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# A REVIEW OF HANSEN et al, 1993
# "HOW SENSITIVE IS THE WORLD'S CLIMATE?"


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## Summary

The 1993 paper by Hansen et al "*How sensitive is the earth's climate?*" National Geographic Research and Exploration (1993) **9**(2) pp. 142-158 (H93) provides a convenient description of the status of climate modeling 5 years after the United Nations Intergovernmental Panel on Climate Change (IPCC) was formed. It contains the same pseudoscientific nonsense about radiative forcings, feedbacks and a climate sensitivity to $CO_2$ that is contained in the 2021 IPCC climate assessment. Little has changed since this paper was published in 1993, except that the computer technology has improved significantly and the climate models have become larger and more complex. The short answer to the title of H93 is that any climate sensitivity to $CO_2$ is 'too small to measure'.

## Introduction

Speculation that changes in the atmospheric concentration of $CO_2$ could cycle the earth's climate through an Ice Age started with the work of Tyndall in the early 1860s [Tyndall, 1861; 1863]. Unfortunately, the climate energy transfer processes that determine the surface temperature were oversimplified using the equilibrium climate assumption. The time dependence was removed and replaced by average values. This approach was used by Arrhenius in 1896 in his calculations of $CO_2$ induced changes in the temperature of the earth. His 'climate' was reduced to a static air column and a 15 °C blackbody surface that were illuminated by an average solar flux. Moist convection and subsurface transport were ignored, so were ocean energy transfer and the ocean to land surface temperature coupling [Clark and Rörsch, 2022]. When the $CO_2$ concentration was changed, this approach had to create climate warming, by definition, as a mathematical artifact of the assumptions used in the calculation [Arrhenius, 1896]. Gradually, the idea that an increase in $CO_2$ concentration could warm the earth became accepted scientific dogma and the focus shifted from the cause of an Ice Age to concern over fossil fuel combustion. When the first computer models were developed in the 1960s, they also relied on the equilibrium assumption and created climate warming by definition as a mathematical artifact of the simplifying assumptions used in the model. The work of Manabe and Wetherald [1967; 1975] and Hansen et al [1981] provided the foundation for the pseudoscience of radiative forcings, feedbacks and climate sensitivity that are still used in the climate models today [IPCC, 2021]. This is discussed in more detail in the post '*Climate Pseudoscience*', VPCP 012. Here the 1993 paper by Hansen et al "*How Sensitive is the World's Climate?*" (H93) is reviewed, [Hansen et al, 1993]. Little has changed since this paper was published, except that the computer technology has improved significantly and the climate models have become larger and more complex.

Hansen et al started from the *a-priori* assumption that the warming artifacts created by the equilibrium climate models were real and that the observed increase in atmospheric concentration of $CO_2$ and other greenhouse gases must be causing an increase in surface temperature. Their argument for this, using selected quotes from page 143 of H93is as follows:

> "The principal climate characteristic to be evaluated is the global climate sensitivity to a perturbing forcing such as a change in atmospheric composition."

> "Climate is always changing. Climate would fluctuate without any change in climate forcings. The chaotic aspect of climate is an innate characteristic of the coupled fundamental equations describing climate system dynamics. Chaotic climate change complicates interpretation of observations, but does not diminish the importance of changes of the mean climate resulting from external forcing."

> "A climate forcing is a change imposed on the planetary energy balance that alters the global temperature."

> "A climate forcing is measured by the change in the heating rate of the earth measured in Watts per square meter (W $m^{-2}$). For example, the increases in greenhouse gases $CO_2$, chlorofluorocarbons, $CH_4$ and $N_2O$ that have occurred since the Industrial Revolution began cause a heating of 2 W $m^{-2}$ by decreasing infrared radiation to space."

> "Climate sensitivity refers to the mean change of climate conditions that occur in response to a specific forcing of global climate. Although many climate parameters - temperature, precipitation and winds for example - change in response to climate forcing, the common measure of climate sensitivity is the change of global mean temperature and the standard forcing is doubling of atmospheric $CO_2$."

This description of 'forcings, feedbacks and sensitivity' raises some important questions about the relationship between global averages and the physics of climate energy transfer.

**What is the physical interpretation of a 'global temperature'?**

In H93, 'climate change' has been reduced to a single parameter, the change in the 'global average temperature'. This is a mathematical construct with no physical meaning. [Essex et al, 2007]. It is an area weighted average of the 'surface air temperature' with the means subtracted to produce a 'temperature anomaly'. In order to create the global average, the raw temperature data has been 'adjusted' through a process of 'homogenization' to eliminate 'bias effects'. Approximately half of the warming in the global record has been created by these 'adjustments'.

Any realistic discussion of climate requires careful consideration of the climate zones defined for example using the Köppen or similar classifications. This includes temperature and rainfall and their seasonal variations. Temperature is an intensive property. The related extensive property is heat content or enthalpy. The average temperature based on measurements from different weather stations is just a number. The minimum daily surface (or 'skin') temperature is a measure of the heat content or enthalpy of the local surface thermal reservoir. The change in surface temperature from minimum to maximum is a measure of the solar insolation absorbed as heat by the surface reservoir. The weather station temperature is the meteorological surface air temperature (MSAT) measured in a ventilated enclosure located at eye level 1.5 to 2 m above the ground. Generally, the minimum MSAT is similar to the minimum surface temperature. The maximum MSAT is lower than the maximum surface temperature. It is measure of the convective mixing of the warm air rising from the surface with the cooler air above at the level of the MSAT thermometer. The minimum and maximum MSAT temperatures are produced by different energy transfer processes. They should be analyzed separately as the minimum MSAT and the change in temperature ($T_{max}$ – $T_{min}$). Even the average daily temperature ($T_{max}$ + $T_{min}$)/2 has little physical meaning.

**What Are Climate Fluctuations?**

The term climate fluctuations used in H93 refers to the variations in an average global temperature that do not correlate with the change in radiative forcing. In 1963, Lorenz demonstrated that the solutions to three coupled non-linear equations used to describe a simple convective flow system were unstable [Lorenz, 1963]. The climate system is also unstable, but the instabilities are heavily damped by the large climate masses and heat capacities involved and by the available energy. There is no reason to expect that the mathematical instabilities in the coupled non-linear equations should have any predictive relationship to the measured climate instabilities.

The earth's surface is 71% ocean. There is no requirement for an exact flux balance between the solar heating of the ocean and the surface cooling. The dominant cooling term is the wind driven evaporation or latent heat flux. Natural variations in wind speed interact with the ocean gyre circulation to produce quasi-periodic variations in ocean surface temperature known as ocean oscillations. The four main ocean oscillations are the El Nino Southern Oscillation (ENSO), the Indian Ocean Dipole (IOD), the Atlantic Multi-decadal Oscillation (AMO) and the Pacific Dipole Oscillation (PDO) [AMO, 2022; ENSO. 2022; IOD, 2022; PDO, 2022]. These oscillations provide a natural 'noise floor' for the ocean surface temperatures. The changes in temperature are quite small, but the effects are large for two reasons. First the temperature change extends from the surface to depths that may easily reach 100 m. Because of the heat capacity of the water column involved, the amount of thermal energy stored and released during an oscillation is very large. For example the change in enthalpy associated with the 2016 EMSO peak was near 800 MJ $m^{-2}$ over a 6 month period. Second, these changes in enthalpy are caused in part by changes in latent heat flux. The change in wind speed for the 2016 ENSO peak was 2 m $s^{-1}$. This produced a change in latent heat flux of approximately 30 W $m^{-2}$ [Clark and Rörsch, 2022]. Such changes in evaporation have a major climate impact on rainfall patterns.

The dominant term in the global temperature anomaly is the AMO [AMO, 2022; HadCRUT4, 2022; Morice et al, 2012; Gray et al, 2004]. The correlation coefficient between the AMO and the HadCRUT4 temperature anomaly series is 0.8, (see the companion post '*Climate Pseudoscience*' VPCP 012.1). In addition to changes in surface temperature over the ocean region itself, the weather systems that form over the N. Atlantic Ocean and move overland couple the ocean surface temperature to the weather station data [Clark and Rörsch, 2022]. The IOD and PDO are dipoles that tend to cancel and the ENSO is limited to a relatively small area of the equatorial Pacific Ocean. The influence of each ocean oscillation extends over a specific region. The concepts of an average climate or an average oscillation 'noise' have no physical meaning.

## What Determines the Radiation Balance of the Earth?

The earth is an isolated planet that is heated by the absorbed solar flux and cooled by LWIR emission back to space. The First Law of Thermodynamics simply requires that any absorbed solar energy that is not returned to space remain somewhere in the climate system. There is no requirement for an exact short term planetary energy balance. The equatorial regions absorb more solar heat than the LWIR flux that they radiate back to space. The excess heat is transported to higher latitudes by the meridional circulation where the net LWIR flux at TOA exceeds the absorbed solar flux. The seasonal variations produced by the axial tilt of the earth shift the band of peak solar flux north and south of the equator by 23.5°. The eccentricity of the earth's orbit changes the incident solar flux at TOA by approximately ±45 W $m^{-2}$. The peak flux at perihelion occurs in early January, near summer solstice in the S. Hemisphere. The absorbed solar flux is stored as heat and as gravitational potential energy in the climate energy storage reservoirs and returned to space as LWIR emission over a wide range of time scales.

The ocean oscillations, particularly the ENSO also change the LWIR flux returned to space [Dewitte and Clerbaux, 2017]. The ENSO is caused by changes in wind speed that are related to the Southern Oscillation Index, (SOI). The LWIR emission to space from the atmospheric absorption/emission bands is decoupled from the downward LWIR emission to the surface by molecular line broadening effects. The IR radiation field in the troposphere is coupled to the convective mass transport. The troposphere functions as an open cycle heat engine that transports part of the absorbed solar heat from the surface to the middle troposphere. The thermal and humidity gradients at the surface adjust as the rate of solar heating changes. Ocean temperatures are determined by balance between the rate of heating of the oceans by the absorbed solar flux and the rate of surface cooling. This is dominated by the wind driven evaporation coupled to the ocean gyre circulation system. The oceans have been warming since the end of the Maunder minimum or Little Ice Age [Akasofu, 2010]. This is the source of the 'radiation imbalance' incorrectly attributed to increases in the atmospheric concentration of greenhouse gases, particularly $CO_2$. The radiation balance is discussed in more detail in the companion post '*The Radiation Balance of the Earth*' VPCP 015.

## There Is No 'Greenhouse Effect Temperature'

H93 pp. 143-144 states:

> "The earth absorbs ~240 W $m^{-2}$ of solar energy, which heats the planet so that it radiates, on average, that amount of thermal energy back to space. The effective radiating temperature requires to yield this outgoing flux is 255 K."

> "Thus the mean surface temperature is 33 °C warmer than it would be if the atmosphere were transparent. This 33 C warming is the present greenhouse effect on earth."

Simple conservation of energy arguments for a sphere with an albedo of 0.3 illuminated by a collimated disk of solar radiation give a planetary average outgoing longwave radiation (OLR) near 240 W $m^{-2}$. This is simply an average cooling flux. It is the cumulative net upward emission from many different levels in the atmosphere. The emission from each level is modified by the absorption and emission of the layers above. The spectral distribution of the LWIR flux at TOA is not that of a blackbody emitter. This was demonstrated by Nimbus 4 satellite observations in 1970 [Hanel et al, 1971]. The average OLR at TOA should not be used to define an 'effective emission temperature' of 255 K. Nor should this be combined with an 'average surface temperature' of 288 K to give a 'greenhouse effect temperature of 33 K. Satellite observations give a 10 year average range of 100 to 300 W $m^{-2}$ [Dewitte and Clerbaux, 2018]. This corresponds to a range of 'effective emission temperatures' from 207 to 273 K (-65 to 0 °C).

**Radiative Forcing by Greenhouse Gases Does Not Change the Energy Balance of the Earth**

Since the start of the Industrial Revolution, about 200 years ago, the atmospheric concentration of $CO_2$ has increased by approximately 140 parts per million (ppm), from 280 to 420 ppm [Keeling, 2022]. This has produced a decrease near 2 W $m^{-2}$ in the longwave IR (LWIR) flux emitted to space within the spectral region of the $CO_2$ emission bands. There has also been a similar increase in the downward LWIR flux from the lower troposphere to the surface [Harde, 2017]. At present, the annual average increase in $CO_2$ concentration is about 2.4 ppm. This produces an average annual increase in the downward LWIR flux to the surface of approximately 0.034 W $m^{-2}$.

The basic assumption of radiative forcing is that the decrease in LWIR flux at TOA produced by an increase in atmospheric greenhouse gas concentration changes the energy balance of the earth. The surface temperature then increases to restore the LWIR flux at TOA. Radiative transfer calculations that show the initial decrease in LWIR flux is correct. However, this is only part of the story. It is also necessary to determine the heating effect that is produced at lower levels in the atmosphere.

An increase in the atmospheric $CO_2$ concentration initially produces a decrease in the outgoing long wave IR (LWIR) radiation or OLR at the top of the atmosphere (TOA). However, this decrease occurs only in the spectral regions of the $CO_2$ band emission, specifically the P and R branches of the $\nu_2$ band near 640 and 700 $cm^{-1}$. There is also some weaker emission by the $CO_2$ overtone bands near 950 and 1050 $cm^{-1}$. [Wijngaarden and Happer 2022]. Furthermore, this decrease or forcing does not magically appear at TOA. It is produced by small changes in the net upward LWIR emission at many different levels in the atmosphere. The emission from each level is also modified by absorption and emission of the layers above. In order to evaluate the atmospheric heating effects from a $CO_2$ doubling' it is necessary to convert the local changes in net LWIR flux to changes in the rates of cooling. The total rate of tropospheric cooling by the LWIR flux at low and mid latitudes is near -2 K per day. [Feldman et al, 2008; Lacis, and Oinas, 1991]. The maximum change in the tropospheric rate of cooling for a doubling of the $CO_2$ concentration is +0.08 K per day [Iacono et al, 2008]. This slight warming is dissipated by a combination of wideband LWIR emission, mainly by the water bands and by minor shifts in altitude that change the gravitational potential of the local air parcel. Any temperature changes are too small to measure. For a lapse rate of -6.5 K $km^{-1}$, an increase in temperature of +0.08 K is produced by a decrease in altitude of approximately 12 meters. This is equivalent to riding an elevator down four floors. The radiative forcing produced by an increase in greenhouse gas concentration does not change the energy balance of the earth.

## Climate Feedbacks

H93 p. 144 states:

> “Climate feedbacks are internal reactions of the climate system to (natural or anthropogenic) climate change. Positive feedbacks amplify the climate change, negative feedbacks diminish it.”

In addition to the wavelength specific decrease in LWIR flux at TOA, an increase in atmospheric greenhouse gas concentration also produces a similar increase in the downward LWIR flux from the lower troposphere to the surface. In order to evaluate the effect of this increase in LWIR flux on the surface temperature it is necessary to consider the surface energy transfer in more detail. In addition, it is necessary to include the effect of molecular line broadening on the downward LWIR flux. This is discussed in more detail in the companion post ‘*Climate Pseudoscience*’, VPCP 012.

Because of molecular linewidth effects, the upward and downward LIWR fluxes are decoupled from each other. Almost all of the downward LIWR flux from the lower troposphere to the surface is emitted from within the first 2 km air layer above the surface and approximately half is emitted from within the first 100 m layer. . The downward LWIR flux from the lower troposphere to the surface establishes an LWIR exchange energy with the upward LWIR flux from the surface. The net LWIR cooling flux is limited to the emission into the LWIR atmospheric transmission window. In order to dissipate the absorbed solar flux, the surface warms up so that the excess heat is removed by moist convection (evapotranspiration). The ocean-air and land-air interfaces have different energy transfer properties and have to be analyzed separately.

The surface temperature is determined by the interactive coupling of four main flux terms to the surface thermal reservoir. These are the net absorbed solar flux, the net LWIR cooling flux, the moist convection or evapotranspiration and the subsurface thermal transport. (Rainfall and freeze/thaw effects are not considered here). A change in temperature is determined from the change in heat content or enthalpy of the thermal reservoir divided by the heat capacity. The change in surface temperature produced by the LWIR radiative forcing from a greenhouse gas has to be determined by adding the change in LWIR flux to the rest of the flux terms and calculating the change in temperature over one or more diurnal cycles.

Over the oceans, the penetration depth of the LWIR flux into the surface is 100 micron or less. Here, any small increase in LWIR flux is fully coupled to the much larger and more variable wind driven evaporation or latent heat flux. Using long term zonal averages, the change in LWIR flux with wind speed over the ±30° latitude bands is at least 15 W $m^{-2}$/m $s^{-1}$. The entire increase in radiative forcing of 2 W $m^{-2}$ produced by the observed 140 ppm increase in the atmospheric concentration of $CO_2$ is dissipated by an increase in wind speed of 13 cm $s^{-1}$. Over land, the minimum surface temperature is reset each day by the change in the diurnal convective transition temperature produced by the local weather system passing through. This means that the change in surface temperature produced by a radiative forcing of 2 W $m^{-2}$ is too small to measure.

Similarly, the average annual increase in radiative forcing of 0.034 W $m^{-2}$ cannot produce any measurable change in surface temperature. This also means that the observed increase in $CO_2$ concentration cannot produce an increase in 'extreme weather events'.

There are no feedbacks that can be produced from an LWIR forcing by a greenhouse gas when the surface temperature change is too small to measure.

## Paleoclimate

H93 pp. 145-147

> "The best empirical information on equilibrium climate sensitivity is provided by climate variations of the past 200,000 years."
>
> "Despite the similarity of the $CO_2$ and temperature curves [in the paleoclimate record], it should not be inferred that the $CO_2$ "caused" the climate change. Indeed the $CO_2$ changes generally lag slightly behind the temperature changes."
>
> "The major instigator of these long term climate changes is usually assumed to be periodic changes in the earth's orbit (for example eccentricity and axial tilt) which alter the seasonal and geographic distribution of the sunlight on earth."
>
> "We take 5 °C as the best estimate of Ice Age cooling which implies a climate sensitivity of 3 °C for doubled $CO_2$ forcing."

As discussed above, a change in LWIR radiative forcing does not change the energy balance of the earth. There can be no 'equilibrium climate sensitivity' to $CO_2$. The Ice Ages are caused by subtle changes in the distribution of the solar flux over the surface of the earth related to Milankovitch cycles. There is almost no change in the total solar insolation reaching the earth. The temperatures change first and the $CO_2$ concentration follows.

## The Industrial Era

> "Present levels of homogenously mixed greenhouse gases cause a forcing of 2.1 ±0.3 W m-2."
>
> "We carried out a series of simulations with the Wonderland model adding climate forcings one by one and making simulations for 3 climate sensitivities."

> "The results show that the more plausible climate forcing scenarios yield a net warming over the period of record reasonably consistent with the observations for climate sensitivities in the range 1.5 to 4 °C for doubled $CO_2$."

A set of contrived radiative forcings has been used to create a temperature series that is similar to the observed one. The dominant term in the observed temperature series is the AMO. The LWIR forcings from greenhouse gases cannot cause a measurable change in the temperature record. There can be no climate sensitivity to $CO_2$.

## Conclusions

In H93, the authors have demonstrated that they have no understanding of climate energy transfer. They have chosen to believe that the simplistic equilibrium climate assumptions introduced by Manabe and Wetherald in 1967 and by Hansen's group in 1981 can be used to determine a fictional average surface temperature of the earth. Physical reality has been abandoned in favor of mathematical simplicity. The description of climate energy transfer in terms of forcings, feedbacks and climate sensitivity is pseudoscientific nonsense. The authors are just playing computer games in an equilibrium climate fantasy land. The name 'Wonderland' for their climate model is entirely appropriate. Sadly, nothing has changed and the same forcings, feedbacks and climate sensitivities are used by the climate models today.

## References

Akasofu, S.-I. (2010), "On the recovery from the Little Ice Age" *Natural Science* **2**(11) pp. 1211-1224. [http://dx.doi.org/10.4236/ns.2010.211149]

AMO (2022), [https://www.esrl.noaa.gov/psd/data/correlation/amon.us.long.mean.data]

Clark, R. and A, Rörsch (2022), *Finding simplicity in a complex world*, Amazon (In Press).

Dewitte, S. and N. Clerbaux (2018), "Decadal Changes of Earth's Outgoing Longwave Radiation" *Remote Sens.* **10**(10) 1539 pp. 1-7. [https://doi.org/10.3390/rs10101539]

Dewitte, S. and N. Clerbaux (2017), "Measurement of the Earth Radiation Budget at the Top of the Atmosphere - A Review" Remote Sensing **9**(11) 1143 pp, 1-13. [https://doi.org/10.3390/rs9111143]

ENSO (2022), [https://psl.noaa.gov/gcos_wgsp/Timeseries/Data/nino34.long.data]

Essex, C.; R. McKitrick & B. Andresen, (2007), "Does a global temperature exist?" J. Non-Equilibrium Thermodynamics, 32(1) pp 1-27. [https://doi.org/10.1515/JNETDY.2007.001]

Available at [https://www.fys.ku.dk/~andresen/BAhome/ownpapers/globalTexist.pdf]

Feldman D.R., K. N. Liou, R. L. Shia and Y. L. Yung (2008), "On the information content of the thermal IR cooling rate profile from satellite instrument measurements" *J. Geophys. Res.* **113** D1118 pp. 1-14. [https://doi.org/10.1029/2007JD009041]

Gray, S. T.; L. J. Graumlich, J. L. Betancourt and G. T. Pederson (2004) "A tree-ring based reconstruction of the Atlantic Multi-decadal Oscillation since 1567 A.D." *Geophys. Res. Letts*, **31** L12205, pp. 1-4. [https://doi.org/10.1029/2004GL019932]

HadCRUT4 (2022), [https://www.metoffice.gov.uk/hadobs/hadcrut4/data/current/time_series/HadCRUT.4.6.0.0.annual_ns_avg.txt]

Hanel, R. A.; B. Schlachman, D. Rogers and D. Vanous (1971), "Nimbus 4 Michelson Interferometer" *Applied Optics* **10**(6) 1376-1382 [https://doi.org/10.1364/AO.10.001376]

Harde, H. (2017), "Radiation Transfer Calculations and Assessment of Global Warming by $CO_2$" *Int. J. Atmos. Sci.* 9251034 pp. 1-30. [https://doi.org/10.1155/2017/9251034]

Hansen, J.; A. Lacis, R. Ruedy M. Sato and H. Wilson (1993), "How sensitive is the world's climate?" *National Geographic Research and Exploration* **9**(2) pp. 142-158. [https://pubs.giss.nasa.gov/docs/1993/1993_Hansen_ha02800o.pdf]

Iacono, M. J., J. S. Delamere, E. J. Mlawer, M. W. Shephard, S. A. Clough, and W. D. Collins (2008), "Radiative forcing by long-lived greenhouse gases: Calculations with the AER radiative transfer models" *J. Geophys. Res.* **113**, D13103 pp. 1-8. [https://doi.org/10.1029/2008JD009944]

IOD (2022), [https://psl.noaa.gov/gcos_wgsp/Timeseries/Data/dmi.had.long.data]

IPCC, *Climate Change 2021: The Physical Science Basis*. *Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* [Masson-Delmotte, V.; P. Zhai, A. Pirani, S.L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M.I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J.B.R. Matthews, T.K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, and B. Zhou (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA. (2021). In Press. [doi:10.1017/9781009157896, https://www.ipcc.ch/report/ar6/wg1/]

Keeling (2022), *The Keeling Curve*. [https://scripps.ucsd.edu/programs/keelingcurve/]

Lacis, A. A. and V. Oinas (1991), "A description of the correlated k distributing method for modeling nongray gaseous absorption, thermal emission and multiple scattering in vertically inhomogeneous atmospheres" *J. Geophys. Res.* **96**(D5) pp. 9027-9063. [https://doi.org/10.1029/90JD01945]

Lorenz, E.N. (1963), "Deterministic nonperiodic flow" Journal of the Atmospheric Sciences **20**(2) pp. 130-141. [https://doi.org/10.1175/1520-0469(1963)020<0130:DNF>2.0.CO;2]

Manabe, S. and R. T. Wetherald (1975), "The effects of doubling the $CO_2$ concentration in the climate of a general circulation model" *J. Atmos. Sci.* **32**(1) pp. 3-15. [https://journals.ametsoc.org/view/journals/atsc/32/1/1520-0469_1975_032_0003_teodtc_2_0_co_2.xml?tab_body=pdf]

Manabe, S. and R. T. Wetherald (1967), "Thermal equilibrium of the atmosphere with a given distribution of relative humidity" *J. Atmos. Sci.* **24** pp. 241-249. [http://www.gfdl.noaa.gov/bibliography/related_files/sm6701.pdf]

Morice, C. P.; J. J. Kennedy, N. A. Rayner and P. D. Jones (2012), "Quantifying uncertainties in global and regional temperature change using an ensemble of observational estimates: The

HadCRUT4 data set" *J. Geophysical Res. Atmospheres* **117** D08101 pp. 1-22. [https://doi.org/10.1029/2011JD017187]

PDO (2022), [https://www.ncdc.noaa.gov/teleconnections/pdo/]

Tyndall, J. (1861), "On the Absorption and Radiation of Heat by Gases and Vapours, and on the Physical Connexion of Radiation, Absorption, and Conduction" *Philosophical Transactions of the Royal Society of London*, **151** pp. 1-36. [https://doi.org/10.1098/rstl.1861.0001]

Tyndall, J. (Jan 23, 1863), "On radiation through the Earth's atmosphere" *Proc. Roy. Inst.* pp 200-206.

Wijngaarden, W. A. van and W. Happer (2022), "IR Forcing by Greenhouse Gases" $CO_2$ Coalition publication 6/10/22, [https://co2coalition.org/wp-content/uploads/2022/03/Infrared-Forcing-by-Greenhouse-Gases-2019-Revised-3-7-2022.pdf]