THE GREENHOUSE EFFECT

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SUMMARY

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 concept 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. 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). However, these are mathematical constructs that are not based on the physics of the climate energy transfer. Similarly, the small change in LWIR flux at the top of the atmosphere produced by the observed increase in atmospheric CO₂ concentration cannot couple down through the atmosphere and cause any kind of change in surface temperature. The use of ‘radiative forcing’ to determine an increase in surface temperature is also invalid.

The sun only illuminates the local surface during the day and the 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. There is no climate equilibrium. The LWIR flux to space is derived from a set of cooling fluxes emitted from many different levels in the atmosphere. 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 flux 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 this 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.

However, the net LWIR flux is only one of several factors that help to set the surface temperature. The energy transfer processes at the earth’s surface are complex and have to be analyzed within the framework of an open cycle tropospheric heat engine. This engine consists of a set of coupled thermal reservoirs that store and transport the heat from the absorbed solar flux to the middle troposphere by moist convection. From here it is radiated back to space, mainly by the water bands that act as the cold reservoir of this heat engine. The surface energy transfer processes include convection, evaporation and thermal conduction, not just the LWIR flux. When these energy transfer processes are examined in detail, including the time dependence, a description of the ‘greenhouse effect’ emerges that is very different from the conventional ‘equilibrium average climate state’ approach that has been used for the last 50 years. This equilibrium approach is based on simplistic conservation of energy arguments. It created global warming as a mathematical artifact of the simplifying equilibrium assumptions used in the radiative convective climate simulation models. The root cause error is the failure to apply the Second Law of
Thermodynamics. In order for the surface to dissipate the absorbed solar flux there must be a time dependent thermal gradient. The LWIR exchange energy limits the net LWIR cooling flux, so the surface must warm up until there is an adequate thermal gradient and/or humidity gradient to dissipate the solar heat by moist convection. The various flux terms have to be interpreted as rates of heating and cooling of a thermal mass. The change in local temperature is the net change in heat content or enthalpy divided by the local heat capacity. The land-air and ocean-air interfaces have very different energy transfer properties and have to be analyzed separately.

At the land-air surface, all of the flux terms are absorbed in a thin surface layer. Solar heating establishes thermal gradients at the surface that drive both the convective cooling (sensible and latent heat flux) and thermal conduction into the subsurface layer. Over the oceans, the net LWIR flux and the wind driven evaporation (latent heat flux) are mixed together in a thin surface layer. Here, any small increase in LWIR flux from an increase in atmospheric CO2 concentration is overwhelmed by the much larger magnitude and variability of the wind driven evaporation. The cooler water produced at the surface sinks and drives a Rayleigh-Benard type convection process that cools the bulk ocean reservoir below. The ocean surface is almost transparent to the solar flux. Approximately 90% of the solar flux is absorbed within the first 10 m layer of the ocean. The surface temperature rise is smaller than that over land because of the much larger heat capacity. This is a major factor in stabilizing the climate temperature. The ocean surface temperature response to the seasonal variation in the solar flux is delayed and produces a phase shift of approximately 6 to 8 weeks. In many regions of the world, this is transported over land by the prevailing weather systems and can be observed in the weather station record. The coupling mechanism is through the night time convection transition temperature.

Convection 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. It is impossible for the increase in LIWR flux produced by the observed increase in atmospheric CO2 concentration to couple to this dynamic thermal reservoir system in way that can produce an observable change in surface temperature. Instead, 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.
1.0 INTRODUCTION AND TECHNICAL BACKGROUND

This report on the greenhouse effect is one of seven articles that describe climate research into coupled thermal reservoirs performed at Ventura Photonics since 2009. The first two articles, ‘A dynamic coupled thermal reservoir approach to atmospheric energy transfer Part I: Concepts’ (DTR1) and ‘A dynamic coupled thermal reservoir approach to atmospheric energy transfer Part II: Applications’ (DTR2) were published in 2013 in a special climate issue of Energy and Environment [Clark 2013a and 2013b]. The next two articles in this series ‘A dynamic coupled thermal reservoir approach to atmospheric energy transfer Part III: The Surface Temperature’ (DTR3) and ‘A dynamic coupled thermal reservoir approach to atmospheric energy transfer Part IV: The null hypothesis for CO₂’ (DTR4) have been published recently as Ventura Photonics Monographs [Clark, 2019b and 2019c]. Two other articles, ‘Fifty Years of Climate Fraud’ [Clark, 2019a] and this report, ‘The Greenhouse Effect’ have also been published as Ventura Photonics Monographs. DTR1 and DTR2 provide an introduction and basic description of the dynamic coupled reservoir approach. DTR3 addresses the calculation of the surface temperature and introduces two important concepts, the convective transition temperature and the seasonal ocean phase shift. DTR4 introduces the null hypothesis for CO₂. ‘The Greenhouse Effect’ provides a detailed spectroscopic description of the atmospheric flux and surface energy transfer. ‘Fifty Years of Climate Fraud’ describes the development of the global warming fraud from speculation and invalid hypothesis to a multi trillion dollar fraud. In addition, a summary report ‘A Dynamic Coupled Thermal Reservoir Approach to Atmospheric Energy Transfer Part V: Summary’ has also been published [Clark, 2019d]

The earth is an isolated planet that is heated and cooled by electromagnetic radiation. The heat source is the sun. The incident solar radiation is a nearly collimated beam (±0.26°) with an average energy flux near 1366 W m⁻². The value depends on satellite radiometer calibration [Wilson, 2014]. The spectral distribution of the solar flux at the top of the atmosphere is similar to that of a blackbody near 5800 K. The cooling radiation is emitted in the LWIR spectral region (>5 µm or <2000 cm⁻¹). The illumination geometry is that of a sphere illuminated by a disk. The albedo (reflectivity) is approximately 0.3. The geometric area ratio is 4, so conservation of energy gives an average emitted cooling LWIR flux of approximately 240 W m⁻². However, the spectral distribution of the LWIR flux is not that of a blackbody emitter. The idea that the LWIR flux emitted by the earth corresponds to an ‘effective emission temperature’ near 255 K derived from Stefan’s Law is incorrect [Taylor, 2006]. The flux terms have to be interpreted as rates of heating and cooling of a set of coupled thermal reservoirs at different levels within the atmosphere [Clark, 2013a, 2013b, 2011; Feldman et al, 2008]. The change in local thermal reservoir temperature is the change in heat content or enthalpy divided by the local heat capacity. The stratosphere is heated mainly by the absorption of the UV solar flux and cooled by emission from the CO₂ bands, and from ozone. The troposphere is cooled mainly by LWIR emission from the water bands that are part of the cold reservoir of the tropospheric heat engine at an altitude near 5 km. The hot reservoirs are the land and the oceans that are heated by the solar flux. The surface heat is dissipated and transported through the troposphere by moist convection [Gilbert, 2010; Jelbring,
Conservation of long term average energy does not imply a short term conservation of flux. There is no ‘average equilibrium climate state’ that can be perturbed by changes in ‘greenhouse gas concentration’. The earth’s orbit is elliptical, the rotation axis is tilted at $23.5^\circ$ to the orbital plane and the period of axial rotation is 24 hours. The peak solar flux at the surface with the sun overhead is near $1000 \text{ W m}^{-2}$. At night, the local solar flux is zero. The absorbed solar flux is stored as heat and released over a wide range of time scales.

The tropospheric heat engine is subject to a number of unique constraints imposed by the basic Laws of Physics. Like any heat engine, the energy transfer is limited by the First and Second Laws of Thermodynamics. In particular, the heat flow must follow the thermal gradient. In addition, the surface evaporation depends on the humidity gradient, which is related to the thermal gradient through the temperature dependence of the water vapor pressure. Convection is a mass transport process that is subject to the Law of Gravity and Conservation of Momentum. As the warm air rises from the surface, it must perform mechanical work to overcome the gravitational potential. This produces cooling as the internal energy of the air mass is reduced. If the air is moist, this convective cooling can produce condensation with the release of latent heat. Convective ascent determines the lapse rate or temperature profile of the troposphere. The earth also rotates. The convection is coupled to the rotation or angular momentum of the earth. This produces the characteristic Hadley, Ferrell and Polar cell convective structure and the trade winds that drive the ocean gyre circulation [UK Met Office, 2017]. The result is the weather patterns that we observe. Climate is the long term average of these patterns. It is an average of the thermodynamic and fluid dynamic properties of the tropospheric heat engine.

The final constraint is a more complex and subtle one. The tropospheric heat engine operates at low temperatures and pressures. This means that the radiative properties of the working fluid, moist air (dilute steam) cannot be described using simple blackbody theory. The radiative energy transfer has to be analyzed using high resolution molecular radiative transfer algorithms. The IR spectrum of the atmosphere consists of many thousands of overlapping spectral lines. Each line is the result of a transition between two specific molecular vibration-rotation states. The molecular collision frequency in the troposphere is $> 10^9$. This means that the lifetimes of the molecular excited states are reduced significantly by the collisions. This produces a pressure dependent line broadening. The underlying cause is the Heisenberg Uncertainty Principle applied to time and energy. An important result is that the molecular lines within the main absorption bands in the lower troposphere are broadened into a quasi-continuum. The upward and downward LWIR fluxes are not equivalent. As the lines narrow with increasing altitude, the upward LWIR flux from the wings of the broader lines below can pass through the gaps between the narrower lines above. However, the downward flux from the narrower lines above is absorbed by the broader lines below.

This line broadening means that the troposphere splits naturally into 2 independent thermal reservoirs. Almost all of the downward LWIR flux reaching the surface originates from within the first 2 km layer of the troposphere. This is the lower tropospheric reservoir. The emission to space occurs mainly from the upper tropospheric reservoir, between 2 km and the tropopause. This
forms the cold reservoir of the tropospheric heat engine. The heat lost to space from the upper
tropospheric reservoir is replaced by heat transported from the surface by convection. As the air
ascends through the troposphere, it must cool as it performs the mechanical work required to
overcome the gravitational potential. An ascent of 5 km at an average lapse rate of \(-6.5 \text{ K km}^{-1}\)
produces a cooling of \(~33 \text{ K}\). This is the source of the so called ‘greenhouse effect temperature’
[Gilbert, 2010; Taylor, 2006; Jelbring, 2003].

At the surface, the absorbed solar flux is dissipated through a combination of moist convection
and net LWIR emission. In order for heat flow to occur, there must be a thermal gradient or
temperature difference. This is of course a consequence of the Second Law of Thermodynamics.
At night, when the surface and surface air temperatures are similar, the downward LWIR flux from
the lower troposphere balances most of the upward LWIR flux from the surface. This is the surface
exchange energy. There is a net LWIR cooling flux emitted through the atmospheric LWIR
transmission window. This depends on humidity and cloud cover. During the day, the local
surface is illuminated by the solar flux. The increase in temperature is insufficient to remove the
solar heat by net LWIR emission. The energy transfer properties of the land and ocean surfaces
are different and need to be considered separately. Over land, the surface warms until the heat is
dissipated by moist convection. The surface heating also establishes a thermal gradient that
conducts heat below the surface. This stored surface heat is released later in the day as the surface
cools and the thermal gradient reverses. An important concept here is the convection transition
temperature at which the land and surface air temperatures equalize each evening. When this
temperature is reached, convection slows or stops and the surface continues to cool more slowly
by net LWIR emission. This convection temperature is reset each day by the local weather system.
The calculation of the surface temperature from the flux terms has been discussed in detail by
Clark and by Rorsch [Clark, 2019b; Rorsch, 2019].

Over the oceans, the surface is almost transparent to the solar flux. Approximately half of the solar
flux is absorbed within the first meter layer of the ocean and 90% is absorbed within the first 10
m layer. The surface cools through a combination of net LWIR emission and wind driven
evaporation [Yu et al, 2008; Yu, 2007]. This cooling takes place within the first 100 \(\mu\text{m}\) layer of
the ocean surface. The cooler water sinks and is replaced by warmer water convected from below.
This is a Rayleigh-Benard type convection process, not simple diffusion. The ocean surface
continues to warm up until the water vapor pressure is sufficient to drive the wind driven
evaporation. There is no equilibrium or exact flux balance between the solar flux and the overall
ocean cooling flux. The ocean surface temperature response lags the solar flux. In particular,
there is a seasonal phase shift or time delay between the peak solar flux and the ocean surface
temperature. Outside of the tropics this may easily reach 8 weeks. This delay is coupled to the
weather systems that form over the oceans and can be transported long distance over land [Clark,
2019b].

Over the last 200 years, the atmospheric \(\text{CO}_2\) concentration has increased by approximately 120
ppm from 280 to 400 ppm [Keeling, 2018]. This has produced an increase in the downward LWIR
flux from the troposphere to the surface near \(2 \text{ W m}^{-2}\), depending on humidity [Clark, 2013a,
2013b, 2011; Harde, 2017]. When this increase in flux is added dynamically to the surface flux balance, the increase in surface temperature is too small to be observed. Instead, climate change can be explained in terms of ocean oscillations, small changes in solar flux coupled into the oceans and long term changes in ocean circulation produced by plate tectonics [Clark, 2019c].

The current description of the ‘greenhouse effect’ is based on the invalid concept of an ‘infrared equilibrium average climate’. This produces global warming as a mathematical artifact created by the simplifying assumptions used in the climate simulations [Clark, 2019a]. Concepts such as an average global temperature and its relationship to an average global flux are incorrect and have little useful physical meaning [Volokin, &. ReLlez, 2014; Essex et al, 2006]. There is no exact ‘equilibrium flux balance’ at the top of the earth’s atmosphere. The upward and downward LWIR fluxes through the troposphere are not equivalent because of line broadening effects. The LWIR flux emitted to space is decoupled from the surface by the tropospheric heat engine. Instead, there are dynamic or time dependent rates of heating and cooling that change the temperature within the thermal reservoirs of the climate system. The local temperature change is the cumulative change in heat content or enthalpy of the local thermal reservoir divided by the local heat capacity. This is illustrated in Figure 1. The technical background related to the various flux terms shown in Figure 1 will now be considered in more detail. These include the solar flux, the net surface LWIR flux, moist convection, molecular linewidth effects, the LWIR emission to space and the weather station temperature. In addition, the energy transfer processes related to long term climate change will also be presented. These topics are covered in Sections 1.1 through 1.7. The surface energy transfer is considered quantitatively in Section 2.0. The greenhouse effect and radiative forcing are addressed in Section 3.0. Conclusions are presented on Section 4.0 and References are provided in Section 5.0. A more detailed description of the OLR flux is given in the Appendix.

1.1 The Solar Flux

The illumination of the earth by the solar flux is illustrated in Figure 2a. The earth is an isolated planet that is heated by the sun and cooled by the emission of LWIR radiation back to space. The average (1 au) solar flux at the top of the atmosphere (TOA) is approximately 1366 W m\(^{-2}\) [VIRGO, 2017]. However, the earth’s orbit is elliptical, the rotation axis is tilted at 23.5° to the orbital plane and the period of axial rotation is 24 hours. The change in solar flux produced by the orbital ellipticity is ±45 W m\(^{-2}\). The illumination geometry is that of a disk of collimated light projected onto a sphere. When light is projected onto a tilted surface, the effective illumination area increases and the intensity decreases with the cosine of the tilt angle. As the solar flux propagates through the atmosphere it is attenuated by absorption and scattering so that the peak ‘clear sky’ flux at the surface with the sun overhead is approximately 1000 W m\(^{-2}\). To compare the solar flux at different latitudes, it is convenient to use the total cumulative daily flux rather than the average. This is the total ‘clear sky’ solar flux available each day to heat the local surface. ‘Clear sky’ values vs. day of the year are plotted for selected latitudes in Figure 2b. The peak values are near 25 MJ m\(^{-2}\) day\(^{-1}\), but the winter values decrease significantly with increasing latitude. Data were calculated using the ‘clean air’ algorithms from IEEE 738 [1993]. The normalized area weighted solar flux and cumulative solar flux at the surface are shown in Figure
2c. More than half (~60%) of the flux is incident in the ±30° latitude bands and ~80% is incident within the ±45° bands.

Figure 1: Thermal reservoirs, surface energy transfer and thermal storage (schematic). The surface is heated by the sun and cooled by a combination of net LWIR emission, convection and evaporation. Heat is stored below the surface and released over a range of time scales. There is no ‘equilibrium average temperature’.
a) The earth is a sphere that intersects a circular disk of the solar flux. The TOA intensity on the sphere decreases with the cosine of the angle of incidence. Only half of the earth is illuminated. The LWIR radiation is emitted from the entire the sphere.

b) Daily total cumulative solar flux vs. day of year for selected latitudes. The intensities are ‘clear sky’ values incident at the surface. This includes atmospheric attenuation and the cosine geometric factor.

c) The normalized and cumulative area weighted solar flux vs. latitude. Approximately 60% of the flux is incident within the ±30° latitude bands and 80% is within the ±45° latitude bands.

Figure 2: The illumination of the earth by the solar flux

1.1.1 The Solar Spectrum and Absorption by Water

It is also important to understand the spectral distribution of the solar flux and the penetration depth of the flux into water. This is illustrated in Figure 3. The overall spectral distribution is similar to that of a black body at a temperature near 5800 K. Below 300 nm, the solar flux is attenuated by stratospheric ozone and below 200 nm by molecular oxygen. The transmitted UV
and blue wavelengths undergo molecular (Rayleigh) scattering. This depends on the inverse fourth power of the wavelength, which explains the blue color of the sky. In the near IR (NIR) spectral region, the solar flux is attenuation by absorption from the water vapor overtones [ASTM. 2012]. The maximum penetration depth for pure water occurs near 500 nm [Hale & Querry, 1973]. This is close to the 550 nm peak of the solar flux. Approximately half of the solar flux is absorbed in the first meter layer of the ocean and 90% is absorbed within the first 10 m. This means that the temperature rise from the solar heating of the ocean is much smaller than that for a dry land surface. Large quantities of heat are stored and released by the oceans. This acts to stabilize the climate temperatures. This ocean heat is also circulated to higher latitudes by the wind driven ocean gyre circulation.

![Solar spectrum and water absorption](image_url)

**Figure 3:** The solar spectrum and water absorption
1.2 The Net LWIR Flux at the Surface

Both the land and the ocean surfaces are close to blackbody emitters in the LWIR spectral region. The total intensity of the emitted flux follows Stefan’s Law and is proportional to the fourth power of the absolute temperature. The spectral distribution follows the Planck curve. The emission peak shifts to shorter wavelength as the temperature increases. The downward LWIR emission from the atmosphere consists of a very large number of overlapping molecular lines [Rothman et al, 2005]. These are mainly transitions between the rotation/vibration states of H$_2$O and CO$_2$. There are also minor contributions from CH$_4$, O$_3$, N$_2$O and other IR active gases. Near the surface, the lines are pressure broadened and merge together to form a quasi-continuum with a blackbody envelope. There is however a transmission window in the 8 to 12 µm (850 to 1250 cm$^{-1}$) spectral region. Blackbody emission curves for 273, 288, 303 and 318 K (0, 15, 30 and 45 C) are shown in Figure 4a. The corresponding increase in the total emission from Stefan’s law is shown in Figure 4b.

The surface LWIR flux balance or exchange energy is illustrated in Figure 4c. 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$_2$O 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. There is a time delay or phase shift between the peak solar flux and the peak surface temperature that may reach 2 hours or more. 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 at night by net LWIR emission. Over land, this night time convection transition temperature is reset each day by the local weather system.
**Figure 4: Blackbody emission and the net LWIR cooling flux**

a) Spectrally resolved blackbody emission, 0 to 2500 cm\(^{-1}\), 273, 288, 303 and 318 K (0, 15, 30 and 45 C)

b) Total blackbody emission, 273 to 323 K (0 to 50 C)

c) 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.

d) Surface LWIR flux balance: Downward atmospheric flux at 300K, 10 and 90% RH, 70% RH with cloud cover (altostratus, 2.4 km base) and surface emission at 300 and 320 K. This shows the change in flux produced by changes in RH and cloud cover.
The magnitude of the net LWIR cooling flux increases as the humidity (water vapor concentration) decreases. It also decreases as the cloud cover increases. Clouds are water (or ice) particles that act as blackbody radiators and absorbers. The downward LWIR emission from the cloud base ‘fills in’ the LWIR transmission window. This is illustrated in Figure 4d. This shows the downward flux at the surface for 300 K air temperature and 90 and 10% humidity. The effect of cloud cover, altocumulus, 2.4 km base, 70% RH is also shown. The 300 K surface emission is also plotted. The data are from MODTRAN calculations.

It is also important to note that almost all of the downward LWIR flux reaching the surface from the air originates from within the first 2 km layer of the troposphere. Approximately half of this originates from within the first 100 m layer. This is a consequence of the pressure broadening of the molecular rotation-vibration lines in the lower troposphere. This is discussed in more detail below in Sections 1.4 and A4.0.

1.3 Moist Convection and the Lapse Rate

Moist convection is usually split into two flux terms, the sensible heat flux or dry air convection and the latent heat flux or surface evaporation. Convection is a complex fluid dynamic process. However, the sensible heat flux is often simplified to just the surface-air temperature difference \((T_s - T_a)\) multiplied by a bulk convection coefficient \(k_{\text{conv}}\).

\[
\Delta Q_{\text{sens}} = k_{\text{conv}}(T_s - T_a)
\]

Over the ocean, \(k_{\text{conv}}\) values near 5 W m\(^{-2}\) K\(^{-1}\) may be used. Over land, higher values near 20 W m\(^{-2}\) K\(^{-1}\) may be used [Clark, 2013a]. Definitions vary, so care is needed when comparing published convection data. Direct convection at the surface involves the transfer of heat (molecular motion) from the surface to the adjacent air molecules. The warm air is buoyant and is replaced by cooler air from above. As the convective heat flux increases, so does the air mass circulated at the surface. In addition to direct convection, indirect heating also occurs. This includes the absorption of excess LWIR flux from the surface mainly by the atmospheric H\(_2\)O and CO\(_2\) bands and the release of latent heat from water vapor condensation as clouds form during convective ascent and cooling. In addition, part of the near IR (NIR) radiation from the direct solar flux is absorbed by the water vapor overtone bands. This NIR absorption can be seen in Figure 3a above. This also contributes to the convection.

Over land, evaporation is a complex process that involves the transfer of moisture to the surface as well as evaporation. This includes loss of moisture from the soil and from vegetation [Mengelkamp et al, 2006]. Over the oceans, the mechanism is wind driven evaporation [Yu et al, 2008; Yu, 2007]. The primary heat source for evaporation is the absorbed solar flux. The thermal energy breaks the hydrogen bonds that hold liquid water molecules together. The water vapor that is removed from the surface carries this thermal energy from the surface as latent heat. This reduces the amount of heat available for the sensible heat flux or the net LWIR emission. The latent heat is released when the water vapor condenses to form clouds at higher altitudes.
1.3.1 The Lapse Rate

As the warm air ascends from the surface it expands and cools. The change in temperature with altitude is called the lapse rate. For a dry air parcel under ideal adiabatic expansion conditions (no heat exchange with the surrounding air), the lapse rate is -9.8 K km\(^{-1}\). This is the magnitude of the acceleration due to gravity. However, under most conditions, particularly over the oceans, the air is moist and water condenses above the saturation level to form clouds. This releases latent heat that reduces the magnitude of the lapse rate below its dry air value [Tsonis, 2007]. Figure 5a shows the calculated lapse rate for surface air temperatures of 273 and 300 K at a surface relative humidity of 70%. Figure 5b shows the corresponding pressure changes and Figure 5c shows the changes in the H\(_2\)O and CO\(_2\) concentration. The H\(_2\)O concentration decreases by approximately 3 orders of magnitude because of the decrease in vapor pressure with temperature. The corresponding change in CO\(_2\) concentration is approximately a factor of 3.

1.4 The Molecular Linewidth

The absorbed solar heat is returned to space as LWIR radiation. As the LWIR flux passes through the atmosphere it undergoes absorption and re-emission by the IR spectral bands. These consist of a large number of individual lines that are transitions between specific molecular rotation-vibration states. Figure 6 shows the locations and line strengths of the \(^1\)H\(^2\)\(^{16}\)O and \(^{12}\)C\(^{16}\)O\(_2\) molecular lines in the 200 to 2000 cm\(^{-1}\) spectral region for line strengths \(>10^{-23}\) at a temperature of 296 K. These data are from the HITRAN database [Rothman et al, 2005]. The absorption and emission properties of these lines depends on the pressure, temperature and species concentration as well as the line strength. The LWIR flux to space therefore has to be analyzed using high resolution radiative transfer techniques that include the linewidth effects.
Figure 5: Tropospheric lapse rate: temperature, pressure and H₂O, CO₂ concentration changes with altitude.
Figure 6: The locations of the $^1$H$_2^{18}$O and $^{12}$C$^{16}$O$_2$ molecular lines in the 200 to 2000 cm$^{-1}$ spectral region for line strengths $>10^{-23}$.

For an air parcel in the atmosphere, within the plane parallel layer approximation, the parcel is absorbing LWIR flux from above and below and is also emitting LWIR flux upwards and downwards. The horizontal flux is assumed to cancel out. The net heating or cooling depends on the difference between the absorption and emission terms as illustrated in Figure 7a. The molecular collision frequency in troposphere is larger than $10^9$. This means that as soon as an IR photon is absorbed, the excited molecular vibration-rotation state is quenched by collisions and the thermal energy is transferred to the local air mass. Conversely, the emission of IR photons removes heat from the local air mass. The absorbed and emitted LWIR flux is fully coupled to the bulk thermal mass of the air in the atmosphere. The change in temperature of an air parcel over a given time $t$ is the cumulative net flux absorbed or emitted divided by the heat capacity of the air volume. The absorption and the molecular linewidths decrease as the pressure, temperature and the species concentration decrease with altitude. In particular, the water vapor concentration decreases rapidly as the temperature decreases because of condensation. The upward radiative transfer process of absorption and emission is gradually replaced by a transition to a free photon
flux. This is illustrated in Figure 7b. The mechanism for line broadening is the decrease in excited state lifetime as the molecular collision frequency increases with pressure. This is a result of the Heisenberg uncertainty principle for time and energy.

The decrease in linewidth with altitude is illustrated in Figure 7c. This shows the H$_2$O and CO$_2$ absorption lines in the 590 to 600 cm$^{-1}$ spectral region at altitudes of 0, 5 and 10 km. The path length is 100 m. The arrows indicate the changes in linewidth for the H$_2$O line near 595 cm$^{-1}$ and the CO$_2$ line near 598.5 cm$^{-1}$ as the altitude increases from the surface to 10 km. The H$_2$O linewidth decreases from approximately 1 cm$^{-1}$ to 0.05 cm$^{-1}$ whereas the CO$_2$ linewidth decreases from 0.19 to 0.04 cm$^{-1}$. These are 5% and 21% of the initial values.

The transition from absorption-emission to a free photon flux for H$_2$O occurs in the middle troposphere at a temperature near 253 K (−20°C). This is location of the cold reservoir of the tropospheric heat engine. As the surface temperature changes, the altitude of the cold reservoir changes. The tropospheric cooling rates vs altitude are shown in Figure 8a for H$_2$O and CO$_2$ at 3 surface air temperatures, 275, 285 and 295 K, 50% RH and 380 ppm CO$_2$. The surface temperatures are 2 K higher at 277, 287 and 297 K. The altitude of the peak cooling rate decreases from 6.4 to 4.8 then 3.4 km as the surface temperature decreases [Clark, 2013b].

Near the surface, the molecular lines within the main absorption bands are sufficiently pressure broadened that they merge into a quasi-continuum. Almost all of the downward flux reaching the surface originates from within the first 2 km layer of the troposphere. Approximately half of this comes from within the first 100 m layer. The cumulative downward flux from H$_2$O and CO$_2$ vs. altitude is shown in Figure 8b. Four cases are plotted for surface temperatures of 272 and 300 K each with relative humidities of 20 and 70%. The downward flux near the surface increases with temperature and humidity. Even for the lowest flux case, 272 K and 20% RH, 95% of the surface flux originates from within the first 2 km layer. This means that the downward flux to the surface is decoupled from the LWIR emission to space. The concept of radiative forcing is invalid [IPCC, 2013]. There is no equilibrium flux that can be perturbed by an increase in ‘greenhouse gas’ concentration.
Figure 7: Molecular line broadening and the transition from absorption/emission to a free photon flux.

b) Transition from absorption-emission to free photon flux as the linewidth decreases with altitude. H$_2$O line near 251 cm$^{-1}$

c) H$_2$O and CO$_2$ absorption lines, 0.5 and 10 km, 100 m path length, 590 to 600 cm$^{-1}$. The decrease in linewidth with altitude is much greater for H$_2$O than for CO$_2$. 

a) Absorption and emission of LWIR flux in an atmospheric air parcel
Figure 8: Line broadening effects. 

a) Tropospheric cooling rates for H₂O and CO₂. The peak cooling rate for H₂O shifts to higher altitudes as the surface temperature increases. This is the main cooling reservoir of the tropospheric heat engine.

b) Cumulative fraction of the downward flux at the surface vs. altitude for surface temperatures of 272 and 300 K, each with 20% and 70% RH. Almost all of the downward flux reaching the surface originates from within the first 2 km layer. This is the lower tropospheric reservoir.

Figure 8: Line broadening effects. a) The water band emission to space from the upper tropospheric reservoir and b) the downward flux at the surface from the lower tropospheric reservoir.
1.5 The LWIR Emission to Space

As discussed above, the total LWIR flux or outgoing longwave radiation (OLR) emitted to space is in approximate long term energy balance with the absorbed solar flux. However, the LWIR emission originates from different altitudes with different temperatures so the spectral distribution is not that of a blackbody. Figure 9a shows the top of atmosphere (TOA) LWIR emission to space from the Niger Valley, N. Africa recorded from the Nimbus 4 satellite, early afternoon May 5th 1970. This figure, or similar ones have been used for many years to justify ‘global warming’ by claiming that an increase in ‘CO₂ absorption’ in the upper troposphere somehow increases the surface temperature [ACS, 2012]. This is simply impossible. The LWIR flux that reaches the surface originates from within the first 2 km layer. The LWIR flux in the upper troposphere is decoupled from the surface because of molecular line narrowing [Clark 2013a]. Starting from the left of Figure 9a, in the 400 to 600 cm⁻¹ region, the emission is from the H₂O rotation band at an effective emission temperature of ~250 K (-23 C) and an altitude near 7 km. In the 600 to 800 cm⁻¹ region, the emission is from the main CO₂ band at an effective emission temperature near 220 K (-53 C) and an altitude near 12 km. Between 800 and 1300 cm⁻¹, the emission is from the hot desert surface at a temperature near 320 K (47 C). There is also some absorption and emission from weak H₂O and CO₂ lines in the atmospheric transmission window. In the middle of this is the O₃ stratospheric band which is absorbing some of the surface flux. Between 1300 and 1600 cm⁻¹, most the emission is from the H₂O ν₂ vibrational band, with some overlapping contribution from CH₄. A simplified emission level diagram is shown in Figure 9b.

The atmospheric temperature profile is set by the lapse rate, not the LWIR emission. As the warm air rises from the surface it expands and cools. At night, in this geographic region, the surface cools to approximately 300 K, (27 C) and the surface emission profile shifts to the region indicated by the blue areas. The net LWIR emission from the surface decreases by over 100 W.m⁻². However, the atmospheric emission bands change little because LWIR emission is coupled to the bulk thermal air mass of the atmosphere. The diurnal temperature fluctuation in the middle troposphere is approximately 2 K or less [Feldman, 2008]. The atmosphere is always cooling by LWIR emission to space. It is heated during the day and early evening by convection from the surface. These complex energy transfer processes should not be reduced to a single ‘equilibrium average emission temperature’. Instead, the LWIR emission to space should be interpreted as a set of cooling fluxes that cool different levels in the atmosphere.
1.5.1 The Dependence of the OLR Flux on Surface Temperature

The dependence of the OLR flux on the surface temperature has recently been discussed by Koll and Cronin [2018]. They reported a linear dependence of $F = 2.22T - 339.6$ for clear sky conditions where $F$ is the outgoing flux in W m$^{-2}$ and $T$ is the absolute temperature. The error margin is approximately 10%. The clear sky OLR flux to space consists to two main parts, a molecular band emission that does not vary significantly with temperature and a temperature dependent transmission window flux that consists of a combination of surface emission and atmospheric emission, mainly from weak H$_2$O lines. The explanation of this requires a careful analysis of the spectral properties of H$_2$O and CO$_2$ and provides additional insight into coupled thermal reservoirs and the LWIR cooling of the atmosphere. This is discussed in more detail in the Appendix.

Figure 9: Satellite observation of the LWIR emission to space and a simplified emission diagram showing the emission at different altitudes.
It is important to note that the OLR flux is not part of any greenhouse effect. Changes in the LWIR flux in the stratosphere or lower troposphere cannot couple to the surface because of molecular line broadening at lower altitudes. Furthermore, at the surface, the change in downward LWIR flux cannot couple below the ocean surface and cause any measurable change in surface temperature. The greenhouse effect is limited to the effect of the surface exchange energy on the dissipation of the absorbed solar flux.

1.6 The Weather Station Temperature

The various heating and cooling flux terms interact with the surface as illustrated above in Figure 1. However, the temperatures recorded by a weather station are not surface temperatures. Instead, the weather station temperature is the meteorological surface air temperature (MSAT). This is the temperature measured in a ventilated enclosure placed for convenience at eye level, 1.5 to 2 m above the ground [Oke, 2006]. Historically in the US, the maximum and minimum daily temperatures were recorded using Six’s thermometer [Benjamin, 2006]. The minimum MSAT generally occurs near dawn. At this time, the surface air layer and the ground are usually at similar temperatures and the minimum MSAT is approximately that of the bulk temperature of the air mass of the local weather system that is passing through. The maximum MSAT is generally recorded in the early afternoon after the peak solar flux. It is the air temperature produced by the convective mixing of the warm air rising from the surface as it interacts with the cooler air at the MSAT thermometer level. Under full summer sun illumination, the bare, dry ground temperature may easily reach or exceed 50 C (~120 F). The maximum MSAT will generally be some 20 C cooler near 30 C (~85 F) [Clark, 2013b; 2011].

The maximum and minimum MSATs measure temperatures are produced by very different processes. In many parts of the world, the weather systems are formed over the oceans and the ocean temperature of formation is ‘carried’ by the air mass over long distances. This information is found in the minimum MSAT data. The sun heats the surface during the day and the surface temperature that drives the convection depends on the solar flux and the surface evaporation. The increase in temperature from the minimum to the maximum is a combined measure of convective mixing, solar flux, cloud cover and surface moisture/precipitation [Clark, 2019b].

1.6.1 Homogenization of the Weather Station Temperature Data

It is also important to understand that the climate record is not simply the average of the weather station data archive. The data have been ‘homogenized’ to produce points on a regular coordinate grid, typically 5 x 5° latitude longitude grids for easier comparison to model output. (The climate models do not have the fidelity to simulate the temperature record that they are supposed to be predicting). Some adjustments are necessary to account for station changes and instrumental bias effects. However, the same groups of climate modelers have also been ‘homogenizing’ the weather station data and well documented extra warming has mysteriously appeared in the climate record. The climate temperature record has been ‘adjusted’ to better fit the modeling results [Parker and Ollier, 2017, Worall, 2017; Johnson, 2015; Cheetham, 2015a; D’Aleo, 2010].
addition, in many locations, the thermometer and enclosure have been changed from mercury in glass in a white painted wooden louvered ‘Stevenson screen’ structure to a thermistor in a smaller, plastic ‘beehive’ structure. This has led to discontinuities in the climate record and concern over electronic averaging times [Marohasy, 2017; Quayle et al, 1991]. Considerable caution is therefore needed when published climate data is used.

1.6.2 The Convection Transition Temperature and Ocean Oscillations

An important concept in the interpretation of the weather station record is the night time transition temperature at which the land surface and air temperatures equalize and convection is significantly reduced [Clark 2019b; 2013b]. During the night, the surface cooling is limited mainly to the net LWIR emission. This is nominally 50 ±50 W m$^{-2}$. During the day, as the sun heats the surface, convection increases and heat is conducted below the surface where it is stored and released later in the day. A major factor that influences the convection transition temperature is the ocean surface temperature in the region of formation of the prevailing weather systems. There is often a seasonal delay or phase shift of 6 to 8 weeks in the weather station temperature response to the peak solar flux at summer solstice. This can only come from an ocean influence. The heat capacity of the ground thermal reservoir is too small to produce such a phase shift [Clark, 2019b]. These ocean temperatures show characteristic regional quasi-periodic fluctuations or oscillations. Three well known ocean oscillations are the Pacific Decadal Oscillation (PDO), the Atlantic Multi-decadal Oscillation (AMO) and the El Nino Southern Oscillation (ENSO). All of these have major impacts on the earth’s climate and their effects can be seen in the climate record [Cheetham, 2015b].

The AMO and PDO have periods of oscillation near 60 years. The AMO is associated with changes in the surface temperature in the North Atlantic Ocean. The PDO is associated with changes in temperatures in the North Pacific Ocean. The ENSO is a short term oscillation with a period between 3 and 7 years. It involves changes in the size and location of the Pacific warm pool and is caused by variations in wind speed over the equatorial Pacific Ocean. Figure 10 shows the PDO, AMO and ENSO oscillations over selected time periods: PDO one and five year averages from 1900; AMO one year averages from 1856 and ENSO monthly averages from 1950 [AMO, 2017; ENSO, 2017; PDO, 2017]. The long term 30 year fluctuations on the PDO and AMO are clearly visible. Figure 11 shows the associated changes in the temperature record related to the ocean oscillations [Clark, 2013b; HadCRUT4, 2018; UAH, 2017].

Figure 11a shows the five year average minimum MSAT record for the Los Angeles civic center from 1925 to 2005. The PDO is also plotted over the same period of record. The characteristic ‘fingerprint’ of the PDO can clearly be seen in the LA data. However, there is a slope to the LA data that does not show in the PDO record. This is an approximate indicator of the urban heat island (UHI) effect in Los Angeles as the surrounding urban area has increased. This ‘PDO’ signature can be seen in most of the minimum MSAT weather station records in California. It provides a reference that can be used as a probe of the urban heat island (UHI) effect and other station anomalies. This analytical technique has also been extended to UK temperatures using the AMO [Clark, 2013b].
Figure 11b shows the 1 year average of the AMO plotted with the HadCRUT4 climate record generated by the UK Hadley Center. Both the longer term maxima and minima and the shorter term ‘fingerprint’ detail can clearly be seen in both plots. The correlation coefficient between the two data sets is 0.8. The influence of the AMO extends over large areas of North America, Europe and parts of Africa through the propagation of the convection transition temperature. The climate trend for the continental US can be reconstructed using a linear combination of the AMO and PDO data [D’Aleo, 2008].

Figure 11c shows the global lower troposphere temperature from 1979 generated by the University of Huntsville Ala. climate group using satellite microwave sounding data. This is plotted with the ENSO data over the same period of record, scaled to match the UAH data. The lower troposphere temperature tracks the ENSO with a delay of a few months. The increase in extent of the Pacific warm pool significantly increases the amount of water vapor released into the troposphere and this in turn heats the troposphere by condensation. The El Nino peaks of 1998 and 2016 can clearly be seen in the data.

The data in Figure 11 clearly demonstrate that changes in ocean surface temperature are a major factor in the changes observed in the weather station record both for single stations and for the global climate record. However, the weather station record only extends back to the latter part of the nineteenth century, although some sparse earlier data are available. Earlier climate changes have to be reconstructed using proxy data such as isotope ratios or historical and archaeological records. These longer term climate trends will now be considered.
Figure 10: Ocean oscillations, PDO 1 and 5 year averages from 1900, AMO 1 year averages from 1856 and ENSO monthly averages from 1950.
Figure 11: Temperature changes related to the ocean oscillations.
1.7 Longer Term Climate Change

Figure 12 shows proxy climate temperature reconstructions for the last 2000 and 10000 years [Paleoclimat, 2017]. Figure 12a shows the medieval maximum, Maunder minimum and modern warming period. These climate changes are related to changes in the solar flux as determined by the sunspot count and other measures of solar activity [Clark, 2019c]. Figure 12b also shows the earlier Minoan and Roman warming periods. The lower plot shows the change in atmospheric CO$_2$ concentration over the last 10,000 years. The earth has been cooling for about the last 6000 years and the modern warming period is just a continuation of the previous warming and cooling cycles with a smaller temperature rise. There is no discernable influence from changes in CO$_2$ concentration. Time zero here is 1950, so the recent increase in CO$_2$ concentration is not shown.

Figure 13 shows the so called Milankovitch cycles or changes in the earth’s orbital and axial motion produced by planetary perturbations, mainly by Jupiter [Milankovitch, 1941; 1920; 2015, Varadi et al, 2003]. Figure 13a shows the type of motion: eccentricity, obliquity and precession. Figure 13b shows the Milankovitch cycles, high latitude solar insolation and stages of glaciation for the last 1000,000 years. The earth has cycled through a series of Ice Ages, with each one lasting approximately 100,000 years. The Ice Age maxima corresponds to periods of low eccentricity and warm periods are associated with higher orbital eccentricity. During the change from cold to warm, the atmospheric CO$_2$ concentration has increased from approximately 200 to 280 ppm. However, the change in CO$_2$ concentration lags the change in temperature [Fischer et al, 1999; Petit et al, 1999]. This means that the increase in ocean temperature produces the increase in atmospheric CO$_2$ concentration as the solubility of CO$_2$ in the oceans decreases with increasing temperature. These solubility changes however involve complex changes in the ocean buffer chemistry of carbonate and bicarbonate ions [Follows, 2006]. Figure 13c shows the Milankovitch cycles on an expanded scale from -200,000 to +100,000 years.

Figure 14 shows proxy reconstructions of the climate temperature and CO$_2$ concentration for the last 65 million years. Figure 14a shows the climate temperature reconstruction from Zachos et al [2001]. Major climate, tectonic and biological events are also included. Figure 14b shows the related changes in the location of the continents produced by plate tectonics and Figure 14c shows the changes in temperature and CO$_2$ from various reconstructions [Paleoclimate, 2017]. There is no discernable relationship between CO$_2$ concentration and temperature over this time period. However, plate tectonics has produced changes in ocean circulation that have had a major impact on the climate. The first of these was separation of S. America from Antarctica with the formation of the Drake Passage and the circumpolar circulation of the Southern Ocean. The second was the formation of the Isthmus of Panama and the closure of the Arctic Ocean to the Pacific Ocean. Both of these events have resulted in climate cooling.

From this discussion it is clear that changes in atmospheric CO$_2$ concentration have had no effect on climate for at least the last 65 million years. Climate change can be understood in terms of ocean oscillations with periods of 3 to7 and 60 to 70 years, changes in solar activity with periods of the order of 100 to 1000 years, Milankovitch cycles (planetary perturbations) with periods of the order of 10,000 to 100,000 years and changes in ocean circulation related to plate tectonics.
over even longer geological time scales. The climate energy transfer processes that underlie surface temperature and temperature change will now be considered in more detail.

Figure 12: Proxy temperature reconstructions for 2000 and 10,000 years.

a) A 2000 year global temperature reconstruction based on non-tree ring proxies. This shows the medieval maximum, the Maunder minimum and the modern warming period.

b) A 10,000 year temperature reconstruction based on GISP ice core data. This shows that the earth has been cooling for about 6000 years. The Minoan, Roman, Medieval and Modern warm periods are indicated. The lower plot shows the change in atmospheric CO₂ concentration, also from the ice core data.
Figure 13: Milankovitch cycles: planetary perturbations of the earth’s orbit and axial rotation
a) $\delta^{18}O$ and $\delta^{13}C$ isotope ratios and temperature reconstruction for the last 65 million years. Major climatic, tectonic and biotic events are also noted.

b) Changes in the location of the continents induced by plate tectonics over the last 69 million years.
Figure 14: Isotope proxy reconstruction of climate temperature and CO\textsubscript{2} over the last 65 million years. The motion of the continents induced by plate tectonic is also included. There is no discernable connection between CO\textsubscript{2} concentration and temperature. However, the effects of plate tectonics including the opening of the Drake Passage, the closure of the Arctic Ocean and the formation of the Isthmus of Panama all have major impacts on the climate temperature.
2.0 QUANTITATIVE ANALYSIS OF THE SURFACE TEMPERATURE

Based on the discussion above, there is no reason to expect that the observed increase in atmospheric CO₂ concentration from 280 to 400 ppm has had any effect on the earth’s climate [Keeling, 2018]. Over land, thermal conduction transports part of the solar heat below the surface. The diurnal variation is dissipated within the first meter layer below the surface and seasonal variation can be detected down to approximately 5 m. Any small changes in LWIR flux from CO₂ produce changes in the rate of cooling of this thermal mass that are simply too small to detect as variations in the surface temperature. Over the oceans, the LWIR flux is absorbed in the first 100 micron layer at the surface. Here it is coupled to the wind driven evaporation flux where again it cannot produce a measurable change in surface temperature. The surface energy transfer and the surface temperature will now be considered in more quantitative detail.

2.1 The Land-Air Interface

Figure 15 illustrates the diurnal flux balance for dry convection over land under full summer sun conditions. This is based on measured flux data from the University of Irvine ‘Grasslands’ monitoring site [Clark, 2013a; 2013b; 2011; Goulden, 2012]. The solar heating flux, the convection and net IR cooling fluxes and the subsurface thermal transfer are plotted for a 24 hour cycle in Figure15a. The corresponding surface and air temperatures are shown in Figure 15b. In this illustrative example, the total thermal flux dissipated by the surface during the 24 hour period from both net LWIR emission and convection in Figure 15a is 25.4 MJ m⁻² representing full summer sun ‘clear sky’ conditions. Of this, approximately 23 MJ m⁻², or 90% is dissipated during the day and early evening. The convective flux is 14.5 MJ m⁻² or 57% of the total flux and the associated LWIR flux is 8.5 MJ m⁻² or 33% of the total flux. Only 2.4 MJ m⁻² is dissipated at night through the LWIR transmission window. The time delay or phase shift between the maximum solar flux and surface cooling flux in this case is almost 2 hours. The convection continues after sunset until the ground and air temperatures equalize. After that the surface cooling is limited to the net IR flux through the LWIR window. Under these conditions, the lower tropospheric reservoir acts as a ‘thermal blanket’ that slows the night time cooling. This is how the surface temperature is maintained at night. The night time surface cooling flux typically varies between 0 and 100 W m⁻², depending on humidity and cloud cover. The solar flux will usually vary, depending on cloud cover. The increase in the downward LWIR flux from a 120 ppm increase in atmospheric CO₂ concentration is approximately 2.0 W m⁻² [Harde, 2017]. This corresponds to 0.16 MJ m⁻² per day or 0.7% of the total clear sky solar flux. This is too small to have any measureable effect on surface temperatures when it is added dynamically to the net LWIR flux term and used to calculate the total flux balance [Clark, 2019b, 2019c, 2013a, 2013b; 2011]. In signal processing terms it is ‘buried in the noise’.

If the solar flux is reduced because of partial cloud cover, the diurnal flux behavior will be similar, but with a reduced magnitude. If water is present, surface evaporation will add a latent heat flux cooling term. This will reduce the surface heating and therefore the LWIR emission and the
sensible heat flux. Energy is still conserved and the latent heat will be released through condensation of the water vapor in the troposphere as the warm air rises from the surface and cools above the saturation level. The surface evaporation will also vary with the wind speed and the humidity gradient. Vegetation will also increase the surface area and reduce the temperature rise. The details of vegetation related photosynthesis and evapotranspiration are complex, but the net result can still be considered in terms of a time dependent net surface flux balance [Mengelkamp et al, 2006]. The important point is that the net LWIR flux is insufficient to dissipate the absorbed solar flux and the excess solar heat must be dissipated by (moist) convection. The observed increase in atmospheric concentration of CO₂, or any other so called ‘greenhouse gases’ cannot produce any ‘global warming’.

Figure 15: Diurnal surface and air temperatures and the dry convection surface flux terms for full summer sun illumination conditions.
2.2 The Ocean-Air Interface

The energy transfer processes at the ocean-air interface are very different from those at the land-air interface. The surface temperature gradients are much smaller, most of the solar flux penetrates below the surface and the dominant cooling process is wind driven evaporation. The cooler water produced at the surface then sinks and cools the bulk ocean layers below. It is replaced by upwelling warm water. This is a Rayleigh-Benard type of convection with columns of water moving in opposite directions. It is not a simple diffusion process. This convection cycle continues to provide heat to the surface at night, so the wind driven evaporation continues at night. Over 50% of the solar flux is absorbed within the first 1 m layer of the ocean and 90% is absorbed within the first 10 m. The thermal storage is not localized and heat is transported and recirculated over very long distances. However, the penetration depth of LWIR radiation from the CO$_2$ bands into water is less than 100 micron. This means that the LWIR flux from CO$_2$ is coupled to the surface evaporation and small changes in this LWIR flux cannot heat the ocean below.

During the summer at most latitudes, the solar heating exceeds the wind driven cooling. The lower subsurface layers are not coupled to the surface by convective mixing and a stable thermal gradient is established. During the winter, the wind driven evaporation exceeds the solar heating and the surface temperatures cool and establish a uniform temperature layer down to 100 m or below. Figure 16 shows the seasonal variation in ocean temperature at nominal depths of 5, 25, 50, 75 and 100 m derived from Argo float data [Clark, 2019b; 2013a; 2013b; 2011]. Figure 16a shows the temperature data from a float drifting in the S. Pacific Ocean at latitudes and longitudes near 21° S and 105° W. Higher latitudes show a similar behavior with lower temperatures because of reduced solar heating. It is also important to note that at high latitudes, the surface area of a spherical zone decreases significantly. This geometric factor increases the depth of ocean currents as they flow to higher latitudes, further limiting their interaction with the surface [Alexander et al, 2001]. Small changes in subsurface ocean temperatures can therefore result in large changes in polar ice formation.

At low latitudes near the equator, the diurnal and seasonal temperature variations may not be sufficient to mix the subsurface layers below the 25 to 50 m levels and heat can accumulate at these depths for extended periods. Figure 16b shows the temperature data from an Argo float drifting in the S. Pacific Ocean at latitudes and longitudes near 1.5° S and 126° W. The diurnal mixing layer is shallow and only extends down to the 50 m level about half of the time. The floats are not tethered and the decrease in near-surface temperature with time is caused by an eastward drift.

Heat continues to accumulate as the ocean water travels westwards with the Pacific equatorial current. This leads to the formation of the equatorial ocean warm pool in the western Pacific Ocean. The ocean surface temperature increases until the wind driven evaporation balances the tropical solar heating at a surface temperature near 30 C and an average wind speed near 5 m s$^{-1}$. Variations in the wind speed across the Pacific Ocean then produce the characteristic ENSO
oscillations. As the wind speed slows, the evaporation decreases and the ocean current velocity decreases. Both of these factors increase the rate of surface heating and the warm pool extent increases.

The energy transfer processes for the Pacific warm pool are illustrated schematically in Figure 17. Here, a change in wind speed of 1 m s\(^{-1}\) produces a change in latent heat flux of approximately 40 W m\(^{-2}\). The observed increase in atmospheric CO\(_2\) concentration of 120 ppm has only produced an increase of 2 W m\(^{-2}\) in the downward LWIR flux at the surface. This corresponds to a decrease in average wind speed of 5 cm s\(^{-1}\). This small change in LWIR flux is simply overwhelmed by the magnitude and variability in the wind driven latent heat flux [Clark, 2019b, 2013b].

The upper plot in Figure 18 shows the air temperature and the ocean temperature at 1.5 and 25 m depths for 40 days starting at the beginning of July 2010. These data were recorded at the TAO/TRITON buoy located on the equator in the Pacific warm pool at a longitude of 156 E. The lower plot shows the corresponding wind speed and solar flux. There is a clear inverse relationship between the diurnal peak in the ocean temperature at 1.5 m depth and the wind speed. The diurnal temperature peaks increased when the wind speed was less than ~4 m s\(^{-1}\). This can be seen in areas indicated by the dotted lines.
Figure 16: Argo float data for average latitudes of 21° and 1.5° S. At 21° S and higher latitudes, the solar heating and wind driven evaporation interact to produce a stable subsurface thermal gradient in the summer that is removed by excess cooling during the winter. Near the equator, the solar heating exceeds the evaporation in the eastern Pacific Ocean leading to the formation of the equatorial warm pool.
Figure 17: Energy transfer in the Pacific warm pool (schematic).

b) Ocean energy transfer in the Pacific warm pool. The approximate magnitudes of the various flux terms are indicated. The cooler water sinks from the surface and is replaced by warmer water from the bulk ocean below. This is a Rayleigh-Benard convective flow process.

a) Ocean surface layer detail. Evaporation occurs from a thin surface layer <1 \mu m thick and NIR absorption/emission is limited to the first 100 \mu m layer. Approximately 5% of the solar flux is also absorbed in first 1 mm layer.
Figure 18: Air and 1.5, 25 m ocean temperatures, wind speed and solar flux, 40 days of data from July 1, 2010, TAO/TRITON buoy data, 0°, 156° E. The two periods with low wind speeds and higher 1.5 m SST are indicated with the dotted lines.
3.0 THE GREENHOUSE EFFECT TEMPERATURE AND RADIATIVE FORCING

In order to try and quantify the so called ‘greenhouse effect’ it is claimed that the surface temperature is 33 K warmer than it would be if the IR active gases were removed from the atmosphere. This is based on the difference between an ‘average surface temperature’ of 288 K (15°C) and an effective LWIR emission temperature to space of 255 K (-18°C) [Taylor, 2006]. First of all the whole concept of a single average temperature for the earth has little useful meaning [Essex et al, 2006]. Secondly, as discussed above in relation to Figure A1 below, the LWIR emission to space comes from a range of atmospheric levels with different temperatures and spectral distributions. In reality, this ‘greenhouse effect’ temperature difference is just the convective cooling produced as an air parcel ascends from the surface to the cold reservoir of the tropospheric heat engine near 5 km with a lapse rate of -6.5 K km⁻¹ [Gilbert, 2010; Jelbring, 2003]. In addition, it is claimed that the temperature of the earth without any ‘greenhouse effect’ would be 255 K based on equilibrium average flux arguments. However, this argument ignores the cosine dependence of the solar flux illumination and uses incorrect flux/temperature averaging techniques. The average temperature of an airless earth has been estimated to be near -75°C (198 K) giving a ‘greenhouse effect temperature’ near 90 K [Volokin & ReLlez, 2014].

The assumption of an ‘average equilibrium infra-red atmosphere’ is also incorrect. This is based on conservation of energy arguments that set aside the Second Law of Thermodynamics and ignore the dynamic nature of the tropospheric heat engine. In the original climate model formulation developed by Manabe and Wetherald (M&W) in 1967, an exact TOA flux balance between the absorbed solar flux and the emitted LWIR flux was used. The surface was assumed to be a blackbody surface with zero heat capacity and a fixed atmospheric distribution of relative humidity was also used [M&W, 1967]. These simplifying assumptions created CO₂ induced global warming as a mathematical artifact of the model calculations [Clark, 2019a]. The ‘average equilibrium infra-red atmosphere’ is just a mathematical construct that leads to a simple set of meaningless flux equations [Held & Soden, 2000; Ramanathan, 1998; Ramanathan and Coakley, 1978].

The modeling errors created by the M&W approach were ignored and this type of model was used to ‘predict’ global warming in the Charney Report and was adopted by NASA [Charney, 1979]. This provided a ‘benchmark’ for future global warming simulation studies. Climate model output was compared using the hypothetical warming produced by a doubling of the CO₂ concentration. Models results were compared to other model results. Physical reality was not allowed to intrude. The M&W model was then ‘improved’ without any attempt to correct the underlying mathematical assumptions. In fact, three more invalid mathematical constructs were added. First, the LWIR flux was coupled into ocean layer 100 m thick even though the penetration depth of the LWIR flux was less than 100 micron [Hansen et al, 1981]. Second, this paper also introduced the concept of ‘radiative forcing’ as an increase in surface temperature from ‘global radiative perturbations’. All of this is based on nothing more than meaningless mathematical ritual: the application of perturbation theory to a fictional equilibrium infra-red climate. Third, the surface temperature was
changed to the weather station temperature or MSAT without any discussion, justification or changes to the modeling algorithms.

An empirical ‘climate sensitivity constant’ $\lambda$ was introduced. This created an increase in surface temperature by assuming a linear relationship between the temperature and the ‘radiative forcing’, RF.

$$\Delta T = \lambda RF$$ (2)

The radiative forcing was defined as the change in flux (downward minus upward) at TOA or the tropopause after the stratosphere had been allowed to ‘adjust’ to a new ‘equilibrium state’ following a change in ‘greenhouse gas’ (or aerosol) concentration. This has no basis in physical reality. There is no equilibrium average flux. The downward emission from the stratosphere and upper troposphere is decoupled from the surface by the molecular line broadening as discussed above in Section 1.4. Almost of the downward LWIR flux at the surface originates from within the first 2 km layer of the troposphere and approximately half of this comes from the first 100 m layer. Furthermore, the increase in downward LWIR flux is absorbed within the first 100 micron layer at the ocean surface. As discussed in Section 2.2, it cannot couple into the oceans and cause any kind of measurable ocean warming. It is overwhelmed by the wind driven evaporation. In the Third Climate Assessment Report, $\lambda$ was given as 0.5 K/(W m$^{-2}$). [IPCC, 2001] This was based on nothing more than a contrived correlation between the calculated increase in downward LWIR flux from CO$_2$ and the observed increase in the average weather station record [Jones et al, 1989; 1999]. Mid twentieth century cooling was ignored. So was the difference between the surface temperature and the weather station temperature or MSAT.

As shown above in Figure 11b, the HadCRUT4 global temperature series is dominated by the AMO. Figure 19 shows Figure 11b with the AMO offset by 0.18 C to align the two series in the period before 1975. A least squares fit to the AMO using a sinusoidal amplitude of 0.21 C, a period of 61 years, a phase shift of -14 years superimposed on a linear slope of 0.0028 C/year is also shown. From Figure 19, the increase in the HadCRUT4 from 1975 is approximately 1 C. Half of the increase may be attributed to the AMO and half to a combination of urban heat island (UHI) effects, poor weather station location, station selection bias, and ‘homogenization’ adjustments.
This ‘climate sensitivity constant’ has been used to create ‘global warming’ using ‘radiative forcing constants’ for every imaginable ‘greenhouse gas’ that can be found in the atmosphere and is featured prominently in the IPPC reports [IPCC 2013]. This is nothing more than empirical pseudoscience. The climate model results are based on a linear extrapolation of the last ocean warming cycle. The Earth is now starting to cool again and this has clearly revealed the climate modeling fraud. The models continue to predict warming based on the increase in atmospheric CO₂ concentration, while there is clearly a ‘pause’ in the measured climate record. The creation of both cooling and warming by ‘cherry picking’ the climate record is illustrated in Figure 19, derived from Akasofu [2010]. The so called ‘pause’ is shown in Figure 20 [Spencer, 2013]. The effect of the AMO on the surface temperature has also been discussed by Gervais [Gervais 2016; 2014] Climate model results have diverged significantly from the measured temperature record, even with ‘homogenization’. The climate models have clearly failed [Clark 2019a, 2019c].
Figure 20: The creation of both global cooling and global warming by ‘cherry picking’ time periods from the climate record [After Akasofu, 2010]. a) Warming period with Keeling curve superimposed and upward extrapolation. b) The recovery of the earth’s climate from the Little Ice Age with long term ocean oscillations superimposed. c) 1970s cooling scare. The sun has now passed through a sunspot maximum and the underlying trend may be expected to change from warming to cooling.
Figure 21: Comparison between tropical mid troposphere temperatures from satellites and balloons with 90 CIMP-5 rdp8.5 model simulations, from Spencer [2013]. The ‘pause’ or divergence of model ‘prediction’ from measurement is indicated.
4.0 CONCLUSIONS

The greenhouse effect has been explained in terms of the influence of the time dependent surface LWIR exchange energy on the surface cooling. This exchange energy reduces the net LWIR emission from the surface. The surface must therefore warm up until the absorbed solar flux is dissipated by moist convection over land or by wind driven evaporation over the oceans. This is of course a consequence of the Second Law of Thermodynamics. These energy transfer processes are dynamic or time dependent and vary on both a diurnal and seasonal time scale. There is no equilibrium. The troposphere functions as an open cycle heat engine that is intermittently heated by the local solar flux and transports the surface heat by convection to the cold reservoir in the middle troposphere. From here the heat is radiated to space. The land and especially the oceans act as the hot reservoirs of this heat engine. The troposphere splits naturally into two independent thermal reservoirs. Almost all of the downward flux reaching the surface originates from the lower tropospheric reservoir within the first 2 km layer. The upper tropospheric reservoir, from 2 km to the tropopause contains the cold reservoir with the LWIR water band emission to space. The radiative transfer of the LWIR flux through the atmosphere has to be analyzed using a high enough spectral resolution to resolve the pressure broadened molecular line structure. The change in linewidth plays a key role in both the downward LWIR emission to the surface and the emission to space. At the surface, within the molecular absorption bands, the pressure broadened lines form a quasi-continuous blackbody. The OLR emission to space from these bands is determined by the molecular spectral properties and is largely independent of the surface temperature. Surface cooling by net LWIR emission is limited to the LWIR transmission window. The (cloud free) downward LWIR flux to the surface and the OLR flux from within this transmission window both vary linearly with temperature. This may be explained when the effect of the Boltzmann distribution on the lower state molecular level populations is considered.

The various flux terms that heat and cool the surface interact with the air-land and air-ocean interfaces. The weather station temperature however is the meteorological surface air temperature (MSAT). This is the temperature measured in a ventilated enclosure paced for convenience at eye level, 1.5 to 2 m above the ground. The minimum MSAT is approximately that of the bulk temperature of the air mass of the local weather system that is passing through. The maximum MSAT is the air temperature produced by the convective mixing of the warm air rising from the surface as it interacts with the cooler air at the MSAT thermometer level. There are two important properties of the surface energy transfer that need to be considered. The first is the convection transition temperature at which the surface and surface air temperatures equalize and convection stops. The second is the seasonal time delay or phase shift between the peak solar flux at summer solstice and the peak temperature response. This can only be produced by the solar heating of the ocean reservoir.

In many parts of the world, the weather systems are formed over the oceans and the ocean surface temperature of formation is ‘carried’ by the air mass over long distances. This is the real source of the ‘global warming signal’ found in the climate record. The oceans have now stopped
warming. This is cause of the so called ‘pause’ in the climate record. The climate temperature record has also been ‘adjusted’ to better fit the climate modeling ‘predictions’ using ‘homogenization’ as a shield. Considerable caution is therefore needed when published climate data is used. There can be no ‘CO\textsubscript{2} signature’ in the weather station records, regardless of the data processing used to create the climate record.

Over the last 200 years, the atmospheric concentration of CO\textsubscript{2} has increased by 120 ppm from 280 to 400 ppm. This has produced an increase in downward LWIR flux at the surface of approximately 2 W m\textsuperscript{-2}. This increase in LWIR flux has to be added to the time dependent surface flux terms used to calculate the change in surface temperature of the land and ocean thermal reservoirs. The resulting temperature changes from the increase in CO\textsubscript{2} flux are too small to measure when realistic values of the flux terms and their short term fluctuations are used.

Climate change can be explained in terms of ocean oscillations, changes in the solar flux and plate tectonics. The ocean oscillations, the ENSO, AMO and PDO produce time dependent changes in the climate record with periods of 3 to 7 years for ENSO and 60 to 70 years for the AMO and PDO. Change in solar activity related to the sunspot cycle have produced climate changes such as the medieval maximum, Maunder minimum and modern warming period with periods in the 100 to 1000 year time frame. Longer term variations in the solar flux are produced by planetary perturbations of the earth’s orbital and axial motion (Milakovich cycles). Over recent geological time these have taken the earth through an Ice Age with a period near 100,000 years. Over longer geological time periods, the motion of the continents produced by plate tectonics has produced climate change by changing ocean circulation patterns. For example, significant cooling was produced by the opening of the Drake Passage and the formation of the Southern Ocean.
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5.0 REFERENCES

Normally, the references given in a report of this nature would be limited almost exclusively to the peer reviewed literature, with limited references to websites that provide access to climate data. Unfortunately, climate science has been thoroughly corrupted by the global warming fraud. The peer review process has collapsed and been replaced by blatant cronyism. Many of the articles published in ‘prestigious’ journals such as Nature, Science, PNAS and others that relate to climate modeling predictions of global warming are fraudulent and should never have been published. Consequently many of the important references given here are to website publications. This should not detract from the integrity of the information provided. Many of these website publications have received a more thorough review that they might have received through the traditional peer review process.

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APPENDIX: THE TEMPERATURE DEPENDENCE OF THE OLR FLUX

A1.0 INTRODUCTION

As described above in Section 1.5.1, the OLR flux increases linearly with surface temperature. This was recently considered by Koll and Cronin [2018]. There are two different contributions to the OLR flux. Within the main H$_2$O 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$_2$O, this transition occurs near a temperature of 253 K (-20 C). As the surface temperature changes, the altitude of the H$_2$O emission band changes. This is illustrated above in Figure 8a. For CO$_2$ it occurs at a lower temperature near 220 K. Most of the CO$_2$ band emission occurs in the stratosphere. The spectral band cooling rates vs altitude for a tropical atmosphere are shown in Figure A1 [Feldman et al, 2008].

![Figure A1: Total and band-averaged IR cooling rate profiles for the Tropical Model Atmosphere on a log-pressure scale [Feldman et al, 2008]](image_url)
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 transmitted to space. The temperature dependence of the OLR in this region includes some spectral changes that require careful examination and explanation.

**A2.0: THE SPECTRAL DISTRIBUTION OF THE OLR FLUX**

Figure A2 shows the OLR and downward surface 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\(^{-1}\). The emission units are in radiance (W cm\(^{-2}\) sr\(^{-1}\)). 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\(_2\)O band from 100 to 600 cm\(^{-1}\), the CO\(_2\) \(v_2\) vibration band from 600 to 750 cm\(^{-1}\) and the H\(_2\)O \(v_2\) vibration band above 1300 cm\(^{-1}\) [Herzberg, 1991]. 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\(_2\)O 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. The downward emission is for 0 km looking up. For reference, blackbody emission curves for 300 to 220 K in 20 K intervals are also plotted.

The downward LWIR flux to the surface (blue line) follows the 300 K blackbody curve through the H\(_2\)O and CO\(_2\) bands to 700 cm\(^{-1}\). It then decreases through the transmission window and returns to the 300 K level near 1300 cm\(^{-1}\) with the onset of the \(v_2\) H\(_2\)O band. Over this spectral range, the 300 K blackbody emission is 424 W m\(^{-2}\) and the downward LWIR flux is 328 W m\(^{-2}\). The difference between the downward flux and the 300 K blackbody emission over the 100 to 1500 cm\(^{-1}\) range is 96 W m\(^{-2}\). This is the net LWIR cooling flux emitted into the LWIR transmission window from the surface in this MODTRAN example. The opacity factor is 0.77. Either the net cooling flux or the opacity factors are measures of the greenhouse effect.

Figure A3 shows the OLR flux from Figure A2 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\(_2\)O emission is from an altitude of ~4.5 km at a temperature of ~270 K. Near 300 cm\(^{-1}\) the H\(_2\)O 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.
Figure A2: Spectral distribution of the OLR and downward LWIR flux to surface for a 300 K surface temperature. The principal spectral features are indicated.

Figure A3: OLR to space, 300 K surface temperature showing the separate atmospheric and surface contributions to the 70 km level emission (MODTRAN calculation).
The total OLR emission is 295 W m\(^{-2}\) of which 213 W m\(^{-2}\) is from the atmospheric emission and 82 W m\(^{-2}\) is from the surface. The difference between the surface blackbody emission and the total OLR emission is 129 W m\(^{-2}\). The LWIR emission from the surface is absorbed and re-emitted at different levels in the atmosphere. The lifetimes of the excited state molecules in the troposphere and lower stratosphere are very short because of molecular collisions. This means that the LWIR re-emission occurs at the bulk temperature of the local air mass. This bulk temperature is set in the troposphere by the convection, not the LWIR emission. For a vertical ascent rate of 1 km per hour, the change in temperature is near -6.5 K per hour at the standard lapse rate. The corresponding cooling rate from LWIR emission does not normally exceed 2 K per day as shown in Figure A1 [Feldman et al, 2008]. This more than 50 times slower.

Figures A4 and A5 show the corresponding plots to Figures A2 and A3 for a surface temperature of 270 K using the MODTRAN mid latitude winter defaults. For clarity, the 270K blackbody emission curve has been added to these plots. The downward LWIR flux to the surface (blue line) now follows the 270 K blackbody curve with reduced emission in the 700 to 1300 cm\(^{-1}\) spectral transmission window. The emission temperature of the main CO\(_2\) P and R bands is still near 220 K. The atmospheric transmission window has widened and there is now a region of partial transmission to low energy of the CO\(_2\) band in the 500 to 600 cm\(^{-1}\) range. This can be clearly seen in the surface emission to space plotted in Figure A5. This additional transmission feature is not simply caused by the decrease in H\(_2\)O concentration with temperature or the decrease in the blackbody emission temperature from 300 to 270 K. Instead, there is an additional temperature sensitivity caused by the decrease in the population of the lower state rotational energy levels relate to the Maxwell Boltzmann distribution law. This is discussed in more detail below.

In Figure A5, the emission from the water bands has shifted to lower temperatures and lower altitudes. The emission peak is near 400 cm\(^{-1}\) at a temperature near 250 K and an altitude of approximately 3 km. At 300 cm\(^{-1}\), the emission temperature is near 230 K and 6 km. This assumes a lapse rate of -6.5 K km\(^{-1}\).

Over the 100 to 1500 cm\(^{-1}\) spectral range, the total 270 K blackbody emission is 286 W m\(^{-2}\). The total OLR emission is 224 W m\(^{-2}\) of which 142 W m\(^{-2}\) is from the atmospheric emission and 82 W m\(^{-2}\) is from the surface. In this MODTRAN example, the widening of the spectral window has offset the decrease in emission with temperature. The surface emission to space at both 300 and 270 K is 82 W m\(^{-2}\). The difference between the surface blackbody emission and the total OLR emission is 62 W m\(^{-2}\).
Figure A4: Spectral distribution of the OLR and downward LWIR flux to surface for a 270 K surface temperature. The principal spectral features are indicated.

Figure A5: OLR to space, 270 K surface temperature showing the separate atmospheric and surface contributions to the 70 km level emission (MODTRAN calculation).
The spectral resolution in Figures A2 through A5 is 2 cm\(^{-1}\). In order to explain the detailed properties of the atmospheric absorption and emission it is necessary to consider the contribution of the individual molecular lines. This typically requires a spectral resolution of 0.01 cm\(^{-1}\). These data are available from the HITRAN database [Rothman et al, 2005]. In particular, there is an additional temperature dependence introduced through the Boltzmann factor.

### A2.1: The Boltzmann Factor

The line strengths in HITRAN are given at 296 K. In order to convert to other temperatures, the Boltzmann factor or change in population fraction of the lower state is used:

\[
S_{\nu T} = S_{\nu 296} Q_T \exp\left(-\frac{(hc/k)v''}{T}\right)\exp\left(-\frac{(hc/k)v''}{296}\right)
\]

Where \(Q_T\) is the ratio of the partition function at temperature \(T\) to that at 296 K, \(h\) is Planck’s constant, \(c\) is the velocity of light, \(k\) is the Boltzmann constant and \(v''\) is the ground state energy level in cm\(^{-1}\). For H\(_2\)O, \(Q_T\) decreases almost linearly from 1.0 at 296 K to 0.64 at 220 K [Torek et al, 2002].

Figure A6 shows the relative change in Boltzmann population with temperature for selected energy levels above the ground state calculated using Eq. (A1). Since water is a lighter molecule than CO\(_2\), the rotational energy levels are more widely spaced and the ground state rotational energy manifold extends to higher energy. H\(_2\)O is also a symmetric top molecule that has 3 rotational constants. This increases the number of lines and leads to irregular line spacing.

Figure A7 shows a scatter plot of the line strengths of both H\(_2\)O and CO\(_2\) plotted against the ground state energy levels using data from the HITRAN database. Figure A8 shows the energy levels on an enlarged scale. For CO\(_2\), the ground state levels are below 600 cm\(^{-1}\) for the main lines of the P, Q, R branches. The temperature sensitivity increases with the ground state energy level \(v''\).

Figure A9 shows a scatter plot of the measured line positions vs. ground state energy level using data from the HITRAN database. Figure A10 shows the energy levels on an enlarged scale. There are relatively few low lying ground state energy levels for water near the atmospheric transmission region.

The overall effect of the Boltzmann term is that there is a spectral shift to lower energy in the H\(_2\)O emission with decreasing temperature. This explains the widening of the spectral window and the surface emission feature in the 500 to 600 cm\(^{-1}\) spectral region in Figure A5.
Figure A6: Change in HITRAN population (intensity) vs. temperature for selected ground state energy levels

Figure A7: Scatter plot of the ground state energy levels vs. line strength for H₂O and CO₂
Figure A8: Scatter plot from Figure A9 with enlarged energy level scale

Figure A9: Scatter plot of ground state energy level vs. line position (cm\(^{-1}\)) for H\(_2\)O and CO\(_2\)
A2.2: The Line Width

Each molecular line in the troposphere and most of the stratosphere has a Lorentzian profile that is produced by pressure broadening. The molecular collision frequency in the troposphere is $>10^9$. This decreases the upper state lifetime and produces line broadening via the Heisenberg Uncertainty Principle for time and energy. In HITRAN, the line broadening term is:

$$L(\nu) = \frac{1}{\pi} \frac{\nu_L}{[(\nu - \nu_0)^2 + \nu_L^2]}$$

Where $\nu_L$ is the line broadening coefficient, $\nu$ is the frequency in cm$^{-1}$ and $\nu_0$ is the line center in cm$^{-1}$. $\nu_L$ in turn depends linearly on the pressure and there may also be a temperature correction term. In the HITRAN analysis presented here, only the air broadening is included. Effects of H$_2$O-H$_2$O collisions and continuum absorption are not considered.

The decrease in linewidth with altitude means that the upward and downward LWIR fluxes in the atmosphere are not equivalent. The upward emission from the wings of the broadened lines at lower altitude are not reabsorbed by the narrower lines above. Conversely the downward emission from the narrower lines at higher altitude are absorbed by the wider lines below. This is illustrated in Figure A11. This shows the change in absorption profile of a single water line near 489.5 cm$^{-1}$ for surface air temperatures of a) 300 K and b) 270 K at 30% relative humidity for a 100 m path length. For the 300 K surface temperature the line is close to saturation with a peak absorption of 0.97. This decreases to 0.5 at an altitudes of 5 km and to 0.07 at 7.5 km. For the 270 K surface temperature the peak line absorption is 0.12. This decreases to 0.06 at an altitudes of 2.5 km and to 0.002 at 5 km. The lower state energy level is 2437.5 cm$^{-1}$, so there is a significant temperature
sensitivity from the Boltzmann factor for this line. Figure A12 shows plots of the input data used in the linewidth calculations.

Figure A11: Line broadening and the non-equivalence of the upward and downward flux terms for the H₂O line near 489.5 cm⁻¹.
Figure A12: Input data to Figure A11 - temperature, pressure, H$_2$O concentration, Boltzmann term, line strength and linewidth plotted vs. altitude for surface air temperatures of 300 and 270 K.

Figure A13 shows the change in linewidth for the R10 line of CO$_2$ at 676 cm$^{-1}$ for a 100 m path length and 400 ppm CO$_2$ concentration. The surface air temperatures are 300 and 270 K. The altitudes are 0, 5 and 10 km. Although the lines do narrow with altitude, the decrease in absorption is much less than for H$_2$O. The line peaks remain saturated with an absorption of 1.0 even at 10 km. The decrease in concentration with altitude is also quite small, from approximately 1E16 to 5E15 molecules cm$^{-3}$. The rotational ground state level for the R10 line is 42.9 cm$^{-1}$, so the change in Boltzmann factor is also much smaller. This means that the CO$_2$ lines continue to absorb and emit LWIR radiation at higher altitudes than H$_2$O.
A2.3: The Line Spacing

The absorption and emission of LWIR radiation through the atmosphere depends on the line strength, linewidth and line spacing. Near the surface within the main H$_2$O and CO$_2$ absorption bands, the lines are broadened into a quasi-continuum that acts as a black body emitter. This downward LWIR flux provides the exchange energy that limits the net LWIR emission from the surface. There is also the atmospheric transmission window in the 750 to 1250 cm$^{-1}$ region. At higher altitudes, the linewidths narrow and the H$_2$O concentration decreases significantly. There is also a spectral shift in the H$_2$O bands produced by the Boltzmann factor. The H$_2$O lines are also spaced irregularly so that small scale ‘transmission windows’ open up between groups of lines.
In contrast, the main CO$_2$ band near 670 cm$^{-1}$ consists of an intense Q branch with many closely spaced lines. On either side are the P and R branches with a regular line spacing near 1.5 cm$^{-1}$. The combination of a slow decrease in concentration with altitude and a lower Boltzmann temperature sensitivity means that the CO$_2$ band continues to absorb and emit radiation throughout the troposphere. The emission temperature of the P and R bands is near 220 K.

Figure A14 shows the absorption and emission of the H$_2$O lines in the 450 to 500 cm$^{-1}$ spectral region at 0, 5 and 10 km for a surface temperature of 300 K and a relative humidity of 30%. The path length is 100 m and the spectral resolution is 0.01 cm$^{-1}$. The decrease in absorption and emission with altitude and the irregular line spacing can be clearly seen. For reference, the blackbody emission at the local air temperature is also shown (orange line).

Figure A15 shows the absorption and emission of the CO$_2$ lines in the 670 to 680 cm$^{-1}$ spectral region at 0, 5 and 10 km for a surface temperature of 300 K and a relative humidity of 30%. The path length is 100 m and the spectral resolution is 0.002 cm$^{-1}$. The main lines are the R4 to R14 progression, with various overlapping overtone lines. At the surface, for a 100 m path length, the lines are almost fully saturated with a minimum absorption near 0.75. At 5 km, the lines narrow and the minimum absorption is near 0.4. However, at longer path lengths, all of the LWIR flux will be absorbed and re-emitted at the local air temperature. At 10 km, the lines continue to narrow and the minimum absorption is near 0.1. However, the main R branch lines are still saturated at line center.

Figure A16 shows part of the LWIR transmission window in the 750 to 800 cm$^{-1}$ spectral region at 0, 5 and 10 km for a surface temperature of 300 K and a relative humidity of 30%. The path length is 100 m and the spectral resolution is 0.01 cm$^{-1}$. This region consists of a series of weak H$_2$O lines with a CO$_2$ overtone progression near 760 cm$^{-1}$. The absorption decreases quite rapidly with altitude and the lines almost disappear at 7.5 km. Only a fraction of the LWIR emission from the surface is absorbed and re-emitted and the remainder is transmitted directly to space.
Figure A14: Absorption and emission of the H$_2$O lines in the 450 to 400 cm$^{-1}$ spectral region at 0, 5 and 10 km. Path length is 100 m. Surface relative humidity is 30%. 


Figure A15: Absorption and emission of the CO₂ R4 to R14 line region from 670 to 680 cm⁻¹ at 0, 5 and 10 km. Path length is 100 m.
A2.4: The Molecular Band and Transmission Window Contributions to the OLR Flux

As discussed above, the spectral distribution of the OLR flux can be divided into five principal regions, 3 molecular absorption bands and 2 transmission windows. Within the 3 main molecular absorption bands, all of the surface flux is absorbed and re-emitted until the emission levels to space are reached. The OLR molecular emission does not change significantly with surface temperature or surface humidity. As shown above in Figure 8a, the H$_2$O emission levels to space shift to higher altitude as the surface temperature increases. The cooling rate however increases with altitude because the pressure (density) decreases and this reduces the specific heat. At the surface, the downward flux is that of a black body near the bulk surface air temperature. For the MODTRAN 100 to 1500 cm$^{-1}$ range, these molecular band spectral regions are 100 to 350 cm$^{-1}$
(H\textsubscript{2}O, rotation), 600 to 720 cm\textsuperscript{-1} (CO\textsubscript{2}, \nu\textsubscript{2}) and 1400 to 1500 cm\textsuperscript{-1} (H\textsubscript{2}O, \nu\textsubscript{3}). The main spectral window, denoted Window 1 is in the 720 to 1400 cm\textsuperscript{-1} region. This consists of weakly absorbing H\textsubscript{2}O and CO\textsubscript{2} lines with absorption bands from other species, particularly stratospheric O\textsubscript{3}. The second spectral window, denoted Window 2 is in the 350 to 600 cm\textsuperscript{-1} region. It is part of the H\textsubscript{2}O rotation band that becomes partially transmitting as the temperature and H\textsubscript{2}O concentration decrease. The temperature dependence is due to both the change in H\textsubscript{2}O vapor pressure and the Boltzmann factor. Figure A17a shows the spectral distribution of the total OLR flux for four cases: surface temperatures of 300 and 270 K and relative humidities of 70 and 30% at each temperature. These are from MODTRAN, 2 cm\textsuperscript{-1} resolution simulations, 70 km altitude, 300 K tropical (Trp), 270 K mid latitude winter (MLW) atmosphere models, 400 ppm CO\textsubscript{2}. For reference, blackbody curves for 300 to 220 K at 20 K intervals are also plotted. A summary plot showing the total flux within each spectral band is shown below the main plot. Within the molecular bands, the OLR emission does not change significantly with temperature or humidity. The emission temperatures are near 240 K for the H\textsubscript{2}O rotation band, 220 K for CO\textsubscript{2} and 250 K for the H\textsubscript{2}O vibration band. The emission temperature in Window 1 is near the surface temperature. In Window 2, near 500 cm\textsuperscript{-1} the emission temperature is near 270 K for the 300 K surface temperature and near 260 K for the 270 K surface temperature.

Figures A17b and A17c show the atmospheric and surface emission components of the total OLR flux plotted in Figure A17a. Figure A17d shows the downward atmospheric LWIR flux at the surface for the same conditions. The summary plots are also shown. In Figure A17b, the approximate location of the molecular band emission is indicated by the red dotted lines. In Window 1 in the 750 to 900 cm\textsuperscript{-1} region, the 300 K flux decreases by about a factor of 2 as the H\textsubscript{2}O concentration is decreases from 70 to 30% RH (blue and gray lines). However, the 270 K flux shows little change with humidity (orange and yellow lines). The H\textsubscript{2}O surface concentrations are 6E17, 2.6 E 17, 8.9E16 and 3.8 E16 molecules cm\textsuperscript{-3} for the 300K/70%, 300K/30%, 270K/70% and 270K/30% cases. In Window 2, 350 to 600 cm\textsuperscript{-1}, the dominant effect is the change in temperature. The 300K 70 and 30% RH plots (blue and gray) overlap with an emission temperature at 500 cm\textsuperscript{-1} near 270 K. The 270K 70 and 30% RH plots (orange and yellow) also overlap with an emission temperature at 500 cm\textsuperscript{-1} near 230 K.

In Figure A17c there is no OLR surface emission from the molecular bands. The corresponding downward molecular band emission in Figure 23d is that of a blackbody near the surface temperature. In Window 1, near 800 cm\textsuperscript{-1}, the 300 K 70% RH surface emission is absorbed more strongly than the 300 K 30% case (blue and gray lines). The 270 K, 70 and 30% RH lines overlap and there is little absorption. The window emission temperature is above 260 K. In window 2, the surface emission increases significantly at 270 K (orange and yellow lines). The downward emission shown in Figure A17d is the real source of the so called ‘greenhouse effect’. This is considered in more detail in Section 4.0 below.
c) Surface emission, MODTRAN 70 km

![Graph showing surface emission with MODTRAN 70 km]

OLR Surface Emission Summary

![Graph showing OLR surface emission summary]

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Figure 17: MODTRAN simulations, 300 and 270 K surface temperatures, 70 and 30% RH, a) total OLR, b) atmospheric and c) surface OLR emission components at 70 km. d) downward emission, 0 km. Upper plot shows spectral emission, lower plot gives a summary of the emission into the 5 spectral regions. For details see text discussion.
A3.0: THE TEMPERATURE DEPENDENCE OF THE OLR FLUX

As discussed in the previous section, the OLR flux consists of 5 main spectral regions. The upward emission from the 3 main molecular bands does not change significantly with temperature or species concentration. The absorption and emission process continues with altitude until the emission level is reached. Here the decrease in concentration and temperature produce sufficient line narrowing that most of the LWIR flux is no longer absorbed and continues to space as a free photon flux. For the H₂O bands, this occurs within the troposphere. The emission level is determined by the temperature and is centered near 250 K. The altitude of this level is determined by the lapse rate and the surface temperature. As the emission level increases in altitude, an ascending air parcel has to perform more mechanical work to overcome the gravitational potential. The emission level for CO₂ is located in the stratosphere.

To investigate the temperature dependence over a wider range, MODTRAN simulations were run at 320, 300, 280, 270, 260 and 240 K; 30 and 70% RH using a mix of tropical, mid latitude summer/winter and sub-arctic winter atmospheric models. The total OLR fluxes in the 5 spectral regions were determined, as shown in the summary plot for Figure 17a. The fluxes from the 3 molecular bands were added together. The results are plotted in Figure 18a and 18b for 70 and 30% RH. Both sets of plots show a similar behavior. The blue line is the 3 molecular band sum. This stays almost flat. The orange line is the Window 2 emission. This increases from approximately 50 to 100 W m⁻² as the temperature increases from 240 to 320 K. The gray line is the Window 1 emission. This increases from approximately 50 to 200 W m⁻² as the temperature is increased from 240 to 320 K. The yellow line is the total OLR from 100 to 1500 cm⁻¹. This increases from approximately 150 to 350 W m⁻² as the temperature is increased from 240 to 320 K. The lines are straight line fits to the data using the Excel Trendline™ algorithm. The equation and the R² values are also shown. All of the R² values are above 0.9 and are above 0.97 for the total OLR. This indicates a good straight line fit.

Figure 19 shows compares the Win1+Win2 OLR flux at 70 and 30 RH with the blackbody flux over the same spectral range (350 to 600 + 720 to 1400 cm⁻¹) and with the linear fit to OLR satellite data from Koll and Cronin (K&C) [2018]. The Win1+Win2 lines for 0.7 and 0.3 RH (blue and orange) almost overlap and have similar slopes and intercepts. The R² values are over 0.97. The slope of the K&C line (green) is similar to the other OLR lines, but is offset by approximately 90 W m⁻². This is because K&C used a wider spectral range from 1 to 3500 cm⁻¹. This incorporated more of the constant molecular band emission from the rotation and ν₁ H₂O bands. The blackbody emission over the window OLR spectral range is almost a straight line with R² = 0.98. The quadratic equation given in Figure 19 gives an exact fit with R² = 1. The difference in slope between the OLR lines and the blackbody emission is caused by the increase in H₂O absorption with temperature. This is produced by a combination of increase in vapor pressure and change in the ground state Boltzmann population.
Figure A18: Band sum and transmission window contributions to the OLR, 240 to 320 K, MODTRAN calculations, 100 to 1500 cm⁻¹, 2 cm⁻¹ resolution, 70 km altitude looking down.
Molecular line narrowing with altitude decouples the upward and downward LWIR fluxes. This is illustrated above in Figures A11 and A13 through A16. Almost all of the downward LWIR flux reaching the surface originates from within the first 2 km layer of the troposphere as illustrated in Figure A20 (and Fig. 8b above) [Clark, 2013a]. This establishes an exchange energy with the surface LWIR emission that limits the net LWIR cooling. Within the molecular band region, the downward LWIR flux is that of a blackbody near the surface air temperature. In order to dissipate the absorbed solar flux, the surface must warm up. Over land, the surface temperature increases until the excess solar flux is dissipated by moist convection. Over the oceans, the excess solar heat is dissipated by wind driven evaporation. The exchange energies for 70 and 30% RH and the blackbody flux over the 240 to 320 K range are shown in Figure A21.
Figure A20: Cumulative downward flux fraction vs. altitude. Over 90% of the downward LWIR flux reaching the surface originated from within the first 2 km layer of the troposphere.

Figure A21: Downward flux (exchange energy) and blackbody emission 240 to 320 K. MODTRAN calculations, 100 to 1500 cm$^{-1}$, 2 cm$^{-1}$ resolution, 0 km looking up.