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#### Model Rain and Clouds over Oceans: Comparison with SSM/I Observations

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#### ABSTRACT

A comparison of global model cloud and rain parameterization output with satellite observed radiances was carried out. Hydrometeor profiles from ECMWF operational short-range forecasts were combined with a microwave radiative transfer model to generate observation-equivalent radiances simulating the Special Sensor Microwave Imager (SSM/I) measurements. These were generated for two 15-day periods in January and July 2001 to be compared to SSM/I observations from three DMSP satellites, namely *F-13, F-14,* and *F-15.* The simulations were analyzed to isolate the relative contributions of water vapor, cloud water, rain, and snow to the total signal given their frequency of occurrence in the global fields. The 19.35-GHz channel has the great advantage of being less sensitive to cloud geometry and model-generated snow, thus providing a more unique relationship between cloud-rainwater and blackbody equivalent brightness temperatures (TBs). The 37.0-GHz channel showed great skill in separating cloud and (moderate to heavy) rainfall. The uncertainties in cloud geometry and ice microphysics inhibit an interpretation of 85.5-GHz brightness temperatures.

The evaluation was based on 1) the calculation of cloud and rain occurrence applying the same TB threshold screening to both observations and simulation, and 2) the analysis of global TB histograms for clouds and precipitation. From the first part, the model tendency to produce too large cloud and rain systems was identified. While some smaller-scale cloud features are missing, the onset of condensation generally produces larger systems than observed. Since the precipitation scheme is diagnostic, the cloud scheme propagates this problem to the rain coverage. With the results from the second part, the overestimation of extent and intensity was quantified to  $\approx 10-15$  K at 19.35 and  $\approx 15-30$  K at 37.0 GHz at horizontal polarization.

This was consistent with a direct estimation of retrieved liquid water paths using a variational retrieval scheme and of rainfall rates from a parametric algorithm. The globally averaged liquid water path from the model's first guess was about 75% higher than that from the retrievals, while globally averaged rain rate was 160% higher than retrieved. The major contribution to this overestimation originated from the Tropics, suggesting the convection scheme and/or its inputs as a major source of overestimation.

#### 1. Introduction

As radiometers do not directly measure the atmospheric constituents, two approaches coexist for the comparison of model and satellite data. Either the observations are converted to model variables (satelliteto-model approach) or synthetic observations are computed from the model parameters (model-to-satellite approach). Each of the two possibilities is affected by different spatial and temporal sampling and resolutions of model data versus observation. Observations represent an integration of information contributions from several sources, that is, emission and scattering of electromagnetic radiation by surface and atmospheric constituents. Thus the observable-parameter relationship may not be unique and discrepancies between models and observations may be difficult to interpret.

For model evaluation purposes, the model-to-satellite

approach tends to be favored because retrieval errors are usually difficult to characterize (e.g., Morcrette 1991; Rizzi 1994; Shah and Rind 1995; Roca et al. 1997; Chaboureau et al. 2000; Chevallier et al. 2001). Therefore both elements of the comparison may be erroneous or at least seriously biased. This aspect is even more important for the assimilation of satellite data and therefore operational weather centers progressively turn to the direct assimilation of radiances instead of retrieved products (e.g., Andersson et al. 1994; Derber and Wu 1998). Aiming at the assimilation of rain-affected radiances, however, it has to be verified that the model clouds can realistically represent observable radiances in terms of grid-averaged cloud geometry and microphysical properties.

This study represents one of the first attempts to characterize the quality of global model precipitation schemes employing the precipitation signature in radiance space. The model-inherent radiation schemes generate radiation budget elements (shortwave and longwave, i.e., wavelengths of 0.3-4 and  $4-40 \mu$ m), which are historically compared to earth radiation budget ob-

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TABLE 1. Forecast ranges used here for the simulation of the SSM/I TBs.

Observation time (UTC)	0300	0600	0900	1200	1500	1800	2100	0000
Forecast range (h)	3	6	9	12	3	6	9	12

servations from satellites (e.g., Cess et al. 1997) but which only provide information relevant to bulk nonprecipitating cloud parameters. Precipitation analyses, however, require the simulation of microwave radiative transfer in the model atmosphere to be compared to available satellite data. Here, the availability of a sophisticated global operational model with simulation scales of the same order as satellite observations provides a unique tool to evaluate the model cloud physics over all synoptic regimes. In order to prepare for the assimilation of rain-affected radiances, this study focuses on the short forecast ranges (less than 12 h).

Our starting point is the description of observational and model data used for the intercomparison as well as a description of the microwave radiative transfer model (section 2). Section 3 begins with a description of the relative information contributions of water vapor, clouds, and precipitation to the simulated radiances. The evaluation is based on 1) the frequency of precipitation occurrence in both model and observations and 2) the analysis of radiance probability density functions (PDFs). The latter are interpreted by use of the information content previously outlined and on the basis of both global datasets and regional case studies. Methodology and results are summarized and general conclusions are drawn in section 4.

#### 2. Data sources

#### a. Satellite data

The Special Sensor Microwave Imager (SSM/I) passive microwave radiometer has been operated since 1987 on board the Defense Meteorological Satellite Program (DMSP) satellites with a near-circular, sun-synchronous, and near-polar orbit. SSM/I imaging is carried out on a conical scan, thus constant surface zenith angle (53.1°), and at four frequencies (19.35, 22.235, 37.0, and 85.5 GHz) with dual polarization, except at 22.235 GHz where only vertically polarized measurements are available. The size of the instantaneous field of view decreases with frequency. The spatial resolution of the 19.35-, 22.235-, and 37.0-GHz channels ( $63 \times 49$ , 50  $\times$  40, and 37  $\times$  28 km<sup>2</sup>, respectively) is comparable to the resolution of the European Centre for Medium-Range Weather Forecasts (ECMWF) forecast model (40 imes 40 km<sup>2</sup>), but the 85.5-GHz channel resolution, 15 imes13 km<sup>2</sup>, is significantly higher (Hollinger et al. 1987). Orbit altitude and active scan angle provide a swath width of about 1400 km.

For the purpose of this study, two periods of 15 days were selected: 1–15 January and 1–15 July 2001. In both cases, observations from three DMSP satellites, *F*-

13, F-14, and F-15, were employed over oceans after screening of sea ice. Since the F-13, F-14, and F-15 orbits have a descending node time of approximately 0600, 0900, and 0730 LST and an ascending node time of approximately 1800, 2100, and 1930 LST, global coverage is achieved during 1 day.

#### b. Model data

Model profiles (temperature, specific humidity, cloud cover, liquid water, ice water, rain, and precipitating snow) and surface characteristics (pressure, temperature, and wind) were extracted from the ECMWF archives with a temporal resolution of 3 h over the two 15-day periods. As a consequence, observations and model data are collocated within 1.5 h. The reference observation times and the corresponding forecast ranges are summarized in Table 1. Short forecast ranges were chosen in order to evaluate the quality of the first guess of the analysis system, described next. The data were produced by cycle 23r4 of the ECMWF forecast system, the characteristics of which are summarized hereafter.

Analyses are produced at nominal times of 0000 and 1200 UTC by the four-dimensional variational data assimilation (4DVAR) system described by Courtier et al. (1994), with an assimilation window of 12 h. The previous forecast is used as first guess to the analysis. Pressure, temperature, water vapor, and wind information are obtained from conventional and satellite observations. Of relevance to the present study is that SSM/I observations are assimilated in the form of retrieved total water vapor content and retrieved 10-m wind speed over oceans in nonrainy areas (Gérard and Saunders 1999). The temperature of the sea surface is prescribed with the National Centers for Environmental Prediction (NCEP) analyses output.

The forecast model is a global spectral  $T_L511L60$ model. It includes a semi-Lagrangian advection scheme together with a linear Gaussian grid (Hortal 1999). The reduced horizontal grid corresponds to a regular grid size of about 40 km from the equator to the poles. In the vertical, a hybrid coordinate of 60 levels between the surface and the top of the atmosphere is used. The physics package is an improved version of that described by Gregory et al. (2000), with the main modifications summarized by Jakob et al. (2000) and Morcrette et al. (2001). In particular, two prognostic equations describe the time evolution of cloud condensate and cloud cover, while rain and snow are diagnostic quantities. Jakob (2000) describes the modifications to the original formulation from Tiedtke (1993). Clouds are formed by convection, diabatic cooling, and boundary layer turbulence. The scheme links their dissipation to adiabatic and diabatic heating, turbulent mixing of cloud air with unsaturated environmental air, and precipitation processes. Precipitation processes are parameterized in the convection scheme and in the stratiform cloud scheme and are computed in terms of rain and snow precipitation rates, with units kg(m<sup>2</sup> s)<sup>-1</sup>. In pure ice clouds, the generation of precipitation is treated as a sedimentation process of cloud ice following Heymsfield and Donner (1990). The parameterization uses a formulation following Sundqvist (1978) in mixed-phase and water clouds. Rain and snow fall out and evaporate consistently with the cloud overlap (Jakob and Klein 2000).

#### c. Radiative transfer model

The computation of model-equivalent SSM/I radiances (expressed as blackbody equivalent brightness temperatures, TBs) is based on a two-stream Eddington approximation model assuming plane-parallel atmospheres (Bauer et al. 1998; Bauer 2002; Moreau et al. 2002). When compared to more accurate multiple-stream or Monte Carlo models, model uncertainties remain below 1–2 K in most situations at SSM/I frequencies (Smith et al. 2002).

The hydrometeor optical properties (i.e., the extinction coefficient, the single scattering albedo, and the asymmetry parameter) are provided to the radiation model from precomputed Mie tables for liquid water, cloud ice, rain, and precipitating ice (Bauer 2001). The conversion from rain and snow rates (as archived from the forecast model) to water contents (as used by the radiative transfer model) is carried out in agreement with the Mie computations assuming standard size distributions and fall speeds of the hydrometeors (Bauer 2001). Extinction coefficients for oxygen and water vapor were obtained from the millimeter propagation model (Liebe et al. 1992).

Polarization is only introduced by the sea surface properties. The latter are obtained in terms of an effective emissivity and an effective reflectivity from version 2 of the Fast Emissivity Model (FASTEM-2) (English and Hewison 1998; Deblonde and English 2000), which accounts for nonspecular reflection by a wind-roughened sea surface within a simple and computationally efficient formulation. The validation of FASTEM-2 shows that the model uncertainty in terms of apparent surface temperature is of the order of 1 K. It is obvious that the impact of FASTEM-2 errors on the TB computation decreases with increasing atmospheric opacity. Polarization may also originate from radiance scattering at spherical and nonspherical particles (Prigent et al. 2001). However, given the rather coarse microphysical detail resolved by global model cloud schemes the neglection of scattering-induced polarization seems of minor importance compared to uncertainties of the hydrometeor profiles and cloud coverage parameterization.

The geometry of the hydrometeor profiles in the forecast scheme is rather complex. Indeed, fractional cloud cover and fractional precipitation cover are defined separately in each atmospheric layer. The cloud layers are overlapped following a maximum random approximation. Precipitation is distributed in the vertical in accordance with the corresponding cloud geometry and the model physics. In order to reduce the computing time of the radiative transfer code for the present study, the geometry of the one-dimensional profiles was simplified in the TB calculations. First, the fractional cloud cover was assumed to be constant in the vertical, with maximum overlap of the cloud layers. The cloud cover for the radiation scheme was chosen as the maximum value of the cloud cover in the liquid water layers provided by the forecast model. Scattering was introduced in the cloudy part of the grid only. The clear and cloudy radiance streams are linearly combined to obtain the final TB, but they do not interact. Second, precipitation coverage is assumed to be equal to the cloud coverage, without any distinction between convective rain and stratiform rain. This simplification of the geometry is not expected to introduce errors in excess of a few kelvins since microwave radiation is sensitive to large amounts of hydrometeors only, for which the cloud cover and precipitation cover are usually close to unity in the forecast model. However, larger errors may occur at the boundaries of cloud systems.

The uncertainty of the total radiance computation is difficult to quantify because the impact of the simplified geometry is hard to verify. However, given the above estimates a total TB uncertainty of about 3 K at 19.35, 22.235, and 37.0 GHz and 3–5 K at 85.5 GHz seems reasonable. Of these, the cloud geometry approximation and the sea surface emissivity model clearly dominate the error budget.

#### 3. Comparison

The first part of the evaluation is dedicated to the representation of precipitation occurrence in both model simulations and observations. An objective rain identification is introduced in TB space rather than on the hydrometeor level. This is because rain parameterization schemes tend to produce too many very small precipitation rates. In that case, an artificial cutoff of erroneously low parts of rain PDFs would have to be used. Therefore, the rain flags of Stogryn et al. (1994) have been implemented here. These flags identify clouds by the increasing depolarization generated by sea surface reflection at 37.0 GHz, that is,  $T_{37V} - T_{37H} \leq 50$  K, and rain if the lower-frequency TBs exceed certain thresholds, that is,  $T_{19V} \geq T_{37V}$  or  $T_{19H} > 185$  K or  $T_{37H} > 210$  K.

Clouds and rain are irregularly spread in the atmosphere and form structures in which the horizontal scale varies by several orders of magnitude. A slight displacement (two grid points, for instance) of a frontal system in the atmospheric model with respect to observations will significantly degrade a point-by-point comparison. In the present case, 115 514 (253 620) rainaffected grid points were detected in the SSM/I observations (in the model) between 1 and 15 January using the above rain flags. Despite the twofold overestimation of the number of rain-contaminated points by the model, only 64 814 grid points are rainy in both the model and observations. Small mislocations of the systems and the width of the collocation time window (1.5 h; see section 2b) explain this number. As a consequence, point-bypoint comparisons would be misleading here. The present validation is thus based on rain and cloud frequency of occurrence as well as on TB PDFs over the two 15day periods.

#### a. Information content of the SSM/I observations

In order to assess the contribution of various atmospheric variables to the SSM/I TBs, a sensitivity study was performed with the data from 1 January. For the 8232 rain-affected model profiles available over the ocean, equivalent SSM/I TBs were computed by adding successively the constituents cloud liquid water, rain, and snow to the clear-sky model profiles. No computation was made for the contribution of cloud ice since it does not significantly affect the SSM/I channels. The impact of the atmospheric variables on the TB PDFs is presented in Fig. 1 for each of the seven channels.

Water vapor is the main contributor to the clear atmosphere emission in all SSM/I channels due to water vapor continuum absorption and a strong absorption line at 22.235 GHz. Since continuum absorption increases with frequency, the 85.5-GHz "window" channel shows a similar sensitivity to water vapor as the 22.235-GHz channel. Liquid water absorption and scattering increases with frequency as well. All histograms (W + L)therefore show a shift to higher TBs indicating more opaque atmospheres above the radiometrically cold ocean background. Adding rain (W + L + R) produces another shift to higher TBs between 19.35 and 37.0 GHz since raindrop absorption is stronger than scattering. However, at 85.5 GHz, scattering becomes important and TBs decrease. Finally, by adding snow (W + L + R + S) only slight effect is observed at 19.35 and 22.235 GHz while scattering dominates at 37.0 and is even stronger at 85.5 GHz.

Since the addition of both cloud liquid water and rain tend to produce a shift of PDFs in the same direction, light rain would be difficult to separate from cloud liquid water (e.g., Bauer et al. 2001). Another aspect is the sensitivity to cloud structure. With increasing frequency the cloud transmission is reduced; thus, higher levels dominate the signal. Therefore the higher-frequency signals depend more strongly on the vertical liquid and ice water distribution while the 19.35- and 22.235-GHz channels mainly respond to the integrated water path. When simulations are compared to observations, the differences will then be driven by different rain column depths and average rainwater contents (or rain rates) in that column.

#### b. Frequency of occurrence

The frequency of occurrence of liquid clouds (nonraining and raining) for January and July is shown in Fig. 2. The results exhibit some of the main patterns of the atmospheric general circulation: the intertropical convergence zone (ITCZ), the South Pacific convergence zone (SPCZ), and the midlatitude storm tracks. The cloud detection used here is too restrictive to display the liquid clouds of the descending-motion regions, such as the cumulus trade winds and the stratocumulus regions off the west coast of the continents. Consistent with previous validations of the ECMWF model (e.g., Chevallier et al. 2001), the patterns are shown to be well reproduced on the short forecast ranges considered with respect to observations. However, the model overestimates the frequency of occurrence in most regions, in particular in the storm tracks, in the Atlantic ITCZ and in the east Pacific ITCZ.

Figure 3 displays the frequency of occurrence of rain for the two 15-day periods. As expected, it exhibits the same regions as for the clouds (Fig. 2), but with thinner structures. The observed structures are also located remarkably well by the model, but they are too large and too intense. Even though the model spatial resolution is high, the generated cloud structures do not represent well the small-scale convection and organized mesoscale convection. Once convection is initiated it will have a tendency to contaminate adjacent grid boxes and thus overestimate the extent of observable clouds.

#### c. Probability density functions

The TB PDFs are presented in Figs. 4 and 5 for January and July, respectively. In order to focus on the rain areas they were restricted to those grid points where rain was detected in either observations or the model at least once over the whole 15-day period. These were the points reproduced in the shaded areas in Fig. 3.

Generally, two peaks can be distinguished in the PDFs that reflect the general difference between midlatitude and tropical temperature regimes. The magnitude of the cold peak is larger inasmuch as the number of midlatitude points is higher as can be seen in Fig. 3. The shape of the distributions and the differences between the model and the observations are similar for the two polarizations. However, the model's coldest TBs, which are therefore cloud free, appear to be biased warm by 2–3 K in the 19.35-, 22.235-, and 37.0-GHz vertically polarized channels. This is not the case in the corresponding horizontally polarized channels and is likely to reflect a bias produced by the surface emissivity model.

The number of occurrence of the highest TBs at 19.35 and 37.0 GHz, which are therefore generated by cloud



FIG. 1. Cumulative impact of water vapor (W), liquid water (L), rain (R), and precipitating snow (S) on the distribution of the computed rain-affected SSM/I TBs for 1 Jan 2001 (8232 cases).

and possibly rain emission, is higher in the model simulations than in the observations. This is consistent with the results of Figs. 2 and 3 that exhibited an overestimation of cloud and rain occurrence in general. Furthermore, it may indicate an overestimation of the rain intensity (and/or of the cloud liquid water paths) for most precipitating cases since the rain-layer depth will be reproduced rather well due to its close correspondence to the freezing-level altitude.

For clear cases, the 22.235-GHz model PDF fits the observed one particularly well (not shown here), which indicates the good representation of water vapor in the

(a) January, model



(b) January, observation





FIG. 2. Frequency of occurrence of clouds in the model and in the observations over ocean. Clouds are detected using SSM/I TBs.



FIG. 3. Frequency of occurrence of rain in the model and in the observations over ocean. Rain is detected using SSM/I TBs.



FIG. 4. Distribution of the observed and computed SSM/I TBs for grid boxes that are affected by rain in the model or in the observations more than once over the period 1–15 Jan 2001 (2 638 376 cases).

model short-range forecast. This is not surprising since thinned SSM/I observations of total water vapor path are operationally assimilated in clear areas. However, in the situations collected here (i.e., with at least one rain contamination per 2-week period) some differences occur. First, the model has a cold bias in the Tropics (at around 260 K in Figs. 4c and 5c). Owing to the positive biases from the emissivity model and the model cloud liquid water, which were noticed at 19.35 and 37.0 GHz, this may indicate a lack of water vapor in the tropical convective systems, which could be explained further by a cold temperature bias in these areas. Second, the



FIG. 5. Distribution of the observed and computed SSM/I TBs between 1 and 15 Jul 2001 in grid boxes that are affected by rain in the model or in the observations more than once over the period (2 693 167 cases).

model has a warm bias in the midlatitudes, in particular in boreal summer, likely because of excessive cloudiness along the storm tracks, as was seen in Fig. 2.

Comparing Figs. 4 and 5 some seasonal variation can be observed. In July, the Pacific ITCZ is intensified and the Indian Ocean monsoon is active while the SPCZ is less well defined. Over the southern oceans rainfall patterns are generally more widespread and precipitation is more intense. Also, smaller-scale features like the rain maximum over the Gulf and Kuroshio streams are well expressed in July. More atmospheric humidity in tropical atmospheres is reflected in the change of magnitude



FIG. 6. Distribution of the observed and computed SSM/I TBs between 1 and 15 Jan 2001 when rain was detected in the model or in the observations (304 320 cases).

of TB peaks at 22.235 GHz (cf. Fig. 4c with 5c). Also those peaks at 19.35 GHz associated with precipitation are amplified by enhanced tropical convection (cf. Figs. 4a,b with 5a,b) and also the peak at larger TBs at 37.0 GHz is more pronounced in July (cf. Figs. 4d,e with 5d,e).

To separate between cloudy and rainy cases, which were accumulated in Figs. 4 and 5, the same PDFs were

reproduced only containing rainy cases. Therefore those samples were selected for Fig. 6 where either the model or observations showed rain (here only shown for January 2001). The sample sizes were 304 320 for January and 322 804 for July. It is noteworthy that in January, 890 839 samples were classified as cloud/rain contaminated from the model and 763 929 from the observations. This quantifies the observation from Fig. 2; that



FIG. 7. Frequency distribution of model first-guess (solid) vs (left) retrieved (dashed) cloud liquid water paths and (right) surface rain rates for 1–15 Jan 2001.

is, the model rain areas are larger than those observed. Together with Fig. 1, Fig. 6 can give some information on model deficiencies. For instance, Fig. 6b indicates the excess cloud occurrence and cloud liquid water/rain amounts in the model simulations. The histogram is shifted to the right and the difference between clouds and rain (which is identified by the small side peak in the observations) disappeared. The shift at lower TBs reaches  $\approx 10-15$  K at 19.35 GHz and  $\approx 15-30$  K at 37.0 GHz at horizontal polarization. Since both shifts are positive and cloud absorption increases linearly with frequency, they are most likely associated with cloud water rather than precipitation.

The 85.5-GHz channel provides information on precipitating ice since the scattering at large ice particles significantly reduces the TBs. From Figs. 4–6f and g, the model appears to produce shallower PDFs at 85.5 GHz than the observations. So there are both cases

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TABLE 2. Averaged cloud liquid water contents (*w*) and rain rates (RR) from model first guesses (FG) and retrievals (RET) for period 1–15 Jan 2001.

Region	w <sub>FG</sub> (kg m <sup>-2</sup> )	w <sub>RET</sub> (kg m <sup>-2</sup> )	$\frac{RR_{FG}}{(mm \ h^{-1})}$	$\frac{RR_{RET}}{(mm \ h^{-1})}$
Global	0.115	0.064	0.151	0.058
Midlatitudes	0.108	0.075	0.133	0.057
Tropics	0.124	0.054	0.181	0.060

where the model generates too much precipitating ice, and cases where it does not produce enough. Deeper analysis of the results shows that the excessive production mainly occurs in the midlatitude storm tracks. Further investigation would be particularly interesting because the model is known to generally lack cloud ice water, in particular in the midlatitudes (Chevallier et al. 2001). Validation of the ice fallout scheme would therefore help in analyzing the causes of this deficiency. However, such a study is hampered by the lower accuracy of the radiative transfer simulations at 85.5 GHz and by the resolution difference between the atmospheric model and the observations (see section 2a).

A means of quantifying the model bias in TB is the comparison of the model first-guess liquid water path, w, with that of the one-dimensional variational retrieval (Phalippou 1996), which is operationally generated at ECMWF along with water vapor path and near-surface wind speed. This only applies to nonprecipitating situations in the observations. The three panels in the left column of Fig. 7a show the w PDFs over the period 1-15 January 2001 comparing the model first guess with the variational retrieval (1DVAR) for all data, the midlatitudes (30-60°N, 30-60°S), and the Tropics (30°S-30°N). The right-hand panels show a similar comparison of near-surface rain rates between the model first guess and those obtained from the SSM/I rain retrieval algorithm of Bauer and Schlüssel (1993). Table 2 summarizes the averaged water contents and rain rates, respectively.

The model shows the tendency to globally overestimate liquid water path above w = 0.03 kg m<sup>-2</sup>. The magnitude of overestimation amounts to 44% in the midlatitudes and to 131% in the Tropics, which reduces to 79% globally. Since the model's rain parameterization is diagnostic, this trend is propagated to the rain production as well. Therefore, a global overestimation of 160% is observed, that is, 134% in the midlatitudes and 200% in the Tropics. The rain-rate PDF of the observations drops off fairly quickly for RR < 0.4 mm h<sup>-1</sup> because a lower threshold for rain detection was used with the Bauer–Schlüssel algorithm.

The overestimation is very dramatic and is far above the expected uncertainty of the retrievals. Also, it is only partly explained by an overestimation of cloud/rain area extent. It also confirms the previously outlined performance in TB space. Since the contribution of convective systems to total cloud occurrence and rainfall is larger in the Tropics than in the midlatitudes, the convection scheme and/or its input data, for example, temperature (as discussed above), may be mainly responsible for the overproduction of liquid water that later becomes precipitation.

#### d. Individual cases

Some individual cases from January 2001 are shown separately in Fig. 8 for the northern Atlantic and in Fig. 9 for the Indian Ocean (TBs at 19.35-GHz, horizontal polarization). The highest TBs indicate rain areas, whereas the lowest TBs correspond to cloud-free scenes. The figures corroborate the information gained from the 15-day statistics: the convective systems are well located, in particular in the midlatitudes, which indicates the good performance of model dynamics. However, the systems are too intense, both in terms of rain and in terms of cloud liquid water.

The extents of the frontal systems are nicely depicted in both observations and model fields (Fig. 8). As previously mentioned, the model simulations exhibit more intense rainfall in the updraft regions while some smaller-scale features in the warm sectors are missing. The intensity difference is again expressed by the TB differences of  $\approx 20.0$  K.

In the Indian Ocean (Fig. 9) two tropical cyclones can be identified, which were Ando on 7 January, southeast of Madagascar, and Bindu on 11 January, east of Madagascar. It is interesting to notice the improvement of the representation of the tropical cyclones between previous studies (e.g., Marécal and Mahfouf 2000, 2002) and the current model version. Both the shape and intensity of Ando and Bindu are much better simulated than were Anacelle and Bonnie (both in 1998). This is a consequence of an increase of forecast model resolution from 60 to 40 km even though it is still not sufficient for the development of an inner eyewall as observed on 11 January (cf. Figs. 9e and 9f).

#### 4. Discussion

Satellite observations have been providing valuable information on cloud profiles generated by the ECMWF model, in particular, in recent years (Jakob 1999; Klein and Jakob 1999; Chevallier and Morcrette 2000; Chevallier et al. 2001; Chevallier and Kelly 2002). This paper extends the scope of these studies to the model precipitation profiles.

When evaluating global model cloud and rain parameterization schemes with satellite data, a comparison in radiance space seems favorable since the retrieval of bulk cloud and rain microphysical quantities from observations is rather difficult. This is in particular true for near-surface rainfall rate or hydrometeor concentration profiles. For this reason, we combined the current operational ECMWF model hydrometeor profiles with a microwave radiative transfer model to generate ob(a) January 5, model

(b) January 5, observations



(c) January 7, model

(d) January 7, observations



(e) January 14, model

(f) January 14, observations



FIG. 8. Model and observed 19.35-GHz TBs (horizontal polarization) over the North Atlantic. The data was taken around 1200 UTC on the dates shown.

servation-equivalent radiances simulating the SSM/I measurements. With this approach, the error sources are restricted to the assumptions made for cloud geometry and particle size distributions (which are also inherent to physical retrieval algorithms) and the models used

for surface emissivity and radiative transfer calculations. The latter are comparably easy to quantify and amount to a few degrees kelvin depending on frequency and polarization.

Observation-equivalent simulations were generated

(a) January 2, model

(b) January 2, observations



(c) January 7, model

(d) January 7, observations



- (e) January 11, Model
- (f) January 11, observations



FIG. 9. Model and observed 19.35-GHz TBs (horizontal polarization), over the Indian Ocean. The data were taken around 1500 UTC on the dates shown.

for two 15-day periods in January and July 2001 to be compared to SSM/I observations from three satellites, namely F-13, F-14, and F-15. In a first step, the simulations were analyzed to isolate the relative contributions of water vapor, cloud water, rain, and snow to the

total signal given their frequency of occurrence in the global fields. The SSM/I 19.35-GHz channel has the great advantage of being less sensitive to cloud structure and to model-generated snow, thus providing a more unique relationship between cloud/rainwater and TBs.

Both cloud and rain could be separated by the superposition of gross emission and occurrence at 37.0 GHz (horizontal polarization); that is, TB histograms showed a cloud-related maximum at 220 K and a rain-related maximum at 250 K. It was evident that rainfall with low intensity would be difficult to distinguish from nonprecipitating clouds. In any case, the influence of water vapor is dominant since almost all observations/simulations contain clear-sky contributions. Snow mainly drives the signal at 85.5 GHz but model cloud ice microphysics, cloud geometry versus SSM/I footprint size, and snow particle size distribution are very uncertain so that the comparison of TBs would be difficult to interpret.

The evaluation was based on 1) calculation of cloud occurrence applying the same TB-threshold screening to both observations and simulation, and 2) the analysis of global TB histograms for clouds and precipitation. From the first of them, the model tendency to produce cloud and rain systems that are too large was identified. While some smaller-scale features are missing, the onset of condensation will generally produce larger systems than observed. Since the precipitation scheme is diagnostic, the cloud scheme will propagate this problem to the rain coverage. From the histogram comparison, the overestimation of extent and intensity was quantified to  $\approx 10-15$  K at 19.35 and  $\approx 15-30$  K at 37.0 GHz at horizontal polarization at the lower end of the TB dynamic range.

In summary, our evaluation confirms previous results from Chevallier et al. (2001) using Microwave Sounding Unit (MSU) data concerning the model tendency to overestimate cloud extent and liquid water path. The SSM/I observations indicate an analogous behavior for the model's rain production resulting in TB biases between 10 and 30 K at SSM/I frequencies. This has to be interpreted as the sum of cloud and rain contributions to the signal since the water vapor contents and surface winds are already strongly constrained through the assimilation of SSM/I observations in nonprecipitating areas. The above comparison already suggests the convection scheme as a starting point.

The analysis introduced above forms the basis for a possible direct usage of cloud- and rain-affected radiances in the assimilation system. This would represent an alternative with respect to the assimilation of rain rates (e.g., Marécal and Mahfouf 2002). The advantages of assimilating radiances are the better knowledge of forward modeling errors as well as the independence of algorithm training datasets, which are known to lack global representativeness. On the other hand, the present study depicts the deficiencies of the model first-guess bulk cloud parameters, which may represent a handicap within the variational assimilation framework.

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