On the influence of different radiation parametrizations on model-generated radiation fields

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SUMMARY

Radiation fields for 10-day forecasts with the operational ECMWF model using three different radiation schemes are presented. Simultaneous measurements of the radiation budget at the top of the atmosphere derived from TIROS-N AVHRR data are compared with the computed budgets. Initial values of the radiation fields computed by the three schemes are compared and large intrinsic differences are found. Discrepancies in the heating rate profiles are located in the stratosphere and in the tropical lower layers. Land–sea contrasts in the maps of outgoing longwave fluxes, related to differences in cloudiness, vary from one scheme to another, and are usually smaller than those derived from satellite measurements. Over the 10-day period of integration, all three schemes lead to similar changes in the cloud fields, with a decrease over the ITCZ and an increase at high latitudes. This effect can be related to deficiencies in the hydrological cycle of the global model. Despite relatively large differences between the initial values of the radiation fields, compensating mechanisms are such that the computed fields, averaged over the 10 days, show smaller deviations from the observed fields.

1. INTRODUCTION

New efficient radiation schemes have recently been designed to be incorporated in large-scale atmospheric models. These schemes, albeit very simplified compared to the high complexity of the full treatment of the radiation transfer in the atmosphere, are particularly efficient because they maintain a good level of accuracy while keeping their share of the computational burden as small as possible. Direct comparisons of the performances of such schemes can be considered from two points of view. From a ‘static’ point of view, radiative fluxes and flux divergences computed by different schemes for the same set of standard atmospheres will indicate the differences between the schemes. However, though necessary, such an approach is not sufficient as it does not provide any insight on the influence of these systematic differences on the general circulation model (GCM) results. To reach this goal, the ‘interactive’ or ‘dynamic’ point of view must be taken, i.e. results from integrations of the same GCM including the different radiation schemes are analysed. Such an approach has been retained in the intercomparison programme for radiation codes used in climate models (given the acronym ICRCCM) launched under the auspices of the WMO/ICSU Joint Scientific Committee and the IAMAP Radiation Commission. The adopted three-step strategy includes: (i) the comparison of radiation codes in ‘stand alone’ mode with each other and reference calculations on the basis of a small number of defined atmospheric profiles, to provide an ‘absolute error calibration’; (ii) the intercomparison of global fields of radiative fluxes and parameters generated instantaneously by radiation codes acting on a field of atmospheric profiles from a selected FGGE data set, to get a ‘relative error calibration’ on a statistical basis; (iii) some sensitivity tests, using different radiation codes in the same GCM to assess the evolution of radiative fields as the integration proceeds, and the sensitivity of climate simulations to different radiation codes. As a contribution to this programme, this paper deals (at least partly) with the second and third folds of the ICRCCM strategy. It proposes a discussion of some comparisons of radiation fields generated by different

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radiation codes within the same GCM, and of their sensitivity to cloudiness and temperature.

The operational ECMWF model is run for three 10-day forecasts (21–31 January 1979, during the first special observation period of FGGE) using three different radiation schemes: either the original radiation scheme (Geleyn and Hollingsworth 1979, hereafter EC); or the scheme designed by the University of Köln (Hense et al. 1982; hereafter KO) for the GCM of the German Weather Service; or the scheme developed for the GCM of the Laboratoire de Météorologie Dynamique (Fouquart and Bonnel 1980; Morcrette et al., to be published; hereafter LI). The radiation schemes are briefly described in section 2. ‘Static’ comparisons, presented in section 3, make use of the initial values of the radiation fields (i.e. computed at the first step of the different integrations). Comparisons are carried out for the latitude–height cross-section of zonal averages of the shortwave heating and longwave cooling, and of the covariance between these radiative heating–cooling rates and the cloudiness or the temperature which can be related to eddy available potential energy. The components of the radiation budget at the top of the atmosphere are derived for the same period from TIROS-N AVHRR measurements, and are used to infer qualitatively some defaults in the parametrizations. In section 4, the ‘interactive’ response of the GCM to the different radiation schemes is analysed, with emphasis on the interaction between radiation fields and the cloudiness.

2. RADIATION SCHEMES

A complete description of the ECMWF model can be found in Burridge and Haseler (1977) and Tiedtke et al. (1979), and some details concerning its radiation interface are given in Geleyn et al. (1982). The radiation parametrizations are fully documented in Geleyn and Hollingsworth (1979) for the EC scheme, in Hense et al. (1982) for the KO scheme and in Fouquart and Bonnel (1980) and Morcrette et al. (to be published) for the LI scheme. The main features of the three schemes are summarized in Table 1.

3. INITIAL RADIATION FIELDS

In this section, the radiation schemes are compared from what we call a ‘static’ point of view. At the initial stage (21 January 1979, 00z), the radiation fields are computed for the same distributions of temperature, cloudiness and absorbers, so that the GCM offers the opportunity of 192×97 column comparisons sampling over all latitudes. Thus we can expect the comparison of the radiation fields computed from the same input data by the three radiation schemes to give an exact idea of systematic differences between the schemes.

(a) Latitudinal distribution of the zonal averages of the radiative heating rates

Figure 1 presents the zonally averaged vertical distribution of cloudiness. While the temperature field is directly analysed from the synoptic network data, the cloud field is computed from a diagnostic relationship developed by Geleyn (1981) that has been tuned to fit the satellite-observed profiles of total cloudiness and net radiation as a function of latitude (Hoyt 1976), and to reproduce as well as possible the estimated globally averaged vertical distributions of cloud cover and radiative cooling (London 1957; Dopplick 1972, combined with Cox and Griffith 1979). For each of the fifteen layers of the model, the cloud cover, C, is evaluated whenever the relative humidity,
<table>
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<tr>
<th>Feature</th>
<th>EC</th>
<th>KO</th>
<th>LI</th>
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</thead>
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<tr>
<td>Number of shortwave and longwave intervals: SW/LW</td>
<td>2/3</td>
<td>4/6</td>
<td>1/3</td>
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<td>Solution of the radiative transfer equation</td>
<td>Two-stream method with the Eddington approximation. Scattering in the LW</td>
<td>Two-stream method with the delta approximation in clouds. No scattering in the LW</td>
<td>Delta–Eddington approximation in the SW. Emissivity-type method in the LW</td>
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<tr>
<td>Cloud overlapping</td>
<td>Maximum overlapping (special boundary conditions at interface between layers)</td>
<td>Random overlapping. The cloudy layer is given a mean optical depth as a function of cloud cover and optical thicknesses of the clear atmosphere and of the cloud</td>
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<td>Absorption/scattering</td>
<td>Path-length method for line-type absorption by gases</td>
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<td>Cloud optical properties as a function of liquid water path</td>
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All schemes compute the radiative fluxes in a fully interactive mode with the large-scale atmospheric model (temperature, humidity, cloud cover and cloud liquid water path).
RH, exceeds the critical relative humidity $RH_c$

$$C = [\max(0, (RH - RH_c)/(1 - RH_c))]^2$$

where $RH_c$ is a function of the vertical coordinate $\sigma$ (pressure/surface pressure):

$$RH_c = 1 - \alpha \sigma(1 - \sigma)[1 + \beta(\sigma - \frac{1}{3})].$$

Furthermore, no cloud is assumed in the well-mixed boundary layer where potential temperature is lower than that at the surface for the layer in question and all layers underneath. When a cloud is diagnosed in a layer, its liquid water content is taken as a certain fraction $R_{lw}$ of the saturation water vapour content of the layer.

From a tuning carried out with the EC radiation scheme, the choice of parameters was $\alpha = 2$, $\beta = \sqrt{3}$, $R_{lw} = 0.002$. Though the diagnostic relationship gives a zonal distribution of total cloud cover consistent with the more recent cloud climatologies (Hoyt 1976; Berlyand and Strokina 1975), it does not provide sufficient amounts of the stratiform low clouds that usually top the marine planetary boundary layer, and of high clouds in the ITCZ. Such high clouds are often remnants of anvils of cumulonimbus clouds travelling away from their sources and have only a weak dependence on the convective activity (Webster and Stephens 1980).

![Figure 1](image.png)

Figure 1. Latitude–height cross-section of the zonal average of cloudiness diagnosed at the initial step of the integration.

The latitudinal distribution of the zonal means of cooling by terrestrial radiation, of heating by solar radiation and of net radiative heating/cooling is shown in Figs. 2, 3 and 4 respectively. In these figures, (a) refers to the EC scheme, (b) to the KO scheme and (c) to the LI scheme. From these figures, we notice the overall agreement between the gross features of the fields computed by the EC and LI schemes. Both schemes produce large terrestrial cooling and solar heating in the summer stratosphere, that partly compensate each other to give a net heating of weaker amplitude. However, the values at a given point are different, for example in the stratosphere where absorption by CO$_2$ and O$_3$ predominates: at the south pole, in the highest layer, shortwave and longwave heating rates from EC scheme are $+5.8$ K/day and $-4.4$ K/day respectively, while the LI scheme gives $+5.0$ K/day and $-4.0$ K/day respectively. At the north pole, the longwave cooling is $1.3$ K/day for the EC scheme and $0.8$ K/day for the LI scheme. From Ramanathan et al. (1983), it appears that a correct treatment of the CO$_2$ and O$_3$ longwave cooling is
necessary to ensure the proper shape, position and intensity of the polar night jet (PNJ). Given the specified distributions for CO2 and O3 in the model, the EC scheme will tend to increase the equator–pole temperature difference, thus increasing the PNJ. The LI scheme, with a smaller contrast between equatorial and polar stratosphere temperatures, should maintain a PNJ with lower intensity than the EC scheme.

In the troposphere, solar heating rates from the EC scheme average 0.25 K/day more than those from the LI scheme. The maximum heating rate is observed around 15S and 500 mb for both schemes, but is 1.4 K/day for the EC scheme and 1.1 K/day for the LI scheme. The lower layers at the equator are warmed less by solar radiation absorption, due to the presence of thick cloud around 800 mb. Heating rates are 0.7 K/day for the EC scheme and 0.35 K/day for the LI scheme. Above Antarctica, a heating rate larger than 1 K/day is seen with the EC scheme, that does not show up with the LI scheme. Such discrepancies have been analysed and correspond in the EC scheme to too large a value for H2O absorptivity within the solar spectrum. The EC scheme uses transmission functions which have been shown (Fouquart 1984, private communication) to overestimate the H2O absorption compared to values computed from a more recent compilation of spectroscopic parameters (McClatchey et al. 1973).

Differences also appear in the troposphere in the longwave spectrum (Figs. 2(a) and

![Figure 2. Latitude-height cross-sections of the zonal average of cooling by longwave radiation (K day⁻¹) calculated at the initial step of the integration by EC (a); KO (b); LI (c).]
The tropical lower layers are cooled less by longwave radiation transfer with the EC scheme than with the LI scheme; in particular the maximum cooling rates near the surface at 15°N and 30°S (2-75 K/day with the LI scheme) are absent due to the absence of e-type H₂O window absorption in the EC scheme. The EC scheme produces a maximum cooling rate of 3-1 K/day at 10°S and 450 mb, and two other regions of cooling larger than 2-5 K/day are located around 45°N and 45°S at 500 mb. The LI scheme gives two maxima of about 2-8 K/day at the equator, 650 mb and 350 mb respectively, and the cooling rates at latitude 45° and 500 mb are 2-1 K/day and 2-3 K/day in the northern and southern hemispheres respectively.

The net radiative heating/cooling rate obviously displays features related to the individual shortwave and longwave components. Their addition gives a difference varying from 0-25 to 1-00 K/day in the net radiative tendency in the layers below 850 mb, with the LI scheme giving the largest cooling tendency. The whole troposphere is cooled by the LI scheme, whereas some areas in the lower layers at the equator and southward of 45°S show a net heating by the EC scheme. In the tropics, the LI scheme cools more and at higher levels than the EC scheme does (at the equator, the maximum cooling is 2-2 K/day at 330 mb for LI, and 2-0 K/day at 500 mb for EC). But the contrary holds at higher latitudes in the northern hemisphere (at the north pole the maximum cooling is...
1.2 K/day at 680 mb for LI, and 1.4 K/day at 590 mb for EC). Thus, if we look at the height of the maximum coolings as a function of latitude, the LI scheme gives a steeper slope than the EC scheme does, leading to different vertical stabilities. Moreover, this feature is likely to induce a difference in the tropopause height as a function of latitude as soon as we proceed in the time integration of the model.

Comparison with results from the KO scheme is more difficult as we suspect some errors in the KO code. The solar heating field (Fig. 3(b)) is very different from the other calculations since the KO scheme does not have any stratospheric heating by ozone. For longwave radiation (Fig. 2(b)), the expected cooling by carbon dioxide does not show up in the stratosphere. Due to the absence of the shielding effect by absorption in the upper layers, the lower layers are made more efficient for absorption and we can observe large solar heating (up to 2.6 K/day) and large longwave cooling (up to 3.6 K/day) in the mid layers of the tropical atmosphere (around 750 mb for shortwave heating and around 500 mb for longwave cooling). For the same reason, near the surface, the cooling to space of the warmer layers by e-type H2O absorption is also overestimated (up to 5 K/day in the tropics). Moreover large radiative effects are also observed over Antarctica that could be related to an error in the vertical distribution of aerosols in the KO scheme (Geleyn et al. 1982).
Figure 5. Latitude–height cross-sections of the covariance between radiative heating rates and cloud cover on sigma surfaces along latitude circles (K day$^{-1}$): (a): between shortwave heating and cloud cover for EC; (b): between longwave cooling and cloud cover for EC; (c): between shortwave heating and cloud cover for LI; (d): between longwave cooling and cloud cover for LI.

Figure 6. Latitude–height cross-sections of the covariance between radiative heating rates and temperature on sigma surfaces along latitude circles (K day$^{-1}$): (a) between shortwave heating and cloud cover for EC; (b): between longwave cooling and temperature for EC; (c): between shortwave heating and temperature for LI; (d): between longwave cooling and temperature for LI.
(b) Covariances between heating rates and temperature or cloud cover

Available potential energy (APE) is created by the differential heating or cooling of the atmosphere and thus its generation is related to the correlation of temperature and the diabatic heating. Together with latent heat release and sensible heat transfer, radiation, both through the absorption of solar radiation and the emission of longwave radiation, produces differential heating and thus generates available potential energy. In Fig. 5 we show for both EC and LI the latitude–height cross-section of the zonal averages of the covariance between radiative heating rates and cloud cover on sigma surfaces along latitude circles, while Fig. 6 shows an equivalent distribution of the covariance between radiative heating rates and temperature. As already discussed by Geleyn (1981), the effect of temperature fluctuations taken alone is clearly one of damping (negative covariance) because Planck’s emission law indicates that warmer parts of the atmosphere will have a stronger cooling than colder ones, all other things being equal. On the other hand, moisture and cloud fluctuations should have an opposite effect, at least over a certain depth of the atmosphere. Clouds generally indicate warm air and their relative radiative effect is a warming within and below the cloud with a strong but localized cooling at the top. Thus if we consider the covariance of temperature and radiative heating to be closely related to eddy available potential energy (EAPE), we can expect generation (positive covariances) in the lower part of the atmosphere, and dissipation in the higher regions. We also expect the dissipation to be strong where temperature waves have large amplitudes and where clouds are present in both warm and cold parts of the wave (baroclinically active regions) and the generation to be strong where clouds are an important heating factor for the atmosphere (tropics).

First, the large covariances between heating rates and temperature (Fig. 6) observed over Antarctica are unrealistic and due to orography not being filtered out in our covariances computed on sigma surfaces.

The first noticeable feature in Figs. 5 and 6 is the small covariance between shortwave heating and either cloud cover or temperature. While this latter result is not a surprise as the only temperature dependence of solar absorption is through the temperature effect applied to the effective amount of absorber, the former is more questionable. We would expect a small generation of APE by solar radiation absorption as the solar absorption in warm, moist air is greater than in cooler, drier air, and as the presence of clouds in the warm, moist air increases the solar absorption. We get such a result from the LI scheme (Fig. 5(c)) but only a small negative covariance between heating rate and cloud cover with the EC scheme (Fig. 5(a)). From the EC results, it appears that, for an increase in the cloud cover, the depletion of incident solar radiation by an increase of the local albedo outweighs the increase of absorption in the cloudy part of the layer. As in the EC scheme, cloud reflectivity, transmissivity and absorptivity are parametrized as a function of the cloud LWP from the relationships of Żdunowski et al. (1967), whereas, in the LI scheme, the cloud optical properties are explicitly computed with the help of the Delta–Eddington method, explanation for this effect in the EC scheme must be sought for in an overestimation of the cloud reflectivity for the low values of LWP linked to $R_{\lambda_0} = 0.002$.

Examining the covariances between longwave cooling rates and either cloud cover (Figs. 5(b), (d)) or temperature (Figs. 6(b), (d)), we first notice the differences in the distribution of the APE generation and dissipation areas between the two schemes. Positive covariances extend over a zone which is wider with EC than with LI. Moreover, EC gives larger values (positive or negative) than LI particularly between 300 and 500 mb. Although this effect can be related to the larger values obtained by the EC
scheme for the cooling rates (see section 3(a), Fig. 2(a)) the latitudinal extension of the positive covariance area at high latitudes is puzzling and casts doubt over the EC scheme results. A thorough examination of the EC scheme has shown that, in the determination of the layer exchange term (Geleyn and Hollingsworth 1979), the absorption by small optical depths is overestimated. Thus corresponding to the small cloud LWPs (and optical depths) given by the ratio $R_{\text{lwp}}$ transmissions between the top and levels in the atmosphere are underestimated, yielding too large cooling rates at too high altitudes. Given this screening effect of the higher layers, the layers underneath undergo a kind of greenhouse regime which explains (Fig. 6(b)) the large dissipation of EAPE in the regions of strong cooling (around 400 mb poleward of 30° latitude) and the generation of EAPE in the layers underneath.

To sum up, covariances between radiative heating/cooling rates and any of their controlling parameters (temperature, cloudiness, humidity) are shown to be useful tools to get insight into the behaviour of the radiative schemes and their sensitivity to these parameters. Thus, these second-order moments of the radiative heating/cooling rates may be of great help for analysing the results of phase 2 of the ICRCCM programme.

(c) Geographical distributions of the radiation fields at the top of atmosphere

Given the scarcity of measurements of radiative divergence and the consequent little knowledge we have of the actual tri-dimensional distribution of shortwave heating and longwave cooling (all existing climatologies, London (1957), Rodgers (1967), Dopplick (1972, 1979), are results of calculations), the measurements of the directional radiances at the top of the atmosphere carried out by radiometers on satellites are at present the only available data against which one can compare results from calculations. However, radiative fields, either derived from satellite measurements or simulated by model calculations, depend on so many parameters and include so many uncertainties that “such a comparison actually fails to provide information on whether discrepancies (or even agreement) are due to inadequate simulations of synoptic structures, poor estimates of the clouds associated with these structures, improper radiation associated with those clouds, or a combination of all of these” (Research Plan for FIRE, 1983). Nevertheless, a comparison of the radiative fields at the top of the atmosphere computed at the initial step of the integration from the three radiation schemes remains interesting in so far as it can give hints of the usefulness of these radiation fields as diagnostics of proper radiative calculations within the atmosphere underneath. In that context, the radiative fields derived from satellite measurements must be seen not as a reference for the calculations, but merely as qualitative indicators of some large-scale atmospheric features such as the pole-equator gradient or the land-ocean contrast that should appear in the computed fields. In this section, we present maps of the outgoing longwave flux (Fig. 7), planetary albedo (Fig. 8), and net radiative budget (Fig. 9) at the top of the atmosphere computed from the three radiation schemes at the initial step of the integration and we compare them with maps of the same quantities derived from measurements from the AVHRR on board TIROS-N (Gruber and Winston 1978).

(i) Radiation fields at the top of the atmosphere derived from TIROS-N data. The total outgoing longwave flux is estimated from the infrared radiances measured in channel 4 (infrared window region between 10.5 and 11.5 μm) by a nonlinear regression model, based on radiation calculations for a set of 99 different atmospheres (Gruber and Winston). The shortwave reflected flux is determined directly from the radiances measured in channel 1 (0.58 to 0.68 μm) without any correction for anisotropy or diurnal variations. From those assumptions, the radiative fields derived from satellite data may
Figure 7. Outgoing longwave radiation (W m\(^{-2}\)) computed at the initial step (21 January 1979, 00h) by EC (b), KO (c) and LI (d), compared to NOAA observations (a).
Figure 8. As Fig. 7, but for the planetary albedo: NOAA (a), EC (b), KO (c), LI (d).
Figure 9. As Fig. 7, but for the net radiation balance (W·m⁻²): NOAA (a), EC (b), KO (c), LI (d).
contain errors of yet unknown magnitude, and the albedo, especially over snow and clouds, may be overestimated (Slingo 1982). Qualitatively speaking, lows and highs in the fields are directly related to the cloudiness fields. Smaller amounts of cloudiness give smaller albedo and higher values for the outgoing longwave flux. From that point of view, in the latitude zone between 0 and 20°S, we can note the strong contrast between oceanic and continental areas. Over South America and South Africa, cloud fields give albedo higher than 40% and outgoing longwave flux smaller than 200 W m⁻² whereas albedo smaller than 15% and outgoing longwave flux larger than 280 W m⁻² correspond to clear areas over the Pacific, Atlantic and Indian Oceans.

(ii) Computed radiation fields at the top of the atmosphere. From qualitative comparisons of the computed and ‘observed’ radiative fields it appears that many differences can be related to an intricate mixture of inadequate simulation of the synoptic structures and poor estimates of the cloudiness associated with these structures. For example, in the 20°N–20°S latitude zone, the model simulates more cloudiness than is observed over the Pacific Ocean (0°N 100°–120°W), the Atlantic Ocean (0°N 20°W) and south of India (0°N 80°E), but less cloudiness over South America and South Africa, so that the computed contrast between continental and oceanic areas is smaller than observed in all cases.

As the radiation schemes use the same diagnosed cloudiness, intercomparison of the computed radiative fields should show intrinsic deficiencies of the schemes. From a qualitative point of view, one can observe similarities between KO and LI maps of outgoing longwave flux (Figs. 7(c) and (d)), and between EC and LI maps of planetary albedo (Figs. 8(b) and (d)). The KO scheme provides a field of albedo with small contrast between clear and cloudy areas. The field does not display any albedo less than 15% over oceanic areas which have cloudiness lower than 20%. Poleward of 50°N, and over the cloudy areas of the equatorial zone, the LI scheme gives a higher albedo than does the EC scheme. This problem in the LI scheme has been analysed and found to be related to a somewhat deficient parametrization of Rayleigh scattering, of multiple scattering for high values of the surface albedo, and of the effective solar zenith angle assumed below a cloud with small optical thickness.

Land–ocean contrast is lacking or even reversed in the map of the outgoing longwave radiation computed by the EC scheme, while it is present in the maps given by the two other schemes, albeit weaker than observed (cf. Fig. 7(b)). For the EC scheme, the screening effect of the higher layers discussed in section 3(b) provides an explanation for the poorly contrasted field of outgoing longwave flux. The outgoing flux can be related to some effective temperature \( T_e \) corresponding to the peak of the weighting function \( \frac{\partial \tau}{\partial \ln p} \) where \( \tau \) is the transmission evaluated from the top of the atmosphere and \( p \) is pressure. An overestimate of the absorption for small optical depths tends to set the maximum of the weighting function to higher altitudes than normal, effectively to a level above the mean cloud top, thus giving a lower effective temperature. This decreases the potentially large temperature contrast between clear and cloudy fractions of the atmosphere. A close agreement between the LI and KO schemes is observed for the outgoing longwave flux at the top of the atmosphere, as the two computed fields are within 10 W m⁻² over most of the globe. A similar comparison between the KO and LI schemes for the net longwave flux at the surface shows that the agreement between the two schemes is within 10 W m⁻², except poleward of 60°N. Given the large discrepancies between the cooling rate profiles computed by the two schemes (see Figs. 2(b) and (c)), especially in the intertropical zone, the agreement between the fluxes at both boundaries of the atmosphere may appear inconsistent. In fact, the fluxes at the boundaries are
mainly related to the tropospheric absorption and it appears from the comparison that this quantity does not differ too much between the two schemes.

The comparisons that we have presented in sections 2 and 3 have allowed us to pinpoint some defects in the three radiation schemes, among others the large H₂O shortwave absorptivity and the overestimation of longwave absorption at short pathlengths in the EC scheme, the poor description of CO₂ and O₃ absorption in the KO scheme, and a deficient parametrization of Rayleigh and multiple scattering in the LI scheme. We have also shown the over-all weak sensitivity of the radiation fields at the top of the atmosphere to those deficiencies in clear sky radiative parametrizations, and therefore the little value of those radiative fields as diagnostics of proper radiative calculations.

Despite all the problems discussed above for the different schemes, we will now consider the results of the 10-day integrations, as they shed some light on how the ECMWF model adjusts to different horizontal and vertical radiative forcings.

4. Time Evolution of the Radiation Fields

Due to the relatively long time scale of radiative dynamical interactions, the 10-day period of integration probably leads to incomplete results in radiative feedback phenomena. However, this period should be long enough to show the direct impact of

Figure 10. Time evolution of the components of the planetary radiation balance (global means): (a) outgoing longwave radiation (Wm⁻²); (b) planetary albedo; (c) net radiation balance (Wm⁻²).

Figure 11. Time evolution of the temperature (globally averaged and vertically integrated) (K).
the different radiation schemes on the evolution of the radiative fields through the evolution of their controlling parameters: cloudiness, temperature and humidity. Figures 10(a), (b) and (c) show the time evolution of the global means of, respectively, outgoing longwave flux, planetary albedo and net absorption at the top of the atmosphere, as computed by the three radiation schemes, together with the same radiative parameters derived from satellite measurements (except for days 2 and 3 when data were lacking).

Compared to the results of Geleyn et al. (1982, their Fig. 1), the present results show a shorter period of adjustment between the dynamics and the physics of the system (one day instead of three due to the better quality of the initial state in this experiment: a well-defined initial state for 21 January 1979 derived from FGGE observations). As already noticed in section 3(c)(iii), the LI scheme gives too large a value for the planetary albedo which leads to a large negative net radiation imbalance. It is worthwhile to notice that during the integration, the outgoing longwave flux remains within 3 W m⁻² of its initial value, while the planetary albedo exhibits a drastic decrease from 0.37 to 0.31, corresponding to a 20 W m⁻² increase in solar absorption. As will be discussed in the next paragraph, an explanation of this behaviour is connected with the time evolution of the atmospheric temperature shown in Fig. 11. The three integrations present similar trends over the period of integration: atmospheric temperature is decreasing, and the larger the net radiative imbalance at the top of the atmosphere in Fig. 10(c), the steeper the slope of this decrease. It can be noticed that, from satellite measurements, the earth-atmosphere system appears to be gaining energy, in conformity with what is expected from the annual cycle of insolation.

While atmospheric temperature is decreasing, so is cloudiness. The total cloud cover as seen from the top of the atmosphere assuming a random overlapping of cloudy layers is shown in Fig. 12 for global means over land and over the oceans. First of all, we notice the greater cloudiness over land than over oceans, consistent with the observed distribution, which shows more convective cloud over land. During the period of integration, a sharp decrease in oceanic cloudiness (from 0.58 to 0.47) and a decrease in continental cloudiness (from 0.61 to 0.57) have occurred and this effect is independent of the radiative scheme. From the diagnostic relationships giving the cloud cover and

![Figure 12](https://example.com/figure12.png)

**Figure 12.** Time evolution of the total cloudiness averaged over oceanic and continental areas separately.
LWP as functions of relative humidity and the saturation mixing ratio respectively, the decrease in cloudiness is linked to a decrease in relative humidity, and the temperature decrease leads to smaller LWPs for cloud. As the optical properties of clouds (reflectivity, transmissivity, absorptivity, emissivity) depend on the LWP in the three radiation schemes, a decrease in the LWP gives more transparent clouds. As the cloud longwave emissivity is saturated for LWPs smaller than for the cloud shortwave albedo, the albedo effect of clouds is more efficient than their infrared effect in compensating for the net radiative imbalance at the top of the atmosphere, as shown in Fig. 10 where the outgoing longwave flux remains almost constant during the integration, whereas the planetary albedo is rapidly decreasing.

Figures 13(a) and (b) present the time evolution of the globally averaged heating by solar radiation absorption and cooling by longwave radiation emission respectively. The fine (but wrong) tuning of the original radiation scheme for the ECMWF model clearly appears in these figures, as both the heating and cooling rates given by ECMWF keep steady values along the period of integration. By comparison, the other two schemes show decreases in heating and cooling rates. However, given the falls of temperature and cloudiness observed in Figs. 11 and 12, two remarks can be made. First, the small sensitivity of the ECMWF radiative results to temperature and cloudiness gives another hint of the deficiency already mentioned in sections 3(b) and 3(c)(ii) (overestimation of the absorption at short pathlengths). Secondly, the stability of the EC results demonstrates that the temperature decrease of the model does not originate solely from the radiative calculations, and suggests that other heating processes are involved in the cooling of the model. The same conclusion can be drawn from Figs. 10 and 11 as temperatures do not start to increase when the net absorption becomes positive. Tiedtke (1981) has reported on the systematic errors present in the version of the ECMWF operational model that is used in this study, and he has related the net cooling of the model's atmosphere with an imbalance between the global radiative cooling and the global heating by surface fluxes, by large-scale condensation processes and by convection.

When looking at the time evolution of the globally averaged vertical profiles of the shortwave heating, longwave cooling and cloudiness, we notice that the decrease in the cloud amount is accompanied by a lowering of the level of the cloudiness maximum

![Graphs](image-url)

Figure 13. Time evolution of the components of the net radiative heating (K day⁻¹): shortwave heating (a), longwave cooling (b).
(from 750 mb at day 0 to 850 mb at day 10), which causes a similar lowering of the mid-tropospheric peak of the longwave cooling. Figure 14 presents the zonal means of the total cloud cover for land and oceanic areas of the model at the beginning (Figs. 14(a) and (c)) and at the end (Figs. 14(b) and (d)) of the integration. An increase in cloudiness at high latitudes, a stable value for ITCZ cloudiness over land, and a drop in the ITCZ cloudiness over the oceans are the features common to the three integrations, thus corroborating a deficiency in the hydrological cycle of the ECMWF model. Geleyn et al. (1983) report that noticeable improvements have been obtained in the ITCZ circulation after three important changes concerning the hydrological cycle were introduced while recoding the physical parametrization for the new spectral version of the ECMWF operational model; thus we can expect more insight into the problem of radiation/convection coupling in future similar experiments carried out with revised versions of the radiation schemes.

Figure 14. Zonal distribution of total cloudiness: (a) averaged over land, initial step; (b) averaged over land, final step; (c) averaged over ocean, initial step; (d) averaged over ocean, final step.
5. TEN-DAY MEANS OF THE RADIATION FIELDS AT THE TOP OF THE ATMOSPHERE

It is common among climate modellers to judge the adequacy of a new parametrization introduced in a GCM by studying the modifications occurring in the model's outputs and by comparing the results against available observations. For the radiative computations, the budget at the top of the atmosphere and its longwave and shortwave components can be derived globally from satellite measurements with little processing of the data and thus have long been used as the reference against which to test radiative parametrizations. However, the usual way of proceeding is to compare time-averaged values of the radiation budget components provided by the GCM to monthly means derived from satellite measurements, such as those compiled by Campbell and Vonder Haar (1980). The validity of such comparisons can be questioned, as comparison on shorter time scales appear to be more representative of the actual accuracy of the cloud/radiation parametrizations.

When comparing maps of the differences between observed and computed radiative fields at the top of the atmosphere at the initial stage of the integration, and averaged over the 10-day period, it appears that smaller differences are obtained with the averaged fields, as many local features have obviously been smoothed out in the time averaging of the fields. Moreover, due to various compensating mechanisms, among them the temperature decrease and the global redistribution of cloudiness, the radiation fields have adapted themselves to the different internal forcings of the model during the integration. This adaptation is clearly seen in Table 2, which presents the globally averaged values of the differences between the observed and computed radiative fields at the top of the atmosphere for the three radiation schemes, at the beginning and at the end of the integration, and averaged over the period of integration.

Consequently, even without addressing the problem of the usefulness of the net radiation balance of the atmosphere as a diagnostic of climate variability (Shukla and Sud 1981), comparisons between time-averaged computed and observed radiative fields at the top of the atmosphere, for the purpose of validating radiation or cloud generation schemes suitable for use in GCMs, are not guaranteed to provide an exact measure of the adequacy of the tested schemes.

As observations from satellites will still remain for a long time the best way to

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All parameters are given at day 0, 5 and 10, or averaged over the 10 days (T0). For 'α', read planetary albedo, for 'IR', outgoing longwave flux, and for 'NET', net radiative budget.
monitor the atmosphere and to derive parameters that can be directly compared with GCM’s outputs, emphasis must be put on obtaining measurements with finer time, space and spectral scales from the next generation of satellites. Another alternative is to use the large-scale fields of temperature, pressure, humidity and winds analysed by the forecast models together with the cloud and radiation parameters derived from the existing satellite system. Large-scale fields can be taken as inputs for GCM-type cloud generation and radiation schemes, and the computed cloudiness and consequent radiation fields are compared with the satellite measurements (Bonnel et al. 1983).

6. CONCLUSIONS

Three 10-day integrations of the ECMWF operational model have been carried out using three different radiation schemes. Deficiencies in each radiation scheme came to light from the differing three-dimensional distribution of the radiative fields at the initial stage of the integrations. Despite the discrepancies in the individual radiative forcings, the three integrations of the ECMWF model have shown similar trends in temperature and cloudiness fields. This behaviour originates in a poor description of the hydrological cycle in the ITCZ. Second-order moments of the heating/cooling rates, temperature and cloudiness are shown to be useful tools for analysing the results of the radiation schemes. For validating GCM-type cloud radiation schemes, the usefulness of time-averaged radiative fields at the top of the atmosphere is questioned.

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