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Using Physical Models to Understand Water Vapor Feedback and Its Impacts

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Abstract:

The Earth's climate system is facing significant challenges due to both natural and human-caused climate change. Comprehending the complex feedback mechanisms in this system is essential for forecasting future climate conditions and formulating efficacious mitigation tactics. Among these, water vapor feedback is one that sticks out as being especially significant, since it can intensify the greenhouse effect and make a major contribution to global warming. This study examines the relationship between surface air temperature and water vapor concentration using a combination of thermodynamic concepts and physical models. It demonstrates how rising temperatures cause an increase in the atmospheric concentration of water vapor, creating a positive feedback loop that amplifies the greenhouse effect. The research also examines the influence of water vapor on the sensitivity of temperatures to CO_2, demonstrating that the existence of water vapor can significantly increase the responsiveness of temperatures to changes in CO_2 levels. These findings emphasize the large effect of water vapor in climate change and provide valuable insights for improving climate models and guiding policy decisions aimed at reducing the impacts of global warming. Beyond just theoretical comprehension, the consequences of this research offer useful applications in environmental policy and climate science.

Keywords: Water vapor feedback, thermodynamics, relative humidity, greenhouse effect

1. Introduction

Climate change is a phenomenon that has garnered significant attention due to its potential to alter the Earth's delicate balance. Climate change threatens ecosystems and societies, making research on climate feedback mechanisms essential for mitigation efforts.

To comprehend the intricate relationships that exist within the Earth's climate system, climate feedback mechanisms must be studied. Climate feedback is the term used to describe the process through which modifications to Earth's climate system cause additional modifications that either increase or decrease the initial effect. Water vapor feedback is one of the most significant and extensive types of climate feedback among many others, such as cloud and albedo feedbacks.

Since water vapor is the most prevalent greenhouse gas in the atmosphere, it plays a crucial role in the climate system. Water vapor has a concentration in the air that varies from 0% to 4%, but because of its vital function in absorbing infrared radiation, it is one of the most significant greenhouse gases in the atmosphere.

There are already many works for water vapor feedback. Alex Hall and Syukuro Manabe compared two ocean-atmosphere model (one with and one without water vapor feedback) to conclude that, in the setting of the model's unperturbed variability, water vapor feedback is positive [1]. Isaac M. Held and Brian J. Soden have given a relative comprehensive analysis of the water vapor feedback in their article, including many important models which will also be talked about in this paper [2]. A negative feedback mentioned by Robert Colman and Brian J. Soden is caused by the rate that atmospheric temperature drops with height [3]. But it is still smaller and less important than the water vapor, substantiating that water vapor is quite seminal [3]. Though many researches reveal that water vapor exacerbates the global warming, the lightness of water vapor that leads to a negative climate feedback and helps to stabilize the climate is mentioned by Seth D. Seidel and Da Yang [4]. This effect as well as other effects means the expectation and restriction of this paper.

This paper aims to give a more quantitative explanation of the physical mechanism of water vapor feedback. This paper is organized as follows. Section 2 mainly talks about the definition of the water vapor feedback and some physical character of water vapor. Section 3 uses detailed physical models and calculations to reveal that a rise in surface temperature leads to a higher concentration of water vapor, which in turn amplifies the greenhouse effect. This positive feedback loop is a critical factor in the amplification of global warming. Section 4 includes the restrictions and expectations of this paper while Section 5 emphasizes and extends the conclusion of this article once again.

In summary, this paper synthesizes the findings of many researchers and utilizes thermodynamics models as well as some simple climate models to provide a comprehensive overview of the physical mechanisms underlying water vapor feedback.

2. Theoretical Basis

2.1 The Physical Properties of Water Vapor

The gaseous form of water, or water vapor, is a common element of the atmosphere on Earth. It is highly variable in concentration, ranging from about 0.25% in dry air to as much as 3% in humid conditions. So the concentration of water vapor has obvious regional differences between tropical areas and polar regions.

A key characteristics of water vapor is its ability to absorb infrared radiation, making it a potent greenhouse gas. As shown in Fig. 1(b) and 1(c), water vapor significantly contributes to the absorption of radiation at both the ground and tropopause levels. This absorption primarily occurs at wavelengths of approximately 1 μm and above 15 μm, which fall within the infrared radiation spectrum.

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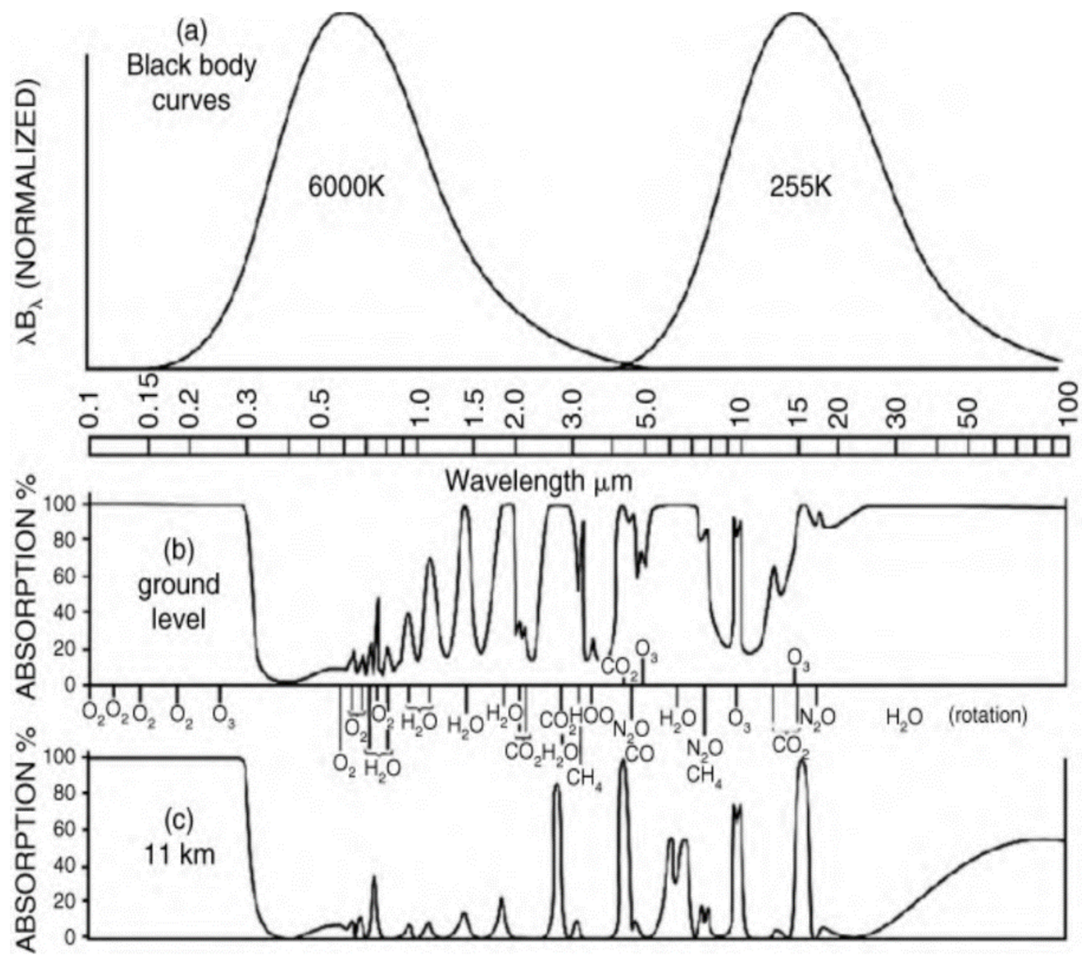

Fig. 1 (a) The Earth's (T = 255 K) and the Sun's (T = 6000 K) normalized blackbody emission spectra as a function of ln λ (top). (b) The percentage of radiation that is absorbed as it rises through the atmosphere from the ground to the top, plotted against wavelength. (c) The percentage of radiation absorbed as a function of wavelength from the tropopause, which is normally located at a height of 11 km, to the top of the atmosphere. Additionally shown are the atmospheric chemicals that contribute significantly to the absorption properties at each frequency [5]

The phase changes of water vapor, from evaporation to condensation, are fundamental to the water cycle. When water vapor condenses, it releases latent heat, which will be discussed later.

2.2 The Definition of Water Vapor Feedback

By definition, water vapor feedback is the link between surface air temperature and water vapor, whereby a change in radiative forcing causes the surface air temperature to fluctuate. This variation in water vapor can then either intensify or decrease the initial temperature change. Clearly in Fig. 2, the rise of temperature will cause changes in the concentration of water vapor, which amplify or weaken the greenhouse effect to alter the temperature.

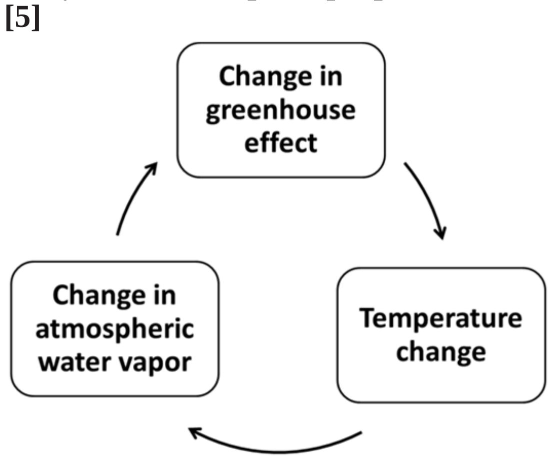

Fig. 2 The definition of water vapor feedback

Research by numerous academics has shown that the water vapor feedback is positive, meaning that as temperatures rise, more water vapor will be released into the atmosphere [2,6]. In the subsequent discussion, the arrows in Fig. 2 implying how the one affects another will be the focus of attention. And this paper tries to give a more quantitative explain of these arrows.

2.3 Some Basic Concepts

In order to quantify the concentration of water vapor in the air, we need to introduce the partial pressure. And according to the Dalton's law, the partial pressure can represent the concentration. So, we can transfer to research how the partial pressure will change when the temperature varies. This part introduces these basic concepts first.
The overall pressure is equal to the sum of the partial pressures of the various gases, according to Dalton's law, which is:

$$p_{total} = \sum_{i=1}^{n} p_i \tag{1}$$

where $p_1, p_2, \ldots, p_n$ reflect each component's partial pressures.

$$p_i = p_{total} x_i \tag{2}$$

pi=ptotalxiwhere x_i is the mixture of all n components' mole fraction of the i-th component. That means the partial pressure of water vapor can represent its quantity.

Assume p is the water vapor partial pressure and p_{total} is the pressure of atmosphere. p is constrained by the saturation water vapor pressure p_s, which defined as in thermodynamic equilibrium with liquid water. When the pace at which the liquid evaporates and the rate at which the vapor condenses, this equilibrium is preserved.

Besides, the ratio $H \equiv p / p_s$ is called relative humidity, which is expressed as a percentage and indicates how close the air is saturated with water vapor.

3. The Mutual Influence Between Temperature and Water Vapor Concentrations

The mechanism is divided into two parts in Section 3: how an increase in temperature leads to a concentration of water vapor, and how an increase in water vapor accelerates temperature rise.

3.1 Temperature Rise Increase Water Vapor Concentration

3.1.1 Saturated Vapor Pressure Equation

According to the Clapeyron's equation, we have

$$\frac{dp_s}{dT} = \frac{L}{T\left(V_m^{\beta} - V_m^{\alpha}\right)} \tag{3}$$

where L represents the phase transition's latent heat absorbed by a 1 mol substance when transitioning from the alpha phase to the beta phase, and T is the temperature of the atmosphere, and $V_m^{\beta}, V_m^{\alpha}$ represents the molar volume of beta phase and alpha phase respectively [7].
Let alpha phase represents the liquid water phase and beta phase represents the water vapor phase. Assume that $V_m^{\beta} \gg V_m^{\alpha}$ and it's ideal gas, $p_s V_m^{\beta} = RT$ We can get:

$$\frac{1}{p_s}\frac{dp_s}{dT} = \frac{L}{RT^2} \tag{4}$$

After accumulating points, we have:

$$lnp_s = -\frac{L}{RT} + C \tag{5}$$

where C is a constant. (5) is called saturated vapor pressure equation. From equation (5), we can find that if the temperature is higher, since L and R are both positive, saturation water vapor pressure p_s will rise.

3.1.2 Relative Humidity

In fact, the atmosphere on Earth is not entirely saturated with water vapor. That means we cannot get the actual concentration of water vapor only through p_s. We need to multiply p_s by relative humidity H so as to get the water vapor partial pressure. Relative humidity as above expresses the degree of the saturation of water vapor. When relative humidity becomes 100%, the water vapor is saturated and start to condense, forming the cloud or contributing to precipitation. So, Sherhood et al. have underscored the importance of the change of relative humidity [8]. A portion of the Earth's atmosphere's relative humidity is depicted in Fig. 3.
One significant theory holds that when the atmosphere warms, its relative humidity stays constant, which has been used since 1963 [9]. This is a great method for simplifying calculations and also appears to be reasonable.
There is an explanation on why the atmosphere's relative humidity doesn't change. Since the ocean makes up the majority of the Earth's surface, we start by taking the evaporation E into account. A reference height (supposed to be 5 m), where T_a is the temperature and H_a is the relative humidity, permits the modeling of E as proportional to the variance between the atmospheric vapor pressure and the saturation vapor pressure at surface temperature T_* [2]. We have,

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$$E \approx C\left(p_s(T_*) - H_a p_s(T_a)\right) \quad (6)$$

Assume that the atmosphere and surface both warm by 1 K and that there is no rise in atmospheric vapor pressure ($p_s(T_*)$ and $p_s(T_a)$ rise while H_a decreases, but $H_a p_s(T_a)$ remains unchanged). The evaporation of water vapor will thus rise in order to avoid the near-surface relative humidity from decreasing noticeably as the environment heats, as it is highly improbable that C will change significantly.

It is true that there are indeed some changes of relative humidity due to the climate changes, but Soden and Held claimed that GCMs (general circulation models) forecast relatively small and inconsistently signed alterations in relative humidity, which do not substantially impact the global water vapor radiative feedback [10]. So we can approximately assume that the relative humidity remains constant.

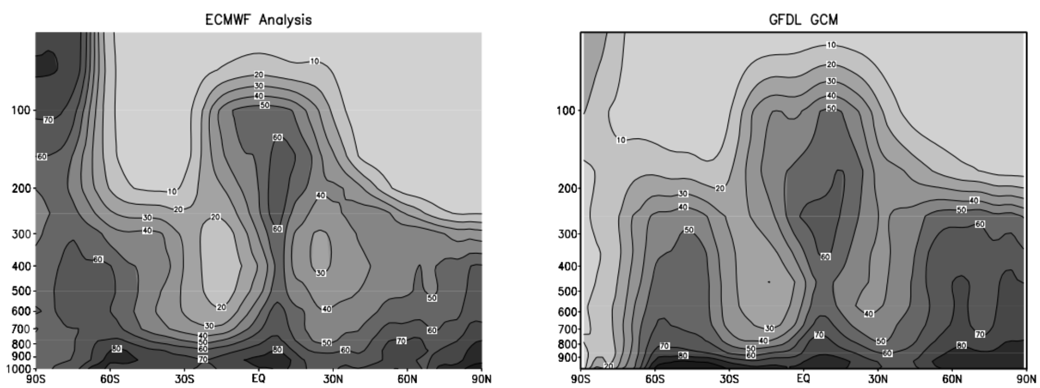

Fig. 3 The general circulation model (GCM) of the Geophysical Fluid Dynamics Laboratory (GFDL) (left) and the analysis system of the European Centre for Medium-Range Weather Forecasts (right) produced height-latitude cross sections of the zonal-mean relative humidity for July 1987 [2]

In summary, according to saturated vapor pressure equation and the unchanged relative humidity, if the air temperature is higher, the saturation water vapor pressure p_s will go higher, then the actual water vapor pressure $p(=Hp_s)$ will go higher. According to Dalton's Law, that means there are more water vapor in the atmosphere.

3.2 An Increase in Water Vapor Concentration Accelerate Temperature Rise

A very important basic thesis in this part is that the Earth's energy balance is the equilibrium between the energy that the planet receives and the energy that it emits.

Assume that the received sunlight flux is S and the outward surface radiation is R, then we have $S = R$. Usually, the power of solar flux is $1367W/m^2$ and S equals to $(1-\alpha_p)\pi a^2 S_0$, where α_p is the average planetary albedo and a is the radius of Earth. Since the surface area of Earth is $4\pi a^2$, so the solar flux per square meter is $S_0/4$. Using Stefan-Boltzmann law we can get that the total emitted terrestrial radiation is $4\pi a^2 \sigma T_e^4$, where T_e is defined as emission temperature. So,

$$T_e = \left(\frac{(1-\alpha_p)S_0}{4\sigma}\right)^{\frac{1}{4}} \approx 255K \quad (7)$$

The real surface temperature T_s is not as cold as the emission temperature, because of the existence of greenhouse effect. So this paper will consider a simple greenhouse model next.

3.2.1 Water Vapor Absorbs Infrared

According to Fig. 4 shown as the greenhouse model in Alan Plumb's book, we suppose the atmosphere has absorptivity ?,$(0<?<1)$ [5]. So $A\uparrow = A\downarrow = \epsilon\sigma T_a^4$ and $S\uparrow = \sigma T_s^4$. Since $S = R$, we can have equation 8 when considering the energy balance per square meter,

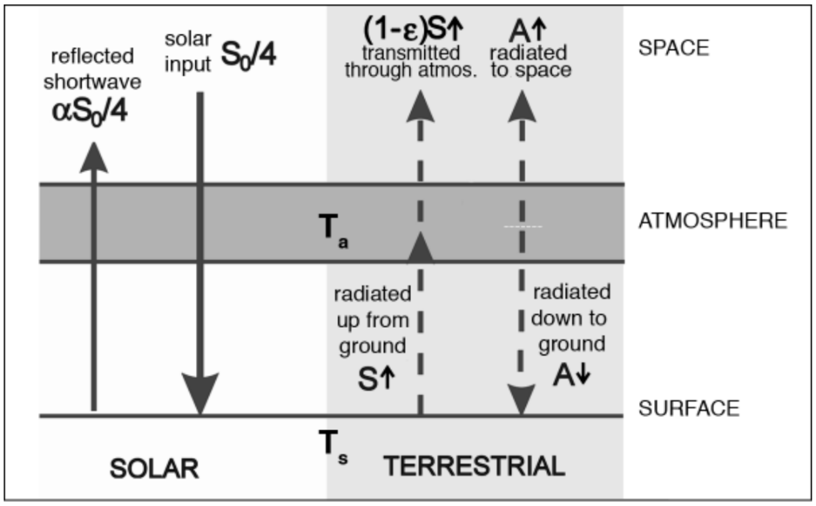

Fig. 4 A straightforward model of a greenhouse with a surface at T_s and an atmosphere at T_a that is exposed to $S_0/4$ solar radiation [5]

$$\frac{(1-\alpha_p)S_0}{4} = \sigma T_e^{\,4} = S\uparrow - A\downarrow = (1-\epsilon)S\uparrow + A\uparrow \qquad (8)$$

Using equation (8), we can get the surface temperature,

$$T_s = \left(\frac{2}{2-\epsilon}\right)^{\frac{1}{4}} T_e \qquad (9)$$

where $T_e = 255K$.

That means if ?0 , $T_s = T_e$; and if $\epsilon \sim 1$, $T_s = 2^{\frac{1}{4}} T_e$. The atmosphere absorbs more energy (ϵ bigger), the surface temperature is higher. It is common knowledge that the primary gaseous source of infrared opacity in the atmosphere is water vapor. Increasing the concentration of the water vapor means that the atmosphere can absorb more infrared, causing higher ϵ, and causing higher surface temperature T_s.

3.2.2 Water Vapor Makes Temperatures More Sensitive to CO2

It is obvious that CO_2 is one of the main reasons of global warming. And water vapor can promote the greenhouse effect. This phenomena has been discussed in Isaac M. Held and Brian J. Soden's work [2]. Listing our mainly considered parameters on which S and R depend, we have, schematically,

$$S(H_2O) = R(T, H_2O, log_2CO_2) \qquad (10)$$

where T is the surface temperature and log_2CO_2 is the logarithm of the carbon dioxide concentration (base 2) [2]. Isaac and Brian considered two conditions, one with fixed water vapor and one with the temperature-dependent water vapor [2].

In the first condition, by perturbing CO_2, the temperature variation dT satisfies

$$\frac{dT}{dlog_2CO_2} = -\frac{\partial R}{\partial log_2CO_2} / \frac{\partial R}{\partial T} \equiv \Delta_0 \approx 1K \qquad (11)$$

when H_2O is stable. However, if we set $H_2O = H_2O(T)$, the reaction of temperature to a doubling of CO_2 is now

$$\frac{dT}{dlog_2CO_2} = \frac{\Delta_0}{1-\beta_{H_2O}} \qquad (12)$$

where,

$$\beta_{H_2O} \equiv \left(-\frac{\partial R}{\partial H_2O} + \frac{\partial S}{\partial H_2O}\right)\frac{dH_2O}{dT} / \frac{\partial R}{\partial T} \qquad (13)$$

By comparing equations (12) and (13), we can determine that the magnitude of the water vapor feedback is measured by the value of the nondimensional ratio, β_{H_2O}. We can derive the estimate $\beta_{H_2O} \approx 0.4$, which indicates there is a ≈ 1.7 increase in temperature sensitivity to CO_2 [2]. That means the growth rate of the temperature of the model with water vapor is 1.7 times that of the model without water vapor.

This indicates that when considering water vapor in the global model, temperature is more sensitive to the increase in carbon dioxide, which is of great significance for predicting global warming

3.3 Conclusion

According to earlier research, a rise in temperature causes the amount of water vapor in the atmosphere to rise, which in turn causes the temperature to rise further—a vicious cycle. Furthermore, as the concentration of carbon

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dioxide rises, the water vapor present will quicken the process of heating the carbon dioxide, intensifying the greenhouse effect.

4. Limitations and Controversies of Current Research

The discussion above proves that water vapor feedback is a positive feedback through physical models and detailed calculation. However, there are many limitations for these results, such as the overly simplified model assumptions. Like the simple greenhouse model talked in 3.2.1, we assume the atmosphere has the same temperature, which is impossible in the real world. Maybe we should divide the atmosphere into more layers with the same temperature, which will certainly increase our computational workload. Similarly, there is still not quantitative way to accurately define the value of (Tex translation failed) and its variation due to the climate change.

Moreover, only parts of the properties of water vapor have been considered. Considering the weight of water vapor, its lightness contributes to a form of negative feedback that stabilizes tropical climates by raising outgoing longwave radiation (OLR), according to research by Seth D. Seidel and Da Yang [4]. Water vapor is also the main cause for the formation of cloud, thus certainly influencing the cloud feedback. Research by Ceppi et al. reveals that changes in cloud cover and properties due to global warming can lead to either positive or negative feedback, complicating the prediction of future climate scenarios [11]. Regional differences in water vapor also needs to be considered for future research, since this difference can more or less increase the effect of water vapor feedback.

5. Conclusion

This paper synthesizes the findings of some researchers and employs thermodynamic models as well as simple climate models to provide a comprehensive overview of the physical mechanisms underlying water vapor feedback.

Water vapor, being the most prevalent greenhouse gas, significantly contributes to the absorption of infrared radiation at both ground and tropopause levels. The study also highlights the importance of relative humidity, which, despite minor variations due to climate change, remains relatively constant, allowing for a stable calculation of water vapor's impact on temperature.

According to the study, there is a positive feedback loop in the water vapor feedback system. A vicious cycle is created when temperatures rise because a higher concentration of H_2O in the atmosphere is caused by an increase in temperature, taking into account the saturated vapor pressure equation and pertinent constant relative humidity. This intensifies the greenhouse effect and raises temperatures even more when a simple greenhouse model is analyzed. Furthermore, the trend of global warming is accelerated by the existence of water vapor, which increases temperature sensitivity to CO_2 concentrations.

In conclusion, the paper investigates how water vapor feedback contributes to climate change. Future research should consider regional differences in water vapor and its effects on cloud formation and feedback, as well as the potential stabilizing effect of water vapor on tropical climates.

References

[1] Hall, A., & Manabe, S. The role of water vapor feedback in unperturbed climate variability and global warming. Journal of climate,1999, 12(8), 2327-2346.

[2 Held, I. M., & Soden, B. J. Water vapor feedback and global warming. Annual review of energy and the environment, 2000 , 25(1), 441-475.

[3] Colman, R., & Soden, B. J. Water vapor and lapse rate feedbacks in the climate system. Reviews of Modern Physics, 2021, 93(4), 045002.

[4] Seidel, S. D., & Yang, D. The lightness of water vapor helps to stabilize tropical climate. Science advances, 2020, 6(19), eaba1951.

[5] Marshall, J., & Plumb, R. A. Atmosphere, ocean and climate dynamics: an introductory text. Academic Press, 1961.

[6] Rind, D. Water vapor feedback. In Frontiers in the Science of Climate Modeling: A Symposium in Honor of Professor Robert D. Cess, 2019.

[7] Koutsoyiannis, D. Clausius–Clapeyron equation and saturation vapour pressure: simple theory reconciled with practice. European Journal of physics,2012, 33(2), 295.

[8] Sherwood, S. C., Ingram, W., Tsushima, Y., Satoh, M., Roberts, M., Vidale, P. L., & O'Gorman, P. A. Relative humidity changes in a warmer climate. Journal of Geophysical Research: Atmospheres,2010, 115(D9).

[9] Möller, F. On the influence of changes in the CO2 concentration in air on the radiation balance of the earth's surface and on the climate. Journal of Geophysical Research, 2019, 68(13), 3877-3886.

[10] Soden, B. J., & Held, I. M. An assessment of climate feedbacks in coupled ocean–atmosphere models. Journal of climate, 2006, 19(14), 3354-3360.

[11] Ceppi, P., Brient, F., Zelinka, M. D., & Hartmann, D. L. Cloud feedback mechanisms and their representation in global climate models. Wiley Interdisciplinary Reviews Climate Change, 8(4),2017.