Comparison of surface radiative flux parameterizations
Part I: Longwave radiation

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Abstract

This paper presents a comparison of several longwave (LW) downwelling radiative flux parameterizations with hourly averaged pointwise surface-radiation observations made at Sodankylä, Finland, in 1997 and 1999. Both clear and cloudy nighttime conditions are considered. The comparisons covered a 2-m temperature range from +11°C all the way to −49°C.

The clear-sky comparisons included eight simple LW parameterizations, which mainly use screen-level input data, and four radiation schemes from numerical weather prediction (NWP) models: the former European Centre for Medium-Range Weather Forecast (ECMWF) scheme, the Deutscher Wetterdienst (DWD) scheme, the High Resolution Limited Area Model (HIRLAM) scheme, and the new ECMWF LW scheme Rapid Radiative Transfer Model, RRTM. Atmospheric-sounding profiles were used as input for the NWP schemes. For the cases with clouds, three simple cloud-correction methods were tested.

Almost all LW schemes usually underestimated the downwelling clear-sky flux, particularly, in cold (surface inversion) conditions. Overall, the RRTM scheme performed best. The simple cloud-correction methods turned out to be useful in the LW region. Finally, some new simple parameterization formulas were developed using the present data. © 2001 Elsevier Science B.V. All rights reserved.

Keywords: Longwave radiation; Surface radiative flux; Empirical formulas; Cloud corrections

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1. Introduction

Downwelling fluxes of longwave (LW, 4.0–100 μm) and shortwave (SW, 0.3–4.0 μm) radiation are key terms of the surface energy budget and vitally important for climate studies and many applications such as agricultural meteorology (e.g. prediction of frost) and air–sea–ice interaction studies. In principle, the surface radiative fluxes can be calculated fairly accurately using rather complex radiative transfer (RT) models, if the relevant properties of the overlying air column are known. The data required include, among other things, the vertical profiles of temperature, water vapour and ozone, and information about other trace gases, aerosols and their optical properties. The microphysical and macrophysical properties of clouds, such as height, cloud water amount and droplet size distribution, should also be known.

However, while temperature and humidity profiles can be obtained from radio soundings, such observations are not always available. Even more rare are detailed profile measurements of aerosol, ozone and cloud properties. Therefore, several parameterizations have been developed that produce estimates for the surface radiative fluxes using synoptic observations only. Typically, these parameterizations use screen-level temperature and humidity information for the calculation of clear-sky fluxes. Cloudy situations are handled by empirical cloud corrections, which mainly depend on the total cloudiness.

Furthermore, whereas satellites can provide global coverage of top-of-the-atmosphere radiation observations, the surface radiation observation network is much more limited, especially so for longwave observations (e.g. Gilgen and Ohmura, 1999). The comparison of surface radiation observations with radiative fluxes produced by numerical weather prediction (NWP) and climate models is also problematic because of the difference in horizontal scale: models compute average radiative fluxes for grid squares of ∼ 100 × 100 km, but radiation observations may be representative of a much smaller area, for example, owing to horizontal variations in the surface albedo. While the synoptic observation network is not truly global either (in particular, it is mainly limited to populated land areas), it is still substantially denser than that for radiation observations. Therefore, if reliable empirical means could be found for estimating the surface radiative fluxes based on synoptic observations, such estimates would be helpful in validating model-produced radiative fluxes and satellite-based estimates of the surface radiation budget (e.g. Rossow and Zhang, 1995).

The evaluation of surface radiative flux schemes has been a widely studied subject over the years. Key et al. (1996) compared several LW and SW formulas in Alaska, USA and Northwest Territories, Canada. They found that the parameterization of Efimova (1961) was the best for the calculation of downwelling LW clear-sky radiation, while Shine’s (1984) method was the best for SW radiation. Both in the LW and SW regions, cloud correction methods of Jacobs (1978) performed well in cloudy situations. Jiménez et al. (1987) have evaluated LW schemes in Spanish conditions. Prata (1996) also studied several LW clear-sky radiation methods using data sets from all around the world. In these studies, his own parameterization proved to be the best in all situations. Radiative fluxes from general circulation models (GCM) have also been studied. Wild et al. (1995) found that the global annual-mean SW flux absorbed at the surface ($ F^i$)
is overestimated and the downwelling LW flux at the surface is underestimated in most GCMs. For example, the ECHAM3 model overestimated the SW flux absorbed at the surface by 10–15 W/m² and underestimated the downwelling LW flux by 10–20 W/m². King and Connolley (1997) also found that the surface LW flux is underestimated, when they studied the surface energy balance of the UK Meteorological Office Unified Climate Model over the Antarctic ice sheets.

This paper presents an evaluation of several LW radiation parameterization schemes using data from Sodankylä, Finland, both in clear-sky and cloudy cases. A similar SW comparison is described in a companion paper (Niemelä et al., 2001). LW radiation was estimated with eight simple clear-sky schemes and three all-sky schemes. In addition, the clear-sky case comparison included radiation codes from NWP models: the former radiation scheme from the European Centre for Medium-Range Weather Forecast (ECMWF) model (hereafter, EC-OLD; Morcrette, 1991), the Deutscher Wetterdienst (DWD; Ritter and Geleyn, 1992) scheme and the High Resolution Limited Area Model (HIRLAM; Savijärvi, 1990) scheme. The LW calculations were also made with the Rapid Radiative Transfer Model (RRTM; Mlawer et al., 1997) scheme, which is currently in use at the ECMWF. The simple schemes have usually been developed for warm and sunny midlatitude and tropical conditions where they perform best, while the NWP RT schemes have to compromise some accuracy for rapidity. These methods have not often been intercompared.

The present article highlights intercomparisons of both the simple and NWP schemes, and extends the comparisons into the very cold and dry conditions of the Northern Finland wintertime, where strong surface inversions are common, especially under clear-sky conditions.

2. Physical background

When scattering is neglected (a good approximation in the LW region especially in cloud-free conditions), the downwelling LW flux at the surface is:

\[
F_{lw} = - \int_0^\infty \int_{p_s}^\infty \pi B_\lambda(T(p)) \frac{dt_s(p_s, p)}{dp} dp d\lambda ,
\]

where \( p \) is pressure, \( p_s \) is the surface pressure, \( T \) is temperature, \( \lambda \) is wavelength, \( B_\lambda \) is the monochromatic Planck function and \( t_s(p_s, p) \) is the monochromatic flux transmissivity from a pressure level, \( p \), to the surface. This may also be written as (e.g. Prata, 1996):

\[
F_{lw} = \varepsilon \sigma T_0^4 ,
\]

where \( \varepsilon \) is the atmospheric emissivity, \( \sigma \) is the Stefan–Boltzmann constant, and \( T_0 \) is the screen-level temperature. It is evident from Eqs. (1) and (2) that the emissivity so defined depends both on the vertical temperature profile and on the vertical distribution of radiatively active constituents, which determines the transmissivity, \( t_s \). The major part of the downwelling flux reaching the surface originates within a few hundred meters of
the surface; therefore, the near-surface temperature profile is of primary importance in determining $F_{\text{lw}}^1$ (e.g., Zhao et al., 1994). The by-far most important (and most variable) atmospheric gas contributing to $F_{\text{lw}}^1$ is water vapour. Some parts of the H$_2$O LW absorption spectrum (especially the central parts of the rotation–vibration and pure rotation bands at $\lambda = 6.3$ and $\lambda > 25$ $\mu$m, respectively) are quite opaque for all typical column water-vapour amounts. However, the downwelling LW flux in the atmospheric window (8–12 $\mu$m) depends strongly on the water-vapour amount, via the dependence of H$_2$O continuum absorption coefficient on the H$_2$O density (e.g., Clough et al., 1992).

Carbon dioxide (CO$_2$) is the second most important gas for $F_{\text{lw}}^1$; O$_3$, CH$_4$, N$_2$O and the CFCs having a smaller role. The effect of aerosols may also be significant, in some cases, primarily in the window region.

The presence of other gases than water vapour implies that a completely dry atmosphere necessarily has a nonzero emissivity. According to computations made with the RRTM scheme, the emissivity of all five McClatchey et al. (1971) atmospheres falls between 0.213 and 0.218 when neglecting water vapour and aerosols (assuming standard O$_3$ profiles and 353 ppmv of CO$_2$, 1.72 ppmv of CH$_4$, 0.31 ppmv of N$_2$O, 280 pptv of CFC-11 and 484 pptv of CFC-12).

When clouds are present they enhance $F_{\text{lw}}^1$, particularly, by “filling” the atmospheric window. The most important cloud properties for $F_{\text{lw}}^1$ are cloud height (via cloud base temperature) and cloud water amount. Low clouds, which are warm and often opaque, emit more efficiently than cold high clouds, which are often semitransparent. In the case of nonblack clouds, the cloud droplet size distribution also has an effect; clouds with smaller droplets emit more efficiently (Savijärvi and Räisänen, 1998).

3. Parameterization schemes

Most of the parameterization schemes presented here are based on empirical relationships derived from observed radiation fluxes, although some methods have their basis on the radiative transfer theory. Empirical schemes can work well in clear-sky cases, especially in climatic conditions similar to those for which they were derived. However, in cloudy situations, their performance degrades severely unless some cloud-dependent corrections are made.

3.1. The clear-sky flux

Seven previously published parameterizations were tested for the calculation of the downwelling LW clear-sky flux, $F_{\text{lw},\text{clr}}^1$. Five of these are of the same form as Eq. (2), where $\varepsilon$ is presented either as a function of screen-level water-vapour pressure, $e_0$, and temperature, $T_0$, or as a function of $e_0$ alone. In the present paper, the unit of the radiative flux is W/m$^2$, the unit of $e_0$ is hPa and the unit of $T_0$ is K.

One of the first parameterizations of this kind was developed by Ångström (1918). He presented a formula in which the effective emissivity of the atmosphere only
depends on the screen-level water-vapour pressure, \( e_0 \). The coefficients of the Ångström scheme used in this study were fitted using summer data from Sodankylä, Finland, 1997:

\[
F_{\text{LW, clr}} = (0.83 - 0.18 \times 10^{-0.067e_0}) \sigma T_0^4. \tag{3}
\]

Another widely used empirical parameterization is Brun’s (1932) scheme in which the effective emissivity is also a function of \( e_0 \) only:

\[
F_{\text{LW, clr}} = (0.52 - 0.065(e_0) \sigma T_0^4. \tag{4}
\]

The coefficients in Eq. (4) are mean values for the northern hemisphere (Brun, 1932) and like in Ångström’s scheme, the values of the coefficients are very sensitive to local conditions.

Brutsaert (1975) developed a much used parameterization, which is based on the analytic solution of Schwarzschild’s equation for a (nearly) standard atmosphere. Brutsaert’s equation:

\[
F_{\text{LW, clr}} = 1.24 \left( \frac{e_0}{T_0} \right)^{1/7} \sigma T_0^4, \tag{5}
\]

gives the downwelling flux as a function of \( e_0 \) and \( T_0 \). According to Prata (1996) and Culf and Gash (1993), Eq. (5) performed very well in warm and wet conditions, but in strong inversion situations, Brutsaert’s scheme tended to underestimate the LW clear-sky flux.

Idso (1981) proposed an empirical formula in which the emissivity of the atmosphere depends both on \( e_0 \) and \( T_0 \):

\[
F_{\text{LW, clr}} = \left[ 0.7 + 5.95 \times 10^{-5}e_0 \exp\left( \frac{1500}{T_0} \right) \right] \sigma T_0^4. \tag{6}
\]

It has been noticed (e.g. Prata, 1996) that in very dry conditions (\( e_0 \to 0 \)), the effective emissivity given by Idso’s scheme reaches 0.7, which is far too large a value for the emissivity by CO\(_2\) and well-mixed trace gases only. This may cause an overestimation of the LW flux.

Prata (1996) derived an equation which is loosely based on radiative transfer theory with coefficients fitted empirically to observations. In essence, Prata’s scheme is an emissivity model with a continuum absorption correction. In this scheme, the effective emissivity of the atmosphere depends on the precipitable water content, \( w \):

\[
F_{\text{LW, clr}} = \left[ 1 - (1 + w) \exp\left( -(1.2 + 3.0w)^{1/7} \right) \right] \sigma T_0^4, \tag{7}
\]

where \( w \) is parameterized using screen-level values of water-vapour pressure [hPa] and temperature [K] (\( w = 46.5(e_0/T_0) \) [cm]). This method provided the best results in Prata’s (1996) own comparison.

Swinbank (1963) derived the simplest empirical formula which differs from Eqs. (3)–(7) in that this method only depends on the screen-level temperature, \( T_0 \):

\[
F_{\text{LW, clr}} = 5.31 \times 10^{-13}T_0^6. \tag{8}
\]
Swinbank (1963) used data from Australia and the Indian Ocean where the conditions were warm. Eq. (8) has been tested in many comparisons (e.g. Prata, 1996; Dilley and O’Brien, 1998) and it has been observed that this scheme usually underestimates the LW clear-sky flux.

Dilley and O’Brien (1998) developed a LW scheme, which depends on the screen-level temperature, $T_o$, and the precipitable water, $w$ [kg/m$^2$]:

$$F_{LW, clr} = 59.38 + 113.7 \left( \frac{T_0}{273.16} \right)^6 + 96.96\sqrt{w/25}. \quad (9)$$

In the present study, we calculate $w$ in Eq. (9) using the same equation as Prata (1996), $w = 465 \left( e_o/T_0 \right)$ [kg/m$^2$]. Dilley and O’Brien (1998) tuned empirically their parametrization using an accurate radiative transfer model. It is interesting to notice that Eq. (9) can be considered as an extension of Swinbank’s scheme (Eq. 8) because of the $T_o^6$-term. Dilley and O’Brien (1998) obtained good results using Eq. (9). However, the scheme underestimated the fluxes slightly in inversion conditions.

3.2. The all-sky flux

The LW all-sky flux has usually been estimated in the simpler schemes by using cloud factors which are proportional to total cloudiness. Jacobs (1978) presented a linear all-sky flux scheme:

$$F_{LW, all} = (1 + 0.26c) F_{LW, clr}, \quad (10)$$

where $F_{LW, all}$ is the LW all-sky flux, $F_{LW, clr}$ is the LW clear-sky flux and $c$ is total cloudiness (in tenths). Jacobs fitted the coefficients of Eq. (10) by using data from Canada. Key et al. (1996) found that Jacobs’ scheme performed very well in the northern regions of Canada and Alaska.

Maykut and Church (1973) used radiation data from Alaska for developing a widely used scheme:

$$F_{LW, all} = (1 + 0.22 c^{2.75}) F_{LW, clr}. \quad (11)$$

The conditions in Alaska were quite cold ($T_0 = -29^\circ$C to $+4^\circ$C). Key et al. (1996) noticed that Eq. (11) performed well in cold conditions, but it underestimated the all-sky flux in warm conditions.

An alternative new all-sky flux parameterization was developed using radiation and SYNOP data from Sodankylä, summer 1997. The new scheme is based on the net all-sky flux scheme by Budyko (1974):

$$F_{LW, all}^{net} = (1 - ac^b)(F_{LW, clr} - F_{LW, s}), \quad (12)$$

where $F_{LW, s}$ is the LW radiation flux emitted by the surface and $a$ and $b$ are constant coefficients (in Budyko, 1974, $b = 1$). On the other hand, the LW net radiation is:

$$F_{LW, all}^{net} = F_{LW, all} - F_{LW, s}. \quad (13)$$
By solving $F_{\text{LW, all}}^1$ from Eqs. (12) and (13), one gets:

$$F_{\text{LW, all}}^1 = \left( 1 + \frac{F_{\text{LW,s}}}{F_{\text{LW,clr}}} - 1 \right) \alpha c^h F_{\text{LW,clr}}^1. \quad (14)$$

Finally, summertime radiation and cloudiness data from Sodankylä were used to determine the coefficients in the above scheme, which resulted in:

$$F_{\text{LW, all}}^1 = \left( 1 + \frac{F_{\text{LW,s}}}{F_{\text{LW,clr}}} - 1 \right) 0.87\kappa_{1.49} F_{\text{LW,clr}}^1. \quad (15)$$

$F_{\text{LW,s}}$ can be calculated using the Stefan–Boltzmann law $\sigma T_s^4$, where $T_s$ is the surface temperature.

### 3.3. Radiation schemes for NWP models

The downwelling surface clear-sky LW fluxes produced by the EC-OLD, DWD, HIRLAM and RRTM schemes were evaluated in this study. A brief description of the main features of these schemes is given below. More detailed documentation can be found in Morcrette (1991) (EC-OLD), Ritter and Geleyn (1992) (DWD), Savijärvi (1990) and Sass et al. (1994) (HIRLAM), and Mlawer et al. (1997) (RRTM).

The LW radiation is calculated in the EC-OLD scheme using an emissivity-type method in which the atmosphere is considered non-scattering, while the DWD scheme uses a $\delta$-two-stream method. In the EC-OLD scheme, the LW part of the spectrum is divided into six intervals, whereas in the DWD scheme, there are five intervals. The gas absorption by $H_2O$, $O_3$, $CO_2$, $CH_4$, CFC-11 and CFC-12 is treated separately in the EC-OLD scheme in the LW part of the spectrum. Also, in the DWD scheme, the absorption by $H_2O$ and $O_3$ is treated separately, but the uniformly mixed gases $CO_2$, $O_2$, $CH_4$, $N_2O$ and CO are treated as a single “hybrid gas”. In this study, the aerosols were not included in the LW calculations.

The HIRLAM LW scheme differs considerably from EC-OLD and DWD. It is an emissivity-type scheme utilizing the Sasamori (1972) approximation. The LW region is handled as a single interval, and only $H_2O$ is treated explicitly. The downwelling LW flux is composed of emission by $H_2O$ line spectrum, $H_2O$ continuum emission and emission by other gases (empirical coefficient). The HIRLAM scheme is much faster than the other NWP schemes, so it could be less accurate.

In the RRTM scheme, the LW spectrum is divided into 16 intervals. The spectral integration is handled using a $k$-distribution method with 16 $k$-values per each interval. The RRTM scheme treats all the absorbing gases separately. Key species ($H_2O$, $CO_2$, $O_3$, $CH_4$ and $N_2O$) are treated with high accuracy, whereas minor gases, such as CFC-11, CFC-12, CFC-22 and CCl$_4$, are treated with less detailed subintervals in the $k$-distribution method. Longwave scattering is not included in the present version of RRTM, but this process is insignificant in cloud-free cases.

The EC-OLD, DWD and RRTM schemes have (formal) wavelength limits of $3.55-\infty$, $4.64-104.5$ and $3.3-1000 \mu m$. However, the black-body emission is actually
\( \alpha T^4 \) in these schemes (i.e. all wavelengths are implicitly included); this is also true for the HIRLAM scheme.

4. Data and measurements

SYNOP observations, radio soundings and radiation measurements around 00 UTC collected at the Sodankylä observatory, Finland (67°22’N, 26°39’E) were used in the comparison. The climate in Sodankylä is characterized by temperate summers (July mean temperature, 14.1°C), subarctic cold winters (January mean temperature, −15.1°C) and moderate precipitation amounts (annual mean, 501 mm). The elevation is 179 m above the sea level. The terrain around the Sodankylä observatory is mainly swamp and boreal forest, and the surrounding area is relatively flat.

The comparisons are composed of two winter periods (1 January–31 March in 1997 and 1999) and one summer period (1 May–31 August, 1997). The 1999 winter was especially cold in Sodankylä. The data included a total of 57 clear-sky cases, 17 in summer 1997, 27 in winter 1997 and 13 in winter 1999. Cloudy conditions were studied only with the summer 1997 data (118 all-sky cases).

The radiation measurements included downwelling and upwelling broadband short-wave flux \( F_{\text{SW}}^{-1} \) and \( F_{\text{SW}}^{+1} \) and net all-wave radiation flux \( F_{\text{NET}} \). All the radiation fluxes were averaged over 1-h intervals. The SW radiation was measured using a Moll–Gorzynski pyranometer and the net radiation flux with a Suomi–Franssila net radiometer. The accuracy of the SW measurements is estimated to be around \pm 5\%, whereas the net radiation flux errors could be even higher, up to \pm 10\%. The latter figure would mean an error of about 5–10 W/m² in the nighttime LW clear-sky comparisons.

The SYNOP observations (00 UTC) were made between 15–30 min, and the radio soundings were launched between 0–15 min of the same hour over which the radiation measurements were averaged. This data provided all the input parameters to the simple parameterization schemes. The simplest LW clear-sky schemes use only screen-level observations such as temperature \( T \) and water-vapour pressure \( e \). The all-sky schemes also need the total cloudiness \( c \).

The conditions were considered cloudless, when the visually observed total cloudiness was zero or one octas. Despite the fact that the observations were made at nighttime, the visual cloud observation is considered reliable in most cases. The summer nights in Sodankylä are so bright that estimation of cloudiness is easy, while in winter, the bright starry sky helps the visual cloud observations. The problem caused by darkness may be present in observations made in late August. However, instantaneous cloud observations cannot rule out cloud contamination during the 1-h radiation measurement interval. Although we do not believe that this is a major error source in the present study (partially, because the strong inversions in winter are indicative of mostly clear sky), it is in principle important to keep it in mind. If there is any cloud contamination, it will cause a high bias in the “observed” clear-sky \( F_{\text{LW}}^{-1} \).

Temperature, pressure and humidity profiles from radio soundings were the input data for the EC-OLD, DWD, HIRLAM and RRTM schemes. The McClatchey et al. (1971) ozone profiles for subarctic winter and for subarctic summer were assumed in the
calculations. All the input profiles were interpolated into the same 72-level vertical grid with very high resolution near the surface (the thickness of the lowest layer was 0.25 hPa). An example is shown in Fig. 2 for the surface—800 hPa layer.

The comparison of the calculated LW fluxes with the measurements was not direct because of the lack of actual downwelling LW radiation measurements. The “observed” downwelling LW flux was estimated utilizing the radiation balance equation:

$$F_{lw} = \frac{1}{\varepsilon_s} \left( F^{net} - F_{SW}^\downarrow + F_{SW}^\uparrow + \varepsilon_s \sigma T_s^4 \right),$$  \hspace{1cm} (16)

where $\varepsilon_s$ is the emissivity of the ground (0.98), $\sigma$ is the Stefan–Boltzmann constant and $T_s$ is the surface temperature. All the LW comparisons were, in fact, made at nighttime 00 UTC so that solar radiation did not interfere much with the net radiation measurements. Another problem was the lack of $T_s$ observations. The only surface temperature value available was the nighttime minimum surface temperature $T_{s\min}$. The surface temperature at 00 UTC was estimated from the minimum temperatures using:

$$T_s = T_0 - (T_{0\min} - T_{s\min} + T_{\text{const}}),$$  \hspace{1cm} (17)

where $T_{0\min}$ is the minimum screen-level temperature. Positive $T_{\text{const}}$ is assumed because the surface temperature tends to approach its nighttime minimum more rapidly than the screen-level temperature (e.g., Tjemkes and Duynkerke, 1989). As our best guesses, $T_{\text{const}}$ was set to be 0.5°C in the summer cases and 1°C in the winter cases. The estimated surface temperature values were not allowed to fall below $T_{s\min}$.

It is difficult to validate the use of Eq. (17) rigorously. However, an upper limit for the error resulting from Eq. (17) can be estimated as follows. Since most clear 00 UTC cases had surface inversions, it is reasonable to assume that the actual surface temperature, $T_s$, is not higher than the screen-level temperature, $T_0$; thus, we have $T_{s\min} \leq T_s \leq T_0$. If we assumed $T_s = T_{s\min}$ instead of Eq. (17), this would decrease $F_{lw}$ computed from Eq. (16) on average by $1 \text{ W/m}^2$ in the summer cases and by $7 \text{ W/m}^2$ in the winter cases. On the other hand, if we assumed $T_s = T_0$ (which we think is farther from the truth), $F_{lw}$ would be increased on average by $10 \text{ W/m}^2$ in the summer cases and by $15 \text{ W/m}^2$ in the winter cases. Based on these considerations, we believe that the RMS error related to the use of Eq. (17) is (at most) $5–10 \text{ W/m}^2$. In cloudy conditions, the cooling of the surface is weaker so the error in the “observed” LW flux is also lower.

A rough estimate for the total uncertainty in “observed” $F_{lw}$ can now be deduced. We assume an RMS error of $5–10 \text{ W/m}^2$ in $F^{net}$ and $5–10 \text{ W/m}^2$ due to the estimation of $T_s$, and $1–2 \text{ W/m}^2$ due to the estimation of $\varepsilon_s$ (which corresponds to a surface emissivity error of $\varepsilon_s \approx 0.02$), and that the errors in $F_{SW}^\downarrow$ and $F_{SW}^\uparrow$ are negligible (generally, the sun is below the horizon at 00 UTC). If these errors are uncorrelated, we have a total RMS error in the range $\sqrt{1^2 + 5^2 + 5^2} - \sqrt{2^2 + 10^2 + 10^2} = 7 – 14 \text{ W/m}^2$.

5. Results

The quality of the LW flux parameterizations is evaluated by considering the mean difference to the observations (bias), the standard deviation around the mean difference,
and the RMS difference. It should be noted that there are several causes for the model-observation differences. The first factor (which we would, of course, ideally like to isolate) is that the models are inaccurate i.e. not exact. The simple formulas grossly approximate the effect of the vertical profiles by using screen-level values as a surrogate, and some of them are tuned using radiative transfer models, which also approximate the radiative transfer physics. Second, the input data used by the simple formulas and the NWP radiation schemes (i.e. the screen-level observations and the radio-sounding profiles) approximate the true state of the atmosphere. Third, the radiative fluxes used for validation are also approximative, in this case, in particular, because $F_{\text{LW}}^i$ has to be estimated using Eq. (16). Systematic measurement errors can make the biases either smaller or larger, whereas random errors should generally increase the standard deviations for all methods.

5.1. Clear-sky results

The differences of the parameterized LW fluxes in clear-sky situations are shown in Fig. 1. The bias, standard deviation and RMS difference of the parameterized fluxes for Sodankylä are given in Table 1. The temperature range in the clear summer night situations of Sodankylä was approximately $-3 \degree C$ to $+11 \degree C$. The range in the winters 1997 and 1999 was $-35 \degree C$ to $+2 \degree C$ and $-49 \degree C$ to $-4 \degree C$, respectively.

All the four radiation schemes aimed for NWP (EC-OLD, DWD, HIRLAM and RRTM) performed well in the clear summer-night conditions, especially with regard to standard deviation. They all had a negative bias, however, which was very small for RRTM ($-1.5 \text{ W/m}^2$), but sizable for the DWD scheme ($-14.8 \text{ W/m}^2$). The RRTM scheme had the smallest RMS difference of the comparison. The standard deviations of

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<td>5.0</td>
<td>15.6</td>
</tr>
<tr>
<td>HIRLAM</td>
<td>-7.0</td>
<td>5.7</td>
<td>9.0</td>
</tr>
<tr>
<td>RRTM</td>
<td>-1.5</td>
<td>5.1</td>
<td>5.3</td>
</tr>
</tbody>
</table>

The average measured LW flux values were 262 W/m² for summer 1997, 191 W/m² for winter 1997 and 162 W/m² for winter 1999.

- Bias (W/m²) = parameterized-measured.
- SD (W/m²) = standard deviation.
- RMS (W/m²) = root-mean-square difference.
Fig. 1. Differences (Diff = parameterization – measurement) in downwelling LW flux in cloudfree conditions.
these four schemes (5.0–5.7 W/m²) did not differ much from each other. The results of the simpler parameterizations, which use only screen-level inputs varied more. Ångström’s (1918) scheme, which was tuned using the summer data, had the smallest bias and RMS difference of these schemes, whereas the lowest standard deviation was obtained by Prata’s (1996) scheme. Also, the bias and RMS difference of the Dilley and O’Brien (1998) scheme were among the smallest. The overestimation by Idso’s (1981) scheme in warm conditions has been noticed in several other comparisons (e.g. Jiménez et al., 1987; Prata, 1996).

In the clear-sky winter situations, all schemes substantially underestimated the downwelling LW flux. The underestimation was most pronounced during winter 1999, which was colder than winter 1997 in Sodankylä. The schemes, which used only screen-level input variables, had the largest underestimation. The reason for such behaviour is that a strong surface temperature and moisture inversion tends to form during cloudless winter nights in the Arctic. In such situations, a large part of the downwelling LW radiation originates from air layers near the inversion top, which are much warmer and moister than the screen-level air. An example of such a typical nighttime temperature and humidity inversion situation in Sodankylä is shown in Fig. 2.

The underestimation shown by the EC-OLD, DWD, HIRLAM and RRTM schemes in Table 1 cannot be explained by inversions only since these schemes receive the actual temperature and humidity profiles as input. As can be seen from Fig. 2, the discretization of the temperature and humidity profiles into the 72-level computational grid cannot cause the low bias either. Some of this underestimation can be caused by the crude estimation of the surface temperature, which is used in our determination of the

Fig. 2. Radio-sounding profiles of (a) temperature and (b) water-vapour pressure measured in Sodankylä at 00 UTC 25 January 1999. The values discretized into the grid used in the computations with the NWP schemes are marked with (•).
“observed” downwelling LW flux (Eq. (16)), but it does not explain all the negative bias. Another partial explanation could be in the humidity measurements of the radio soundings, which may be biased low in the cold and rapidly changing conditions during the initial ascent. In principle, it is also possible that the net flux measurements would be biased high. Nonetheless, the underestimation of the downwelling LW radiation by NWP/GCM radiation schemes in cold situations is consistent with previous studies (e.g. King and Connolley, 1997).

At any rate, the four NWP radiation schemes gave the best results in the cloudless winter situations. The RRTM scheme had the smallest bias and RMS difference overall. The other radiation schemes underestimated the LW flux far more severely. The schemes, which use only screen-level input, gave quite variable results. The schemes of Prata (1996) and Dilley and O’Brien (1998) performed better than most others, the bias and standard deviation were among the smallest. Also, Idso’s (1981) scheme seemed suitable in winter conditions, except that the scatter in the results was relatively high.

The differences in the standard deviations between winters 1997 and 1999 are related to inversions. In 1999, all the clear-sky 00 UTC winter situations had strong surface inversions, whereas in 1997, half of the cases were noninversions. This difference is reflected in the higher standard deviation values in 1997 for all the simpler schemes.

The observed effective emissivity, \( \varepsilon_{\text{eff}} = F_{\text{LW, clr}} / \sigma T^4_0 \), of the clear atmosphere is shown in Fig. 3 as a function of screen-level temperature, \( T_0 \), and water-vapour pressure \( e_0 \) for the three periods. The lowest values of \( \varepsilon_{\text{eff}} \) are obtained when the temperature is about \(-10^\circ\)C or the vapour pressure is about 2 hPa. The higher values of \( \varepsilon_{\text{eff}} \) in cold and dry surface conditions are explained by the then prevailing strong inversions. The data in Fig. 3b suggests that a new empirical LW parameterization of the form:

\[
F_{\text{LW, clr}} = \begin{cases} 
(0.72 + 0.009(e_0 - 2)) \sigma T^4_0 & \text{if } e_0 \geq 2, \\
(0.72 - 0.076(e_0 - 2)) \sigma T^4_0 & \text{if } e_0 < 2,
\end{cases}
\]

(18)

could be employed. The results of Eq. (18) in Sodankyla were better than for any other scheme which uses screen-level input values only. The improvement was significant.

\[\text{Fig. 3. The “observed” clear-sky effective emissivity (} \varepsilon_{\text{eff}} = F_{\text{LW, clr}} / \sigma T^4_0 \text{) of the atmosphere in Sodankyla. (a) } \varepsilon_{\text{eff}} \text{ as a function of temperature. (b) } \varepsilon_{\text{eff}} \text{ as a function of water-vapour pressure.}\]
especially in cold and dry conditions. The bias and standard deviation in summer 1997, winter 1997 and winter 1999 were \((-0.4/8.3), (-0.2/9.5)\) and \((-3.2/7.1)\) [W/m\(^2\)], respectively. It needs to be stressed that this formula is based on nighttime observations at a single site. Naturally, the performance is expected to be worse in climatic conditions significantly different from Sodankylä. However, we do believe that the general behaviour seen in Fig. 3 is typical for all high-latitude continental stations, where surface inversions are common in clear-sky winter conditions (see e.g. Dutton, 1993; Walden et al., 1998).

5.2. Clear-sky sensitivity experiments

Above, the precipitable water, \(w\), was estimated using \(T_0\) and \(e_0\) in the schemes of Prata (1996) and Dilley and O’Brien (1998). The LW fluxes for the Dilley and O’Brien (1998) scheme were recalculated using \(w\) derived from the atmospheric-sounding profiles. The bias and standard deviation in summer and in winter 1997 were \((-7.7/6.4)\) and \((-17.6/8.8)\) [W/m\(^2\)], respectively. The results improved significantly especially in the winter due to the detection of the humidity inversion; the performance was equally good as for the NWP schemes.

Prata (1996) presented a pressure-based elevation correction, which should be included in the simple schemes, if the observation site is not located at the sea level. For the Sodankylä observatory (alt 179 m), this correction is only around \(-1\) W/m\(^2\) and it was neglected for simplicity in the present study.

A sensitivity test for cloud contamination effects was also made using the Prata (1996) scheme. It indicated that if the maximum allowed reported cloud cover for a

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Fig. 4. Differences (Diff = parameterization – measurement) in downwelling LW flux in all cases in Sodankylä, summer 1997. \(F_{\text{LW,cl}}\) is calculated using the new scheme (Eq. (18)). (a) No cloud correction. (b) Jacobs (1978). (c) Maykut and Church (1973). (d) The new scheme (Eq. (15)).
Table 2
Results of the LW comparison in all-sky situations

<table>
<thead>
<tr>
<th>Schemes</th>
<th>Bias (W/m²)</th>
<th>SD (W/m²)</th>
<th>RMS (W/m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>No correction</td>
<td>−25.6</td>
<td>22.9</td>
<td>34.4</td>
</tr>
<tr>
<td>Jacobs</td>
<td>21.0</td>
<td>18.9</td>
<td>28.2</td>
</tr>
<tr>
<td>Maykut and Church</td>
<td>3.3</td>
<td>14.5</td>
<td>14.9</td>
</tr>
<tr>
<td>Eq. (15)</td>
<td>−0.7</td>
<td>11.8</td>
<td>11.8</td>
</tr>
</tbody>
</table>

The average measured LW flux value was 300 W/m².

The difference of parameterized LW all-sky fluxes is shown in Fig. 4. The biases, standard deviations and RMS differences are given in Table 2. In all cases, the clear-sky fluxes were calculated using the new scheme Eq. (18), because its bias and standard deviation were low in summer conditions of Sodankylä. Therefore, most of the “clear” case were set to 0 or 2 octas instead of 1 octa, the bias and standard deviation would differ only by ≤ 1 W/m² from the present results.

5.3. All-sky results

The differences of the parameterized LW all-sky fluxes are shown in Fig. 4. The biases, standard deviations and RMS differences are given in Table 2. In all cases, the clear-sky fluxes were calculated using the new scheme (Eq. (18)), because its bias and standard deviation were low in summer conditions of Sodankylä. Therefore, most of the
bias in all-sky calculations is related to the cloud corrections. If a greatly biased clear-sky scheme were used, the conclusions regarding the cloud corrections would also be erroneous.

The use of simple all-sky schemes for calculations of the downwelling LW flux in cloudy conditions provides rather accurate results overall. The new all-sky scheme (Eq. (15)) gave the best results in all respects. The standard deviation and RMS difference of the parameterization of Maykut and Church (1973) were a little higher than those of the new scheme. However, the new scheme is site-specific due to tuning with summertime data from a single station.

In Fig. 5, the different cloud corrections are compared with observations as a function of total cloudiness. Jacobs’ (1978) linear scheme clearly overestimates the all-sky fluxes. The curves of the new scheme follow the mean of the “measured” values a little better than the other schemes. The value of the correction factor used in the new scheme varies between the maximum and minimum correction lines.

6. Conclusions

The goals of this study were to evaluate the performance of several simple and more complex radiation schemes in computing the downwelling LW radiative fluxes, especially in cold conditions, and to find the optimum simple LW parameterization in both clear and cloudy conditions. The calculated fluxes were compared to hourly averaged radiation observations made at the Sodankylä observatory in Finland, in 1997 and 1999, at 00 UTC. Most of the parameterization schemes were empirical methods, whose input variables were screen-level weather observations (temperature and/or water-vapour pressure). Importantly, comparisons were also made with four different radiation schemes used for NWP. Input to these was provided by radio soundings. As these schemes also need cloud water profiles, which are not observed, their comparisons were restricted to clear-sky cases only.

Better agreement between computed and observed longwave clear-sky fluxes was obtained in summer than in winter. Most schemes performed reasonably well in summer, although they generally tended to underestimate the downwelling LW flux. In the winter cases, many of which had strong surface inversions, the negative bias was more severe, especially for those schemes which use screen-level input variables ($T_0$ and $e_0$) only. The radiation schemes of the four NWP models gave the best results overall, as expected. The best of these was the RRTM scheme, which was one of the least biased, particularly, in the winter conditions. The results of the simple scheme of Dilley and O’Brien (1998) improved when the precipitable water $w$ was calculated from sounding data.

Out of the schemes which use only screen-level input variables, the suggested new scheme (Eq. (18)) gave the best results. This new scheme implicitly assumes inversion conditions when $e_0$ is less than 2 hPa, but it performed well even during summer nights. Other similar simple schemes underestimated the downwelling flux strongly in the winter conditions, especially during strong inversions. However, it needs to be empha-
sized that the new scheme is derived using observations from a single station only and it is very likely site-specific.

The LW all-sky fluxes were calculated using simple cloud correction factors, which depend on total cloudiness, by using Eq. (18) for the LW clear-sky flux. The most accurate all-sky results were provided by the new cloud correction scheme (Eq. (15)).

A major limitation of the present study is that it was made using data from a single station only. Furthermore, the inclusion of nighttime cases only could mean that surface inversions are overpresented. To get better geographic (and temporal) coverage, the study should be extended to a larger set of stations. It could also be interesting to compare the results with ERA (ECMWF Reanalysis, Gibson et al., 1997) or National Center for Environmental Prediction (NCEP, Kalnay et al., 1996) reanalysis data sets, although it should be noted that reanalysed radiative fluxes are model-dependent.

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