Klimasystem der Erde

Lecture script S2025

Aiko Voigt

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Preface

The book serves as a script for Klimasystem der Erde (BSc Meteorologie und Klima) in the summer semester of 2025.

1 Translation of scientific terms

- absolute humidity: absolute Feuchte
- AMO (also: AMV): Atlantische Multidekadische Oszillation
- AMOC, Atlantic Meridional Overturning Circulation: Atlantische Meridionale Umwälzzirkulation
- angular momentum: Drehimpuls
- aphelion: Aphel (sonnenfernster Punkt)
- apparent force: Scheinkraft
- Archean: Archaikum
- atmosphere: Atmosphäre
- biosphere: Biosphäre
- blackbody: Schwarzkörper
- brightness temperature: Helligkeitstemperatur
- Clausius-Clapeyron equation: Clausius-Clapeyron-Gleichung
- climate predictions: Klimavorhersagen
- climate projections: Klimaprojektionen
- convergence: Konvergenz
- Coriolis force: Corioliskraft
- cryosphere: Kryosphäre
- deep ocean: tiefer Ozean
- divergence: Divergenz
- DJF: Dezember-Januar-Februar, d.h., nordhemisphärischer Winter
- eddies: Wirbel
- Ekman spiral: Ekmanspirale
- equatorial Pacific cold tongue: äquatoriale Pazifische Kaltwasserzunge
- equilibrium climate sensitivity (ECS): Gleichgewichtsklimasensitivität
- escape velocity: Fluchtgeschwindigkeit
- (potential) evapotranspiration: potentielle Evapotranspiration
- feedback: Rückkopplung
- Ferrel cell: Ferrelzelle
- fresh water: Frischwasser
- geosphere: Geosphäre
- glacial: Glazial (Warmzeit)
- greenhouse effect: Treibhauseffekt
- Hadean: Hadaikum
- Hadley circulation/cell: Hadleyirkulation/Hadleyzelle

- halocline: Halokline
- homogenization: Homogenisierung
- hydrosphere: Hydrosphäre
- interglacial: Interglazial, Kaltzeit
- JJA: Juni-Juli-August, d.h., nordhemisphärischer Sommer
- Last Glacial Maximum (LGM): Letzteiszeitliches Maximum
- latent heat flux: Verdunstungswärme, latenter Wärmestrom
- mass stream function: Massenstromfunktion
- meridional energy transport: meridionaler Energietransport
- Milankovitch cycles: Milankovic-Zyklen
- mixed layer: Deckschicht
- NAO: Nordatlantische Oszillation
- ocean gyre: großskaliger Ozeanwirbel
- outgoing longwave radiation (OLR): ausgehende langwellige Strahlung, thermische Abstrahlung
- perihelion: Perihel (sonnennächster Punkt)
- Phanerozoic: Phanerozoikum
- planetary albedo: planetare Albedo
- polar jet stream: Polarfrontjet
- precipitation: Niederschlag
- Proterozoic: Proterozoikum
- pycnocline: Pyknokline (Pykno = Dichte)
- Quaternary: Quartär
- reanalysis: Reanalyse
- reference system: Bezugssystem
- relative humidity: relative Feuchte
- residence time: Verweilzeit
- salinity: Salzgehalt
- saturation vapor pressure: Sättigungsdampfdruck
- sea-surface height: Meeresspiegelhöhe
- sea-surface temperatures (SST): Meeresoberflächentemperaturen
- sensible heat flux: fühlbarer Wärmestrom
- shortwave radiation: kurzwellige Strahlung, solare Strahlung
- sleet: Eisregen/Schneeregen
- saturation specific humidity: spezifische Feuchte für gesättigte Luft
- specific humidity: spezifische Feuchte
- subtropical jet: Subtropenjet
- summer solstice: Sommersonnenwende
- thermocline: Thermokline
- top of atmosphere (TOA): Oberrand der Atmosphäre
- total column water vapor: atmosphärischer Säulenwassergehalt
- trade winds: Passatwinde
- vernal equinox: Tag- und Nachtgleiche des nordhemisphärischen Frühlings

- weather forecasting: Wettervorhersage
- wind stress: Windschub

2 Lecture 1

In this lecture we will discuss the following topics:

- How is climate defined? How is climate different from weather?
- What are the components of the climate system?
- How is climate characterized regionally?
- What are climate classifications?
- What is the energy balance at the top of the atmosphere and what factors determine it?
- How are energy balance and energy transport related?

2.1 Definition of climate and weather

Weather, Witterung, Climate

- Weather is the current state of the atmosphere at a given location.
- Witterung is the weather averaged over a few days to weeks (e.g. "Altweibersommer" in September or "Eisheiligen" in May).
- The classical definition of climate is the average weather or the totality of meteorological phenomena that characterize the average state of the atmosphere at any point on the Earth's surface. (Julius von Hann, 1883)

Today, the classical definition of climate has been replaced by a modern, broader definition, given by the American Meteorological Society (AMS).

Modern definition of climate by AMS (Link)

The slowly **varying** aspects of the **atmosphere–hydrosphere–land surface** system. It is typically characterized in terms of **suitable averages** of the climate system over periods of a month or more, taking into consideration the **variability in time** of these averaged quantities. Climatic classifications include the **spatial variation** of these time-averaged variables. Beginning with the view of local climate as little more than the annual course of long-term averages of surface temperature and precipitation, the concept of climate has broadened and evolved in recent decades in response to the increased understanding of the underlying processes that determine climate and its variability.

Climate is no longer understood as a simple time average at a given location. Modern climate science considers not only averages, but also variations and extremes, such as the frequency of heat waves or changes in the intensity of heavy precipitation events, typically from a global perspective.

2.2 Components of the climate system

One way to appreciate the complexity of the climate system is through a visualization provided by NASA, available at https://svs.gsfc.nasa.gov/31139.

NASA says the following about it: "The visualization reveals that the Earth system comprises diverse components that interact in complex ways. Shown first, the Multi-Scale Ultra-High Resolution (MUR) sea surface temperature (SST) dataset combines data from the Advanced Very High-Resolution Radiometer (AVHRR), Moderate Imaging Spectroradiometer (MODIS) Terra and Aqua, and Advanced Microwave Spectroradiometer-EOS (AMSR-E) instruments. Constantly released into the Earth's atmosphere, heat and moisture from the ocean and land influence Earth's weather patterns—represented here as wind speeds from the Modern-Era Retrospective analysis for Research and Applications (MERRA) dataset. Moisture in the atmosphere—represented as water vapor (also from MERRA)—forms clouds (shown here using cloud layer data from the NOAA Climate Prediction Center) and precipitation. Precipitation (data from GPM IMERG) significantly impacts water availability, which influences soil moisture (data from NASA-USDA-FA) and ocean salinity."

The climate system consists of five components, shown in Fig. 2.1, and includes physical, chemical, and biological processes. A key feature of climate is that it is complex, nonlinear, and multiscale. There are many interactions and fluxes among its components, resulting in feedbacks and cycles of, for example, energy, water, and carbon. Climate encompasses space and time scales spanning many orders of magnitude, from the micrometer scale of a single cloud droplet to planetary-scale circulations of the atmosphere and ocean, and from hourly variations in land surface cloud formation to changes in the deep ocean on timescales of centuries to slow millennial-scale variations in ice sheets (Fig. 2.2). The long timescale of the deep ocean results from the high specific heat capacity of water and the large volume of water (Fig. 2.3), as well as from limited mixing and the slow ocean circulation.

2.3 Weather forecasts, subseasonal to decadal climate predictions, and climate projections

Weather forecasting is an initial value problem for which the initial state of the atmosphere must be known as accurately as possible ("predictability of the first kind"). Boundary conditions such as sea surface temperatures and CO2 content of the atmosphere can be assumed to be constant over time. The chaotic behavior of the atmosphere limits the predictability of

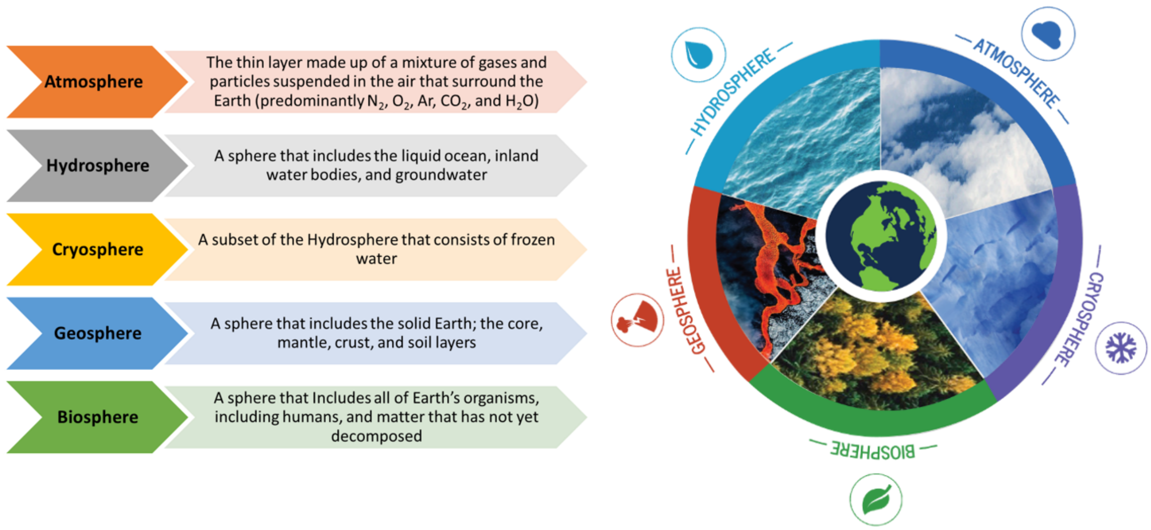

Figure 2.1: Components of the climate system. Source: NASA.

the weather to time scales of typically 10 days. Weather forecasts make detailed statements about the weather over the next couple of days, for example how cold it will be in the coming night and how wind patterns will evolve (Fig. 2.4, left).

Climate projections, on the other hand, make statements for the long term, typically up to the end of the 21st century. Climate projection is a boundary value problem for which the state of the atmosphere at the beginning of the projection is irrelevant ("second-order predictability"). However, changes in sea surface temperatures themselves must be included and projected, and assumptions must be made about the evolution of external forcings such as atmospheric CO2 content and solar irradiance. Climate projections are not capable of predicting the weather at a given time and place in the future. Rather, they aim to project how the climate and weather statistics will evolve under a given set of external forcings (Fig. 2.4, right).

Climate predictions target the time horizons from weeks to about a decade that are too long for traditional weather forecasting and too short for climate projections. Unlike climate projections, climate predictions are influenced by both initial conditions and external forcings. Initial conditions provide a source of predictability from relatively slow components of the climate system, such as the state of the stratosphere and the ocean. The information provided by climate prediction is important for decision-making in sectors like agriculture, water management, and energy production. One example of climate prediction are forecasts of El Niño-Southern Oscillation (ENSO) events, which influence weather patterns around the globe (Fig. 2.4, middle).

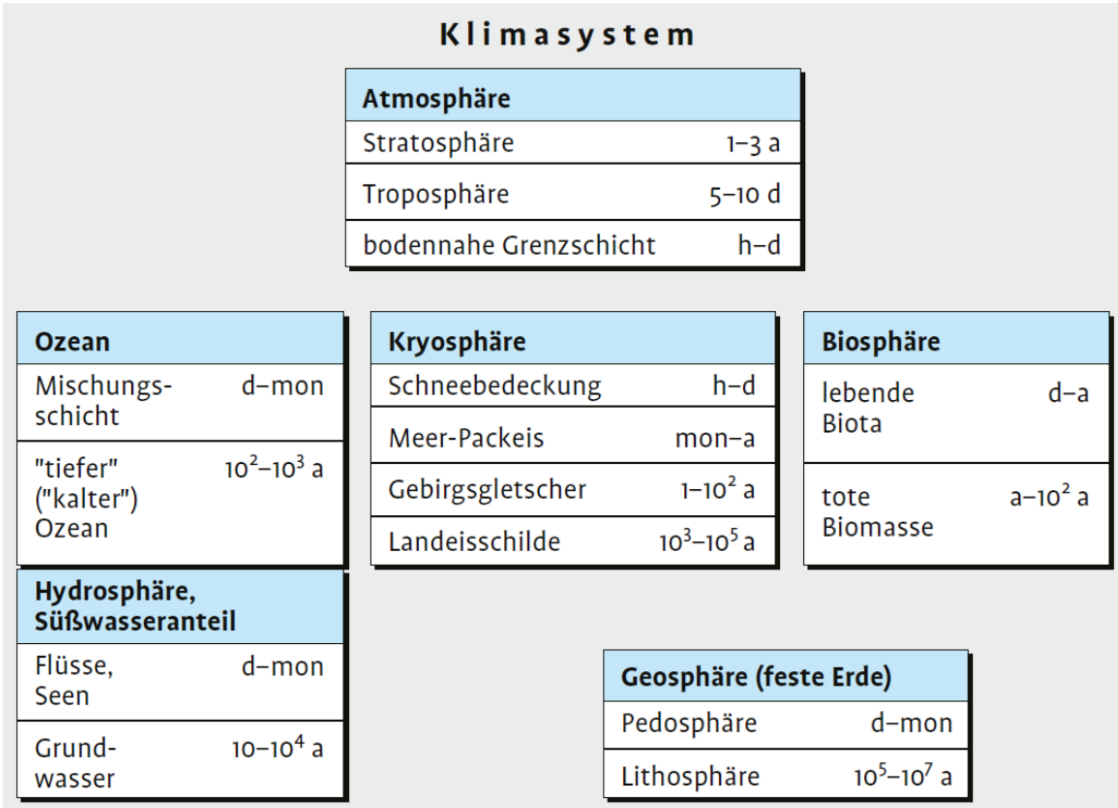

Abb. 14
Charakteristische Zeiten im Klimasystem (nach SALTZMANN 1983, verändert; vgl. Abb. 8).

Figure 2.2: From Schönwiese (2020).

2.4 Climate elements, climate factors and climate classifications

The climatic state is described by a series of climate elements. Climate elements are physical measurement variables. Examples include air temperature, air pressure, precipitation, wind, and sunshine duration. Climate elements are a subset of what is called “Essential Climate Variables” (ECVs). ECVs expand on climate elements by including not only atmospheric parameters but also variables from the ocean and land, including biological and chemical variables. The Global Climate Observing System (GCOS) currently specifies 55 ECVs (online list; Fig. 2.5). Climate indices can be derived from the climate elements. Well-known indices include, for example, heating degree days, the length of the growing season, or the number of days with precipitation.

The regional climate depends on a number of climate factors. These include, among others, astronomical factors (length of day and night, zenith angle of the sun), geographical latitude,

Tab. 3 Quantiative Übersicht der Komponenten über das Klimasystems (viele Quellen, vgl. Literaturverzeichnis 1).

Komponente		Grenzfläche in 10^6 km^2 / in %	Masse in 10^{18} kg	Dichte in kg m^{-3}	Spezif. Wärmekapazität in J kg^{-1} K^{-1}
Atmosphäre		510 / 100%	5	1.3	1000
Ozean[1)]		361 / 70.8%	1350	1000	3900
Kryosphäre[2)]	Meereis[3)]	26 / 5.1%	0.4	800	2100
	Landeis[4)]	14.5 / 2.8%	28	900	2100
Biosphäre[8)]		103 / 20.2%	0.002	100–800[5)]	2400
Land, oberster Bereich		149 / 29.2%	—[6)]	2000[7)]	800

1) ohne Meereis; zur Hydrosphäre gehören darüber hinaus die Süßwassergebiete (ca. $2 \cdot 10^6$ km^2).
2) ohne Chionosphäre (Schneebedeckung, $20 \cdot 10^6$ km^2) und ohne Grundeis.
3) 7.2 % der Ozeanfläche, jahreszeitlich aber stark variabel, vgl. auch Tab. 11.
4) 9.4 % der Landfläche.
5) der untere Wert gilt für Blätter, der obere für einen Eichenstamm.
6) gesamte feste Erde (Geosphäre) $5.98 \cdot 10^{24}$ kg.
7) Mittelwert für Geosphäre 5517 kg m^{-3} (=5.517 g cm^{-3}), für Pedo-/Lithosphäre (Erdkruste) 2600 kg m^{-3}.
8) 69 % der Landfläche.

Figure 2.3: From Schönwiese (2020).

altitude, the relative position to the ocean and prevailing wind direction, as well as local vegetation, soil conditions, and urban areas. Examples of the importance of climate factors are shown in Fig. 2.6. Western Europe is much warmer in winter than Canada, even though both are at the same latitude. This is because the prevailing westerly winds bring relatively warm air from the Atlantic Ocean into Europe, dampening the seasonal cycle. The importance of prevailing wind direction can also be seen in South America. Here, the prevailing westerly winds at about 40 degrees latitude, in combination with the Andes, cause the western part of the southern tip of South America to receive substantial precipitation, while the eastern part on the leeward side of the Andes receives little precipitation. The difference in rainfall manifests itself in the vegetation pattern. Further north, where the prevailing wind direction is from the east, the situation is reversed.

Climate classifications aim to provide a typification of the characteristic geographical differences of climate, and are typically presented in the form of global maps. There are several types of climate classifications.

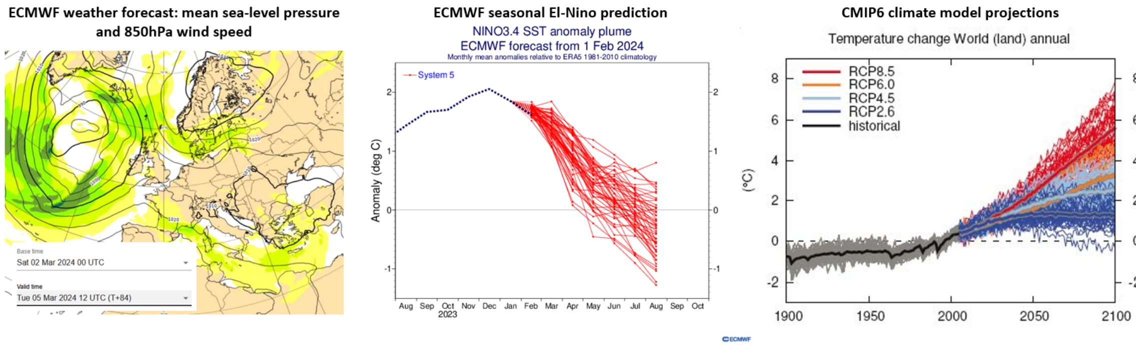

Figure 2.4: Sources: ECMWF (left), ECMWF (middle), Bildungsserver (right).

Climate classifications

- Genetic classifications refer to the radiation and energy balances and the atmospheric-oceanic circulation. They hence classify regional climate based on its origin. Genesis is Ancient Greek for origin.
- Descriptive classifications are based on the typical conditions of the most important climate elements (usually temperature and precipitation), including their annual and diurnal variation.
- Effective classifications are based on the effects of climate, usually considering the potential natural vegetation and sometimes also the soil.
- There are also mixed classification forms. One example is the Koeppen-Geiger classification shown in Fig. 2.7, which is a descriptive-effective classification.

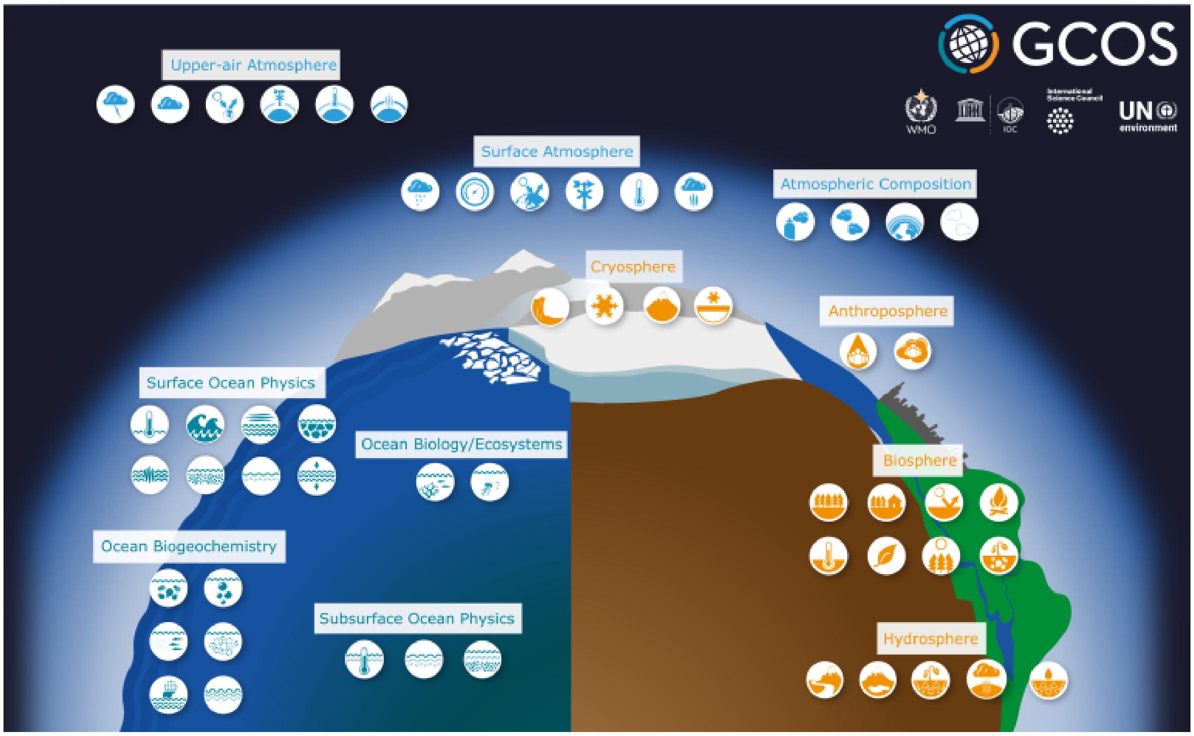

Figure 2.5: Essential Climate Variables. Source: GCOS.

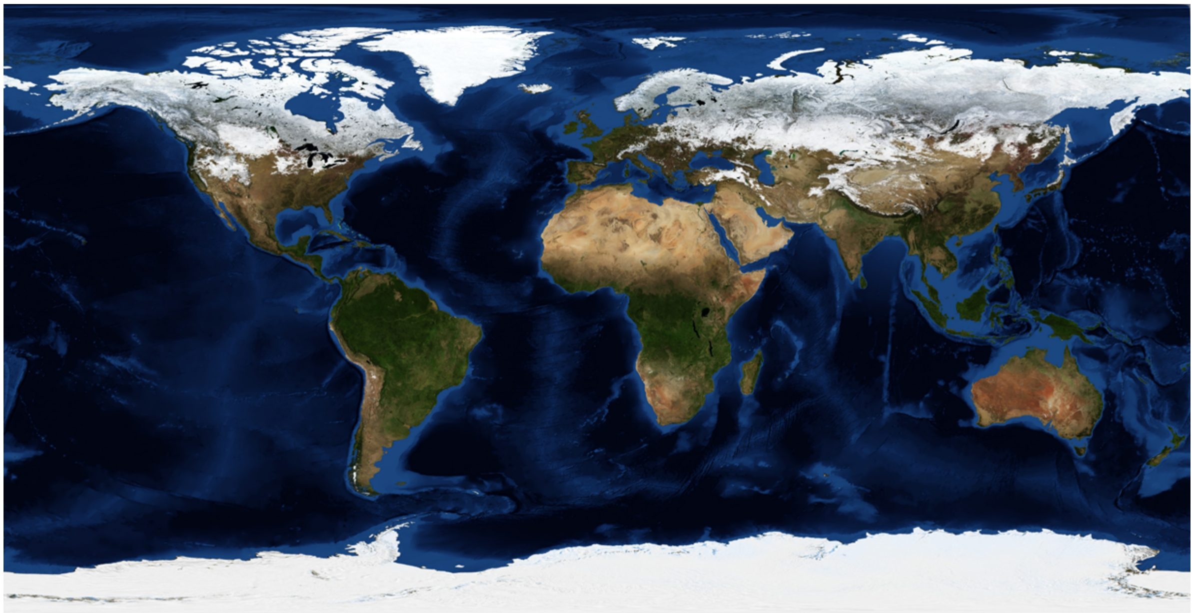

Figure 2.6: Source: NASA Visible Earth.

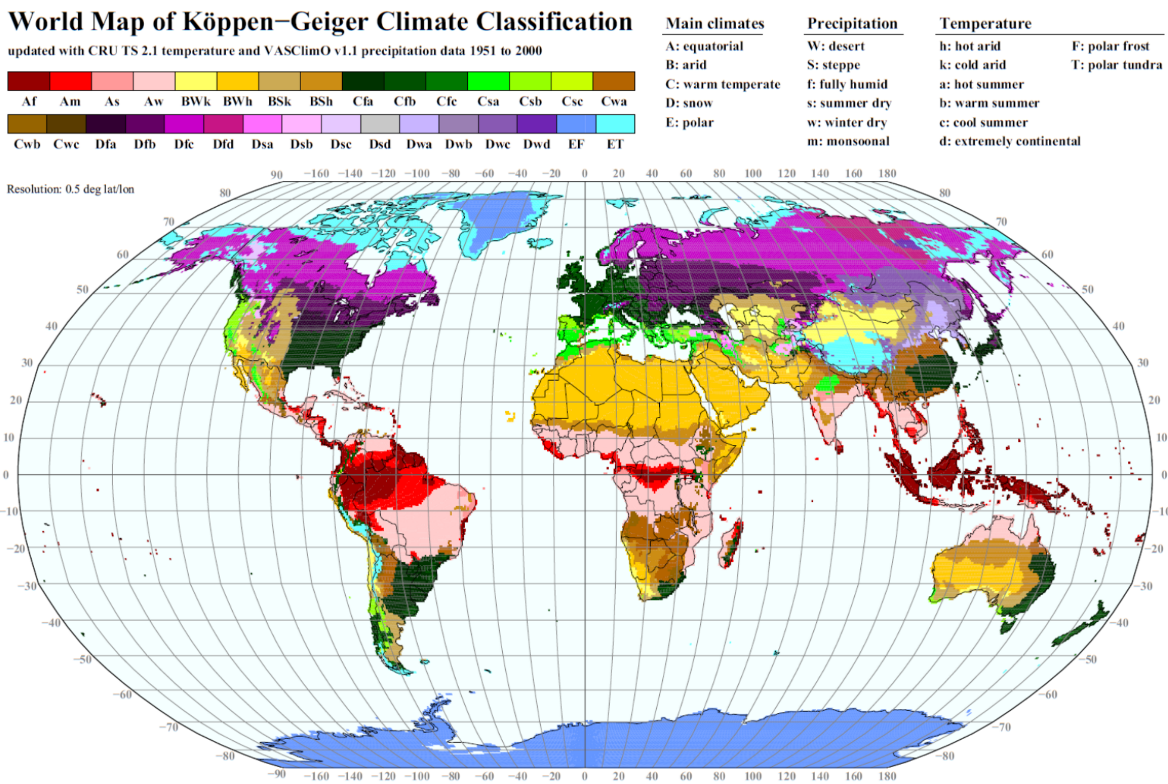

Figure 2.7: Köppen-Geiger classification. Fig. 1 from Kottek et al. (2006).

2.5 Earth's energy budget

In climate science, the "top of the atmosphere" (TOA) is defined as the upper boundary of the atmosphere. At the TOA, the atmosphere becomes so thin that mass transport is negligible and the vertical exchange of energy is exclusively by radiation. The energy budget of Earth as a whole is hence determined by the radiative fluxes at the TOA.

TOA energy budget

$$dE/dt = N = I - R - L$$

- dE/dt: time rate of change of energy content of the Earth system ("storage term")
- N: net radiation
- I: incoming shortwave radiation
- R: reflected shortwave radiation
- L: outgoing longwave radiation

dE/dt is given in units of Jm^{-2}; the other quantities are given in units of Wm^{-2}. All quantities are normalized with respect to Earth's surface area, which explains why the units are Wm^{-2} instead of W. Note that shortwave radiation is often referred to as solar radiation and longwave radiation is referred to as thermal radiation.

It is important to think about the signs of the individual contributions to the energy budget. I, R, and L are always equal to or greater than zero. N, on the other hand, can be positive or negative, depending on the relative magnitudes of the three individual radiative fluxes. For example, if the incoming shortwave radiation exceeds the sum of reflected shortwave radiation and outgoing longwave radiation, then N is greater than zero. This implies a situation where the Earth system is gaining energy and the climate is warming. Conversely, if N is smaller than zero, the Earth system looses energy and the climate is cooling. Finally, if $N = 0$, the Earth system is in "TOA energy balance" and there is no need for the climate to cool or warm. In this case, the climate is said to be in equilibrium.

The Clouds and the Earth's Radiant Energy System (CERES) project, operated by NASA, has been providing satellite-based observations of the Earth's energy budget and clouds since 1997. It uses radiometric measurements from CERES instruments on several generations of satellites, along with data from many other instruments. An image of one of the CERES instruments is shown in Fig. 2.8, together with an illustration of the NOAA-20 environmental satellite that, among other instrument, carries a CERES instrument.

Earth's energy budget is quantified in Tab. 2.1 and Fig. 2.9, where the small differences in the values between Tab. 2.1 and Fig. 2.9 indicate the measurement uncertainty. The overall picture is not affected by the differences. Note that Fig. 2.9 also includes the energy budget at the Earth's surface and in the atmosphere; these will be discussed in subsequent lectures. In the present-day climate, net radiation is slightly positive as a result of anthropgenic emissions of

Figure 2.8: A CERES instrument on the left and onboard the NOAA-20 satellite on the right. Sources: NASA and NOAA.

carbon dioxide and other greenhouse gases. While a value of 1 Wm^{-2} may seem small compared to the values of I, R and L, the continuous energy input over many years and decades is the reason for the observed global warming.

Global-mean time-mean Earth's energy budget for July 2005 – June 2015

Table 2.1: Values from Tab. 5 of Loeb et al. (2018) in units of Wm^{-2}.

			Contribution by clouds
Incoming shortwave radiation	I	340	0
Reflected shortwave radiation	R	99	46
Outgoing longwave radiation	L	240	-28
Net radiation	N	1	-18

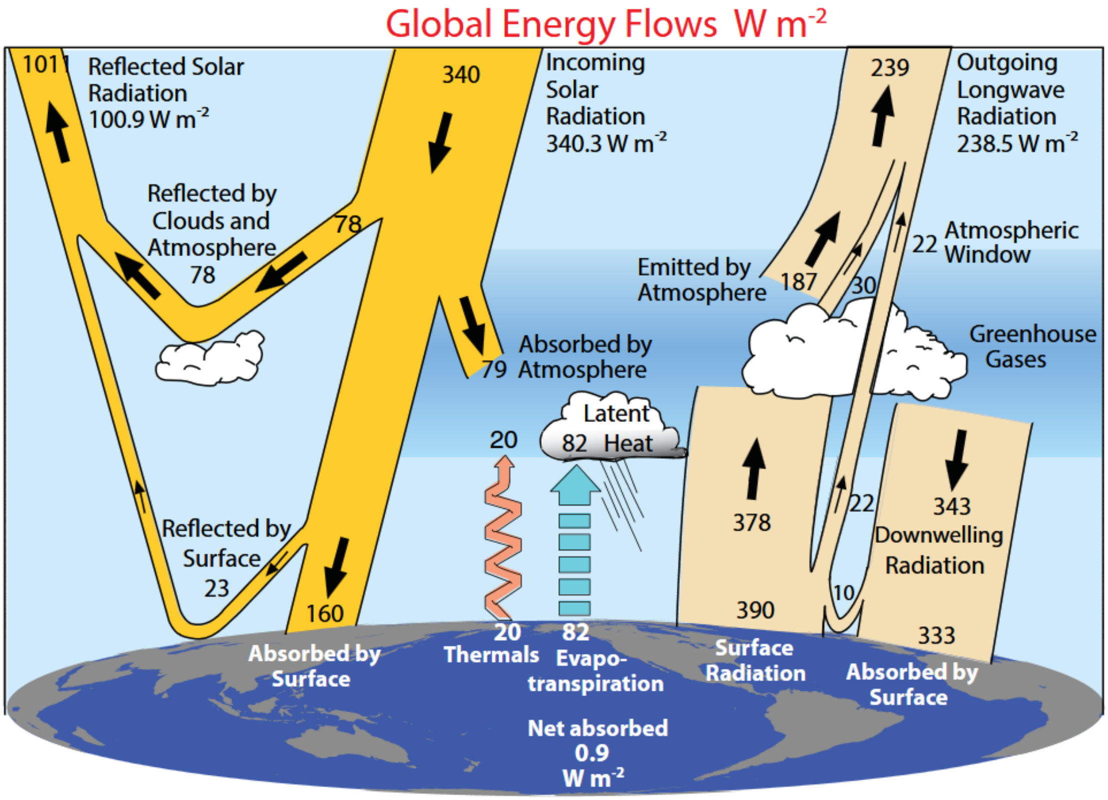

Figure 2.9: Fig. 3.1 of Trenberth (2022).

Clouds play a crucial role in Earth's energy budget by regulating both shortwave and longwave radiation. They have a significant cooling effect by reflecting a large portion of incoming shortwave radiation back into space. According to Tab. 2.1, clouds contribute 46 Wm^{-2} to reflected shortwave radiation, meaning that without clouds, the reflected amount would be only about half as much (53 Wm^{-2} instead of 99 Wm^{-2}). At the same time, clouds absorb and re-emit longwave radiation, reducing the outgoing thermal radiation from 268 Wm^{-2} to the observed 240 Wm^{-2}. Overall, the net radiative effect of clouds is a cooling, as their 46 Wm^{-2} increase in shortwave reflection outweighs their 28 Wm^{-2} reduction in outgoing longwave radiation. Without clouds, Earth's net radiation would be 18 Wm^{-2} higher, leading to a warmer climate. This interplay between shortwave and longwave effects is evident in everyday life: cloudy days are cooler due to increased reflection of sunlight, while cloudy nights are warmer as clouds trap heat that would otherwise escape to space.

A helpful concept in the context of Earth's energy budget is the planetary albedo. The planetary albedo is the ratio of reflected shortwave and incoming shortwave radiation at the top of the atmosphere,

$$\alpha_p = \frac{R}{I}.$$

The planetary albedo is a function of time and space and depends in particular on the reflectivity (or albedo) of clouds and Earth's surface, with some example values given in Tab. 2.2. The global-mean time-mean planetary albedo of Earth can be easily calculated from Tab. 2.1 as

$$\alpha_p = \frac{R}{I} = \frac{99}{340} \approx 0.3.$$

As expected from the discussion above, the clear-sky planetary albedo, which is the planetary albedo that would result if clouds did not contribute to the reflection of shortwave radiation, is much lower,

$$\alpha_p^{\text{clear-sky}} = \frac{R}{I} = \frac{53}{340} \approx 0.15.$$

In addition to the global mean, it is instructive to consider the spatial variations in the Earth's energy balance, as these are closely related to energy transports and the circulation of the atmosphere and ocean. Fig. 2.10 shows noticeable geographical variations of the planetary albedo. It is highest in the polar regions, where extensive cloud and snow cover, as well as large average solar zenith angles, lead to increased reflectivity. Bright surfaces such as deserts, sea ice, and the ice sheets of Greenland and Antarctica also significantly increase albedo. The effect of clouds in increasing planetary albedo is clearly seen in the Intertropical Convergence Zone, in regions with extensive subtropical low-level cloud decks, and in the extratropical storm tracks. On the other hand, low planetary albedo values occur over tropical and subtropical ocean areas with sparse cloud cover due to the low albedo of the ocean surface.

Planetary albedo and incoming shortwave radiation set the absorbed shortwave radiation (ASR), $I - R = (1 - \alpha_p)I$, which is shown in Fig. 2.11. In the tropics and subtropics, where the sun remains nearly overhead at midday throughout the year, ASR reaches 300 $\mathrm{Wm^{-2}}$ and more, with the highest values occuring over cloud-free ocean areas. Much lower values values occur of around 200 $\mathrm{Wm^{-2}}$ over the Sahara because the relatively bright sand surface leads to a high planetary albedo. In the polar regions, ASR falls below 100 $\mathrm{Wm^{-2}}$ due to dark winters and the effects of continuous summer daylight being counterbalanced by high solar zenith angles, extensive cloud cover, and the reflective nature of ice-covered surfaces.

The spatial distribution of outgoing longwave radiation (OLR) is depicted in Fig. 2.12. Compared to ASR, OLR varies less strongly from the equator to the poles, along with increased regional variability within the tropics. The meridional gradient reflects the contrast in surface air temperature between the equator and the poles. Regional variability within the tropics arises from high clouds with cold tops that create regions of particularly low OLR, such as over Indonesia, parts of the tropical continents and the intertropical convergence zone. The highest

Table 2.2: Tab. 3.1 of Brönnimann (2018).

Tab. 3-1

Albedo im sichtbaren Spektrum und langwelliger Emissivität (vgl. → Kap. 3.3) einiger Oberflächen (* die Albedo von Wasser ist stark vom Einfalls- und Betrachtungswinkel abhängig).

Oberfläche	Albedo
Eis	0.6–0.8
Frischer Schnee	0.80–0.90
Alter Schnee	0.45–0.90
Wolken	0.60–0.90
Sand	0.30
Granit	0.3–0.35
Gras	0.18–0.23
Poliertes Aluminium	0.7
Wasser	0.05–0.2*
Teer	0.15

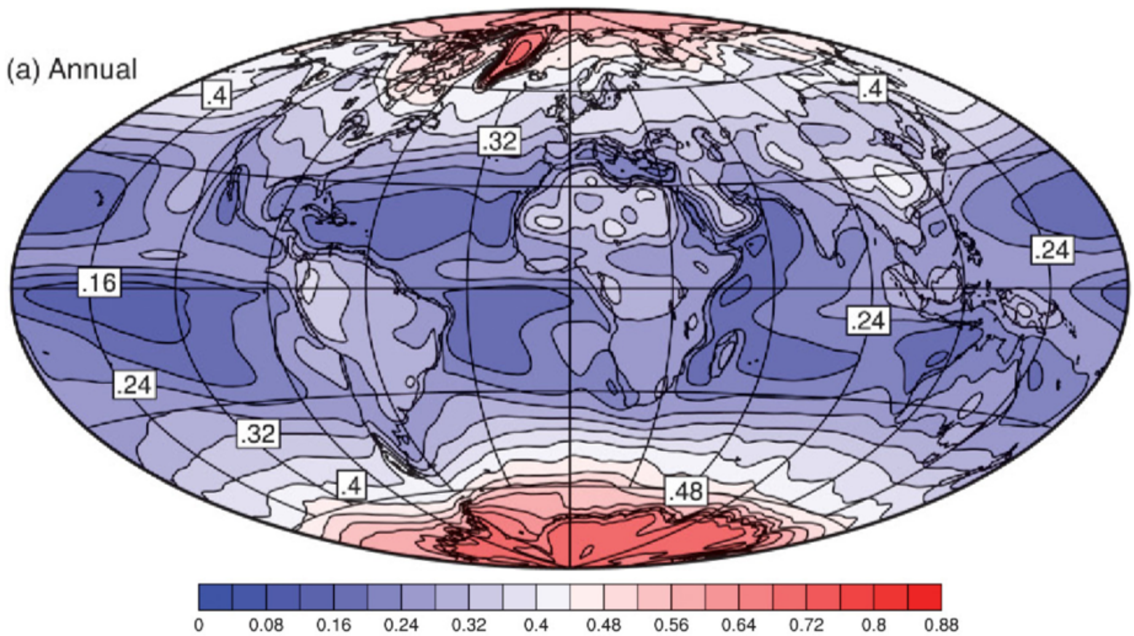

Figure 2.10: Global map of annual-mean planetary albedo derived from CERES. Fig. 2.9 of Hartmann (2016).

annual mean OLR occurs over deserts and equatorial dry zones in the tropical Pacific, where the atmosphere is relatively dry and lacks significant cloud cover, allowing more radiation from the Earth's surface to escape to space. These regions are sometimes referred as the radiator fins of Earth's climate.

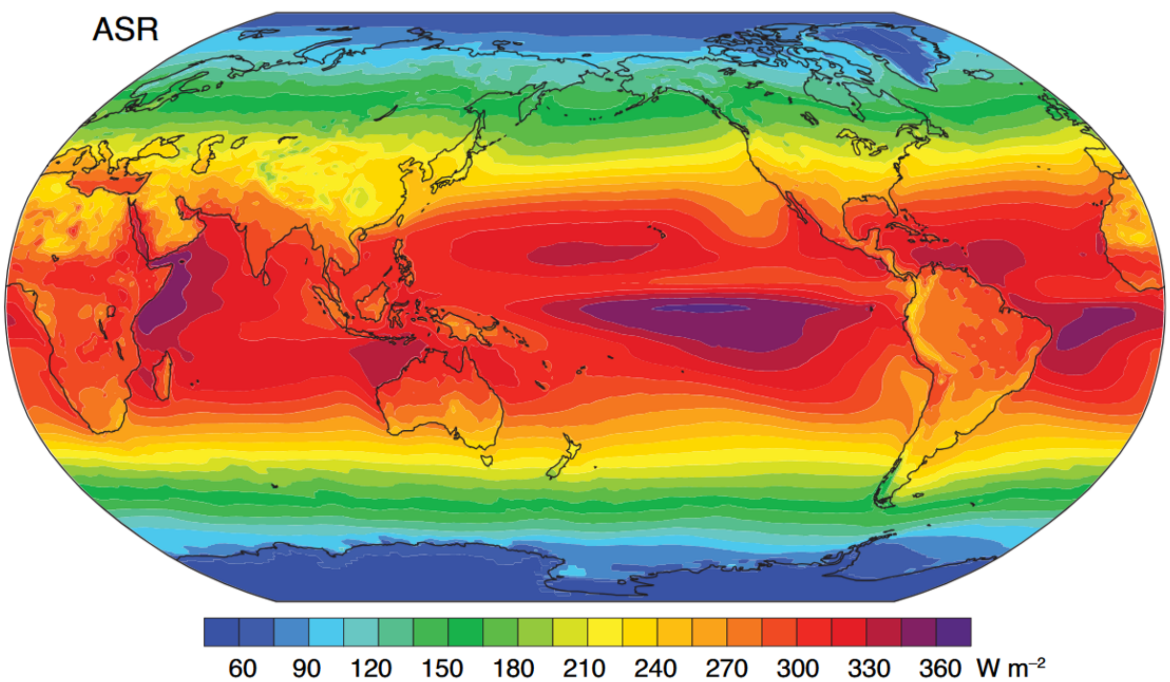

Figure 2.11: Global map of absorbed shortwave radiation derived from CERES. Fig. 5.8 of Trenberth (2022).

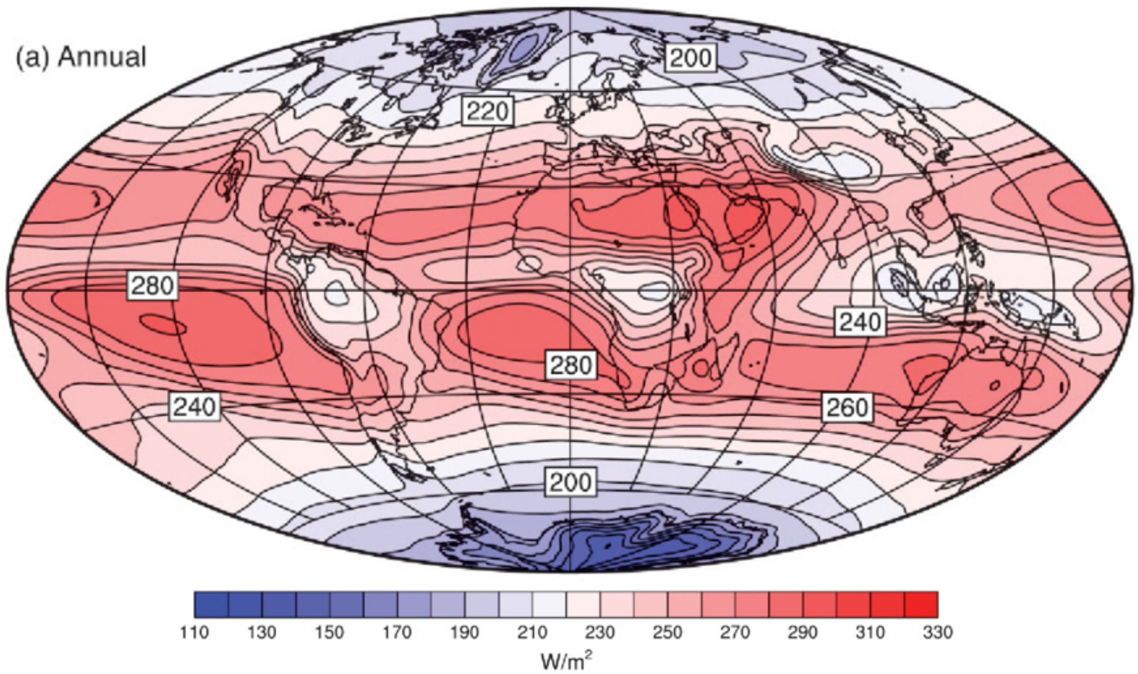

Figure 2.12: Global map of annual-mean outgoing longwave radiation derived from CERES. Fig. 2.10 of Hartmann (2016).

Given the strong meridional contrast in ASR and the more gentle meridional variation in OLR, it is not surprising that net radiation is positive in low latitudes and negative in mid and high latitudes. This is shown in Fig. 2.13. The Sahara and Arabian Peninsula stand out as interesting regions: their high OLR and high planetary albedo make them low-latitude areas with a net radiation deficit.

Fig. 2.14 shows the meridional pattern of Earth's energy balance, with the absorbed shortwave radiation given by $I - R$. In the tropics and subtropics, net radiation is positive, while it is negative poleward of about 30 degrees latitude. This contrast in low-latitude energy surplus and mid- and high-latitude energy deficit means that energy must be transported from the tropics and subtropics to mid and high latitudes, as otherwise the tropics and subtropics would warm, and the mid and high latitudes would cool. This transport is accomplished by the circulation of the atmosphere and the ocean and is an integral part of the factors that shape regional climate.

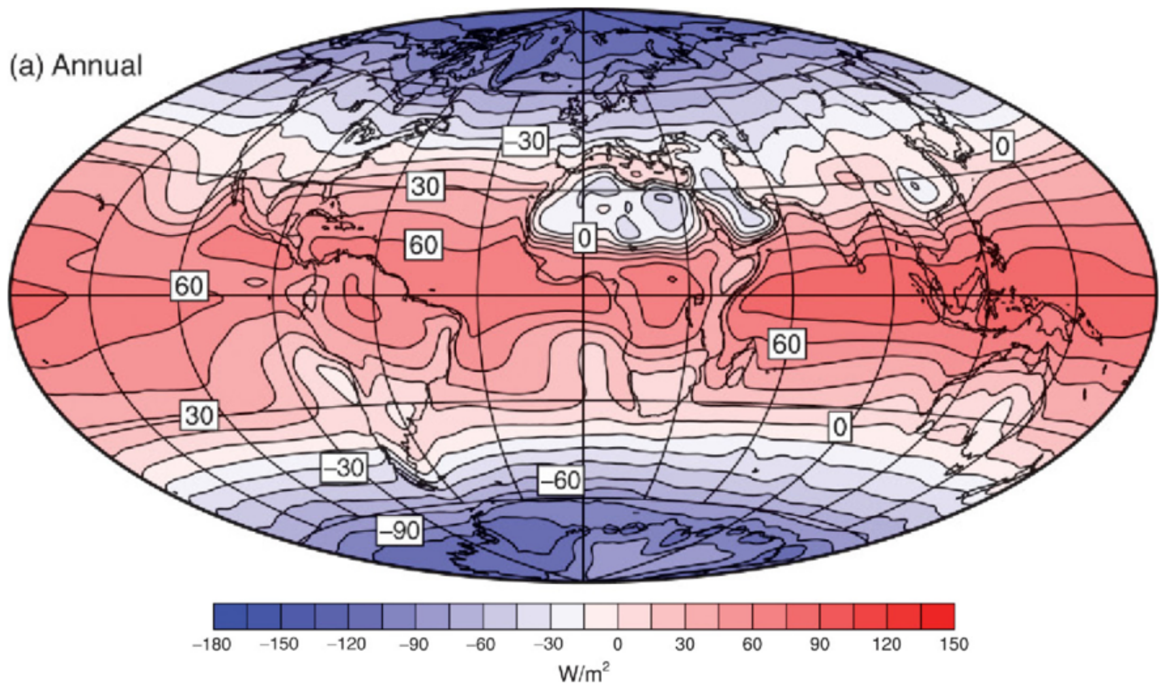

Figure 2.13: Global map of annual-mean net radiation derived from CERES. Fig. 2.11 of Hartmann (2016).

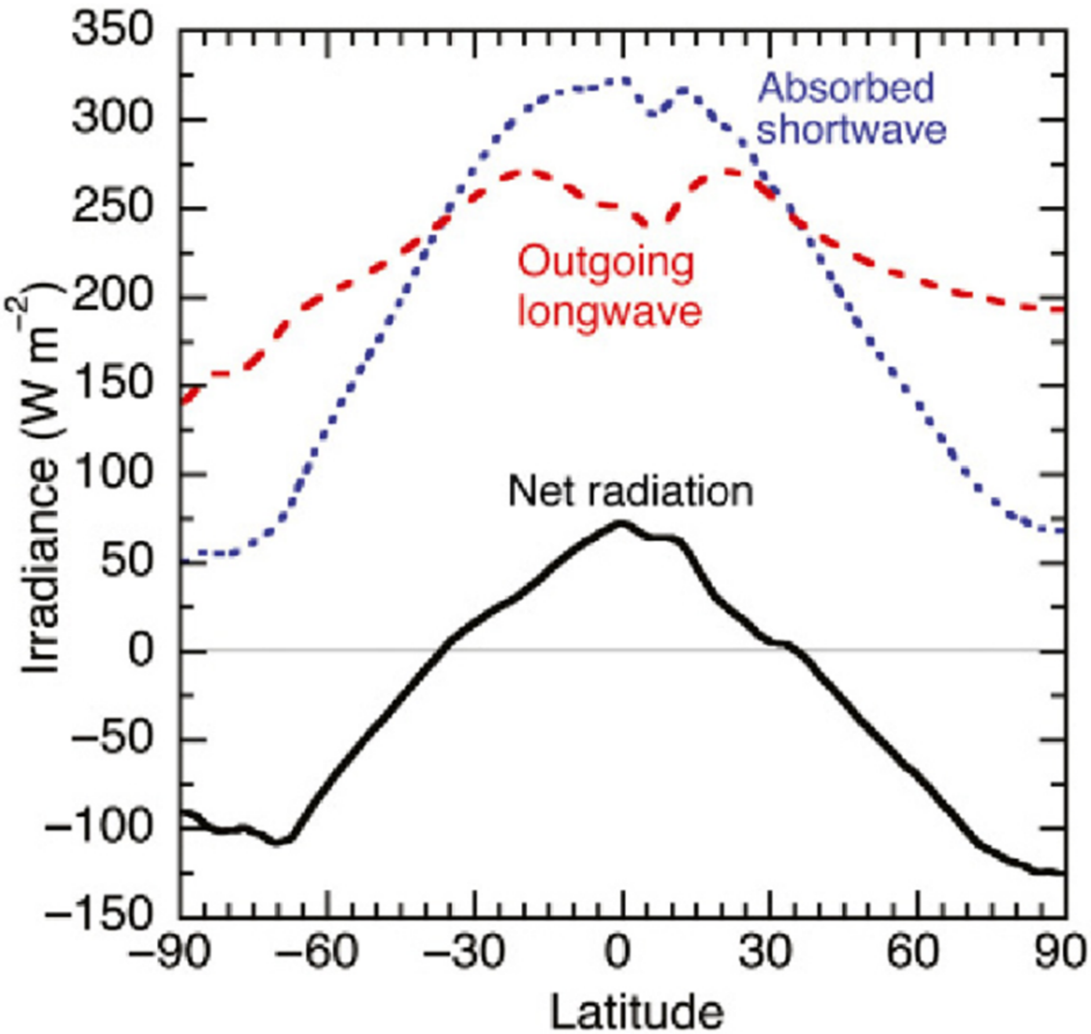

Figure 2.14: Zonal-mean annual-mean radiative fluxes at the TOA. Fig. 2.12 of Hartmann (2016).

2.6 Meridional energy transports

The relation between Earth's energy budget and meridional energy transports is captured by the following budget equation that expresses the conservation of energy:

$$\frac{dE(\varphi)}{dt} = N(\varphi) - \text{div}F(\varphi).$$

Here, φ is the latitude, and the term on the l.h.s. is the energy storage term. N is the annual-mean net radiation at the top of the atmosphere discussed in the previous section, but now as a function of latitude and integrated over the zonal direction, giving it units of Wm^{-1} instead of Wm^{-2}. F is the transport of energy by the atmospheric and oceanic circulation in the meridional direction (i.e. in the North-South direction) in units of PW, where 1 PW is 10^{15} W. div denotes the divergence of F at latitude φ. Divergence is a mathematical concept that is used to describe whether a quantity spreads out from or flows into a specific location. The former situation corresponds to a positive divergence, the latter to a negative divergence (sometimes also referred to a convergence). Because div has units of m^{-1}, $\text{div}F(\varphi)$ has units of Wm^{-1}, consistent with the units of N integrated over the zonal direction.

On monthly time scales, the storage term can be substantial, but when averaged over one year or longer, it is close to zero. This means that for annual averages and longer, the budget equation becomes

$$N(\varphi) = \text{div}F(\varphi).$$

The meridional profile of F is shown in Fig. 2.15. Positive values mean a northward energy transport, negative values a southward transport. To understand the shape of the meridional profile, consider the latitude of 20 deg N as an example. F is positive, meaning there is a northward transport. Also, the derivative of F with respect to latitude is positive, meaning that more energy is transported out of the region to the north than is transported into the region from the south. Thus, there is a divergence of energy transport at 20 deg N, consistent with the energy input from the TOA radiative fluxes at this latitude. This kind of reasoning also explains why the energy transport peaks at the latitudes where $N = 0$. This is roughly the case at 30 deg N and 30 deg S.

Both the atmosphere and the ocean contribute to the transport of energy from the low to the high latitudes. Outside the inner tropics, the atmospheric contribution dominates. Near the equator, the ocean and atmosphere transport energy in opposite directions, with the ocean importing energy across the equator into the Northern hemisphere and the atmosphere exporting energy from the Northern into the Southern Hemisphere. The cross-equatorial northward energy transport by the ocean is crucial for understanding why the Northern Hemisphere, as a whole, is warmer than the Southern Hemisphere and why the ITCZ is located several degrees north of the equator in the zonal and annual mean.

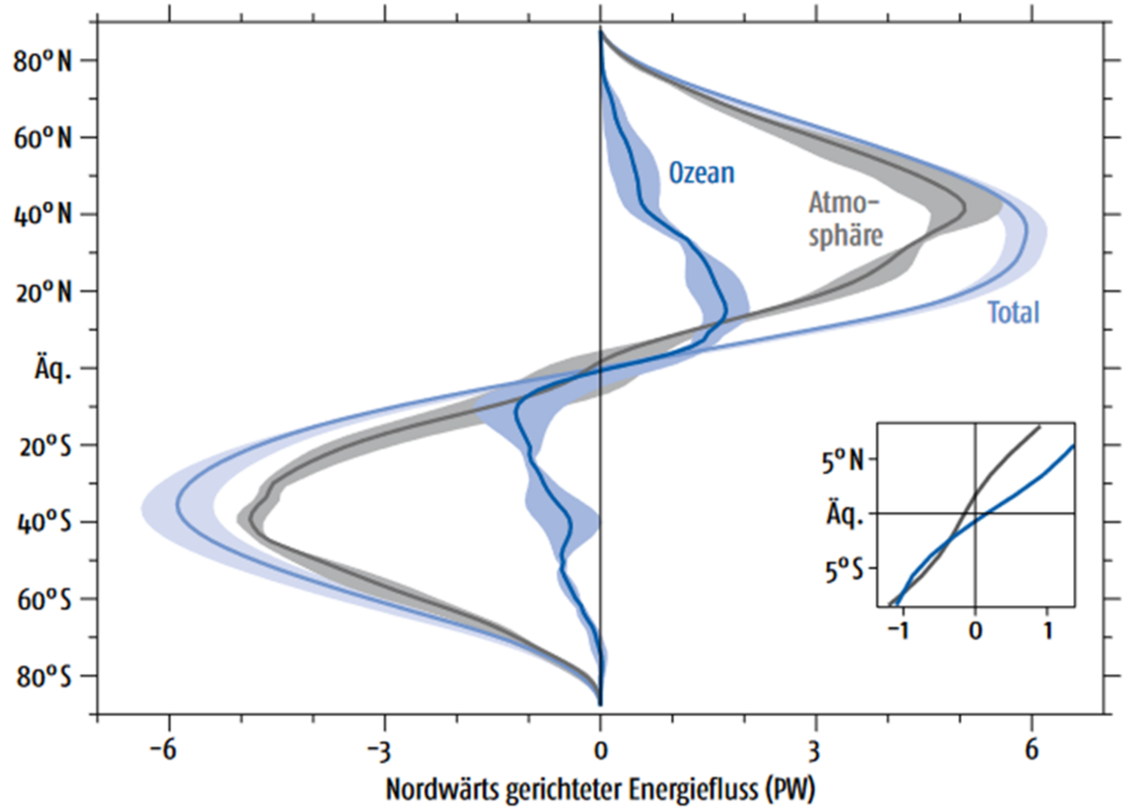

Figure 2.15: Fig. 6.5 of Brönnimann (2018).

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