Total Precipitable Water and the Greenhouse Effect

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Revised[1]

Summary

Total precipitable water is an important climate parameter as it is a measure of the total amount of water vapour in the atmosphere, which is the most important greenhouse gas. Water vapour increases with global warming and in the climate models it amplifies the direct small warming caused by anthropogenic greenhouse gas emissions. It is often incorrectly assumed that an increase in total precipitable water corresponds to a positive water vapour feedback. The greenhouse effect is much more sensitive to water vapour in the upper atmosphere than near the surface. This article shows that, based on humidity data from a major reanalysis dataset, declining humidity in the upper atmosphere fully offsets the greenhouse effect of increasing humidity in the lower atmosphere. The greenhouse effect of increasing water vapour in the atmosphere may not have caused a positive water vapour feedback, contrary to climate models. This may explain why the climate models have simulated a global lower troposphere warming from 1979 to 2019 of over twice the satellite observed warming. Eliminating the water vapour and lapse rate feedbacks, both of which are caused by increasing water vapour, from climate models would reduce the multi-model mean equilibrium climate sensitivity[2] from 3.2 °C to 1.7°C and would reduce the social cost of carbon dioxide calculated by the FUND economic model, with two updates, from ${}_{2018}$US\$-1.79/tCO_2 to ${}_{2018}$US\$-7.14/tCO_2 at 3% discount rate. The negative signs indicate that climate change is beneficial.

Water vapour is the most important greenhouse gas. A 1% change in the amount of water vapour has 5.4 times the effect on outgoing longwave radiation (OLR) as a 1% change in amount of CO_2 in the atmosphere. The quantity of water vapour varies greatly over time, by altitude and geographical location. The total precipitable water (TPW) at a given location is the depth of liquid water that would result from precipitating all of the water vapour in a vertical column of unit area from the surface to the top of the atmosphere. It is usually expressed in mm of liquid water depth. Precipitable water (PW) can be defined as the depth of water precipitated from an air column between specific atmospheric pressure levels.

Water vapour causes an important positive feedback in climate models, with a value more than 5 times that of the surface albedo feedback. Warming initiated by greenhouse gas emission causes an increase in the amount of water vapour in the atmosphere that amplifies the initial warming. As the TPW is a measure of the total amount of water vapour in the atmosphere, is it often assumed that an increase in TPW corresponds to a positive water vapour feedback. This means that an initial temperature rise caused by an increase in anthropogenic greenhouse gases, which is mainly carbon dioxide (CO_2) in the atmosphere causes an increase in amount of water vapour which results in a further increase in temperature, thereby amplifying the initial temperature increase. The troposphere[3] is the layer from the surface up to where temperatures cease to decrease with altitude. It contains 99% of the water vapour in the atmosphere. The amount of water vapour declines dramatically with altitude, so it is often assumed that upper troposphere water vapour trends are of little importance. However the greenhouse effect of a change in the amount water vapour increases dramatically with altitude. If the trend of upper troposphere water vapour is different from the trend near the surface, the TPW would not correspond to a positive water vapour feedback.

The effect on OLR of a 0.3 mm change in precipitable water vapour at various pressure levels in the atmosphere was evaluated by Dr. Ferenc Miskolczi using the line-by-line radiative transfer code HARTCODE.[4] The results of these calculations are shown in Figure 1.

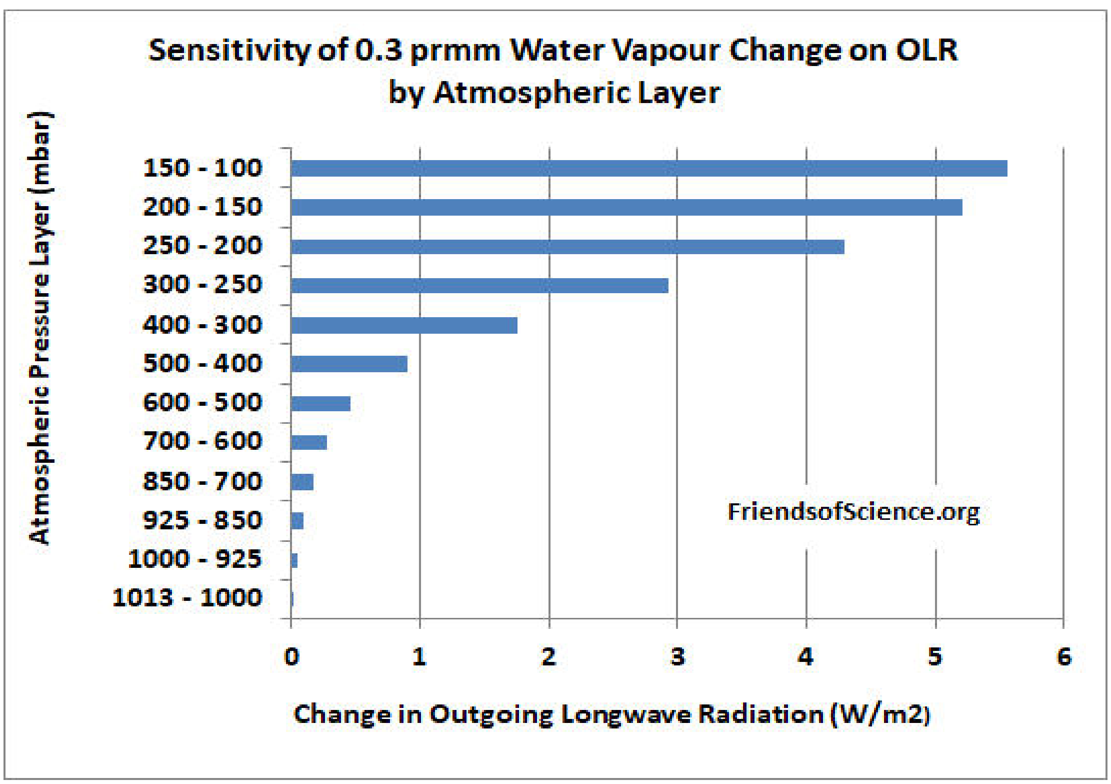

Figure 1. Sensitivity of water vapour change on OLR by layer.

Figure 1 shows that adding 0.3 mm of water in the 150 to 100 mbar layer would reduce the OLR by 5.56 W/m^2, and adding 0.3 mm of water in the 1013 to 1000 mbar layer would reduce the OLR by only 0.020 W/m^2. A 0.3 mm change of PW in the layer 150 to 100 mbar pressure layer has 280 times the greenhouse effect as the same change in the 1013 to 1000 mbar near-surface layer.

Relative humidity (RH) is the percent fraction of water vapour in a parcel of air compared to its saturated value. In general, climate models project that the RH in the atmosphere remains approximately constant with global warming, even in the upper troposphere. This makes sense in the lower atmosphere because air immediately above the ocean surface and in clouds are at (or very near) 100% RH, or fully saturated, as the water vapour is in equilibrium with the liquid water. However, RH in the upper troposphere is much lower than near the surface and is little constrained by the saturation limit. Weather and precipitation processes in the upper troposphere can cause a drying of the air. A map of RH at the 850 mbar level is shown in Figure 2.

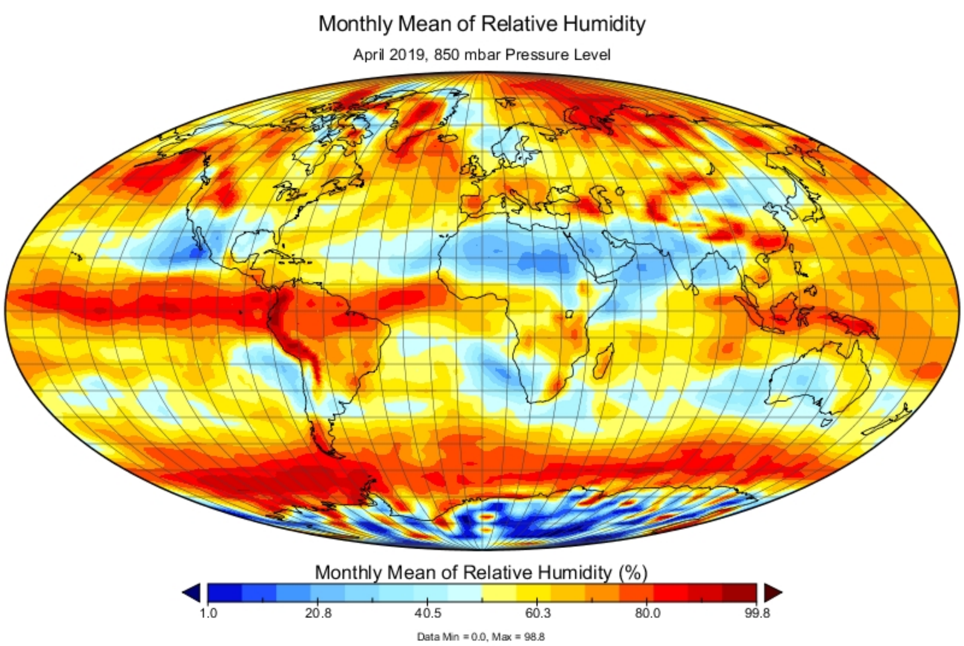

Figure 2. Relative humidity in April 2019 at 850 mbar pressure level.

The amount of water vapour in air is commonly characterized by the specific humidity (SH), which is the mass of water per a unit mass of moist air. An increase in temperature with constant RH causes an increase in SH because warm air can hold more water vapour than cool air.

We use the NCEP (National Center for Environmental Predictions) reanalysis 1 dataset here to evaluate the precipitable water vapour trends by pressure level, and evaluate the greenhouse effect of those trends. The lowest pressure level that includes relative and specific humidity is 300 mbars, so we use the ERA5 dataset accessed via Climate Explorer here for those quantities at the 200 mbar pressure level.[5]

The NCEP reanalysis 1 dataset presents data from 1948 to the present, but concerns have been raised that the humidity values, largely based on radiosonde measurements, may be unreliable in the early decades. Therefore, we will use trends from 1970. The reanalysis presents RH, SH and temperature at various pressure levels.

Figure 3 shows the global average RH data of pressure levels 300 to 700 mbars [10 mbars = 1 kPa].

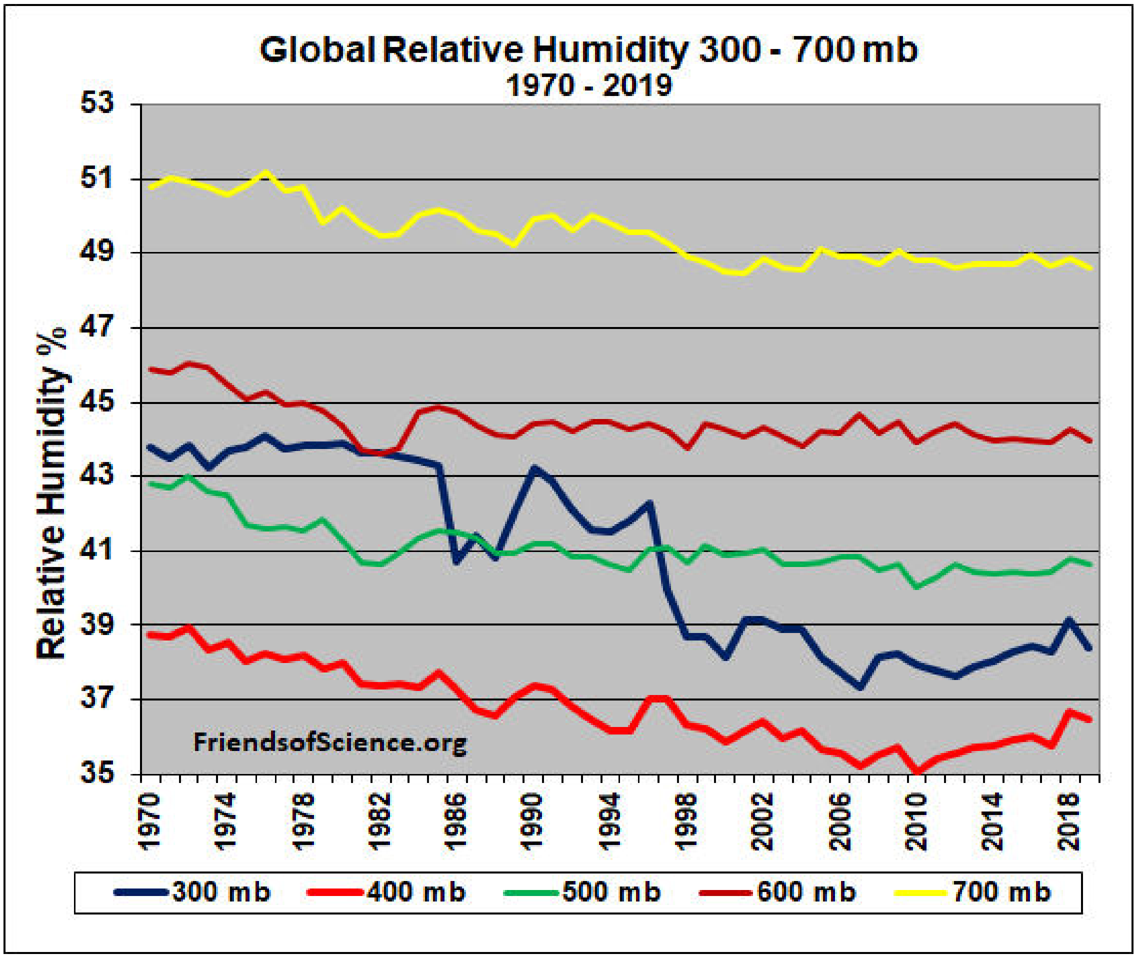

Figure 3. Global relative humidity in the upper atmosphere has generally been declining since 1970, but the there has been a recent increase since 2010 at the 300 and 400 mbar levels.

Specific humidity is unsuitable as a direct measure of the quantity of water vapour because water is in the numerator and the denominator of its definition: the mass of water per mass of moist air. The absolute humidity (AH) is the mass of water per a unit volume of air. The AH must be used to determine the PW in an atmospheric layer. AH is calculated my multiplying the SH by the density of moist air. The density of moist air for each layer is calculated by the ideal gas law.[6]

The trends of the SH and AH are shown in Table 1 and a graph of AH is shown as Figure 4.

Specific Humidity (SH) and Absolute Humidity (AH) Trends over 1970 to 2019									
mbar	200	300	400	500	600	700	850	925	1000
SH mg/kg/decade	0.57	-5.24	-6.15	-0.56	13.75	15.57	28.00	74.74	91.47
AH mg/m3/decade	-0.19	-2.46	-3.72	-0.94	9.57	11.53	23.38	77.91	101.89

Table 1. Trends of specific humidity and absolute humidity.

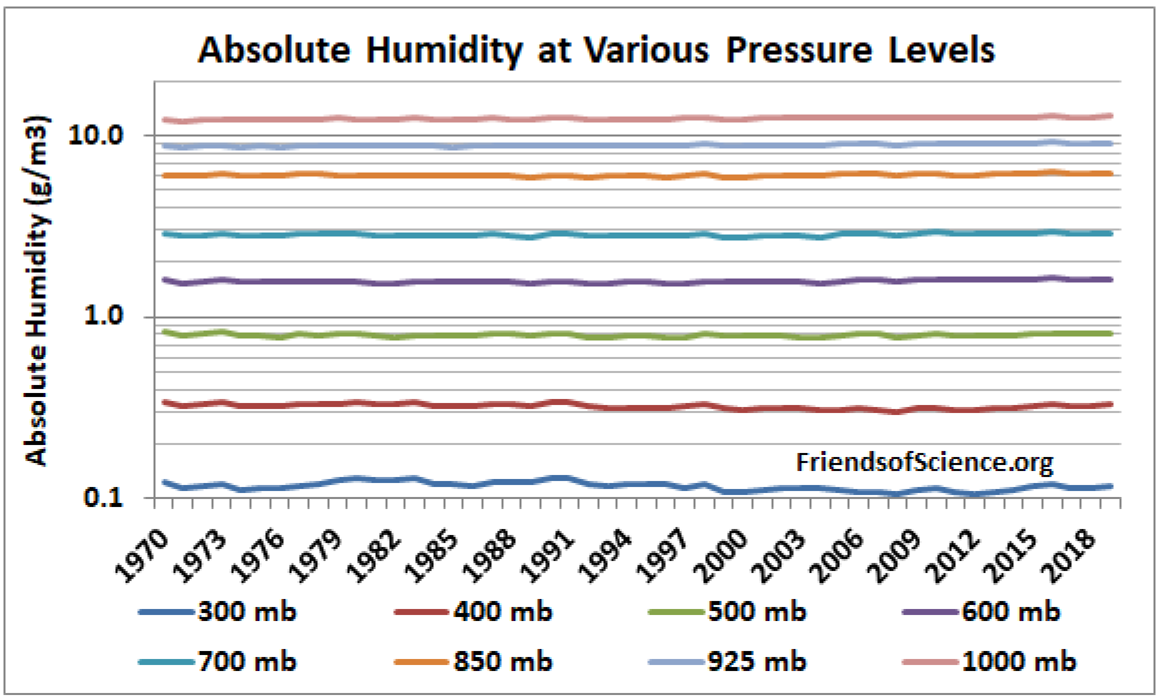

Figure 4. Absolute humidity at pressure levels 300 mbar to 1000 mbar, 1970 to 2019, calculated from NCEP Reanalysis 1. The data is presented on a logarithmic scale.

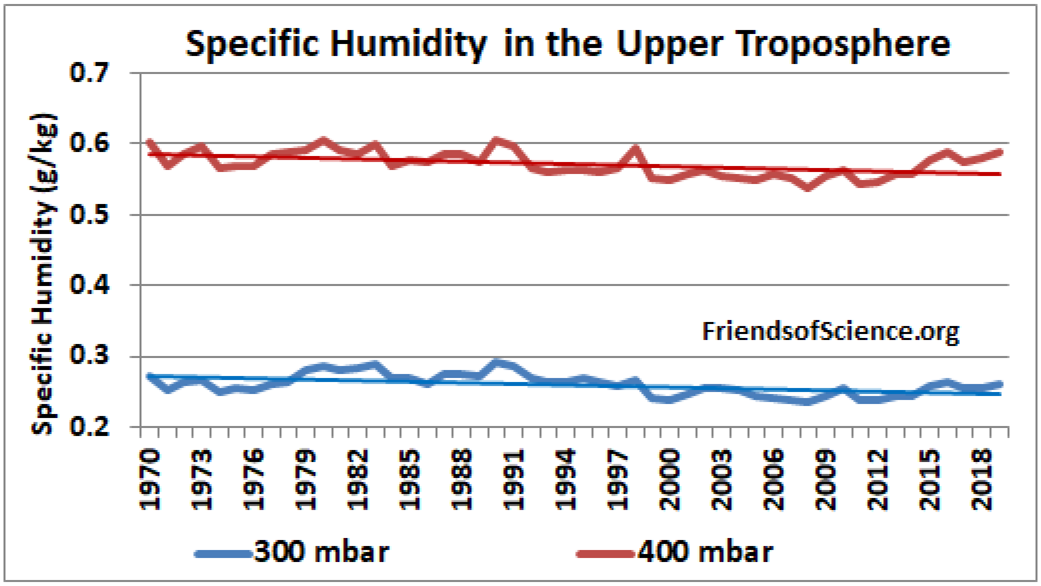

Figure 5. Specific humidity in the upper troposphere from NCEP Reanalysis 1 at the 300 and 400 mbar pressure levels. The trends at both pressure levels from 1970 to 2019 are downward.

The trends of the absolute humidity were calculated at each pressure level, and the trends of absolute humidity of each layer are assumed to be the average of the trends at the top and bottom of each layer. The absolute humidity trends in mg/m^2/decade of each layer over 1970 to 2019 are shown in Table 2.

Absolute Humidity Trends over 1970 to 2019									
mbar	200-300	300-400	400-500	500-600	600-700	700-850	850-925	925-1000	1000-1013
g/m^2/decade	-3.46	-6.28	-3.86	6.06	12.91	27.66	35.68	59.23	11.20

Table 2. Absolute humidity trends in the top three layers are negative and the trends are positive in the other layers.

Table 3 shows the sensitivity of OLR to water vapour changes of the nine atmospheric layers relative to the lowest layer, the layer thicknesses, the water vapour mass and mass fraction averaged over 2014-2019, the OLR effect fraction and the humidity trends by layer.

Layer	Rel. OLR Sensitivity to Water Vapour	Layer Thickness	Mass of Water Vapour Ave. 2014-2019	Mass Water Vapour Fraction 2014-2019	OLR Effect Fraction	Trend 1970-2019
mbar		m	g/m^2	%	%	g/m^2/decade
1013 - 1000	1.00	110	1405	5.2%	0.47%	11.2
1000 - 925	2.57	659	7220	26.5%	6.18%	59.2
925 - 850	4.72	705	5399	19.8%	8.50%	35.7
850 - 700	8.76	1584	7214	26.5%	21.09%	27.7
700 - 600	13.89	1223	2770	10.2%	12.83%	12.9
600 - 500	23.46	1405	1697	6.2%	13.28%	6.1
500 - 400	46.0	1657	932	3.4%	14.30%	-3.9
400 - 300	89.4	2032	446	1.6%	13.30%	-6.3
300 - 200	184.4	2694	164	0.60%	10.06%	-3.5
Total		12069	27246	100.0%	100.0%	

Table 3. Outgoing longwave radiation (OLR) relative sensitivity, water vapour by mass and mass fraction percent, OLR effect fraction and humidity trends by layer.

The second column of table 3 indicates that a change of water vapour in the 300 to 200 mbar layer has 184 times the effect on OLR as the same change in the near-surface layer. The OLR effect fraction (6th column) is the relative OLR sensitivity (2nd column) times the water vapour mass (4th column) of each layer expressed as a percentage of the sum of the products of those two columns of all the layers. We set the OLR sensitivity to the 1013-1000 mbar layer to 1.00, corresponding to a 0.020 W/m^2 change in OLR due to a 0.3 mm change of PW in the layer. The table shows that the bottom 1013-1000 mbar layer contains 5.2% of the water vapour mass (in the period 2014-2019), but a 1% water vapour change there has only 0.47% of the OLR effect of a 1% change in all layers. The upper troposphere 300-200 mbar layer (about 9.4 to 12.1 km altitude) contains only 0.60% of the total water vapour mass, but a 1% water vapour change there has 10.06% of the OLR effect as a 1% change in all layers. Accordingly, percentage changes of water vapour in the 300 – 200 mbar layer cause over 21 times the greenhouse effect of percentage changes of water vapour in the 1013-100 mbar layer. A percentage change of water vapour in a 100 m thick layer at 11 km altitude causes 79% of the greenhouse effects of a percentage change of water vapour in a 100 m thick layer at the surface despite the absolute humidity near the surface being 211 times that at 11 km altitude. The last column of table 3 shows the trends of absolute humidity by layer. The trends are negative in the three lowest-pressure, highest-altitude layers.

Precipitable water is calculated for each year in each layer between the pressure levels, estimated to be the average of the absolute humidity at the top and bottom of each layer times the layer thickness.[7] The TPW is the sum of the water mass per unit area of each layer from 200 mbar to 1013 mbar. The global average TPW 2014 to 2019 is 27.2 mm of liquid water depth.

The TPW trend from 1970 to 2019 is 0.139 mm/decade. That tells us almost nothing about the greenhouse effect of increasing water vapour because the effect of a change in the amount of water vapour in the upper atmosphere is much greater than a same change in a near surface layer. We calculate an Effective PW which is the sum of the PW weighted by the sensitivity of OLR to water vapour in each layer each year. The result is shown in Figure 6.

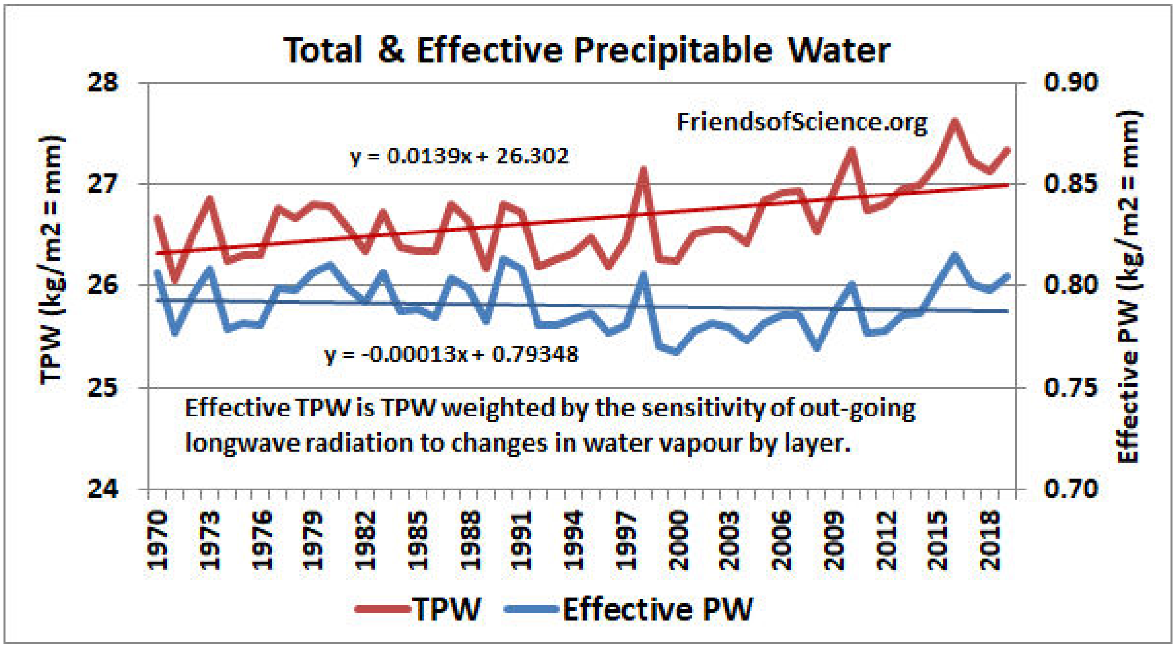

Figure 6. The graph shows the total precipitable water (TPW) and the effective precipitable water (Eff PW) from 1970 to 2018. The effective PW is the sum of the precipitable water by layer weighted by the sensitivity of OLR to a small change in the amount of water in each layer. The trend of the TPW is up (red curve, left scale) while the trend of the Eff PW (blue curve, right scale) is down.

The trends of the TPW and Eff PW over two time periods are summarized in table 4.

Time interval	TPW	Eff PW
	mm/decade	mm/decade
1970 to 2019	0.139	-0.0013
1980 to 2019	0.201	-0.0012

Table 4. Trends of TPW and Eff PW over two time periods.

Note that applying the weighting to the TPW greatly reduces the value of the eff PW. Averaged over 2014 to 2019, the TPW is 27.2 mm, and the Eff PW is 0.80 mm.

As global temperatures increased by 0.76 °C from 1970 to 2019 (as per HadCRUT4.6), the TWP increased by 0.14 mm/decade. This does not imply a positive water vapour feedback. Accounting for the sensitivity of OLR to changes in water vapour in the different layers, the effective TPW has a small declining trend of -0.0013 mm/decade. This may mean that water vapour did not cause a positive feedback on temperatures, contrary to the climate models. The lack of a large positive water vapour feedback may be the reason that the climate models on average simulate a global warming of the lower troposphere from 1979 to August 2020 of about 2 times the satellite measured warming as shown in Figure 7.[8]

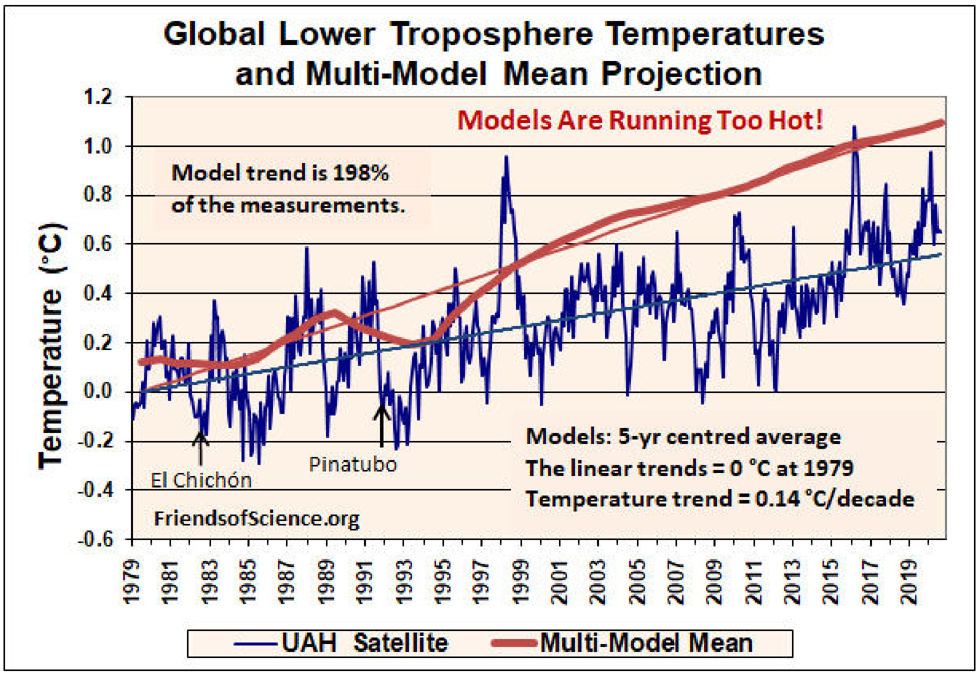

Figure 7. Global lower troposphere temperatures shown in blue have been increasing at 0.14 °C/decade from 1979 to Aug. 2020. Over the same period the multi-model trend corresponding to the same atmospheric layer weighting is 0.27 °C/decade, or 198% of the measured trend.

The atmospheric lapse rate is the rate that temperatures decrease with altitude in the troposphere. Climate models predict that the temperature in the upper troposphere will warm faster than the near-surface temperatures, so in the models the lapse rate decreases with global warming. This effect causes a small negative feedback which offset a part of the larger water vapour feedback. The lapse rate feedback is strongly correlated with the water vapour feedback in climate models. Both the water vapour feedback and the lapse rate feedback are caused by the climate models' predicted increase of water vapour in the upper troposphere.

The NCEP1 dataset shows an insignificant increase in the lapse rate as shown in Figure 5 rather than the model predicted decrease.

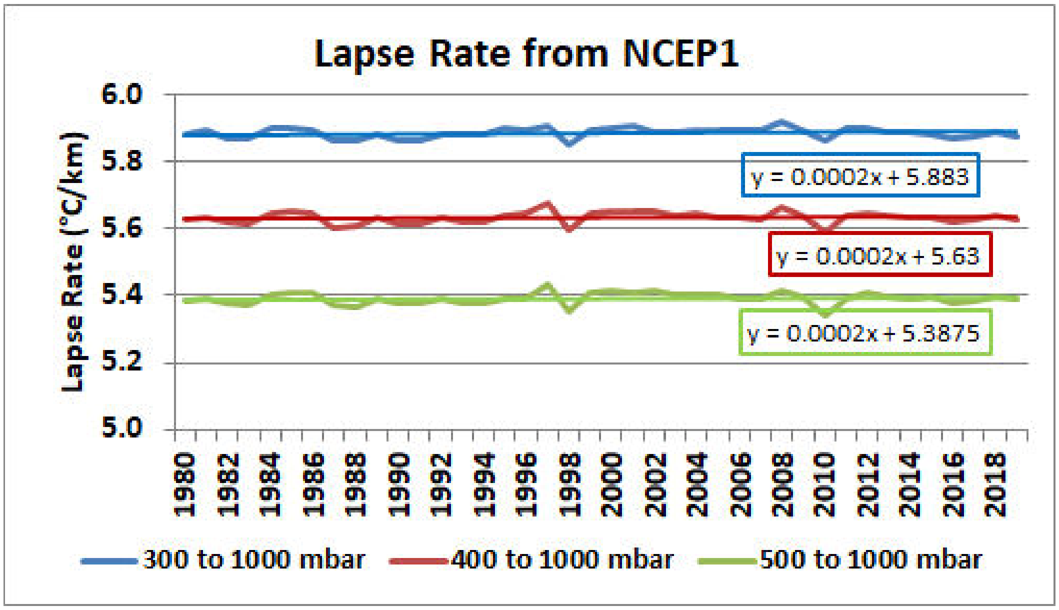

Figure 8. Lapse rates according to the NCEP1 dataset from pressure levels 300, 400 and 500 mbars to 1000 mbars. The lapse rate trends of each of the pressure ranges are near zero over the period 1980 to 2019.

The above analysis data shows that both the water vapour and lapse rate feedbacks are near zero so if the NOAA dataset is accurate both feedbacks should be eliminated from climate models. We do this to show the consequences to the multi-model mean equilibrium climate sensitivity (ECS).

The IPCC's AR5 report shows in Table 9.5 that the multi-model mean (ECS) to a doubling of CO_2 is 3.2 °C. The table gives a water vapour feedback of 1.6 W/m^2/°C and a lapse rate feedback of -0.6 W/m^2/°C. The direct effect, without feedbacks, of a doubling of CO_2 is estimated at 1.15 °C assuming a radiative forcing of 3.7 W/m^2).

The sum of all feedbacks is calculated using this equation; ECS = F2x · K/(1 – b · K), where K is the Plank feedback factor of 0.313 °C/(W/m^2), F2x is the forcing from a doubling of CO_2 of 3.7 W/m^2 and b is the sum of all feedback factors. See here for an article by Christopher Monckton explaining this equation.

By rearranging the terms of the equation, b = 1/K – F2x/ECS.

b = 1/0.313 – 3.7/3.2 = 2.04 W/m2/°C

The feedback sum without water vapour and lapse rate feedbacks (hereafter together will be called the water vapour feedbacks) is then bx = 2.04 – 1.60 – (-0.60) = 1.04 W/m^2/°C. Recalculating ESC with this feedback sum we obtain;

ESC = F2x · K/(1 – bx · K)

ESC = 3.7 · 0.313/(1 – 1.04 · 0.313) = 1.72 °C

This shows that eliminating the water vapour feedbacks from the climate models would reduce the multi-model mean ECS from 3.2 °C to only 1.7 °C. Correcting the climate models to match the NOAA water vapour data would reduce the ECS to CO_2 by 47%.

The economic impact of this reduction in ECS is evaluated using the economic model FUND. The best estimate of all values in FUND and of climate sensitivity is used, that is, we don't consider the probabilistic distribution of parameters.

The economic costs and benefits of CO_2 emissions are often expressed by the social cost of CO_2 ($SCCO_2$). This value is calculated by FUND by calculating the annual damages and benefits of greenhouse gas emissions from 1900 assuming continued greenhouse gas emissions without mitigation policies. Economic and social impacts are calculated in response to the temperature increases. These impacts are subtracted from another model run where a pulse of 10 $MtCO_2$ is emitted in 2020 over ten years. The resulting annual impacts from 2020 are discounted by a specified discount rate and divided by 10 million to get the discounted impact per tCO_2.

We make two corrections to the FUND model based on new peer-reviewed papers.

The recent paper, Dayaratna, McKitrick & Michaels 2020 (DMM2020), here shows that the FUND integrated assessment model has outdated CO_2 fertilization parameters that were determined in the early 1990s. DMM2020 says the CO_2 fertilization effect should conservatively be increased by 30% due to higher contemporary estimates of CO_2 fertilization effects.

A new paper by P. Lang and K. Gregory 2019 (L&G2019) shows that the FUND model space heating and cooling components are misspecified. The empirical data indicates that energy expenditure decreases as temperatures increase, suggesting that global warming reduces US energy expenditure and thereby has a positive impact on US economic growth. Extending this analysis to global impacts, 3 °C of global warming would reduce energy expenditures and have an economic impact of +0.05% of gross world product (GWP). FUND without the correction forecasts 3 °C of global warming would increase global energy expenditures resulting in an economic impact of -0.80% of GWP.

Table 5 below shows the $SCCO_2$ in $/$tCO_2$ for emissions in 2020 at ECS = 3.2 °C as per the climate models with water vapour feedbacks, and at ECS = 1.7 °C without those feedbacks, calculated by FUND at 3% and 5% discount rates. The upper part of the table includes corrections of a 30% increase to the CO_2 fertilization effect as recommended by DMM2020 and corrections to the space heating and cooling energy impacts as recommended by L&G2019. The lower part includes only the CO_2 fertilization update.

Incorporating the two corrections, FUND calculates, using a 3% discount rate, a $SCCO_2$ of $-1.79/t$CO_2$ at ECS of 3.2 °C, and $-7.14/tCO2 at ECS of 1.7 °C. All values are in constant US 2018 dollars. Eliminating the water vapour and lapse rate feedbacks reduces the $SCCO_2$ by $5.35, a change of -299%! At a 5% discount rate the $SCCO_2$ declines from $-3.66/t$CO_2$ to $-4.20/t$CO_2$.

Using only the +30% CO_2 fertilization correction and a 3% discount rate, FUND calculates a $SCCO_2$ of $-0.38/t$CO_2$ with an ECS of 1.7 °C, which is a reduction of $8.32/tCO2 from the case with an ECS of 3.2 °C. At 5% discount rate the SCCO2 drops from $-0.41/tCO2 to $-1.17/t$CO_2$ by eliminating the water vapour feedbacks. The net benefits of CO_2 emissions increase by $0.76/t$CO_2$ and the net effects of emissions change from net harmful to net beneficial. The negative signs of $SCCO_2$ indicate that the benefits of CO_2 emissions exceed the social costs.

	FUND Social Cost of CO_2 in $_{2018}$US Dollars per tonne CO_2				
	Corrected for +30% CO_2 Fertilization and Energy				
Disc. Rate	ECS = 3.2 °C	ECS = 1.7 °C	Change $	Change (%)	ECS = 1.0 °C
3%	-1.79	-7.14	-5.35	-299%	-11.22
5%	-3.66	-4.20	-0.54	-15%	-5.76
	Corrected for +30% CO_2 Fertilization Only				
3%	7.94	-0.38	-8.32	-105%	-9.31
5%	-0.41	-1.17	-0.76	-184%[9]	-5.03

Table 5. FUND calculated $SCCO_2$ at various ESCs at two discount rates, with updates to CO_2 fertilization and energy impacts. Negative values mean the net impacts are beneficial.

Note that there are other serious problems with the climate models that exaggerate climate sensitivity. The climate models fail to consider the urban heat island effect (UHIE), which contaminates the surface temperature record, and natural climate change from ocean oscillations and solar activity, which are falsely attributed to greenhouse gas warming. This article by me shows that using the energy balance method and considering the UHIE and natural climate change, the ECS best estimate is 1.0 °C. The last column on Table 5 shows, with two corrections to FUND, the $SCCO_2$ becomes $-11.22 at 3% and $-5.76/t$CO_2$ at 5% discount rate.

All data and calculations are in an Excel file here.

ENDNOTES;

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[1] This is a major revision to an article published 2019-06-22.

[2] Equilibrium climate sensitivity is defined as the global mean surface temperature change due to a doubling of the CO_2 concentrations in the atmosphere after allowing time for the oceans to reach temperature equilibrium, which for the top 3 km takes about 1,500 years.

[3] The height of the troposphere varies by latitude and the season. The average height in the tropics is 17 km and at the poles about 9 km.

[4] HARTCODE (High Resolution Atmospheric Radiative Transfer Code) is a line-by-line radiative transfer software program developed by Dr. Ferenc Miskolczi. As a senior principal scientist he worked on several NASA projects related to atmospheric remote sensing problems and the evaluation of the Earth's radiation budget. In 2005 he resigned from the AS&M Inc. (a NASA contractor).

[5] The ERA Interim data starts in 1979, so we use the 1979 value of AH at 200 mbar for years 1970-1978 to calculate the PW in the 200-300 mbar layer for those years.

[6] Density = mass/unit volume = PM/(RT), where M is the molecular weight of moist air, P is pressure, R is the gas constant and T is temperature in Kelvin. The molecular weight of moist air is calculated for each pressure layer using the molar absolute humidity and the molecular weights of water and dry air. The molar mass of moist air increases from 28.78 g/mole in the 1000-1013 mbar layer to 28.96 g/mole in the 200-300 mbar layer.

[7] Each layer thickness (H) is the scale height (S) times the natural logarithm of the ratio of the pressures at the top and bottom of each layer. $H = S \cdot \ln(P1/P2)$. The S of each layer is $R \cdot T/(M \cdot g)$, where R is the gas constant, T is the layer average temperature, M is molar mass, g is acceleration of gravity. Scale height is the height at which the pressure declines by a factor of e = 2.71828… This is calculated at each pressure layer.

[8] The climate model lower troposphere trend from 1979 to 2019 is 0.269 °C/decade. The lower troposphere UAH6.0 satellite trend January 1979 to August 2020 is 0.136 °C/decade. The discrepancy is a factor of 1.98.

[9] Where the $SCCO_2$ is negative at ECS is 3.2 °C, the percent change is mathematically positive, but it is shown here as negative indicating the change is towards a more negative value.