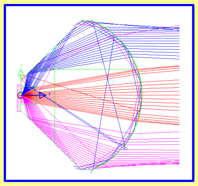

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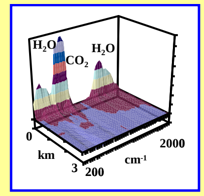

What Do We Mean By The 'Greenhouse Effect'?

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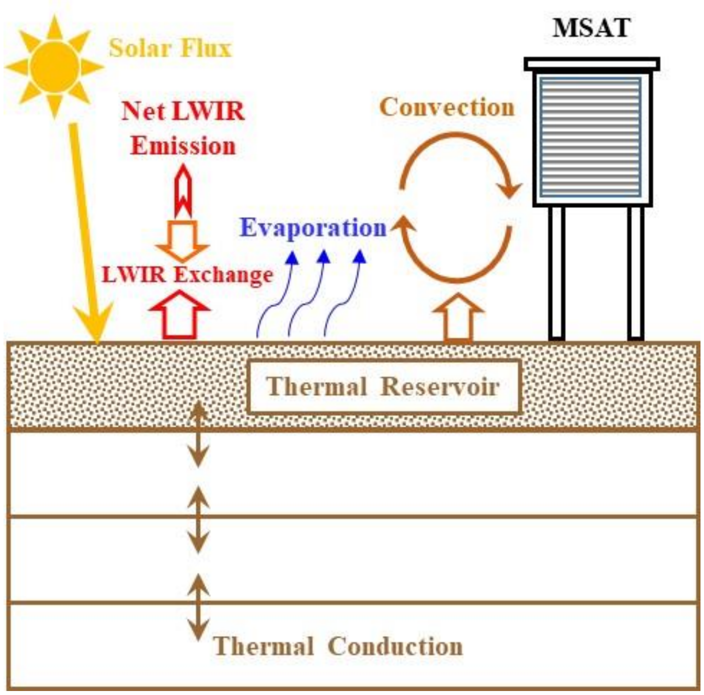
The basic concept underlying the so called 'greenhouse effect' is that the earth's surface is warmer than it would be without the presence of IR absorbing gases in the atmosphere. While this is correct, the current description of the 'greenhouse effect' in terms of an increase in temperature produced by the 'absorption and emission' of long wave IR (LWIR) flux in the atmosphere is wrong [Clark, 2019d]. This is because it is based on the invalid assumption of an 'equilibrium average climate'. Using this assumption., a 'greenhouse effect temperature' of 33 K is defined as the difference between an 'average surface temperature' of 288 K (15 C) and an 'effective emission temperature' to space of 255 K (-18 C) [Taylor, 2006]. An increase in atmospheric CO_2 concentration is then supposed to perturb this climate equilibrium so that it shifts to a new state with a higher surface temperature. However, these are simplified mathematical constructs that are not based on the physics of the climate energy transfer. In order to understand how the 'greenhouse effect' really works it is necessary to abandon the assumption of an 'equilibrium average climate'.

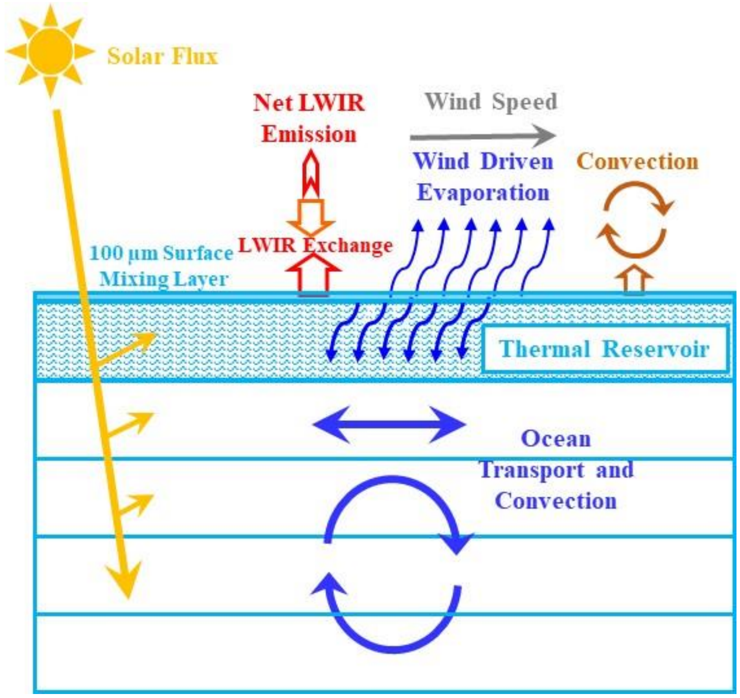
The sun only illuminates the local surface during the day and the local solar flux varies on both a daily and a seasonal time scale. At night, the local solar flux is zero. Furthermore, the spectral distribution of the LWIR emission to space is not that of a blackbody. The LWIR flux to space is derived from a set of LWIR cooling fluxes emitted from many different levels in the atmosphere at different temperatures. Therefore, the 'greenhouse effect' cannot be defined as a temperature. Instead, it has to be defined in terms of the surface exchange energy. The downward LWIR flux from the lower troposphere establishes a time dependent exchange energy with the upward blackbody emission from the surface. The downward and upward LWIR flux components simply exchange photons at the surface without any heat transfer. This significantly reduces the net LWIR cooling flux emitted by the surface. In order to dissipate the absorbed solar heat, the surface must warm up until the excess heat is removed by moist convection. The greenhouse effect therefore has to be defined either as the net LWIR cooling flux emitted by the surface or as an opacity factor. This is the ratio of the exchange energy to the total blackbody emission from the surface [Rorsch, 2018].

The LWIR emission from the surface can still be used to measure the non-equilibrium surface temperature. However, a change in 'equilibrium LWIR flux' cannot be used to calculate a change in 'equilibrium surface temperature'. Instead, the change in temperature over a given time interval has to be determined using the change in heat content or enthalpy stored in the local surface thermal reservoir divided by the local heat capacity. This includes all of the heating and cooling flux terms, not just the LWIR flux [Clark, 2019a, 2013 a, b].

The energy transfer processes at the land and ocean surfaces are different and have to be analyzed separately. Over land, all of the flux terms are absorbed into a thin surface layer. Solar heating establishes a thermal gradient at the surface that drives both the convective cooling (sensible and latent heat flux) and thermal conduction into the subsurface layer. Over the oceans, the water surface is almost fully transparent to the solar flux. Approximately 50% of the solar flux is absorbed in the first meter layer of the ocean and 90% is absorbed within the first 10 m layer. The surface temperature rise is smaller than that over land because of the larger heat capacity. This is a major factor in stabilizing the climate temperature. The penetration depth of the LWIR flux into water is 100 micron or less. The net LWIR flux and the wind driven evaporation (latent heat flux) are mixed together in a thin surface layer. The cooler water produced at the surface sinks and drives a Rayleigh-Benard type convection process that cools the bulk ocean reservoir below. It is also important to understand that the weather station temperature used in the climate record is not the surface temperature. Instead it the meteorological surface air temperature (MSAT). This is the air temperature measured in a ventilated enclosure located for convenience at eye level, 1.5 to 2 m above the ground. These surface energy transfer processes are illustrated in Figure 1.



a) Energy transfer at the land-air interface



b) Energy transfer at the ocean-air interface

Figure 1: Energy transfer a) at the land-air interface and b) at the ocean-air interfaces (schematic)

The greenhouse effect is produced by the time dependent surface exchange energy that limits the net LWIR cooling flux emitted by the surface. The spectral distribution of the upward and downward LWIR fluxes at the surface are illustrated in Figure 2. This shows the surface emission at 300 and 320 K and the downward LWIR flux from the atmosphere at 300 K surface air temperature. The spectral data were calculated using MODTRAN at 2 cm^{-1} resolution from 100 to 1500 cm^{-1} [MODTRAN, 2017]. (Wavenumbers are the inverse of the wavelength in cm, 1000 cm^{-1} = 10 µm. These are the units used in the HITRAN database). The surface relative humidity was 70% and the CO_2 concentration was 380 ppm. The tropical model option was used. The downward flux from the atmosphere balances most of the upward flux from the surface. In this example, the net LWIR cooling flux at 300 K surface and air temperature is 94 W m^{-2}. This is 22% of the total flux emitted by the surface. This gives an opacity factor of 0.78. The net cooling originates from the shaded orange area between the two 300 K spectral curves. When the surface temperature is increased to 320 K (47 C) to simulate the increase in the land surface temperature, the net cooling flux increases to 203 W m^{-2}. The increase comes from the blue shaded area in Figure 4c. However, approximately 60% of this additional flux is emitted outside of the LWIR transmission window. It is absorbed by the atmospheric H_2O and CO_2 bands near the surface and the heat generated produces additional convection. The increase in LWIR flux from the increase in surface temperature is insufficient to dissipate the excess solar heat. Instead this heat must be removed from the land surface by moist convection. The surface temperature continues to heat up until the convection is sufficient to remove the excess heat.

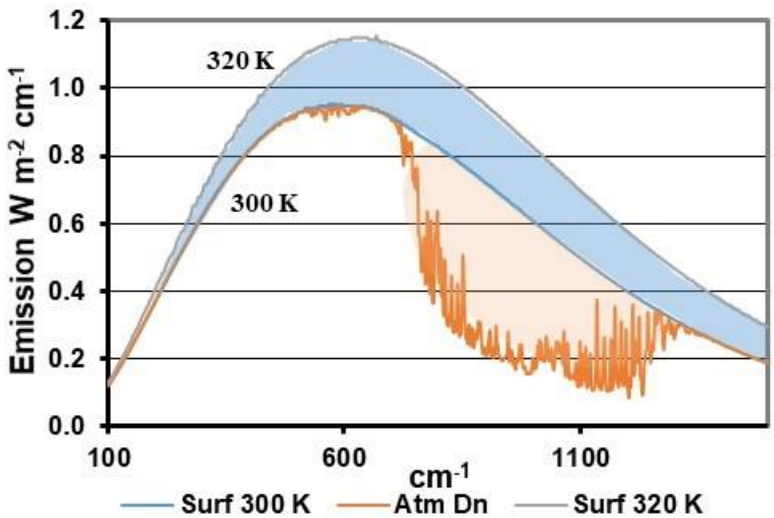


Figure 2: Surface LWIR flux balance: Downward atmospheric flux at 300K, 70% RH, surface emission at 300 and 320 K. In this example, the net cooling flux increases from 94 to 203 W m^{-2} as the surface temperature is increased. This is insufficient to dissipate the solar heat. Additional moist convection is required.

An important and generally neglected property of the surface energy transfer is the time delay or phase shift between the peak solar flux and the temperature response. There is both a daily and a seasonal phase shift. The daily phase shift may reach 2 hours or more although this is not usually recorded as part of the weather station record. The seasonal delay may reach 6 to 8 weeks. A more detailed analysis of the surface energy transfer shows that this delay can only come from the ocean surface temperature [Clark, 2019a]. The heat capacity of the land thermal reservoir is too small to produce a phase shift of this magnitude. This seasonal phase shift can be found at weather stations that are a long way from the ocean. The ocean surface temperature information is carried over long distances by the weather systems that are formed over the oceans and the move over land. The coupling mechanism is through the convection transition temperature.

Over land, the surface temperature continues to increase until the moist convection is sufficient to remove the excess heat. The peak surface and MSAT temperatures are reached in the early afternoon, after the solar flux has peaked at local noon. The surface then cools later in the day until the air and surface temperatures equalize. Under these conditions, convection essentially stops and the surface continues to cool more slowly at night by net LWIR emission. Over land, this night time convection transition temperature is reset each day by the local weather system. As the surface warms during the day, heat is also conducted into the subsurface layers. Later in the day, this thermal gradient reverses and the stored subsurface heat is returned to the surface where it adds to the convection. These energy transfer processes for a dry land surface are given in Figure 3. These are illustrative plots for the full summer sun diurnal heating of a dry surface. Data for Figure 3 are based on measurements from the University of Irvine 'Grasslands' site. [Clark, 2013a].

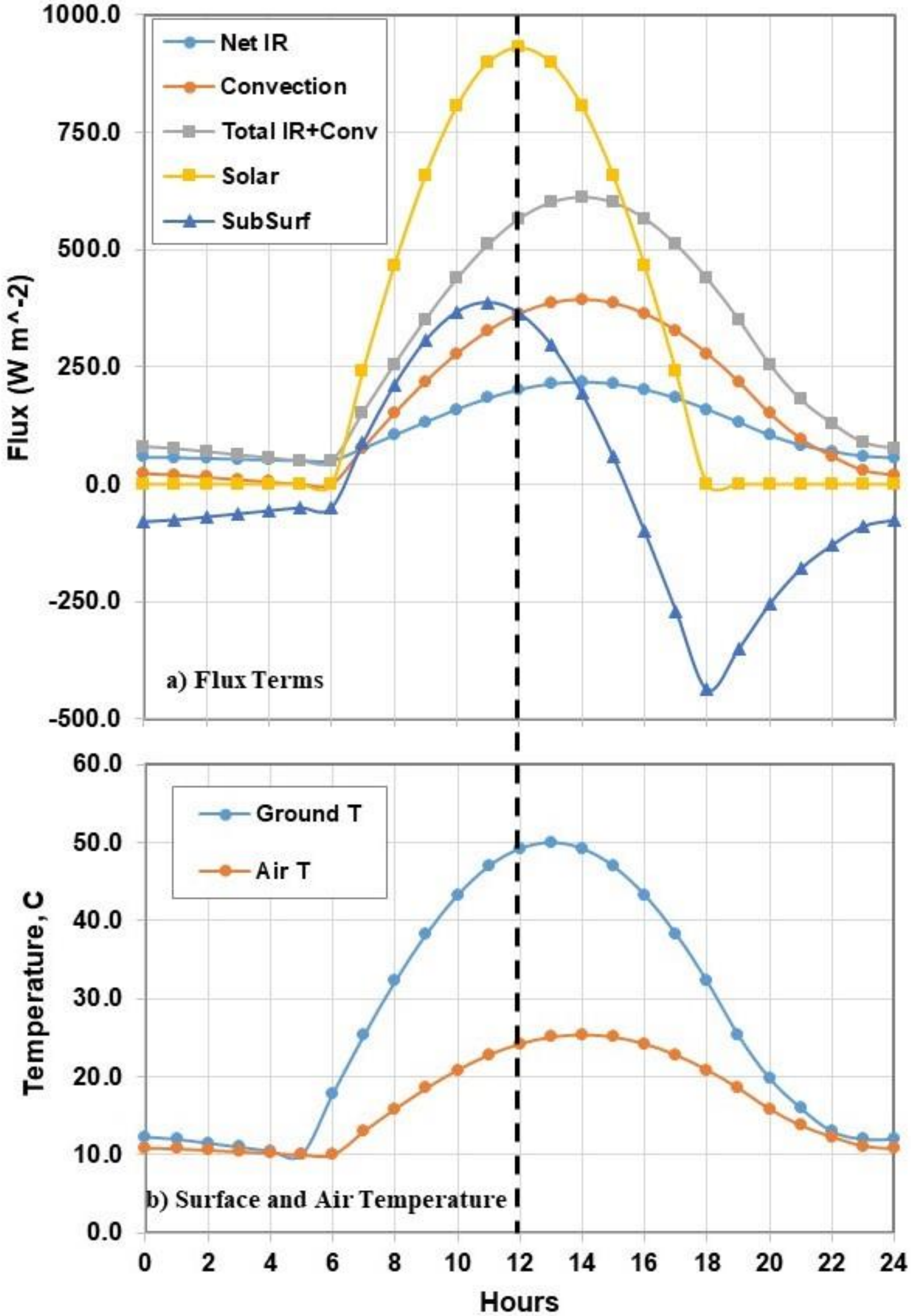


Figure 3: a) Flux terms and b) surface and air temperatures for a dry surface under full summer sun illumination conditions. Derived from UC Irvine 'Grasslands' data.

The troposphere functions as an open cycle heat engine that removes heat from the surface by convection. The land and especially the oceans form the hot reservoirs of this heat engine. The troposphere splits naturally into two thermal reservoirs because of molecular linewidth effects. Almost all of the downward LWIR flux to the surface originates from within the first 2 km layer above the ground. This forms the lower tropospheric reservoir. Above this, the upper tropospheric reservoir extends from 2 km to the tropopause. This acts as the cold reservoir of the heat engine. Here, heat is radiated back to space and replaced by heat transported by convection from below. Most of the heat is radiated from the water bands. This is the real source of the so called 'greenhouse effect temperature'. The altitude of the water bands is typically centered near 5 km. Using the lapse rate of -6.5 km K^{-1}, from the US standard atmosphere, the cooling produced by convective ascent from the surface is approximately 33 K.

The downward LWIR flux to the surface and the upward TOA OLR atmospheric emission to space are almost fully decoupled by molecular linewidth effects. Near the surface, the molecular lines from H_2O and CO_2 and other so called 'greenhouse gases' are pressure broadened and form a quasi-continuous blackbody emitter within the main H_2O and CO_2 absorption-emission bands. As the temperature and pressure decrease with altitude, the molecular lines narrow. The upward emission from the wings of the broader lines from below can pass through the gaps between the narrower lines above. However, the downward emission closer to line center from the narrower lines above are absorbed by the wider lines below and cannot reach the surface. This is discussed in more detail by Clark [2019d].

Figure 4 shows the OLR and flux for a surface and surface air temperature of 300 K at 70% surface relative humidity (RH). The spectral range is from 100 to 1500 cm^{-1} at a resolution of 2 cm^{-1}. These spectra are from MODTRAN calculations using the default tropical atmosphere with a CO_2 concentration of 400 ppm [MODTRAN, 2018]. Starting from left to right, the main spectral features are the rotational H_2O band from 100 to 600 cm^{-1}, the CO_2 ν_2 vibration band from 600 to 750 cm^{-1} and the H_2O ν_2 vibration band above 1300 cm^{-1}. P and R denote the CO_2 band structure associated with the P ($\Delta J = -1$) and R ($\Delta J=+1$) rotational transitions. Between 750 and 1250 cm^{-1} there is a spectral transmission window that consists of weak H_2O lines and two CO_2 overtone bands near 950 and 1050 cm^{-1}. There is also an absorption feature from stratospheric ozone, O_3 that occurs near 1050 cm^{-1} in the OLR emission. The OLR is for 70 km looking down. For reference, blackbody emission curves for 300 to 220 K in 20 K intervals are also plotted.

Figure 5 shows the OLR flux from Figure 4 split into the separate atmospheric and surface emission contributions. Assuming a lapse rate near 6.5 K km^{-1}, each 20 K decrease in temperature corresponds approximately to a 3 km increase in altitude. In the 500 to 600 cm^{-1} region, the H_2O emission is from an altitude of ~4.5 km at a temperature of ~270 K. Near 300 cm^{-1} the H_2O emission temperature has decreased to ~240 K at an altitude of ~9 km. However, the emission temperature of the main CO_2 P and R bands is ~220 K indicating that the absorption and emission process continues through the troposphere and into the stratosphere.

The OLR flux increases linearly with surface temperature. This is shown in Figure 6 [Koll and Cronin, 2018]. There are two different contributions to the OLR flux. Within the LWIR transmission window in the 800 to 1200 cm^{-1} region, the surface emission is only partially absorbed and emitted and some is emitted to space. Here, the clear sky OLR increases linearly with surface temperature. Within the main H_2O and CO_2 absorption bands, the OLR emission does not change significantly with surface temperature. The absorption and emission process continues with increasing altitude until the molecular linewidths narrow sufficiently to allow the transition to a free photon flux to space. For H_2O, this transition occurs near a temperature of 253 K (-20 C). As the surface temperature changes, the altitude of the H_2O emission band changes, but the emission does not. For CO_2 the free photon transition occurs at a lower temperature near 220 K. Most of the CO_2 band emission occurs in the stratosphere.

The OLR emission to space is not part of any 'greenhouse effect'. Instead, the OLR flux defines an overall cooling rate for the atmosphere. This consists of the emission from many levels of the atmosphere, each attenuated by the absorption of the intervening atmosphere above. The spectral band cooling rates vs altitude for a tropical atmosphere are shown in Figure 7 [Feldman et al, 2008].

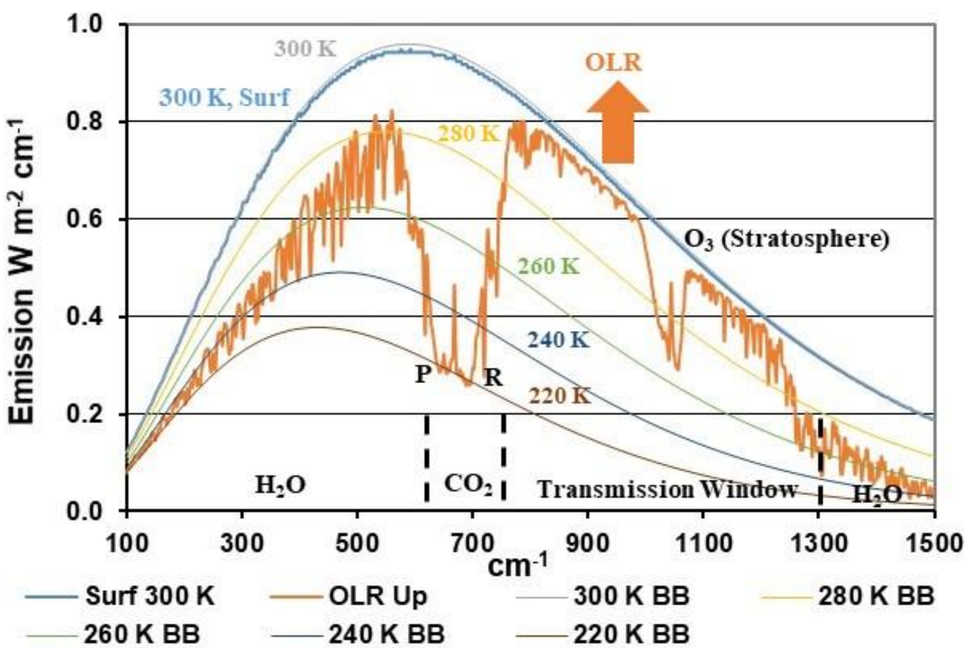


Figure 4: Spectral distribution of the OLR for a 300 K surface temperature. The principal spectral features are indicated. Blackbody emission curves at 300 to 220 K in 20 K intervals are also shown for reference (MODTRAN calculation).

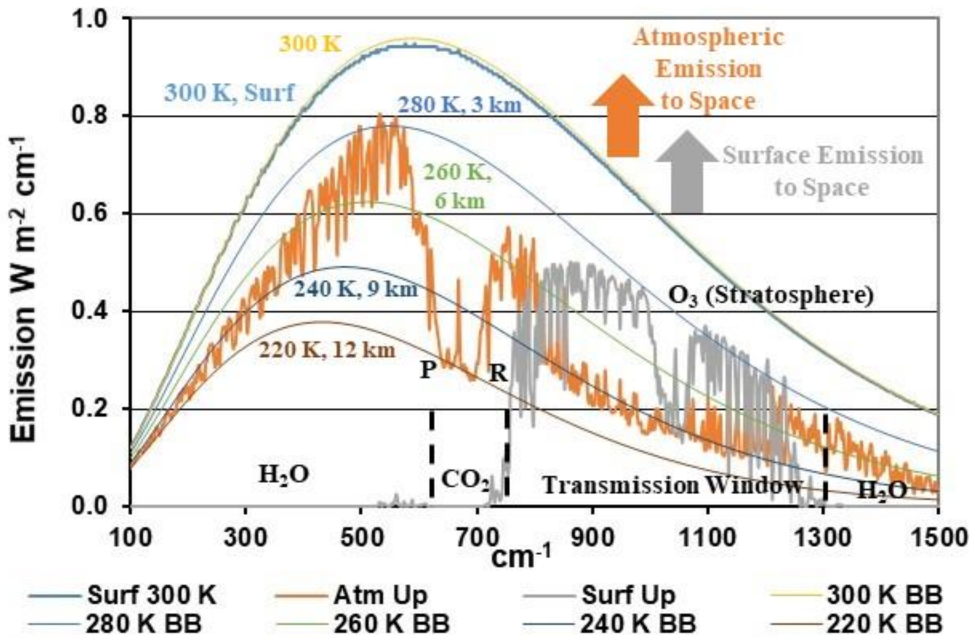


Figure 5: OLR to space, 300 K surface temperature showing the separate atmospheric and surface contributions to the 70 km level emission (MODTRAN calculation).

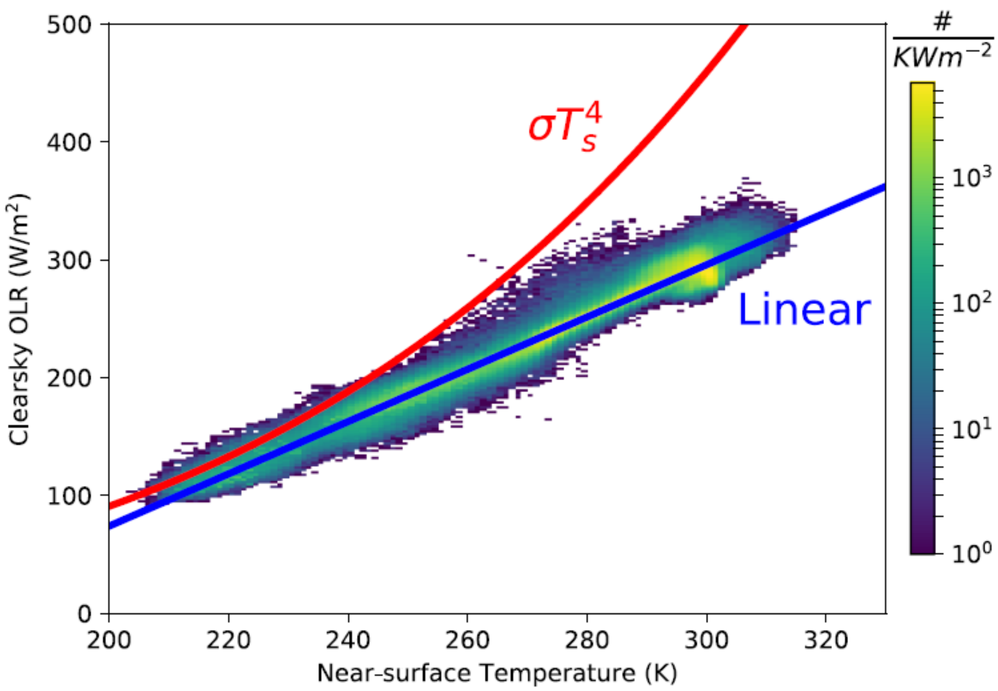


Figure 6: Clear sky OLR emission showing the linear dependence on 'near surface temperature'.

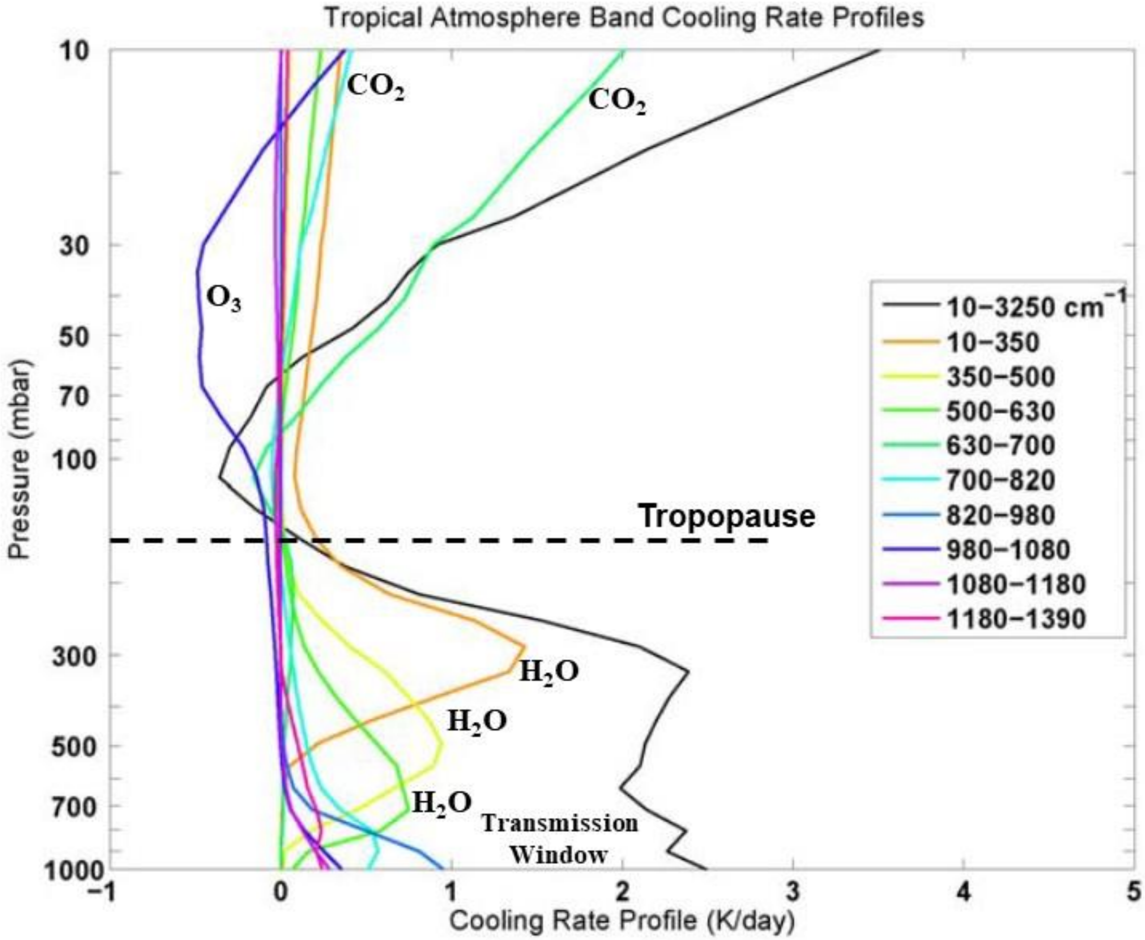


Figure 7: Total and band-averaged IR cooling rate profiles for the Tropical Model Atmosphere on a log-pressure scale [Feldman et al, 2008]

Over the last 200 years, the atmospheric CO_2 concentration has increased by 120 ppm, from 280 to 400 ppm. The corresponding increase in downward LWIR flux at the surface is approximately 2 W m^{-2}. When this increase in LWIR flux is added to the surface energy flux balance, the change in surface temperature is too small to measure. Over land, the 2 W m^{-2} has to be included in the total enthalpy change in the surface reservoir. Over the oceans, the 2 W m^{-2} is mixed with the wind driven evaporation within the first 100 µm surface layer. The evaporation term is much larger and more variable than the change in LWIR flux from CO_2. This means that any increase in ocean surface temperature caused by the increase in the CO_2 LWIR flux is too small to measure. There can be no 'global warming' in the climate temperature record.

The troposphere acts as an open cycle heat engine that transports the surface heat to the middle troposphere by convection. This is a mass transport process that is coupled to both the gravitational potential and rotation of the earth. This coupling produces our basic weather patterns. Climate change can be explained in terms of ocean oscillations, small changes in solar flux that accumulate in the oceans and long term changes in ocean circulation produced by plate tectonics [Clark, 2019b, d].

When the surface energy transfer processes are examined in detail, including the time dependence, the so called 'greenhouse effect' is just the surface exchange energy or opacity factor.

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