WATER AND THE EARTH'S HEAT BUDGETS

Water plays a dominant role in all of the global energy budgets. It accounts for some three-fourths of the global absorption of incoming solar radiation. It accounts for almost three-fourths of the "greenhouse" process in the atmospheric absorption and emission of thermal infrared radiation. It plays a dominant role in the conduction of sensible heat from the Earth's surface to the overlying atmosphere; and it is the sole actor in the hydrologic heat pump process. Finally, most of the energy that heats the atmosphere comes from water and most of the energy that heats the Earth's surface goes into water. Water dominates all forms of energy transfer in the earth-atmosphere system.

Budgets

A budget is a device for analyzing and displaying incomes and expenditures, gains and losses, inflows and outflows. There are a number of different budgets in the physical sciences, most of them having to do with energy and mass. The Earth's heat budget deals with energy.

Scientific global heat budgets have been offered since Dines presented his suggestions to the Royal Meteorological Society in 1917. Many other scholars have taken a try at it. The major stumbling block was that we had no precise information on either total incoming energy or total outgoing energy. We live at the bottom of the atmosphere, and all our early measurements were taken down here. We were poorly informed as to what happened to incoming solar radiation as it passed in through the atmosphere, and to what happened to terrestrial radiation as it passed out through that same atmosphere.

It was difficult to prepare a budget under those circumstances, but some scholars came up with budgets that hold up surprisingly well under the light of current knowledge.

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Starting early in the last century, we began to get information on the atmospheric attenuation of insolation and terrestrial radiation from balloons and rockets. But even these devices had their limits. Since 1977, however, we have had the benefit of measurements taken by earth-orbiting satellites. These satellites were able to measure both incoming solar radiation and outgoing terrestrial radiation at the top of the atmosphere.

It should be noted, however, that these measurements are still short-term by conventional climatic standards. Moreover, these measurements are neither as precise nor as comprehensive as we might wish them to be. Therefore, judgments based on these measurements must still be considered to be somewhat tentative.

The Solar Constant – Satellite measurements over a period of twenty-two years (two complete eleven-year sunspot cycles), have produced a value for ***in***coming ***sol***ar radi***ation*** (***insolation***) at the "top" of the Earth's atmosphere of 1,366 joules per square meter per second**,** measured normal to the earth's disc [Scafetta & West, 2005]**.** This is the new ***solar constant***. It replaces earlier estimates, and will be replaced by a better value in the fullness of time. This is the starting point for all current studies of the various heat budgets of the Earth.

Annual global budget constraint – For historical reasons, heat budgets are usually given in units of watts per square meter, averaged over the Earth's entire surface. One watt is one joule per second. Since the Earth's surface area is exactly four times its disc area, this gives us an energy income for our global heat budget of 342 watts per square meter—more or less. That value is the constraining value for our budget. Ignoring storage considerations, we must therefore have a total outflow of that same amount over any reasonable period of time.

The Sun as the Ultimate Source of Energy

Virtually all of the earth's heat energy comes ultimately from the sun. It may come directly as sunshine or indirectly as moonshine (solar radiation reflected from the surface of the moon) or even more indirectly from the energy of solar tidal forces on the world ocean and world atmosphere. It may make itself manifest immediately, as in the warming rays of the sun on your skin. It may be stored in various ways and become sensible heat at some later time, as in the warming of the night air by the warm earth or as in the burning of fossil fuels. However it comes, the Sun is the source of virtually all of the earth's heat. When early peoples spoke of the sun as the source of all life, they spoke truly.

Non-solar sources of energy – A very small part of the earth's heat budget comes from non-solar sources. These include the steady flow of heat from the earth's molten interior to the surface of the planet and radiation from parts of the universe other than the sun. Heat flux from the interior is the next largest source of energy after insolation, but is still less than twenty thousandths of one percent of the solar energy input. The total energy from the rest of the universe is even less. The energy that mankind releases to the atmosphere in an entire year is less than the Earth gets from the Sun in ten minutes. All non-solar sources put together are—for all intents and purposes—insignificant in devising heat budgets for the earth and its components and in understanding climatic changes.

Nature of Electromagnetic Radiation

In this paper, we will treat all electromagnetic radiation, including insolation, as streams of photons. Photons are defined as massless packets of energy traveling at the speed of light (***c***). As they travel, the photon's energy contents are believed to alternate rhythmically between electrostatic and electromagnetic states.

Frequency – The time rate at which this alternation occurs is called the frequency of the photon or radiation. It is measured in cycles per second (cps) or Hertz (Hz), and is customarily symbolized by the Greek lower-case letter ***nu*** (***ν***).

Wavelength – The distance traveled by a photon in the time it takes to complete a single alternation in energy states is termed the wavelength of the radiation or photon. It is commonly measured in nanometers (nm) or microns (μ), and is customarily symbolized by the lower-case Greek letter ***lambda*** (**λ**). For atmospheric studies, wavelength is more useful than frequency, and we will use that measure unless there is specific reason to do otherwise.

Equivalence – The frequency and wavelength of a photon are related to the speed of light by the formula:

$$\nu\lambda = c \qquad \text{WHB01}$$

That is, the frequency times the wavelength is equal to the speed of light.

Energy Levels – The energy content of each photon is directly and rigorously related to its frequency and wavelength. This energy is expressed as:

$$e = \mathrm{h}\nu = \mathrm{h}\frac{c}{\lambda} \qquad \text{WHB02}$$

Here e is the energy content of the photon and **h** is Planck's constant. The other parameters have their previously defined values. Note that high energy photons have short wavelengths and high frequencies. Low energy photons have long wavelengths and low frequencies.

Quantum Constraints – The essence of quantum thermodynamics is that the photons emitted by a substance or absorbed by it have rigorously set values. Each chemical (H_2O, CO_2, O_3, etc.) has a very precise set of wavelengths at which it may either absorb or emit photons. This set (the spectrum of that substance) may be quite large, but it is not infinite.

(For those of you who are not physical scientists, it is axiomatic that if a substance is capable of absorbing photons of a specific wavelength or frequency or energy level, then it is also capable of emitting photons of that identical wavelength or frequency or energy level if conditions are right.)

No substance may absorb or emit photons of any wavelength not included in its spectrum under any conditions. This characteristic of matter is the foundation of spectrographic analysis. By examining the wavelengths that a substance emits or absorbs, we may ascertain its chemical composition.

It should be noted that individual substances may share segments of their spectra. That is, both substances may absorb and emit at one or more particular wavelengths. However, their overall spectra will be different. For example, both water vapor and carbon dioxide gases absorb and emit at some of the same wavelengths, but not at others. Each of these two atmospheric gases has its own specific spectral signature.

Liquids and solids present special cases. In gases, the molecules are discrete entities as they move about. They only come into "contact" with one another during their frequent collisions. In liquids and solids, the molecules are in close contact with many other molecules, and are sometimes bonded to them in certain ways.

In terms of quantum thermodynamics, this means that liquids and solids possess many, many more possible energy levels. Consequently, the spectra of liquids and solids present virtually continuous bands. The individual energy levels are present in these bands, but our current technology is incapable of distinguishing them. For this and other reasons, solids and liquids are usually converted into gases before spectrographic analysis is attempted.

Solar Spectrum – The wavelength of maximum intensity for insolation is 475 nanometers. This wavelength is toward the green end of the visible spectrum. However, the scattering of a portion of the blue light component of that greenish radiation by the intervening atmosphere allows us to perceive sunlight as somewhat yellow light. Some 98% of solar radiation has wavelengths between 30 nm (gamma rays) and 3,000 nm (thermal infrared).

Broad Classification of Insolation – It is common to group the various wavelengths into three broad classifications based on wavelength. Different sciences use different groupings for their different purposes. We will use the following classification: infrared (>740 nm), visible (740 to 400 nm), and ultraviolet (<400 nm).

About 46% of the incoming solar radiation at the outside of the atmosphere is in this infrared range, some 45% in the visible range, and the remaining 9% in the ultraviolet range. These proportions change as the radiation passes through the atmosphere. Here, at the surface, only 3% of the solar radiation is in the ultraviolet range, some 43% is in the infrared range, leaving the bulk of the radiation—54%—in the visible spectrum.

In scholarly articles on global heat budgets, it is common to refer to solar radiation as "shortwave" and terrestrial radiation as "longwave" so as to clearly distinguish between the two different sources of radiation when both are present in the atmosphere. I will go a step farther in the interests of clarity and describe all solar wavelengths in nanometers (nm) and all terrestrial thermal infrared radiation in microns (**μ**). Not only does this practice avoid possible misunderstandings, but it is in keeping with scientific tradition.

There is a very small area of overlap between the solar spectrum and the terrestrial one. This occurs between 3,000 and 9,000 nanometers in the solar spectrum and three to nine microns in the terrestrial one. However, both spectra are near the respective tails of their distribution curves and are relatively low in intensity in that area of overlap. Hence, it is both possible and convenient to treat them as two separate streams of photons.

It should be noted that that range of wavelengths held in common is strongly absorbed by water vapor and—to a lesser extent—carbon dioxide.

Attenuation of Insolation by the Atmosphere

When a photon of solar radiation enters the top of the Earth's atmosphere and encounter a molecule of matter, three things (and only these three) can happen to it.

Absorption – Firstly, it may be absorbed, and cease to exist. In that case, its energy content becomes an equivalent amount of kinetic energy and goes to warm whatever does the absorbing.

Only photons of certain wavelengths can be absorbed by a specific kind of molecule. If a photon does not have one of those specific wavelengths, it will not be absorbed. Water vapor absorbs only photons of specific energy levels (wavelengths) and will not absorb any other photons. The complete set of the various wavelengths that water vapor will absorb is called its absorption spectrum.

Each isotope of each chemical substance has a different absorption spectrum. Each dimer or polymer of each chemical substance has a different absorption spectrum. Thus water vapor has a wide variety of absorption spectra—one for each isotope and several for each dimer or polymer.

Exactly the same thing is true for each and every gas molecule that makes up the atmosphere. Its chemical structure, its isotopic structure, and its polymeric structure will determine which photons it will absorb, which it will deflect, and which it will transmit unaltered.

Table WHB01 shows some 102 Wm^{-2} of insolation being absorbed by the Earth's atmosphere. This absorption goes directly into heating the molecules that do the absorbing. Since these molecules undergo billions of collisions per second with their neighboring molecules, this increase in temperature is quickly transmitted to these neighboring molecules via simple molecule-to-molecule conduction. This is but one of the many sources of heat received by the atmosphere.

Most of this absorption of solar radiation is accomplished by ozone and oxygen in the ultraviolet portion of the insolation; by clouds, ozone, and water vapor in the visible portion of the insolation; and by clouds, water vapor, and carbon dioxide in the infrared portion.

A Cautionary Note on "Re-radiation": Scholars who should know better (I have done it myself) sometimes use the term reradiation to describe the absorption of a photon by a molecule and the subsequent emission of a photon. This usage is almost always false and misleading. It does sometimes happen that a molecule will absorb a photon of a specific wavelength and subsequently emit a photon of the identical wavelength, but this is relatively rare.

The wavelengths of emitted photons are highly temperature dependent. A molecule of water or carbon dioxide or ozone may readily absorb a short wavelength/high energy photon of solar radiation, but is extremely unlikely to emit such a photon. Instead, the molecule will most likely emit several photons of a longer wavelength and lower energy content.

Therefore, neither the atmosphere nor the Earth's surface absorbs and reradiates radiant energy. Both absorb radiation and both emit radiation. Over a sufficient period of time, the total energy content of the absorption will equal the total energy content of the emission if the temperatures remain constant. However, the number of photons absorbed and their wavelengths will **not** equal the number of photons emitted. Moreover, the set of wavelengths absorbed will **not** be the same as the set of wavelengths emitted.

For all practical purposes, re-radiation does not take place in the Earth-atmosphere system.

Scattering – The second thing that can happen to a solar photon when it encounters atmospheric matter is that it may be deflected from its original path without being absorbed. This deflection can be caused by a cloud droplet or ice crystal, a particle of dust or some other particulate, or even an air molecule (Rayleigh scattering). Again, only photons of certain wavelengths will be deflected; and different atmospheric substances will deflect different photons of different wavelengths. If a photon does not have one of those specific wavelengths (as determined by the particular substance it encounters), it will not be deflected.

Table WHB01 shows some 134 Wm^{-2} of insolation being deflected and scattered by various components of the atmosphere.

Implicit in this selective deflection is the idea that a photon that is deflected once because of its wavelength is likely to be deflected many times. The end product of this multiple deflection is called radiative scattering. Some of the photons so scattered will eventually find themselves heading back into space. Table WHB01 shows some 77 Wm^{-2} scattered back into space. Astronauts will see this upscattered insolation as a major part of our planet's "earthshine".

Some of the scattered photons will eventually reach the Earth's surface. This is diffused solar radiation. Table WHB01 shows some 57 Wm^{-2} of this diffused solar radiation as reaching the surface. Here on Earth, we see the visible photons of this diffused solar radiation as "skylight". This is the light that comes directly from the sky, as opposed to the light that comes at us directly from the sun. On overcast days, it is the only light we have.

We can only see the visible part of this skylight, of course. In addition to the photons that we can see, skylight contains photons of both ultraviolet and infrared radiation. Since ultraviolet photons pass readily through great depths of water, the scanty water droplets in clouds barely reduce their number at all. You can get a sunburn on a cloudy day and a sunburn while scuba diving deep underwater.

It is the scattering of the blue photons of visible light by air molecules that gives the sky its blue color.

Transmission – Finally, photons that do not get absorbed by the atmosphere or deflected from their original paths, reach the surface of the Earth as direct beam solar radiation—direct sunshine, rather than diffused sunshine. Table WHB01 shows only some 106 Wm^{-2} of the original 342 Wm^{-2} reaches the surface of the Earth as direct beam solar radiation. There, it is joined by the 57 Wm^{-2} of diffused solar radiation, producing roughly 163 Wm^{-2} of combined direct and diffused radiation.

Disposition of Insolation

Table WHB01 shows a summary of what happen to insolation as it passes through the atmosphere. Some of it is absorbed (30%); some of it is scattered (39%); and some of it is transmitted unscathed through the atmosphere to impact on the Earth's surface (31%).

Once it reaches the surface, both the direct beam sunshine and the diffused skylight may either be absorbed by the surface (82%) or scattered and reflected back into space (18%).

Table WHB01

Disposition of Insolation

DISPOSITION OF INSOLATION	%	%	%	Wm^{-2}
Incoming solar radiation (top of atmosphere)	100			342
Ultraviolet radiation (<400nm)		9		31
Visible radiation (400 to 740 nm)		45		154
Infrared radiation (>740 nm)		46		157
Incoming solar radiation (top of atmosphere)	100			342
Absorbed by the atmosphere		30		102
Scattered by the atmosphere		39		134
Scattered back into space			57	77
Scattered down to the surface (skylight)			43	57
Transmitted through the atmosphere		31		106
Incoming solar radiation (surface of earth)	100			163
Ultraviolet radiation (<400nm)		3		5
Visible radiation (400 to 740 nm)		54		88
Infrared radiation (>740 nm)		43		70
Incoming solar radiation (surface of earth)	100			163
As direct beam sunshine		65		106
As diffused skylight		35		57
Incoming solar radiation (surface of earth)	100			163
Absorbed by the surface		82		133
Absorbed by water, snow, and ice			74	98
Absorbed by dry land and vegetation			26	35
Reflected back into space by the surface		18		30
Reflected by water, snow, and ice			80	24
Reflected by dry land and vegetation			20	6

The absorption shown for clouds in the above table includes the amount often described as "anomalous cloud shortwave absorption". The values for absorption by water vapor include a proportional share of the "overlap" absorption with other minor gases, recent additions of new absorption bands in both visible and infrared solar spectra, and new discoveries of absorption by water dimers.

Variations in Global Albedo – Recent studies of earthshine reflected off the moon suggest that the Earth's albedo changes much more rapidly and to a much greater degree than previously thought. It appears that decadal variations in the Earth's albedo may have a climate-forcing effect several times greater than that of the increases in atmospheric concentrations of carbon dioxide, methane, nitrous oxide, and all of the various halocarbons put together.

Satellites, until recently, were not set up to directly measure global albedo. Therefore, we have a very short direct measurement record, and must rely on indirect measurements and proxies. It will be interesting to see what future direct measurements tell us about the variations in the Earth's albedo and the direction that these variations are taking.

Global Dimming – The Earth's albedo (and the cloud cover that produces most of it) is thought to have been increasing over the northern hemisphere from the industrial revolution onward. Significant "global dimming" was first noted by Ohmura in 1989, this has been confirmed by subsequent studies [Stanhill & Cohen, 2001]. This was thought to be due to the increased production of industrial pollutants—especially particulates. Particulates and industrial gases are a significant initiating factor in cloud formation.

Global dimming has a cooling effect on the Earth's climate, since (on the whole) clouds reflect more sunshine back into space than they absorb. This is particularly true for the thicker clouds. Increasing cloudiness thus counterbalances the global warming effect of an increase in greenhouse gases.

However, there is some slim evidence that there has been a significant diminution of global dimming in recent years due to efforts to reduce pollution. If true, the most recent trend is toward decreasing particulate concentrations and decreasing cloud cover in the atmosphere. Further studies are obviously needed.

The Atmosphere's Heat Budgets

To calculate the atmosphere's heat budget, we must take the solar shortwave absorption shown in Table WHB01 and add to it the terrestrial longwave absorption produced by the surface of the earth. Then, we must add the heat conducted to the cooler atmosphere by the hotter earth, and the enthalpy added by the hydrologic heat pump. Table WHB02A shows the results for the inflow side of the budget, while Table WHB02B shows the results for the outflow.

Note that water in its various forms dominates both processes. It accounts for almost three-fourths of the atmospheric absorption and the same for atmospheric emissions.

The amount of water vapor in the atmosphere represents a state of dynamic equilibrium with the watery surface of the planet. Any increase in atmospheric temperature will result in an increase in the mean water vapor concentration. This in turn, will result in increased global precipitation, as the residence time of water vapor in the atmosphere is a matter of days, not years.

Globally, the total annual precipitation increased by some 2% in the period from 1900 to 1980 [Dai *et al*, 1997]. Water vapor concentration is thus thought to be increasing.

The total emissivity of the atmosphere of 390 Wm^{-2} is that which would be produced by a blackbody at 288°K. That just happens to be the mean global atmospheric temperature at sea level used in the International Standard Atmosphere. Thus, this part of the budget is in keeping with thermodynamic reality, since more than half of the atmospheric heat radiation received by the Earth's surface originates in the lowest 100 meters of the atmosphere.

This means that most photons emitted by either the Earth's surface or the components of the atmosphere do not travel very far before being absorbed. Most will get less than a hundred meters. The exceptions are those photons whose wavelengths place them in the atmospheric "windows".

Table WHB02A

Energy Budget of the Atmosphere – Inflow

SOURCES	%	%	Wm^{-2}
Energy absorbed by the atmosphere	100		390
Solar shortwave radiation (insolation)	26		102
Absorbed by water vapor		63	64
Absorbed by clouds and particulates		19	19
Absorbed by ozone and oxygen		19	19
Terrestrial longwave radiation	69		268
Absorbed by water vapor		48	128
Absorbed by clouds and particulates		22	59
Absorbed by carbon dioxide		20	53
Absorbed by ozone and oxygen		6	17
Absorbed by methane and nitrous oxide		4	11
Conduction from the earth's surface	4		17
Conduction from water, snow, and ice		71	12
Conduction from dry land and vegetation		29	5
Hydrologic heat pump (enthalpy cycling)	1		3

The Infrared "Windows" – There are some wavelength bands where atmospheric (clear sky) absorption is poor, where infrared radiation passes through the clear air with only limited absorption. These bands are known as infrared "windows". The most significant of these is centered on ten microns, and is known as the "ten micron window". Another lesser band is centered on nineteen microns. There are other very minor windows. None of these windows are really clear. All absorb some of the terrestrial radiation. Ozone is particularly active in the ten micron window.

These windows are used by satellite sensors to measure terrestrial infrared radiation and are used by aircraft-based sensors to produce infrared imagery of the

Earth's surface. They are also used in many of the various "night sights" for military, police and sporting use.

Clouds and particulates block the windows virtually completely. Indeed, the absorption of terrestrial thermal radiation in these bands accounts for much of the energy absorption of both clouds and particulates

Table WHB02B

Energy Budget of the Atmosphere – Outflow

SOURCES	%	%	Wm^{-2}
Energy radiated by the atmosphere	100		390
Radiated to the Earth's surface	62		242
Radiated by water vapor		60	145
Radiated by carbon dioxide		19	45
Radiated by clouds and particulates		17	41
Radiated by methane and nitrous oxide		4	9
Radiated by ozone and oxygen		1	2
Radiated to outer space	38		148
Radiated by water vapor		39	57
Radiated by clouds and particulates		32	47
Radiated by ozone and oxygen		23	34
Radiated by carbon dioxide		5	8
Radiated by methane and nitrous oxide		1	2

The atmosphere and its various active components are all in a continuous (day and night) exchange of thermal infrared energy, endlessly radiating and absorbing, each molecule in its own permitted wavelengths.

This intra-atmospheric emission and absorption makes up the overwhelming bulk of all absorption and emissions. Both the radiation to the surface and the radiation to outer space comprise only a very small fraction of one percent of the atmosphere's total emissions. You might say that those two activities are only incidental to the atmospheric molecules' real business of exchanging photons with one another.

The Heat Budgets of the Earth's Surface

Just as the atmosphere is heated primarily by heat radiation from the Earth's surface (and only secondarily from sunshine), so the surface of the Earth is heated primarily by heat radiation from the atmosphere—and only secondarily by sunshine.

Table WHB03A

Energy Budget of the Earth's Surface– Inflow

SOURCES	%	%	Wm^{-2}
Energy absorbed by the Earth's surface	100		375
Energy radiated by the atmosphere		65	242
Energy radiated by the Sun		35	133
Energy absorbed by the Earth's surface	100		375
Radiated by water vapor		39	145
Radiated by the Sun		35	133
Radiated by carbon dioxide		12	45
Radiated by clouds and particulates		11	41
Radiated by methane and nitrous oxide		2	9
Radiated by ozone and oxygen		1	2
Energy absorbed by the Earth's surface	100		375
Absorbed by water, snow, and ice		74	277
Absorbed by dry land and vegetation		26	98

Note that water vapor alone radiates more heat to the Earth's surface than does the Sun. When you add radiation from clouds, the role of water becomes even more potent.

Table WHB03B

Energy Budget of the Earth's Surface– Outflow

SOURCES	%	Wm^{-2}
Energy outflow from the Earth's surface	100	375
Radiated by the surface to the atmosphere	71	268
Radiated by the surface directly to outer space	23	87
Conducted to the atmosphere by surface contact	5	17
Conducted to the atmosphere by enthalpic cycling	1	3

The surface emissivity of 375 Wm^{-2} is the emissivity that would be produced by a surface at a temperature of 285°K with a coefficient of emissivity of 0.95. The Earth's surface is normally assumed to be at a temperature of 288°K. I have chosen this lower temperature deliberately for a number of reasons.

Problems with Estimating Surface Temperatures: First of all, the 288°K value represents temperatures taken in instrument shelters used in the world-wide network of meteorological stations. Such temperatures are not surface temperatures, but are measured at varying distances from the surface. Most are at a standard height of from one to two meters from the surface. Some are mounted on building of various heights. As any number of studies in the field of microclimatology show, shelter temperatures are not surface temperatures.

Secondly, the network is dominated by urban and airport locations. Many urban locations have measurements that are biased upward due to urban heat island effects. Airports also suffer from increasing urbanization and have biases produced by radiation and advection from aircraft engines, runways, taxiways, and nearby structures. Neither location is typical of the surrounding countryside.

There are other systematic biases. Forest measurements are taken in clearings rather than under the forest canopy, where it is significantly cooler. Marine temperatures are often extrapolated from island stations which are almost always warmer. And so on and so forth. Climatologists have long lamented the fact that the network of observations is actually poorly suited for measuring the climates of the globe.

Finally, the instrument shelter itself produces an upward bias in temperatures. These shelters absorb radiation differently than do natural surfaces. The screens that keep out insects, rodents, and birds and the louvers that keep out low-angle direct sunlight both serve to reduce air circulation. Day and night, temperatures inside an instrument shelter are significantly higher than temperatures in the surrounding free atmosphere.

This is manifest in countries that measure both ground frosts and shelter frosts. The ground frosts virtually always outnumber the shelter frosts. This suggests that temperatures in the shelters are warmer than temperatures on the surface of the ground.

Hence, my decision is to go with a lower temperature.

The use of the coefficient of emissivity in the value of 0.95 is in keeping with natural emissivities over the surface of the globe. The assumption that either the Earth's surface or its atmosphere may be treated as a blackbody is not justified by either theory or observation.

Sources of Earthshine

This last table rounds out the collection in a symmetrical fashion. We started with incoming solar radiation. We looked at how the atmosphere is heated and where than heat goes. We looked at how the surface was heated and what happened to that heat. Finally we look at the energy leaving the planet and venturing into outer space.

We are all familiar with images of how the Earth looks from the moon or from orbiting satellites. Table WHB04 shows where that light is coming from. We only see the light, of course. There is more than just visible light. Most of the Earth's radiation lies in the invisible thermal infrared range. Beings with optical sensitivities in that range might see an even more magnificent sight.

Table WHB04

Sources of Earthshine

SOURCES	%	%	%	Wm^{-2}
Outgoing radiation at the top of the atmosphere	100			342
Upscattered and reflected solar radiation	31			107
Upscatter by atmospheric constituents		72		77
Upscatter by clouds and particulates			79	61
Upscatter by gas molecules			21	16
Reflected by the Earth's surface		28		30
Reflected by surface water, snow, and ice			80	24
Reflected by dry land			20	6
Emitted terrestrial thermal infrared radiation	69			235
Emitted by atmospheric constituents		63		148
Emitted by water vapor			39	57
Emitted by clouds and particulates			32	47
Emitted by ozone and oxygen			23	34
Emitted by carbon dioxide			5	8
Emitted by methane and nitrous oxide			1	2
Emitted by the Earth's surface		37		87
Emitted by surface water, snow, and ice			62	54
Emitted by dry land			38	33

Summary

Water plays the dominant role in each of the Earth's various heat budgets. No other substance even comes close. Anything that affects water affects the planet's climates. Water is just as essential to the life **of the** planet as it is to life **on the** planet.

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