Total Precipitable Water and the Greenhouse Effect

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Summary

Total precipitable water is an important climate parameter as it is a measure of the total amount of water vapour which is the most important greenhouse gas in the atmosphere. Water vapor 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 very sensitive to water vapour in the upper atmosphere. This article shows that based on humidity data from a major reanalysis dataset, declining humidity in the upper atmosphere 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 vapor feedback, contrary to climate models. This may explain why the climate models have simulated a global surface warming from 1979 to 2018 of over twice the satellite observed warming.

Water vapour is the most important greenhouse gas. The quantity of water vapour varies greatly in time, 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 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 vapor in the atmosphere, is it often assumed that an increases in TPW corresponds to the water vapour feedback. 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 unit change in the amount water vapour increases dramatically with altitude. If the trend of upper troposphere water vapor is different from the trend near the surface, the TPW would not correspond to the water vapour feedback.

The effect on out-going longwave radiation (OLR) of a 0.3 mm change in precipitable water vapour at various pressure levels in the atmosphere was evaluated by a line-by-line radiative transfer code.[1] The results of this calculation is shown in figure 1.

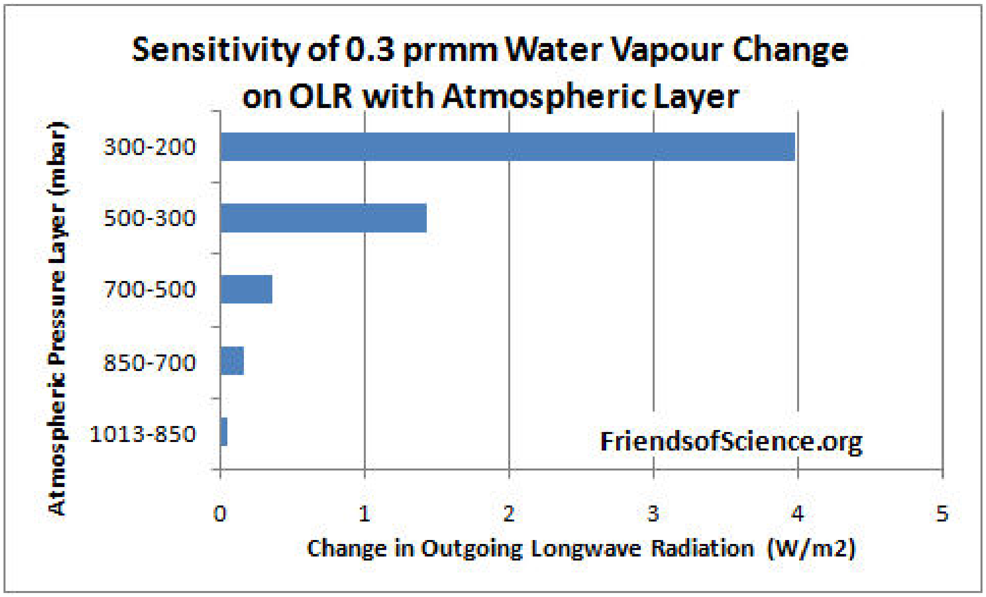

Figure 1.

Figure 1 shows that adding 0.3 mm of water in the 300 to 200 mbar layer would reduce the OLR by 3.97 W/m^2, and adding 0.3 mm of water in the 1013 to 850 mbar layer would reduce the OLR by only 0.049 W/m^2. A 0.3 mm change of PW in the layer 300 to 200 mbar pressure layer has 81 times the greenhouse effect as the same change in the 1013 to 850 mbar near-surface layer.

Relative humidity (RH) is the fraction of water vapor 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.

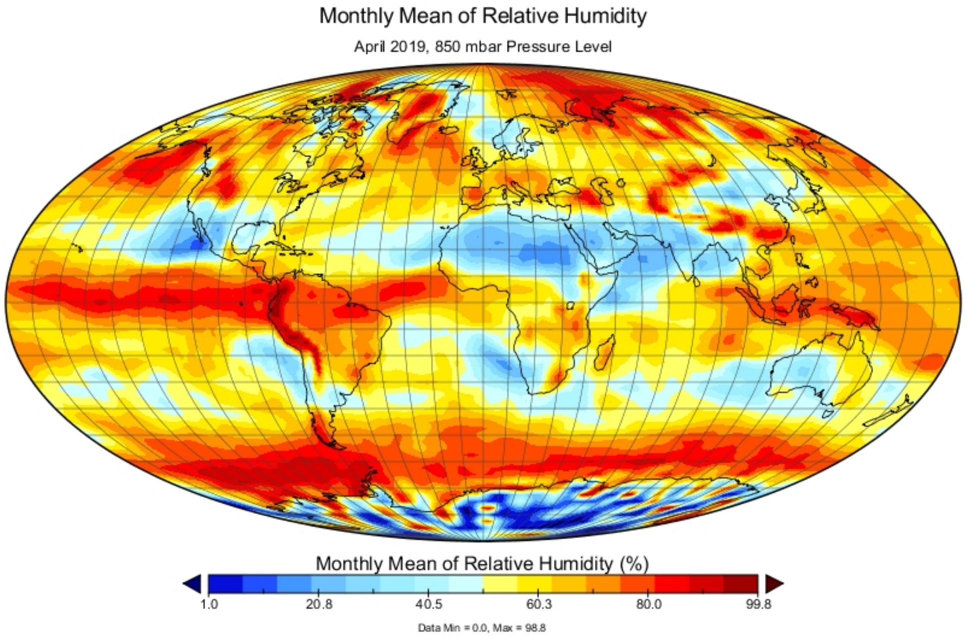

Figure 2. Relative humidity in April 2019 at 850 mbar pressure level.

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 NECP (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 ERA Interim dataset accessed via Climate Explorer here for those quantities at the 200 mbar pressure level.[2]

The NECP reanalysis 1 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].

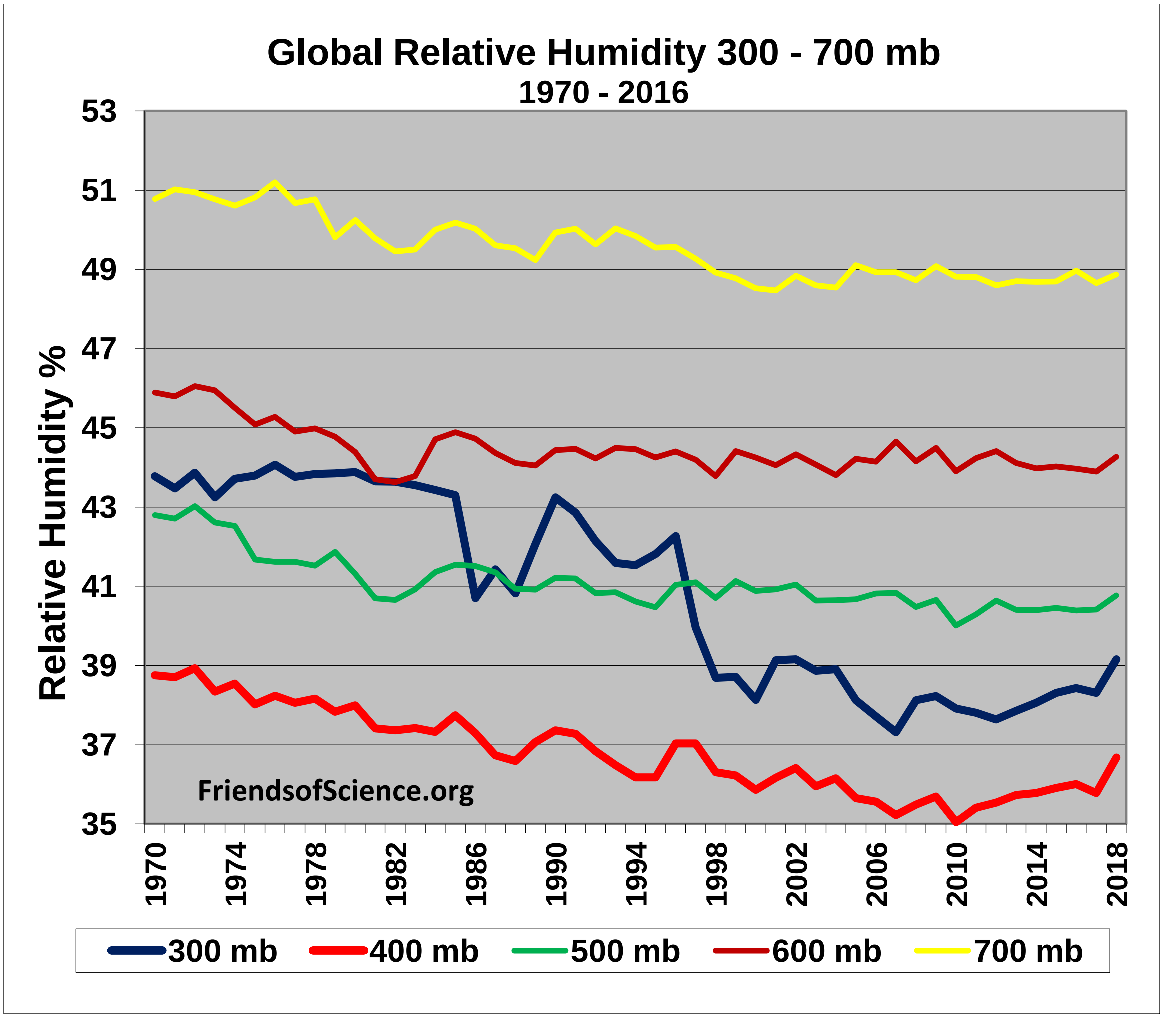

Figure 3. Global relative humidity in the upper atmosphere has generally been declining since 1970, but the there has been a recent increase at the 300 and 400 mbar levels.

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.[3]

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

Specific Humidity and Absolute Humidity Trends over 1970 to 2018									
mbar	200	300	400	500	600	700	850	925	1000
SH mg/kg/yr	0.041	-0.556	-0.694	-0.107	1.332	1.429	2.570	7.33	8.95
AH mg/m3/yr	0.013	-0.260	-0.416	-0.128	0.926	1.044	2.100	7.64	9.96

Table 1. Trends of specific humidity and absolute humidity.

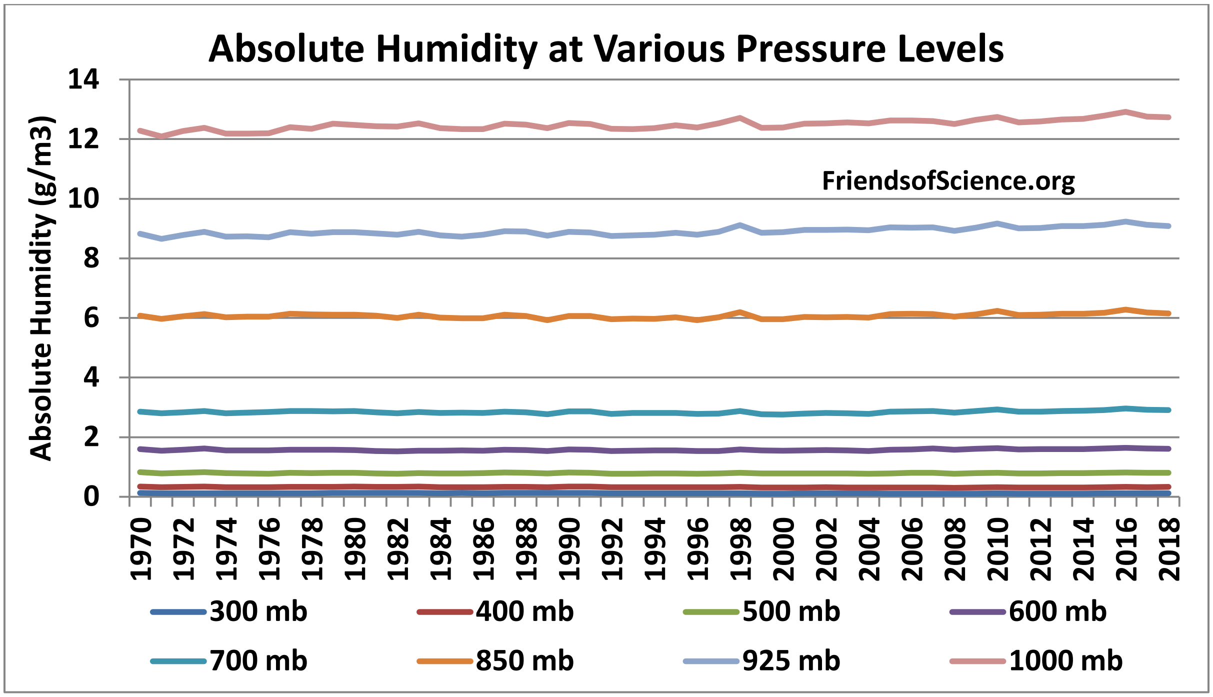

Figure 4. Absolute humidity at pressure levels 300 mbar to 1000 mbar calculated from NECP Reanalysis 1.

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 trend in mg/m^2/decade of each layer over 1970 to 2018 are shown in Table 2.

Absolute humidity trends over 1970 to 2018									
mbar	200-300	300-400	400-500	500-600	600-700	700-850	850-925	925-1000	1000-1013
mg/m^3/decade	-1.24	-3.38	-2.72	3.99	9.85	15.72	48.69	88.00	99.63

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

Table 3 shows the sensitivity of OLR to water vapour changes of five atmospheric layers, the water vapour mass fraction averaged over 2014-2018, the OLR effect fraction and the humidity trends by layer.

Layer	OLR sensitivity to Water V.	Mass of water vapor 2014-2018	Mass water vapor fraction 2014-2018	OLR effect fraction	Trend 1970-2018
mbar		g/m^2	%	%	mg/m^2/decade
1013-850	1.00	14013	51.5	12	74.03
850-700	3.01	7209	26.5	18	15.72
700-500	7.26	4468	16.4	27	7.62
500-300	28.94	1376	5.1	33	-2.93
300-200	80.62	165	0.607	11	-1.24
Total		27231	100	100	

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

Since we have sensitivity of OLR to water vapor changes only for these five layers, the mass humidity trends of layers of table 3 that encompass two or three layers of table 2 are calculated as the mass weighted average of the corresponding layer trends in table 2. The OLR effect fraction is the OLR sensitivity of a water vapor change times the water vapor mass of each layer expressed as a percentage of the sum of the OLR sensitivity times the mass of all the layers. We arbitrarily set the OLR sensitivity to the 1013-850 mbar layer to 1.00. The table shows that the bottom 1013-850 mbar layer contains 51% of the water vapor mass (in the period 2014-2018), but a percent water vapor change there has only 12% of the OLR effect of a percent change in all layers. The upper troposphere 300-200 mbar layer (about 9 to 12 km altitude) contains only 0.61% of the total water vapor mass, but a percent change in water vapor there has 95% of the greenhouse effect of a percent change in the 1013-850 layer (surface to 1.5 km altitude) that has 85 times the water vapor mass.

Precipitable water is calculated 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.[4] 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 in 2018 is 27.12 mm of liquid water depth.

The TPW trend from 1970 to 2018 is 0.131 mm/decade. That tell us almost nothing about the greenhouse effect of increasing water vapour because of 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 a TPW weighted by the sensitivity of OLR to water vapor in each layer each year, which we call an Effective TPW. The sensitivity factor for the 500-700 mbar layer is set to 1.0, so the lower layer 850-1013 is 0.14 and the 200-300 mbar layer is 11.1. This results in the standard error of the Effective TPW to be very close to that of the TPW. We set the Effective TPW to equal the TPW in 1970. The result is shown in figure 5.

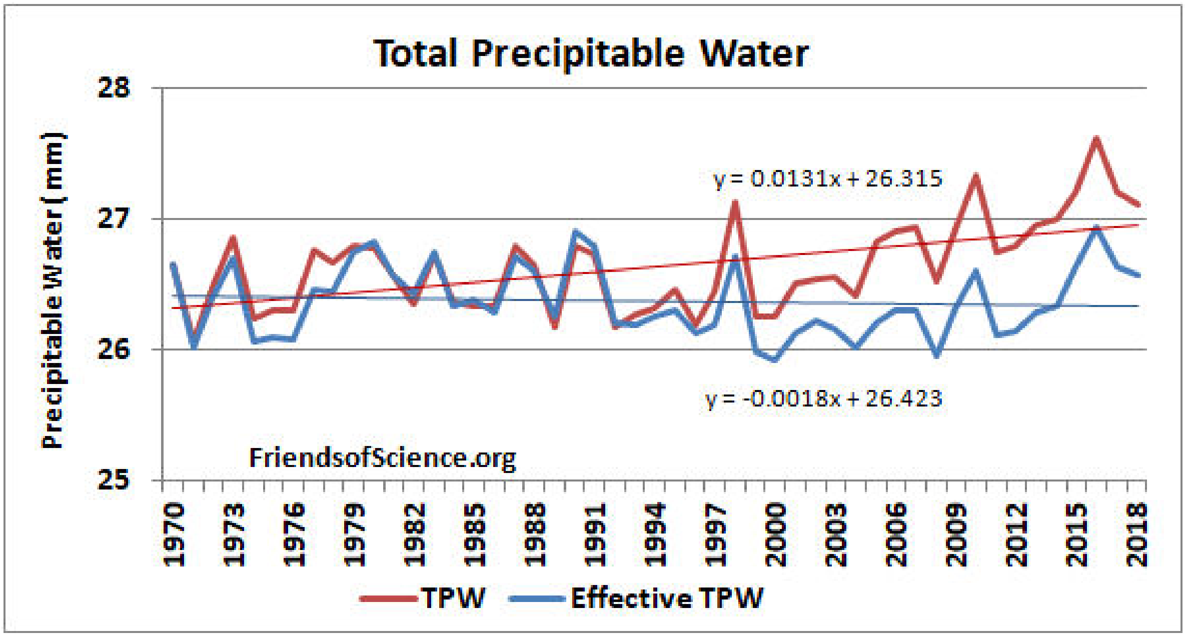

Figure 5. The total precipitable water and the Effective total precipitable water from 1970 to 2018.

As global temperature have increased by 0.62 °C from 1970 to 2018 (as per HadCRUT4.6) the TWP has increased by 0.13 mm/decade. This does not imply a positive water vapor feedback. Accounting for the sensitivity of OLR to changes in water vapor in the different layers, the effective TPW has a small declining trend. This may mean that water vapor did not cause a positive feedback on temperatures, contrary to the climate models. The lack of a large positive water vapor feedback may be the reason that the climate models on average simulate a global warming at the surface from 1979 to 2018 of 2.1 times the satellite measured warming.[5]

All data and calculations are in an Excel file here.

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[1] These calculation were performed by Dr. Ferenc Miskolczi using the radiative transfer code HARTCODE.

[2] 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.

[3] 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.

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

[5] The climate model lower troposphere trend from 1979 to 2019 is 0.270 °C/decade. The lower troposphere UAH6.0 satellite trend 1979 to May 2019 is 0.128 °C/decade. The discrepancy is a factor of 2.11.