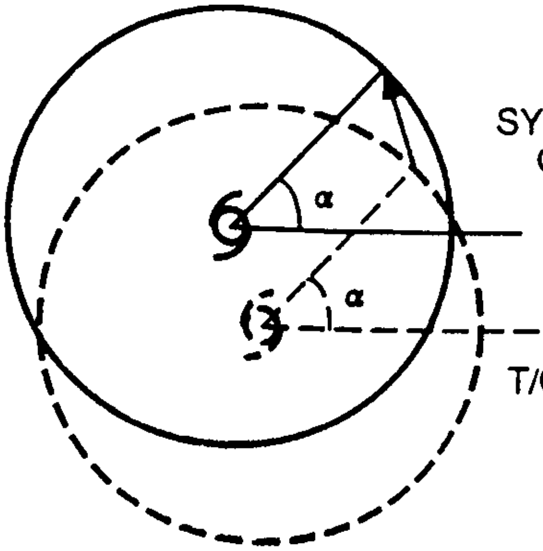


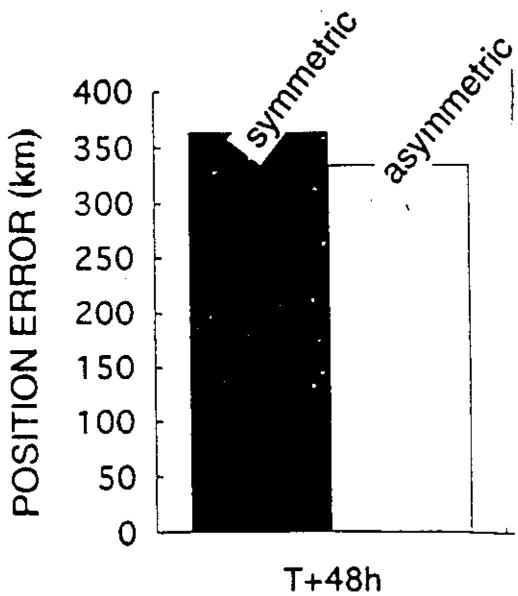
RMSE of central pressure (hPa)
30
25
20
15
10
5
0
0 6 12 18 24 30 36 42 48 54 60 66 72 78 84
forecast hours
GSM
TYM
PER

Fig. 14

Impact of Asymmetric Typhoon Bugusing

Asymmetric component is taken from first-guess field (6-hour forecast field by Global Spectral Model (GSM)) and then overlayed on symmetric T/C centered at analyzed position





symmetric for T9401～T9416
asymmetric for T9417～T9436

> inhomogeneous cases

Global Spectral Model (GSM)

implemented into Global & Regional ANALYSIS 8/23/94