Impacts of Diabatic Initialization and Cumulus Parameterization on Numerical Typhoon Prediction

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Abstract

Numerical experiments were conducted with a regional atmospheric model to investigate the suitability of the model for simulation/prediction of tropical cyclones (TCs). The model uses primitive equations and is similar in construction to a regional atmospheric model, called RegCM, which has been used extensively for regional climate modeling. The suitability of the model for TC study was tested in the mode of short-range forecasts to find out how well the model can reproduce TC behaviors with a special attention on their genesis and development. Objective analysis data for typhoons Ed (9018) and Flo (9019) in September 1990 were used as the input data. In addition, “observed” precipitation (PR) rates estimated from hourly infrared satellite measurements were used.

In the prediction experiments, we focused on two aspects: One was to study the impact of data initialization. The other was to examine the sensitivity of forecast depending on the choice of two cumulus parameterizations, Kuo and relaxed Arakawa-Schubert (RAS) schemes. The initialization to the input data was done through the combination of diabatic nonlinear normal mode initialization for dynamical fields and cumulus initialization for moisture. The diabatic heating rate was determined from radiative and condensation heating rates using the input data, including observed PR rates. The initialization of moisture was done through the inversion of cumulus scheme for a specified PR rate.

Positive impacts of the initialization on reproducing the behaviors of both typhoons are clearly demonstrated in the use of both cumulus schemes. In particular, the initialization results in successful simulations of initial PR field without spinup problems. Thus, the positive impact is greatest in the case of TC genesis. The reproducibility of PR by the model with RAS scheme is superior, and the RAS scheme appears more suitable than the Kuo scheme for the intensity prediction of developing typhoons. However, the use of the Kuo scheme produces better scores in mean displacement errors.

1. Introduction

This study was undertaken because of our interest in the impacts of human-caused global warming on

the behaviors of tropical cyclones. Because the outcome of such an investigation has political as well as socioeconomic implications, it is important to establish scientifically credible findings. A recent article by Henderson-Sellers *et al.* (1998) reviews the current approaches to investigating the impacts of global climate changes on tropical cyclones. They discuss the prospect of three approaches based on statistical analyses of past records, theoretical con-

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siderations of the maximum potential storm intensities, and numerical simulation experiments with prediction models. Since no single approach is sufficient, it is imperative to rely on all the available means to study, including the numerical modeling approach.

Earlier, Tsutsui and Kasahara (1996) examined the question on how well a global climate model with a horizontal grid resolution of approximately 300 km can simulate the behaviors of tropical-cyclone (TC)-like disturbances in long-term climate integrations with specified sea surface temperatures. One interesting finding was that the seasonal and geographical variations of simulated TC formations reproduced observational statistics reasonably well, even in such a coarse resolution model. However, the trajectories and durations of simulated TCs were clearly too short in comparison with observations. We attributed this deficiency to the model's coarse resolution.

In tandem with our efforts to use a global model for the study of TCs, we have been developing a regional TC prediction model to investigate the problems for which coarse global models are not appropriate. Our TC model is based on a regional climate model of Hirakuchi and Giorgi (1995), which was developed to study the impacts of doubled CO₂ concentration in the atmosphere on eastern Asia monsoons. One of the objectives of the present study is to document the performance of our TC prediction model by conducting numerical experiments in a short-range prediction mode using analyzed synoptic data as the input. The details of the regional atmospheric model are presented in Section 2.1 and of the physical processes included in the model are in Section 2.2.

Concerning short-range forecasting experiments using analyzed synoptic data for a research purpose, it is desirable to set up the input data for primitive-equation models that are free from the generation of unwanted gravity-wave motions (noise). The procedure is referred to as initialization. In the case of TC forecasting, in addition to controlling the generation of noise, it is preferable to enhance the quality of input data, because conventional data networks are often not adequate to define TC structures in objective analyses. One such a data enhancement technique is called bogusing, which is a manual specification of TC vortex built into the analysis. Many operational centers practice TC bogusing that adjusts the intensities as well as the positions of TCs to match with various observations (Lord, 1991; Hall *et al.*, 1993; Ueno, 1995). However, the efficacy of bogusing on improvement of TC forecasting has not yet been fully demonstrated. For example, Serrano and Unden (1994) at ECMWF (European Centre for Medium-Range Weather Forecasts) found that TC bogusing has negative impacts on medium-range

forecasts even though it helps to improve the initial depiction of TC structures and short-range forecasts. At best, short-range TC track forecasting will likely be improved by a careful vortex specification as described by Kurihara *et al.* (1993) and Bender *et al.* (1993).

In this study, no attempt is made to modify the input data by additional adjustments other than the so-called "physical initialization." One difficulty in the prediction of TC without a proper initialization is that the model is unable to produce realistic precipitation distributions in the beginning of forecast. This phenomenon is known as a precipitation spinup problem. This difficulty is caused by the extreme sensitivity of cumulus-convection formation upon details of the atmospheric states (Kasahara *et al.*, 1992). The need for special procedures to ameliorate the precipitation (PR) spinup problem was recognized earlier by Krishnamurti *et al.* (1984) who coined the term "physical initialization" in contrast to the initialization for dynamics to suppress gravity-wave noise. In Section 2.3 our physical initialization is discussed. It consists of the combination of diabatic normal mode initialization for dynamical fields and cumulus initialization for moisture. One of our objectives with this study is to investigate the efficacy of our physical initialization procedure.

As our case study, forecast experiments are conducted for a dual system of Typhoons Ed (9018) and Flo (9019) over the western Pacific in September, 1990. These typhoons appeared during a special field observational program called SPECTRUM (Special Experiment Concerning Typhoon Recurvature and Unusual Movement). See Elsberry (1990). The description on these typhoons is given in Section 3.1 and on the input data for prediction in Section 3.2. One feature of this study is the use of "observed" precipitation rates estimated from hourly infrared (IR) measurements from the Geostationary Meteorological Satellite (GMS), as discussed in Section 3.3, for our physical initialization. The use of radiometric measurements from satellites as supplementary data to improve the prediction of TCs has been actively explored by many investigators in connection with the implementation of physical initialization (*e.g.*, Davidson and Puri, 1992; Krishnamurti *et al.*, 1993; Mathur, 1995; Peng and Chang, 1996; Aonashi *et al.*, 1997).

Another objective is to examine the sensitivity of TC forecasts on the choice of two cumulus parameterizations. Because the latent heat of water vapor released in cumulus convection provides the major energy source of TCs, the performance of cumulus scheme in the prediction model is a great concern of TC modelers. Kuma *et al.* (1993) reported an improvement of typhoon track forecasts using Arakawa-Schubert cumulus scheme over those

with Kuo scheme. In this study, numerical experiments are conducted to compare the performance of two cumulus parameterizations, Kuo and relaxed Arakawa-Schubert schemes, as discussed in Section 2.2. The design of forecast experiments is presented in Section 4.1 and synoptic features of three different cases in Section 4.2. The description of forecast results is given in Section 4.3, focusing on the aspect of storm intensity changes. The displacement errors of movement forecasts are discussed in Section 4.4. Conclusions and further discussions are presented in Section 5.

2. Description of forecasting procedures

2.1 Prediction model

The prediction model used in this study is essentially the same as the limited area model developed by Giorgi *et al.* (1993a,b), based on the Pennsylvania State University-NCAR mesoscale model, referred to as the MM4 (Anthes *et al.*, 1987) and is extensively used for regional climate studies (*e.g.*, Hirakuchi and Giorgi, 1995). It is a hydrostatic, compressible, primitive-equation, and grid-point model.

A system of the prediction equations for momentum, temperature, water vapor mixing ratio, and surface pressure on the Mercator map projection is solved by a finite-difference method over a limited domain, centered at 17.5°N and 135°E. An orthogonal regular grid consisting of 135(west-east) $\times$ 111(south-north) grid points is constructed on the projected domain with a grid increment of 50 km.

In the vertical direction, the model uses terrain-following sigma coordinates, defined by $\sigma = (p - p_t)/(p_s - p_t)$, where p is the pressure, p_s is the surface pressure, and p_t denotes p at the top of model atmosphere. The model has unevenly-spaced 14 vertical levels with its top at 80 hPa. Table 1 shows σ values and pressure levels at the full and half- σ levels.

The time integration of the prediction equations is performed using the split-explicit technique of Madala (1981) that allows for the use of a longer time step than used originally in the MM4. The time integration is done with a 2-minute time step.

Since this is a regional model, the lateral boundary conditions are required to solve the system of prediction equations. They are obtained from global synoptic data as discussed later. In order to smooth out discontinuities between specified dependent variables on the lateral boundary and predicted variables in the interior of the domain, the relaxation boundary conditions are used as in the MM4.

The dynamical conditions at the model top and the earth's surface are that $d\sigma/dt$ vanishes, where t denotes time. In addition, the model requires the initial conditions for the calculations of ground temperature and soil moisture. For the initial ground

Table 1. Values of σ at full and half vertical k -levels. Corresponding pressure (p) values are calculated by assuming that $p_t=80$ hPa and $p_s=1000$ hPa

k	full σ -level		half σ -level	
	σ	p [hPa]	σ	p [hPa]
1	0.000	80.0	0.020	98.4
2	0.040	116.8	0.070	144.4
3	0.100	172.0	0.135	204.2
4	0.170	236.4	0.210	273.2
5	0.250	310.0	0.300	356.0
6	0.350	402.0	0.405	452.6
7	0.460	503.2	0.510	549.2
8	0.560	595.2	0.615	645.8
9	0.670	696.4	0.720	742.4
10	0.770	788.4	0.815	829.8
11	0.860	871.2	0.895	903.4
12	0.930	935.6	0.950	954.0
13	0.970	972.4	0.980	981.6
14	0.990	990.8	0.995	995.4
15	1.000	1000.0		

temperature, the air temperature at the lowest level is used. For the initial soil moisture, a climatological value field is adopted. The sea surface temperature in the model is updated using monthly observation data by Reynolds and Smith (1994).

2.2 Physical processes

The prediction model has a state-of-the-art physics package. A diurnal cycle is included to treat the details of interactions between the atmosphere and the underlying earth's surface through the exchanges of radiative, sensible, and latent heat. The atmospheric boundary-layer parameterization, to calculate the vertical fluxes of momentum, sensible heat, and moisture, adopts a combination of BATS (Biosphere-Atmosphere Transfer Scheme, Dickinson *et al.*, 1986) and the planetary boundary-layer formulation of Holtslag *et al.* (1990). The surface sensible and latent heat fluxes and momentum flux are calculated by using stability-dependent bulk transfer formulas. The roughness length over land is specified geographically, while it is constant over the ocean. The shortwave radiative flux at the ground and heating rate in the atmosphere are calculated by the radiative transfer scheme of Briegleb (1992). The longwave counterparts are calculated following Kiehl *et al.* (1987). Clouds used in the radiative transfer calculations are obtained as a function of local relative humidity (Giorgi *et al.*, 1993a).

Two types of precipitation, stable precipitation and convective precipitation, are included in the model. The stable precipitation and its associated heating rate are computed when the water vapor mixing ratio exceeds its saturation value. On the other hand, the convective precipitation and its heating rate are calculated using two different cumu-

Fig. 1. Flow chart of the diabatic and cumulus initialization procedure.

lus parameterizations. One parameterization, which is referred to as Kuo scheme in this study, is the standard one in the MM4 as described by Anthes *et al.* (1987), which is based on Kuo (1974).

Another cumulus parameterization is the relaxed Arakawa-Schubert scheme (RAS) developed by Moorthi and Suarez (1992). This scheme is based on the original formulation of Arakawa and Schubert (1974). However, several modifications are introduced to make the scheme more efficient. The major changes are that 1) the normalized mass flux for each cloud type in the ensemble of clouds is a linear function of height; 2) all liquid water is carried to the cloud top where part is precipitated and part is evaporated, depending on the cloud type; and 3) the quasi-equilibration of the cloud is achieved by each cloud type, neglecting the interaction involving different types of clouds.

2.3 Initialization procedure

In order to suppress the generation of unwanted gravity-wave noise in the prediction model, the following initialization steps are performed on the input data. Figure 1 illustrates the flow chart of initialization. There are two kinds of input data. One is synoptic data from operational objective analyses. The other is precipitation data estimated from IR measurements aboard meteorological satellites. It is important to take into account the effect of diabatic heating in the model initialization, because the irrotational circulation in the tropics is essen-

tially supported by diabatic heating.

The diabatic heating rate is approximated as the sum of radiative and condensation heating rates. The radiative heating rate is calculated from the input data using the model's radiation algorithms. The vertical distribution of condensation heating rate is estimated from the precipitation rate by assuming a parabolic function in the vertical. This is the same parabolic function of σ used for calculation of the convective heating rate in the MM4 using the Kuo scheme (Anthes *et al.*, 1987). The same MM4 algorithms are also adopted for the determination of the cloud base and top.

Once the diabatic heating rate is obtained, the input data of wind velocity, temperature and surface pressure are adjusted by application of the implicit nonlinear normal mode initialization (NNMI) program (Errico and Bates, 1988; Errico *et al.*, 1994) with the specification of the diabatic heating rate thus obtained. The NNMI improves substantially the input divergence field consistent with the input precipitation distribution, while the input vorticity field is intact. The temperature field is changed slightly, *i.e.*, smaller than observational errors. The surface pressure is generally modified within ± 2 hPa.

Even though the divergence field becomes consistent with the distribution of precipitation rate, there is no guarantee that the model can produce the initial precipitation rate as expected unless the moisture field is properly initialized. In this study,

the inversion methods of Kasahara *et al.* (1996) are adopted to initialize the moisture field. The cumulus parameterization for calculation of the convective precipitation rate P can be expressed symbolically as

$$P = F(q, T, D, \dots), \quad (1)$$

where F denotes a function of the mixing ratio of water vapor q , temperature T , horizontal divergence D , and other model variables, such as pressure p , indicated by dots.

Given the input data of q_i, T_i, D_i , where the subscript i indicates the input value, it is straightforward to calculate the initial precipitation rate P_i from (1). The problem of initialization is to determine the optimally adjusted values $q_a(p), T_a(p)$, and $D_a(p)$, where the subscript a refers to the adjusted value, such that P_a is made close to the observed value P_{obs} . Because the task is underdetermined, various constraints are imposed to restrict the possibility of solutions.

One such constraint is that the horizontal divergence D is unchanged during the initialization of moisture. In the case of the Kuo cumulus scheme, the divergence D appears explicitly in the parameterization. Therefore, if we invert (1) allowing the value of D to vary, then the diabatic initialization, denoted by "Normal Mode Initialization" and the moisture initialization, denoted by "Cumulus Initialization" in Fig. 1 are coupled and must be solved simultaneously. The question whether it is worthwhile to consider that the two initialization steps are coupled was studied by Kasahara and Mizzi (1996), who solved the coupled system by iteration in the case of Kuo scheme. Their conclusion was that the number of such iterations to solve the coupled system does not have much effect on the score of short-range forecasts. In other words, it appears sufficient to perform the moisture initialization by using the adjusted divergence from the NNMI. In this work, it is assumed that T and D are as given by the NNMI and are unchanged during the moisture initialization. Thus, the mixing ratio q is initialized by solving (1) under the specification of observed precipitation P_{obs} using the inversion methods described in Kasahara *et al.* (1996) for Kuo and RAS schemes.

It should be mentioned that the adjusted moisture distribution after cumulus initialization is noticeably different depending on the cumulus parameterization used. In the case of the Kuo scheme, a considerable enhancement of input moisture was necessary to match the P with P_{obs} . In contrast, the RAS scheme requires only a slight adjustment of the input moisture distribution. As pointed out by Kasahara *et al.* (1996), however, the RAS scheme can still produce a wrong geographical distribution of precipitation unless the cumulus initialization is performed.

3. Input Data

3.1 Typhoon cases

In this study, we conducted forecast experiments on a dual system of Typhoons Ed (9018) and Flo (9019) over the western Pacific in September, 1990. These typhoons existed simultaneously for more than one week and behaved rather differently in terms of their movement and intensity changes. Figure 2 shows the best tracks of Ed and Flo as recorded by the National Climatic Data Center (1994). Similarly, Table 2 lists the 6-hourly positions, maximum wind speeds, central sea-level pressures, and classifications of Ed and Flo.

Typhoon Ed formed northwest of the Marshall Islands as a tropical depression (TD) on 7 September. Then, it moved westwards, and became a tropical storm (TS) on 11 September and upgraded to a typhoon (TY) by 14 September. Ed continued to move west and maintained a steady strength until it landed on the shore of Vietnam on 18 September.

The origin of Flo as TD can be traced back to southeast of the Marshall Islands on 8 September. It moved northwest over 3000 km before it reached TS on 1200 UTC 13 September. Then, it became TY on 0000 UTC 15 September and continued to move northwest. When it reached the peak of intensity at 890 hPa on 0600 UTC 17 September near Okinawa, Flo started to turn clockwise, toward the north, and then northeast, speeding its movement, and eventually landing on Honshu, Japan. Even after the landfall, Flo maintained its strength as TY until 20 September and later transformed to a midlatitude cyclone. Among typhoons that hit the Japanese islands during the last 19 years, Flo was the most intense.

3.2 Synoptic data

The fields of temperature T , wind velocity east-west (u) and south-north (v) components, water vapor mixing ratio q , and surface pressure p_s as the input data to the prediction model are obtained from the T106-resolution uninitialized-operational-objective analyses produced by ECMWF. Since the grid interval of the prediction model is 50 km while the resolution of the ECMWF analyses is about 120 km, the ECMWF data are interpolated onto the prediction domain. Figure 2 shows the prediction domain. The lateral boundary conditions for u, v, T, q , and p_s are updated through a temporal interpolation from the 6-hourly ECMWF data. Since observed data are used as the lateral boundary conditions, the meaning of prediction applies only to the interior flow.

The positions and intensities of TCs in the input data do not necessarily agree with those listed in Table 2, because the ECMWF objective analyses do not adopt TC bogusing. In this study, no attempt

Fig. 2. Tracks of Ed and Flo from best track data. Times and dates are displayed at the positions where the storms reach tropical storm, typhoon, and peak intensity.

Table 2. 6-hourly positions, maximum wind speeds, central sea-level pressures, and stages of Ed and Flo

Day	Hour	9018 (Ed)					9019 (Flo)				
		Lat	Lon	Wind (kt.)	PSL (hPa)	Stage	Lat	Lon	WInd (kt.)	PSL (hPa)	Stage
12	00	19.9N	136.8E	35	998	TS	10.5N	149.1E	20	1004	TD
12	06	19.9N	135.5E	40	992	TS	11.4N	147.9E	20	1002	TD
12	12	19.9N	134.2E	45	990	TS	12.5N	147.1E	25	1002	TD
12	18	19.9N	132.9E	45	990	TS	13.6N	146.1E	25	1000	TD
13	00	20.0N	131.4E	45	990	TS	14.5N	144.7E	25	998	TD
13	06	20.0N	129.8E	45	985	TS	15.1N	143.3E	30	996	TD
13	12	20.0N	128.2E	45	985	TS	15.6N	142.2E	35	996	TS
13	18	20.0N	126.6E	55	980	TS	16.3N	141.1E	40	994	TS
14	00	19.8N	125.0E	65	975	TY	17.1N	140.0E	45	990	TS
14	06	19.4N	123.5E	65	970	TY	18.0N	138.9E	50	985	TS
14	12	19.0N	121.9E	70	970	TY	18.8N	137.7E	55	980	TS
14	18	18.6N	120.5E	70	975	TY	19.5N	136.5E	60	975	TS
15	00	18.2N	119.3E	70	975	TY	20.2N	135.4E	65	970	TY
15	06	17.8N	118.1E	70	975	TY	20.9N	134.4E	70	965	TY
15	12	17.4N	116.9E	70	970	TY	21.6N	133.4E	75	960	TY
15	18	17.1N	115.9E	70	970	TY	22.2N	132.4E	85	950	TY
16	00	16.7N	114.9E	75	965	TY	22.8N	131.5E	100	935	TY
16	06	16.4N	114.2E	75	965	TY	23.3N	130.7E	115	920	TY
16	12	16.1N	113.5E	80	965	TY	23.7N	130.0E	130	905	TY
16	18	16.0N	113.0E	90	965	TY	24.2N	129.5E	135	895	TY
17	00	15.9N	112.5E	90	965	TY	24.8N	129.1E	135	890	TY
17	06	15.9N	111.9E	85	965	TY	25.6N	128.9E	145	890	TY
17	12	15.9N	111.2E	80	965	TY	26.2N	129.0E	145	895	TY
17	18	15.9N	110.5E	80	965	TY	26.8N	129.2E	135	900	TY
18	00	16.2N	109.7E	75	965	TY	27.5N	129.6E	123	905	TY

(Note) PSL: central sea level pressure, TD: Tropical depression, TS: tropical storm, TY: typhoon.

is made to modify the input data by additional adjustment other than the diabatic and cumulus initialization procedures already described.

3.3 Precipitation data

Precipitation rates used for the initialization of the prediction model are estimated from hourly IR data from the Geostationary Meteorological Satellite (GMS). For this purpose, a modified form of the Arkin and Meisner (1987) algorithm is used. It is based on the assumption that the fractional coverage of "cold" cloud A_f over a search domain is related to the precipitation rate (P) averaged over the search domain by the following relation

$$P = \text{const.} \times A_f. \quad (2)$$

Here, A_f is calculated as the ratio of the area occupied by the temperature below 225 K to the search domain of 3.4° latitude $\times$ 3.4° longitude. The value of 5.5 is used for the constant. These parameter values are selected empirically by consideration of collocated precipitation rates estimated from the Special Sensor Microwave Imager (SSM/I) data using the algorithm of Aonashi and Shibata (1994). Note that the SSM/I retrieved precipitation rates were smoothed using a running average of 2.8×2.8 -degrees area, to remove excessive spatial variations for comparison between the two datasets.

Although SSM/I precipitation rates are presumably more accurate than GMS precipitation (PR) rates, the former data taken from a moving platform do not cover the entire prediction domain, even allowing a ± 3 -hour window. It is very important to have precipitation data of uniform coverage over the entire forecast domain even though their accuracy is sacrificed. Peng and Chang (1997) also formulated an algorithm of PR rates of typhoon Flo based on IR data by taking into account SSM/I-retrieved PR rates for physical initialization of predicting typhoon Flo. Their findings show that use of the IR-inferred PR rates as a supplement to SSM/I-retrieved PR rates has a positive impact on the prediction of Flo, in contrast to the use of only SSM/I PR rates, whose distributions are often incomplete due to limited satellite coverage.

4. Results

4.1 Design of forecast experiments

Four different types of 48-hour predictions are performed for three different synoptic cases, starting from 12, 14, 16 September all at 0000 UTC. The four different types are with and without diabatic and cumulus initialization for two different cumulus parameterizations of Kuo and RAS.

4.2 Synoptic features

In Figs. 3 to 5, 2-h, 24-h, and 48-h predictions by the four different types of experiments are compared

with observations. Each figure contains 15 panels, showing sea-level pressure (SLP) field using contours with an interval of 2 hPa and precipitation (PR) with the two kinds of stippling. Light and heavy stippled regions show the PR rates of 1 mm h^{-1} and 2.5 mm h^{-1} , respectively. Observed SLP fields are obtained from the ECMWF analyses. Observed PR fields are constructed from the GMS data.

In each figure, three panels are grouped together to show the four types of experiments; (a) Kuo scheme, no initialization, (b) RAS scheme, no initialization, (c) initialized-Kuo, and (d) initialized-RAS. The last three panels in (e) show verifications from ECMWF SLP and GMS PR at the initial map time, at 24 hours, and 48 hours later, respectively. The map time is indicated by the eight-digit number shown above each panel.

4.2.1 0000 UTC 12 to 0000 UTC 14, September

In this period, Ed had already existed at the beginning and moved west to the north of the Philippine Islands while developing. In contrast, Flo was still a tropical depression at the beginning and was hardly noticeable on the SLP. However, the PR field in Fig. 3e clearly reveals a wide area of PR near the depression.

In the two experiments in which the diabatic and cumulus initialization is not performed (Figs. 3a and 3b), both model runs do not produce PR at the beginning, and both fail to predict the genesis of Flo. One can see large differences in the distributions of PR between the two runs, despite the use of the same initial conditions. The model run with Kuo scheme suffers from a severe PR spinup problem, which causes not only the failure of Flo's genesis, but also the forecast errors that Ed becomes weak and moves northwestward unfavorably. In contrast, although the model run with the RAS scheme is affected slightly by a spinup problem, the PR distribution does not agree with the observed at the outset. It is remarkable that the initial responses of the two cumulus schemes to the same initial conditions without initialization are so contrasting.

On the contrary, in the two experiments in which the initialization is performed, the model runs produce expected PR distributions and result in successful predictions of both storms, particularly the genesis of Flo (see Figs. 3c and 3d). The release of latent heat from cumulus convection seems to be appropriately represented in both runs. Although the calculated PR distributions in both runs show a close similarity with each other at the start, the similarity diminishes gradually in time due to the differences in the two cumulus schemes. The RAS scheme tends to generate weaker PR in wider areas, while the Kuo scheme tends to produce relatively intense PR rates in narrower regions. This difference indicates that a cumulus scheme produces, in gen-

Fig. 3. Panels (a) to (d) show 2-h, 24-h, and 48-h predictions from 0000 UTC 12 September 1990 for sea-level pressure (SLP) with contours by 2-hPa interval, and precipitation (PR) rates with light (1 mm h^{-1}) and heavy (2.5 mm h^{-1}) stippled areas. The precipitation rates are averaged for the preceding 2-h period. (a) and (b) are for runs with Kuo and RAS schemes, respectively, without the initialization. (c) and (d) are the same as (a) and (b), except for performing initialization. Panel (e) shows the corresponding verifications of SLP from ECMWF analyses and PR estimated from GMS IR data.

eral, a rather distinct characteristic spectrum of PR rates. Moreover, the "observed" PR rates also have a distinct characteristic in terms of the PR spectrum and are likely to be different from satellite data depending on the algorithm used to estimate the PR rates. Thus, the temporal evolution of the PR rate spectrum in the 48-h forecasts exhibits a drift of the initial PR spectrum to an equilibrium one unique to a particular cumulus scheme adopted in the prediction model. Although it appears that the RAS scheme performs better in comparison with the "observed" PR rates, more quantitative investigation is required in terms of the characteristics of PR rates produced by the cumulus schemes in the future.

4.2.2 0000 UTC 14 to 0000 UTC 16, September

The results of this case are shown in Figs. 4a to 4e. In this period, the two storms existed side by side on the latitude line near 20°N at the beginning and, then, proceeded in different directions; Ed reached the South China Sea, moving west across the northern tip of the Philippine Islands, while Flo moved northwestward. Although both storms intensified during this period, the observed PR patterns evolved differently, as seen in Fig. 4e. On one hand, Ed's PR area remained in a concentric form within the storm throughout the period, which inferred that the storm was in a mature stage. On the other hand, the PR distribution associated with Flo changed dramatically. At the beginning of this period, just after Flo reached the tropical storm stage, it was accompanied by a wide and comma-shaped PR area, extending southwestward as far as a few thousand km. The comma-shaped PR region resembles a feeder band, *i.e.*, a large-scale convective region that spirals inward over an extended distance from the southwest in the northern hemisphere cyclones (Holland, 1987). In two days, the intense PR region on the eastern side of Flo turned anticlockwise and remained in a concentric fashion after being sucked into the storm. This PR evolution is deemed favorable for its further development, as seen from its rapid intensification indicated in the best-track data (Table 2).

As seen from Figs. 4c and 4d, the evolutions of the two typhoons are well reproduced in the experiments with the diabatic and cumulus initialization for both cumulus schemes. In particular, the model with RAS scheme simulated remarkably well the contrasting behaviors of storm evolutions, namely a rather steady evolution of Ed and a rapid intensification of Flo. The characteristic differences in the PR patterns in the models with Kuo and RAS schemes in this case are similar to those of the previous case.

A remark should be added concerning the impacts of initialization in this case. Comparing the maps of 48-h predictions of all experiments, a cursory look

gives an impression that the PR patterns of the typhoons are all similar, even though significant differences are seen among different experiments in the evolution of PR rates and the circulation structures throughout the developmental stages. Unlike the previous case, Flo was already well defined in the initial pressure field. Thus, even the model run without initialization was able to generate reasonably intense PR distributions after the spinup time of less than 24 hours. Under this circumstance, we need to examine the impacts of initialization and different cumulus schemes more specifically on the predictions of intensity changes and movement errors. This will be discussed in Sections 4.3 and 4.4.

Another feature to be mentioned in this period and the subsequent 48-h period is a bogus storm that emerged around 150°E in some experiments. The emergence of such a storm is not totally unrealistic, because an active convective region is present in the neighborhood of bogus storm as revealed in the GMS/IR PR patterns. However, it is also true that the diabatic and cumulus initialization may create initial conditions too favorable for storm genesis. It may be a difficult task to design the initialization scheme which is case-selective, *i.e.*, to forecast the genesis of only a certain type of storm.

4.2.3 0000 UTC 16 to 0000 UTC 18, September

Figures 5a to 5e show the results in this period. As seen from Fig. 2, Ed continued to move west in the South China Sea, approaching Vietnam and maintaining the same central SLP. The observed PR area remained concentric within Ed. In contrast, Flo started to turn clockwise and move north, approaching Okinawa with the central SLP deepening rapidly. Significant changes of GMS PR rates were seen within Flo in this period. While the PR rates near the center of Flo had increased, Flo's core PR area began to merge with a PR area over western Japan as Flo continued to move north.

As Figs. 5c and 5d show, both model runs with Kuo and RAS initialized exhibited the tendency to predict an overdevelopment of Ed and a moderate intensification of Flo. Although the rapid intensification of Flo was not fully simulated, the impact of the initialization on the model performance was positive for both cumulus schemes as the initialization contributed to its development. Moreover, if one compares the PR forecasts of Flo with a more reliable PR observation, such as the SSM/I-retrieved PR shown by Fig. 3 in Peng and Chang (1996), it is found that the initialized run remarkably improved the 48-h PR forecast. On the other hand, no measurable impacts of the initialization were seen in the prediction of Ed, particularly with RAS scheme.

Concerning the overprediction of Ed's intensity, we speculate that the initial location of Ed, which was too close to the western boundary, may be re-

Fig. 4. Same as Fig. 3, except for the case starting from 0000 UTC 14 September 1990 and corresponding verifications.

sponsible. Moreover, Ed was still moving west in this period. In the prediction model, the lateral boundary conditions are obtained from the uninitialized ECMWF analysis and not subjected to any

adjustment such as the moisture initialization. This means that inflow from the lateral boundary possibly leads to unrealistically vigorous or suppressed cumulus convection near the boundary, depending

Fig. 5. Same as Fig. 3, except for the case starting from 0000 UTC 16 September 1990 and corresponding verifications.

on cumulus schemes.

The reason for the failure to reproduce such a rapid intensification of Flo is attributed to the model's inability to produce PR sufficiently during

this period. In fact, as seen from Fig. 5e, Flo accompanied the region of intense PR in more concentrated form than Ed, which implies that Flo was a very compact typhoon in which heavy rains and

strong winds were present near the center. A higher resolution model may be needed to simulate the development of such a compact typhoon. Besides, it is likely that the model lacks effective physical mechanisms for typhoon development, or the SST distribution specified in this period may be inappropriate. As discussed by Ginis (1995), the physical processes involved in air-sea interactions in tropical storms are very complex. As the tropical cyclone strengthens, the evaporation rate grows due to the increase in the surface wind speed. Together with adiabatic cooling of the low-level inflow air toward lower pressure, the strengthening of surface wind speed may also contribute to the increase of sensible heat flux from the sea surface. However, as the storm continues to intensify, the increasing surface wind stress generates strong turbulent mixing that deepens the ocean mixed layer. The associated SST decrease may then result in a reduction of the latent and sensible heat flux into the atmosphere and lead to a decrease in storm intensity. It is beyond our task in the present study to investigate the failure of Flo's rapid intensification in our model.

4.3 Intensity changes

Figure 6 shows the plots of central SLPs of Ed and Flo against the prediction periods for various experiments of three cases. The left- and right-hand panels are for Ed and Flo, respectively. In Fig. 6b, the value of SLP for Flo at 0 hour is not shown, because we were unable to determine the position of Flo from the input data taken from the ECMWF analysis at that map time, due to the weak gradient of SLP. This figure is intended to illustrate the impacts of different cumulus parameterizations and of initialization. In general, the initialization clearly produced the deeper central SLPs in both typhoons. Also, the RAS scheme produced deeper central SLPs than the Kuo scheme with and without initialization. By taking the difference between the initialized and uninitialized cases, we conclude that the impacts of initialization on the storm intensity are about the same for both cumulus schemes.

Since both typhoons went through different developmental stages during the forecast periods, we must individually examine the impacts of different cumulus schemes and initial conditions on the predictions of storm intensity changes. One question related to this subject is how we should compare the predicted central SLPs with the observed. The predicted central SLPs are considered to be only the averages over a 50 km square domain. Thus, the direct comparison of predicted central SLPs with the values listed in the best-track data (Table 2), and even the values from objective analyses, may not be totally appropriate. Therefore, it is unavoidable that our following discussions become qualitative.

Ed and Flo were in the developmental and forma-

tive stages, respectively, in the earlier period. As discussed earlier, the benefit of initialization on the prediction of Flo genesis was very clear. Even for the prediction of Ed, the positive impact of initialization was obvious. Looking at the changes of central SLPs, the RAS scheme performed better for both storms. Similar propensities are seen from the results of Flo prediction after 14 September. However, even the RAS scheme was unable to simulate the continued deepening of Flo.

Notice that in the forecasts from 14 September the RAS scheme model exhibited an excessive development of Ed, while in reality Ed maintained its strength unchanged. Moreover, the initialization run demonstrated a tendency to accentuate deepening of Ed. As far as maintaining a constant strength of Ed was concerned, the Kuo scheme model with initialization performed better.

As seen from Fig. 6c, both RAS scheme experiments exhibited a temporary weakening of Ed's central SLPs in their 24-h forecasts. This temporary weakening of Ed was actually observed, as is seen from the best-track data in Table 2. It seems that this phenomenon is related to the passage of Ed over the Philippine Islands. In the Kuo scheme experiments, however, such temporary weakening did not occur, although Ed similarly moved over the Philippine Islands. This different sensitivity to the passage over islands reflects one of the different aspects of the two schemes. In the Kuo scheme, cumulus convection depends on the horizontal convergence of column-integrated moisture. In the RAS scheme, by contrast, moist instability is essential for the generation of cumulus convection, the root of which lies in the atmospheric boundary layer. From this difference the RAS scheme may be considered to be more sensitive to surface boundary conditions than the Kuo scheme. However, the definitive explanation to this different aspect of cumulus sensitivity remains to be seen.

4.4 Errors of movement forecasts

Figure 7 shows the mean errors of predicted displacement of both typhoons averaged over all the experiments to highlight the impacts of two different cumulus schemes and the application of initialization on the movements of storms. However, one sample of Flo forecast from 0000 UTC 12 September is excluded from the averaging, because Flo did not form in the non-initialized runs throughout the 48-hour period. The center position was determined by interpolation as the location of the minimum SLP by fitting a parabola to the nine lowest SLP values. This was done for both the input and predicted SLP patterns. The displacement error is defined as the distance between the predicted position and the corresponding position determined from the input data. In fact, there are differences between the po-

Fig. 6. Individual plots of predicted central sea-level pressures of Ed (left panels) and Flo (right panels) for four different experiments and three prediction cases at 12-hour intervals during 48-h periods.

sitions taken from the input data and those from the best-track data. Of course, the latter data are more realistic. However, we use the former data as the reference positions, because we focus on the impacts of the cumulus schemes and the initialization rather than apparent position errors, and our experiments started from the initialized data without bogusing. Also, note that the SLP field is subjected to change due to the application of NNMI, and that the position of the storm on the initialized SLP differs about 25 km on average from the position of the storm on the input SLP.

One interesting result seen from Fig. 7 is that the growth of initial displacement errors was reduced during the period of 12 to 24 hours in the initialized forecasts. This did not happen in the case of non-

initialized forecasts. These findings apply to both cumulus parameterization experiments. Moreover, as far as the mean errors are concerned, the positive impact of initialization appeared larger with the Kuo scheme than the RAS scheme, having smaller displacement errors with the Kuo scheme. The direct effect of the initialization is seen from improvement in the PR forecast initially. Obviously, the initial improvement of PR distribution was not beneficial to the movement of storm at the beginning of forecast. Nevertheless, the indirect effect of the initialization did show up gradually in 24 hours. It is likely that the accurate diabatic heating distribution in the storms has a positive impact on producing correct interactions between the storms and their environment. This may explain why the growth of

Fig. 7. Mean displacement errors averaged over three prediction cases of Ed and the two prediction cases of Flo, excluding one sample of the case from 0000 UTC 12 September.

displacement errors is reduced in the initialized forecasts. In fact, this finding may be consistent with a negative impact of TC bogusing on medium-range forecasts reported by Serrano and Unden (1994). In our experiments no TC bogusing was applied. In other words, we made no changes in the input data to specifically adjust the initial location of storm or the initial direction of TC movement. It is an interesting question whether the combination of TC bogusing with the physical initialization would further reduce TC displacement errors.

Figures 8a and 8b show the predicted and analyzed trajectories of Ed and Flo, respectively, for the individual experiments of three cases. The storm positions are plotted every 12 hours. The analyzed positions from the input data are shown by dotted lines. The illustrations are self-explanatory, except for the following two points. One is that the position of Flo at 0000 and 1200 UTC 12 September was not determined from the input data as mentioned earlier. Presumably, the input data contain a relatively large uncertainty in determining the position of a weak and wide depression system, such as Flo on 12 September. Therefore, the discrepancy on the order of 150 km continued to appear between the predicted and analyzed positions after 0000 UTC 13 September. However, if this caveat is taken into account, the overall features of predicted trajectories are in good agreement with the analyzed trajectories.

The other point is that the 12-h predicted position of Flo, starting from 0000 UTC 14 September with the initialized RAS scheme, deviated markedly. In fact, this significant displacement error is reflected in the case averages shown in Fig. 7, as noted ear-

lier. As seen from Fig. 4e, there was a relatively intense PR area in the east side of Flo at the initial time, and the PR area actually turned anticlockwise during the forecast period. This asymmetric distribution of PR may have produced an irrotational circulation, which became off centered initially by the diabatic initialization. This presumably created a dynamical imbalance with the rotational circulation and resulted in a brief jolt of the storm, but it did not last more than 12 hours. This may indicate that there is a possibility of producing an irregular motion of storm if observed PR is significantly asymmetric in a storm initially. However, it is unclear why the RAS scheme is more sensitive to this tendency than the Kuo scheme.

5. Conclusions and discussions

5.1 Effects of diabatic and cumulus initialization

One conclusion of this study is the efficacy of diabatic and cumulus initialization on prediction of TCs in their formative stage. This is clearly demonstrated in the forecast of Flo from 12 September. Because the intensity of a cyclonic vortex at its incipient stage is very weak, the prediction model is unable to yield moist convective activity as expected in reality unless the irrotational wind and moisture fields are suitably initialized. Therefore, PR rates estimated from satellites are valuable as additional input data to the initialization of a TC prediction model.

Although the degree of benefit may be reduced, the efficacy of diabatic and cumulus initialization is still present in the prediction of TCs in their mature stage. The benefit may come from the amelioration of a PR spinup problem. Having "well-posed"

Fig. 8. Individual predicted trajectories of Ed (a) and Flo (b) for three prediction cases and four different experiments together with the verification positions from ECMWF analyses. Note that the verification position of Flo at 0000 and 1200 UTC 12 September 1990 is not plotted. See the text for explanation.

diabatic heating and divergence fields that are in balance with the rotational wind field, the movement of the storm may improve. Such an example is seen in the prediction of Ed from 12 September with the Kuo scheme, shown in Fig. 8a. The diabatic and cumulus initialization may have improved the initial conditions for not only Ed, but also Flo in its incipient stage. It is possible that the successful simulation of Flo's genesis created the environmental flow conducive to the improvement of Ed's movement. Such an inference appears to hold with respect to the use of either cumulus scheme in the forecasts beyond 24-hour period, as discussed earlier

in connection with Fig. 7.

It is fair to mention, however, that the efficacy of the diabatic initialization is not totally obvious for prediction of TCs when they become fully matured in reality and the analysis of TC vortex is too weak. In the case of prediction of Ed from 14 September, the intensity of Ed remained almost steady in reality. However, the initialized forecasts with both cumulus schemes exhibited excessive intensification relative to the initial condition. When the model started from 0000 UTC 14 September, for example, the initial SLP of Ed was only 997 hPa, while it should be 975 hPa according to the best-track data.

This difference between the model and observed intensity may be responsible for the problem of continued TC intensification in the model calculations. In this connection, Bender *et al.* (1993) reported that the prediction of pressure deepening tends to delay 1–2 days when analyzed vortex was used instead of a specified vortex with realistic intensity. Once a TC reaches a mature stage having an intense cyclonic circulation, the associated diabatic circulation field would be generated fairly rapidly during the model integration within 12 hours or so. Apparently, such a spinup problem could be tolerated in the case of an intense storm. Therefore, unless the diabatic circulation field obtained by the initialization happens to be consistent with that in the equilibrium state of the storm, the diabatic initialization may not be effective and may even result in excessive intensification.

It should also be noted that the diabatic initialization is not a substitute of a vortex specification known as bogusing, since the diabatic initialization adjusts only the irrotational circulation of storm. When a storm reaches the mature stage and its cyclonic circulation derived from the objective analysis is too weak in reality, the diabatic initialization is not necessarily effective even though the estimated PR rates are accurate. Moreover, from the view point of disaster prevention, TC bogusing is required for the specification of correct TC location and intensity or for the elimination of erroneous TCs that might be present in objective analysis and forecasts. It would be ideal if we could combine a proper TC bogusing with diabatically initialized analysis utilizing observed PR data. In this regard, progress is being made to develop the method of four-dimensional variational data assimilation (4D-VAR), aiming at improvement of tropical analysis by incorporating observed PR rates, such as those obtained from the Special Sensor Microwave/Imager (SSM/I) (*e.g.*, Tsuyuki, 1997). The use of observed PR rates in continuous application of 4D-VAR at operational centers day after day will improve even the analysis of rotational wind field through dynamical adjustment having accurate irrotational wind and moisture analyses. Of course, the need of sufficient grid resolution in the 4D-VAR for TC analyses will demand large computing resources.

5.2 Differences in the performance of two cumulus schemes

The major difference in the performance of the Kuo and RAS schemes is found in the propensity of PR. In the experiments without the initialization, the initial conditions are identical in two runs with the Kuo and RAS schemes. However, virtually no PR was generated by the Kuo scheme at the beginning of the forecast, while the RAS scheme run produced a wide-spread PR pattern, which is unfor-

tunately not very realistic. Both situations are of course not satisfactory. These contrasting behaviors can be explained by the differences in the PR sensitivity of the cumulus scheme on the input moisture field. The PR sensitivity of the cumulus scheme on moisture changes can be examined by calculating PR rates in response to a gradual shift of the initial vertical profile of moisture toward the saturation moisture profile, as shown in Fig. 10 of Kasahara *et al.* (1996) in the case of RAS scheme. The PR rate increases gradually as the moisture in the vertical column increases. However, in the case of the Kuo scheme, the increasing trend of PR rate, as the moisture in the vertical column increases, is relatively slow until the moisture profile becomes very close to the saturation profile. This circumstance is very similar to the Hack scheme shown in Fig. 17 of Kasahara *et al.* (1996).

Once the diabatic and cumulus initialization is applied, the short-term (in the order of a few hours) PR distributions are very similar in both runs with the RAS and Kuo schemes. However, the initialized moisture distributions with the RAS and Kuo schemes are different beyond just observational and analysis errors. In the case of the RAS scheme, the magnitude of moisture adjustment after the initialization is small on the order of analysis errors. In contrast, in the case of the Kuo scheme the magnitude of moisture adjustment after the initialization is rather large and more than the analysis errors. This implies that the cumulus scheme used in the data assimilation at ECMWF, a mass flux scheme by Tiedtke (1989), is more similar in characteristics to the RAS scheme than the Kuo scheme.

Even though the PR distributions are very similar to each other in the beginning of two initialized forecasts with the RAS and Kuo schemes, the evolutions of two PR forecasts eventually differ substantially as time progresses. The following summary is made concerning the performance scores of the two cumulus schemes, with respect to the PR distribution, storm intensity and movement.

In the case of the Kuo scheme, we see a pattern of PR distribution being concentrated in a spotty fashion as time progresses. We don't see this propensity in the case of RAS scheme. Rather the RAS scheme produces smooth temporal changes of the PR distributions more or less consistent with the GMS rain distributions. Therefore, as far as the PR distribution is concerned, the RAS scheme seems superior.

As far as the prediction of storm intensity is concerned, both schemes responded reasonably well. It is difficult to make any categorical conclusion as to the superiority of one scheme over the other, because such a judgment may be case-dependent.

Regarding the mean displacement errors, the Kuo scheme scored better because the RAS scheme inclined to produce larger displacement errors during

the first 12-hour period. This may be related to the asymmetry of observed PR distribution with respect to the storm center mentioned earlier. Since this tendency appeared only momentarily in the beginning of the forecast, this finding should not be regarded as a liability to the RAS scheme.

In conclusion, we see different responses of two cumulus schemes for different aspects of TC prediction. Although more case studies would certainly be needed to confirm those specific propensities of each cumulus scheme, the present study points out the characteristics of the cumulus schemes required for further improvement. For example, there seems to be room for tuning of the RAS scheme in such a way that it would reduce too much drizzle and produce a more intense PR rate. This will shift the peak intensity of the PR rate toward the higher PR rate. These aspects should be investigated in our future study.

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References

- Anthes, R., E.-Y. Hsieh and Y.-H. Kuo, 1987: Description of the Penn State/NCAR Mesoscale Model Version 4 (MM4). *Tech. Note NCAR/TN-282+STR*, NCAR, Boulder, Colorado, 66pp.
- Aonashi, K., K. Kuma and Y. Matsushita, 1997: A physical initialization method for the economical prognostic Arakawa-Schubert scheme. *J. Meteor. Soc. Japan*, **75**, 597–618.
- Aonashi, K. and A. Shibata, 1996: An over-ocean precipitation retrieval using SSM/I multichannel brightness temperatures. *J. Meteor. Soc. Japan*, **74**, 617–637.
- 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.
- Arkin, P.A. and B.N. Meisner, 1987: The relationship between large-scale convective rainfall and cloud over the western hemisphere during 1982–1984. *Mon. Wea. Rev.*, **115**, 51–74.
- Bender, M., R.J. Ross, R. Tuleya and Y. Kurihara, 1993: Improvements in tropical cyclone track and intensity forecasts using the GFDL initialization system. *Mon. Wea. Rev.*, **121**, 2046–2061.
- Briegleb, B.P., 1992: Delta-Eddington approximation for solar radiation in the NCAR Community Climate Model. *J. Geophys. Res.*, **97**, 7603–7612.
- Davidson, N.E. and K. Puri, 1992: Tropical prediction using dynamical nudging, satellite-defined convective heat sources, and a cyclone bogus. *Mon. Wea. Rev.*, **120**, 2501–2522.
- Dickinson, R.E., P.J. Kennedy, A. Henderson-Sellers and M. Wilson, 1986: Biosphere-Atmosphere Transfer Schemes (BATS) for the NCAR Community Climate Model. *Tech. Note NCAR/TN-275+STR*, NCAR, Boulder, Colorado, 69pp.
- Elsberry, R.L., 1990: International experiments to study tropical cyclones in the western North Pacific. *Bull. Amer. Meteor. Soc.*, **71**, 1305–1316.
- Errico, R.M. and G.T. Bates, 1988: Implicit Normal-Mode Initialization of the PSU/NCAR Mesoscale Model. *Tech. Note NCAR/TN-312+IA*, NCAR, Boulder, Colorado, 112pp.
- Errico, R.M., K. Raeder and T. Vukićević, 1994: Mesoscale Adjoint Modeling System Version 1. *Tech. Note NCAR/TN-410+IA*, NCAR, Boulder, Colorado, 214pp.
- Ginis, I., 1995: Ocean response to tropical cyclone. Chapter 5 of *Global perspectives on tropical cyclones*. WMO/TD-No. 693, World Meteorological Organization, Geneva, Switzerland, 198–260.
- Giorgi, F., M.R. Marinucci and G.T. Bates, 1993a: Development of a second-generation regional climate model (RegCM2). Part I: Boundary-layer and radiative transfer processes. *Mon. Wea. Rev.*, **121**, 2794–2813.
- Giorgi, F., M.R. Marinucci and G.T. Bates, 1993b: Development of a second-generation regional climate model (RegCM2). Part II: Convective processes and assimilation of lateral boundary conditions. *Mon. Wea. Rev.*, **121**, 2814–2832.
- Hall, C.D., J.C.R. Hunt and A.M. Radford, 1993: Forecasting tropical cyclones and near surface wind conditions. In *Tropical cyclone disasters*. Proceedings of ICSU/WMO International Symposium, October 1992, Beijing, China, Peking University Press, 232–257.
- Henderson-Sellers, A., H. Zhang, G. Berz, K. Emanuel, W. Gray, C. Landsea, G. Holland, J. Lighthill, S.-L. Shieh, P. Webster and K. McGuffie, 1998: Tropical cyclones and global climate change: A post-IPCC assessment. *Bull. Amer. Meteor. Soc.*, **79**, 19–38.
- Hirakuchi, H. and F. Giorgi, 1995: Multiyear present-day and 2xCO₂ simulations of monsoon climate over eastern Asia and Japan with a regional climate model nested in a general circulation model. *J. Geophys. Res.*, **100**(D10), 21105–21125.
- Holland, G.J., 1987: Mature structure and structure change, In *A global view of tropical cyclones* (R.L. Elsberry, Ed), Off. of Nav. Res., Arlington, VA, 13–52.
- Holtlag, A.A.M., E.I.F. de Bruijn and H.-L. Pan, 1990: A high resolution air mass transformation model for short-range weather forecasting. *Mon. Wea. Rev.*, **118**, 1561–1575.
- Kasahara, A. and A.P. Mizzi, 1996: Use of precipitation data for diabatic initialization to improve the trop-

- ical analysis of divergence and moisture. *Meteorol. Atmos. Phys.*, **60**, 143–156.
- Kasahara, A., J. Tsutsui and H. Hirakuchi, 1996: Inversion methods of three cumulus parameterizations for diabatic initialization of a tropical cyclone model. *Mon. Wea. Rev.*, **124**, 2034–2321.
- Kasahara, A., A.P. Mizzi and L.J. Donner, 1992: Impacts of cumulus initialization on the spinup of precipitation forecasts in the tropics. *Mon. Wea. Rev.*, **120**, 1360–1380.
- Kiehl, J.T., R.J. Wolski, B.P. Briegleb and V. Ramanathan, 1987: Documentation of radiation and cloud routines in the NCAR Community Climate Model (CCM1). *Tech. Note NCAR/TN-288+IA*, NCAR, Boulder, Colorado, 114pp.
- Krishnamurti, T.N., H.S. Bedi and K. Ingles, 1993: Physical initialization using SSM/I rain rates. *Tellus*, **45A**, 247–269.
- Krishnamurti, T.N., K. Ingles, S. Cocke, T. Kitade and R. Pasch, 1984: Details of low latitude medium range numerical weather prediction using spectral model. *J. Meteor. Soc. Japan*, **26**, 613–649.
- Kuma, K., C-H Cho, C. Muroi and M. Ueno, 1993: Improvement of typhoon track forecast by the JMA global model: An impact of cumulus parameterization. Papers presented at the third Technical Conference on SPECTRUM. Report No. TCP-33, WMO/TD-No. 595. World Meteor. Org., Geneva, Switzerland, IV-1–IV-8.
- 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.
- Lord, S.J., 1991: A bogusing system for vortex circulations in the National Meteorological Center Global Forecast Model. Preprints, 19th Conference on Hurricanes and Tropical Meteorology, Miami, FL May 1991. *Amer. Meteor. Soc.*, 328–330.
- Madala, R.V., 1981: Efficient time integration schemes for atmosphere and ocean models. In *Finite-difference techniques for vectorized fluid dynamics calculations* (D.L. Book, Ed.), Springer-Verlag, 56–74.
- Mathur, M.B., 1995: Amelioration of convective and nonconvective condensation with the assimilation of rainfall for improving initial conditions. *Mon. Wea. Rev.*, **123**, 1851–1861.
- Moorthi, S. and M.J. Suarez, 1992: Relaxed Arakawa-Schubert: A parameterization of moist convection for general circulation models. *Mon. Wea. Rev.*, **120**, 978–1002.
- National Climatic Data Center, 1994: Global Tropical/Extratropical Cyclone Climatic Atlas (GTECCA), [CD-ROM], Clim. Serv. Div., NOAA Asheville, N.C.
- Peng, M.S. and S.W. Chang, 1996: Impacts of SSM/I retrieved rainfall rates on numerical prediction of a tropical cyclone. *Mon. Wea. Rev.*, **124**, 1181–1198.
- Peng, M.S. and S.W. Chang, 1997: Predicting typhoon Flo of 1990 with assimilation of rainfall rates inferred from infrared brightness temperatures. *J. Meteor. Soc. Japan*, **75**, 1073–1089.
- Reynolds, R.W. and T.M. Smith, 1994: Improved global sea surface temperature analysis using optimum interpolation. *J. Climate*, **7**, 929–948.
- Serrano, E. and P. Uden, 1994: Intercomparison of tropical cyclone bogusing method in data assimilation and forecasting. *Mon. Wea. Rev.*, **122**, 1523–1547.
- Tiedtke, M., 1989: A comprehensive mass flux scheme for cumulus parameterization in large-scale models. *Mon. Wea. Rev.*, **117**, 1779–1800.
- Tsutsui, J. and A. Kasahara, 1996: Simulated tropical cyclones using the National Center for Atmospheric Research community climate model. *J. Geophys. Res.*, **101(D10)**, 15013–15032.
- Tsuyuki, T., 1997: Variational data assimilation in the tropics using precipitation data. Part III: Assimilation of SSM/I precipitation rates. *Mon. Wea. Rev.*, **125**, 1447–1464.
- Ueno, M., 1995: A study on the impact of asymmetric components around tropical cyclone center on the accuracy of bogus data and the track forecast. *Meteor. Atmos. Phys.*, **56**, 125–134.

台風の数値予報に対する 非断熱初期値化および積雲パラメタリゼーションの効果

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領域大気モデルを用いた数値実験を行い、熱帯低気圧のシミュレーションならびに予報に対するモデルの適合性を研究した。このモデルはプリミティブ方程式を支配方程式として用いるもので、これまで地域気候モデリングの研究に広く利用されてきた RegCM と呼ばれる領域大気モデルと同様な構成である。熱帯低気圧の研究に対しては、短期予報のモードでモデルの適合性を評価することとし、熱帯低気圧の性状をモデルがどの程度良く再現できるかということを、特に発生や発達に注目して調べた。入力データには 1990 年 9 月の台風 Ed (9018) および Flo (9019) に対する客観解析データを用いた。また、一時間毎の赤外衛星データから推定される降水強度の「観測値」も合わせて利用した。

予報実験では二つの点に重点をおいた。一つは、データの初期値化の効果を調べることである。もう一つは、二つの積雲パラメタリゼーション、Kuo および relaxed Arakawa-Schubert (RAS) スキームに対する予報の感応度を調べることである。入力データに対する初期値化は、力学的な場に対する非断熱、非線形ノーマルモード初期値化と、水蒸気に対する積雲の初期値化との組合せによって行った。非断熱加熱率は放射および凝結による加熱率から決定し、降水強度の観測値を含む入力データを適用して求めた。水蒸気の初期値化は、与えられた降水強度に対して積雲スキームを逆算することによって行った。

初期値化のもたらす台風の再現性向上の効果は、どちらの台風に対しても積雲スキームの種類に関わらずはっきり示される。特に、初期値化によって初期の降水場が正しくシミュレートされ、降水スピナップが解消される。したがって、初期値化は台風の発生の場合に最も効果的である。RAS スキームを用いたモデルは降水場の再現性に優れており、発達中の台風に対する強度予報に対しては、Kuo スキームより RAS スキームの方が適しているようである。しかしながら、Kuo スキームは平均的な進路予報誤差において良いスコアを出している。