

# Understanding Global Cloud Radiative Impacts

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## Introduction

The influence of clouds on the radiation budget is one of the most important facets of the Earth’s climate. Satellite observations in the last 35 years have helped us understand the bulk radiative effects of different classes of clouds. Bill Rossow has spearheaded efforts in that direction, demonstrating the value of the International Satellite Cloud Climatology Project (ISCCP) cloud retrievals as a foundation for the full reconstruction of Earth’s Radiation Budget components.

This main aim of this document is to provide an overview of the *global* radiative impacts of clouds at *annual* time scales. While geographical and seasonal aspects receive some attention, it is cloud radiative effect decomposition by cloud category (or “class”) that is the main focal point. Furthermore, this document addresses the large-scale radiative behavior of clouds only for the *current climate*, with no further discussion of how this behavior may change in the future and what its climatic impact may be [please refer to Del Genio (2018) for an excellent overview of this topic].

Cloud classes can be defined in many ways, and are often referred to with terms such as “cloud type” and “cloud regime”. Some of the definitions are more meaningful at the level of individual instrument footprints (“pixels” for passive or “rays” for active satellite observations) while others for larger areas (e.g., “mesoscale”). This distinction will become apparent below.

## Global annual cloud radiative influence

The most common framework for analyzing and discussing cloud radiative impacts separates atmospheric radiation into solar or shortwave (SW) radiation originating from the Sun and thermal infrared (IR) or longwave (LW) radiation emitted by the Earth (atmosphere and surface). A cloudless Earth is characterized by radiative warming of the surface (due to absorption of SW and LW radiation) and radiative cooling of the atmosphere (due to LW emission exceeding LW and SW absorption). *Our goal here is to examine how clouds affect this fundamental distinctive behavior.* We have conveniently defined the Cloud Radiative Effect (CRE) as a quantity to measure the impact of clouds on radiative fluxes (irradiances) over an area. CRE is defined as the difference between all-sky (including clouds) and cloudless-sky (clear-sky) fluxes. The common convention to ascribe a negative CRE when we want to convey a cooling effect of clouds, compels us to define CRE in terms of net, downward minus upward, fluxes. Thus:

$$CRE_{LW,SW} = F_{LW,SW}^{all} - F_{LW,SW}^{clr} \quad (1)$$

where  $F = F^\downarrow - F^\uparrow$

This definition applies to both the top-of-the-atmosphere (TOA) and the surface (SFC). The radiative impact of clouds on the atmospheric column as a whole (ATM) is obtained by subtracting the SFC from the TOA CRE:

$$CRE^{ATM} = CRE^{TOA} - CRE^{SFC} \quad (2)$$

Finally, the LW and SW CREs are often combined to obtain the overall (“total”, often called “net”) radiative effect of clouds:

$$CRE_{TOT} = CRE_{LW} + CRE_{SW} \quad (3)$$

Satellite and other observations, assisted by radiative transfer modeling, indicate that the radiative effect of clouds on the current climate (i.e., on a global annual basis) can be summarized as follows:

- Clouds cool the planet (climate), i.e.,  $CRE_{TOT}^{TOA} < 0$ .
- Clouds cool the Earth’s surface, i.e.,  $CRE_{TOT}^{SFC} < 0$ .
- Clouds have a near-neutral radiative effect on the Earth’s atmosphere, i.e.,  $CRE_{TOT}^{ATM} \approx 0$ .

The above statements can be further elaborated as follows:

- The cooling effect of clouds on the climate results from SW cooling ( $CRE_{SW}^{TOA} < 0$ ) exceeding LW warming ( $CRE_{LW}^{TOA} > 0$ ), i.e.,  $|CRE_{SW}^{TOA}| > |CRE_{LW}^{TOA}|$ .
- The cooling effect of clouds on the surface results from SW cooling ( $CRE_{SW}^{SFC} < 0$ ) exceeding LW warming ( $CRE_{LW}^{SFC} > 0$ ), i.e.,  $|CRE_{SW}^{SFC}| > |CRE_{LW}^{SFC}|$ .
- The near-neutral radiative effect of clouds on the atmosphere results from a small overall LW effect  $CRE_{LW}^{ATM} \approx 0$  being combined with a small overall SW effect  $CRE_{SW}^{ATM} \approx 0$ ; however, as we will see below, the range and distribution of LW atmospheric radiative effect values is much broader than that of the SW.

Again, the above summary of cloud radiative effects pertains to global annual conditions. As we will see below, deviations for different cloud classes are numerous and important. The overall impact depends on the mean radiative effect of the individual cloud classes and how often they occur. Deviations also arise because of seasonal effects, mainly because of the great hemispheric seasonal contrasts in  $F_{SW}^{TOA, \downarrow}$ .

We will now explore the radiative behavior of clouds in more detail, through a closer examination of how they alter the radiative behavior of a cloudless atmosphere in both the LW and SW part of the electromagnetic (EM) spectrum (cf. Slide 2).

### Radiative effects of clouds in the LW

The temperature of the troposphere generally decreases with height. Keeping this in mind is essential for understanding LW radiative effects of clouds. Also, clouds increase atmospheric opacity, which means that they add extinction optical depth to the atmosphere (i.e., increase the atmosphere’s ability to block LW radiation). Because the scattering effect of clouds can be largely neglected in the LW, the extinction effect of clouds comes mostly in the form of absorption. A completely opaque cloud (not allowing any LW radiation to be transmitted) absorbs all incoming radiation and is often called a “black” cloud. Many clouds are black or

nearly-black, but many are also transmissive of LW radiation. Like any object in thermodynamic equilibrium, clouds also emit EM energy, which per our conventions belongs to the LW part of the spectrum (energy emitted by the Earth's surface and atmosphere), the bulk of which resides between  $5\mu\text{m}$  and  $50\mu\text{m}$  (at terrestrial temperatures EM energy outside this range is considered negligible). So, what happens when a cloud is inserted in the Earth's atmosphere? The opacity of the atmosphere increases. More LW is absorbed and more is emitted (upward and downward) for a fixed temperature. A surface observer in a cloudless atmosphere senses the cumulative effect of the atmosphere's radiation emitted from all levels that are partially absorbed as they traverse the atmospheric column. The higher (colder temperatures) the radiation originates from, the fewer chances it has to survive its downward journey. If one inverts  $F_{LW}^{SFC,\downarrow}$  using the Stefan-Boltzman law, an *effective temperature of emission*  $T_{eff}^{SFC}$  can be calculated, corresponding to the temperature of a black-body atmosphere emitting towards the surface the same amount on average as the actual atmosphere. Using a standard atmospheric profile, this temperature can be converted to an effective emission height. Clouds increase  $F_{LW}^{SFC,\downarrow}$ , and therefore reduce the *effective emission height*  $H_{eff}^{SFC}$  of LW radiation towards the surface. In other words, with a cloud present, it is as if the LW radiation comes from lower in the atmosphere. This effect depends on the additional opacity added by the cloud, but also on the location of the cloud (mostly its base for a relatively opaque cloud): if the cloud base is above the  $H_{eff}^{SFC}$  of the clear atmosphere (i.e., *high* cloud) the increase in  $F_{LW}^{SFC,\downarrow}$  will be smaller because the LW radiation has greater chances of being absorbed and re-emitted by the atmosphere below the cloud. The increase in opacity brought by a *low* cloud has a greater effect because the cloud base temperature is likely higher than  $T_{eff}^{SFC}$ , and its base therefore below  $H_{eff}^{SFC}$ , so increases to  $F_{LW}^{SFC,\downarrow}$  are more dramatic. In summary, the lower and more opaque the cloud, the greater its impact on  $F_{LW}^{SFC,\downarrow}$ , the greater the contrast between clear and cloudy downward fluxes, and thus the greater the value of  $CRE_{LW}^{SFC}$ . At the same time, upward fluxes at the SFC between clear and cloudy conditions are virtually the same on average.

The LW effect at TOA can be understood with similar arguments. Where clouds occur, the additional atmospheric opacity blocks a portion of the LW radiation emitted upward by the lower (warmer) parts of the atmosphere and more of the upward emission now appears to be coming from colder cloud tops, i.e.,  $F_{LW}^{TOA,\uparrow}$  decreases, which can also be viewed as a decrease in  $T_{eff}^{TOA}$ , or equivalently a raising of the effective emission height  $H_{eff}^{TOA}$  compared to a cloudless atmosphere. The higher the cloud top, i.e., the higher it is above the  $H_{eff}^{TOA}$  of the *clear* atmosphere, the more dramatic the decrease in  $T_{eff}^{TOA}$  and  $F_{LW}^{TOA,\uparrow}$ , and the larger the contrast between clear and cloudy fluxes, thus the greater  $CRE_{LW}^{TOA}$ . Low clouds have small  $CRE_{LW}^{TOA}$  because despite the increase in atmospheric opacity, their cloud tops remain below  $H_{eff}^{TOA}$ , resulting in only a small reduction in  $T_{eff}^{TOA}$  since the radiation emitted by the cloud has a greater chance of being absorbed and re-emitted upward by the colder atmosphere above.

Given this picture of LW radiation propagation in the atmosphere, high and low clouds exhibit a rather distinct behavior: low clouds have a small instantaneous radiative impact at TOA and a large one at the SFC; high clouds have a large instantaneous radiative impact at TOA and a small one at the SFC. The impact on the atmosphere itself depends on the difference between the

TOA and SFC boundaries and can be thought of in terms of the distinct net flux divergence for the two classes of clouds, for the same clear sky conditions. For high clouds, the net input from the surface is almost the same as it is for clear-skies, with the upward surface flux only weakly counteracted by a downward LW which is barely affected by high clouds; at the same time, substantially less LW flux escapes to space, so the net flux divergence is smaller than in clear conditions and, therefore LW energy retention increases. For low clouds, the net energy input at the surface is smaller since upward emission is strongly counteracted by enhanced downward emission; at the same time the LW flux escaping to space is not much reduced compared to clear skies, yielding a net flux divergence that is larger than that of clear skies, i.e., more efficient cooling. Simply put, for high clouds almost the same LW energy as clear-skies is supplied from below while less escapes, while for low clouds far less LW energy compared to clear skies is supplied from below while almost the same as clear skies escapes to space. Reduced cooling (warming compared to clear skies) happens in the former case, and enhanced cooling in the latter case. In terms of Eq. (2),  $CRE_{LW}^{ATM} > 0$  for high clouds because  $CRE_{LW}^{TOA} > CRE_{LW}^{SFC}$ , while  $CRE_{LW}^{ATM} < 0$  for low clouds because  $CRE_{LW}^{TOA} < CRE_{LW}^{SFC}$ .

### Radiative effects of clouds in the SW

For the SW, interpretations of cloud radiative effects are much simpler: Increased opacity (extinction) compared to clear skies manifests mostly as increased scattering, reduced transmission, and to a lesser extent enhanced absorption. This yields enhanced reflectance to space  $F_{SW}^{TOA,\uparrow}$  compared to clear skies, ( $CRE_{SW}^{TOA} < 0$ ) and reduced transmitted flux towards the surface  $F_{SW}^{SFC,\downarrow}$  ( $CRE_{SW}^{SFC} < 0$ ) far exceeding any differences in surface upward fluxes. Column atmospheric absorption increases ( $CRE_{SW}^{ATM} > 0$ ). While this may at first glance seem unavoidable given that clouds add absorptive liquid droplets and ice crystals to the atmosphere, the atmospheric absorption increase is actually not universal since the additional absorption by the cloud particles is counteracted by reduced water vapor absorption below the cloud due to reduced SW transmission. On a global basis the particle absorption exceeds the reduced water vapor absorption slightly, so that  $CRE_{SW}^{ATM} \approx \text{positive, but small}$ .

### Additional perspectives of the global cloud radiative influence

In the following we will be attaching specific numbers to the radiative effects of clouds. Specifically, we will examine how much brighter the planet becomes because of clouds, how much dimmer clouds make the surface, how much colder clouds make the Earth appear from space, and how much warmer they make the atmosphere appear from the perspective of a surface observer. These numbers are obtained from the CERES (Clouds and the Earth's Radiant Energy System) broadband satellite radiometer, specifically the EBAF (Energy Balanced and Filled) Ed4.0 dataset (Loeb et al. 2018).

*Increase in planetary albedo ( $F_{SW}^{TOA,\uparrow} / F_{SW}^{TOA,\downarrow}$ ):* Planetary albedo increases from 0.16 for a cloudless planet to 0.29 for a cloudy planet, an increase of 81%. This can be thought also as decrease in planetary absorption (i.e., cooling), expressed in energy units as  $CRE_{SW}^{TOA} = (340-99) - (340-53) = -46 \text{ Wm}^{-2}$ . (cf. Slide 3).

Decrease in solar radiation reaching (transmitted to) the surface ( $F_{SW}^{SFC,\downarrow} / F_{SW}^{TOA,\downarrow}$ ): From 0.72 for a cloudless planet to 0.55 for a cloudy planet, a decrease of 23%. This can be thought also as decrease in surface absorption (i.e., cooling), expressed in energy units as  $CRE_{SW}^{SFC} = (187-23) - (244-30) = -50 \text{ Wm}^{-2}$ . (cf. Slide 4).

The enhanced greenhouse effect due to clouds can be viewed as either a colder planet from space (TOA) or a warmer planet from the surface (SFC).

*From the TOA perspective:* A “greenhouse factor” can be expressed as the ratio  $F_{LW}^{TOA,\uparrow} / F_{LW}^{SFC,\uparrow}$  which can be thought of as the effective transmission of the atmosphere which is different for clear (0.67=268/398) vs cloudy (0.60=240/398) conditions, i.e., ~ 11% less thermal IR radiation escapes to space with clouds present. In energy units  $CRE_{LW}^{TOA} = (0-240) - (0-268) = +28 \text{ Wm}^{-2}$ . In terms of effective temperature, a cloudy atmosphere makes the planet appear colder by about 7 K since for cloudy skies  $T_{eff}^{TOA} \approx 255\text{K}$ , while for clear skies  $T_{eff}^{TOA} \approx 262\text{K}$ . (cf. Slide 5)

*From the surface perspective:* The enhanced downwelling LW flux under cloudy conditions can be expressed as the ratio of  $F_{LW}^{SFC,\downarrow}$  for cloudy vs clear conditions which is ~1.1 = 345/315, i.e., an enhancement of ~10% because of clouds. In energy units  $CRE_{LW}^{SFC} = (345-398) - (315-398) = +30 \text{ Wm}^{-2}$ . The cloudy atmosphere appearing warmer than the clear atmosphere to the surface observer can also be expressed in terms of  $T_{eff}^{SFC}$  which is 279 K for a cloudy atmosphere and 273 K for a clear atmosphere, i.e., the planet (atmosphere) appears 6 K warmer from the surface with clouds present (cf. Slide 6).

The table below provides a summary of the different components of the CRE (cf. Slide 7). The combined effects of SW and LW is under the “TOT” column and conveys the earlier statement that clouds on an annual global basis cool both the Earth’s surface and the planet as a whole. Because the SFC cooling is about  $2 \text{ Wm}^{-2}$  greater, this means that a cloudy atmosphere retains a small amount of additional energy compared to clear skies. Because many fluxes have to be combined to obtain this number, a high uncertainty should be attached to it. According to CERES EBAF Ed4.0, it comes from the SW side, where the small enhanced absorption by clouds exceeds the small enhanced LW cooling (we have previously indicated that these two quantities are nearly zero). Recall that a clear atmosphere cools radiatively because the net (absorption minus emission) LW cooling far exceeds SW warming (due to absorption). The table below suggests that clouds do not change this by much on average: they add some warming in the SW and some cooling in the LW, but the changes are small and of opposite sign (according to CERES), further contributing to a smaller overall effect. We stress again that atmospheric CRE, coming from (in the case of TOT) double differences, is more uncertain than the other components, so the exact magnitude and sign (for LW and TOT) may change slightly in the future as new measurements and improved products are introduced.

**Table 1.** Global annual CRE components according to CERES EBAF Ed4.0

Perspective	LW	SW	TOT	Impact
TOA (“Planet, “Climate”)	+28	-46	-18	Cooling
Surface (SFC, BOA)	+30	-50	-20	Cooling
Atmosphere (ATM)	-2	+4	+2	Slight Warming (?)

## **CRE decomposition by cloud class**

We will now examine the CRE contributions of different cloud classes. As stated earlier “cloud class” is a general “umbrella” term meant to convey different ways of categorizing the world’s clouds. Here we will show results for four different classifications: Cloud Type (CT), Cloud Regime (CR), aka Weather State, Cloud Vertical Structure (CVS), and Cloud (thermodynamical) Phase (CP). Because these cloud classes are related through common cloud features, consistencies are seen among the decomposition choices of the various CRE components. Appropriately equipped GCMs that can create such cloud classes can then be evaluated based on whether the details of their own CRE decomposition are consistent with observations.

### Cloud type

The earliest decomposition of CRE employs CT and traces back to Hartmann et al. (1992), H92. CTs are defined via somewhat arbitrary boundaries in a joint histogram of cloud top pressure and cloud optical thickness defined over synoptic/mesoscale domains (~100 km and above). H92 divided the histograms first introduced by ISCCP (Rossow and Schiffer 1991) to create 5 basic CTs (Slide 8) and developed a method to collocate the CTs with CREs from the Earth Radiation Budget Experiment (ERBE, Barkstrom, 1984). Chen et al. (2000), C00, used a different division of the histogram that comprised 9 parts, each mapped to one of the standard cloud types common in surface observer classifications. The CRE of each CT was determined by a radiative transfer (RT) algorithm calculating irradiances for clear and cloudy skies with input coming from passive imager retrievals. Stephens et al. (2018), S18, used active CloudSat and CALIPSO (CC) cloud retrievals in an effort to update the H92 results whereby the nine ISCCP CTs were grouped into the five H92 CTs and CRE was calculated again from RT calculations operating on CC cloud retrievals. Slide 8 shows a summary of CRE findings for TOA. The H92 and S18 results are shown as total CRE zonal means by CT (separately for the winter and summer seasons), while the C00 results are provided as a table where global values with SW and LW components are given separately, and are weighted by the frequency of occurrence of each CT. The common feature of all results is that total CRE at TOA is rarely positive, with only high thin clouds (cirrus) producing consistently such values, while the negative values are mainly contributed by low clouds and are stronger for the high illumination summer season.

### Cloud Regime (Weather State)

Although sometimes confused with CT, the CR is a fundamentally different concept. A CR or Weather State (WS) is commonly defined by a centroid representing the mean of joint histograms that have similar co-variations of cloud extinction (expressed by cloud optical thickness) and cloud vertical location (expressed by cloud top pressure) at scales ~ 100 km (Rossow et al. 2005). The CRs thus come from the same joint histograms used to define CTs, but are in principle mixtures of CTs, one of which being usually dominant within a CR. Besides ISCCP, CRs have been also derived from 12 years of MODIS joint histograms and their occurrences have been collocated with CERES gridded one-degree fluxes (Doelling et al. 2013) in order to composite CREs by CR. Slide 9 shows the 12 MODIS CRs centroids (Oreopoulos et al., 2016) and plots the total TOA CRE vs the total SFC CRE for each of the CRs, weighted by their global relative frequency of occurrence (RFO). All CRs have negative total CRE at both TOA and SFC indicating that all CRs cool the planet and the surface. The CRs above the diagonal are

dominated by low clouds and cool the atmosphere ( $CRE_{TOT}^{ATM} < 0$ ), while those below diagonal are dominated by high clouds and warm the atmosphere ( $CRE_{TOT}^{ATM} > 0$ ). CR4 and CR5 with plenty of mid-level clouds are close to the diagonal and have almost a neutral effect on the atmosphere ( $CRE_{TOT}^{ATM} \approx 0$ ). The plot demonstrates that CRs provide a meaningful description of the diversity of CRE produced by the Earth's cloud systems.

### Cloud Vertical Structure

Active observations such as those by the CALIPSO and CloudSat satellites carrying a lidar and a radar, respectively, can be used to determine the boundaries of clouds in an atmospheric column, and therefore cloud vertical structure (CVS). Oreopoulos et al. (2017) used a combined CC product to count the frequencies of the most common CVS defined by the occurrence of either isolated High (*H*), Middle (*M*), and Low (*L*) clouds or the co-occurrence of such clouds at various configurations (two or three occurring simultaneously in an atmospheric column, either as contiguous or non-contiguous entities), as in Tselioudis et al. (2013). Another CC product based on RT calculations applied to CC cloud retrievals allows then the calculation of CRE at TOA, SFC (BOA=Bottom of the Atmosphere) and within ATM for each configuration, at both the SW and LW (blue and red bars in Slide 10, respectively). The Slide 10 results account for the frequency of occurrence of each CVS class. All CVS classes except two have negative  $CRE_{TOT}^{TOA}$  (blue bars bigger than red bars) so most CVS classes cool the planet. All CVS classes have negative  $CRE_{TOT}^{SFC}$ , and therefore radiatively cool the surface. Six CVS classes radiatively warm the atmosphere (positive difference between TOA and BOA total CRE), three cool it, and one (CVS = "M") is near neutral (red, blue, and no hue in the middle part of the plot). To warm the atmosphere a CVS has to include *H* clouds, to cool it, it has to comprise *L* clouds. CVS = "L" has a huge CRE contribution to planetary (TOA) cooling, followed by CVS = "H×M×L", but a much smaller contribution to surface cooling, because of large positive  $CRE_{LW}^{SFC}$ . Note that even the CVS = "H" (isolated high clouds) provides instantaneous radiative cooling to the surface.

### Cloud Phase

The CRE breakdown by CVS described above is broadly consistent with results from Matus and L'Ecuyer (2017) based on the same dataset, but relying on a cloud (thermodynamical) phase classification. Four CP categories are identified, three representing liquid, ice and mixed phase clouds, and one where phase cannot be assigned because multi-layer clouds of potentially different phases coexisting in the atmospheric column. Slide 11 shows the TOA, SFC, and ATM total CRE for each CP class, and their combination, all weighted by their frequency of occurrence. Only ice clouds warm the planet (recall that both CVS classes with positive  $CRE_{TOT}^{TOA}$  included *H* clouds), clouds of all phases cool the surface (again consistent with the CVS analysis), while the atmosphere is warmed by all CP categories other than liquid clouds (recall that all CVS classes with negative  $CRE_{TOT}^{ATM}$  included *L* clouds) but with the combined effect exhibiting large spatial variability. The last column is repeated in Slide 12, which also shows the SW and LW components of the atmospheric CRE. Consistent with our earlier discussion clouds of all CP categories warm the atmosphere in the SW ( $CRE_{SW}^{ATM} > 0$ ), while the  $CRE_{TOT}^{ATM}$  and  $CRE_{LW}^{ATM}$  patterns are very similar, indicating that the former is just the outcome of applying an offset, in the form of a uniformly positive  $CRE_{SW}^{ATM}$ , to the latter.

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## Slide Notes

**Slide 1:** Cover slide.

**Slide 2:** The effect of clouds on the Earth's Radiation Budget can be viewed as the story of the competition between their distinct interactions with thermal IR (LW) radiation where clouds absorb and emit (very little scattering), and the solar SW where clouds scatter and absorb. A standard way to measure the impact of clouds on the flow of energy over a given area is through the so-called Cloud Radiative Effect CRE (used to be called "Cloud Radiative Forcing"), the difference between all-sky and clear sky radiative fluxes (irradiances). The difference is properly defined with net = down – up fluxes, when clear-sky flux is subtracted from all-sky flux so that positive values indicate warming and negative values indicate cooling *regardless of the perspective* [planet (TOA), surface (SFC/BOA), atmosphere (ATM)]. The total CRE is the sum of the SW and LW CRE components. From space, we see what is commonly called the Top-of-the-Atmosphere (TOA) CRE. The TOA CRE gives the combined effect of clouds on the surface and atmosphere, in other words the impact of clouds on the "planet" or the "climate". In the SW, and at TOA, clouds have a negative SW CRE: They reflect more than clear-skies, so less is absorbed by the planet, and we state that clouds have a "cooling effect" on the planet. The thicker and more extensive the cloud, the greater the cooling. Now at the SFC, clouds also produce a negative CRE, with the cooling stemming from the reduction of energy being available to be absorbed by the SFC. What happens in the atmosphere is not obvious since it depends on the relative magnitudes of TOA and SFC cooling (but it turns out to be positive since clouds enhance atmospheric absorption relative to clear skies). In the LW, CRE at TOA is positive indicating warming largely because atmospheric temperature drops with height. Clouds increase the atmospheric opacity in the IR and because they emit to space at lower temperatures than the clear atmosphere (in other words they "raise the upward effective emission height"), we say that they help the planet "trap more radiation", i.e., they induce a stronger greenhouse effect. The higher and colder the cloud the more reduced the emission to space, thus the stronger the trapping and the planetary warming. The increase in IR opacity also means greater emission toward the surface ("lowering the downward effective emission height") which is a warming effect (positive LW CRE) at the surface as well. The effect on the surface is greater the lower the cloud (base). Again, what the effect is on the atmosphere is not obvious, as it depends on the relative magnitudes of TOA and SFC LW CRE (it turns out to be a slight cooling, but within the uncertainty of the measurements).

**Slide 3:** Here we address the SW and the TOA perspective. The fundamental question is: How much more reflective is the Earth because of clouds? Satellite observations (CERES) indicate that without clouds the Earth would reflect about 16% (i.e., clear-sky planetary albedo=0.16) of incoming solar energy and would exhibit a large contrast between ice-free ocean (less reflective) and continents/sea-ice (more reflective). The atmosphere contributes more to the clear-sky reflectance than the surface according to analysis by Stephens et al. (2015). Adding clouds increases the albedo to 29% (i.e., current planetary albedo = 0.29). The albedo increase contributed by clouds is almost universal (except over highly reflective surfaces), but is more prominent over ocean. The relative increase in albedo due to clouds is about 81%, and in

energy units, namely SW CRE, about  $46 \text{ Wm}^{-2}$  (negative) on annual basis. The additional reflection due to clouds has a cooling effect on the planet since it reduces solar absorption.

**Slide 4:** Moving on to the surface, one can look either at how much difference clouds make in the amount of solar radiation surviving its propagation through the atmosphere and reaching the surface (transmittance), or perhaps more importantly, in the fraction of solar radiation absorbed by the surface. The top right panel shows that the spatial variations of clear-sky transmittance are quite substantial and depend mainly on water vapor (and ozone) amounts and the angle of illumination. When clouds are added, the transmittance map changes dramatically (lower right panel). The absolute change is as big or bigger than albedo, but the relative changes are smaller because clear-sky transmittance and clear-sky surface absorption are much larger than clear-sky albedo. Ultimately, clouds decrease the solar radiation reaching (and being absorbed by) the surface by 23%. In energy units, the cooling effect at the surface in terms of SW CRE is  $50 \text{ Wm}^{-2}$  (negative), according to CERES EBAF Ed4.0 indicating less surface absorption. The difference between TOA and SFC SW CRE is  $4 \text{ Wm}^{-2}$ , i.e., the atmosphere absorbs an additional  $4 \text{ Wm}^{-2}$  with clouds present, or 5% more in relative terms. This result is the outcome of some compensation between additional absorption by cloud particles and reduced water vapor absorption since clouds partially shield the water vapor-rich lower levels of the troposphere from incoming solar radiation. We should note here that surface radiative fluxes are not directly observed, but are obtained by performing a significant amount of modeling while the observed TOA fluxes are used as a constraint.

**Slide 5:** We now examine cloud LW effects, namely cloud “greenhouse effects”. Again, either a space (TOA) or a surface perspective can be adopted. Starting with the TOA perspective, one way to measure the greenhouse (GH) effect is the GH factor, namely the ratio of LW emitted to space to the LW emitted upward from the surface. This provides a LW emission “reduction factor”, which can also be thought as a conversion factor that scales surface emission to planetary emission. Without clouds the global value is 0.67. i.e., 67% of the surface emission escapes to space. There is a fair amount of spatial variability in the GH factor with smaller values in the more humid tropics (upper right panel). When clouds are added, the global value reduces to 0.60 and the regional contrasts become stronger (lower right panel). In terms of this measure, clouds then increase the GH effect by 11% ( $0.60/0.67 \approx 0.89$ ). But we really do not have to compare (take the ratio of) ratios. We can directly compare TOA upward LW fluxes between clear and all-sky conditions, by either taking a ratio or a difference (i.e., CRE). The cloud impact either as a ratio of fluxes or GH factors is the same because the upward flux at the surface is virtually the same for clear and cloudy conditions. In energy units, the warming effect in the LW expressed as CRE is  $28 \text{ Wm}^{-2}$  (positive, less emitted to space). Yet another way to measure the GH effect from space is the planetary effective temperature i.e., the temperature perceived from space of a blackbody planet, obtained from the Steffan-Boltzmann law. With clouds the Earth appears about 7 K colder (255 K vs 262 K).

**Slide 6:** From the surface perspective, the cloud GH effect can be measured as either the ratio or the difference between downward LW fluxes under clear and cloudy conditions. The ratio indicates about 10% more downwelling LW due to clouds, which as a difference represents an

additional  $30 \text{ Wm}^{-2}$ . The maps look rather similar in terms of variability between clear and cloudy conditions. The surface increase is larger (within uncertainties) than the TOA decrease by only  $2 \text{ Wm}^{-2}$  globally, with the difference representing a reduction in LW absorption (i.e., a cooling) due to clouds. The global  $-2 \text{ Wm}^{-2}$  value is the net result of large spatial variations from various cloud classes as we will see later. Blackbody effective temperatures can be used again as a measure of the cloud GH effect on the surface. In this case, what is being measured is how much warmer on average a cloudy atmosphere appears to a surface observer compared to a clear atmosphere. When inverted through the Steffan-Boltzmann law, the downwelling fluxes from the CERES product indicate a 6 K warming (279 K for cloudy vs 273 K for clear).

**Slide 7:** This table provides a summary of the global annual CREs, with additional interpretive information coming from slides 8-12. The SW cooling effect exceeds the LW warming effect at both TOA and SFC. Because the SFC cooling is greater than the TOA cooling, clouds have a warming effect on the atmosphere. Although the atmospheric warming originates from the SW, the variability is much larger in the LW (see Slide 12). In other words, all clouds add some SW atmospheric warming, but the smaller negative value in the LW is actually the overall result of a lot of compensation between warming and cooling. So, on a planetary scale clouds do not affect much the clear-sky radiative cooling, with the compensation needed to achieve energy equilibrium coming mainly from latent heating (precipitation).

**Slide 8:** Attempts to answer the question of how different cloud classes affect the Earth's radiation budget were first made about 2.5 decades ago. Hartman et al. (1992) combined ERBE and ISCCP observations to break down the CRE at the TOA of five broad cloud types in terms of seasonal zonal averages. These results have been recently updated by Stephens et al. (2018) using CloudSat and CALIPSO data. ISCCP has previously also tried to address the same problem using different cloud types, and the same methodology central to the Stephens et al. analysis, namely obtaining flux estimates from supplying cloud property retrievals into a radiative transfer code. From the perspective of the planet as a whole (TOA), these studies find that, with the exception of high-thin or cirrus clouds, all other cloud classes exhibit a negative total CRE overall, i.e., a cooling effect on the Earth-Atmosphere system. These type of CRE breakdowns are possible with other cloud classifications as well, as shown below.

**Slide 9:** One such alternate cloud classification is the Cloud Regime (CR) classification. The most recent set of MODIS CRs were derived by Oreopoulos et al. (2016) (represented by the twelve mean joint histograms on the right), and their daily occurrences around the globe were matched with CERES CREs in order to assess the radiative effect of each regime. Here we show again global annual mean results. This plot summarizes the mean radiative effect of the MODIS CRs after being weighted by their frequency of occurrence. The SW and LW CRE were combined to estimate the total CRE at both the TOA and SFC and these two total CREs were plotted against each other in order to infer visually the total CRE divergence (which is the total CRE of the atmosphere). All MODIS CRs cool the planet, with the effect being stronger for low-cloud dominated CRs which have much stronger negative SW CRE than positive LW CRE. All of them also cool the SFC (negative total CREs), with stronger values for high-cloud dominated CRs. When the cooling of the SFC exceeds that at TOA, the CR exerts a warming on the ATM (below

diagonal), while a radiative cooling contribution to the ATM occurs when the negative TOA CRE exceeds the negative SFC CRE. In short, CRs dominated by high clouds warm the atmosphere, while those with predominantly low clouds cool the atmosphere.

**Slide 10:** Another cloud classification can be achieved using a joint CloudSat/CALIPSO product identifying cloud vertical locations. Oreopoulos et al. (2017) devised a scheme that uses the standard ISCCP layers separating clouds into Low (*L*), Midlevel (*M*), and High (*H*) using the 440 and 680 hPa atmospheric levels and numerous simplifications/assumptions to assign cloud layers to either one, two or three of the standard ISCCP layers. The end result were ten cloud vertical configurations which they called Cloud Vertical Structures (CVSs), and which mirror those of Tselioudis et al. (2013), but come from a different cloud profile assignment algorithm. Clouds can either occupy a single standard layer, two standard layers as a single entity, three standard layers as a single entity, and either two or three standard layers simultaneously as separate entities. Another CloudSat/CALIPSO product allowed them to calculate the CRE (TOA, SFC/BOA, ATM) of each configuration, both SW (blue bars) and LW (red bars). In the middle of the graph the total atmospheric CRE is shown, calculated as the difference between the TOA total (=SW+LW) and SFC total CRE. The numbers shown are weighted by the frequency of occurrence of each CVS class. All CVS classes except two have negative TOA total CRE (blue bars bigger than red bars) so most CVS classes cool the planet. All CVS classes have negative BOA (SFC) total CRE, so cool the surface. Six CVS classes warm the atmosphere (positive difference between TOA and BOA total CRE), three cool it, and one (isolated mid-level clouds) is near neutral. To warm the atmosphere a CVS has to include *H* clouds, to cool it has to have *L* clouds. The “*L*” CVS class has a huge CRE contribution to TOA net cooling (followed by “*H*×*M*×*L*”), but a much smaller contribution to surface cooling, because its positive LW SFC CRE is also large. Note that even the “*H*” CVS class cools the SFC instantaneously, so the planetary warming effect of these clouds is realized through warming of the atmosphere.

**Slide 11:** Another possible cloud classification accounts only for their thermodynamic phase. This undertaking was documented by Matus and L’Ecuyer (2017) who used the same datasets as in Slide 10. SW, LW, and total CREs were derived for the TOA, SFC, and ATM, including the geographical distribution. In their representation, atmospheric columns containing multi-layer clouds cannot be assigned a phase, and are presented separately from the “mixed” class which contains contiguous cloud layers where both phases may co-exist in the same cloud volume. The phase classification indicates that only ice clouds warm the planet, clouds of all phases cool the surface, while the atmosphere is warmed by all clouds other than liquid clouds. The combined effect for the atmosphere exhibits large spatial variability with large swaths of negative and positive values depending on the geographical preference of clouds of particular phases.

**Slide 12:** A more detailed look at the atmospheric (ATM) CRE requires separate examination of the SW and LW components. One can see that the spatial variability of the total CRE (rightmost column) is driven by the LW (middle column) which has very strong negative values for liquid clouds. The overall LW ATM CRE is almost zero, but comes as a result of widespread

cancellation. The SW ATM CRE (leftmost column) is uniformly positive with all clouds enhancing the SW atmospheric absorption, but with substantial cloud phase dependence.

**Slide 13:** Summary of global cloud radiative impacts.

**Slide References**

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