The Water Vapour Feedback from Two Reanalysis Datasets

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ABSTRACT

Water vapour is the most important and abundant greenhouse gas. According to the Intergovernmental Panel on Climate Change (IPCC), water vapour acts as a feedback by increasing its quantity in the atmosphere in response to a warming initiated by an increase in anthropogenic greenhouse gases, thereby greatly amplifying the initial warming. Here we use temperature, pressure and relative humidity data of 12 atmospheric layers obtained from two state-of-the-art global reanalysis datasets and results from a line-by-line radiative code to calculate the water vapour feedback. The results suggest that the water vapour feedback is about 66% of the IPCC's assessed value; 67% using the ERA5 dataset and 65% using the NECP2 dataset. We show that a change of water vapour mass in the 100-150 mbar pressure atmospheric layer causes a change in radiative forcing that is 284 times greater than in the 1000-1013 mbar near-surface layer. We determine the water vapour feedback by summing the contributions of 12 layers. The global surface temperature of the 1980s is 0.66 °C higher in the NECP2 reanalysis than in ERA5. The surface warming trend from 1980 to 2022 from ERA5 is 14.6% higher than from NECP2. The relative humidity values in the Polar Regions are much different between the two datasets. ERA5 gives the relative humidity at the 250 mbar pressure level at the South Pole at 2.5% while NECP2 says it is 64%. At the 400 mbar pressure level, the relative humidity discrepancies between the datasets are 58 percentage points at the South Pole and 47 percentage points at North Pole. Large humidity discrepancies between the datasets and water vapour feedback estimates show that climate science is far from settled and the projections of future warming are exaggerated.

Introduction

The amount of water vapour in the lower atmosphere at the global scale is mostly determined by the air temperature, but it varies greatly by altitude, geographical location and time. Changes in water vapour give rise to a water vapour feedback and a temperature lapse rate feedback. The lapse rate feedback is caused by a change in the rate of temperature decrease with altitude. The water vapour feedback is the change in global longwave radiative flux at the top of the atmosphere (TOA) caused by an increase in the atmospheric water vapour concentration associated with an increase in global mean surface air (GMST) temperature, usually expressed in W/(m^2·°C). The IPCC's sixth assessment report (AR6) [WG1 Chapter 7, 7.4.2.2] says "Greater atmospheric water vapour content, particularly in the upper troposphere, results in enhanced absorption of LW [longwave] and SW [shortwave] radiation and reduced outgoing radiation. This is a positive feedback." Chapter 7 says that the water vapour feedback value obtained by satellite data and climate models is 1.85 W/(m^2·°C) and 1.77 W/(m^2·°C), respectively. AR6 assessed that the water vapour feedback at 1.80 W/(m^2·°C).)[i]. AR6 estimates that a doubling of carbon dioxide (CO_2) in the atmosphere would increase global mean surface temperatures by 1.22 °C[ii] if other factors are held constant. Climate feedbacks, which are dominated by the water vapour feedback, increase the temperature change for a doubling of CO_2 to about 3.0 °C[iii] according to the IPCC.

Sensitivity of OLR to Water Vapour by Pressure Level

We want to compare the AR6 estimate of the water-vapour feedback to what is implied by the HARTCODE line-by-line radiative transfer code model combined with the NOAA and European reanalysis datasets. Dr. Ferenc Miskolczi used the HARTCODE model to calculate the reduction in out-going longwave radiation (OLR) at the TOA in 11 layers of the global atmosphere due to an increase in water vapour of 0.3 mm of precipitable water vapour (prmm). Atmospheric layers are defined by pressure levels in mbar. Note that 1 mbar = 1 hPa = 100 Pa. Total precipitable water vapour is the thickness of liquid water that would result from the precipitation all the water vapour in a vertical column of air. The simulation result is shown in Figure 1.

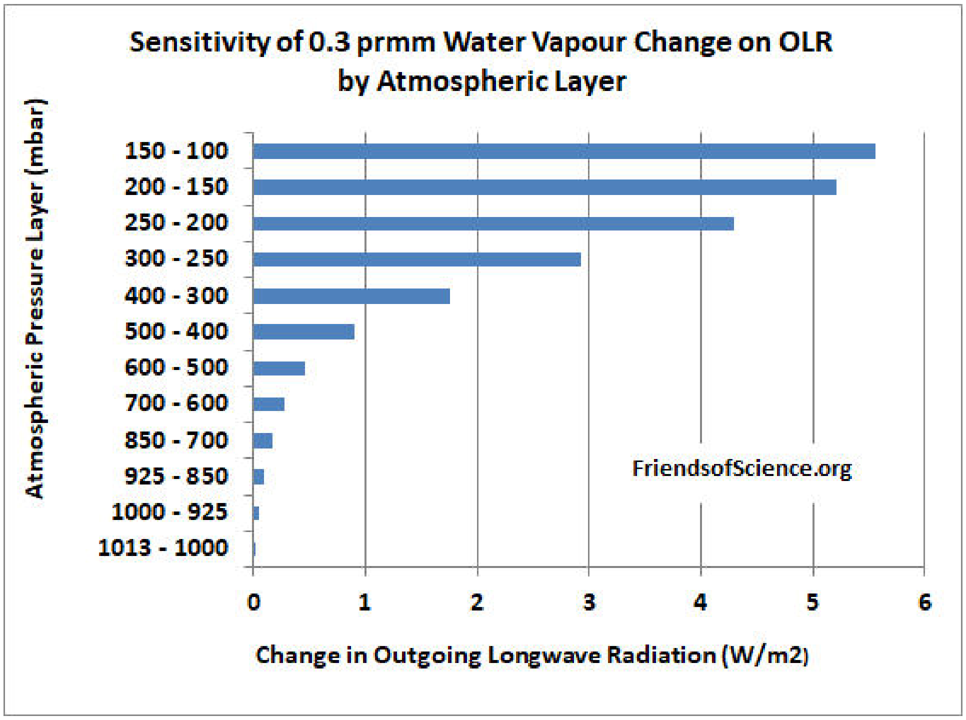


Figure 1

A kilogram of water vapour in a column of air over an area of one square metre, if condensed to liquid water, would have a thickness of one mm over that area, so 1 prmm = 1 kg/m^2 of water vapour. The graph shows that a given change in the amount of water vapour in an atmospheric layer at high altitude (low pressure) causes a much greater reduction of out-going longwave radiation (OLR) than the same change in low altitude (high pressure) layers, before any change in surface temperature. For example, a given 0.3 prmm change of water vapour in the 100 – 150 mbar pressure layer (about 13.8 to 16.3 km altitude) causes a reduction of OLR of -5.56 W/m^2 while the same change of water vapour in the near surface layer (0 to 0.11 km altitude) reduces the OLR by only 0.0196 W/m^2, assuming constant surface temperatures. In other words, the OLR is 284 times as sensitive to changes in the amount of water vapour in the 100 – 150 mbar layer as in the 1013 – 1000 mbar near surface layer.

Humidity Data

I obtained temperature and relative humidity data from two new reanalysis datasets; ERA5 and NECP2.

The ERA5 data is available from the Copernicus website. Copernicus is the Earth observation component of the European Union’s Space program. The ERA5 reanalysis is a product of the European Centre for Medium-Range Weather Forecasts (ECMWF)

The website says “ERA5 is the fifth generation ECMWF reanalysis for the global climate and weather for the past 8 decades. Data is available from 1940 onwards. ERA5 replaces the ERA-Interim reanalysis. Reanalysis combines model data with observations from across the world into a globally complete and consistent dataset using the laws of physics. This principle, called data assimilation, is based on the method used by numerical weather prediction centres.” The data is available on a monthly basis from 1940 on a regular latitude-longitude grid of 0.25° X 0.25° resolution.

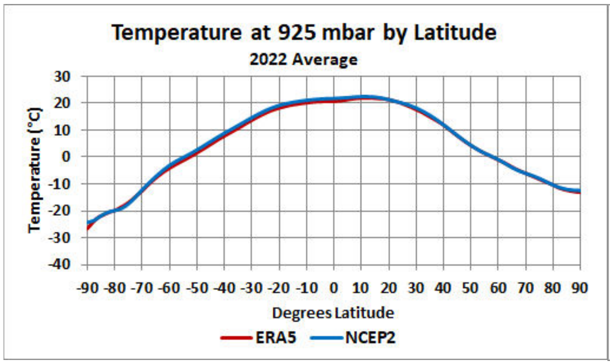
NECP2 data is available from the NOAA website. NCEP-DOE Reanalysis 2 is an improved version of the NCEP Reanalysis 1. NCEP is the National Centers for Environmental Prediction. The website says “The NCEP-DOE Reanalysis 2 project is using a state-of-the-art analysis/forecast system to perform data assimilation using past data from 1979 through near present.” The monthly data is available on a regular latitude-longitude grid of 2.5° X 2.5° resolution.

Monthly temperature and relative humidity data of the two datasets for 12 pressure levels were downloaded. The longitudinal values were averaged. The NECP2 data of each 2.5° of latitude and the ERA5 data of each 2.0° of latitude were copied into a spreadsheet.

Comparing ERA5 to NECP2 Reanalysis

Before discussing absolute humidity calculations, let's first compare the ERA5 temperatures and relative humidity data from the ERA5 and NECP2 reanalysis datasets.

Figures 2 and 3 compare the 2022 average temperatures by latitude of the two datasets at pressure levels 925 and 300 mbar. The negative latitudes are in the southern hemisphere. The North Pole is at the right side of the graphs.



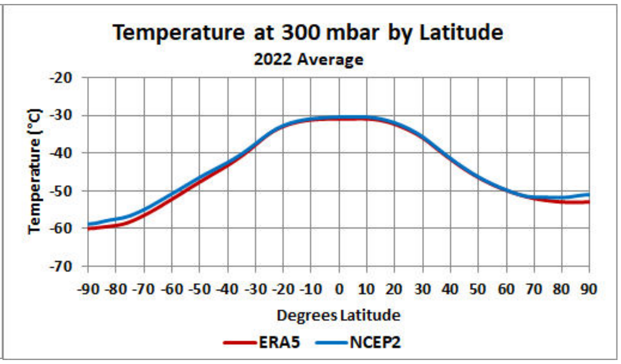


Figure 2

Figure 3

The temperature differences between the datasets are mostly less than 1.5 °C from 300 mbar to 100 mbar. They match very well from 40°S to 70°N. The match is even better at higher pressure levels (lower altitudes). The temperature differences between the datasets are mostly less than 0.5 °C from 1000 mbar to 400 mbar.

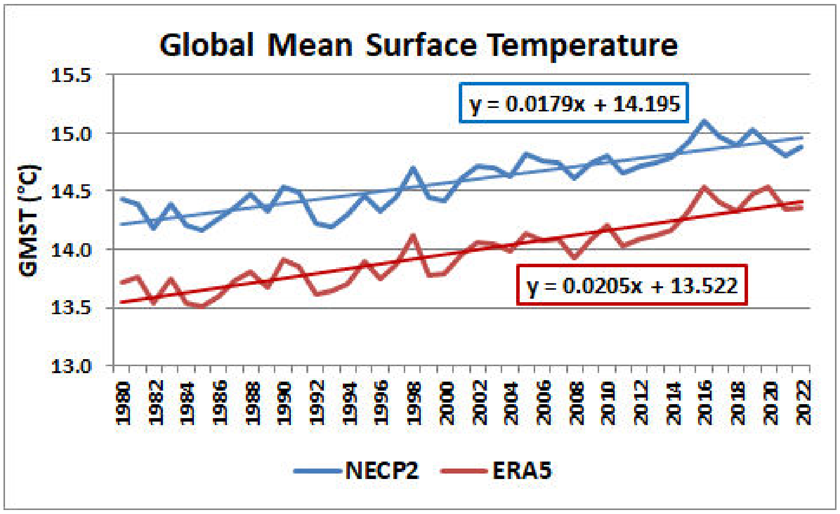


Figure 4

The global mean near surface temperatures, defined at 2 m from the surface, of the datasets are shown in Figure 4. The warming trend of ERA5 is 0.205 °C/decade, 14.6% greater than the 0.179 °C/decade trends of NECP2. The 1980s average temperature the NECP2 is 0.66 °C higher than ERA5. This large surface temperature difference is problematic as any forecast of ice and snow melt or sea level rise that uses a dataset with large errors in surface temperatures can't be accurate or credible.

Unfortunately, the relative humidity values of the datasets don't match very well. Figure 5 shows the relative humidity comparison at the 250 mbar level. In the northern hemisphere, the datasets match at 40°N but they diverge going to the North Pole where ERA5 is at 38.9% and NCEP2 is at 12.9%, a difference of 26 percentage points. The discrepancy at the equator is over 24 percentage points. At the South Pole the ERA5 relative humidity is 63.6% while NECP2 says it is only 2.5%, a discrepancy of over 61 percentage points. At the 400 mbar pressure level there is no match in the tropics and the northern hemisphere as shown in Figure 6. The datasets match from 20°S to 45°S but they diverge to a discrepancy of 58 percentage points at the South Pole. The discrepancy at the North Pole is 47 percentage points. It seems amazing that these two state-of-the-art reanalysis give such different relative humidity values in the tropics and Polar Regions! Is climate science so uncertain that scientists can't tell the difference between 2.5% and 61% relative humidity over Antarctica? This is very disappointing to say the least. On a global average basis, the relative humidity discrepancy of the 1991-2020 average between the ERA5 and NECP2 reanalysis datasets is 13.4 percentage points in both the 250-300 and 300-400 mbar layers.

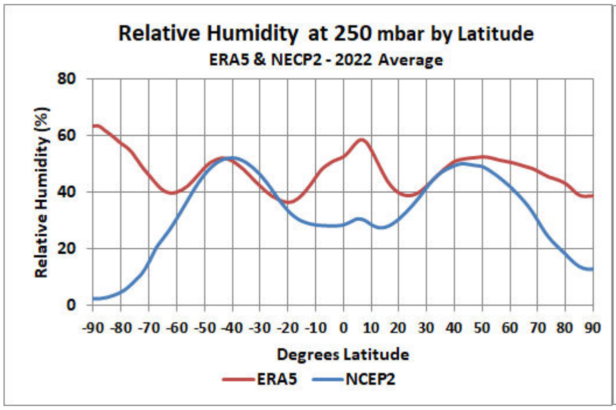


Figure 5

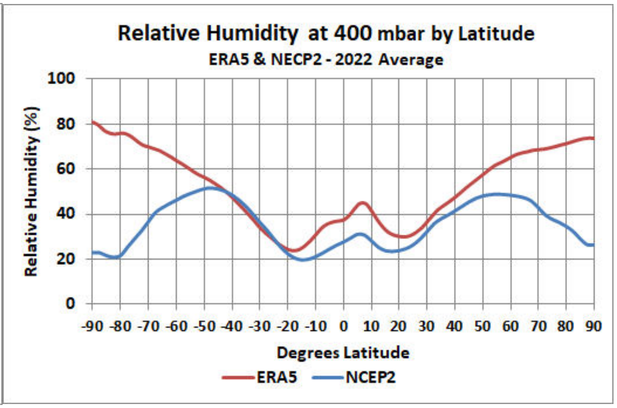


Figure 6

To view an animation of relative humidity of all pressure levels click here.

Figures 7 and 8 show maps of the global relative humidity at the 400 mbar pressure level as of April, 2020 from the NECP2 and ERA5 datasets, respectively. The pattern of relative humidity of the datasets is significantly different, especially in the Polar Regions.

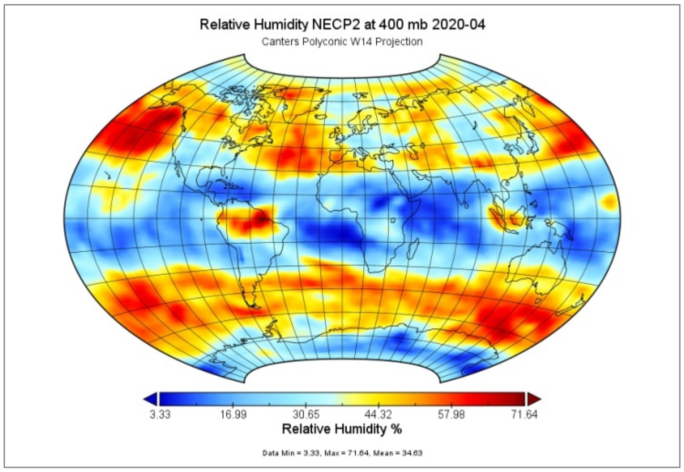


Figure 7

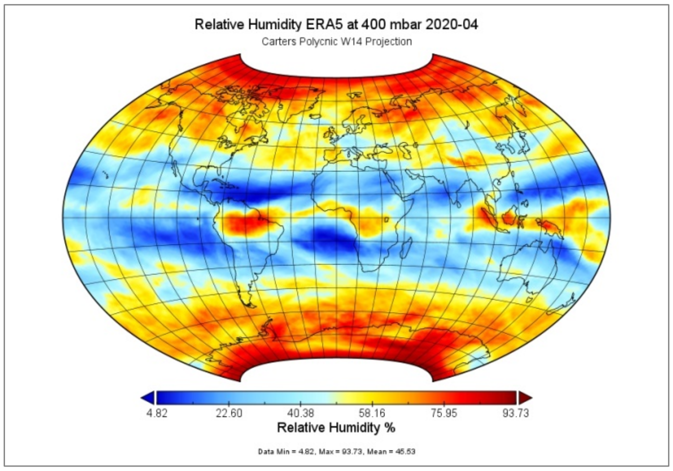


Figure 8

Water Vapour Content by Layer

I need the absolute humidity in mass of water vapour per unit volume to calculate the water vapour feedback. Neither dataset provides absolute humidity values. Absolute humidity is equal to the density of air in kg/m^3 times the specific humidity in g/kg, which gives g/m^3. The ERA5 dataset contains a specific humidity parameter by pressure level, but the definition is not standard as the definition includes cloud liquid water and ice mass. Cloud liquid and ice causes a cloud feedback which can't be included in the calculation of the water vapour feedback. The NECP2 data page doesn't provide any humidity parameter by pressure level other than relative humidity. The absolute humidity must be calculated from the pressure, temperature and relative humidity for each layer of the atmosphere up to 100 mbar. See the appendix for more information on the specific humidity.

The Physical Processes documentation of the ERA5 reanalysis provides equations for calculating the saturated water vapour pressure in section 7.4.2 here. Since the saturated water vapour pressure is a non-linear function of temperature, it was calculated for each month at each latitude value in the spreadsheet, rather than from global averaged values. Relative humidity is the ratio of the partial pressure of water vapour to the saturation partial pressure of water vapour over either a plane of water or ice. The saturation partial pressure of water vapour is calculated with respect to water for temperatures warmer than 0°C, with respect to ice for temperatures colder than -23°C, and a quadratic interpolation of the two in the 0 °C to -23 °C temperature range. Then the monthly global average temperature, relative humidity and saturated water vapour pressure for each pressure level was calculated as the average across all latitudes weighted by the cosine of the latitudes. The yearly global average water vapour pressure was calculated as the yearly global average saturated water vapour pressure divided by the yearly global average relative humidity. This was used to calculate the yearly global average specific humidity and absolute humidity at each pressure level. Further details are given in the appendix.

The average value of each parameter within each atmospheric layer defined by the pressure levels is assumed to be the average of the values at the top and bottom of each layer. According to the ERA5 dataset, the average layer temperatures ranges from -65.0 °C in the 100-150 mbar layer (averaged over 1991-2020) to +15.3 °C in the 1000-1013 °C layer. The water vapour mass of each layer is the average absolute humidity in g/m^3 times the layer thickness in metres expressed in kg/m^2. The datasets extrapolate relative humidity values and temperatures down under the land surface to the 1000 mbar level. The land elevations extend above the 700 mbar pressure level, so the absolute humidity values in the layers below 600 mbar are adjusted to account for the land elevation. Tables of the layer parameters (temperature, thickness, altitude, relative and absolute humidity and water vapour mass in the layers) are given in the appendix.

Table 1 gives parameters by atmospheric layer related to the water vapour feedback. The second column gives the change in outgoing longwave radiation per change of water vapor mass (ΔOLR/ ΔWV) of a column of air in each pressure level expressed in W/kg.

The third column shows the precipitable water vapour (PWV) in each layer in kg/m^2. It is the average absolute humidity in kg/m^3 times the layer thickness. The humidity dramatically decreases with altitude. The absolute humidity in mass of water vapour per volume near the surface is 3100 times that in the 100 –150 mbar layer. The sum of all the layers is the atmosphere's total precipitable water vapour (TPW) in kg/m^2, which is often reported in mm of equivalent liquid water depth as prmm.

The fourth column shows the trends of PWV with respect to time over the period 1980 to 2022. In the ERA5 dataset, all pressure layers have a positive trend except the topmost layer at 100-150 mbar. In the NECP2 dataset, the top four layers from 100 mbar to 250 mbar have negative trends and the bottom eight layers have positive trends.

The fifth column shows the trends of PWV with respect to the near surface 2 m temperatures as given in each dataset. The highest trend is in the 700-850 mbar layer in both datasets. Only the top layer of ERA5 has a negative trend but the top three layers of NECP2 have negative trends.

The sixth column shows the water vapour feedback ($W/m^2/°C$) contribution of each layer. It is the change of OLR per change of water vapour mass (W/kg) of column 2 times the absolute humidity trend with respect to GMST ($kg/m^2/°C$) of column 5.

Table 1	**ERA5 Water Vapour Analysis**				
1	2	3	4	5	6
Air Pressure	ΔOLR/ ΔWater Vapor	PWV in Layer 1991-2020	PWV Trend 1980-2022	PWV Trend 1980-2022	Water Vapour. Feedback
mbar	W/kg	kg/m^2	g/m^2/yr	kg/m^2/°C	W/m^2/°C
100-150	18.52	0.0097	-0.017	-0.0003	-0.0063
150-200	17.37	0.0130	0.007	0.0007	0.0122
200-250	14.34	0.0295	0.051	0.0031	0.0446
250-300	9.73	0.0705	0.125	0.0075	0.0729
300-400	5.83	0.429	0.746	0.0427	0.2489
400-500	3.00	0.996	1.475	0.0835	0.2504
500-600	1.53	1.817	2.143	0.1198	0.1833
600-700	0.906	2.90	3.126	0.1721	0.1560
700-850	0.572	7.37	4.769	0.2956	0.1690
850-925	0.308	5.14	2.236	0.1485	0.0457
925-1000	0.167	5.69	2.066	0.1381	0.0231
1000-1013	0.065	0.97	0.297	0.0210	0.0014
Total		25.4			1.2013

Table 2	**NECP2 Water Vapour Analysis**				
1	2	3	4	5	6
Air Pressure	ΔOLR/ ΔWater Vapor	PWV in Layer 1991-2020	PWV Trend 1980-2022	PWV Trend 1980-2022	Water Vapour. Feedback
mbar	W/kg	kg/m^2	g/m^2/yr	kg/m^2/°C	W/m^2/°C
100-150	18.52	0.0092	-0.022	-0.0006	-0.0115
150-200	17.37	0.0129	-0.039	-0.0012	-0.0210
200-250	14.34	0.0254	-0.050	-0.0011	-0.0164
250-300	9.73	0.0519	-0.012	0.0017	0.0168
300-400	5.83	0.320	0.525	0.0355	0.2072
400-500	3.00	0.839	1.574	0.0951	0.2854
500-600	1.53	1.689	2.698	0.1595	0.2442
600-700	0.906	2.93	2.507	0.1685	0.1527
700-850	0.572	7.72	4.827	0.3313	0.1894
850-925	0.308	5.35	4.002	0.2453	0.0756
925-1000	0.167	5.92	4.315	0.2602	0.0436
1000-1013	0.065	1.02	0.671	0.0413	0.0027
Total		25.9			1.1685

The sum of the water vapour feedback contributions of each layer gives the total water vapour feedback, which is 1.20 W/m^2/°C from ERA5 and 1.17 W/m^2/°C from NECP2.

Comparing the water vapour feedbacks by layer, the feedbacks are higher in ERA5 in six layers but lower in the other six layers than in NECP2. The larger feedback contributions are in the five layers from 300 mbar to 850 mbar. The layers with the largest discrepancies between the datasets are the 200-250 mbar layer where ERA5 is larger by 0.061 W/m^2/°C and the 500-600 mbar layer where ERA5 is smaller by 0.061 W/m^2/°C than NECP2.

Table 3 compares the water vapour feedback by the reanalysis calculations to that estimated by the IPCC.

Table 3	Units	**Water Vapour Feedback**		
Source		IPCC	ERA5	NCCP2
Water Vapour Feedback	W/m^2/°C	1.80	1.20	1.17
Fraction of IPCC			67%	65%

Table 3 shows that the ERA5 and NECP2 data implies that the water vapour feedback is 67% and 65%, respectively, of the value accessed by the IPCC in AR6.

Total Precipitable Water Vapour

The total precipitable water vapour (TPW) values can be directly obtained from the ERA5 and NECP2 websites. I have calculated the TPW by layer using temperature, pressure and relative humidity data. In both datasets, the TPW obtained directly from the datasets are less than that I calculated as shown in Figures 9 and 10.

The trend of TPW directly from NECP2 is 0.220 mm/yr, which is 27% higher than the ERA5 trend of 0.173 mm/yr. However, the water vapour feedback calculated from NECP2 is about 3% lower than from ERA5. This highlights that trends of TPW is poorly related to the water vapour feedback. Instead, individual PWV layer trends that have vastly different effects on OLR changes determine the water vapour feedback.

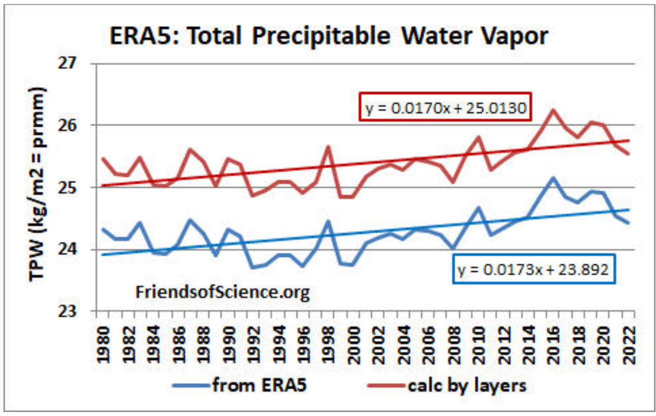


Figure 9

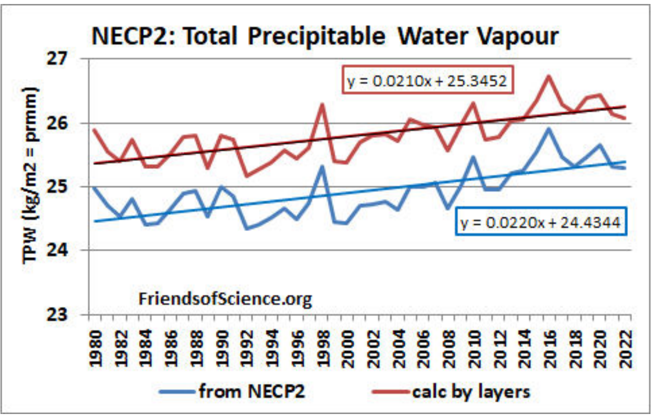
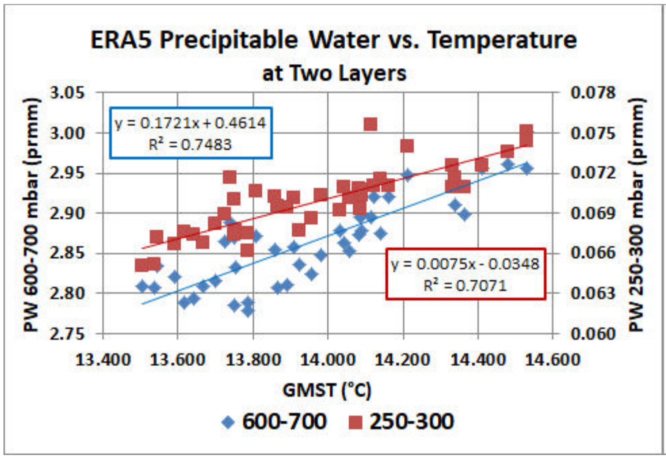


Figure 10

Figures 11 and 12 shows scatter plots of PWV versus near-surface temperatures at the 600-700 mbar and the 250-300 layers from the ERA5 and NECP2 datasets. Note that the 250-300 mbar layer (red squares) corresponds to the right-side axis.



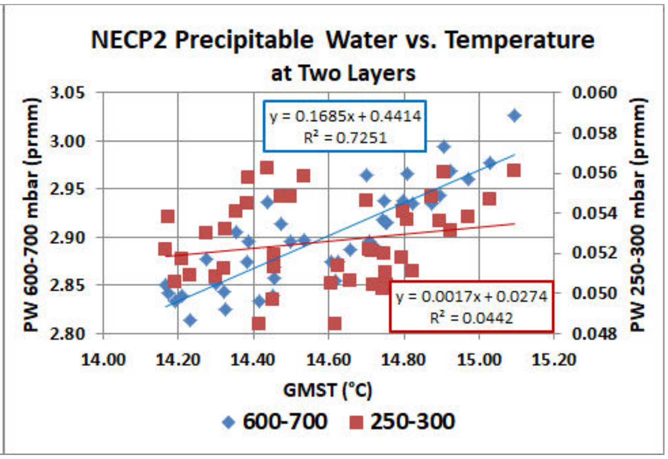


Figure 11

Figure 12

The first term of the linear regression equations correspond to column 5 of tables 1 and 2. The R^2 coefficient of determination values for the 600-700 mbar layer are 0.748 and 0.725 of the ERA5 and NECP2 analysis, respectively, which is reasonably good for a climate science relation. The altitude of the layer mid-point is about 3.7 km. At this altitude, increasing temperatures is strongly related to increasing water vapour mass. The R^2 value of ERA5 analysis for the 250-300 mbar layer is 0.707 which is reasonably good. The altitude of the layer mid-point is about 10.0 km. However, the R^2 value for the 250-300 mbar layer of the NECP2 analysis is only 0.044 which is very low indicating that increasing temperatures is poorly related and has little effect on increasing water vapour mass. The R^2 values drop to 0.044 and 0.059 in the 100-150 mbar layer of the ERA5 and NECP2 analysis, respectively. The NECP2 value of R^2 is higher than ERA5 in 7 of the 12 layers. A table of R^2 values is presented in the appendix.

An article published in May 2023 by Andy May shows that TPW from NECP2 and ERA5 are poorly related to surface temperatures, especially in the 1979 to 2005 time period. He notes that AR6 says;

> *According to theory, observations and models, the water vapour increase approximately follows the Clausius–Clapeyron relationship at the global scale with regional differences dominated by dynamical processes …. Greater atmospheric water vapour content, particularly in the upper troposphere, results in enhanced absorption of LW [longwave] and SW [shortwave] radiation and reduced outgoing radiation.*

Andy May wrote “Obviously, global temperatures are not the only thing influencing TPW and the impact of temperature is not that significant.” He says that surface wind speed has a large effect on the evaporation rate. Unlike the IPCC’s simplistic narrative that temperature is the main driver of upper troposphere water vapour, there must be many important drivers of water vapour changes.

I have shown that changes in water vapour mass in the upper troposphere are poorly related to surface temperature. This casts considerable doubt on the CMIP6 model results, which rely only on the Clausius-Clapeyron relation. Humidity values are difficult to measure and state-of-the-art reanalysis datasets give very different results especially in the Polar Regions. It seems that the science of climate change is not settled at all and the projections of future warming are exaggerated.

Homework Assignment

Thanks for reading, but you aren’t finished yet! Your homework assignment it to determine why the sum of the PWV of the 12 atmospheric layers as calculated here is greater than the TPW given directly in the ERA5 and NECP2 datasets as shown in figures 9 and 10. You will have to read the appendix and view the Excel file. Contact the author kbgregory3 at domain gmail.com.

Data and calculations are given in an Excel file here. (76,094 KB)

Appendix

Tables A1 and A2 provide global average atmospheric parameters of 12 layers as given by the EAR5 and NECP2 reanalysis. Note that the relative humidity and the absolute humidity assume that air extends to sea level over the land area. The precipitable water vapour (PWV) is adjusted to account for the elevation of the land surface using factors 99.1%, 96.1%, 90.3%, 80.0% and 72.0% from the five layers 600-700 to 1000-1013, respectively.

The percentages of the Earth's land surface above elevations by km were taken from figure 2.4 a, which is partially reproduced at Figure A1.

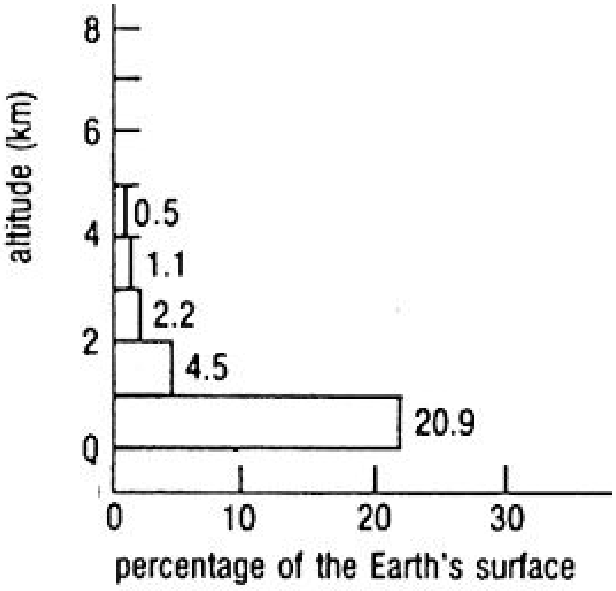


Figure A1. Part of figure 2.4 (a) of Deep-Sea Biology: A Natural History of Organisms at the Deep-Sea Floor

Figure A1 shows the percentage of Earth's surface above sea level by 1 km increments. The pressure levels at each km altitude up the 5 km were calculated. The cumulate land percent of Earth's surface at our pressure levels was interpolated from 1000 to 600 mbar. The percentage of the layer calculated humidity that is above the land surface is 100% minus the average of the land percent of the Earth's surface above the top and bottom of the atmospheric layer.

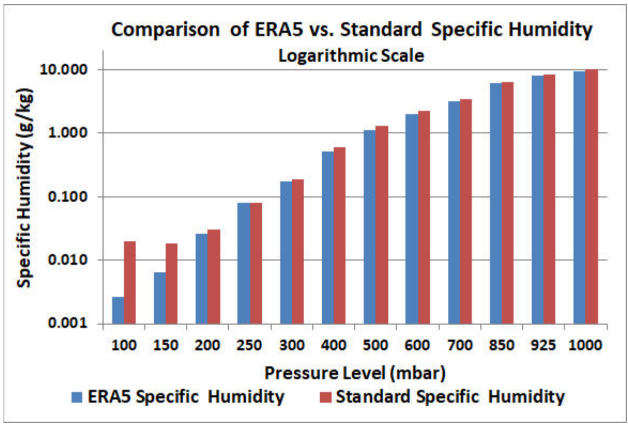
Table A1	**ERA5 Layer Parameters (Average of 1991 – 2020)**					
Air Pressure	Air Temperature	Layer Thickness	Altitude at Top	Relative Humidity	Absolute Humidity	PWV in Layer
mbar	°C	m	km	%	g/m^3	kg/m^2
100-150	-65.0	2470	16.32	34.5	0.0039	0.0097
150-200	-58.1	1811	13.85	37.7	0.0072	0.0130
200-250	-51.0	1451	12.03	44.3	0.0203	0.0295
250-300	-43.6	1225	10.58	47.8	0.0575	0.0705
300-400	-32.6	2026	9.36	46.2	0.212	0.429
400-500	-20.0	1654	7.33	43.6	0.602	0.996
500-600	-10.4	1404	5.68	44.1	1.294	1.817
600-700	-2.8	1222	4.27	47.1	2.374	2.90
700-850	4.3	1582	3.05	57.1	4.849	7.37
850-925	9.6	703	1.47	71.2	8.100	5.14
925-1000	13.2	657	0.77	76.0	10.813	5.69
1000-1013	15.3	110	0.11	74.9	12.322	0.97
Total						25.4

Table A2	**NECP2 Layer Parameters (Average of 1991 – 2020)**					
Air Pressure	Air Temperature	Layer Thickness	Altitude at Top	Relative Humidity	Absolute Humidity	PWV in Layer
mbar	°C	m	km	%	g/m^3	kg/m^2
100-150	-64.1	2481	16.34	30.4	0.0037	0.0092
150-200	-57.3	1818	13.86	35.0	0.0071	0.0129
200-250	-50.3	1456	12.05	36.8	0.0175	0.0254
250-300	-43.0	1228	10.59	34.4	0.0423	0.0519
300-400	-32.4	2028	9.36	32.9	0.158	0.320
400-500	-20.2	1653	7.33	35.8	0.507	0.839
500-600	-10.5	1403	5.68	40.5	1.204	1.689
600-700	-2.9	1222	4.28	47.0	2.400	2.93
700-850	4.4	1582	3.05	59.6	5.079	7.72
850-925	9.9	704	1.47	72.1	8.414	5.35
925-1000	13.8	659	0.77	75.8	11.24	5.92
1000-1013	15.9	110	0.11	75.3	12.90	1.02
Total						25.9

Standard versus ERA5 Definitions of Specific Humidity

The standard definition is specific humidity of the mass of water vapour per mass of moist air, where most air means dry air plus water vapour, in a parcel of air. There is no liquid or solid water (ice or snow) in the denominator. The ERA5 documentation says that the denominator in their definition is the mass of dry air plus water vapour, cloud liquid and ice as well as rain and snow. For the purposes of determining the water vapour feedback, we need to exclude liquid water and ice from the definition. As for a given parcel of air, such as a grid box in the reanalysis model, the ERA5 specific humidity has a larger mass in the denominator than in the standard specific humidity definition so ERA5 values are less than the standard definition of specific humidity values.

Figures A2 and A3 compare the ERA5 specific humidity as downloaded from the ERA5 website to the standard specific humidity definition as calculated from the temperature, pressure and relative humidity.



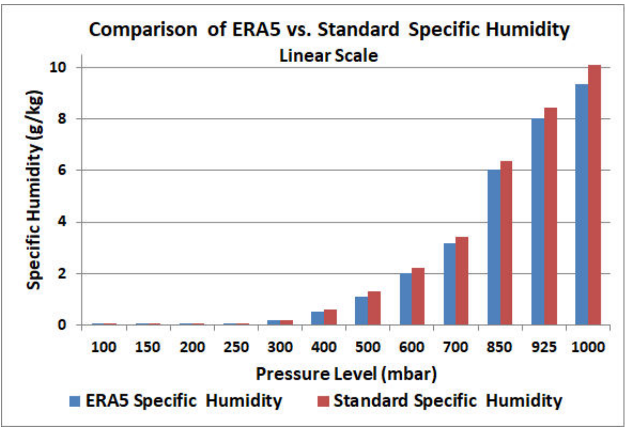


Figure A2

Figure A3

Figure A2 shows the ERA5 and standard specific humidity on the logarithmic scale and Figure A3 show the same parameters on a linear sale. The ERA5 specific humidity values at the 925 mbar and 850 mbar levers are 5.0% and 5.3% less than the standard specific humidity values. The differences increase to 16% at the 400 mbar level and decreases to 1.6% at the 250 mbar level. The differences are large at 100 and 150 mbar levels on a percentage basis but are small on an absolute basis.

Absolute Relativity

The monthly saturated water pressures were calculated by each 2.5° latitude band of the NECP2 dataset and by each 2.0° latitude band of the EAR5 dataset from January 1980 to December 2022 for each of 12 pressure levels. I was unable to determine what equations were used to determine the saturated water pressures for the NECP2 dataset, so I used a set of equations given in the ERA5 documentation, section 7.4.2 here, for both datasets. Therefore the actual specific and absolute humidity values of the NECP2 dataset might be slightly different from those calculated in my spreadsheet and presented is this article. The comparison differences of absolute global average humidity values of the two datasets should be understood to be what they would be if NECP2 used the same saturated water pressure equation as used by ERA5. The differences in absolute humidity values between the datasets arise from differences in their temperature and relative humidity values.

The monthly global average temperatures, relative humidity and saturated water pressures were averaged for each year to get annual global average values. The yearly global average water vapour partial pressure was calculated as the corresponding relative humidity fraction times the saturated water pressure. The molar mass of the air in units of g/mole is the molar mass of water vapour times the ratio of the water partial pressure to the pressure level, plus the molar mass of dry air times the ratio of the dry air pressure to the pressure level. The air density (kg/m^3) at each pressure level was calculated by the ideal gas law. The air density is the pressure level (mbar) divided by 10 (for unit conversion) times the air molar mass divided by the product of the ideal gas constant (m^3·Pa/(K·mole) and the absolute temperature in Kelvin. The specific humidity (g/kg) is the product of the water partial pressure and the water molar mass times 1000 divided by the product of the pressure level and the moist air molar mass.

The absolute humidity (g/m^3) can be calculated two ways; it is the air density (kg/m^3) times the specific humidity (g/kg), or the water partial pressure times the molar mass of water vapour time 100 divided by the product of the ideal gas constant and the absolute temperature.

The average absolute humidity within each layer is assumed to be the average of the absolute humidity values at the pressure levels that define the layer's top and bottom. The absolute humidity at 1013 mbars was extrapolated from the values at 925 to 1000 mbars.

The PWV in each layer thickness in kg/m^2 is the average humidity (g/m^3) times the layer thickness (m) divided by 1000. Each layer thickness is the scale height times the natural logarithm of the ratio of the bottom to top pressure levels, where the scale height is the ideal gas constant times the layer average absolute temperature divided by the product of the air molar mass, the acceleration of gravity and 1000.

R^2 Coefficient of Determination of PWV versus GMST by Layer

Table A3	R^2 Values PWV vs GMST	
Layer (mbar)	ERA5	NCEP2
100-150	0.044	0.059
150-200	0.264	0.118
200-250	0.682	0.044
250-300	0.707	0.044
300-400	0.785	0.615
400-500	0.782	0.825
500-600	0.767	0.866
600-700	0.748	0.725
700-850	0.589	0.748
850-925	0.606	0.895
925-1000	0.644	0.901
1000-1013	0.571	0.865

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[i] This is the difference of the combined water vapour and lapse rate feedback of 1.30 W/(m^2·°C) less the lapse rate feedback of -0.50 W/(m^2·°C) as given in AR6, WG1, 7.4.2.2, pages 969-970.

[ii] This is the effective radiative forcing of a doubling of CO_2 of 3.93 W/m^2 [AR6, WG1, 7.3.2.1 page 945 and Table 7.4, page 945] divided by the planck response of 3.22 W/m^2/°C [AR6, WG1, 7.4.2.1, page 968 and Table 7.10, page 978].

[iii] AR6, WG1, 7.5.5, page 1005 and figure 7.81(a), page 1006.