

Article

Evolution of Meteosat Solar and Infrared Spectra (2004–2022) and Related Atmospheric and Earth Surface Physical Properties

José I. Prieto Fernández ¹  and Christo G. Georgiev ^{2,*}

¹ PraproSL, 06420 Castuera, Spain; jprieto@prapro.com

² Forecasts and Information Service Department, National Institute of Meteorology and Hydrology, 1784 Sofia, Bulgaria

* Correspondence: christo.georgiev@meteo.bg; Tel.: +359-2-462-4603

Abstract: The evolution of atmospheric and Earth surface physical properties over a period of 15 years (based on data from the longer period from 2004 to 2022) is analyzed through the radiance fluxes measured by the Meteosat second generation (MSG) satellite series. The results show significant changes in the solar (−2.6% to −1.2%) and infrared (+0.4% to +1.0%) domains, with −3.9% for the CO₂ absorption band (near 13.4 μm), all variations consistent with results from similar studies of radiation fluxes. Whereas the variation at 13.4 μm radiation is explained by the increase in the CO₂ concentration in the atmosphere, the flux increase towards the satellite in the remainder of the infrared spectra measured by MSG corresponds to surface warming (as documented in external sources like the IPCC, the Intergovernmental Panel on Climate Change). The solar outgoing flux decrease exposes a recent reduction in the Earth's cloud cover under the nominal field of view of Meteosat at 0 degrees longitude (MFOV). Radiance evolution at 6.2 μm and 7.3 μm, a spectral region of intense absorption by water vapor, is interpreted in terms of sensitivity to the humidity content in the middle and upper troposphere by means of a simple radiation transfer model.

Keywords: satellite observations; radiance; absorption of thermal radiation; radiation flux; long-term series



Citation: Fernández, J.I.P.; Georgiev, C.G. Evolution of Meteosat Solar and Infrared Spectra (2004–2022) and Related Atmospheric and Earth Surface Physical Properties. *Atmosphere* **2023**, *14*, 1354. <https://doi.org/10.3390/atmos14091354>

Academic Editor: Stephan Havemann

Received: 25 June 2023

Revised: 21 August 2023

Accepted: 23 August 2023

Published: 28 August 2023



Copyright: © 2023 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (<https://creativecommons.org/licenses/by/4.0/>).

1. Introduction

Satellite measurements are used as a primary source of information about radiation reflected and emitted by the Earth. The measurements also depict Earth-surface and atmospheric physical properties (for instance, cloudiness, concentrations of absorbing gases, ocean and land surface temperatures), which modify the radiative balance of the Earth system [1].

The radiation budget of the Earth surface, which consists of downward and upward fluxes in the shortwave and longwave spectra, describes the energy exchanges between the atmosphere and the Earth surface. Changes in the Earth's radiation balance, due to natural climate variability or human activity, result in the earth surface warming or cooling. For studying the recent trends in climate change, various products and dataset based on satellite measurements from low-Earth orbit [2] and geostationary [3,4] satellites are being used to derive the components of Earth's radiation budget (ERB) at the top of the atmosphere (TOA), recognized as one of the essential climate variables [5]. Meteosat Second Generation (MSG), the European geostationary satellite system, has provided excellent temporal samples to capture information at 15-min intervals about the diurnal cycles of the radiation reaching the TOA since 2003. MSG satellites contain a Spinning Enhanced Visible and InfraRed Imager (SEVIRI) radiometer in 12 spectral channels at a resolution of 3 km (or 1 km in one visible channel) over the sub-satellite point [6] and the broadband geostationary Earth radiation budget (GERB) instrument [7].

GERB is the only geostationary broadband radiometer providing TOA shortwave and longwave fluxes with nominal spatial resolution at a nadir of 50 km and a full scan time of

6 min (see [8]). Such broadband spectrally integrated measurements of the reflected solar radiation and outgoing longwave radiation emitted by the Earth have also been made by other satellite sensors for over four decades and used in a wide variety of environmental and climate studies (see [9]). However, they integrate all the energy in the shortwave or longwave into two values. Climate processes affecting a narrow spectral region, like variations in atmospheric humidity observed in the water vapor absorption region around 6 μm , get masked by larger changes in other spectral regions as a consequence of atmospheric absorbers or thermal anomalies. Also, the cloud remains a strong absorber of the infrared (IR) radiation emitted by the ground and reduces the outgoing longwave radiation (OLR) to space. The transparent spectral region around 900 cm^{-1} (11 μm wavelength) is more influential in the radiative balance of the Earth than the absorption region around 1600 cm^{-1} (6 μm). The relevance of the CO_2 absorption region (around 14 μm or 700 cm^{-1}) is moderate because it is closer to the peak in the blackbody emission by the Earth surface (further explained in Section 2.2), but with strong absorption.

Spectrally resolved measurements of the outgoing radiation make it possible to identify and monitor the effects of many different processes relating to the response of clouds, water vapor, and temperature. The review paper [10] summarizes the advances in the utilization of hyperspectral radiation measurements, including the direct use of spectral observations to evaluate climate models.

Now, the aim of the current study is to report the results of analyses of the averaged radiances based on MSG spectral measurements within the period 2004–2022. We make use of statistical analyses and a simplified numerical transfer model to demonstrate significant aspects of “long term” (15 years) variations in the key parameters of the Earth’s climate system, measured through its spectral albedo and thermal emission. Indirect keys are global cloudiness and water vapor, strong absorbers of the IR radiation from the ground, which reduce in the troposphere the OLR to space. Also, the CO_2 concentration and the land surface temperature are key variables.

SEVIRI channels’ bandwidths often overlap with each other and do not completely cover the visible and infrared domains, but we are convinced that long-term average radiance groups (water vapor, infrared, and CO_2) of spectrally resolved MSG measurements demonstrate significant changes in the solar and infrared domains, in line with those reported in previous studies of radiation fluxes.

Additional recent work points to a decrease in the Earth’s shortwave albedo in the course of the period 1998–2017, as measured from the earthshine on the Moon by using photometric techniques [11], corresponding to a net climate forcing in the solar domain of about 0.5 Wm^{-2} , uncorrelated to solar radiative oscillations. Based on satellite data from instruments like the cloud and Earth’s radiant energy system (CERES) for a more recent period, D  bal and Vahrenholt [12] conclude a decrease of 1.4 Wm^{-2} in shortwave radiation (<4 μm) exiting the Earth for the period 2001–2020, somewhat different from the earthshine study.

An analysis by Feng et al. [13] shows a trend of increase in surface downward longwave radiation (4–100 μm) of 1.8 Wm^{-2} per decade in the period 2003–2018, calculated by using atmospheric parameters like air temperature 2 m above the surface, relative humidity at the 1000 hPa level, total water vapor content, surface downward shortwave radiation, and altitude. Satellite data is used for the long-term, high-spatial-resolution assessment of outgoing surface longwave radiation [14]. The evaluation of the radiative energy flux variations by using CERES data in the period 2001–2020 [12] shows increasing longwave upwelling fluxes (or outgoing longwave radiation, OLR) in the “cloudy” (1.34 Wm^{-2}) and the “clear sky” areas (0.93 Wm^{-2}). The heat uptake for the period July 2000–June 2014 reported in [15] is roughly 0.39 Wm^{-2} .

The present study expands and partially confirms, at the high spectral resolution of SEVIRI, the conclusions from other instruments and interprets the evolution of shortwave and thermal emissions in the light of variability in cloud, tropospheric humidity, CO_2

concentration, and surface temperature. Finally, we present estimates of flux changes and forcings as climate change indicators.

2. Materials and Methods

2.1. MSG Data

The primary MSG satellites located near 0 degrees longitude, which performed the measurements during the studied periods of the analyzed dataset, are shown in Figure 1. Meteosat second-generation satellites have measured operationally since 2003 shortwave and longwave radiation from the Earth and its atmosphere in 11 regular channels with a time frequency of 15 min. Each new set of measurements of the Meteosat field of view (MFOV), or operational cycle of 15 min, is considered a slot.

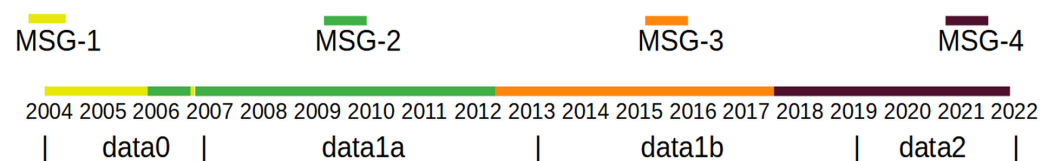


Figure 1. Primary Meteosat second generation satellites period of activity along with the periods of the dataset used for this study.

The methodology used in this study is designed to evaluate the trends of the measured radiation for each MSG channel in the course of 15 years embedded in the period 2004–2022, by comparing average radiances measured over the MFOV for an initial, remote period of time (‘data0’, as indicated in Figure 1) and a final, recent period data2’.

We used for trend analysis pairs of MSG satellite data; each pair lagged in time precisely 15 years $\pm$ 3 days. For instance, we compare the MFOV average data from Meteosat captured at the nominal date and time of Thursday 1 July 2004, at 12 00 UTC with the data 15 years and 3 days later, on Thursday 4 July 2019, at 12 00 UTC. Data from 28 June 2007 are paired with those on 30 June 2022, as shown in Table 1. Similarly for intermediate times. We chose a constant weekday for all the sampled data to avoid possible (though improbable) changes in the images due to different human activities on different weekdays. Other tested choices for a weekday, or pairing with the previous Thursday in the recent data, did not significantly alter the analysis presented here.

Table 1. Dataset composition.

Meteosat Dataset	Points	Periodicity	Span in Days	Start Date	Central Date	End Date
data0	157	weekly	1092	1 July 2004	29 December 2005	28 June 2007
data1a	72	monthly	2162	7 July 2007	22 June 2010	7 June 2013
data1b	72	monthly	2162	7 July 2013	22 June 2016	8 June 2019
data2	157	weekly	1092	4 July 2019	31 December 2020	30 June 2022

The choice of a 3 year basis for the trend calculation and not a longer or shorter basis results from the need for an intermediate reference (the one provided by data1a+data1b in the central 12 years) to help confirm the existence of a trend in values by discarding cycles shorter than 15 years. Had we chosen for an initial (remote) and final (recent) period a duration of, say, 9 years, we would be left with just two reference times for establishing a variation, which could also due to differential phasing in a longer cycle. On the other hand, a 3-year span grants a low error average, describing the climate in a particular time period and mitigating exceptional years anomalies.

The weekly choice, rather than a more frequent data sampling, proves robust since a week is a typical decoupling time for satellite imagery on a global scale. A weekly data frequency renders sufficient statistical significance with a moderate computational effort. As a measure of similarity, images separated by 24 h for a channel show typical Pearson

correlation coefficients of 0.95. They show only 0.48 if the two images are separated by one week, but around 0.71 if we compare monthly image averages for consecutive months, where the rapid movement of clouds is averaged out. For example, the $0.6\ \mu\text{m}$ solar correlation between the 3-year averages around January 2006 and January 2021 is 0.992.

Taking Tuesday's data instead of Thursday's for the 12 UTC slot representing a week affects the radiance average difference by less than 0.4% at each solar channel and less than 0.2% at each infrared channel. The database consists of 157 weekly slots for each of the two periods of three years, labeled data0 and data2 in Table 1, where the duration and interval of the dataset used are presented.

On an initial (remote) and a final (recent) base, 'data0' and 'data2', respectively, each three years long and consisting of 157 slots, we attain statistical significance for the results of the comparison, not improved by choices of longer periods to define them. Such a data choice of 3 + 3 years throws light on the physical processes responsible for changes in shortwave and longwave radiation at the TOA, as reported in studies by other authors mentioned in the Section 1.

The dataset also contains 144 monthly slots for trend analyses for the intermediate period. A monthly frequency for the intermediate period provided sufficient statistical significance.

The SEVIRI radiometer on board MSG scans the MFOV at eleven different wavelengths, with a subsatellite-point horizontal resolution of $3\ \text{km} \times 3\ \text{km}$. The achieved data resolution is better than $\pm 0.1\ \text{K}$ for brightness temperatures as a result of data grouping in 4×4 pixel boxes.

2.2. Data Utilization

A summary of the method used for the comparisons in the plots is contained in Figure 2 and Table 2.

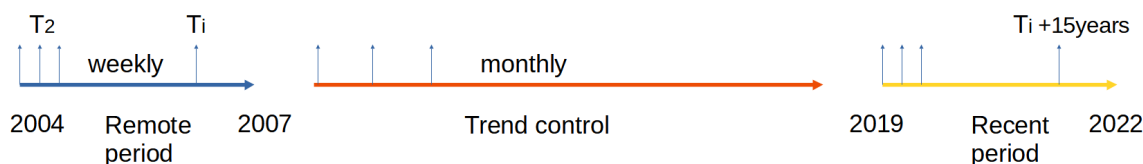


Figure 2. Summary of the data processing used in the paper: Time sequence of the Meteosat observations.

Table 2. Summary of the data integrations used in the paper for different comparisons: The integration over pixels in the MFOV at the same time slot is indicated with $\langle X \rangle$. The integration of different slots over time with $\langle T \rangle$. The comparison of different channels with C_k versus C_k' .

Integration Variable	Integration Applied to RADIANCE (Time[T], Pixel[X], Channel[C])	Comparison	Graphic Results in
All pixels in the MFOV	Σ_X RADIANCE (T_i , $\langle X \rangle$, C_k)	Pairs apart by 15 years, same channel	Section 3
Time in remote or recent 3-year period	Σ_T RADIANCE ($\langle T \rangle$, X_j , C_k)	Variations of the averages (Remote—Recent) for each pixel, same channel	Section 3.5
Time in remote or recent 3-year, comparing channels	Σ_T RADIANCE ($\langle T \rangle$, X_j , C_k versus C_k')	Changes of the averages (Remote—Recent) for a large sample of pixels, with inter-channel comparison	Sections 3.2 and 3.5

We use the 157 pairs of data in three ways: (a) MFOV averages for each pair and channel used for the statistical trend analyses are shown in the initial part of Section 3. (b) Local change of pixel averages, shown in Section 3.5, for two channels. (c) Pixel sampling for interchannel comparisons for the analyses in Sections 3.2 and 3.5. Ways (a) and (b) provide precise conclusions for the central wavelengths of SEVIRI channels.

Conclusions for spectral regions are more vague and affected by larger errors due to the problem of the representativeness of the channels in the spectral domain, discussed below.

The intervening period of 12 years (July 2007 to July 2019) was analyzed for trend control, considering 72 pairs of monthly slots (periods of data acquisition for a full scan representing the month). Slots were always taken at 12 UTC to keep the solar illumination conditions constant, apart from the yearly seasonal oscillation. The results are presented graphically in the initial part of Section 3.

The characteristics of the SEVIRI channels are shown in the first four columns of Table 3. The information from Meteosat is available at the EUMETSAT data portal <https://eoportal.eumetsat.int>, (accessed on 22 August 2023), free registration is required to access data at <https://data.eumetsat.int/extended?query=seviri> (accessed on 22 August 2023). We extracted calibrated and rectified (level 1.5) radiance series from July 2004 to June 2022 at 12 UTC over the MFOV from the satellites at 0° longitude. The Meteosat data are served as files with a count value for each pixel and the nominal time of the slot. The count value is converted into radiation units ($10^{-3} \text{ Wm}^{-2} \text{ sr}^{-1} (\text{cm}^{-1})^{-1}$) with the help of two calibration coefficients specific for the particular slot and the data scan of the MFOV every 15 min. In this study, we just use the slot labeled 12 UTC, which contains MFOV data captured between 1200 UTC and 1212 UTC, acquired from south to north. The trends estimated in this study (defined here as the change between the final and initial measurements) do not require any regression model and are taken directly as the differences in measured values in the 15 year period on the 11 different channels of SEVIRI (see Table 3, first four columns).

Table 3. Characteristics of Meteosat SEVIRI channels (labeled from 1 to 11) and estimates of average values of the spectral radiance (5th column) and radiance average of pair differences in 15 years (spectral values for the average difference of the observations' pairs in the 6th column and integrated spectral values within the channel interval in the 7th column). The 8th (last) column groups the integrated variations from the 7th column in spectral regions for separate analysis.

Domain	Meteosat Channel	Central Wavelength, μm	Channel Interval, μm	Spectral Radiance $10^{-3} \text{ Wm}^{-2} \text{ sr}^{-1} (\text{cm}^{-1})^{-1}$	15-Year Average Difference $(\text{cm}^{-1})^{-1}$	Difference by Channel, Wm^{-2}	Final-Initial Difference by Domain, Wm^{-2}
solar	1	0.64	0.56–0.71	2.62	−0.059	−0.20	
solar	2	0.81	0.74–0.88	3.32	−0.040	−0.19	
solar	3	1.64	1.50–1.78	2.67	−0.039	−0.19	Channels 1–4
solar+infrared	4	3.92	3.48–4.36	0.56	−0.015	−0.03	sum solar = −0.62
water vapor	5	6.25	5.35–7.15	2.35	0.043	0.08	Channels 5–6
water vapor	6	7.35	6.85–7.85	10.11	−0.004	0.00	sum WV = 0.08
infrared window	7	8.7	8.30–9.10	36.75	0.378	0.19	
infrared ozone	8	9.66	9.38–9.94	31.28	0.127	0.04	Channels 7–10
infrared window	9	10.8	9.80–11.80	61.76	0.297	0.09	sum IR = 0.40
infrared window	10	12.0	11.00–13.00	70.14	0.250	0.07	
CO ₂ absorption	11	13.4	12.40–14.40	58.12	−2.310	−0.76	sum CO ₂ = −0.76

For the interpretation of the evolution, we group Meteosat SEVIRI channels in four spectral categories (last column in Table 3), which requires the integration of the measurements in solid angle (in the Lambertian hypothesis for radiation emission from a surface, it is a multiplication by the number π), plus integration in wavenumber, assuming that the channel wavelength intervals (Table 3) extend to cover the full solar-infrared spectrum. Here we confront a limitation of channel representativeness in the spectral domain. As seen in the 4th column of Table 3, the bandwidths in SEVIRI channels partially overlap with each other and do not completely cover the infrared domain or the solar domain. The channel grouping therefore introduces considerable errors in the estimates of variation in Wm^{-2} for a spectral region, which do not affect this work's conclusions since the error only affects the magnitude of the climate balance and our main conclusions are divided by spectral region. We used a Monte-Carlo approach on a collection of random choices for nominal boundaries separating the central channel wavenumbers and integrated between two consecutive boundaries in wavenumber the precise variation for the chosen bandwidth. For instance, the limit between channel 7 (centered at $8.7 \mu\text{m}$ or 1150 cm^{-1}) and channel 8 (at $9.66 \mu\text{m}$ or 1035 cm^{-1}) (Table 3) could also be chosen at, say, 1070 cm^{-1} or 1100 cm^{-1} ,

or at any other intermediate value. The Monte-Carlo choices allow an estimate of errors of $\pm 0.15 \text{ Wm}^{-2}$ for each group of integrated radiances (last column in Table 3) except 'WV', which looks large in comparison with the grouped differences. The errors in differences by channel are much smaller, in the order of $\pm 0.03 \text{ Wm}^{-2}$, and are mainly due to the filter function in SEVIRI channels, which favors a portion of the channel bandwidth. Those channel differences offer a coherent result when compared within each region—for instance, a constant sign—and are the main anchor of our analysis of other physical variables.

The satellite renders spectral radiances (in units of $10^{-3} \text{ Wm}^{-2} \text{ sr}^{-1} (\text{cm}^{-1})^{-1}$), which we integrate in the spectral domain and angular domain to result in radiances (in units Wm^{-2}) through the simple integration formula:

$$\text{Radiance variation} = \text{Const} \times \text{Spectral radiance variation} \times \text{Channel spacing} \quad (1)$$

with $\text{Const} = 1$ for solar channels (1 to 4) and $\text{Const} = \pi$ for infrared channels (5 to 11). The first value ($\text{Const} = 1$) averages day and night out of the measured day data at 12 UTC, assuming a typical cycle of 12 h of night and 12 h of day and describing the illumination evolution as a positive sine function.

The climate is driven by the net amount of radiation entering and leaving the Earth's atmosphere system, which is essentially made up of the Earth's reflected shortwave (RSW) and the outgoing longwave radiation (OLR), since the sun's incident radiation is taken for a constant in this work. These two quantities, RSW and OLR, can be respectively assessed from Meteosat solar (numbered 1 to 4 in Table 3) and infrared channels (5 to 11). See [16] for details.

SEVIRI spectral channels measure outgoing longwave radiation (OLR) in the range of 700 to 1870 cm^{-1} in wavenumber, or 5 to $14 \text{ }\mu\text{m}$ in wavelength. Wien's radiation law connects the wavelength of maximum radiation from a black body with its temperature. (Figure 3). Assuming an approximate black body behavior of the Earth surface at 288 K , the maximum radiation is near 600 cm^{-1} in spatial frequency units (or $16.5 \text{ }\mu\text{m}$ in wavelength units). Proximity to this maximum and also absorption by atmospheric gases determine the relevance of the contribution of a spectral region to the energy balance. Water vapor is a strong radiation absorber in the region around 6 and $7 \text{ }\mu\text{m}$ (1600 to 1400 cm^{-1}), preventing much radiation from escaping to space. Even in the absence of vapor, the water vapor spectral region is a minor portion of the ground radiation escaping to space, dominated by radiation around 600 cm^{-1} . The almost transparent infrared (IR) thermal regions show a strong signal near that peak. Additionally, poor absorption by gases in that transparency region increases its weight in the climate balance at the top of the atmosphere (TOA). The climate balance is the difference between the solar incoming radiation (SIR) at TOA and the Earth's reflected shortwave radiation (RSW) plus infrared emission (OLR) to space by the Earth-atmosphere system. As an equation for the climate balance (CB), we have:

$$\text{CB} = \text{SIR} - \text{RSW} - \text{OLR} \quad (2)$$

That balance translates into Earth surface temperature changes, which have been mostly positive in recent decades [17]. From the satellite perspective of this paper, we consider positive changes in measured radiances to correspond to a reduction of the CB (an increase of energy leaving towards space) and negative changes to correspond to an increase of the CB.

To calculate daily averages in the solar channels, we estimate the average radiance in the illumination curve in 24 h, including 12 h in darkness, as the maximum value for the MFOV (at 12 UTC) divided by the number π . We divide solar values by π to account for the fact that we used only images at 12 UTC, hence maximum MFOV illumination, instead of a combination of night and day images, missing the actual day-night variation, replaced by a sinusoidal cycle of 12 h plus a null night period.

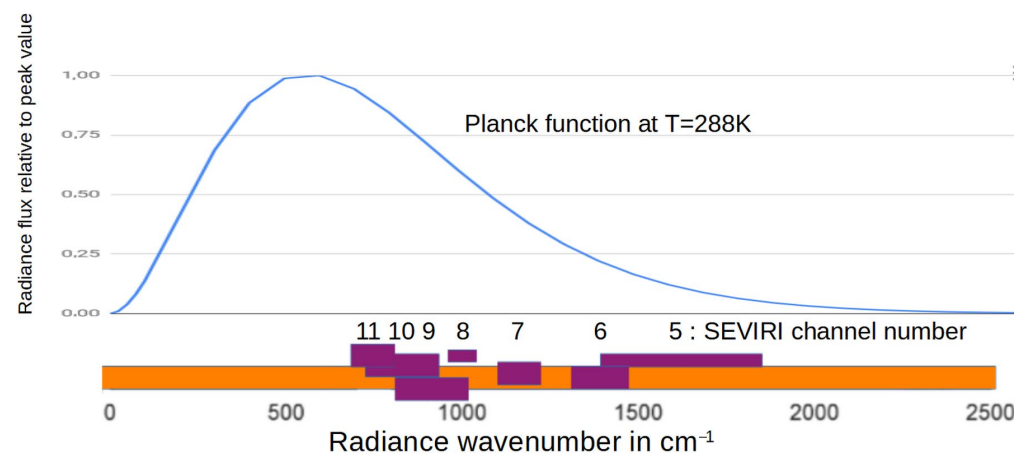


Figure 3. Curve for a blackbody emission by a surface with a temperature of 288 kelvin (K), which can be assimilated to the Earth surface, versus wavenumber (horizontal axis). Lower bar (in ocher) represents the infrared domain from 0 to 2500 cm^{-1} (or inversely from 4 μm to infinite), with dark magenta bars for the SEVIRI infrared channels' bandwidths, labeled from 5 to 11 and described in Table 3.

2.3. Data Interpretation

For the interpretation of radiance values for the channels at 6.2 and 7.3 μm , we have built a simple numerical transfer model on a calculation sheet (called 'our model' from now on), with twelve temperature levels based on an international standard atmosphere plus humidity at 50% of the saturation values. The basic atmospheric state of the model is adjusted to render brightness temperatures at the satellite equal to those measured by MSG for those channels, namely 233 K and 246 K, corresponding to scene average radiances via the Planck function. An additional assumption is made to obtain the theoretical expectations for the two water vapor channels, i.e., an atmospheric warming at any level is followed by an adjustment of moisture contents to re-establish the nominal 50% humidity. This simple model is implemented on a standard calculation sheet, taking into account at each level the radiation coming from lower levels plus the radiation generated upwards by the level layer emissivity, a function of its water vapor content.

To help the interpretation of radiance values at the carbon dioxide absorption channel 11 (centered at 13.4 μm), a similar numerical model is used with a standard atmosphere model covering the whole troposphere. To connect the modifications in radiance at the TOA with physical atmospheric changes, the model uses 12 levels of temperature between 200 K and 288 K with humidity at 50% of its saturation level, where each level absorbs part of the upwelling radiation (dependent on humidity content or CO_2 concentration) and supplies additional radiance emitted at the level temperature as a gray body. The body emissivity is proportional to humidity or CO_2 concentration, depending on the main absorption characteristics of the channel.

The statistical results are interpreted in terms of the evolution of atmospheric and Earth surface physical properties. A synthesis of the physical properties of the Earth system, which can be studied by using data from the measurements by the SEVIRI instrument of MSG, is shown in Table 4.

The data samples and their channel grouping, as shown in Table 3, throw further light on the physical processes responsible for changes in shortwave and longwave radiation at the TOA. The MSG satellite sensors are designed to observe first of all atmospheric properties, which are critical for operational weather forecasting purposes, but these parameters are significant for surface, climate, and climate change studies as well. Observing atmospheric CO_2 was not a priority in the MSG motivation; however, the important greenhouse effect of CO_2 on global warming and the significant change in its concentrations in the last two decades enhance its weight among the MSG observations.

Table 4. Physical properties of the Earth system that can be retrieved from Meteosat second generation satellites (adapted from [18]).

Property	Level	Main Domain	Weight	Further Dependencies	Radiation Effects
Temperature	Surface	Infrared	High	Insolation	Surface is a primary source of infrared radiation, eventually reaching space
Atmospheric humidity	Low level	Infrared	Low	Atmospheric temperature	Humidity reduces solar incoming and heat outgoing radiation
Atmospheric humidity	High/Mid level	6–7 μm spectral region	High	Atmospheric temperature	Molecular absorption blocks surface radiation around 6 μm
Emissivity	Surface	Infrared	High	Soil humidity and composition	Dry ground has a lower infrared emissivity than humid
Albedo	Surface	Solar	High	Snow and vegetation cover	Vegetated areas show lower reflectivity than dry or desert areas
Cloudiness	Low level	Solar	High	Atmospheric humidity	Cloud reduces absorption by the Earth-atmosphere
Cloudiness	High level	Solar and Infrared	High	Upper-level dynamics	High cloud prevents radiative heat from escaping the Earth-atmosphere
Atmospheric CO ₂	Mostly low level	Infrared	Moderate	Human activity	An increase in CO ₂ levels traps heat in the low atmosphere

2.4. Strengths and Limitations

A summary of strengths and limitations addressed in our study is presented in Table 5.

Table 5. Evaluation of the data and methods used in the study.

	Strength	Limitation
Source data (SEVIRI)	High accuracy after calibration and intercalibration	Only for Meteosat field of view, not whole world surface
Spectral integration	Accuracy obtained through averaging	Limited representativity of SEVIRI channels for integrated radiances
Radiation Transfer model	Good calibration through CO ₂ concentrations from other reliable sources	Disregards cross absorption effects
Temporal data sampling	Largely independent from neighbors, ENSO-Niño independent	Exposed to rarely extended multi-year anomalies
Connection to climate	Immediate connection of satellite radiances to climate variables	Slightly short period (15 years) for sound climate conclusions
Contribution to similar studies	Conclusions on a wider data basis than in other studies	Discrepancies on the role of cloud and its oscillations
Future analyses	Easy transition to invaluable trends in regional surface properties	Lack of globe coverage, requiring use of polar satellites (LEO) for optimal spectral view

3. Results

The resulting average radiances measured in the spectral domain of the SEVIRI channels, plus estimates of flux variations according to channel, are shown in columns 5 and 6 of Table 3.

Figure 4 summarizes the 15-year spectrally integrated variation in Wm^{-2} for the eleven MSG channels. The radiances can be grouped in four regions by wavelength, as seen in Table 3, labeled: solar, water vapor, infrared, and CO₂ spectral domains. The radiance changes in Wm^{-2} for the four groups, with uncertainties of $\pm 0.15 \text{ Wm}^{-2}$, are also indicated.

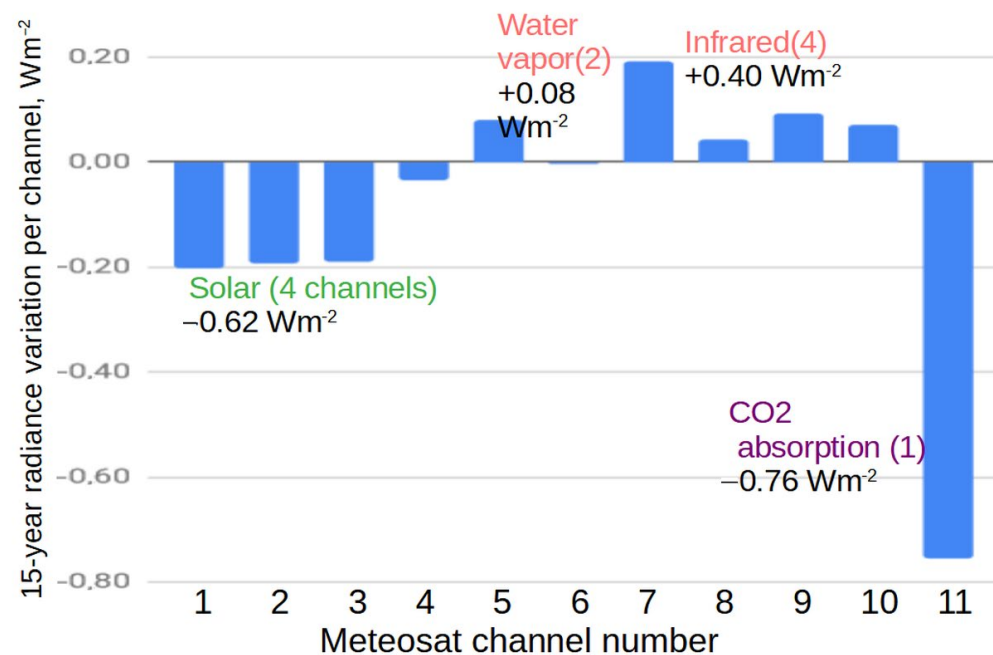


Figure 4. Relative radiance change for the MSG channels 1–11, as defined in Table 3, from 2006 to 2021. Labels give the sums of the 15-year variation within 2004–2022 period in Wm^{-2} for the solar, water vapor, infrared and CO_2 absorption spectral regions.

Excepting the channel centered at $7.3 \mu m$, all others show significant changes in the (spectral) radiance per unit of wavenumber (usually cm^{-1}). For the solar channels (SEVIRI channels 1 to 4) and for the CO_2 channel (SEVIRI channel 11 at $13.4 \mu m$), a negative trend is observed in measured radiances at the satellite, which we interpret as due mainly to the reduction of cloudiness and to surface heating through the CO_2 absorption of outgoing thermal radiation, respectively.

For statistical analysis of the changes in radiances measured by MSG, we show the results in panels for six of the eleven SEVIRI channels (Figure 5). The other channels are omitted since they show similar results to some of those. They are available from the authors. Each panel shows three graphs and, at the top right-hand side, the channel number plus three statistical parameters:

- The average radiance values over all 157 weekly slots in the initial reference period 2004–2006 (data0 in Figure 1) in units of $10^{-3} W.m^{-2} sr^{-1} (cm^{-1})^{-1}$;
- The actual variation in the 15 years (from 2006 to 2021) radiance difference (preceded by '+' or '-', positive or negative), expressed in the same units;
- The standard deviation of the average (preceded by ' $\pm$ ') as a measure of uncertainty due to the limitation in the number of processed slots, expressed in the same units.

The upper right dot diagram in each panel shows as a dot the average (X-axis) and standard deviation (Y-axis) inside each channel slot of the 157 sample images, colored according to the month. The standard deviation (SD) is a proxy for contrast inside the image, almost linearly growing with the average radiance of the image but modulated by the sun's incidence angle on highly reflective surfaces like the Saharan area and by the cloud cycle at high latitudes.

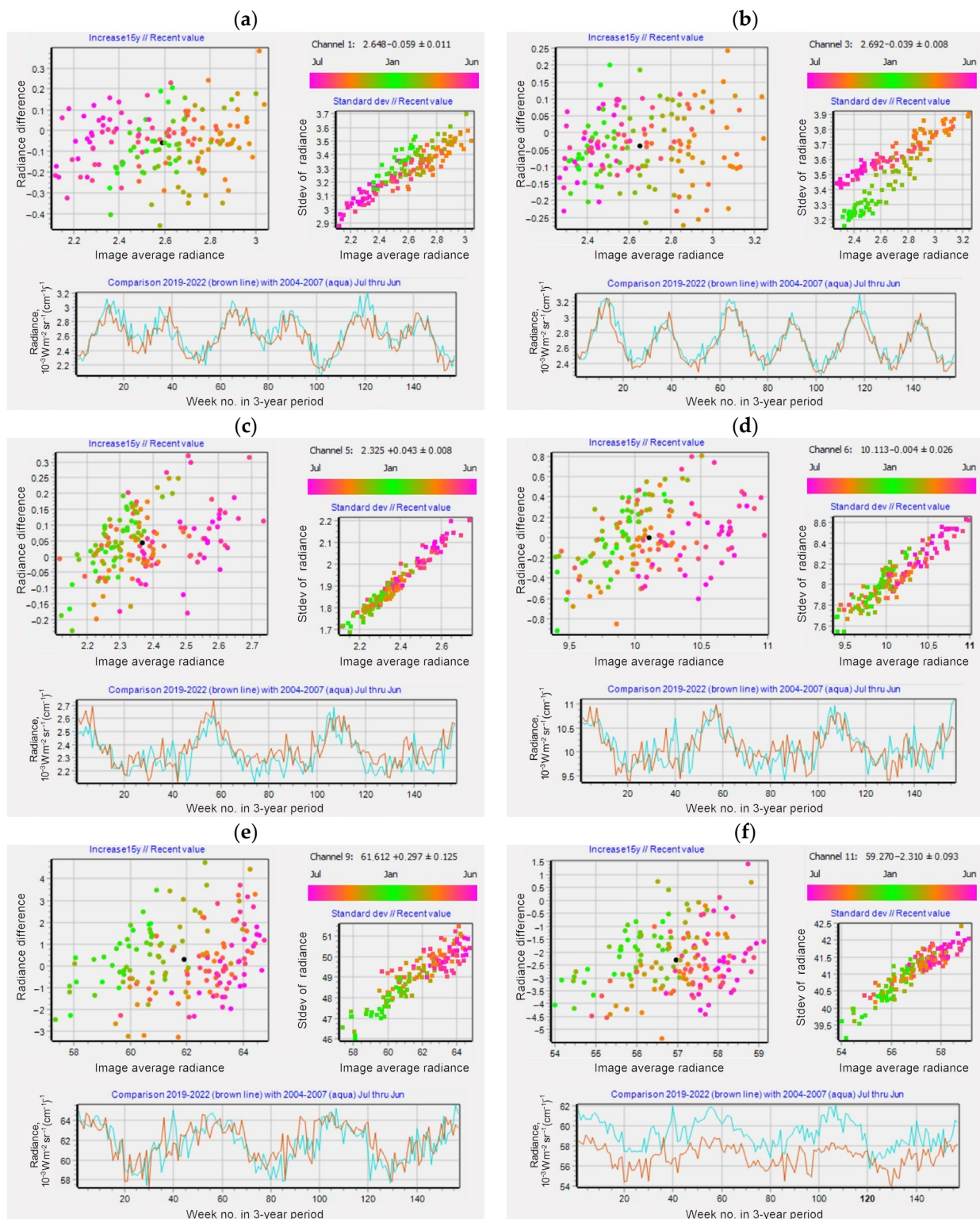


Figure 5. Statistical characterization of radiances and their variations for SEVIRI channels at (a) 0.6 μm ; (b) 1.6 μm ; (c) 6.2 μm ; (d) 7.3 μm ; (e) 10.8 μm ; (f) 13.4 μm . Upper left scatter plot: SEVIRI radiance increase (+) or decrease (−) in the 15-year pair of weekly observations versus radiance average for every pair. The black dot is the average of all weekly values. Upper right scatter plot: standard deviation of radiance for every dot representing a week versus radiance average for every dot. Lower scatter plot: Radiance every week versus week number for the initial (in cyan) and final (in brown) periods of three years.

In the infrared channels, such as channel 9 at 10.8 μm (Figure 5e), the radiated heat from the Earth decays from the time of the northern hemisphere winter solstice to the summer equinox and vice versa, resulting in a growth of contrast from January to July. The least and most scattered diagrams are obtained for channels 5 (6.2 μm) and 9 (10.8 μm), respectively, the least and most sensitive infrared channels to thermal radiation emitted by the Earth surface. In the MFOV, the higher contribution to the intra-image contrast comes from the Northern Hemisphere because of the larger area covered by land compared with the Southern Hemisphere and the higher amplitude of the thermal intra-annual variation. Another interesting result seen in Figure 5 is the highly scattered diagram of SD for 1.6 μm radiance. In the northern hemisphere winter months, the abundance of frozen cloud tops reduces the global reflectivity at channel 3 (1.6 μm). The result is a decrease in the standard deviation on the right upper graph of Figure 5b. A much higher deviation corresponds to a reflective cloud, as happens in the summer months for liquid tops (magenta dots). However, for other solar channels, e.g., channel 1 (0.6 μm) in Figure 5a, frozen cloud has the same weight in the radiance deviation axis as droplet-top cloud since icing of the tops has a low impact on reflectivity. The summer months then show less overall cloudiness.

The upper left dot diagram compares the same radiance average (X-axis) with the 15-year increase in that average (Y-axis), always in units $10^{-3} \text{ W.m}^{-2} \text{ sr}^{-1} (\text{cm}^{-1})^{-1}$. On the Y-axis, the minus sign for visible channels indicates less exiting solar radiation or planet heating due to increased absorbed solar radiation. A plus sign in the infrared channels shows cooling contributions through outgoing thermal radiation. In June–July, the lowest radiances in solar channels (magenta dots) occur as a result of the predominant cloud-free conditions. This is a period of highest radiance in the infrared channels due to high land surface temperatures (LST), usually above the ocean surface temperature.

The lower two-line graph shows the weekly evolution in the initial (around 2006) and recent (around 2021) three-year periods, the basis of the comparison. Its X-axis is labeled in weeks starting from 1 July 2004 (cyan line) and from 1 July 2019 (brown line). The Y-axis shows once again the channel's radiance. The radiances vary seasonally, and the radiance oscillations vary from year to year. For the IR window channel (Figure 5e bottom panel), the maximum radiance appears in July due to the highest LST around the summer solstices in the Northern Hemisphere and a stronger oscillation in OLR than for the Southern Hemisphere, with much more sea surface inside the MFOV. The effect of the Sahara Desert must also be an important factor in the dominant thermal infrared contribution of the Northern Hemisphere. For the absorption channels (Figures 5c and 3d,f, bottom panels), the summer maxima result from increased emitter temperatures, the ground, or the absorbing gases favoring the Northern Hemisphere. The solar channel radiance (Figure 5a, bottom panel) is bimodal in time and exhibits two yearly minima (around the solstices) and two yearly maxima (around the equinoxes), a composite effect of the yearly cloud cycle and the tilting of highly reflective surfaces like the Sahara.

Figure 6 shows average radiances measured in the eleven SEVIRI channels at the initial 3-year period (2004–2007, in blue), at the intermediate years (2007–2019, red), and at the final period (2019–2022, ochre). Here we show the values in the 7th column of Table 3 after Lambert's angular integration and wavenumber integration, taking the central wavenumbers of the MSG channels as a basis for the width of the channel intervals. Notice the sharp decrease on channel 11 (13.4 μm) due to the increase in the CO_2 atmospheric concentration over the period 2004–2022.

We also considered the intermediate period of 12 years, 2007–2019 (effective length of 6 years after averaging in two time spans) for an estimate of the trend constancy (red columns in Figure 6). The results indicate, though with a higher error margin, a trend acceleration in the infrared channels, except for 13.4 μm . For the 13.4 μm channel, the decrease is slowing down if we look at the 2007–2019 value (red bar).

Results from the trend analysis for each group of wavelength ranges as defined in Table 3 are presented in Sections 3.1–3.4. They point to atmospheric and Earth surface physical properties.

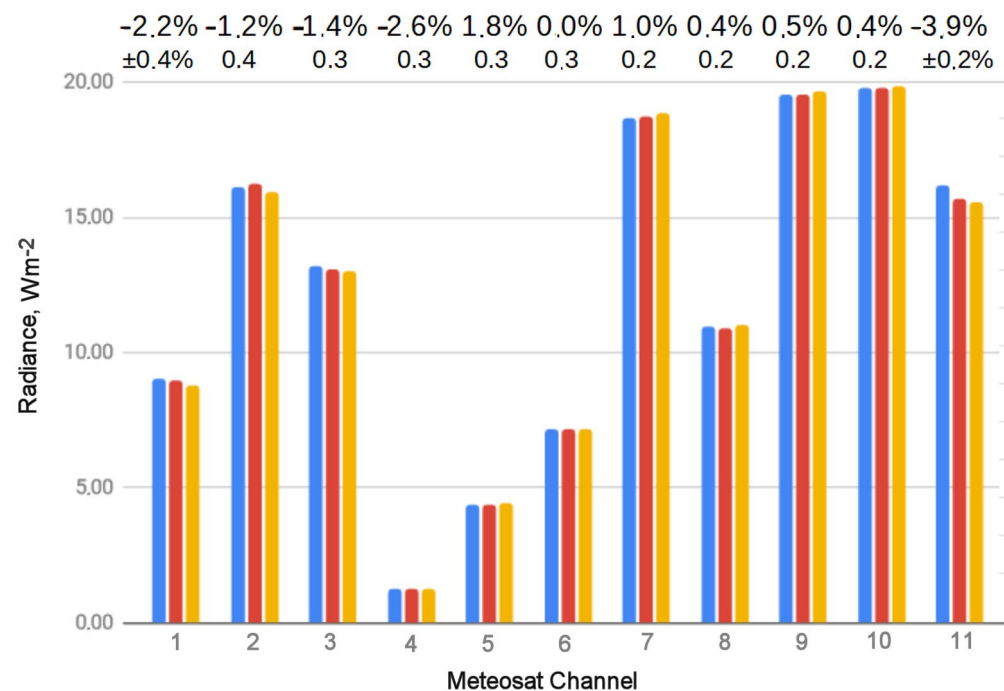


Figure 6. Meteoros channels from channels 1 through 11 left to right on the X-axis. Color legend: (blue) Initial period (2004–2007) radiance averages (ochre) Final period (2019–2022); (red) Average based on one image a month for the intervening period as a trend control. Vertical units of Wm^{-2} after integration in the wavenumber associated with the spectral band.

3.1. Evolution of Radiances in the Solar SPECTRAL Regions

Four MSG channels are centered in the solar spectrum (under $4 \mu\text{m}$). As seen in Figure 6, variations in the range -2.6% to -1.2% are obtained. This is a significant modification in the outgoing shortwave radiation, which is interpreted as a reduction of cloud in the course of the 15 years of the study. Alternative reasons based on less reflective aerosol [19] cannot be excluded, but based on Meteoros data, we are not able to draw a conclusion for such changes due to aerosol.

The -2.6% variation on channel 4 ($3.9 \mu\text{m}$) is higher than for the other solar channels, as seen in Figure 6. This is in agreement with the fact that this channel is sensitive to thermal radiation affected by CO_2 absorption lines, which reduce atmospheric transparency as the CO_2 concentration grows.

3.2. Evolution of Radiances in the Spectral Region with Strong Water Vapor Absorption

The thermal radiation from the water vapor (WV) absorption channels at $6.2 \mu\text{m}$ and $7.3 \mu\text{m}$ originates at humidity layers high in the troposphere. Water vapor in concentrations typically high in the troposphere is semi-transparent to radiation; significant amounts of radiation originate below and pass unaffected through these layers. The complication due to the layered moisture is a significant factor in WV imagery interpretation that is discussed in Georgiev et al. (2016) [20] and Weldon and Holmes (1991) [21]. In the case of moist air at the height of around 220 K and comparatively dry air lower in the troposphere (240 K), the result is a warmer brightness temperature (more radiation reaching the satellite) than for moist air around the level of 240 K air temperature. This result is called the cross-over effect [20,21] and expresses that high-level tropospheric humidity appears to be more transparent to these wavelengths than humidity at a low level. See also Donny et al. 2003 [22] for a discussion of these physical aspects.

The channel centered at $6.2 \mu\text{m}$ shows a significant increase of $1.20 \pm 0.3\%$ in 15 years (Figure 5c) in response to humidity changes above 500 hPa in the atmosphere or even to the cloud changes suggested above in Section 3.1. This relative increase is stronger than in the

window channels of the infrared domain (Section 3.3 below), in the range from 8 to 13 μm , where radiation from the surface supplies the main contribution to the satellite signal and has grown only by about 0.4%. The 6.2 μm channel is mostly insensitive to moisture below 500 hPa. The warming of the upper layer of humidity in the atmosphere, seen at 6.2 μm , is either due to a small drying of the upper troposphere (500 to 300 hPa) or alternatively to an air warming at that layer.

Figure 7 shows the averaging kernels describing the different sensitivity to temperature of the satellite readings at channels 6.2 μm (blue) and 7.3 μm (brown) according to the calculations by our model described in Section 2. The model also illustrates that the two ‘water vapor’ (WV) channels are sensitive to water vapor at different levels in the troposphere. A hypothetical temperature jump of 1 K at the layer of about $250 \text{ K} \pm 5 \text{ K}$, while allowing for more humidity there to re-establish 50% relative humidity (RH), will increase by 0.4% the radiance signal at the satellite for both water vapor channels. Also, a 1 K warming in the layer at $(223 \pm 5 \text{ K})$ would result in a 0.5% reduction in the 6.2 μm radiance measured by Meteosat and a 0.25% reduction at 7.3 μm .

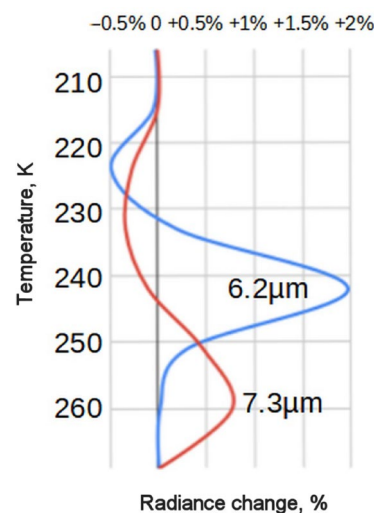


Figure 7. Average values of radiance changes in channels 6.2 μm (blue) and 7.3 μm (brown) for atmospheric height levels, indicated in the Y-axis by their temperature, after a warming of one degree kelvin (1 K) at the level while adjusting humidity to re-establish 50% RH.

Overall, the channel at 7.3 μm (responding to water vapor mainly in the middle and upper troposphere) shows no significant change ($0.0 \pm 0.3\%$) in the radiances measured by Meteosat for the last 15 years. This result contrasts with the clear increase at 6.2 μm . An explanation of the discrepancy between the two channels in the H_2O absorption region is the additional absorption by CH_4 between 7 μm and 8 μm (van Wijngaarden et al. [23]), since this gas has also increased its atmospheric concentration by 6% in the period of the study. This absorption region strongly overlaps with the 7.3 μm channel bandwidth.

For the interpretation of radiance changes in the water vapor absorption channel 6.2 μm (channel 5), including temperature and humidity changes in cloudy scenes, we compared water vapor data with radiances measured in the solar 0.6 μm (channel 1). Results are shown in the graphs in Figure 8 as a dot for each randomly chosen location in MFOV, considering average radiance values in the initial (data0) and final (data2) three-year periods at the indicated channels and BT differences.

The scatter plot in Figure 8a (left panel) suggests that a majority of pixels with high 0.6 μm reflectivity (and so more cloudy, marked in red) have suffered an albedo decrease in the past 15 years (values <0 on the horizontal axis). At the same time, the change in 6.2 μm radiance covers relative increases around 2% (Y-axis), mainly in the interval $[0\%, 5\%]$, pointing to a variety of regions with no definite pattern of humidity loss. However, cloudy pixels (in red) show a higher percentage of increased 6.2 μm radiance (above zero in

Figure 8a, Y-axis), which means a reduction of cloud height globally or just a radiative consequence of the cloud reduction in those pixels.

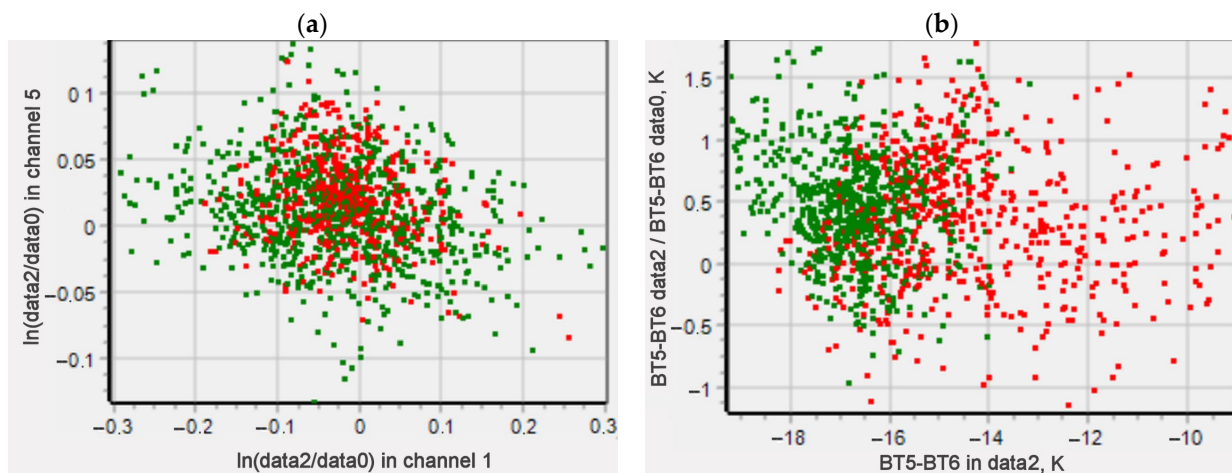


Figure 8. Scatter plots of changes in the radiance ratios of the averages on randomly chosen pixels at the beginning and the end of the studied period (data0 and data2 in Table 1). (a) Logarithm of data2/data0 in channel 5 (vertical) vs. logarithm of data2/data0 in channel 1 (horizontal). (b) Vertical: BT5-BT6 (in data2)/BT5-BT6 (in data0) vs. horizontal: BT5-BT6 (in data2). Red dots are for image pixels with values over the median for $0.6\ \mu\text{m}$ reflected radiance or under the median for $6.2\ \mu\text{m}$ radiance, typically the cloudier half. Green dots for the rest.

The $6.2\ \mu\text{m}$ channel provides an observation of the upper troposphere's moisture, and the $7.3\ \mu\text{m}$ is sensitive to moisture content in a wider layer around the tropospheric mid-level. Thus, the brightness temperature (BT) difference between the two Meteosat water vapor channels ($\text{BT5-BT6} = 6.2\ \mu\text{m}-7.3\ \mu\text{m BT}$) can be used as a parameter summarizing the troposphere conditions on the vertical dimension. Figure 8a (right plot) shows a scatter plot of BT5-BT6 changes versus the recent value of BT5-BT6, where the pixels with radiance under the median for $6.2\ \mu\text{m}$ radiances (in red) and those with radiance above the median (in green) are disaggregated. The plot scattering of the colder (red dots) and warmer (green dots) pixels can be interpreted under the perspective provided by differential images of the two Meteosat WV channels as the following:

- BT5-BT6 differences above $-14\ \text{K}$ are associated only with radiances under the median for $6.2\ \mu\text{m}$ radiances (red dots), so only cloudy or very moist air masses in the middle/upper troposphere appear with these values;
- The range between $-14\ \text{K}$ and $-16\ \text{K}$, where the pixels in red and green are equally present, is representative of pixels with radiances around the median that indicate moderate moisture content in the upper troposphere and mid-level moist or low-level cloudy conditions;
- BT5-BT6 differences under $-16\ \text{K}$ represent upper-level dry air and potential instability in the case of moist air in the middle/lower troposphere seen as colder BT. A great part of the pixels falling under the range $-16\ \text{K}$ to $-18\ \text{K}$ with warmer-than-the-median $6.2\ \mu\text{m}$ radiance (in green) show an increase in the 15 recent years (values > 0 on the vertical axis). The colder-than-the-median $6.2\ \mu\text{m}$ radiance (in red) suffered a decrease;
- Only pixels warmer than the median (green, which corresponds to upper-level dry air) are associated with BT5-BT6 colder than $-18\ \text{K}$, and an increasing trend has been observed in the past 15 years;
- Due to the absence of a significant increase in BT6 in our results, the growth of the BT5-BT6 absolute difference warmer than $-16\ \text{K}$ suggests overall drying of upper-level air and increased potential instability in the convective environment prior to thunderstorm developments (see [20]).

3.3. Evolution of Radiances in the Infrared Windows and Ozone Absorption Spectral Regions

Three Meteosat infrared window channels from 8 μm to 12 μm plus channel 9.7 μm with ozone absorption show an increasing trend in measured radiance (+0.4% to +1.0%, see Figure 6). This is probably a result of a higher surface temperature and the reduction of cloud, which opens passages to the OLR (Section 3.5), as confirmed by other instruments, ground-based as well as from remote sensing [23,24]. The trend is less pronounced for the radiance in ozone channel 9.7 μm , since the stratospheric ozone layer acts as a filter for radiation from below and reduces the magnitude of the change.

3.4. Evolution of Radiances in the Carbon Dioxide Absorption Spectral Channel

The carbon dioxide absorption region (roughly from 13 to 17 μm) is only represented at SEVIRI by one channel, centered at 13.4 μm , namely at $750 \pm 50 \text{ cm}^{-1}$ in the wavenumber domain. Here, the decrease in the radiation reaching the satellite is $-3.9 \pm 0.4\%$ (Figure 5e). Our transfer model suggests an expected decrease of $-4.0 \pm 0.9\%$. The CO_2 channel radiation warming is numerically compensated with the cooling by increased outgoing longwave radiation of the infrared spectrum from 4 μm to 13 μm .

The evolution in 13.4 μm radiance seems not to be uniform (it shows during the intervening period a deceleration for its decreasing values), as seen in Figure 5f's lower two-line graph. The periods labeled data1a and data1b in Table 1 show a decrease of $-2.3 \pm 0.2\%$ in the two 6-year periods. However, it "jumps" back within the transition between periods (see Figure 5f around the weeks 35, 85, and 120), as if some rapid effect could have reduced the CO_2 concentration in the atmosphere. We do not observe a similar jump for window channels like 10.8 μm .

CO_2 absorption lines around 14 μm constitute the main contribution to the radiation greenhouse in the atmosphere [23]. Based on doubling rates of CO_2 in the infrared domain [23], an upper limit for the change of 9%, or equivalently 0.3 Wm^{-2} is calculated for the spectral subregion from 12.5 μm to 17.5 μm , excluding the effect of changes in the surface temperature. Meteosat measurements refer to the narrower subregion from 12.4 μm to 14.4 μm , known as channel 11 at 13.4 μm [25]. Using CO_2 absorptivity values typical of that channel bandwidth, we simulate in our model an expected value of -4.2% in radiance, very close to the measured -3.9% , and even closer after considering the surface warming in the period, as proxied by the +0.4% change in channel 9 at 10.8 μm .

3.5. Estimating Flux Change and Climate Balance

The evolution of the radiation flux in the period of the study is based on accurate data for the eleven central wavenumbers of the channels, but their representativity in the spectral domain is limited, and we cannot consider the SEVIRI channel measurements to describe changes outside of their bandwidth, as given in Table 3. Even if not essential to the conclusions of this paper, rough estimates of flux change in the 15-year period have been obtained for four spectral regions. Based on wavenumber distances between the eleven channel central wavenumbers, the result is a variation of $-0.90 \pm 0.23 \text{ Wm}^{-2}$ (planet warming) for the spectral range between 0.4 μm and 14 μm in the 15 years, which includes $-0.62 \pm 0. \text{ Wm}^{-2}$ change in the solar domain (described by the four channels centered at 0.6, 0.8, 1.6, and 3.9 μm). The absence in the Meteosat SEVIRI radiometer of a channel for the thermal region above 15 μm , with an important greenhouse reduction by water vapor of the outgoing longwave radiation, introduces an uncertainty around $\pm 0.30 \text{ Wm}^{-2}$ for a grand total estimate. Window channels and water vapor channels together change their values by $+0.48 \pm 0.25 \text{ Wm}^{-2}$, the plus sign indicating a loss of energy in the Earth-atmosphere system for that spectral region, which results from a warming surface.

Regional or local variations in the reflected shortwave radiation (RSW) and the outgoing longwave radiation (OLR), as depicted in Figure 9, show a statistically higher amplitude than the global average for the MFOV and can reach up to 20 K for pixel-sized regions ($\sim 10 \text{ km}^2$) in the 12.0 μm OLR flux. The OLR flux is not changing uniformly over the MFOV and sometimes shows drastic regional variations, for instance around Madagascar

or Tunisia, around 8% in RSW and in excess of 15% in OLR (Figure 9a,b). This kind of result was expected since areas with less cloud in the final period than in the initial period will allow an easier escape route to space for the outgoing longwave radiation. The anomaly correlation for the regional changes in the two channels ($0.6\ \mu\text{m}$ and $10.8\ \mu\text{m}$) is -0.46 , which is therefore significant and also turns into an intuitive result: with less cloud, the Earth is able to release more heat into space as infrared radiation.

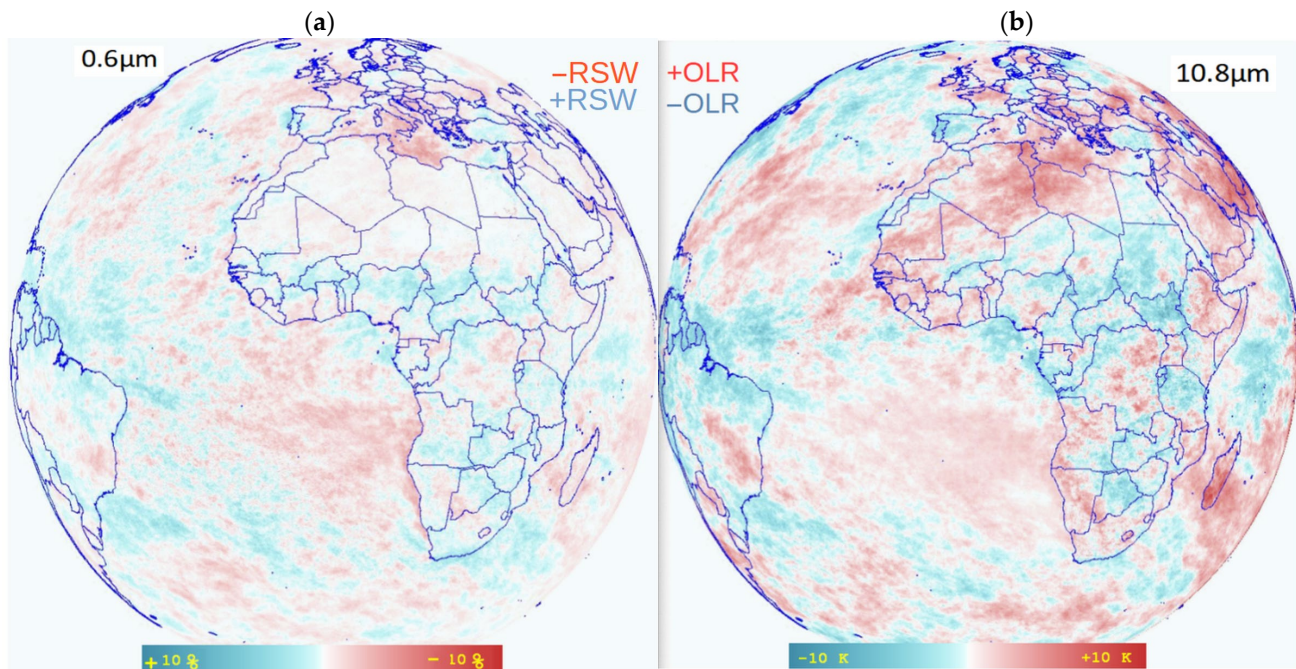


Figure 9. Comparison between the regional net variations of solar and infrared radiation over the MFOV. (a) Solar channel $0.6\ \mu\text{m}$, with units of solar albedo after comparison of the radiance with the solar constant. In red, areas of reduction in 15 years in the reflected shortwave radiation (RSW) corresponding to the channel, and in blue increases. (b) Infrared thermal channel at $10.8\ \mu\text{m}$, in units of kelvin (K), after conversion of the radiance through the Planck function into a brightness temperature. In red, areas of increase in 15 years of the outgoing longwave radiation (OLR) associated with the channel and, in blue, areas of reduction of OLR.

The actual flux changes in 15 years are illustrated in Figure 9, considering the regional variations in visible and infrared radiation measured over the Meteosat field of view. Areas of increased outgoing longwave radiation (OLR) correlate with areas of decreased reflected shortwave radiation (RSW).

Desert regions like the Sahara, with scarce cloudiness throughout the year and marginal land use transformation, show minimal changes in RSW but considerable changes in OLR in the past 15 years. The authors conjecture that the modifications in radiance can be explained by soil temperature increases, not excluding aerosol (dust) changes. Maritime regions like the South Atlantic show a high correlation between RSW and OLR changes, mostly for less reflected and more emitted radiation. In an area with a very low presence of human-related aerosols, we think that most of the change is in the cloud amount. In fact, a decrease in cloud cover optimally explains that less solar radiation is reflected into space (negative RSW) and that more heat from the surface can reach space (positive OLR). Further studies could address a proper analysis of correlated changes in the different variables mentioned above, beyond the scope of the current work.

To estimate land surface albedo, thermal emissivity, and associated land-atmosphere interaction, we compare changes in pixels of the Meteosat solar channel 1 and the window channel $10.8\ \mu\text{m}$ (channel 9), as well as temperature differences between the two window

channels 10.8 μm and 12.0 μm , considering the initial and final averages of the radiances (Figure 10).

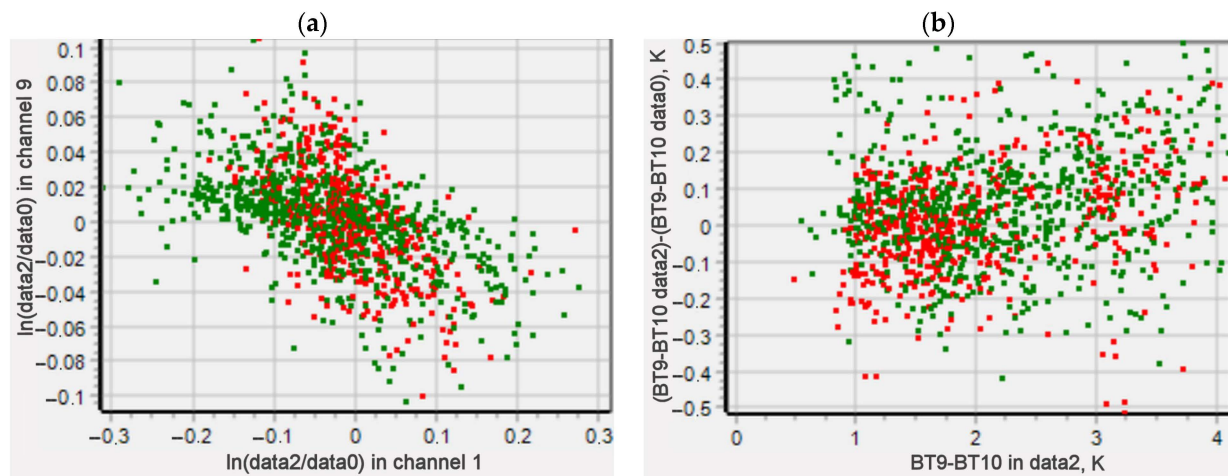


Figure 10. Scatter plots of changes in the radiance ratios of pixel averages at the beginning and the end of the studied period (data0 and data2 in Table 1). (a) *Vertical*: logarithm of data2/data0 in channel 9 vs. *horizontal*: logarithm of data2/data0 in channel 1. (b) *Vertical*: BT9-BT10 (in data2)—BT9-BT10 (in data0) vs. *horizontal*: BT9-BT10 (in data2). Red dots are for image pixels with values above the median at 0.6 μm reflected radiance or under the median for 10.8 μm radiances, typically the cloudier half. Green dots for the other pixels.

The left panel of Figure 10 shows the local variations in 15 years at 0.6 μm (vertical) and at 10.8 μm (horizontal) for a large collection of pixels under the MFOV. The negative correlation of -0.46 seen in Figure 10a between shortwave and longwave variation is considerable (more OLR is linked with less RSW) and suggests a reaction mechanism to the Earth's warming through reduced cloudiness or aerosol. For a decision on low-cloud evolution, we use the brightness temperature difference BT10.8–BT12 in Figure 10b, which shows a negative bias in BT10.8–BT12 for a majority of pixels with difference values under 2.5 K, in particular for those pixels with lower heat emission (in red). For differences bigger than 2.5 K, more to the right-hand side of the plot (Figure 10b), the bias is positive, suggesting either a thinner or higher cloud in a majority of regions, an ambiguity not resolved by this choice of a diagram by itself. Again, new studies involving more variables will help to break this ambiguity.

4. Discussion and Conclusions

Radiances measured by MSG satellites (over the period from 2004 to 2022) reflect the climate evolution of atmospheric and Earth-surface physical properties such as: (i) global cloudiness and water vapor in the troposphere; (ii) carbon dioxide concentration; (iii) land surface temperature and albedo; (iv) thermal emissivity; and (v) land-atmosphere interaction.

Our results show a negative trend in the evolution of the radiance in the solar spectrum (under 4 μm) measured by Meteosat (around -0.62 Wm^{-2}) over its MFOV. They are in line with the finding of D  bal et al. [12] that declining outgoing shortwave radiation is the most important contributor to a positive TOA (top of the atmosphere) net flux of 0.8 Wm^{-2} globally over a slightly longer period of 2001–2020.

This change in reflected shortwave radiation (RSW) can be interpreted as (a) a reduction of cloud, (b) a reduction of aerosol on a global scale, (c) a change in land use, which reduces the soil albedo, (d) a reduction of ice or snow surfaces, or (e) others, like a reduction of sulfate pollution, the impact of volcano eruptions, or solar cycles. We believe that soil and ice are not responsible for the negative long-term trend of albedo at the TOA, given the limited fraction of pixels affected. However, changes in attenuation of the global solar

irradiance in the atmosphere due to absorbing and scattering substances [26] can also play a minor role.

As a verification point, we also focused on the South Atlantic area, known for very slight pollution (from air traffic or ships) and outside of the paths of African dust. There, the RSW changes in 15 years show a much smaller connection to OLR changes than in the global MFOV, as is typical of low-level reflectors. Since aerosol changes in the area plausibly only affect the high levels of the atmosphere, we believe that the area suffers a marked decrease in low-level cloudiness, which is the first driver of the albedo reduction seen in Figures 4 and 6 for the complete MFOV.

An increase in longwave upwelling fluxes is shown in Section 3 over the MFOV, consistent with studies by other authors for clear sky areas [12] and considered a result of the higher surface temperatures [14]. As reported in the study by Liu et al. [24], the annual average land surface temperature (LST) obtained by two satellite instruments (AIRS and MODIS) and one re-analysis (ERA5-Land) showed an increasing global trend in the period 2003–2017.

The result of the net flux accumulation of 0.9 Wm^{-2} (climate forcing) over the Meteosat area obtained in a 15-year period in the current study almost doubles that reported in [15] of 0.38 Wm^{-2} obtained in a comparable but shorter period. Supplementary data from interferometry, such as those from IASI or AIRS sensors on board meteorological/environmental satellites, will supply additional insight.

An increase in surface temperatures is not necessarily enforcing a similar temperature increase in the atmosphere. For the $6.2 \text{ }\mu\text{m}$ WV channel, the radiance relative increase in 15 years is higher than the increase in the window IR channels (in the range from 8.0 to $12.0 \text{ }\mu\text{m}$), where radiation from the surface is the main contribution. The $6.2 \text{ }\mu\text{m}$ channel is generally not sensitive to moisture below the level of 500 hPa , so a hypothetical decrease in the moisture content in the upper troposphere provides an explanation of the measurements. The trend in the CH_4 concentration increase, cloud changes, water vapor redistribution, and temperature scenarios can explain in different ways the disparity in the changes at $6.2 \text{ }\mu\text{m}$ and $7.3 \text{ }\mu\text{m}$, respectively $1.8 \pm 0.3\%$ and $0.0 \pm 0.3\%$. We do not draw here a conclusion on the real cause of these two divergent values for the water vapor absorption channels.

For the CO_2 absorption channel (at $13.4 \text{ }\mu\text{m}$), a variation of $-3.9\% \pm 0.4\%$ is estimated for the span of 15 years. This change is mainly a consequence of the increasing CO_2 concentrations in the atmosphere following an increase in human-made carbon emissions.

The cloud feedback in the IPCC report, version AR5 [19], sets the effect of the amount of cloud at around $-0.46 \pm 0.3 \text{ Wm}^{-2}\text{K}^{-1}$, at least two times smaller than our estimate of -0.62 Wm^{-2} for the roughly $+0.25 \text{ K}$ ground temperature increase in the period 2006–2021 [23], equivalent to $-2.5 \pm 0.8 \text{ Wm}^{-2}\text{K}^{-1}$. We conclude that the climate forcing must also be due to a cloud cover reduction not yet completely reproduced by IPCC model studies. There is no evidence that it could result from a major change in aerosol concentrations.

As a conclusion from Figure 10, cloudiness correlates weakly with OLR (Pearson correlation of -0.46). The fact that cloudy pixels (in red) show high infrared increases with small decreases in solar albedo suggests a reduction of high-level cloudiness, which modifies OLR more than low-level cloud variations. But we do not discard an additional loss of low-level cloudiness, in particular in the South Atlantic.

The split window difference between $10.8 \text{ }\mu\text{m}$ and $12 \text{ }\mu\text{m}$, BT10.8–BT12 (sensitive to the presence of high cirrus, ground moisture, and air humidity at low levels) shows a prevailing negative evolution for differences under 2.5 K (Figure 10b), interpreted as either a change in the low-level cloud or a reduction of humidity near the ground, which decreases the brightness temperature (BT) difference. Also, an increase in vegetation would work in the same direction through a stronger ground emissivity at $12 \text{ }\mu\text{m}$. The difference seems globally neutral, with high regional variability, for instance, between the Sahara and the South Atlantic (regional comparisons are not detailed in this paper).

The magnitudes of flux changes shown in Section 3.5 ($-0.62 \pm 0.13 \text{ Wm}^{-2}$ change in the solar domain and $0.48 \pm 0.25 \text{ Wm}^{-2}$ change for the window channels and water vapor channels together) are consistent with the findings of other authors. The result of D  bal and Vahrenholt [12] (based on satellite data from the CERES project from 2001 to 2020 and supported by surface flux data) shows a decrease in cloudiness. This decline in the outgoing shortwave radiation (or RSW) at the TOA has a planet warming effect, only partially compensated by an increased outgoing longwave radiation (OLR).

We have confirmed a trend towards less cloudiness under Meteosat (MFOV). Taking into account global studies like the moon's earthshine, this trend is probably global. Such a cloud comes probably together with a drier mid-level atmosphere.

The current study will be followed by analyses of different geographical regions where confusing factors like temperature and humidity can be resolved, for instance the Saharan region, with a noticeable absence of clouds, or the South Atlantic, least affected by the increasing air traffic. So we expect to confirm the connection between the negative variation of outgoing shortwave radiation and the reduction in cloudiness. Also, an extension of the main conclusions above to the globe using data from interferometers like IASI with a higher spectral resolution is a suggested project.

Author Contributions: Conceptualization, J.I.P.F.; methodology, J.I.P.F.; software, J.I.P.F.; validation, C.G.G. and J.I.P.F.; formal analysis, J.I.P.F. and C.G.G.; investigation, J.I.P.F. and C.G.G.; resources, C.G.G. and J.I.P.F.; data curation, J.I.P.F.; writing—original draft preparation, J.I.P.F. and C.G.G.; writing—review and editing, C.G.G. and J.I.P.F.; visualization, J.I.P.F. and C.G.G.; funding acquisition, C.G.G. All authors have read and agreed to the published version of the manuscript.

Funding: This research was partially funded by the EUMETSAT SALGEE project (grant number PO 4500021883/04-October-2021).

Data Availability Statement: <https://navigator.eumetsat.int/start> (accessed on 22 August 2023).

Acknowledgments: This study uses as a main source the Meteosat data store from EUMETSAT, the European Organization for the Exploitation of Meteorological Satellites. We thank Vesa Nietosvaara and Ivan Smiljanic for their initial suggestions for the paper and fruitful discussions. Thanks are due to Richard Swifte for his devoted contribution to improving the text and his valuable comments. The reviewers' comments and suggestions were critical for the quality of the publication.

Conflicts of Interest: The authors declare no conflict of interest. The funders had no role in the design of the study, in the collection, analyses, or interpretation of data, in the writing of the manuscript, or in the decision to publish the results.

References

1. Dewitte, S.; Nevens, S. *Earth's Radiation Budget from 1979 to Present Derived from Satellite Observations*; Copernicus Climate Change Service (C3S) Climate Data Store (CDS), Copernicus Programme, EU: Brussels, Belgium, 2021. [CrossRef]
2. Xu, J.L.; Liang, S.L.; Jiang, B. A global long-term (1981–2019) daily land surface radiation budget product from AVHRR satellite data using a residual convolutional neural network. *Earth Syst. Sci. Data* **2022**, *14*, 2315–2341. [CrossRef]
3. Gupta, S.K.; Ritchey, N.A.; Wilber, A.C.; Whitlock, C.H.; Gibson, G.G.; Stackhouse, P.W. A Climatology of Surface Radiation Budget Derived from Satellite Data. *J. Clim.* **1999**, *12*, 2691–2710. [CrossRef]
4. Payez, A.; Dewitte, S.; Clerbaux, N. Dual View on Clear-Sky Top-of-Atmosphere Albedos from Meteosat Second Generation Satellites. *Remote Sens.* **2021**, *13*, 1655. [CrossRef]
5. Bojinski, S.; Verstraete, M.; Peterson, T.C.; Richter, C.; Simmons, A.; Zemp, M. The Concept of Essential Climate Variables in Support of Climate Research, Applications, and Policy. *Bull. Am. Meteorol. Soc.* **2014**, *95*, 1431–1443. [CrossRef]
6. Schmetz, J.; Pili, P.; Tjemkes, S.; Just, D.; Kerkmann, J.; Rota, S.; Ratier, A. An Introduction to Meteosat Second Generation (MSG). *Bull. Am. Meteorol. Soc.* **2002**, *83*, 977–992. [CrossRef]
7. Harries, J.E.; Russell, J.E.; Hanafin, J.A.; Brindley, H.; Futyan, J.; Rufus, J.; Kellock, S.; Matthews, G.; Wrigley, R.; Last, A.; et al. The Geostationary Earth Radiation Budget Project. *Bull. Am. Meteorol. Soc.* **2005**, *86*, 945–960. [CrossRef]
8. Aebi, C.; Clerbaux, N.; Baudrez, E.; Moreels, J.; de Buyl, P.; Russell, J.E. Preliminary Validation of 18 Years of Broadband Radiation Data from the Geostationary Earth Radiation Budget (GERB) Instruments. In Proceedings of the International Radiation Symposium (IRS), Thessaloniki, Greece, 4–8 July 2022. Available online: https://gerb.oma.be/PapPrePos/2022_IRS/Aebi_IRS2022_short.pdf (accessed on 5 August 2023).

9. Bantges, R.J.; Brindley, H.E.; Chen, X.H.; Huang, X.L.; Harries, J.E.; Murray, J.E. On the Detection of Robust Multidecadal Changes in Earth's Outgoing Longwave Radiation Spectrum. *J. Clim.* **2016**, *29*, 4939–4947. [CrossRef]
10. Brindley, H.E.; Bantges, R.J. The Spectral Signature of Recent Climate Change. *Curr. Clim. Change Rep.* **2016**, *2*, 112–126. [CrossRef]
11. Goode, P.R.; Pallé, E.; Shoumko, A.; Shoumko, S.; Montañes-Rodriguez, P.; Koonin, S.E. Earth's albedo 1998–2017 as measured from earthshine. *Geophys. Res. Lett.* **2021**, *48*, e2021GL094888. [CrossRef]
12. Döbal, H.-R.; Vahrenholt, F. Radiative Energy Flux Variation from 2001–2020. *Atmosphere* **2021**, *12*, 1297. [CrossRef]
13. Feng, C.; Zhang, X.; Wei, Y.; Zhang, W.; Hou, N.; Xu, J.; Yang, S.; Xie, X.; Jiang, B. Estimation of Long-Term Surface Downward Longwave Radiation over the Global Land from 2000 to 2018. *Remote Sens.* **2021**, *13*, 1848. [CrossRef]
14. Zeng, Q.; Cheng, J.; Dong, L. Assessment of the Long-Term High-Spatial-Resolution Global Land Surface Satellite (GLASS) Surface Longwave Radiation Product Using Ground Measurements. *IEEE J. Sel. Top. Appl. Earth Obs. Remote Sens.* **2020**, *13*, 2032–2055. [CrossRef]
15. Loeb, N.G.; Thorsen, T.J.; Norris, J.R.; Wang, H.; Su, W. Changes in Earth's Energy Budget during and after the “Pause” in Global Warming: An Observational Perspective. *Climate* **2018**, *6*, 62. [CrossRef]
16. Kidder, S.Q.; von der Haar, T.H. *Satellite Meteorology—An Introduction*; Academic Press: Cambridge, MA, USA, 1995; p. 466.
17. Rohde, R. Global Temperature Report for 2022. Berkeley Earth, U.S. Non-Profit Organization Focused on Environmental Data Science and Analysis. Available online: <https://berkeleyearth.org/global-temperature-report-for-2022/> (accessed on 25 June 2023).
18. Letu, H.; Shi, J.; Li, M.; Wang, T.; Shang, H.; Lei, Y.; Ji, D.; Wen, J.; Yang, K.; Chen, L. A review of the estimation of downward surface shortwave radiation based on satellite data: Methods, progress and problems. *Sci. China Earth Sci.* **2020**, *63*, 774–789. [CrossRef]
19. Armour, K.; Collins, W.; Dufresne, J.-L.; Frame, D.; Lunt, D.J.; Mauritsen, T.; Palmer, M.D.; Watanab, M.; Wild, M.; Zhang, H.; et al. The Earth's Energy Budget, Climate Feedbacks, and Climate Sensitivity. In *IPCC Sixth Assessment Report. Working Group 1*; Forster, P., Storelvmo, T., Eds.; WMO: Geneva, Switzerland; UNEP: Geneva, Switzerland, 2007. Available online: <https://www.ipcc.ch/report/ar6/wg1/chapter/chapter-7/> (accessed on 25 June 2023).
20. Georgiev, C.G.; Santurette, P.; Maynard, K. *Weather Analysis and Forecasting. Applying Satellite Water Vapor Imagery and Potential Vorticity Analysis*, 2nd ed.; Elsevier Academic Press: Cambridge, MA, USA, 2016; p. 343.
21. Weldon, R.B.; Holmes, S.J. *Water Vapor Imagery: Interpretation and Applications to Weather Analysis and Forecasting*; NOAA Technical Report; NESDIS 57; NOAA, US Department of Commerce: Washington, DC, USA, 1991; p. 213.
22. Donny, M.A.A.; Ottenbacher, A.; Hanson, C.G.; Pili, P.; Muller, J.; Blancke, B.; Jacquet, B.; Bianchi, S.; Coste, P.; Pasternak, F.; et al. Meteosat Second Generation: The MSG-1 imaging radiometer performance results at the end of the commissioning phase. In Proceedings of the SPIE 5151, Earth Observing Systems VIII, San Diego, CA, USA, 10 November 2003. [CrossRef]
23. van Wijngaarden, W.A.; Happer, W. Dependence of Earth's Thermal Radiation on Five Most Abundant Greenhouse Gases. *arXiv* **2020**, arXiv:2006.03098. [CrossRef]
24. Liu, J.; Hagan, D.F.T.; Liu, Y. Global Land Surface Temperature Change (2003–2017) and Its Relationship with Climate Drivers: AIRS, MODIS, and ERA5-Land Based Analysis. *Remote Sens.* **2021**, *13*, 44. [CrossRef]
25. EUMETSAT. Meteosat-8/MSG 1-Channel Spectral Bands. Available online: https://www-cdn.eumetsat.int/files/2020-04/pdf_ten_052561_msg1_spctrbnds.pdf (accessed on 25 June 2023).
26. Bai, J.; Heikkilä, A.; Zong, X. Long-Term Variations of Global Solar Radiation and Atmospheric Constituents at Sodankylä in the Arctic. *Atmosphere* **2021**, *12*, 749. [CrossRef]

Disclaimer/Publisher's Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.