Downwelling Longwave Irradiance at the Ocean Surface: An Assessment of In Situ Measurements and Parameterizations

FRANCOIS-MARIE Bréon, ROBERT Frouin AND CATHERINE Gautier

California Space Institute, Scripps Institution of Oceanography, La Jolla, California

(Manuscript received 18 December 1989, in final form 18 June 1990)

ABSTRACT

Two sets of ocean surface longwave irradiance measurements collected during the FASINEX and MILDEX experiments are analyzed for quality and variability studies. Using concomitant radiosonde data, the clear-sky contribution to the downward flux at the surface is computed and, subsequently, the effect of clouds from the surface measurements is deduced. The longwave irradiance computations are performed using a broadband model, a simpler parameterization, and an empirical formula. The three schemes are chosen because they represent different, possible approaches for computing surface longwave irradiance. They are intercompared, separating clear and cloud components, and verified against in situ measurements.

During both experiments, which took place in midlatitudes during different seasons, variations in the downward longwave flux associated with clear-sky variations (air temperature, humidity changes) and cloud effects are found to be of the same order of magnitude (≈70 W m⁻²). Applied to radiosonde profiles, the two more physical schemes provide consistent results with a 4 W m⁻² the standard deviation of the differences is only 4 W m⁻². These schemes, however, exhibit a 4 W m⁻² relative bias, which is comparable to the desired accuracy for monthly-mean longwave flux estimates. Intercomparisons with the empirical formula yield larger standard deviations, demonstrating the formula's inability to reproduce adequately the clear-sky flux variability. For all three schemes, the scatter around the measured values is rather large (20–25 W m⁻²); surprisingly, the empirical formula gives the best results. This is explained by the large uncertainty in the cloud parameters used as input to the schemes; when no reliable estimates of these critical variables can be made, it may be more accurate to take a simple parameterization for the cloud effect on the longwave flux.

1. Introduction

Understanding air–sea interactions, manifested by exchanges of heat, water, and momentum across the interface, is of major importance to earth climate studies. Because the first ten meters of the ocean contain as much heat as the entire atmosphere, the oceans constitute huge reservoirs of energy that can be transported far from source regions and released into the atmosphere. Viewed globally, the oceans absorb energy in equatorial and tropical regions and carry it to higher latitudes where it is released to the atmosphere. On a seasonal time scale, oceans absorb energy during summer, and release it during winter, driving temperate climates over adjacent land areas.

Although this general pattern has been known for many years, the success of climate understanding and prediction resides largely in accurate monitoring of the global surface heat balance on smaller spatial and temporal scales. The determination of global fields has become necessary with the development of global circulation models (GCMs), which have to be validated and/or constrained at the surface. Characterizing surface heat fluxes is also important for understanding major climatic phenomena, such as the Indian Monsoon or the El Niño, so that their interannual variability and associated effects on human activities can be predicted.

The net heat flux at the ocean surface is the balance between the radiative, latent, and sensible heat fluxes. Radiative fluxes can be roughly separated into two components below and above 3 μm. Shorter wavelengths are mainly incident from the sun, whereas longer wavelengths correspond to the thermal emission of the atmosphere, including clouds, and the surface. Although the shortwave radiative flux is generally greater in magnitude and exhibits larger variability, surface heat budget computations require a knowledge of other components.

Several techniques have been proposed to estimate the downwelling shortwave radiative flux at the surface, or insolation, from satellite visible observations (e.g., Gautier et al. 1980; Moser and Rashi 1984; Pinker and Ewing 1985; Dedieu et al. 1987). Of those methods, however, only that of Gautier et al. (1980) has been validated over the ocean. Insolation estimates from most methods are accurate to about 10% on a daily time scale, and better for longer averaging periods.

© 1991 American Meteorological Society
The upwelling component of the net shortwave flux is deduced from the downwelling component and the surface albedo, a rather well modeled quantity over the ocean (e.g., Payne 1972).

The net longwave flux at the surface is also the balance between upwelling and downwelling components. The two components are about one order of magnitude larger than their balance, which partly explains the difficulty in obtaining an accurate net flux. The upwelling flux emitted by the surface is given by the formula

\[ F_{up} = \varepsilon \sigma T_s^4 \]  

where \( T_s \) is the surface temperature and \( \varepsilon \) is the surface emissivity, which is fairly constant over the ocean and equal to 0.98. Accessible accuracy of \( T_s \) from satellite longwave or microwave observations is about 0.5 K, resulting in an accuracy on \( F_{up} \) equal to about 3 W m\(^{-2}\) (Schlüssel et al. 1987). The downwelling flux, however, is much more difficult to estimate since it depends on the atmospheric column state, principally its temperature and water-vapor profiles, as well as cloud parameters, which are presently not retrievable with the same accuracy as the sea surface temperature (SST).

Before satellite observations were available, global coverage of the longwave flux could only be estimated from surface atmospheric observations (temperature, humidity, cloudiness) taken from ships of opportunity. Since no exact relation exists between surface parameters and longwave flux, empirical bulk formulas were used (Fung et al. 1984). Now that satellites allow for global coverage of the oceans, several methods have been proposed to derive the longwave flux from such remote observations. Some methods are statistical, based on regressions between satellite observations and surface measurements (e.g., Smith and Woelf 1983; Morcrette and Deschamps 1986). Others make use of a simple parameterization applied to operational TIROS-N Operational Vertical Sounder (TOVS) products (e.g., Gupta 1989). The more sophisticated employ a radiative transfer model applied to satellite-estimated atmospheric profiles (e.g., Darnell et al. 1983; Frouin et al. 1988). Although the values obtained with these methods are reasonable by comparison with climatology, their accuracy is not sufficient for most applications. The major problem in cloudy conditions is to determine cloud base pressure and atmospheric profiles below clouds.

The accuracy needed for radiative fluxes may vary depending on the application, but "very little work has been done to establish accuracy requirements for Surface Radiation Budget (SRB)" (NASA 1986). However, according to this NASA report, a mean accuracy of 10 W m\(^{-2}\) for monthly averages in 2° × 10° (tropical) and 5° × 5° (extratropical) boxes is adequate for climate studies, and "estimates of lower accuracy will still be valuable for research, although the research goals may become more limited if lower precision is achieved." The accuracy that is currently achieved from the referenced methods is in fact difficult to assess because of a lack of reliable surface longwave measurements over the ocean.

Most satellite-based methods for estimating the longwave flux proceed in two steps: 1) retrieve atmospheric parameters from satellite observations (inverse problem); 2) employ those retrievals in radiative transfer models, or parameterizations, to compute the longwave flux at the surface (direct problem). It is unclear whether the larger uncertainty originates from the first or second step.

In this context, the present study has two main objectives:

1) To critically evaluate two sets of in situ longwave radiation measurements over the ocean. The variability of the fluxes will be described in attempt to distinguish between cloud and clear atmosphere contributions. This study will also point out some of the general problems linked to longwave measurements and the implications for validation activities.

2) To compare various algorithms used to estimate longwave fluxes from atmospheric parameters obtained from satellite or conventional observations. For computing longwave fluxes over large extents of ocean, a method is sought that is not only as precise as possible, but also computationally efficient.

The assessment of in situ longwave measurements is conducted in section 2. Section 3 describes the three methods investigated and compares their longwave irradiance estimates to other method outputs and in situ measurements. Section 4 reviews the study's main results and discusses their implications for conducting future in situ measurement campaigns, selecting longwave estimation methods, and performing climate studies.

2. In situ measurements of downwelling longwave surface fluxes

a. Dataset description

This study uses measurements acquired during two oceanic experiments in midlatitude regions: the Frontal Air–Sea Interaction Experiment (FASINEX) during February–March 1986, in the vicinity of an oceanic thermal front in the Atlantic Ocean, and the Mixed Layer Dynamic Experiment (MILDEX) during October–November 1983, off the California Coast. Even though both experiments took place in midlatitudes, they provided data under a wide range of atmospheric conditions, allowing for a meaningful variability study.

FASINEX was designed to study air–sea interactions in the vicinity of a pronounced oceanic thermal front. During the special observing period, from 5 February to 6 March 1986, two ships, the R/V Oceania and R/V Endeavor, took measurements in the vicinity of the front. These measurements included atmospheric
temperature and water vapor profiles, surface wind speed and direction, and shortwave and longwave surface radiation fluxes. In addition, buoy, aircraft, and satellite observations (NOAA series, GOES) were also acquired (Stage and Weller 1985, 1986). Downwelling longwave fluxes were measured on both ships by an Eppley precision infrared radiometer (model PIR) and were averaged every hour. While the instrument exposure was generally excellent, the radiometer’s field of view aboard R/V Oceanaus was partially obstructed by a wind sensor, and the instrument’s measurements were slightly contaminated. The radiation sensors were regularly cleaned and maintained to ensure measurement quality (Katsaros and Lind 1986). The two ships were rather close to one another, therefore allowing for measurements intercomparisons. However, since they were located in the vicinity of a strong oceanic front, large SST differences between the ships are expected. Recent studies (e.g., Gautier and Bates 1988; Bates and Gautier 1989) have shown that the cloudiness, which strongly influences the longwave downwelling flux, is also different on each side of a front.

MILDEX took place from 26 October to 12 November 1983, in a region approximately 300 km west of Santa Barbara, California, far from any land surface or particular ocean thermal structure. It was designed to observe the surface forcing of the oceanic mixed layer and the dissipation of energy within the layer. Two research vessels, R/V Wecoma and R/V Acania, and a research platform, R/P FLIP, measured surface parameters. Aboard R/P FLIP and R/V Acania, which stayed a few kilometers apart, downwelling longwave fluxes were monitored with Eppley precision infrared radiometers (model PIR) installed at selected locations in order to minimize contamination by radiation emanating from ship structures (Lind and Katsaros 1987).

b. Data quality

Longwave flux measurements are technically difficult to make and require great care in order to give scientifically meaningful results. The most important source of errors comes from solar heating of the radiometer dome that can, when not properly compensated, produce an overestimation as high as 90 W m\(^{-2}\) (Alados-Arboledas et al. 1988; Enz et al. 1975; Weiss 1981; Ryznar and Weber 1982). Another concern is instrument calibration, which has to be done carefully and may need periodic adjustment. The possible input of solar radiation, incorrectly assumed as thermal, may also be a source of error. However, it is believed this last uncertainty is small, on the order of a few watts per square meter (Berdahl and Fromberg 1982; Alados-Arboledas et al. 1988).

Before examining the longwave flux data for variability studies and validation purposes, their consistency was checked. Because several years have passed since the pyrgeometers were deployed, it is not easy to assess their accuracy. Owing to the uncertainties in the relationship between longwave flux and atmospheric parameters, even large biases can be difficult, if not impossible, to detect in some cases. A method to check the quality of pyrgeometer data is to compare simultaneous measurements at nearby locations. If one can assume that, over a sufficiently long time period, the atmospheric conditions are similar at the two locations, one may then be able to detect an eventual bias between the two sets of measurements. Since the atmospheric parameters that govern the longwave flux (temperature, humidity profiles, cloudiness) generally have smooth spatial variations, except perhaps in the case of inhomogeneous cloudiness, two nearby measurements should give very similar results when averaged on time scales of a few hours to compensate for potential broken cloud effects. However, local anomalies of geophysical parameters, such as temperature, humidity, or cloudiness at the instrument location, can affect the temporal sampling. Such singularities are generally not expected over the ocean, where geophysical parameters are homogeneously distributed, except in the vicinity of strong oceanic thermal features. Inhomogeneous topography over land, on the other hand, strongly influences atmospheric parameters, and land-based pyrgeometer measurements may not be representative of surrounding areas. This is one reason why this study was limited to ocean-based measurement experiments.

Even though the measurements were consistent with one another, they could have the same deficiencies, especially since, for a given experiment, the various measurements are generally made with similar instruments that are calibrated with the same procedure. Therefore, it is not possible, through a consistency check alone, to completely trust the pyrgeometer measurements, and their inaccuracy may well be the reason for discrepancies with estimates based on satellite observations, or direct radiative models using atmospheric parameters as input.

Figure 1 compares the hourly downwelling longwave flux measured by R/V Oceanaus and R/V Endeavor during FASINEX, and Fig. 2 displays the difference between hourly measurements taken by the two ships as a function of distance separating the ships. R/V Oceanaus measurements are biased high by 6.8 W m\(^{-2}\). This bias might be explained by the presence aboard R/V Oceanaus of the wind speed sensor in the radiometer field of view. Since the sensor has a radiometric temperature higher than that of the sky, its presence increases the measured value. Also, even though the research vessels did not always stay on the same side of the front, different mean atmospheric conditions may have had a systematic effect on the longwave irradiance. The standard deviation is nearly 20 W m\(^{-2}\) for the hourly measurements, but reduces to 11 W m\(^{-2}\) for daily averages (not shown here). The differences do not appreciably depend on ship distance. In most cases, the two ships were about 30 km apart. At such
a distance, air masses and major cloud systems are strongly correlated, and this correlation does not vary significantly as distance increases. On the contrary, minor cloud systems (convective type) have a low spatial correlation, which may explain why the standard deviation between the two measurements is relatively large on a short time scale.

Next, the diurnal cycle of the measurements was examined, which if present, can indicate an error associated with solar heating of the radiometer. Figure 3 shows the mean diurnal variation of the longwave flux measurements for both ships. As shown, measurements are not correlated to the solar cycle (maximum around 1700 UTC). Although it is still possible that an actual diurnal cycle of the longwave flux exists, it would have to be compensated by a cyclic error caused by the solar heating. This is rather unlikely, and Fig. 3 provides evidence that there was neither a solar heating error, nor a diurnal cycle in the longwave flux during the FASINEX experiment.

Figures 4a–c compare hourly averages of downwelling longwave flux from the three ships that were used during MILDEX. The measurements from R/P FLIP and R/V Acania are the most closely correlated, which is expected since the two ships were very close to one another. However, the comparisons also show a bias on the order of 7 W m$^{-2}$ (R/V Acania measurements are lower). Such a bias provides evidence that at least one of the two datasets is systematically biased. Comparisons with R/V Wecoma data do not show the same correlation, which is also expected since the ship was further away. However, since the ships were in the same area, one expects differences on a hourly basis, but not a systematic bias. Still a bias is present, on the order of 4 W m$^{-2}$ for R/V Acania and 16 W m$^{-2}$ for R/P FLIP. Since the longwave dataset contains several periods without measurement by at least one of the instruments, the three comparisons were not done for the same exact time periods, which explains why the three biases are not consistent with one another (the sum of two should be equal to the third). Objective reasons exist to place more confidence in R/P FLIP measurements. In particular, the instrument was new and well-calibrated. Moreover, the pyrgeometer was located on a pole, which considerably reduces contamination by radiation emanating from the ship.

As was done for FASINEX data, the diurnal variability of the measurements was studied to detect an eventual improper radiometer-heating correction. Figure 5 shows the diurnal variation for the three ships. Although there is some dependence with local time (minimum around local noon), the signal is too weak.
To conclude this section, a tentative quantitative assessment of the longwave flux's accuracy during FASINEX and MILDEX is provided. In both datasets, biases were found between the various instrument outputs that can hardly be explained by different atmospheric conditions. These biases are within the instruments' accuracy specifications. The authors were able, although without convincing evidence, to favor one over the other. The rms differences between the instrument outputs can be explained by the spatial variability of atmospheric parameters, mainly broken cloudiness. Moreover, the common large errors that can be made with pyrgeometers due to the solar heating were checked for and found no evidence of such errors.

Estimates from appropriate atmospheric variables (temperature, moisture, cloudiness) applied to bulk formulas cannot be more reliable than the measurement itself. A natural blackbody covering the instrument could provide a possible validation. A dense, thick fog is close to such a situation. However, to be useful, one must be certain that its temperature is fairly constant, and that the fog is really "black." Such a situation was not recognizable during either the FASINEX or the MILDEX datasets. Therefore, one cannot give more than an estimate of the measurement accuracy, based on the instrument specifications and the fact that no large errors were detected. This accuracy estimate is \( \pm 10 \, \text{W m}^{-2} \).

c. Longwave flux variability

The "clear" fluxes obtained during FASINEX and MILDEX were studied. These were calculated by ap-

and the dataset too small to draw any meaningful conclusions regarding both the diurnal longwave flux cycle and a poor compensation of the instrument solar heating.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{fig4.png}
\caption{Intercomparison of hourly longwave measurements during MILDEX between \textit{R/V We coma}, \textit{R/V Acania}, and \textit{R/P FLIP}.}
\end{figure}

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{fig5.png}
\caption{Diurnal cycle of downwelling longwave flux during MILDEX, as measured by \textit{R/V We coma}, \textit{R/V Acania}, and \textit{R/P FLIP}.}
\end{figure}
Fig. 6. Time series of the “clear flux” during FASINEX (a) and MILDEX (b). The values, given in W m\(^{-2}\), were obtained using Morcrette’s radiative transfer model with the soundings launched from the research vessels as input. The time origin is 0000 UTC 15 February 1986 for FASINEX and 25 November 1983 for MILDEX.

Applying the Morcrette (1984) radiative transfer model to the profiles obtained from radiosondes launched from the experiment ships and assuming a clear sky. Figure 6a shows the results obtained for the two FASINEX ships, \textit{R/V Oceanus} and \textit{R/V Endeavor}, and Fig. 6b, shows those for the MILDEX ship, \textit{R/V Acania}. Examining these figures, the following comments can be made:

1) The variability (differences between maximum and minimum values) of the “clear” longwave flux was 72 W m\(^{-2}\) during FASINEX and 63 W m\(^{-2}\) during MILDEX. Moreover, the standard deviation was lower during MILDEX because the two extremes were reached only once during the last days of the experiment (passage of a pronounced meteorological disturbance). Before this the variability did not exceed 35 W m\(^{-2}\). Some basic statistics on the variability of the “clear” fluxes are presented in Table 1.

2) Additionally, the temporal changes of the “clear” longwave flux are relatively smooth, typically 1–2 W m\(^{-2}\) h\(^{-1}\), and can be accurately depicted with a temporal sampling of 6 h. More rapid changes were possible when a front crossed the experiment zone, but this was not what was observed. This is understandable, however, since atmospheric thermal fronts are wedge-shaped, and the downwelling longwave flux integrates the flux emitted by all atmospheric layers.

3) Finally, Fig. 6a shows that the main features characterizing the evolution of the clear longwave flux, as recorded from the two FASINEX ships, are the same. This is expected since the two ships were about 40 km apart and, therefore, in the same air mass.

Also presented (Fig. 7a–c) is a time series of the in situ measurements, together with the clear flux values estimated from the soundings and the radiative transfer model. For FASINEX, the time series was obtained from hourly averages, and for MILDEX, from half-hourly averages. In the figures the dots correspond to the computed clear flux values at the time the radiosondes were launched. The variability in the downwelling longwave flux, even when averaged on hourly or half-hourly periods, is rather large. It is not uncommon to observe a difference of several tens of watts per square meter from one measurement to another. Since the clear flux varies rather smoothly, these large gaps between measurements are attributable to the cloud effect, resulting from a change in the mean cloudiness. However, most of the low-frequency variability depicted by the time series is retrieved in the clear values. This can be explained by the fact that, although both components of the longwave irradiance have the same variability, the clear flux has the greater time scale and is therefore responsible for the large features. There is a variable difference between “clear” and measured fluxes, which corresponds to the sum of the cloud effect, an eventual bias of the measurements, and a possible error on the clear-flux estimates. The difference is always positive, which is expected since the cloud effect increases the downwelling flux. The clear-flux values, however, should follow the time series more closely during clear-sky conditions. From the minimal difference between the measurement and clear-sky estimate, we suspect a bias of about 10 W m\(^{-2}\) that may originate.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Ship</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Endeavor</td>
<td>Oceanus</td>
<td>Acania</td>
</tr>
<tr>
<td>Minimum value</td>
<td>287</td>
<td>294</td>
<td>274</td>
</tr>
<tr>
<td>Maximum value</td>
<td>359</td>
<td>366</td>
<td>337</td>
</tr>
<tr>
<td>Mean</td>
<td>326</td>
<td>330</td>
<td>314</td>
</tr>
<tr>
<td>Standard deviation</td>
<td>20</td>
<td>21</td>
<td>16</td>
</tr>
<tr>
<td>Number of points</td>
<td>40</td>
<td>49</td>
<td>30</td>
</tr>
</tbody>
</table>
An attempt to relate the cloud effects on both the longwave and the shortwave irradiance was made knowing that these two forcings of the surface radiation budget somehow compensate: clouds tend to decrease the incoming shortwave radiation at the surface, whereas they increase the longwave radiation. The parameter, Cld, can be defined with the equation:

\[ I_{\text{surf}} = I_{\text{clear}} (1 - \text{Cld}) \]  

(2)

where \( I_{\text{surf}} \) is the insolation at the surface and \( I_{\text{clear}} \) is the insolation that would be measured under clear sky conditions. The cloud parameter, Cld, as defined by (2) varies between 0 (clear sky) and 1 (overcast, impervious clouds). The term \( I_{\text{surf}} \) can be measured with a pyranometer and a climatological value of \( I_{\text{clear}} \) is a good approximation.

Figure 8 shows the longwave cloud effect, defined as the difference between the measured flux and clear-sky estimate, as a function of the shortwave cloud parameter averaged over the length of the day during FASINEX and MILDEX. The magnitude of the longwave cloud effect is about 65 W m\(^{-2}\), which is comparable to the variability of the clear atmosphere contribution. It is interesting to note that this value (65 W m\(^{-2}\)) agrees well with the theoretical estimation of the cloud effect for typical midlatitude clouds found by Frouin et al. (1988).

The mean slope of the relation between the longwave cloud effect and the shortwave cloud parameter is 95 W m\(^{-2}\), imposing the best-fit curve to pass through the origin (no cloud). The corresponding rms is 14.4 W m\(^{-2}\). This scatter around the best-fit curve has several causes:

1) If the cloud is thick enough to be opaque to the infrared radiation, an increase in thickness will change the shortwave cloud parameter without changing the longwave cloud effect.

![Fig. 7. Time series of the downwelling longwave flux measured on board the research vessels (line) and clear-flux estimation from the soundings using Morcrette's radiative transfer model (dots). Values are in W m\(^{-2}\). (a) was obtained from Oceanus data, (b) from Endeavor data, and (c) from Acania data. Time origins are the same as in Fig. 6.](image)

![Fig. 8. Daily values of longwave cloud effect, given in W m\(^{-2}\), as a function of shortwave cloud parameter for both FASINEX and MILDEX experiments. The line represents the best regression fit when forced to pass through the origin (clear conditions).](image)
2) For given cloud properties (thickness, liquid-water concentration), the shortwave cloud parameter is nearly insensitive to the atmospheric level of that cloud, whereas the longwave cloud effect is very sensitive to cloud base temperature, which is related to the cloud base pressure.

Moreover, uncertainties remain in the clear flux estimate and the in situ measurements, which, using the present estimation method, leads to uncertainty in the longwave cloud effect. However, these uncertainties are much smaller than the total variability of the cloud effect and may result in a bias rather than a scatter.

Estimating the longwave cloud effect as a linear function of the cloud parameter can lead, on a daily basis, to uncertainties as high as several tens of watts per square meter. However, these uncertainties are reduced with longer time scale averages, which makes this approach useful for climate studies.

3. Parameterizing downward longwave irradiance at the surface

Because of the importance of longwave flux for climate studies, as well as other applications, several sophisticated radiative transfer codes have been developed for estimating the longwave flux at the surface. However, estimating this parameter over large ocean extents and long time periods can be computer time-consuming if sophisticated radiative transfer models are used. Accordingly, simplified models have been proposed. In this paper, three models are presented that vary in their degree of sophistication. This paper intercompares their clear flux and cloud effect estimates and matches these outputs against in situ surface measurements.

a. Method description

1) Morcrette’s Radiative Transfer Model

A highly parameterized scheme has been developed by Morcrette for global circulation models (GCMs) (Morcrette 1984; Morcrette and Fouquart 1985; Morcrette et al. 1986). It is presently used in the European Centre for Medium-Range Weather Forecast (ECMWF) model. The scheme considers six spectral intervals and accounts for absorption by water vapor (lines + continuum), carbon dioxide, and ozone. Absorption by minor gaseous constituents (e.g., methane and nitrous oxide) and aerosols is neglected. Unlike the other models presented below, Morcrette’s model was designed to compute not only the flux at the surface, but also the upwelling and downwelling fluxes at each level of the atmosphere.

Validation of this model was performed during the Inter Comparison of Radiation Codes for Climate Models (ICRCCM) using five atmospheric profiles typical of tropical, summer midlatitude, winter mid-latitude, summer polar, and winter polar conditions (WMO 1984). The comparisons, made only for clear sky conditions, were performed with line-by-line radiative transfer models. They showed good agreement between the Morcrette and line-by-line algorithms, demonstrating that Morcrette’s parameterization accuracy is close to that of line-by-line models.

2) Gupta’s Parameterization

Recently, Gupta (1989) modeled the downwelling longwave flux at the surface as a function of atmospheric parameters that can be obtained from TOVS observations (Kidwell 1981). The longwave flux at the surface is computed as the sum of a clear flux and a cloud effect. The clear flux is parameterized from a weighted mean atmospheric temperature below 700 mb and the total atmospheric water-vapor content. The cloud effect is obtained as a function of the cloud base temperature (obtained from the cloud-top pressure assuming that the cloud is 50 mb thick) and the water-vapor content below the cloud.

Because of its simplicity, Gupta’s model is well-adapted to monitoring surface longwave fluxes on a global scale. The parameterization coefficients, however, have been obtained from a limited set of atmospheric situations. The accuracy of the results are questionable for atmospheric profiles very different from those contained in the dataset used in the regression. This is a general concern for regression-based methods compared with those based on physical principles.

3) Anderson’s Empirical Formula

Over the ocean, most in situ observations are made from commercial ships equipped with simple meteorological instruments. They measure air temperature, water vapor mixing ratio, wind speed, and direction. Some observations of cloudiness (fractional cover, cloudiness) and sea surface temperature can also be made, but there is no information on the atmospheric vertical structure. An accurate estimation of the downwelling surface longwave flux requires a description of the air composition and temperature not only at the surface itself, but also in the overlying atmospheric layers. Since very few in situ measurements of atmospheric profiles are made over the ocean, several authors have attempted to relate the conventional surface measurements to the longwave flux. This approach is justified because the longwave flux at the surface depends mainly on the lower atmospheric layers, and because surface and atmospheric parameters are highly correlated, at least on daily and longer time scales.

Fung et al. (1984) reviewed bulk formulas commonly used to estimate the net longwave flux at the surface, \( F_{\text{net}} \). They compared these formula estimates to computations from a radiative transfer model applied to theoretical atmospheric profiles (six typical
profiles and the same profiles shifted warmer, colder, wetter, and dryer). Some of the formulas reproduce the surface fluxes to 10 W m$^{-2}$ or better for the typical profiles, and to 15 W m$^{-2}$ or better for the perturbed ones. One important conclusion of this theoretical study is that the bulk formulas cannot reproduce the cloud effect correctly other than on seasonal time scales since the cloud base altitude, which has a very important effect on the flux, is not taken into account.

Bulk formulas do not apply perfectly in our study, which focuses on downwelling longwave flux rather than the net longwave flux. However, since the surface emission is given by $\varepsilon T_S^4$, where $T_S$ is the sea surface temperature (SST), one can derive formulas specific for the downwelling flux. Surprisingly, these new formulas are still a function of the SST. Despite the fact that SST and near surface air temperature are similar, it would certainly be better to have a net longwave flux formula that clearly distinguishes the upwelling flux, a function of the SST alone, from the downwelling flux, a function of atmospheric parameters.

Among the eight proposed bulk formulas, Anderson’s (1952) was chosen because it fits well with the radiative transfer estimates of Fung et al. (1984), and because, in clear conditions, it clearly separates the upwelling and downwelling components. The Anderson (1952) formula states:

$$ F_{\text{net}} = \varepsilon T_S^4 - T_a^4 (0.74 + 0.0049 P_{\text{H}_2\text{O}}) \varepsilon (N) $$

where $P_{\text{H}_2\text{O}}$ is the water vapor pressure at the surface and $\epsilon(N)$ is a function of the cloud cover (equal to 1 when $N$ is equal to 0). In clear conditions we therefore obtain:

$$ F = \varepsilon T_a^4 (0.74 + 0.0049 P_{\text{H}_2\text{O}}), $$

which depends only on atmospheric parameters since $\varepsilon$ can be considered as a constant.

Finally note that in cloudy conditions the downwelling flux [obtained by subtracting $\varepsilon T_S^4$ from (3)] depends on sea surface temperature when, physically speaking, it should not. All bulk formulas proposed in the literature, unfortunately, take into account the effect of clouds in a similar way.

b. Method intercomparison

1) CLEAR SKY

Table 2 gives the clear-sky downwelling longwave flux at the surface as estimated by the three models described above and the 4A line-by-line model of Scott and Chédin (1981) for the five ICRCCM profiles. Morcrette’s and the 4A models exhibit very close values, with differences on the order of 4 W m$^{-2}$. When compared to the 4A model, Gupta’s model shows a bias ranging from 7 to 14.5 W m$^{-2}$, with a mean of 10 W m$^{-2}$. Differences with the bulk formulas are much larger; they are as high as 24 W m$^{-2}$ for the midlatitude winter atmosphere, and 20 W m$^{-2}$ for the polar winter. These differences are, with one exception, positive, meaning that the line-by-line model gives generally smaller values than the other models.

The same kind of comparisons were made with a larger set of atmospheric profiles. These are the soundings collected during FASINEX and MILDEX. This study does not include as wide a range of atmospheric conditions as the ICRCCM profiles. Rather, it concentrates on certain types of profiles, allowing one to examine how well the various models describe the variability of the downwelling longwave flux.

Figure 9 compares the clear fluxes obtained with the different approaches, except 4A, when applied to about 100 FASINEX and MILDEX soundings (4A was excluded because of its large computer-time requirements). The variability of these computed fluxes is, as was shown in section 2c, about 70 W m$^{-2}$.

The Gupta and Morcrette models agree well with one another. Their bias is slightly positive (4 W m$^{-2}$ higher for Gupta’s), but the standard deviation is less than 4 W m$^{-2}$. When comparing Anderson’s bulk formula to the other two models the differences are larger; Anderson’s formula yields a 3 W m$^{-2}$ bias when compared to Gupta’s model, and a 7.5 W m$^{-2}$ bias when compared to Morcrette’s model. In both cases standard deviation is close to 8 W m$^{-2}$.

2) CLOUD EFFECT

As was done for the clear flux, the cloud effect was compared as given by the three approaches. This was accomplished for the five ICRCCM test atmospheres by computing the increase in surface longwave flux resulting from the presence of an overcast, optically black cloud located at various atmospheric levels, ranging from 1013 to 200 mb.

In Anderson’s formulation, the cloud effect does not depend on the cloud-base pressure or temperature, since these parameters cannot be easily monitored from

<table>
<thead>
<tr>
<th>Situation</th>
<th>Tropics</th>
<th>Midlatitude summer</th>
<th>Midlatitude winter</th>
<th>Polar summer</th>
<th>Polar winter</th>
</tr>
</thead>
<tbody>
<tr>
<td>4A model</td>
<td>390.6</td>
<td>341.8</td>
<td>213.1</td>
<td>289.3</td>
<td>165.1</td>
</tr>
<tr>
<td>Morcrette’s</td>
<td>395.1</td>
<td>346.2</td>
<td>214.9</td>
<td>295.7</td>
<td>163.8</td>
</tr>
<tr>
<td>Gupta’s</td>
<td>399.5</td>
<td>351.5</td>
<td>223.5</td>
<td>303.9</td>
<td>172.0</td>
</tr>
<tr>
<td>Anderson’s</td>
<td>398.1</td>
<td>352.3</td>
<td>237.0</td>
<td>307.1</td>
<td>185.0</td>
</tr>
</tbody>
</table>
the surface. For each profile, therefore, there is one cloud effect, whose value is displayed in Table 3 for an overcast situation ($N$ equal to 1). The cloud effect ranges from 40 to 50 W m$^{-2}$.

Unlike Anderson’s formula, Morcrette’s model and Gupta’s parameterization take into account the cloud base pressure explicitly or implicitly. Therefore, the cloud effect was computed for each of the ICRCCM profiles as a function of cloud base pressure. The results are presented in Figs. 10a,b and the differences between the cloud effect obtained by the two models is shown in Fig. 10c. As expected, cloud effect increases with cloud-base pressure. The only exception to that rule is found in the lower layers of the polar winter profile, for which the Morcrette model estimate decreases slightly with increasing pressure; this is explained by the presence of a sharp temperature inversion in that boundary layer. Such a decrease in downwelling longwave flux is not captured by Gupta’s parameterization. However, it does present a much lower increase than is found in the other profiles. In fact, it will show below that Gupta’s model results are not accurate for cloud base located below 800 mb.

For levels above 800 mb, the differences between the results of the two approaches are rather small: always less that 8 W m$^{-2}$. For the lower atmospheric layers, however, Gupta’s parameterization gives values much higher than Morcrette’s, with differences reach-

**Table 3.** Clear-sky contribution and cloud effect on downwelling longwave flux at the surface the ICRCCM model atmospheres as predicted by Anderson formula.

<table>
<thead>
<tr>
<th>Model atmosphere</th>
<th>Clear-sky flux (W m$^{-2}$)</th>
<th>Cloud effect (W m$^{-2}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tropical</td>
<td>398.1</td>
<td>39.8</td>
</tr>
<tr>
<td>Midlatitude summer</td>
<td>352.3</td>
<td>46.4</td>
</tr>
<tr>
<td>Midlatitude winter</td>
<td>237.0</td>
<td>48.3</td>
</tr>
<tr>
<td>Polar summer</td>
<td>307.1</td>
<td>50.4</td>
</tr>
<tr>
<td>Polar winter</td>
<td>185.0</td>
<td>40.7</td>
</tr>
</tbody>
</table>
where $T_{cb}$ is the temperature of the cloud base that can be approximated by the surface temperature. The cloud effect reduces to:

$$F_{cloud} = \alpha T_{cb} - F_{clear}. \tag{5}$$

This value was computed using the clear flux given by Gupta's parameterization. The results are summarized in Table 4.

The theoretical estimates ($\sigma T_{cb} - F_{clear}$) are in complete disagreement with Gupta's value (cloud effect), which is much too high. The same study applied to Morcrette's model, however, gives consistent results, which is expected since the scheme is more physical. The poor results obtained with Gupta's parameterization in the case of very low clouds is in contrast to the consistent ones yielded for the clear fluxes and cloud effect in the case of higher clouds. This may be explained by the fact that the coefficients of Gupta's formulas have been obtained by regression with a dataset containing very few profiles with low clouds.

c. Comparisons with in situ measurements

The logical next step for this study was to compare the various method results with the in situ measurements. The temperature and water-vapor profiles, as measured by the radiosondes, were used to specify the temperature and water vapor for the three investigated approaches. The ozone profile required in Morcrette's model was taken from climatology by using the midlatitude winter ICRCCM profile. The main difficulty was to estimate the cloud parameters needed in the various approaches, principally cloud-base pressure and fractional cloud cover. The cloud-base pressure was estimated from the temperature and dewpoint sounding profiles. The cloud cover was extracted from hourly reports of cloudiness logged aboard the ships. Due to a lack of cloud emissivity information, we had to assume that the clouds were black. Cloud parameters determined from the in situ observations are therefore highly subjective, and great precaution must be taken when analyzing the comparisons between in situ measurements and model estimates. Moreover, the surface measurements were time-averaged, whereas calculations resulted from instantaneous observations.

Figures 11a–c show the results of the comparisons between hourly in situ measurements and model estimates. Several comments can be made:

1) The comparison between in situ measurements and Morcrette's model estimates (Fig. 11a) reveals a positive bias greater than 10 W m$^{-2}$ and an rms difference of 27 W m$^{-2}$.

These statistics can be explained by a poor estimation of the cloud effect. The uncertainty originates from the input cloud parameters, cloud amount, and cloud base pressure, whose accuracies are questionable. The assumption that the cloud is black regarding longwave radiation needs to be mentioned since it is possible that, in some cases, and par-
particularly for very low clouds, the cloud liquid-water content was so small that the clouds were grey. Values of about 5 g m$^{-2}$ for the liquid-water content of marine stratuscumulus have frequently been observed (e.g., Stephens 1978). Since the clouds were assumed to be black, conditions with such low liquid-water content would lead to an overestimation of the cloud effect, which in turn could explain the positive bias.

2) The systematic overestimation of the cloud effect by Gupta's model for very low clouds is clearly seen on Fig. 11b. Frequent occurrence of low clouds was reported during both experiments, a situation represented in the results. This also indicates that the statistics obtained with this limited dataset are not representative of global mean atmospheric conditions.

3) Surprisingly, the simplest model, Anderson's
bulk formula, gives the most accurate results or, from a less optimistic point of view, the least noisy results. The bias is closer to zero, and the rms difference is less than 17 W m$^{-2}$. Since for each model most of the error is due to the cloud-effect estimate, it suggests that it might be better to take a climatological value for the cloud effect rather than inaccurate cloud characteristic estimates together with an uncertain knowledge of its effects.

4. Summary and conclusions

In the first part of this paper two sets of in situ longwave measurements taken during the FASINEX and MILDEX experiments were investigated. Although these measurements were carefully taken, biases were found in the data of nearby instruments that are of the same order of magnitude as the required accuracy for the longwave flux estimation ($\approx 10$ W m$^{-2}$). This shows, once again, the extreme difficulty in acquiring reliable longwave in situ measurements. Even when no bias is present, it is impossible to fully trust the measurements because the instruments are identical and calibrated with the same procedure, and thus their measurements may have the same deficiencies. This situation is not exceptional. Other sets of longwave measurements acquired during atmospheric or oceanic experiments studied also showed questionable values. These experiments include HAPEX-MOBILHY (André et al. 1986), TROPIC-HEAT (Nilier 1984), and FIFE (Sellers et al. 1988). Recent assessments (De Luisi 1989) of the quality of longwave measurements suggest that an absolute accuracy better than 5% cannot be achieved with existing pyrgeometers. New methods to acquire reliable longwave measurements should be investigated for more precise verifications. However, the accuracy of the instruments used in this study was assumed to be sufficient to assess the clear flux and cloud effect variabilities.

No noticeable diurnal cycle of the longwave flux was found during the two oceanic experiments investigated. This is in contrast to the large cycle (up to 30 W m$^{-2}$) found over land during the FIFE experiment (Bréon et al. 1990). Two oceanic experiments are obviously insufficient to extend this conclusion to the whole ocean; it is, however, an important result since the satellites currently used for monitoring surface longwave fluxes are heliostations.

The variability of the “clear” component of the flux, as computed using a radiative transfer model applied to radiosonde profiles, was found to be fairly smooth, typically on the order of 1–2 W m$^{-2}$ h$^{-1}$, even when an atmospheric front crossed the experiment area. Moreover, variations in the clear longwave flux associated with air mass changes, as well as variations due to cloud effects, were found to be of the same order of magnitude ($\approx 70$ W m$^{-2}$). This shows that the cloud effect accounts for a large portion of the longwave flux variability and should therefore be estimated with great care. However, none of the investigated methods provides an accurate cloud effect estimation, at least for short time scales. Moreover, the variabilities of the clear flux and the cloud effect given in this paper are representative of a given month in midlatitude areas. If the experiments had lasted the entire year, a higher clear flux variability but a similar cloud effect variability might have been found.

Carefully taken in situ longwave flux measurements, such as those obtained during the two experiments investigated, are very rare over the ocean. Monitoring this flux over large extents of ocean requires the use of simplified approaches that estimate longwave flux from other measured atmospheric parameters. Three approaches were investigated: a rather complex scheme (Mocrette 1984), a simpler parameterization (Gupta 1989), and a “surface only” bulk formula (Anderson 1952).

Applied to clear radiosonde profiles, the two more sophisticated approaches (Mocrette’s model and Gupta’s parameterization) provided very consistent results. However, results from both approaches exhibited a relative bias of the same order of magnitude as the desired accuracy for the longwave flux estimates. If more reliable ground truth measurements become available, the bias should be investigated in order to favor, if possible, one of the two methods. Comparisons with the bulk formula yielded a higher scatter that showed that this parameterization is unable to fully represent the clear-flux variability. The cloud effect parameterization was also investigated using five atmospheric profiles typical of summer and winter situations over tropical, midlatitude, and polar regions. The bulk formula gives only a climatological estimate that does not depend on the cloud-base pressure. However, this estimate compares well with the mean value given by the two other methods. These methods are fairly consistent with one another, except in the case of low clouds, for which Gupta’s estimate is definitely too high. This problem could easily be remedied to give a more accurate version of Gupta’s parameterization by constraining cloud effect for low-level clouds or computing new regression coefficients using a dataset containing numerous low level clouds. However, this inaccuracy is typical of what might be obtained with a statistical scheme for conditions different from those used to obtain the regression coefficients. This strongly suggests the use of simple yet physical algorithms.

Finally, surface longwave flux estimates from the three approaches were compared with in situ measurements. This was difficult due to a lack of reliable cloud parameter measurements. The cloud-base pressure was estimated in an ad hoc manner from the temperature and humidity profiles, while the cloudiness was obtained from the ship observations. For all three methods, the scatter around the ground-truth measurement was rather large and, surprisingly, the bulk formula gave the least noisy results. This is explained
by the large uncertainty in the cloud parameters (cloud-base altitude and emissivity). When no reliable estimate of those crucial parameters can be made, it appears to be more accurate to use a climatological value for the cloud effect on the longwave flux, as is done implicitly in bulk parameterizations. However, the accuracy achieved with this method is not satisfactory and methods to retrieve valuable cloud parameters must be developed.

During the two oceanic experiments that were studied here, not enough clear cases occurred for a complete validation of the clear-flux estimates with the three methods tested. Cloudy cases could not yield definite conclusions because of the uncertainties in the cloud parameters. However, a validation of the clear flux was made possible using the FIFE measurements (Bréon et al. 1990). One conclusion from this study, performed over land, is that clear-flux estimate accuracy was well within the uncertainty of the measurements (10–15 W m⁻²). The radiative transfer computation in cloudy conditions, outside of clouds, is theoretically not more difficult than in clear conditions. One can therefore expect that, if the cloud parameters (emissivity, base pressure, effective radiating temperature) were known with sufficient accuracy, the longwave-flux estimate would have the same accuracy in clear and cloudy conditions. In other words, the uncertainty of the cloud effect is due to the uncertainties in cloud parameters rather than in the radiative model itself. However, the knowledge of those cloud parameters requires better modeling and understanding of the radiative transfer within the clouds.

Climate diagnostic studies require accurate estimates of the net surface radiation flux (about 10 W m⁻²) in order to understand the impact of the surface radiative forcing and its variability on various surface processes (e.g., upper-ocean heat content variability, land surface evapotranspiration). These types of requirements are very stringent and probably cannot be achieved with existing technology for surface measurements (particularly longwave measurements as this study and others suggest) even if a sufficiently dense network were established. In any case, the cost for implementing such a network is probably prohibitive for the international scientific community and alternatives such as combining in situ measurements and satellite estimations must be sought for global monitoring. In this context, this study provides some idea of the limitations to be expected from available approaches using current technology and computational methods.

It is believed that the type of work reported here is also important for studies pertaining to global change. Accurate predictions of the magnitude of global warming can only be achieved with precise atmospheric GCMs. It is now commonly accepted that the major uncertainty in the magnitude of CO₂-induced global warming lies in the cloud feedback on the earth's warming. Cloud parameterizations in GCMs are still rather crude, and the GCM grid is much larger than natural cloud spatial variability. However, the warming prediction does not necessarily require a precise three-dimensional cloud description in the GCMs, but rather an accurate estimate of their mean radiative effects. Therefore, an extremely useful way to validate current GCMs would be to compare their estimated longwave flux at the surface with accurately estimated fields of this parameter. This comparison could be done either over limited regions selected for their homogeneity where in situ measurements could be representative of the area, or globally, using remotely sensed longwave flux fields. The former requires highly accurate in situ measurements that are not currently available, and the latter needs prior validation of satellite-derived methods for the estimation of surface longwave fields. Improvements in GCM cloud parameterizations that may result from such comparisons will benefit climate studies that make use of these GCMs.

Acknowledgments. This work was supported by ONR Contract N00014–87–K and by the California Space Institute under Grant CS89–89. We wish to thank K. Katsaros and R. Lind who provided and commented on the data used in this study. The editing help of K. Shapiro and B. Bloomfield is greatly appreciated. We would like to thank the reviewers for their criticisms and comments, which helped us improve this paper.

REFERENCES


WMO-ICSU, 1984: The intercomparison of radiation codes in climate models. World Climate Research Program Report WCP-93, Geneva,