A New Method of Observed Rainfall Assimilation in Forecast Models

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ABSTRACT

A method to assimilate observed rain rates in the Tropics for improving initial fields in forecast models is proposed. It consists of a 6-h integration of a numerical forecast model; the specific humidity at every time step at each grid point is modified (nudged) in such a way that the total model precipitation accumulated during this integration becomes very close to that observed. An increase in the model precipitation is achieved by moistening the lower troposphere above a grid point with prescribed supersaturation; a decrease in the model rainfall is brought about by decreasing the specific humidity in the lower troposphere in proportion to the difference between the model and reference specific humidity profiles. The modified values depend on the difference between the model and target precipitation. The depth of the atmospheric column in which the humidity is changed is proportional to the target rain rate. Quality criteria of a rain assimilation procedure are proposed.

The quality of the assimilation method was verified using a test in which precipitation generated by a forecast model without nudging ("control" experiment) was considered to be "quasi-target" data and the nudging procedure was used for assimilation of the rain produced in the control experiment. The following experiments were performed: control (C)—without nudging, "simulated nudge" (S)—nudging to the 6-h accumulated rainfall from the C experiment, and "satellite nudge"—nudging to the 6-h accumulated satellite-retrieved (observed) rainfall. Each experiment consisted of a 6-h forecast (first guess), analysis, next 6-h forecast (first guess), next analysis, and 24-h forecast. Nudging was applied during the two successive 6-h calculations of the first guess over the tropical belt. Parameters of the nudging procedure were determined in such a way that the assimilation procedure converged quickly and simulated the observed precipitation very closely. The difference in forecast fields between the S and C experiments after a 24-h forecast turned out to be small, indicating high quality of the assimilation procedure. The high sensitivity of forecast fields to the quality of rain retrieval is demonstrated.

1. Introduction

The initial fields of temperature, wind, and humidity often are not analyzed well over tropical areas because of lack of observations. Because tropical motions are driven largely by diabatic processes, observations of precipitation could be a valuable data source for improving initial fields. Rainfall estimates over a significant portion of the tropical belt currently can be obtained from satellites. To assimilate this rainfall, it is necessary to solve two problems. The first is to retrieve rainfall from satellite data in the Tropics with sufficient accuracy. The second problem is to assimilate satellite-retrieved rainfall accurately using an initialization procedure.

There have been a number of studies to assimilate observed tropical precipitation using a "reverse" scheme (Krishnamurti et al. 1984, 1988, 1991, 1995; Donner and Rasch 1989; Heckley et al. 1990; Mathur et al. 1992). To simulate the target precipitation, the reverse scheme changes temperature and humidity at each time step and redistributes these changes in the vertical, as in the forward convective parameterization scheme. Krishnamurti et al. (1984) suggested changing the vertical velocity simultaneously with the reverse Kuo scheme. Heckley et al. (1990) introduced diagnosed rainfall fields into the European Centre for Medium-Range Weather Forecasts data assimilation system as diabatic heating through the nonlinear normal-mode initialization scheme. Donner and Rasch (1989) used synthetic diagnosed distributions of latent heat release and divergence generated by integrating the model for 3 days from an analysis valid 3 days prior to the initialization time. Kasahara et al. (1992) developed a diabatic initialization on the basis of the Kuo scheme. The authors changed the divergence and the specific humidity and minimized these changes in the least mean squares sense with prescribed weights and several constraints. The reverse Kuo scheme was used in the National Centers For Environmental Prediction (NCEP, previously

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known as the National Meteorological Center) Global Data Assimilation System (GDAS) for the ingestion of rainfall data by Mathur et al. (1992). Manobianco et al. (1994) assumed that the modification to the heating is proportional to the magnitude of the original heating. The constant of proportionality was the ratio of the difference between satellite and total model precipitation normalized by the model value. Mathur (1995) used a regional tropical cyclone model for testing assimilation schemes. The forecast rainfall fields from a model integration in which the initial relative humidity in the inner storm area was over 90% were used as the target fields. Treadon (1996) examined the impact of assimilating outgoing longwave radiation (OLR) rain rates into the NCEP global analysis and forecast system. The author developed reverse algorithms for the simplified Arakawa–Schubert cumulus parameterization by redistributing moisture in the column so that the vertically integrated change in moisture was approximately zero. The authors of the studies mentioned above reported a positive effect of rainfall assimilation on the analysis and forecast.

It is known that the Kuo-type parameterization methods have serious constraints and limitations (Emanuel 1991). The reverse convective parameterization methods have the same constraints as the direct ones do and are not exhaustive with respect to rain assimilation problems. State-of-the-art methods of rainfall assimilation have not been considered satisfactory enough to be implemented operationally, and the problem needs further investigation. In the current work, the second problem cited in the beginning of this section, that is, to assimilate satellite-retrieved rainfall accurately using an initialization procedure, is approached. A new rain assimilation procedure that can adjust very closely the total model precipitation to the target satellite-retrieved precipitation is introduced. It is shown that this procedure converges and that it leads to creation of large-scale updrafts in the area of heavy precipitation. The rest of the paper has the following structure. Precipitation parameterization in the NCEP medium-range forecast (MRF) is discussed in section 2. Section 3 includes a short description of rainfall retrievals from satellite observations. Description of the nudging method for simulating the target precipitation in a model is discussed in section 4. Section 5 is devoted to formulation of quality criteria for a rain assimilation procedure and description of a test for verification of this procedure. Section 6 contains results of experiments. Section 7 is devoted to discussion. The conclusions can be found in section 8.

2. Precipitation parameterization in the NCEP MRF model

A rain assimilation procedure depends on the forecast model used for assimilation of the target (observed) rainfall. We assimilated the satellite-retrieved rainfall in the NCEP MRF model (Sela 1980; Kanamitsu et al. 1991; Kalnay et al. 1991, 1996). Large-scale precipitation is parameterized in MRF in a standard way. Layers having a relative humidity in excess of 100% are brought back to the saturated state by an approximate wet-bulb process, with all of the resulting liquid water assumed to go into rain and none into cloud water or ice. If the next lower layer is unsaturated, that layer is moistened and cooled by the evaporation of some or all of the falling rain, also according to a wet-bulb process. An analysis of model integration shows that, at the grid points with significant rainfall, the stratification in the lower troposphere is very close to saturation. We stress that simulated latent heat release leads to an increase in temperature and to a corresponding increase in the humidity. As a result, only some fraction of the initial excess over saturation value transforms to precipitation; the other fraction yields a moisture increase.

To understand what part of water vapor over the saturation level the large-scale parameterization scheme turns into heating (large-scale precipitation) and into moistening (increase humidity), let us assume that we have, before calculating the large-scale precipitation, temperature $T_1$ and specific humidity $q_1 = q_{1w} + \delta q$, where $q_{1w}$ is the saturation specific humidity, and $\delta q$ is specific humidity over the saturation value. After calculating large-scale precipitation, we obtain parameters $T_2$ and $q_{2w}$. The large-scale precipitation parameterization scheme conserves

$$c_pT_1 + Lq_{1w} + L(\delta q) = c_pT_2 + Lq_{2w}.$$ 

It divides humidity over the saturation value into heating and moistening:

$$\delta q_1 = c_p/L(T_2 - T_1)$$

and

$$\delta q_2 = q_{2w} - q_{1w} = \delta q^* \overline{\delta T}_p(T_2 - T_1)$$

so that we need to compare

$$c_p/L \quad \text{and} \quad \delta q^* \overline{\delta T}_p.$$ 

Using the definition

$$q^* = 0.623E/p$$

and the Clausius–Clapeyron equation

$$dE/dT = LE/(R_v T^2)$$

and scaling these conditions for the lower tropical troposphere, we can obtain

$$\overline{\delta q^* \overline{\delta T}}_p = Lq^*/(R_v T^2) \approx 1.2 \, \text{g}_w \, (\text{kg}_w \, \text{K})^{-1}, \quad \text{and} \quad (1)$$

$$c_p/L \approx 0.4 \, \text{g}_w \, (\text{kg}_w \, \text{K})^{-1}. \quad (2)$$

In the above equations, $c_p$ is the specific heat of dry air at constant pressure, $L$ is the latent heat of condensation, $E$ denotes constant pressure, $E$ is saturation vapor pressure, $p$ is atmospheric pressure, $R_v$ is the gas constant for water vapor, and the subscripts w and a on the units indicate water vapor and air, respectively. Comparison of (1) and (2) shows that the large-scale precipitation...
parameterization scheme used in the MRF model turns only about 25% of supersaturation into the large-scale precipitation and 75% goes to increase humidity.

A simplified Arakawa—Schubert (1974) scheme is used in the MRF model for the parameterization of convective precipitation (Grell 1993; Pan and Wu 1994). A single effective cloud with updraft and downdraft branches is used in this version. The quasi-equilibrium closure assumption of Arakawa—Schubert is formulated in the form suggested by Lord (1978), namely, a reference profile (value for one cloud) of the cloud work function is used to define large-scale forcing and to calculate mass flux at the cloud base. All parameters in the cloud (including precipitation) are described through the mass flux at the cloud base.

3. Rainfall retrievals from satellite observations

To estimate tropical rainfall, infrared (IR), Advanced Very High Resolution Radiometer, Special Sensor Microwave/Imager (SSM/I), radar, and rain gauge data have been used. IR data are available from several geostationary satellites that cover a significant part of the tropical belt. Rain gauges are located only over the land areas, islands, and atolls.

The IR data provide only cloud-top temperature information. To estimate rain rate from IR data, Arkin’s (1979) method generally is used. The author made a comparison of 6-h radar rainfall accumulations over the Global Atmospheric Research Program Atlantic Tropical Experiment B array (hexagon with 1.5° sides) and fractional coverage of clouds above various threshold heights, as determined from satellite IR brightness temperature. The maximum correlations were found at 10 km (235 K) for zero time lag. Arkin suggested that the rainfall rate was proportional to fractional coverage of clouds with tops above 10 km. Arkin and Meisner (1987) defined a Geostationary Operational Environmental Satellite Precipitation Index (GPI), which has been used in many studies. GPI was calculated as the product of the mean fractional coverage of cloud colder than 235 K, the length of the averaging period in hours, and a constant of 3 mm h⁻¹.

The clouds with tops over 10 km are either cirrus or very large cumulonimbus with very intense rainfall (Rogers and Yau 1989). The fractional coverage of such cumulonimbus is very small. Thus, in GPI, the rainfall is proportional to the coverage by thick cirrus clouds used as an indicator of cumulus clouds.

The SSM/I microwave measurements give information about liquid water and ice in clouds. Therefore, this instrument could, in principal, give better results than IR does in retrieving rainfall. SSM/I currently is limited to polar-orbiting satellites, however. Any 1° × 1° area is covered by SSM/I data from one satellite less than twice a day. In the Tropics, this area is covered not more than 32 times a month (Berg and Chase 1992). Thus, even the monthly rainfall totals obtained with this platform are subject to large sampling errors. The launch of several polar-orbiting satellites with SSM/I-like radiometers would improve this situation.

Gairola and Krishnamurti (1992) compared maps of rainfall, accumulated for a 24-h mean over a 1° × 1° area, retrieved from SSM/I data with the algorithms by Olson et al. (1990) and estimates obtained from IR data using Arkin’s (1979) procedure. It is interesting that these two satellite approaches give very different descriptions of synoptic processes. The sizes of the rain patterns retrieved from SSM/I data are a factor of 10 less than the sizes of the patterns retrieved from IR data, and the locations of these patterns do not coincide over a significant number of grid points. Over the tropical belt, instantaneous SSM/I rainfall was used as the 24-h mean (there was only one observation per day over each 1° × 1° area). The instantaneous rainfall differs very much from the 24-h mean and can be used as not more than the 3-h mean. GPI overestimates areas of heavy rainfall, which has resulted in attempts to correct GPI data (Morrissey and Greene 1993; Heckley et al. 1990; Kasahara et al. 1994).

In the current study, we use GPI to verify our rainfall assimilation procedure. There are several reasons for this choice. GPI data were used in nearly all rainfall assimilation studies mentioned in this paper. GPI rain estimates are produced operationally at NCEP every half hour on a 0.5° × 0.5° grid over a considerable portion of the tropical belt. To obtain these data, brightness temperatures from 4 km pixels are used. At the time of this study, GPI data were the only operationally available product with near-global coverage and good space–time resolution. For verification of a rain assimilation procedure, it is not very important what kind of satellite data are used, provided that the data yield reasonable rainfall estimates and cover large portions of the tropical belt. GPI meets these criteria but can create anomalously large areas of heavy rainfall. It is more difficult to assimilate closely such large area rainfall in a model. We use data for August of 1994, a period for which GPI data covered the whole tropical belt with large and small areas of heavy, moderate, and light rainfall. Thus GPI data provide an opportunity to verify a rain assimilation procedure not only in the very difficult conditions of large areas of heavy rainfall but in a variety of rain events.

4. The rain assimilation method

Significant precipitation averaged over an area of 1° × 1° (the resolution of the NCEP global model used in the study) usually is connected with tropical disturbances (cloud clusters). Observations show that large-scale vertical motions have a high correlation with precipitation in the Tropics, because a tropical disturbance is characterized mainly by large-scale updrafts, with convergence in the lower troposphere and divergence in the upper troposphere (Falkovich 1979).
The main idea of the method is to adjust the model humidity field by assimilation of satellite-retrieved (observed) precipitation. The choice of the humidity as the field to adjust is based on the following.

1) There is a high correlation between the mean tropospheric mixing ratio and convective activity accompanied by heavy rain (e.g., Ruprecht and Gray 1974; Falkovich 1979). The high correlation can be attributed to the convectively induced moisture flux from the atmospheric boundary layer to the middle and upper troposphere and evaporation of precipitate particles. In turn, high values of mixing ratio preserve convective clouds from dilution with the environment and favor the development of high convective towers.

2) Both convective and large-scale model precipitation are very sensitive to ambient humidity (Khain 1984; Kurihara and Tuleya 1981).

3) Values of humidity are poorly known in the Tropics, and errors in model humidity (and precipitation) in the Tropics are large. These facts offer a strong reason to utilize satellite precipitation in prognostic models. Variability in space and time of the humidity in the Tropics is noticeable (Ruprecht and Gray 1974; Falkovich 1979). Ruprecht and Gray (1974) showed that, in cloud clusters, relative humidity in the middle troposphere was 30%–40% higher than in surrounding areas. It allows utilization of large variations of the humidity as a proxy for rain assimilation.

4) The utilization of air moisture variations as the proxy for rain assimilation purposes has some advantages over the utilization of temperature variations. The variation of the moisture leads to changes of temperature in a gradual manner via the model precipitation scheme. Thus, possible model shocks induced by temperature jumps are eliminated in this case. Note in this connection that changes of temperature in tropical disturbances are very small, so that moist static energy (total enthalpy) changes are caused primarily by variations of moisture. This effect is partially taken into account by the large-scale precipitation parameterization, as discussed above [see (1) and (2)].

From this brief discussion, we now can formulate the algorithm for our precipitation assimilation procedure. Humidity adjustment in the lower layer of the troposphere is accomplished according the following rules: if \((r_{sat} > r_{mod})\) then

\[
q_{new}(k) = q^*(k) + c(t, k)(r_{sat} - r_{mod}), \; \text{ else}
\]

if \((r_{sat} < r_{mod})\) then

\[
q_{new}(k) = q(k) + d(t, k)[q(k) - q_{ref}(k)]
\]

\[
	imes (r_{sat} - r_{mod}), \; \text{ and}
\]

\[
q_{new}(k) \geq q_{ref}(k).
\]

Here \(r_{sat}\) is the mean satellite rain rate over 6 h, \(r_{mod}\) is the mean total model rain rate over the time from \(t = 0\) up to a current step, \(q_{ref}\) is a reference profile of specific humidity, \(k\) is a sigma level, \(t\) is a discrete time during the integration, and \(c(t, k)\) and \(d(t, k)\) are parameters of the nudging procedure.

Some comments about this algorithm follow. Where the total model rainfall accumulated up to a current time step is less than the target, we assume that after the calculation of large-scale advection there is not enough water vapor over the saturation level to match the model rainfall with the target. Then we increase the specific humidity over the saturation level in proportion to the difference between the target and model rain rate. We do this before calculating the large-scale rainfall parameterization, which turns about 25% of the supersaturation water vapor into heating (creating large-scale precipitation) and the larger portion (75%) into increasing the humidity (see section 2). In the following time step, the model convective precipitation scheme redistributes heat and moisture in the vertical and creates convective precipitation from nearly all the 75% portion of initial supersaturation. To excite the convection, we change humidity only in the lower layer of the troposphere and make the depth of this layer proportional to the target rain rate. Thus, we achieve our goal to increase precipitation without explicitly changing the temperature and wind fields.

Where total model rainfall accumulated up to a current time step exceeds the target, we decrease the humidity in proportion to the difference between the target and model rainfall and also in proportion to the difference between the current and reference profiles of specific humidity. We also make sure the result is not smaller than a reference profile of specific humidity. A specific humidity reference profile is used so that we do not decrease humidity to lower than reasonable values. We chose this profile to be typical of conditions in downdraft areas over the tropical oceans. We decrease the humidity before calculating convective precipitation. We assume that the depth of the layer where humidity is changed is proportional to the intensity of the target precipitation.

We do not adjust the rain rate all in one time step but rather do it gradually through the process of nudging. At each grid point, the model rain rate can change considerably from one time step to another. For example, there may be model grid points with heavy mean 6-h rainfall but zero rainfall during the first several hours of the integration. A nudging procedure that forces instantaneous adjustment to the target rainfall can shock the model. The parameters in the nudging scheme depend on time. They increase from small values at the beginning of nudging, when the accumulated rain rate differs very little from the instantaneous rate, up to \(t = 3\) h and do not change to the end of nudging.

To determine the nudging parameters and the depth of the layers where the humidity is changed, we imposed
the conditions of convergence and other criteria described in the next section.

We find that our rain assimilation procedure has advantages over the reverse scheme. For instance, it can assimilate precipitation freely in the case of high cloud coverage, as well as in the case when precipitation is not purely convective. The scheme does not demand the existence of convective instability in the area of the target precipitation. It is not limited by constraints on the mass flux at the cloud base, and so on. Thus, the proposed algorithm allows one to assimilate the target precipitation over a wide range of situations in which utilization of the reverse scheme would lead to large differences between the target and model rainfall.

Our procedure differs from Treadon’s (1996). He relied on the assumption that the total precipitable water retrieved from SSM/I data (these retrievals were used operationally at NCEP when he accomplished his work) put the proper amount of water vapor in the column. In his approach, the model moisture is redistributed in the vertical, and the vertically integrated moisture is conserved. Although this is a good idea, SSM/I observations cover any 1° × 1° area only once per day, and this lack of coverage weakens his initial assumption. The total precipitable water retrievals currently are not used operationally at NCEP. Our scheme does not conserve the vertically integrated moisture, because, in general, if we have large moisture errors in the initial data, we also will have large errors in the vertically integrated moisture. In the future, if we have eight satellites with the SSM/I instrument, this idea will be very useful, however. We adjust the total rain and allow humidity to reach supersaturation. We do not adjust instantaneous rain at the current time step but rather adjust the rain accumulated up to the current time step. We use our procedure only to stimulate convection to increase or decrease the rain rate and do not try to obtain an exact value at the current moment. This requirement would be difficult, because the convection scheme has constraints. We choose the layer in which we change humidity to be proportional to the target rain intensity, and it does not depend on initial conditions of convection.

In the next section, a test of the algorithm verification is proposed. We determine the nudging parameters from the conditions that the procedure must converge and meet certain criteria.

5. Verification criteria and a test for verification of a rain assimilation procedure

Instantaneous rainfall observations (direct and indirect) have errors and gaps. The quality of observations also depends on the interval between observations. To decrease the influence of observation and sampling errors, it is common to use precipitation accumulated over a period as a mean constant rain rate over this period. The longer this period and the shorter the interval between observations, the smaller will be the influence of observational and sampling errors, but this period cannot differ too much from the scales represented in the model. The higher the model resolution, the shorter the period of rain accumulation. For a global model with a horizontal resolution of T126, accumulations of no more than 6 h are appropriate; for a mesoscale model, a shorter period of 1–2 h would be appropriate.

Our goal is to assimilate tropical precipitation data into the analysis–forecast system. We use a version of the NCEP T126 GDAS. Observations are inserted into the system every 6 h during the analysis step, which optimally blends observations with a 6-h forecast (first guess) from the previous analysis (Parrish and Derber 1992; Derber et al. 1991). Precipitation in the model is accumulated during each 6-h interval. Extended-range forecasts are performed at 0000 and 1200 UTC with two successive GDAS cycles (first guess and analysis) between them.

To ensure that the nudging procedure is adjusted properly to the model, we suggest using the following test. Let us assume that a forecast model describes exactly the atmospheric processes and gives exact information about rainfall and other fields. We take the rainfall accumulated during the 6-h model integration without rain assimilation [“control” (C) experiment] as the “quasi-target” rainfall and repeat the integration with nudging to this 6-h constant target rain rate [“simulated-nudge” (S) experiment]. Differences between these two runs will characterize the difference between a time-dependent, model-determined, latent heating and one that is nearly constant over 6 h at every grid point where rain occurs. In this test, a rain assimilation procedure can only deteriorate the forecast fields. If it recovers the target precipitation well but changes the forecast fields significantly at the end of 6-h nudging in the S experiment in comparison with a 6-h first guess in the C experiment, this procedure is not acceptable. In our tests, we define the control run C as a 6-h first-guess run without rain assimilation, and a simulated-nudge experiment S is defined as a run with nudging using the accumulated 6-h rainfall from C as the target, as described above. We also need to be sure that the differences between the forecast fields in these two runs are small at the end of a 24-h straight (without nudging) forecast, after two successive GDAS cycles (6-h first guess and analysis in the C experiment and 6-h nudging and analysis in the S experiment).

Thus, we use the following criteria to evaluate the quality of our rain assimilation procedure:

1) the rain assimilation procedure should be able to adjust the model rainfall accumulated for 6 h closely to the average 6-h satellite-retrieved (observed) rainfall, and
2) there should be only small deviations of the forecast fields in “assimilation” run S from those in control run C.

If there are several nudging procedures, all of which
can adjust the model rainfall to the “observed” satellite rain with prescribed accuracy, we choose the one that minimizes the distance between the forecast fields from C and S. This minimum distance depends on the model and the period of rainfall accumulation.

We note that the test proposed is an effective tool for verification of any assimilation procedure, independent of the type of assimilation scheme and numerical model used. It is evident that, if we increase the period of rainfall accumulation very much, a nudging procedure cannot meet the criteria of this test. Thus, this test also checks the proper choice of the period of rainfall accumulation.

To verify the rain assimilation procedure, the following experiments were performed:
1) control (C)—without rain assimilation,
2) simulated nudge (S)—nudging to the mean 6-h accumulated rainfall from the control experiment, and
3) satellite nudge (O)—nudging to the mean 6-h accumulated satellite-retrieved (observed) rainfall.

Each experiment consisted of two 6-h GDAS cycles and a 24-h forecast after the last GDAS cycle. Nudging was applied over the tropical belt, from 30°N to 30°S, during the two 6-h forecasts linking successive GDAS analyses. Nudging was not used during the first 0.5 h in each 6-h forecast because of spinup in the model rainfall during the first steps of the integration, nor was it used during the last hour of integration, when the model was allowed to “relax” after the nudging.

6. Results of verification

Figure 1 shows that the number of grid points in the Tropics for which the absolute value of the difference between the model and target rain rate is more than 4 mm (6 h)$^{-1}$ gradually decreases with time to very small values for the S and O experiments. This result means that the initial imbalance between the target and model rainfall decreases rapidly during the nudging, and the nudging procedure converges well, within about 4–5 h.

We are not aware of any previous demonstration of convergence of a nudging procedure. To find parameters of the nudging procedure for increasing and decreasing the model rainfall, we analyzed convergence for the difference between the target and model rain rates, more than 1 mm (6 h)$^{-1}$ or less than −1 mm (6 h)$^{-1}$. The number of points with these differences also decreased rapidly to some limiting values that were significantly less than the initial imbalance but more than zero. Because satellite data have errors, model precipitation was increased only at the grid points for which the satellite
(target) rainfall was more than 4 mm (6 h)\(^{-1}\). Besides that, the difference of 1 mm (6 h)\(^{-1}\) is very small to decrease the number of those points to zero. We speculate that these limiting values depend on the resolution of the model and the parameterizations used in it. For each model, there is some level of limiting values that no single nudging scheme can decrease. It is interesting that the rate of convergence of the nudging is similar for both the simulated (S) and the real satellite “observations” (O).

We performed the same experiments for other dates in August of 1994 for which we had operational information from four geostationary satellites, which covered the whole tropical belt, and in every case obtained the same qualitative results. After we adjusted the nudging procedure for optimum performance, the accuracy of rain assimilation and convergence of the nudging procedure changed very little from one date to another.

As the nudging procedure converges, it has to simulate the model rainfall very close to the target. Figure 2 shows maps of satellite rainfall accumulated for (a) 6 h, and (b) that resulting from nudging to these data (O experiment). As the target, we used GPI data (see section 3). We found that the nudging procedure adjusted the model precipitation to the satellite observations exceedingly well. The difference in rain rate between (a) and (b) is more than 2 mm (6 h)\(^{-1}\) only at grid points for which there was no information from satellites. At these points, the satellite-derived rain rate is zero. Nudging was not applied at these points, and so precipitation developed freely and could differ significantly from zero. If a nudging procedure is satisfactory, it has to create strong large-scale updrafts in the areas of heavy rainfall. Figure 3 shows the meridional circulation along 70°E. The nudging procedure changed dramatically the distribution of vertical velocity in the O experiment in comparison with that of C. It created very strong updrafts in nearly all areas of heavy rainfall. This fact demonstrates that the nudging procedure creates a disturbance with strong large-scale updrafts in the area of heavy rainfall.

We determined the nudging parameters such that the procedure converged and, as a consequence, simulated the target (observed) rainfall very closely. This criterion alone is insufficient for improving the analysis, however. We need to find nudging parameters such that the procedure can also meet the criteria of section 5. Let us compare results of the C and S experiments. Figures 4a,b demonstrate that the nudging procedure successfully produces the target simulated precipitation for amounts exceeding 4 mm (6 h)\(^{-1}\). Figures 4c,d show the same as Figs. 4a,b but at the end of 24-h forecasts from 1200 UTC after two successive 6-h first guesses and nudging. We see that the position and intensity of rain patterns did not change significantly in the S experiment with respect to those of C after the 24-h forecast. Such quality of precipitation adjustment is present over the whole tropical belt. We analyzed the same maps for the model large-scale and convective rain (not shown). These maps indicate that the nudging procedure slightly decreases the model large-scale precipitation and slightly increases convective rain in the S experiment in comparison with those of C but that the total precipitation in the S experiment is reproduced very closely to that of C. We also calculated the mean (over the tropical belt) large-scale, and convective rainfall (not shown) and obtained the same result.

For purposes of more detailed analysis, we chose a small area in which there are several centers of heavy rainfall, with large gradients of rain rate, in the C experiment. The vertical cross section through the precipitation center at the end of the nudging period (Fig. 5) indicates that the nudging procedure in the S experiment simulates the structure of the vertical velocity very closely to that in C.

In the proposed nudging procedure, we had to increase the humidity in order to increase precipitation and vice versa. But this increase does not lead to significant changes in precipitable water and humidity in the S experiment as compared with C. Figure 6 shows the precipitable water distribution over the same small area at the end of 6 h of nudging. The vertical cross section of relative humidity and meridional circulation through these centers (not shown) indicates that the maxima of humidity, after nudging, became only slightly smaller and meridional circulation changes were very small in the S experiment in comparison with those in C. The same is true for changes in temperature.

To find the best distribution for the vertical structure of imposed moistening and drying, we made many sensitivity experiments in which we changed parameters in the rain assimilation procedure. We found several sets of parameters that produced very well the target rainfall in both the O and S experiments. The procedure converged in both cases, but the forecast fields deteriorated significantly in the S experiment in comparison with C. After nudging, the fields of relative humidity, precipitable water, and, especially vertical velocity in the S experiment, differed much from the same fields in C. For example, when we moistened the middle and upper layers, the target rainfall was simulated very closely, but there were very strong updrafts in the upper troposphere in the S experiment, and vertical velocity in the S experiment differed strongly from that in C. Gradually, we changed the vertical structure of the imposed moistening and made many experiments before we were able to create a nudging scheme that did not cause the vertical velocity in the S experiment to deteriorate strongly in comparison with that of C. The results of these experiments showed that, if the structure of vertical velocity is close to each other in S and C in strong disturbances as in Fig. 5, all other fields in S do not deviate significantly from those in C.

In the C experiment, all fields are changed at each time step according to the equations of the forecast model. In the nudging experiment, changes occur from both
FIG. 2. Total mean rain rate [mm (6 h)$^{-1}$] over one-quarter of the tropical belt from 60° to 150°E from 0600 to 1200 UTC 4 Aug 1994 (a) retrieved from OLR satellite data with Arkin's scheme and (b) obtained in nudging to satellite rainfall (satellite nudge). Light hatched area corresponds to rain rates less than 5 mm (6 h)$^{-1}$; interval between isolines—5 mm (6 h)$^{-1}$.

nudging and the forecast. When, at the end of the S experiment, the forecast fields are close to those in C, it means that integrated changes in time for both experiments are close to each other. The nudging scheme simply redistributes changes in time and makes the integrated changes at each grid point from nudging and forecast in the S experiment close to the integrated changes from forecast in the C experiment. The changes at each time step from nudging are not necessarily small in the S experiment.

More definite conclusions about the quality of the rain assimilation scheme can be deduced from the results of a prognostic part of the experiments, when the nudging was switched off. According to our results, the vertical velocity field in the S experiment does not deviate significantly at the end of the 24-h forecast from that in
the C experiment. Figure 3 shows the vertical cross sections of vertical velocity through the same center as in Fig. 5, which moved from 111°W to 108°W for the 24-h forecast. Differences between the fields in the C and S experiments after 24 h of free forecast are not much more than after 6-h nudging.

These results show that the rain assimilation procedure did not much change fields of humidity, temperature, or even vertical velocity to the end of nudging and to the end of the 24-h forecast, after two successive 6-h nudgings in the S experiment in comparison with C. This result is the one for which we were hoping. It means that the nudging procedure meets the criteria of the test of section 5, and the choice of the period of rainfall accumulation (6 h) is appropriate (see section 5).

Thus, we found parameters of the rain assimilation procedure such that this procedure converged and, as a consequence of the convergence, simulated the target satellite-retrieved rainfall very closely, creating strong large-scale updraft in the areas of heavy target precipitation. In addition, when we sought these parameters, we adjusted the procedure to the model to such degree that it met the criteria of the test in section 5.
The same qualitative results were obtained for other dates. We therefore can conclude that this rain assimilation procedure for the NCEP MRF model, with the 6-h period of accumulation precipitation, is a viable solution to the rain assimilation goal cited at the beginning of this paper.

7. Discussion

In the previous section, we showed that the rain assimilation method introduced in this paper succeeds in making the total model rainfall nearly equal to the satellite-retrieved rainfall. This method produces an insignificant deterioration of the forecast fields in the S experiment when compared with C. Satisfaction of these criteria was the goal of this paper. The next task is to understand what rainfall data and retrieval methods are available, what the accuracy of these methods is, and whether it is possible to use them to improve short-range forecasts markedly. This task will be the subject of future work. Here we make only some comments.

Let us compare Figs. 2a and 4a. The characters of the precipitation retrieved from satellites and that calculated during the integration of the model are very different. The same nudging procedure adjusts very closely to both distributions of rainfall (experiments O and S). Comparison of Figs. 4a and 2b indicates that the nudging procedure dramatically changed the rainfall distribution to simulate the target satellite-retrieved rain rate. The area of light rain after nudging (Fig. 2b) is even larger than on the satellite map (Fig. 2a) though we did not increase rainfall if the satellite rain rate was less than 4 mm (6 h)^{-1}. Figure 4 shows the same for the C and S experiments. The area of light rainfall did not decrease in Fig. 4b in comparison with that in Fig. 4a. This result means that the model overestimates slightly the area of light rain. GPI rainfall data, on the other hand, significantly overestimate the area of heavy rain (see section 3). The areas of heavy rainfall are unrealistically large on the satellite maps. Such large areas of heavy rainfall are not observed in nature or in the model integration. We analyzed each 6-h map of GPI retrieved rainfall during August of 1994 when four geostationary satellites covered the whole tropical belt. There were very large areas of heavy rainfall over the Indian Ocean every day. These areas were unrealistically large and persisted for several days. In other regions in August, such areas also were observed, but not so often. Let us compare a rain rate in these areas with the composite tropical cyclone (TC) rain rate. According to Frank (1977), the composite TC in the ring from 2° to 4° from the center has rain rate about 8–11 mm (6 h)^{-1}. Over the circle with radius 2° from the center, the composite TC has rain rate about 20–25 mm (6 h)^{-1}. Comparison showed that, in the ring from 2° to 4° from the center of large areas of heavy rainfall on the satellite maps, rain rate is more than in a tropical cyclone. In the center of these areas, rain rate was usually 18 mm (6 h)^{-1} (maximum value for GPI-retrieved rain rate). In strong disturbances of the ITCZ (Falkovich 1979), mean rate over A/B area (six ships formed a hexagon with 3.5° to a side, and one worked in the center at 8.5°N, 23.5°W) is about 7 mm (6 h)^{-1}. In the ring from 2° to 4° from the center of such a disturbance, rain rate is significantly less than the mean value. We see five large areas of heavy rainfall in Fig. 2a, and only one of these areas was occupied by TC Doug, with the center at 15.0°N, 133.9°E at 1200 UTC. It is evident that large areas covered by thick cirrus were taken to be areas of heavy rainfall. Comparison of Figs. 2a and 8a shows that the large areas of heavy rainfall persisted during a day. They changed their forms and positions but again are unrealistically large.

On the model rain maps, the heavy rain, with intensity more than 10 mm (6 h)^{-1} (Figs. 4a,c), occupies a much smaller area (the circle with the radius of about 1°) than on the satellite maps (Figs. 2a, 8a). on which such an area can have a radius several times larger.

Analysis of the model integration shows that the stratification is very close to saturation at the low levels in the areas of heavy rainfall. When we simulate heavy rainfall over a very large area, we create initial conditions for a forecast with a large area of convective instability. Such initial conditions are unstable. Indeed, Figs. 8a,b compare the 6-h accumulated rainfall obtained from GPI data with the total 6-h accumulated rainfall in the O experiment, after a 24-h forecast started at the end of the two 6-h nudgings to satellite-retrieved GPI data (from initial conditions of Fig. 2b). During the 24-h forecast, the areas of heavy rainfall (Fig. 2b) decreased their sizes to the sizes normal for the model. The large area of heavy rainfall near 70°E collapsed, and two short-lived smaller-scale disturbances with very strong rain rate developed there. This result indicates the danger for rainfall assimilation in using unrealistically large areas of heavy rainfall derived from satellite-retrieved data. Assimilation of such precipitation can deteriorate the forecast. These results show the sensitivity of forecast fields to quality of rainfall data. To improve initial fields for a forecast with a rain assimilation procedure, we need to improve significantly the quality of satellite-retrieved rainfall.

In this study, we did not attempt to correct satellite-retrieved rainfall or create a more sophisticated method of rainfall retrievals. This effort will be the subject of a future study. Here we want to stress only that our procedure differs from the others, mainly in that it simulates the total model rainfall very closely to the target satellite-retrieved rainfall.

In this study, we used 6-h accumulated precipitation. Heckley et al. (1990) used the coverage of the High-Resolution Infrared Sounder data from only within 3 h from 1200 UTC with weights, which were progressively reduced according to the degree of asymptoticity of the data. We believe that for improving a short-range forecast it is better to use an accumulation period that is
much shorter than 24 h, because, over 24 h, the area of precipitation can become very large, and it is possible to lose the details of smaller-scale phenomena described by the model. For example, it would be difficult to define properly the positions of troughs in easterly waves with which tropical disturbances usually are connected. Easterly waves move to the west with a mean velocity about $6^\circ$ day$^{-1}$, and their typical length is 2000 km (Falkovich 1979). The 24-h-averaged rain area for them can be larger than 1000 km. Thus, taking into account that the spatial scales of the precipitation fields are comparably small, the nudging to the mean 24-h rainfall would lead to undesirable smoothing of model fields. It would lead to significant deviations of prognostic fields in the S experiment from those in C. The utilization of a 6-h accumulation period turns out to be more suitable for this goal.

To estimate the skill of precipitation forecasts with the MRF model for North America (Pan and Wu 1994), 12–36-h accumulated model rainfall was compared...
with rain gauge observations over each $1^\circ \times 1^\circ$ area provided by the National Oceanic and Atmospheric Administration River Forecast Centers' large rain gauge network over the United States. The equitable threat score (Gandin and Murphy 1992) for different intensities of rainfall for the MRF model decreases—as shown by Pan and Wu (1994)—from 0.35–0.4 for very low rain rate to 0.25–0.3 for rain rate of 4 mm $(6\text{ h})^{-1}$ and to 0.1–0.2 for rain rate of 6 mm $(6\text{ h})^{-1}$ and becomes very small for heavy rain. For a very good forecast, the threat score is close to 1, and, for a very bad forecast, it is close to 0. Thus the predictability for a light rain is not bad but is poor for a heavy rain. This low predictability for a heavy rain is caused partly by errors in initial data (only these errors can be decreased with a rain assimilation procedure) and partly by imperfections in the model (not enough resolution, imperfect parameterizations of subgrid-scale processes, and, especially, parameterization of precipitation). In the nudging procedure, we do not change anything in the model and adjust rainfall with the same imperfect parameterizations. Thus the improvement of
heavy-rain forecasts depends also on improvement in the model parameterizations.

8. Summary and conclusions

Because of the scarcity of observations over tropical oceans, we should try to use all pertinent available data for improving initial fields in forecast models. It will be very important to assimilate satellite-retrieved rainfall, especially from geostationary satellites that cover significant portions of the tropical belt. Achieving this goal requires solving two problems. The first problem is to retrieve rainfall from satellite data with sufficient accuracy to improve the initial fields. The second problem is to assimilate the retrieved rainfall in such a way that the model can reproduce precipitation close to that observed.

In this work we reported results only for the second problem. A nudging procedure that adjusts the model rainfall very closely to the target satellite-retrieved rainfall was developed. The procedure consists of a 6-h integration of the numerical model, with changes to humidity at every time step (nudging) at each grid point, in such a way that the total model precipitation accu-
mulated during the 6-h becomes very close to that observed. Increasing model precipitation at a grid point is achieved by moistening the troposphere column with a prescribed supersaturation proportional to a difference between the model and target precipitation. The depth of the column in which humidity is changed is made proportional to the target precipitation. Decreasing model precipitation is done by decreasing humidity proportionally to the difference between the model and target precipitation. The depth of the column is again made proportional to the target rain rate.

We first showed that this nudging procedure converges, simulating observed precipitation very closely, and leads to creation of large-scale updrafts in the area.
of observed heavy precipitation. The nudging procedure was tested and adjusted to the NCEP global model by using the model accumulated rainfall. Taking rainfall accumulated during a 6-h period of the model integration without nudging (control experiment) as the simulated target rainfall, the integration was repeated with nudging to this 6-h mean simulated rainfall. A comparison of the control and simulated nudge experiments showed that, as desired, the rain assimilation procedure was able not only to reproduce the accumulated rain but also to reproduce other fields such as vertical velocity, temperature, and so on, in the assimilation experiment very close to those of the control. The results show that the nudging procedure proposed in this work solved the problem of reproducing satellite-retrieved (observed) rain. This condition is necessary to ensure that nudging to satellite-retrieved precipitation will improve the initial conditions.

We showed that the characters of rainfall fields retrieved from IR satellite data (the GPI) and those calculated in the model without nudging are very different. The model overestimates slightly the area of light rain, and GPI significantly overestimates areas of heavy rainfall. The simulation of such areas of heavy precipitation

Fig. 7. As in Fig. 5 but along 108°W, 5°N lat is on the left; 20°N is on the right, at 1200 UTC 5 Aug 1994, after 24-h forecast.
in the model creates large areas of convective instability in initial data and can lead to deterioration of a forecast. Thus, the problem of realistic rain retrieval awaits solution. We did not attempt to correct satellite-retrieved rainfall or create a new method of rainfall retrievals in this work. Future study will be devoted to this problem.

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