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Observed instantaneous cirrus radiative effect on surface-level shortwave and longwave irradiances

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[1] Data collected at the SIRTA Observatory, 20 km south of Paris, are analyzed to determine the instantaneous surface cloud radiative effect (CRE) induced by cirrus clouds. CRE is here defined as the difference between overcast-sky and clear-sky surface radiative fluxes obtained by ground-based measurement of broadband fluxes and clear-sky parametric models, respectively. Clear-sky periods detected by a double threshold based on lidar and radiative fluxes analysis show a root mean square error for clear-sky models smaller than 6.5 W m⁻² for shortwave flux and 4 W m⁻² for longwave flux. Over 100 h in 2003–2006 characterized by homogeneous overcast cirrus clouds are analyzed. Fifty percent of this cirrus population is subvisible and semitransparent, that is, with optical thickness less than 0.3. The mean surface shortwave cirrus cloud radiative effect (CRE_{SW}) is found near -50 W m^{-2} . We establish the relationship between CRE_{SW} and cirrus optical thickness (COT) to be about -90 W m^{-2} per unit of COT. This SW sensitivity ranges from $-80 \text{ W m}^{-2} \text{ COT}^{-1}$ to $-100 \text{ W m}^{-2} \text{ COT}^{-1}$ for turbid to pristine atmospheres, respectively. We also establish the relationship between surface longwave cloud radiative effect (CRE_{LW}) and the irradiance emitted by the cirrus cloud derived from cloud infrared emissivity and cloud temperature. The average surface CRE_{LW} is about +5 W m⁻². CRE_{LW} is found to be about 10% of the cloud irradiance. This LW effect ranges from 5 to 15% of the cirrus irradiance depending on atmospheric humidity for the wet and dry atmosphere, respectively.

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1. Introduction

[2] Clouds at all levels of the atmosphere modulate both the radiation incident upon the surface and the radiative balance at the top of atmosphere (TOA). On the one hand, scattering by clouds reduces the shortwave irradiance reaching the Earth's surface and thus results in a surface cooling effect. On the other hand, clouds absorb upwelling longwave radiation emitted by the surface and lower atmosphere while they radiate both upward and downward. Highaltitude clouds emitting at temperatures significantly cooler than that of the surface, reduce the infrared energy escaping the Earth-atmosphere system. These cloud radiative effects (CRE) on shortwave (CRE_{SW}) and longwave (CRE_{LW}) irradiances are quantified as the difference between all-sky and clear-sky irradiances. A clear-sky irradiance is defined as the irradiance that one would measure if the cloud was not present.

[3] The International Satellite Cloud Climatology Project (ISCCP) [*Rossow et al.*, 1996] defines cirrus clouds as those with an optical thickness less than 3.6 and a cloud top

pressure less than 440 mb. Several studies reveal their relative abundance, with mean cloud fraction ranging from 13% on the global scale [*Chen et al.*, 2000; *Eleftheratos et al.*, 2007] to 45% in the Tropics [*Stubenrauch et al.*, 2006]. The significant coverage of cirrus clouds is likely to yield an important contribution to the total radiation budget.

[4] Effects of cirrus clouds on TOA irradiances have been studied by several authors [e.g., Stubenrauch et al., 1999, Futyan et al., 2005]. Long time series of shortwave and longwave TOA irradiances are available from satellite missions such as the Clouds and Earth's Radiant Energy System (CERES) [Wielicki et al., 1996] or the Geostationary Earth Radiation Budget (GERB) [Harries et al., 2005]. Several studies show that CRE_{SW} causes a cooling of the Earth, whose magnitude depends on cloud cover and optical thickness as well as solar zenith angle [e.g., Poetzsch-Heffter et al., 1995; Stubenrauch et al., 1999, 2006; Chen et al., 2000; Futyan et al., 2005]. They show also that CRE_{LW} at the TOA can vary between 0 and 150 W m⁻² depending on cloud type and cloud cover. Contrary to lowlevel and midlevel clouds, characterized by a significant negative net radiative effect ($CRE_{NET} = CRE_{SW} + CRE_{LW}$) at the TOA ranging from -28 to -78 W m⁻², cirrus clouds are likely to switch sign of TOA CRE_{NET} (5.4 W m⁻²) [Chen et al., 2000].

[5] Several studies focusing on the effect of cirrus clouds on the surface radiation budget are available in the litera-

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ture. Using satellite observations and radiative transfer calculations, Chen et al. [2000] find that, on average, the effect of a cirrus cloud on surface irradiances is +8 W m⁻² for CRE_{LW} and -22 W m^{-2} for CRE_{SW} . These effects are small compared to effects of low-level clouds (e.g., for stratus clouds $CRE_{LW} = +39 \text{ W m}^{-2}$ and $CRE_{SW} = -88 \text{ W}$ m^{-2}). However, *Chen et al.* [2000] show that the relative abundances of cirrus and stratus clouds result in similar cumulative effects (1.1 W m⁻² against 1.2 W m⁻² for CRE_{LW} and -3.6 W m⁻² against -2.6 W m⁻² for CRE_{SW}). Mace et al. [2006] further document the CRE on SW and LW irradiances as a function of cloud type, on the basis of 1 year of vertically resolved observations at the Southern Great Plains (SGP) Central Facility (Atmospheric Radiation Measurement Program, ARM) [Ackerman and Stokes, 2003]. Mace et al. [2006] establish that the predominant surface CRE are associated with thin cirrus cloud layers and thick low-level clouds, due in part to their very frequent occurrence compared to other types of clouds. Recent studies focus on quantifying the sensitivity of surface CRE to cloud fraction. [Dong et al., 2006] and [Shupe and Intrieri, 2004] establish correlations between cloud fraction and surface CRE as increasing functions for CRE_{LW} (average slope of 0.6 W m⁻² per % cloud fraction) and decreasing functions for CRE_{SW} (average slope of -1 W m^{-2} per % cloud fraction) at the ARM SGP facility and during the Surface Heat Budget of the Arctic (SHEBA) field experiment [Persson et al., 2002], respectively. Moreover, these studies show that CRE_{SW} is driven by solar zenith angle and surface albedo and ranges from -3 W m^{-2} [Shupe and Intrieri, 2004] to as much as -37 W m^{-2} [Dong et al., 2006] whereas CRE_{LW} depends on both the temperature of the cloud (with a sensitivity of 1 W m⁻² K⁻¹) and the water vapor below the cloud [Shupe and Intrieri, 2004].

[6] We focus, in this paper, on radiative effects of cirrus clouds on surface irradiances, and study the effects of cloud optical depth on shortwave radiation, and cloud emissivity and temperature on longwave radiation. In section 2, we present the ground-based measurements used in this study and the methods to identify both clear-sky and persistent cirrus cloud situations. Parametric models used to simulate longwave and shortwave irradiances in clear-sky conditions are described and evaluated in section 3. Section 4 presents (1) the sensitivity of surface CRE_{SW} to cloud optical thickness (noted CRE_{SW}^*) and (2) the sensitivity of the surface CRE_{LW} to both cloud emissivity and cloud temperature (noted CRE_{LW}^*). Finally, we quantify (3) the influence of aerosol optical thickness and integrated water vapor on CRE_{SW}^* and (4) the influence of integrated water vapor on CRE_{LW}*.

2. Observation Data Set

2.1. Instrument Description

[7] This study uses a data set provided by the SIRTA observatory (Site Instrumental de Recherche par Télédétection Atmosphérique) [*Haeffelin et al.*, 2005], located 25 km south of Paris, France. SIRTA gathers active and passive remote sensing instruments to monitor high-quality SW and LW irradiances, vertical profiles of temperature, surface-level temperature and water-vapor pressure and to retrieve cloud and aerosol macrophysical and optical properties and column-integrated water vapor density.

[8] Downwelling SW irradiances are monitored by a CH1 pyrheliometer and a shaded CM22 pyranometer. The pyrheliometer measures the direct solar radiation $(0.3-4.0 \ \mu\text{m})$, while the shaded pyranometer measures the downwelling diffuse solar radiation scattered by the atmosphere $(0.3-4.0 \ \mu\text{m})$. The two measurements are then combined to produce the global solar irradiance incident at the surface, as recommended by the Baseline Surface Radiation Network [*Ohmura et al.*, 1998]. This combination allows the SW irradiance to be measured with a 1-2% uncertainty [*Harrison et al.*, 1997; *Michalsky et al.*, 1999]. Downwelling LW irradiances are measured by a shaded CG4 pyrgeometer with a $\pm 0.3\%$ uncertainty [*Philipona et al.*, 2001].

[9] Temperature, pressure, relative humidity and wind profiles are obtained from RS90 radiosonde measurements performed by Météo-France in Trappes (15 km West of SIRTA) at 0000 and 1200 UTC. A standard weather station monitors surface-level wind speed and direction, temperature, pressure, humidity and precipitation.

[10] The vertical distribution of particle layers (clouds and aerosols) in the 0.5-15 km range is monitored by a dual-channel backscatter depolarization Lidar [*Haeffelin et al.*, 2005; *Morille et al.*, 2007]. The backscatter Lidar is used to identify the presence of liquid or ice water in the atmospheric column and to derive cloud base height, cloud top height and cloud layer optical thickness [*Cadet et al.*, 2005; *Morille et al.*, 2007]. Lidar and radiosonde measurements are combined to calculate the cloud top and cloud base height).

[11] Aerosol optical thicknesses at four wavelengths (440, 670, 870, and 1020 nm) are monitored by a CIMEL 318-CE Sun photometer that is part of the PHOTONS/AERONET network [*Holben et al.*, 1998]. Level 1 data, which are not cloud-screened for nonopaque clouds, are used in this study.

[12] Integrated water vapor (IWV) measurements are provided by the Drakkar vertically pointing dual-channel microwave radiometer. Drakkar participated in a microwave radiometer intercomparison carried out during the CLIWANET project [*Van Meijgaard and Crewell*, 2005] and was successfully operated during the CLOUDNET project [*Illingworth et al.*, 2007].

2.2. Clear-Sky and Overcast Period Detection

[13] In this study, the term "clear-sky" is defined as a sky without any liquid water or ice cloud (high or low altitude, high or low cloud fraction). Clear-sky periods during daytime are selected by two automated methods: one using SW irradiance measurements [Long and Ackerman, 2000] and one using LW irradiance measurements [Dürr and Philipona, 2004]. In order to remove optically thin clouds (e.g., cirrus clouds) from this clear-sky data set, that are difficult to detect by radiative flux algorithms alone [Dupont et al., 2008b], we add a third threshold algorithm based on lidar measurements [Morille et al., 2007]. Lidar backscatter measurements allow us to detect clouds with optical depth as low as about 0.005. Using these methods, 86 h of clear-sky conditions are found in the 2004–2005 period, corresponding to 16 different days.





Figure 1. Accuracy of Dutton et al. [2004] and SWCS parameterizations.

[14] Observed periods are defined as overcast when all lidar profiles within 1 h contain clouds (i.e., 120 profiles per hour). Only clouds with base altitude higher than 7 km are considered. Additionally, only overcast periods longer than 3 h are considered to ensure a persistent impact on LW and SW irradiances. On the basis of these criteria, we identify 113 h of overcast cirrus clouds, corresponding to 23 different days in the 2003–2006 period.

3. Reference Clear-Sky Irradiances

[15] Cloud radiative effect estimations require precise references of solar and infrared irradiances for the cloudfree atmosphere. In this study, reference values are obtained from parameterizations fitted directly to observed data.

3.1. Shortwave Clear-Sky Reference

[16] ShortWave Clear-Sky (SWCS) reference irradiances are parameterized as

$$SWCS = a \times \cos(SZA)^b \times c^{1/\cos(SZA)} + \Phi_{(AOT+WVOT)}, \qquad (1)$$

where SZA is the solar zenith angle, *a* is a coefficient that accounts for effects of Sun-Earth geometry, *b* and *c* are coefficients that represent average scattering effects of the cloud-free atmosphere [Dutton et al., 2004]. Φ is a corrective function defined as

$$\Phi = d + e \times [\log(AOT + WVOT)]^2, \tag{2}$$

where AOT is the aerosol optical thickness at 675 nm, a wavelength chosen to best represent the mean broadband aerosol scattering effects [*Blanchet*, 1982] and WVOT is the water vapor optical thickness. WVOT is derived from IWV using

$$WVOT = 0.104 \times IWV^{0.3}, \tag{3}$$

established by *Darnell et al.* [1988] and *Lacis and Hansen* [1974]. Φ is computed from hourly values of AOT and WVOT to account for effects of rapid variations of aerosol optical thickness and water vapor optical thickness. A



Figure 2. Accuracy of Brutsaert [1975], Prata [1996], and LWCS parameterizations.

simple regression fit is made to irradiances observed under clear-sky conditions to provide optimized parametric coefficients b = 1.0987, c = 0.9472, d = -33.3 W m⁻² and $e = 36.0 \text{ W m}^{-2}$. Φ ranges from 0 to 100 W m⁻² for AOT+WVOT~0.38 and AOT+WVOT~0.15, respectively. Figure 1 shows the distribution of model errors for the Dutton et al. [2004] and SWCS parameterizations. Accounting for hourly variations in AOT and WVOT improves significantly the accuracy of the clear-sky reference model. The root mean square error (RMSE) is near 6.5 W m^{-2} for SWCS against 17 W m⁻² from *Dutton et al.* [2004]. RMSE = $[\sigma^2 + \Delta^2]^{0.5}$, where σ is the standard deviation and Δ is the residual bias that is near 0 W m⁻² as equation (1) is fitted on measured SW irradiances. The uncertainty, at the 95% confidence level, in the SWCS irradiance bias, is given by the standard error, computed from a population of independent clear-sky situations, and defined as Std. $Er = \frac{2 \times \sigma}{C}$ where n is the number of independent clear-sky days and σ is the standard deviation of the difference between SWCS and measured clear-sky irradiances for each day. The standard error in the SWCS parameterization is found to be 2.8 W m^{-2} , meaning that any cloud effect on surface shortwave irradiances less than 3 Wm⁻² cannot be considered statistically significant.

3.2. Longwave Clear-Sky Reference

[17] Considering that the atmosphere is a gray body, LongWave Clear-Sky (LWCS) reference irradiances can be estimated by Stephan-Boltzmann's law [*Angström*, 1918; *Brunt*, 1932, *Swinbank*, 1963]:

$$LWCS = \varepsilon \times \sigma \times T^4, \tag{4}$$

where T is the near-surface air temperature in Kelvin (K), σ is Stephan-Boltzmann's constant (σ =5.67 × 10⁻⁸ W m⁻² K⁻⁴), and ε is the apparent clear-sky emissivity of the atmosphere. In clear-sky conditions, ε can be expressed either as a function of surface air temperature and water vapor pressure near surface, noted *e* in hPa [*Brutsaert*, 1975], as a function of integrated water vapor (IWV in cm of precipitable water) [*Prata*, 1996] or as a combination of *e* and IWV [*Dupont et al.*, 2008a]. In work by *Dupont et al.* [2008a], the LWCS parameterization is expressed as

$$LWCS = \frac{\alpha \times (e/T)^{1/7}}{\Gamma_{(e, T, IWV)}} \times \sigma \times \left[\frac{T}{\Pi_{(T)}}\right]^4,$$
(5)





Figure 3. Occurrence frequency of COT for low-, medium-, and high-altitude cirrus cloud.

where α is a constant adjusted on clear-sky periods, Γ is a function that takes into account the effect of vertical distribution of humidity on the apparent clear-sky emissivity, and Π is a function that represents the time lag between surface and atmosphere heating and cooling in the diurnal cycle.

[18] LWCS parameterization errors are derived from the difference between simulated (equation (5)) and measured (section 2.1) longwave irradiances for clear-sky periods. Figure 2 shows the distribution of model errors for the *Brutsaert* [1975], *Prata* [1996] and LWCS parameterizations. The LWCS root mean square error is found to be about 4 W m⁻², compared to near 10 W m⁻² for other parametric models [*Brutsaert*, 1975; *Prata*, 1996]. The standard error at the 95% confidence level is found to be 2.2 W m⁻².

4. Cirrus Cloud Radiative Effect

[19] This study is focused on nonopaque high-altitude clouds that are named cirrus in the ISCCP cloud classification (cloud base pressure > 440 mb, cloud optical depth < 3.6 [*Rossow et al.*, 1996]). The effects of cirrus clouds on both longwave and shortwave irradiances are

quantified using the shortwave and longwave parametric models described in section 3. Cloud radiative effects are defined as $CRE_{SW} = SW - SWCS$ and $CRE_{LW} = LW - LWCS$, where SW and LW are, respectively, shortwave and longwave irradiances measured in overcast situations.

4.1. Correlation of CRE_{SW} With COT

4.1.1. COT Retrieval Method

[20] Cirrus clouds affect predominantly the direct component of solar radiation incident upon the surface. In midlatitudes, solar zenith angles ranges predominantly between 30° and 80° , hence the horizontal distance at cloud height between zenith and the direct solar path ranges between 7 and 70 km. Because of cirrus cloud spatial inhomogeneities, it is important to retrieve cirrus optical thickness along the direct solar path. Hence, in what follows, we present a method that combines lidar and Sun photometer measurements to retrieve cloud optical thickness along the direct solar path.

[21] In overcast situations, the Sun photometer measures a total optical thickness (TOT) that corresponds to the sum between the aerosol optical thickness (AOT) and the cloud optical thickness (COT*). AOT is proportional to the measured Lidar integrated attenuated backscatter (IAB)



Figure 4. (a) COT*, AOT, and TOT for 16 March 2005 depicted in dots, solid line, and dashed line, respectively. (b) Shortwave measurements (solid line) and shortwave clear-sky reference values (dashed line) for 16 March 2005.

[*Ferrare et al.*, 2000]. The proportionality coefficient between AOT and IAB is adjusted in cloud-free periods when the Sun photometer provides a direct measure of AOT. Hence in overcast situations, the cloud optical thickness along the direct solar path is derived as $COT^* = TOT_{Sun photometer} - AOT_{lidar}$. In this method, we assume that the aerosol optical depth is spatially homogeneous in a 7–70 km scale.

[22] A Sun photometer, with a finite Field Of View (FOV of 2.4°), in cirrus overcast conditions, measures not only the attenuated direct radiance but also the forward scattered radiance, as ice crystals can produce significant forward scattering. Hence, the radiance scattered into the Sun photometer FOV yields an erroneous transmission, resulting in an underestimated optical thickness [*Shiobara and Asano*, 1994; *Shiobara et al.*, 1996]. *Shiobara et al.* [1996] developed a method based on Monte Carlo radiative transfer simulations for multiple scattering in cirrus clouds to establish that $COT = [2.15 \pm 0.35] \times COT^*$, where COT^* is the apparent cloud optical thickness derived from a Sun photometer and COT is the true optical thickness. This correction is applied in our study.

[23] Figure 3 shows the distribution of COT for three types of cirrus clouds: low (7 to 9 km), medium (9 to 11 km) and high (11 to 15 km) cloud base altitudes. Cirrus clouds

are also classified according to their cloud optical thickness ranges: subvisible (COT < 0.03), semitransparent (0.03 < COT < 0.3) and thick (0.3 < COT < 3.0) [Sassen and Bensen, 2001]. Subvisible, semitransparent and thick cirrus clouds represent 5%, 45% and 50% in our data set, respectively. For the high-altitude class, subvisible and semitransparent represent 80% of occurrences. The detection limit of the spatial passive remote sensing instruments is typically given to be 0.1 [Stubenrauch et al., 1999], which represents 20% of our population.

[24] Figure 4a shows COT*, AOT and TOT for 16 March 2005 depicted in dots, solid line and dashed line, respectively. Figure 4b displays shortwave measurements (solid line) and shortwave clear-sky reference values (dashed line) for 16 March 2005. According to the variations of COT, this day can be divided into three parts: (1) a thick cirrus cloud before 1230 UTC, (2) a clear-sky period (1230–1500 UTC) and (3) a semitransparent cirrus cloud (1500–1700 UTC). Variations of CRE_{SW} are consistent with cloud optical thickness evolutions.

4.1.2. Relationship Between CRE_{SW} and COT

[25] Figure 5 shows a scatterplot of the shortwave high-altitude cloud impact (CRE_{SW}) versus COT for our 23-day cirrus data set. The solid line is the best linear fit optimized by the method of the least squares applied on the



Figure 5. Scatterplot of the shortwave high-altitude cloud impact (CRE_{SW}) versus COT for our 23-day cirrus data set. The solid line is the best linear fit optimized by the method of the least squares applied on the CRE_{SW} median every 0.1 COT step.

CRE_{SW} median every 0.1 COT step. The slope of this fit is $-92 \text{ W m}^{-2} \text{ COT}^{-1}$ with a correlation factor of 0.79. The empirical standard error in the slope, computed from independent samples (23 days), is near 8 W m⁻² COT⁻¹. It defined the 95% confidence interval around the mean slope.

[26] The uncertainty in the relationship between CRE_{SW} and COT is due to the following factors: SW irradiance measurement uncertainties (1–2%), clear-sky reference uncertainties (1%), and cloud optical depth retrieval uncertainties associated with total optical depth measurements, aerosol optical depth measurements, and correction for forward scattering. Particles in cirrus clouds exhibit a strong spatial and temporal variability in size, shape and orientation [*Noël and Chepfer*, 2004]. On the basis of radiative transfer calculations, *Schlimme et al.* [2005] and *Wendisch et al.* [2005] show that the sensitivity of downwelling shortwave irradiance to cloud optical thickness is modulated by 10 to 30% as a result of ice crystal geometry, and ice particle size in cirrus clouds. Similarly, *Shiobara et al.* [1996] assign a $\pm 15\%$ uncertainty in their forward scattering correction function. Hence, the total theoretical uncertainty in the relationship between CRE_{SW} and COT should be near $\pm 17\%$ (i.e., ± 16 W m⁻² COT⁻¹). A relative homogeneity in

	Cirrus Cloud Base Altitude Classes				
Cirrus Cloud COT Classes	High (CBH > 11 km)	Medium (9 km < CBH < 11 km)	Low (7 km < CBH < 9 km)	All Classes	
Subvisible (COT < 0.03)	-7.9 (79)	-18.3 (352)	-5.8 (183)	-13.7 (710)	
Semi-transparent $(0.03 < COT < 0.3)$	-37.5 (50)	-47.6 (548)	-34.1 (915)	-39.4 (1743)	
Thick (COT > 0.3)	/	-93.3 (159)	-121.8 (249)	-113.2 (585)	
All classes	-25.4 (315)	-62.2 (3153)	-60.4 (3822)	-56.0 (7325)	

^aUnit is W m⁻². Sampling for each class is mentioned in parentheses. Cirrus cloud classes yielding CRE values significantly different from clear-sky references are in bold.



Figure 6. Relationship between CRE_{SW} and cirrus optical thickness for the 10% most turbid and 10% most pristine situations in our data set. Data shown correspond to median point for 0.1 step of cloud optical thickness.

cloud microphysics in our cirrus data set could explain that the empirical standard error is twice smaller than the theoretical uncertainty (± 8 against ± 16 W m⁻² COT⁻¹). [27] The CRE_{SW} ranges between +40 W m⁻² and

[27] The CRE_{SW} ranges between +40 W m⁻² and -350 W m⁻² throughout all overcast cirrus cloud situations in our 23-day data set. The average effect is near -56 W m⁻². Table 1 shows the CRE_{SW} for each cirrus cloud class according to their cloud optical thickness and their cloud base height. The CRE_{SW} associated to low-altitude and midaltitude cirrus clouds are quite similar (-60 W m⁻²) while high-altitude cirrus clouds have a smaller radiative impact (-25 W m⁻²). Thick cirrus clouds (COT > 0.3) have a much stronger CRE_{SW} than subvisible and semitransparent cirrus clouds (-113 W m⁻² compared to about -20 W m⁻²).

4.1.3. Impact of Atmospheric Composition Below Cirrus Cloud on \mbox{CRE}_{SW}

[28] The cirrus cloud effects on surface solar irradiance can also be modulated by the aerosol and the water vapor content located between the ground surface and the cirrus cloud base. Figure 6 shows the relationship between CRE_{SW} and cirrus optical thickness for the 10% most turbid and 10% most pristine situations in our data set. Data shown

on Figure 6 correspond to median point for 0.1 step of cloud optical thickness. Turbid situations correspond to high humidity (WVOT > 0.3) and high aerosol load (AOT > 0.12) while pristine conditions are characterized by WVOT < 0.25 and AOT < 0.08. The CRE_{SW} -to-cirrusoptical-thickness sensitivity is $\sim -80 \text{ W m}^{-2} \text{ COT}^{-1}$ and $\sim -100 \text{ W m}^{-2} \text{ COT}^{-1}$ for turbid and pristine conditions, respectively. Hence, the effect of a cirrus cloud of a given optical thickness on the surface solar irradiance can be 20% greater for a pristine atmosphere than in a turbid atmosphere condition. In view of the uncertainties discussed above ($\pm 8 \text{ W m}^{-2} \text{ COT}^{-1}$ on the mean linear fit), these difference between pristine and turbid atmosphere may not be statistically significant as they could be masked by cirrus microphysics variability. These sensitivities will have to be studied on further data sets.

4.2. Correlation of CRE_{LW} With Infrared Emissivity (ε) and Cloud Temperature (T_C)

4.2.1. Retrievals of ε and T_C

[29] The effect of cirrus clouds on surface longwave irradiances can be evaluated with respect to the longwave irradiance emitted by the cirrus cloud, noted LW_{cirrus}.

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Figure 7. (a) Diurnal variations of ε and T_{CBH} and (b) modeled clear-sky (dashed line) and measured all-sky longwave irradiances (solid line) for 16 March 2005.

LWcirrus is computed from Stephan-Boltzmann's law (equation (4)) on the basis of the cirrus cloud infrared emissivity and thermodynamic temperature. The cloud infrared emissivity can be derived from the cloud optical thickness on the basis of a parametric relationship [e.g., Rossow et al., 1996]. The cloud thermodynamic temperature is derived by combining radiosonde and Lidar measurements that provide temperature profiles and cloud mean altitude, respectively. Temperatures are interpolated between radiosoundings at the time and altitude of lidar observations.

[30] In terms of visible cirrus cloud classes, namely subvisible, semitransparent and thick cirrus clouds, infrared emissivities range from 0 to 0.025, 0.025 to 0.14 and 0.14 to 0.7, respectively, while mean cloud temperatures range from 207 K to 220 K, 212 K to 237 K and 232 K to 254 K, respectively. The average infrared emissivity and temperature of our data set are 0.18 and 232K, respectively.

4.2.2. Relationship Between CRE_{LW}, ε , and T_C

[31] Figure 7a shows diurnal variations of ε and T_{CBH} while Figure 7b displays modeled clear-sky (equation (5)) and measured all-sky longwave irradiances for 16 March 2005. The cirrus cloud present before 1200 UTC is in the optically thick category and comparatively warmer than the cloud present after 1500 UTC that is semitransparent and significantly colder. Before 1200 UTC, CRE_{LW} range between 5 and 15 W m⁻², while after 1500 UTC, CRE_{LW} ranges between 2 and 7 W m⁻², which is consistent with the temperature and emissivity evolutions.

[32] The two-dimensional graph displayed on Figure 8 shows the relationship between the longwave irradiance emitted by the cirrus cloud (LW_{cirrus}) and the surface CRE_{LW}. The solid line is the best linear fit adjusted by the method of the least squares applied on the CRE_{LW} median every 5 W m^{-2} LW_{cirrus} step. The slope of the fit is $\sim 0.10 \pm 0.017$, meaning that about 10% $\pm 1.7\%$ of the LW irradiance emitted by the cirrus cloud is received at the ground, the intercept is $\sim 2 \text{ W m}^{-2}$ and the correlation factor is about 0.78. Uncertainties in the relationship between CRE_{LW} and LW_{cirrus} are due to the following factors: LW irradiance measurement uncertainties (1-2%), clear-sky parametric model uncertainties (1%), and cloud emissivity (±15%) and temperature (2%) uncertainties. As a result the uncertainty in the relationship between CRE_{LW} and LW_{cirrus} can be estimated to be 20%, which is close to the empirical standard error (17%).



Figure 8. Relationship between the longwave irradiance emitted by the cirrus cloud (LW_{cirrus}) and the surface CRE_{LW} . The black line is the best linear fit adjusted by the method of the least squares applied on the CRE_{LW} median every 5 W m⁻² LW_{cirrus} step.

[33] The CRE_{LW} ranges from -6 W m^{-2} to $+30 \text{ W m}^{-2}$, with a mean impact near 5 W m⁻², for the 23 days in our data set. Table 2 shows the CRE_{LW} for each cirrus cloud class according to cloud optical thickness and cloud base height. The CRE_{LW} associated with high-altitude cirrus clouds are not statistically different from 0. Middle- and low-altitude cirrus clouds however, produce significant effects on the surface longwave irradiances at 2 and 8 Wm⁻² levels. For low-altitude cirrus clouds in particular, the subvisible class yield significant effects on surface longwave irradiances.

4.2.3. Impact of IWV on the Relationship Between CRE LW, ε , and T_C

[34] As water vapor is an efficient absorber of longwave radiation and water vapor content is highly variable on synoptic and seasonal scales, measured CRE_{LW} is likely to be affected by the water vapor content of the atmosphere between surface and cloud base. To study the impact of IWV on CRE_{LW} , eight overcast days are selected among the 23-day data set. Four days correspond to high IWV values (IWV > 21 mm) and four other days are in the dry range (IWV < 14 mm). Overcast situations lasting more than 4 h

are selected to avoid effects related to nonhomogeneous cloud fields. Figure 9 displays the range of the CRE_{LW} -to- LW_{cirrus} sensitivity (noted CRE_{LW}^*) for humid and dry situations. Results show that CRE_{LW}^* are 0.04 (correlation coefficient of 0.81) and 0.014 (correlation coefficient of 0.75) for dry and humid periods, respectively. In view of the uncertainties discussed above, these sensitivities can be considered as significantly different. Hence, water vapor can be an efficient mask of longwave radiation emitted by cirrus clouds. For cirrus clouds of equivalent emissive power (ε and T_{CBH}), CRE_{LW}^* is 3.3 times greater for dry atmosphere than for a humid atmosphere.

5. Conclusion

[35] Surface-based observations gathered at the midlatitude SIRTA Observatory are used to quantify the impact of cirrus clouds on surface shortwave and longwave irradiances. Over 100 h of observations, scattered over 23 days in 2003 to 2006, are selected for their persistent cirrus cloud overcast conditions. This cirrus cloud population contains 50% subvisible and semitransparent clouds, that is, with an

	Cirrus Cloud Base Altitude Classes				
Cirrus Cloud COT Classes	High (CBH > 11 km)	Medium (9 km < CBH < 11 km)	Low (7 km < CBH < 9 km)	Average	
Subvisible (COT < 0.03)	-0.4 (79)	0.9 (352)	5.2 (183)	1.8 (710)	
Semi-transparent $(0.03 < COT < 0.3)$	0.2 (50)	3.4 (548)	6.9 (915)	5.2(1743)	
Thick ($COT > 0.3$)	Î.	5.5 (159)	8.6 (249)	11.5 (585)	
Average	0.1 (315)	2.3 (3153)	7.7 (3822)	4.8 (7325)	

Table 2. CRE_{LW} for Each Cirrus Cloud Class^a

 a Unit is W m⁻². Sampling for each class is mentioned in parentheses. Cirrus cloud classes yielding CRE values significantly different from clear-sky references are in bold.

optical thickness smaller than 0.3, an infrared emissivity less than 0.28 and an average temperature less than 214 K. In this paper we derive (1) the sensitivity of surface CRE_{SW} to the cloud optical thickness (noted CRE_{SW}^*) and (2) the sensitivity of surface CRE_{LW} to both cloud emissivity and cloud temperature (noted CRE_{LW}^*). Next, we quantify (1) the influence of aerosol optical thickness and integrated water vapor on CRE_{SW}^* and (2) the influence of integrated water vapor on CRE_{LW}^* .

[36] The major conclusions derived from our midlatitude observation analyses are as follows.

[37] 1. Recently developed parameterizations allow us to estimate clear-sky shortwave and longwave irradiance refer-

ences with standard errors of 2.8 W m^{-2} and 2.2 W m^{-2} , respectively.

[38] 2. Measured SW irradiance at the surface is affected significantly by all cirrus clouds, even those classified as subvisible. In addition the impact of cirrus clouds on surface SW irradiance is itself modulated by the aerosol and water vapor content below the cloud. We find that for the selected overcast cirrus population the average CRE_{SW} * ranges from 80 to 100 W m⁻² COT⁻¹ from turbid (AOT+WVOT > 0.45) to pristine (AOT+WVOT < 0.33) conditions. The subvisible cirrus class, that represents 10% of the population, will affect the surface SW irradiance by -6 to -18 W m⁻², which is beyond the clear-sky model uncertainty and is



Figure 9. Impact of IWV on the relationship between impact of cirrus cloud at the surface and longwave irradiance emitted by the cirrus cloud.

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hence significant. The radiative impact of semitransparent cirrus clouds is about -40 W m^{-2} , while that of the thicker cirrus (0.3 < COT < 3) is greater than 100 W m⁻² on average.

[39] 3. The measured surface LW irradiance shows a significant sensitivity to the presence of cirrus clouds. CRE_{LW} at the surface is well correlated with the cirrus cloud irradiance (LW_{cirrus}), driven by its infrared emissivity and temperature. Additionally, we find a significant influence of the integrated water vapor content below the cloud on the surface CRE_{LW}. We establish that, on the basis of the analyzed population, CRE_{LW} ranges between 5 and 15% of the cloud irradiance, from wet (IWV > 21 mm) to dry (IWV < 14 mm) conditions. For the subvisible and semi-transparent cirrus clouds, we find that only the lowest altitude class (CBH = 7–9 km) induce a significant increase in surface LW irradiance at the 5–7 W m⁻² level. In the presence of thick cirrus, the surface LW irradiance increases 5 to 10 W m⁻² on average.

[40] Our analyses quantify the range of cirrus cloud impact on both SW and LW surface irradiances for subvisible to thick overcast cirrus clouds over a midlatitude European observatory. The sensitivities CRE_{SW}^* and CRE_{LW}^* to aerosol and water vapor content indicate that the cirrus cloud forcing is likely to be seasonal and latitudinal dependent. Future work will therefore consist in applying our analysis method to other observatories, such as the U.S. Atmospheric Radiation Measurement sites in the U.S. southern Great Plains, north slope of Alaska or tropical western Pacific, to investigate the range of shortwave and longwave cirrus cloud forcing in a variety of climate regimes.

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