The Use of Infrared Satellite Cloud Imagery Data as Proxy Data for Moisture and Diabatic Heating in Data Assimilation

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ABSTRACT

Geostationary and polar-orbiting satellites can provide useful proxy sources of moisture data and diabatic heating. It is shown that the use of this information during data assimilation leads to improved precipitation in the tropics and has the potential to minimize spinup in the model. Furthermore, the use of moisture initialization leads to improved agreement between the model and observed precipitation during the early stages of model integration.

1. Introduction

Diabatic processes play a major role in determining the circulation in the tropics. Current numerical prediction models have problems in adequately handling these processes for a number of reasons. These include sparsity of data, deficiencies in the parameterization of physical processes (particularly cumulus convection), failure of analysis schemes to include information on diabatic heating, and the inability to provide initial fields that are dynamically consistent and sensitive to regions of heating and cooling. These factors lead to poor model performance in the tropics. More specifically, they lead to model spinup where the precipitation and evaporation take one to two days to reach equilibrium values (e.g., Tiedtke et al. 1988).

One of the reasons for the poor representation of tropical diabatic forcing is sparsity of moisture data. Geostationary satellites such as the Japanese Geostationary Meteorological Satellite (GMS) provide useful proxy sources of moisture data. For example, the Japan Meteorological Agency (JMA) operationally derives moisture data from the GMS satellite based on collocations between radiosondes and satellite radiances (see Baba 1987), and the use of this data has been shown to be beneficial to model performance in the tropics. Procedures similar to those used at JMA have also been developed at the Bureau of Meteorology Research Centre (BMRC) by Mills and Davidson (1987) who have shown the impact of this data in a limited-area model covering the Australian region.

One aspect of spinup in the tropics is the lack of consistency in the initial fields between the divergent circulation, diabatic heating, and the moisture field. Although it is possible to define a balanced divergence field that is consistent with the diabatic heating using diabatic normal-mode initialization (NMI) (see Wergen 1987), the balance will be rapidly lost if the moisture field is not consistent with the diabatic forcing (Puri 1987). One way of overcoming this problem is to adjust the initial moisture field so that the precipitation (or latent heating) in the early stages of the model integration is consistent with the heating rates used during diabatic normal-mode initialization. Moisture initialization, which is also referred to as physical initialization, was introduced by Krishnamurti et al. (1984) and has also been used by Donner (1988) and Puri and Miller (1990). In this scheme the initial moisture field is adjusted so that the rainfall rate in the early stages of the model integration is close to the observed rate.

In this paper the impact of the satellite-based moisture bogus data, diabatic heating, and moisture initialization in the BMRC global data-assimilation system is presented. Puri (1987) and Kasahara et al. (1988) carried out preliminary studies to use satellite data in numerical models for diabatic NMI and as a means of improving the divergent wind analysis in tropics. As was noted earlier in this section, the pioneering work on moisture initialization was carried out by the Florida State University (Tallahassee) group headed by Krishnamurti, who showed that it could have positive impact on simulating aspects of the Indian summer monsoon. Donner and Rasch (1989) performed a number of experiments with a global spectral model with synthetic diagnosed distributions of latent heat release and divergence obtained by integrating the

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model for three days prior to the initialization time of an experimental forecast. They showed that physical initialization of Donner (1988) can recover initial distributions of latent heating reasonably well but that a further spinup (overshooting) still occurs. Turpeinen et al. (1990), in an attempt to alleviate the spinup problem in the Canadian regional finite-element model, used latent heating profiles directly in the model. The estimates of heating rates were based on precipitation rates inferred from Geostationary Operational Environmental Satellite (GOES) and infrared and visible imagery. They also enhanced the relative humidity fields to 95% wherever the probability of precipitation was larger than 40%. They showed that for the case of an extratropical storm the spinup time of vertical motion, initially of order of 9 h, could be practically eliminated, although some short-lived spinup still occurred. Turpeinen (1990) further studied the dependence of spinup time on the initial humidity field, the vertical structure of the latent heating profile, and the precipitation rates used in initialization. His results indicate that diabatic initialization alone does not lead to any reduction in spinup if no humidity enhancement is applied where latent heat is released. Furthermore, he found that the results were not very sensitive to the accuracy of the specified rain rates, although the identification of rain areas is important.

Puri and Miller (1990) applied the procedure of diabatic initialization using heating rates estimated from satellite-derived rainfall rates in the European Centre for Medium-Range Weather Forecasts (ECMWF) data-assimilation system. They also developed a moisture initialization scheme. In the current study the work of Puri and Miller (1990) has been extended by (a) using bogus moisture data, (b) implementing the moisture initialization scheme within a data-assimilation system, and (c) applying the procedures in conditions as close as possible to real-time applications with the objective of real-time implementation. The procedures are only applied to the tropics, and this together with the use of bogus moisture data and the use of date assimilation distinguishes this study from that of Turpeinen et al. (1990).

A brief description of the assimilation system, der-
Fig. 1b. As in Fig. 1a but for 1100 UTC 15 January 1990.

Fig. 2. GMS-based bogus observations together with conventional observations for mixing ratio (g kg$^{-1}$) at 850 hPa for 1100 UTC 14 January 1990.

Fig. 3. An example of derived rainfall rate (mm day$^{-1}$) from GMS imagery for 1100 UTC 14 January 1990. Contour interval is 10 mm day$^{-1}$. 
ivation of the bogus moisture and heating rates, and moisture initialization is given in section 2. Results are presented in section 3, followed by conclusions in section 4.

2. Description of components of the experimental system

a. BMRC data-assimilation system

The BMRC Global Assimilation Prediction (GASP) System has been used operationally by the Australian Bureau of Meteorology since September 1990, although it has been used in the research mode for a number of years. A detailed description of the system has been given by Bourke et al. (1990). The prediction model is a global spectral model that has nine sigma levels in the vertical and is truncated at wavenumber 31 (homboidal truncation), which is approximately equivalent to a 350-km grid resolution. The physical processes include the constant flux layer that is parameterized by using the Monin–Obukhov formulation in which the drag coefficients are a function of stability near the surface. The vertical eddy transports in the free atmosphere are parameterized using the mixing-length formulation in which the mixing lengths are stability dependent. The model can be run with the Kuo cumulus convection parameterization (Kuo 1974), the
Betts–Miller convection scheme (Betts and Miller 1986), or the convective adjustment scheme of Manabe et al. (1965). In the current study the Kuo parameterization was used, although a limited number of experiments were performed with the Betts–Miller scheme. Large-scale condensation is applied if the relative humidity exceeds a specified threshold and a separate shallow convection scheme (Tiedtke 1987) is used to simulate transport of heat and moisture by low-level nonprecipitating clouds. Linear second-order horizontal diffusion is applied to all model variables (except log surface pressure). Ground hydrology and heat conduction through the soil are also included. The Fels–Schwarzkopf scheme (Fels and Schwarzkopf 1975, 1981) is used to parameterize radiative transfer. Cloud amounts and heights used in the experiments described here are fixed zonal averages for each season using the climatology of London (1957), although the current operational model includes a diagnostic cloud scheme.

b. Generation of bogus moisture data from GMS infrared imagery

The generation of bogus moisture data and its impact on forecasts in a regional model are described in Mills
Fig. 5. (a) (left panels) Accumulated precipitation (mm) during data assimilation from 1100 UTC 14 January to 1100 UTC 15 January 1990 from CNTL (top) and GMSQ (bottom) experiments. Contours shown are 10, 20, 40, 60, 80, . . . mm day$^{-1}$, (b) (right panels) As in (a) but for GMS1 (top) and GMSH (bottom).

and Davidson (1987). The method involves diagnosing cloud characteristics (amount, height, and standard deviation of cloud-top temperature over a 50-km-radius circle) for a specified latitude–longitude grid and then assigning a dewpoint depression profile corresponding to the diagnosed clouds. The dewpoint depression profiles have been previously derived from a large data sample by matching collocated moisture soundings and satellite cloud data. The matchup gives dewpoint depression profiles for 19 groups, namely, clear and broken clouds below 850 hPa, scattered clouds below 850 hPa, and two cloud types and amounts for four higher layers. The profiles compare reasonably well with their equivalents in the JMA system (Baba 1987). The main difference is in the layer below 850 hPa where dewpoint depressions from the JMA system are around 2°C less (more moist) than those from the BMRC system. A typical coverage of the bogus moisture observations at 850 hPa corresponding to the satellite imagery in Fig. 1 (1100 UTC 14 January 1990) is shown in Fig. 2, together with the more conventional satellite and radiosonde observations. Note that the coverage does not coincide with the full-disc satellite imagery because of some limitations in the procedure used at the time of this study: these limitations have now been overcome to generate data over the full disc. Further-
more, the bogus data is not used over land. The developmental dataset on which the statistics were based was biased toward stations with a maritime climate. Thus, the profiles cannot adequately represent the low-level dryness found over the inland of large continents.

c. Estimation of heating rates

Puri and Miller (1990) have proposed two procedures for estimating heating rates. Both rely on first obtaining estimates of rainfall rate $R$, which is essentially a measure of the vertically integrated heating rate at a particular location. In the first method the vertical profile is specified based on observations of typical profiles in convective situations, and the intensity can then be readily evaluated. The use of the same specified vertical profile of heating throughout a particular domain is unsatisfactory, however, because 1) observational evidence indicates that profiles can vary with location, 2) profiles can vary according to the stage in the life cycle of a convective system, and 3) the specified profile may not be consistent with the parameterization used in the model. Although not used in this study, it is possible to overcome these problems by deriving the heating rates from the convective parameterization used in the model. For the Kuo parameterization, given $R$, the moisture convergence is set to $R \times 2 \Delta t$, where $\Delta t$ is the model time step and the moistening parameter
tropics, the heating rates are only applied in this area, namely, 25°N–25°S.

d. Moisture initialization

The moisture initialization is based on the Betts–Miller parameterization and has been described in Puri and Miller (1990). The scheme attempts to adjust the initial moisture field so that the rainfall rate in the early stages of the model integrations is close to the observed rate. A practical application of the moisture initialization proceeds as follows. If $\tilde{R}$ and $\tilde{R}_m$ (both greater than zero) refer to the observed rate obtained from the GMS imagery and the rate obtained by integrating the model for one time step, respectively, we compute $\Delta \tilde{R} = \tilde{R}_m - \tilde{R}$. If $\rho$ is a subsaturation pressure difference $\rho = p - p_*$ where $p_*$ is the pressure to which a parcel at pressure $p$ must be lifted to reach saturation, then $\Delta \rho$ is converted to a vertically integrated $\Delta \rho$ from a tephigram or a more rigorous relationship (see Puri and Miller 1990). A vertical profile of $\Delta \rho$ is estimated by choosing a linear profile of $\Delta \rho$ such that the maximum change in $|\Delta \rho|$ is at the freezing level with no change at cloud top or bottom. The adjustment in the moisture field ($\delta q$) can now be derived. In practice the following combinations can occur:

(a) $\tilde{R}_m \leq \tilde{R}$ then $q_a = q_i + \delta q$, where $q_i$ and $q_a$ are the unadjusted and adjusted mixing ratios, respectively;

(b) $\tilde{R}_m = 0$; that is, no convection diagnosed by the model and $\tilde{R} > 0$. The current scheme cannot cope with this, and no adjustment is made.

Some notable features of the scheme are as follows:

(i) Only the moisture field is modified, and the temperature is left unchanged.

(ii) The observed rainfall is assumed to be convective rainfall, which is approximately true in the tropics but not in midlatitudes, and thus, the scheme is only applied in the tropics.

(iii) The moisture adjustment will only occur in regions where convection is diagnosed in the model. One possible way of overcoming (iii) would be to modify the temperature field so that the relevant layer or layers become convectively unstable. The temperature analyses, however, are much more reliable than moisture analyses, and it is preferable not to modify the temperature during initialization.

3. Results

A number of data-assimilation experiments were performed to assess the impact of (i) GMS-based bogus moisture data and diabatic heating and (ii) moisture initialization. The period chosen for the experiments was from 1100 UTC 11 January 1990 to 1100 UTC 16 January 1990. This period had significant convective
activity in the tropics to the north of Australia and included three tropical cyclones, namely, Koryn in the central Pacific, Sam off the coast of northwest Australia, and Rosita in the central Indian Ocean. An example of these systems can be found in the satellite imagery in Fig. 1.

a. Impact of GMS-based bogus moisture data and diabatic heating

The following data-assimilation experiments were performed:

CNTL: control as in the operational system
GMSQ: CNTL + moisture bogus data at 1100 and 2300 UTC,

GMSI: GMSQ + diabatic NMI with heating rates estimated from GMS cloud-top temperatures using the first method of section 2c, only during initialization, and

GMSH: GMSI + heating rates specified during the first 2 h of model integration during the data-assimilation cycle.

Note the moisture initialization was not used in these experiments; this is considered in section 3b. In addition to the data assimilation, 5-day model forecasts were performed from the assimilation analyses for 1100 UTC 14 and 15 January. Note that the bogus moisture data was only used at 1100 and 2300 UTC. In CNTL
and GMSQ adiabatic NMI was used, whereas diabatic NMI in the GMS domain was used in GMSI and GMSH and adiabatic NMI outside. Following Wergen (1987) the heating rates were held constant during initialization. In all cases, four vertical modes were initialized and four nonlinear iterations were performed. The impact of the bogus moisture data and diabatic heating is considered in terms of the convective activity in the model during assimilation and forecast stages. A sensitive measure of convective activity in the model is the local vertically integrated convergence of moisture (\( \text{TOTDVQ} = \int \nabla \cdot \mathbf{V} q dq \)), where \( \mathbf{V} \) is the horizontal wind vector and \( q \) is the moisture mixing ratio. Figures 4a–d show the analyzed integrated moisture convergence from the four data-assimilation cycles valid at 1100 UTC 14 and 15 January. The GMS IR imagery for the two dates is shown in Fig. 1. Comparison of the patterns of TOTDVQ with the GMS imagery shows a marked qualitative improvement with the addition of bogus moisture data particularly in the region of the cloud band in the Pacific. The convergence off the coast of western Australia shows an improvement over CNTL for 14 January with the use of the bogus moisture data, although the improvement is not as marked for 15 January. Part of the reason for this can be seen in Fig. 2, which shows that bogus moisture is not used in the region off the west Australian coast because the 10° latitude–longitude box file containing the data for this region is excluded due to its overlap with land. This limitation will be removed in future work when only land areas will be excluded and not the whole box. The convergence of moisture shows good agreement with GMS imagery for both 1100 UTC 14 and 15 January for the GMSI and GMSH experiments in which both the GMS-based bogus moisture and heating rates are used. The accumulated precipitation from 14 to 15 January during assimilation and during model forecasts (presented in Figs. 5 and 6, respectively) also shows a marked qualitative improvement with the use of bogus moisture and heating rates over the CNTL experiment. When compared to the satellite imagery shown in Fig. 1, the latter experiment shows little or no precipitation in the region of the tropical cyclone off the west Australian coast and is deficient in the region of the cloud band in the Pacific. A feature of these results is that GMSQ, GMSI, and GMSH are more similar to each other than any of them are to CNTL, and that GMSI and GMSH are more similar to each other than either is to GMSQ.

As was indicated earlier, one of the major deficiencies in model performance in the tropics is spinup of precipitation. For the BMRC model this manifests itself in the tropical precipitation that takes 1–2 days to reach its equilibrium value. An indication of the impact of the GMS-based data on model spinup is given in Fig. 7 which shows the 12-h accumulated precipitation averaged over the domain 25.7°S–25.7°N, 82.5°E–180° for 5-day model forecasts from 1100 UTC 14 and 15 January. The CNTL forecast displays the typical spinup signature of the model. The GMSQ forecast has similar features but with a reduced amplitude. The GMSI and GMSH forecasts that use GMS-based heating rates in addition to the bogus moisture have no spinup. Thus, for the two cases considered here, the use of information from satellite imagery during data assimilation has the potential to minimize model spinup in the tropics.

b. Impact of moisture initialization

Although the GMSI and GMSH forecasts minimize model spinup in the tropics, examination of the precipitation amount shows significant variation spatially (see Figs. 5 and 6, for example). One way of overcoming this is to initialize the moisture field so that the precipitation in the early stages of the model integration is close to the observed precipitation. This initialization scheme, which is commonly referred to as physical initialization, was introduced by Krishnamurti et al. (1984) within the framework of the Kuo cumulus parameterization. Donner (1988) and Donner and Rasch (1989) have also developed a scheme for the same parameterization. Puri and Miller (1990) have developed a moisture initialization scheme for the Betts–Miller (Betts and Miller 1986) convective scheme, and results of experiments with this scheme will now be described.

Two further data-assimilation experiments for the period considered in section 3a were performed:

- **BTSM:** as in GMSI experiment but using the Betts–Miller scheme instead of the Kuo scheme, and
- **BTMQ:** BTSM + moisture adjustment.

Figures 8a and 8b show the mixing ratios before moisture adjustment and changes resulting from moisture initialization at 500 hPa in BTMQ for 1100 UTC 14
and 15 January. The 500-hPa level is shown because the adjustment scheme is designed to produce maximum changes at this level. The changes in the mixing ratio are small for both cases, with some changes occurring in the cloud band in the Pacific and off the western Australian coast. Figure 9 illustrates the impact of the moisture initialization more graphically. It shows the area mean 6-h accumulated precipitation during data assimilation for the BTSM and BTMQ experiments together with observed precipitation that was used to initialize the moisture field. The precipitation from the BTMQ experiment agrees very closely with the observed precipitation that indicates the effectiveness of the moisture initialization. The 24-h accumulated precipitation during assimilation and forecasts from 14 January from the two experiments is shown in Figs. 10a and 10b, respectively. The precipitation patterns from both experiments are similar, with the main differences being in the amounts. This is consistent with the feature of the initialization scheme that allows moisture adjustment only where convection is diagnosed in the model. Note that the initialization can lead to increased or decreased precipitation. This can be seen in the accumulated precipitation during assimilation where the initialization leads to increased precipitation off the western Australian coast and decreased rainfall in the Pacific. Comparison of Figs. 10a, b with the observed precipitation used in moisture initialization and shown in Fig. 11 indicates reasonable agreement with the precipitation from BTMQ during

*FIG. 10.* (a) (left panels) As in Fig. 5a but for BTSM (top) and BTMQ (bottom). (b) (right panels) As in Fig. 6a but for forecasts from BTSM (top) and BTMQ (bottom) analyses.
Fig. 11. Observed precipitation (mm) from 1100 UTC 14 January 1990 to 1100 UTC 15 January 1990. Contour interval is 10 mm day\(^{-1}\).

assimilation and model forecast. The BTMQ precipitation also shows somewhat better agreement than from BTSM.

Although the emphasis in this paper has been on precipitation and model spinup, the beneficial impact of the bogus moisture data and diabatic heating is not confined to these quantities only. The use of diabatic heating during initialization or early stages of model forecasts also results in stronger cyclonic circulation in the region of the cyclones. As with the precipitation, however, these conclusions are only qualitative because of the difficulty of independent quantitative verification resulting from lack of relevant data. Furthermore, the results presented are for a very limited number of cases, and the conclusions cannot be regarded as definitive. Mills and Davidson (1987), however, also found that the use of bogus moisture data results in analyses that subjectively better reflect observed cloud features than do analyses that use only conventional data. Further, in some cases, they also found that the additional moisture detail in these analyses can impact positively on model forecasts.

4. Conclusions

A major problem in tropical numerical weather prediction is the inability to adequately represent tropical diabatic forcing in the models. One of the reasons for this is the sparsity of moisture data that often results in poor analysis of the moisture field. Geostationary (and polar-orbiting) satellites such as the GMS satellite provide useful proxy sources of moisture data and diabatic heating. In this study, an attempt has been made to assess the impact of these data on precipitation and spinup in the model. Furthermore, the impact of a moisture initialization scheme in conjunction with these data is considered. The results show that the use of bogus moisture data alone leads to improved precipitation during assimilation. The spinup in the model, however, is still present even though it is at a reduced amplitude. The use of bogus moisture data in conjunction with satellite-based diabatic heating minimizes spinup in the model. Moisture initialization leads to much improved agreement between area mean observed and model precipitation during data assimilation and also leads to reduced spinup. These results indicate the feasibility of using data such as bogus moisture and precipitation in current models. The procedures used here rely on obtaining reasonable estimates of observed precipitation. Considerable effort has been devoted toward improving satellite-derived precipitation rates (see Adler and Negri 1988), and forms an important component of the Global Energy Water Cycle Experiment (GEWEX) and the Tropical Rainfall Measuring Mission (TRMM). There is also a reasonable raingage network over a number of countries in the tropics, and more reliable estimates of rainfall could be obtained by merging the conventional network with satellites. Furthermore, global models used at major operational centers are starting to provide reasonable estimates of precipitation. Thus, analysis of precipitation using model first guess, conventional raingage network, and satellite estimates in regions of no data will soon be a feasible option. The current study shows that these analyses could be readily implemented in models and have the potential to improve forecasts in the tropics.

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