Validation of downwelling longwave computations with surface measurements during FIFE 89

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Abstract. The amount of longwave radiation reaching the surface is a necessary parameter for climate modeling. As no extensive array of surface-based stations exists for monitoring the downwelling longwave surface flux \( (F_{\downarrow}(0)) \), satellites are expected to provide the data necessary for its computation. Before global fields of satellite-derived values of \( F_{\downarrow}(0) \) can be used for climate modeling, computations of \( F_{\downarrow}(0) \) need to be validated with surface measurements. In this study the validation of computations of \( F_{\downarrow}(0) \) is carried out for both clear and cloudy conditions using data from the 1989 phase of the First ISLSCP Field Experiment (FIFE 89). FIFE 89 data is particularly useful for this study, as it contains lidar measurements of cloud base height and cloud fraction, thereby eliminating the need to estimate these parameters from other available data. Using a combination of the delta-Eddington approximation for atmospheric scattering and the LOWTRAN 7 transmission functions, the computation of \( F_{\downarrow}(0) \) was carried out with particular emphasis on the reliability of the available data. Our results show that the two largest sources of discrepancies between the measured and calculated \( F_{\downarrow}(0) \) values are the lack of knowledge of cloud optical depth and the measurement error inherent in pyrgeometer instruments. The uncertainty due to the lack of optical depth information ranges from 1 to 22 W/m², while the uncertainty of the pyrgeometer measurements ranges from 15 to 23 W/m². For both clear and cloudy conditions the radiative transfer model was able to predict surface irradiance values within 4% of the measured values. In each case the standard deviation of the calculated values fell within the accuracy range of the pyrgeometer. As more detailed observations become available, such as those from the Atmospheric Radiation Measurement program, we anticipate a refinement in our ability to compute \( F_{\downarrow}(0) \).

1. Introduction

The amount of longwave radiation reaching the surface of the Earth is a key indicator of the strength of the greenhouse absorbers in the atmosphere and hence a key indicator of climate. As such, the downwelling longwave surface flux \( (F_{\downarrow}(0)) \) is a necessary parameter for climate modeling. Since no global network exists for monitoring \( F_{\downarrow}(0) \), the monitoring of \( F_{\downarrow}(0) \) relies heavily on satellites to provide those parameters necessary for its computation. Before global fields of \( F_{\downarrow}(0) \) computed from satellite-derived data can be effectively used for climate modeling, the computations need to be validated with surface measurements. Calculations of \( F_{\downarrow}(0) \) are difficult due to its strong dependence on the vertical distribution of temperature, water vapor, and cloud. In this study we validate surface based measurements using a physically based radiative transfer model. Both physically and statistically based methods, with varying degrees of sophistication, have been developed for the computation of \( F_{\downarrow}(0) \). These methods, however, are still in their infancy, particularly for cloudy conditions.

Using a wideband radiative transfer model, Frouin et al. [1988] calculated \( F_{\downarrow}(0) \) within 8% of measured values using satellite derived input. Cloud base height was determined from cloud top height and an estimate of liquid water path from top of the atmosphere reflectance measurements. Cloud fraction was estimated from high-resolution visible data using a threshold technique. Wu and Cheng [1989] developed two methods for the determination of cloud base height for their calculations of \( F_{\downarrow}(0) \). For overcast conditions, cloud base height was fixed to the same height as the top of a well mixed layer. For partly cloudy conditions, cloud base height was determined from a statistical approach based on the frequency of infrared radiances. Wu and Cheng computed global fields of the downward longwave flux using satellite derived input for January and July but have not compared the results with any surface measurements. Gupta et al. [1992] computed \( F_{\downarrow}(0) \) from parameterized equations derived from a detailed radiative transfer model validated to measured surface fluxes. Cloud base temperature and water vapor burden below the cloud base were modeled from satellite observations using a constant cloud thickness. Harshvardhan et al. [1990] provided a theoretical framework for estimating the monthly mean net longwave surface flux. Their method is based on the relationship between the mean longwave cloud radiative forcing at the top of the atmosphere and at the surface. This method eliminates the need for cloud base height and cloud fraction information. Sugita and Brutsaert [1993] incorporate several different measurements of cloudiness into the clear sky calculations of \( F_{\downarrow}(0) \) to account for the presence of clouds. These measures include visually obtained cloud type information, TIROS Operational Vertical Sounder (TOVS) derived cloud coverage, and the use of a "clearness index" as a measure of cloudiness. When compared to measured values at the surface, the most reliable estimates of the instantaneous downward longwave surface flux were obtained when both cloud type and cloudiness factors were considered.

Of these methods, in situ validation has been more successful...
for clear sky conditions than for cloudy sky conditions. In situ validation of cloudy sky conditions is not easily obtained because of the difficulty of modeling clouds and the lack of in situ observations. On a climatological basis, monthly averages of $F(0)$ are more indicative of climate change than instantaneous values are. Before reliable monthly averages can be obtained we need confidence in the methods which are used to determine the values comprising the monthly averages. Once confidence in the techniques is achieved we can have confidence when they are applied to global fields for which surface validation is not available.

This leads to an important issue: how well do radiative transfer models perform in cloud conditions? Under clear conditions the Intercomparison of Radiation Codes used in Climate Models (ICRCCM) [Ellington et al., 1991] program has provided us with an idea of how various models compare for the calculations of the downwelling longwave surface radiation under clear conditions. The recent Spectral Radiation Experiment (SPECTRE) [Ellington et al., 1993] has demonstrated that high spectral resolution models provide accuracies on the order of 2-3 W/m² (R. G. Ellington, personal communication, 1994). Similar extensive and detailed studies under cloudy conditions are still forthcoming. The goal of this paper is to perform a study of such nature with data available from the First ISLSCP Field Experiment (FIFE) [Sellers et al. 1992]. While the FIFE experiment was not explicitly designed for such studies, it has devoted considerable attention to obtaining those parameters necessary for the calculation of climatologically significant longwave surface parameters. The 1989 phase of FIFE produced the data necessary to compute the downwelling longwave surface irradiance for both clear and cloudy conditions and provided in situ pyrgeometer measurements for validation. The FIFE data set is particularly useful for the calculation of the longwave flux under cloudy conditions since it provides direct lidar measurements of cloud base height and cloud coverage, eliminating the need to estimate these two cloud parameters. All data were collected during the fifth Intensive Field Campaign (IFC5) of FIFE 89 and are described in section 2. Section 3 discusses the radiative transfer code employed to compute $F(0)$. The procedures used to obtain the calculations are presented in section 4 while the results are compared to in situ measurements in section 5. A summary follows in section 6.

2. Data

The FIFE experimental site covers an area 15 x 15 km² on the Konza Prairie near Manhattan, Kansas. The terrain is relatively flat (+/- 50 m elevation) and the vegetation is mostly native tallgrass. IFC5 covers the time period from July 24 through August 12, 1989. Our study uses four types of measurements: radiosonde, lidar, pyrgeometer, and pyranometer. These data were collected from surface stations identified in Figure 1. The radiosonde, pyrgeometer, and pyranometer data are available from the FIFE Information System (FIS) [Strebel, 1990] while the lidar data has been obtained directly from the principal investigator responsible for its data collection.

Radiosondes launched from the experimental site provide temperature and moisture profiles. Approximately six radiosondes were launched per day at 2-3 hour intervals between 0900-1800 CDST. The vertical resolution of the soundings is 15-20 m. Radiosondes provide measurements of the vertical profiles of wet and dry bulb temperature from which actual water vapor pressure can be calculated according to the psychrometric equation [Kalogiros and Helmis, 1993]. Details of the radiosonde flights are described in more detail by Sugita and Brutsaert [1990].

Collocated pyrgeometer and pyranometer collected measurements of the downwelling radiation from a height of 1.75 m above the surface. The pyrgeometer blocked out solar wavelengths below approximately 3 μm and the pyranometer blocked out infrared wavelengths above approximately 3 μm. The two data sets provide downwelling radiation measurements averaged over one-half-hour intervals throughout the duration of the campaign.

Cloud base altitudes and cloud coverages were obtained from measurements taken by a Volume Imaging Lidar (VIL). The VIL scans a volume of approximately 100 km³ with a spatial resolution of 15-100 m and a temporal resolution of 3 min/scan. Cloud base height is determined for the entire VIL scanning area volume. Cloud coverage is calculated for a sector 5 km in length and is determined from the number of profiles which impact clouds near the cloud base altitude. The cloud coverage data is reported to be most reliable for small cloud coverage percentages. For higher cloud cover percentages the algorithm used to determine cloud cover may miss gaps between the clouds resulting in an overestimation of cloud coverage. Cloud base height and cloud coverage data available for this study have been passed through a 10-min minimum filter and a 10-min average filter, respectively.

Although the above instruments are not collocated, they comprise the most complete set of data available for the described experiment. The distance separating the instruments is shown in Figure 1. The largest uncertainty caused by the distance separating the instruments is the relationship between the scanning volume of the lidar and the atmosphere influencing the pyrgeometer. To determine the similarity between the scan volume of the lidar and the atmosphere influencing the pyrgeometer, a cloud index was established at the surface flux station from pyrgeometer measurements. The cloud index is computed from the following equation:

\[
\text{cloud index} = 1 - \frac{\text{measured surface insulation}}{\text{modeled clear sky surface insulation}}
\]

Only those profiles for which there is reasonable agreement between the cloud index and the lidar cloud fraction are used in this study. Figure 2 identifies the profiles accepted for this study and the corresponding cloud index and lidar cloud fraction. Times at which the cloud coverage exceeded 5% were considered cloudy, while cloud coverages of less than 5% were considered clear. When the lidar cloud coverage measurement was less than 5% and the computed cloud index was greater than 10%, the atmosphere was considered cloudy. In these cases, the cloud index was used as a proxy for cloud fraction. Although cloud fraction and cloud index are two different measures of cloudiness, cloud index provides an indication of cloud fraction, as Figure 2 suggests.

3. Radiative Transfer Code

The goal of this paper is to perform a preliminary investigation identifying how well radiative transfer models (RTMs) perform under cloudy conditions. With this in mind we chose a sophisticated model, a combination of the LOWTRAN 7 [Kneizys et al., 1988] transmission functions and the delta-Eddington approximation [Joseph et al., 1976] for scattering. The combined RTM provides a numerically stable algorithm to solve the equations of radiative transfer in a plane-parallel atmosphere.
The LOWTRAN 7 code is a low-resolution band model developed from degraded line-by-line spectra and validated against laboratory measurements. It calculates transmission and radiance values for 20 cm⁻¹ wavenumber intervals. LOWTRAN 7 contains separate band models which account for the radiative effects of water, carbon dioxide, ozone, methane, nitrous oxide, and carbon monoxide along with five other atmospheric gases. The water vapor continuum absorption has been modified from earlier versions of LOWTRAN according to laboratory and atmospheric measurements [Pierluissi et al., 1989].

The k distribution method is incorporated within LOWTRAN 7 for integrating absorption over frequency. The k distribution method is a curve fit of three individual components providing an accurate representation of absorption for given frequency band. A benefit of the k distribution method is that it provides a fast and reliable method for treating the vertical inhomogeneity of the atmosphere. [Goody et al., 1989]. As altitude increases, k distributions are correlated in frequency space. That is, the strongest absorption occurs at the same frequency at all altitudes [Stephens, 1984].

The pyrgeometer measurements used for in situ validation capture wavelengths greater than 3 μm. The delta-Eddington approximation for scattering is included to account for the contribution to the surface flux of the scattering of solar wavelengths beyond 3μm. Figures 3a and 3b illustrate the importance of the inclusion of the delta-Eddington approximation on the spectral variation of $F_{\downarrow}(0)$ over the entire spectral region under both clear and cloudy conditions. Figure 3a refers to a clear sky atmosphere with a low solar zenith angle (25°). When integrated over the longwave spectral region, the delta-Eddington approximation accounted for a 7 W/m² increase in the downwelling longwave surface flux, a non-negligible impact on the expected range of the downwelling longwave surface flux (300-450 W/m²). Figure 3b refers to a cloudy atmosphere with a cloud optical thickness (τ) of 10, a cloud base height of 1 km, and a solar zenith angle of 25°. Integrated over the entire wavelength region, the inclusion of scattering increases $F_{\downarrow}(0)$ by 3.44 W/m².

Under cloudy conditions the model calculates the flux to the surface assuming homogeneous plane-parallel clouds. Clouds are assumed to have the same vertical extent as the layer they are contained in. The cloud optical depth input into the model is the optical depth at 0.55 μm. The model then computes the spectral variation of optical depth based on the extinction efficiency for each wavelength region.

4. Procedure

Each of the atmospheric profiles used in this study is represented by 34 plane-parallel layers. For consistency, a model atmosphere defined by a pressure thickness of each layer was developed. Each radiosonde profile was fit to the model atmosphere as closely as possible. Since water vapor density has its highest concentration and variation in the lower atmosphere, the thinnest pressure layers were defined for the lower atmosphere. The structure of the model atmosphere is outlined in Table 1.

Temperature and humidity profiles were determined through the interpolation of the radiosonde profiles according to the pressure levels described in Table 1. Layer thicknesses were

Comparison of Lidar Cloud Fraction and Computed Cloud Index

![Graph](image-url)
adjusted in the event of a water vapor or temperature inversion to capture the inversion. When the wet bulb thermometer reaches 0°C the water surrounding the thermometer freezes and the wet bulb temperature loses its efficacy. Thus data located above the wet bulb freezing point were disregarded. During IFC5, atmospheric temperatures typically reached freezing around 600 mbar. For heights above the freezing levels the temperature and humidity profiles were obtained from climatological values based on the McClatchey midlatitude summer standard atmosphere [McClatchey et al., 1972]. The water vapor profiles were then examined and adjusted, if required, to ensure that the actual mixing ratio did not exceed the saturation mixing ratio. Ozone profiles for all levels of the atmosphere were interpolated from the McClatchey midlatitude summer atmosphere.

Cloud properties were determined from the VIL data. Cloud base heights and cloud coverages were interpolated from the lidar data to coincide with the time of the radiosonde launches. Under cloudy conditions the radiosonde profiles were initially interpolated to fit the structure of the model atmosphere. But in order to ensure proper treatment of cloud base height in the RTM, the profile layers were then adjusted so that the cloud base was located at a layer boundary.

Table 1. Structure of the Model Atmosphere

<table>
<thead>
<tr>
<th>Layer(s)</th>
<th>Pressure Thickness, mbar</th>
</tr>
</thead>
<tbody>
<tr>
<td>1-11</td>
<td>5</td>
</tr>
<tr>
<td>12-18</td>
<td>10</td>
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<tr>
<td>19-22</td>
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<td>23-31</td>
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<td>located at 220</td>
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<td>33</td>
<td>located at 1</td>
</tr>
<tr>
<td>34</td>
<td>located at 0.003</td>
</tr>
</tbody>
</table>
The cloud parameters required by the radiative transfer model are cloud base height, \( \tau \), and water droplet effective radius \( r_e \). Of these, cloud base height is known, while \( \tau \) and \( r_e \) are unknown. The value \( r_e \) is a difficult parameter to account for, as few measurements of \( r_e \) are available. The majority of clouds in this study have cloud base heights between 0.5 and 2 km. According to the cloud classification provided by Stephens [1978] these clouds are most likely stratus, stratocumulus, or cumulus. The \( r_e \) for these categories reported by Slingo and Schrecker [1982] suggests a range of values from 5.40 to 12.19 \( \mu \)m.

The sensitivity of \( F_L(0) \) to a range of \( r_e \) from 5 to 12 \( \mu \)m shows that under midlatitude summer conditions and a cloud base height of 1 km, \( F_L(0) \) varies by 1.9 W/m\(^2\) for \( \tau=5 \) and 0.3 W/m\(^2\) for \( \tau=10 \). Because of the low sensitivity of \( F_L(0) \) to \( r_e \) under these cloud conditions and the difficulty in determining \( r_e \), \( r_e \) was held constant at 8 \( \mu \)m.

Since \( \tau \) values were not available, \( F_L(0) \) was computed as a function of optical depth. The temperature and emissivity of the cloud base determine the amount of energy emitted by the cloud. As the liquid water content increases, \( \tau \) increases, and the amount of outgoing longwave energy absorbed by the cloud increases. Also, as the liquid water content increases, cloud emissivity increases while the temperature of the cloud base remains the same. As illustrated in Figure 4 for a cloud base height of 1 km the downwelling longwave surface irradiance is most sensitive to low values of \( \tau \) (\( \tau < 5 \)). Therefore, values of optical depth chosen for this study are 1, 5 and 10. Optical depth values greater than 10 produce minimal changes in \( F_L(0) \). As the emissivity of the cloud approaches 1, the relationship between optical depth and surface irradiance becomes asymptotic.

Since the RTM is based on plane parallel theory, cloud fields are assumed to be completely overcast. To determine \( F_L(0) \) for a fractional cloud coverage \( N \) the following equation was used:

\[
F_L(0)_{\text{fsc}} = (1 - N) F_L(0)_{\text{clt}} + (N) F_L(0)_{\text{cldy}}
\]

where \( F_L(0)_{\text{clt}} \) represents the longwave surface flux for the corresponding clear sky atmosphere as computed by the RTM. The corresponding clear sky atmosphere is the same profile as the cloudy atmosphere, however, the cloud is removed.

5. Results and Discussion

The downwelling longwave surface irradiance was computed for 15 clear and 40 partially cloudy profiles over a period of 16 days. During this time, cloud coverage ranged from 0 to 77%. No completely overcast conditions were available from this data set (see Figure 2). It should be noted that because of the small number of observations available, the statistical results presented in this section are valid only for this data set and are not meant to be representative of larger data sets. Rather, the results from this data set are meant to provide a preliminary indication of how well RTMs can estimate \( F_L(0) \), particularly under cloudy conditions, given the limitations of the available data.

Clear Sky Conditions

Figure 5 shows a time series of the pyrgeometer, half-hourly averaged, in situ downwelling longwave surface irradiance measurements and the RTM estimates for clear sky conditions. The shaded area represents +/- 5% of the pyrgeometer values, an approximation of the accuracy of the pyrgeometer. A +/- 5% pyrgeometer accuracy translates to a range of +/- 15 to +/- 23 W/m\(^2\) based on the pyrgeometer values measured for this study. As reported by the manufacturer the accuracy of the radiosonde wet and dry bulb temperature readings is +/- 0.5øC. Hence the range of actual RTM surface irradiance calculations, taking into consideration the accuracy of the temperature measurements, is shown by the length of the bars. These range from 4.9 to 8.3 W/m\(^2\) depending on the moisture content of the atmosphere. \( F_L(0) \) is less sensitive to wet and dry bulb temperature for drier conditions than for moister conditions. The RTM is able to capture the day-to-day variability of the downward longwave surface flux as well as the variability of \( F_L(0) \) caused by the daytime temperature variation. This is particularly evident for day of year 218 and beyond. The sharp decrease in the longwave surface flux over days of year 218 and 219 was caused by the movement of a cold, dry air mass into the area. The lower curve in Figure 5 represents the column integrated water vapor which mimics \( F_L(0) \) and illustrates the dependency of \( F_L(0) \) on the total column water vapor amount. The RTM was able to duplicate this sharp decrease in \( F_L(0) \) as well as its increase as the air mass moves out of the area. It is interesting to note that during the 2-day period the cold dry air mass moved into the area, the cloud coverage did not differ significantly from other days, illustrating the magnitude that the water vapor and temperature has on the longwave surface flux. Over this 2-day period the combined effect is on the order of 100 W/m\(^2\). The ability of the RTM to duplicate shorter term variations is evident for day of year 216. An increase in \( F_L(0) \) of 22.7 W/m\(^2\) is observed with the pyrgeometer over a 7-hour time period, whereas the RTM suggests an increase of 36.4 W/m\(^2\). This rapid change in \( F_L(0) \) is a result of both an increase in temperature and an increase in atmospheric water vapor content. Over this time period, surface temperature increased by 7.8øC and column integrated water vapor increased by 1.4 g/m\(^2\).

The correlation between the clear sky measured and calculated longwave surface irradiance values is shown in Figure 6. The correlation coefficient of 0.97 indicates high agreement between the measured and calculated values and does not account for pyrgeometer or radiosonde uncertainties. In this Figure the crosses represent the pyrgeometer and radiosonde measurement uncertainties. The horizontal components of the crosses represent the uncertainty of the pyrgeometer and the vertical components of the crosses represent the uncertainty of the radiosonde. The slope of the regression line is 1.2, suggesting the RTM tends to underestimate low pyrgeometer values and tends to overestimate high pyrgeometer values. It may also be the case that...
that the RTM may be more reliable than the pyrgeometer. In case the pyrgeometer overestimates low values of $F_{\downarrow}(0)$ and underestimates higher values of $F_{\downarrow}(0)$. The time series of the difference between the measured and calculated irradiance values is shown in Figure 7. The bias of -0.7 W/m² indicates, overall, that the RTM computations have little bias by comparison with the observed values. The standard deviation is 11.0 W/m² and is within the accuracy range of the pyrgeometer and slightly larger than the uncertainty range of radiosonde measurements. The root mean square error of 10.6 W/m² indicates the RTM can predict the overall clear sky $F_{\downarrow}(0)$ values within 4% of the measured values.

Figure 5. Comparison of half-hourly averaged in situ $F_{\downarrow}(0)$ measurements (bold line) to RTM calculations under clear sky conditions. The shaded area represents the accuracy range of the pyrgeometer measurements. The bars denote the range of possible values taking into consideration the uncertainty of the radiosonde measurements. The lower curve represents column-integrated water vapor.

Figure 6. Correlation between clear sky measured and calculated $F_{\downarrow}(0)$ values. The horizontal components of the crosses represent the uncertainty of the pyrgeometer measurements, while the vertical components represent the uncertainty of the radiosonde measurements.
Cloudy Sky Conditions

The time series of in situ downwelling longwave surface irradiance values and those calculated by the RTM under cloudy conditions are shown in Figure 8. Surface irradiance for each profile was computed for three different values of optical depth, namely 1, 5, and 10. The calculated irradiance values shown in the Figure are the interpolated values according to the cloud coverage provided by the lidar data. The shaded area depicts the accuracy range of the pyrgeometer. The bars indicate the possible computed values taking into consideration the reported uncertainties of the radiosonde measurements combined with the range of uncertainties associated with the three values of optical depth. The magnitude of the bars varies from 5.4 to 22.6 W/m². As optical depth is increased from 1 to 10, the sensitivity of $F(0)$ ranges from 1.4 to 21.9 W/m² for the measured radiosonde temperature values. For an optical depth value of 5 the magnitude of the radiosonde uncertainty varies from 0 to 7.8 W/m². $F(0)$ is more sensitive to cloud optical depth uncertainties than to the temperature inaccuracies of the radiosonde. Given the uncertainty of the radiosonde temperature measurements and the uncertainty of the optical depth, calculations for each of the profiles fall within the accuracy range of the pyrgeometer. For an optical depth value of 5 the root mean square error of 10.4 W/m² suggests, overall, the RTM can predict $F(0)$ within 4% of the measured values.

The RTM is able to capture the variability of $F(0)$ caused by the presence of cloud. The crosses in the Figure represent the corresponding clear sky irradiance values as calculated by the RTM. These points indicate the magnitude of the longwave surface cloud forcing. The longwave surface cloud forcing is dependent on optical depth. For an optical depth value of 5 the longwave surface cloud forcing ranges from -2.8 to -42.9 W/m² with a mean value of -15.5 W/m². As cloud fraction increases and cloud base height decreases, the magnitude of the surface longwave cloud forcing increases. The partially cloudy conditions prevalent during this field campaign limit the magnitude of the cloud forcing. The cloud forcing is approximately half that of the impact of temperature and water vapor on the surface flux. While temperature and water vapor have had the largest influence on $F(0)$, the maximum values of $F(0)$ are found during cloudy conditions.

For the above calculations, actual lidar data has been used without an associated uncertainty range since the accuracy of the lidar measurements has not been quantified. Sensitivity of $F(0)$ due to potential uncertainty of the lidar is addressed here. As one illustration, we assigned a +/- 20% uncertainty range to the cloud fractions reported by the lidar. Using the measured radiosonde values and an optical depth value of 5, recalculation of $F(0)$ shows a range of sensitivity from 1.1 to 17.1 W/m² with a mean of 6.0 W/m². Because of the low cloud fractions the sensitivity of a +/- 20% change in cloud fraction is small for this data set. Similarly, we calculated a sensitivity range of 0.1 to 6.5 W/m² for a +/- 20% change in the lidar cloud base height. The cloud base height reported by the lidar is the lowest cloud base in the lidar scan and does not account for the possibility of multiple layered clouds with multiple cloud base heights. To determine the influence of multiple cloud base heights, we assigned four clouds to each profile. Each cloud base was separated by 0.5 km and had an optical depth value of 1.25. The sensitivity of $F(0)$ to multiple cloud base heights ranges from -1.6 to 5.6 W/m² with a mean value of 2.4 W/m². For this dataset, $F(0)$ is relatively insensitive to multiple cloud base heights. However, the maximum value of 5.6 W/m² suggests multiple cloud base heights can play a significant role in estimating $F(0)$.

Using the measured radiosonde, lidar, and pyrgeometer values, the correlation coefficient between the measured and calculated...
irradiance values was computed for the three values of optical depth. In each case the correlation coefficient is 0.94 and the slope of the regression line is approximately 1 (1.03, 1.04, and 1.06, respectively). For an optical depth value of 1 the regression line remains below the one-to-one agreement line. As the optical depth is increased to 5 and 10 the regression line intersects the perfect agreement line with lower measured values falling below the perfect agreement line and higher measured values falling above the perfect agreement line. Points below the agreement line can be interpreted as being underestimated by the RTM or overestimated by the pyrgeometer. Similarly, points above the agreement line can be interpreted as being overestimated by the RTM or underestimated by the pyrgeometer. For points which remain below the agreement line an additional increase in optical depth does not increase the value of \( F_{\downarrow}(0) \) sufficiently to agree with the pyrgeometer. The asymptotic relationship between optical depth and \( F_{\downarrow}(0) \) limits the amount of uncertainty that can be attributed to the optical depth.

Figure 9 shows the correlation between the measured and calculated irradiance values for an optical depth value of 5 and includes the potential uncertainties identified in this study. The values for the correlation coefficient, the slope of the regression line, and the root mean square error presented in the Figure pertain to the measured pyrgeometer, radiosonde, and lidar values. The crosses in the Figure represent the uncertainties of the calculations. The horizontal components of the crosses represent the uncertainty of the pyrgeometer, while the vertical components of the crosses represent the uncertainties of the radiosonde measurements, a +/- 20% variation in cloud fraction and a +/- 20% variation in cloud base height. From Figure 9 it is evident the pyrgeometer measurements contribute a large source of uncertainty to the comparison of measured to calculated irradiance values. More sophisticated methods for measuring the surface flux are required, such as those used during SPECTRE, to better interpret our results. The difference between the measured and calculated values of \( F_{\downarrow}(0) \) is shown in Figure 10. The bias of -0.9 W/m\(^2\) suggests, overall, the RTM computations have almost no bias. As for the clear sky conditions the standard deviation of 10.5 W/m\(^2\) lies within the accuracy range of the pyrgeometer.

While the pyrgeometer, radiosonde, and lidar measurements and optical depth have been addressed as potential causes of the discrepancies between measured and calculated irradiance values, other possibilities exist. One such possibility is the nonhomogeneous volume of atmosphere influencing each of the instruments. The lidar scan volume may not always match the atmosphere viewing the pyrgeometer. Although special attention was given so the lidar cloud fraction and the pyranometer cloud index showed similar degrees of variability, the cloud fraction and the cloud index are different measures of cloudiness and cannot be assumed equivalent. The lidar cloud fraction is a geometrical measure of cloud coverage, while the cloud index is a measure of the amount of solar radiation reaching the surface. Consider a completely overcast atmosphere. In this case the cloud fraction is 1 while the cloud index is lower, that is, 1 less the ratio of measured to theoretical insolation values. Hence the cloud index will always be a smaller number than cloud fraction. As to not further limit the number of observations available for this study, when the lidar indicated a cloud fraction of zero and the cloud index was greater than 10%, the cloud index was used as a proxy for cloud fraction. Furthermore, the radiosonde profile does not represent the instantaneous three-dimensional (3-D) water vapor field influencing the pyrgeometer. The pyrgeometer and the radiosonde station are located 9.6 km apart. For a partially cloudy atmosphere the 3-D distribution of the water vapor profile is not uniform. If the radiosonde does not ascend in the vicinity of the cloud, the water vapor profile may be underrepresented. This is likely to be the case for this data set because for atmospheres assumed to be cloudy based on the combination of the lidar cloud fraction and the computed cloud
Figure 9. Correlation between cloudy sky measured and calculated $F_{\downarrow}(0)$ valued for a $\tau$ of 5. The crosses represent the combined effect of all of the uncertainties identified in this study.

Figure 10. Difference between measured and calculated cloudy sky $F_{\downarrow}(0)$ values for a $\tau$ of 5.
index, many of the radiosonde profiles did not have relative humidity values consistent with a cloudy atmosphere, that is, increased moisture content in the cloud layer.

The reliability of the RTM itself is an important issue worth further investigation. The LOWTRAN 7 transmission functions have been developed from line-by-line spectra and validated against laboratory measurements. Under clear sky conditions the LOWTRAN 7 transmission functions have been validated according to ICRCCM. The longwave portion of the ICRCCM validation program has mainly been concerned with clear sky conditions and does not account for scattering. As the pyrgeometer is influenced by wavelengths as low as 3 μm, we included the delta-Eddington approximation for scattering in our computations. These scattering effects are small but not negligible. Under cloudy conditions, our study provides a preliminary indication of how well RTMs can calculate $F_{\downarrow}(0)$. Additional comparative studies will enable us to relate our computations to computations obtained from other RTMs. Agreement among models is essential, particularly in regard to the accuracy of the pyrgeometer. The uncertainty range of the pyrgeometer is within the accuracy required for the calculation of the downwelling longwave surface flux. More reliable ground truth are available from high spectral resolution interferometers, such as the Fourier Transform Infrared Radiometer (FTIR) used during SPECTRE. Publication of an intercomparison of radiation codes using SPECTRE input data as well as observed high resolution surface radiance values is forthcoming (R. G. Ellingson, personal communication, 1994).

Lastly, discrepancies may exist between measured and calculated irradiance values because of the assumed linear equation relating cloud fraction to the surface irradiance. Harshvardhan and Weinman [1982] investigated the influence of broken cloudiness on the transfer of infrared radiation through the atmosphere. Since the sides of cloud also interact with the radiation field, there is not a simple linear relationship between $F_{\downarrow}(0)$ and cloud fraction as assumed in this study. This simple linear relationship is expected to underestimate $F_{\downarrow}(0)$.

### 6. Summary and Conclusions

In this study we computed the downwelling longwave surface flux for both clear and cloudy conditions with particular emphasis on the reliability of available data. The calculations of $F_{\downarrow}(0)$ focused on the uncertainties of the pyrgeometer, radiosonde, and lidar measurements. Other factors were also addressed as potential causes of the discrepancies between measured and calculated irradiance values. Because of the many possibilities for which the discrepancies can be attributed to, it is difficult to determine the source of the discrepancies. At best, we can establish a ranking of several of the potential uncertainties (see Table 2). Because of the nature of the remaining uncertainties (e.g., atmospheric homogeneity, the relationship between cloud fraction and $F_{\downarrow}(0)$, the accuracy of the RTM), it is difficult to apply a quantification to these uncertainties. The two largest sources of error which we have been able to identify are the sensitivity to optical depth and the uncertainty of the pyrgeometer measurements. Taking these two uncertainties into consideration, the RTM performed quite well. The RTM was able to compute $F_{\downarrow}(0)$ within the uncertainty range of the measured values. The reliability of the RTM is largely a function of the quality and resolution of the atmospheric profiles and the data describing the cloud properties. As more sophisticated data sets become available, we can reduce the number of uncertainties. The Atmospheric Radiation Measurement (ARM) [DOE, 1990] program is an observational program which provides Raman lidar measurements of water vapor profiles and atmospherically emitted radiation interferometer (AERI) measurements of surface radiance. Using the frozen turbulence hypothesis, time series of these measurements can be used to assess the horizontal homogeneity of the atmosphere. During time periods in which there is little variability in the measurements, the atmosphere can be assumed to be horizontally homogeneous, with respect to the parameters measured by these instruments. This type of investigation can be carried one step further by taking measurements from aircraft. Aircraft measurements, such as those from the unmanned aerospace vehicle (UAV), can be used to assess the horizontal homogeneity of the atmosphere without the frozen turbulence hypothesis. Furthermore, ARM provides measurements of cloud liquid water content from upward looking microwave radiometers, which can eliminate the uncertainty due to optical depth.

This study which is based on a data set not specifically collected for the purpose for which it has been used here shows the accuracy bounds that one can expect with routine but high-quality observations and semioperational radiative transfer models. It does not achieve the quality in radiative transfer computations that can be brought up by line-by-line models (such as those used in SPECTRE, for instance) or sophistication in in situ measurements such as those that can be achieved by the ARM program. It nevertheless provides a quantitative indication of what will be possible in future global monitoring programs of the surface longwave radiation flux based on space observations. The next step of this research is therefore to extend this approach to the use of satellite observations to perform the longwave retrievals attempted here.

### Table 2. Sources and Ranges of Uncertainties Identified in the Computation of $F_{\downarrow}(0)$

<table>
<thead>
<tr>
<th>Source</th>
<th>Range, W/m²</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pyrgeometer</td>
<td>+/- 15 to +/- 23</td>
</tr>
<tr>
<td>Radiosonde</td>
<td>4.9 - 8.3</td>
</tr>
<tr>
<td>Cloudy</td>
<td>0 - 7.8</td>
</tr>
<tr>
<td>Lidar</td>
<td>10.1 - 6.5</td>
</tr>
<tr>
<td>Cloud fraction</td>
<td>1.1 - 17.1</td>
</tr>
<tr>
<td>Cloud base height</td>
<td>10.1 - 6.5</td>
</tr>
<tr>
<td>Multiple cloud base heights</td>
<td>-1.6 - 5.6</td>
</tr>
<tr>
<td>Optical depth</td>
<td>1.4 - 21.9</td>
</tr>
<tr>
<td>All uncertainties combined</td>
<td>14.9 - 24.8</td>
</tr>
</tbody>
</table>
Acknowledgments. This study has been supported under grants NASA NAG5-900, NASA NAS5-31574, and DOE DE-FG03-90 ER61062. We thank Paul Ricchiazzi for development of the radiative transfer code, and Antti Piironen for supplying the lidar data. Additionally, we like to thank W. Brutsaert, E. Eloranta, and E. Smith for providing radiosonde, lidar and surface flux data, respectively.

References


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(Received June 20, 1994, revised December 5, 1994; accepted January 2, 1995.)