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Water vapour and greenhouse effect

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Water content of the atmosphere and its role in the greenhouse effect is investigated. Values of solar constant measured by satellite Nimbus-7 channel 100 have been used for calculating effective temperature of the atmosphere by Stefan-Boltzmann's law. The greenhouse effect is defined as the difference between the surface temperature and the atmospheric effective temperature. The yearly variation of greenhouse intensity was calculated. It was found that relation between greenhouse intensity and water vapour content is logarithmic.

Keywords: greenhouse effect, water vapour

1. Introduction

Greenhouse gases of anthropogenic origin and their effect on atmospheric temperature have been widely studied (*e.g.* Shine, 1991; Wuebbles et al., 1995), along with uncertainties involved. Though water vapour is not anthropogenic in origin, it is the most important greenhouse gas.

Water vapour and clouds are one of the most important parameters for understanding climate change. Manabe and Wetherald (1967) have shown a long time ago that water vapour feedback plays an important role in the behaviour of the climate system. The complete understanding of this feedback and the distribution of water vapour should be known as completely as possible, and its radiative effects must be considered in detail (Gutzler, 1992).

A comprehensive radiation scheme was developed by Slingo and Schrecker (1982) including, among others, the absorption by water vapour and ozone, the scattering, and the absorption by cloud drops. The scattering properties of the cloud drops were examined in terms of water content and equivalent radius.

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The annual cycle of tropospheric water vapour was studied by Gaffen et al. (1992) using radiosonde data. Major humidity variables: dew point (Td), relative humidity (RH) at various levels, and precipitable water (PW) for two layers (up to 500 hPa) were determined. Precipitable water is a measure of the column water vapour content integrated between two levels of specific humidity. It was found that in middle and high latitudes RH is approximately constant throughout the year, but in low latitudes it shows a seasonal variation. The annual cycle of the PW is similar to that of RH. In middle and high latitudes PW follows the variation of the temperature. Based on the existence of distinct humidity regimes we must conclude that humidity parameters should not be applied globally.

Stephens (1990) emphasized the necessity of involving satellite data to measure the atmospheric water vapour. He used data obtained by SMMR (Scanning Multichannel Microwave Radiometer) on Nimbus-7. It was found that high increase in the monthly mean atmospheric water vapour is accompanied by increase of the sea surface temperature (SST) above about 20 °C. It was also revealed that annual cycle of water vapour on regional scale generally correlates with the annual cycle of SST.

Raval and Ramanthan (1989) made an attempt to provide a quantitative relationship between the greenhouse effect and the water vapour content using satellite measurements. They defined the greenhouse effect as the difference between the amount of infrared energy emitted by the surface and measured at the top of the atmosphere. Under cloudless skies it was found that the greenhouse effect increases linearly with increasing SST and logarithmic with PW. The rate of increase of the greenhouse effect with SST shows that a positive feedback exists between the sea-surface temperature, the water vapour and the greenhouse effect.

Duvel and Breon (1991) investigated the response of the clear-sky greenhouse effect to SST change using outgoing clear-sky longwave radiation measurements. The greenhouse effect and the precipitable water content were also analyzed. Similar to results above it was found that greenhouse intensity depends logarithmically on PW. The dependence of both quantities on SST was also found to be non-linear, especially for high SST (>25 °C). The sensitivity of the greenhouse effect to interannual SST changes was studied. The largest sensitivity was found to occur for extreme temperature ranges.

Stephens and Greenwald (1991) used data set of ERBE (Earth Radiation Budget Experiment) and Nimbus-7 data sets for exploring the relationship between the greenhouse effect, water vapour and SST. Model calculations for the equilibrium condition were also executed. The radiative equilibrium theory predicts that greenhouse effect is directly proportional to the gray body optical depth of the clear atmosphere and proportional to the precipitable water content. It is also known that the atmospheric greenhouse trapping increases with SST and that the water vapour content can be explained by simple thermodynamical arguments, except for the so-called super greenhouse effect found at high SST (above 25 °C).

Based on radiative transfer theory and satellite observations Hallberg and Inamdar (1993) state that the super greenhouse effect arises when the middle and upper troposphere is particularly moist and the temperature lapse rate is very unstable. The most probable reason of the super greenhouse effect is the increase of temperature lapse rate and that of atmospheric water vapour caused by the tropical atmospheric circulation. In this way, both thermodynamical and dynamical processes play an important role in the atmospheric greenhouse trapping.

Stephens et al. (1993) examined the interactions between the hydrology and the radiative processes. The effect of the clear sky, the cloud albedo and cloud radiative forcing on the SST were examined. Model results and observations were compared. Qualitative agreement was found between the variations of greenhouse parameter with both column water vapour and SST. However, quantitative differences exist that were found between the simulated and the observed radiative properties of clouds.

Rind et al. (1991) – using both observational and model results – also support the conventional positive feedback provided by water vapour. Cess (1991) argues those results and makes an attempt to revise our understanding of water-vapour feedback. Reference is made to Lindzen (1990), who suggests that increased convection due to warmer climate will cause negative water-vapour feedback by drying the atmosphere. The point that convection will be enhanced in the case of global warming can be accepted, since 19 GCMs had been applied for prediction using different parameterization of convection (Rind et al., 1991). However, it is doubtful whether convection results in moisture or dryness in the atmosphere.

Contrary to Lindzen (1990), Shine and Sinha (1991) used radiative transfer calculations to show whether it is true that only changes in the upper atmospheric water vapour can alter the radiation budget of the atmosphere causing thereby positive water vapour feedback. It was found that Earth's radiation budget mostly results in changes of water vapour concentration in the lower troposphere.

Sinha (1995) investigated relative influence of lapse rate and water vapour on the greenhouse effect using a normalized parameter to measure the greenhouse effect, as defined in Raval and Ramanthan (1989). It was found that beyond tropics the lapse rate feedback exceeds the water vapour feedback (particularly over land). Utilizing a radiative-convective model, it was stated that increasing lapse rate by 6%, the lapse rate feedback amplifies the modeled water vapour feedback by 40%, but a 12% reduction in the magnitude of lapse rate completely nullifies the water vapour feedback.

Chahine (1992) emphasizes that uncertainties in estimating the future climate are primarily due to an inadequate understanding of the hydrological cycle. The author refers to recently analyzed data from the NOAA weather satellites showing that independent of seasons the water vapour content of the atmosphere increases throughout the troposphere as a function of increased sea surface temperature. It is also suggested that for the observation of hydrological cycle traditional operational weather data and satellites must be combined.

Summarizing the results above it can be concluded that there are two main types of studies. One type states that there exists a linear relationship between the greenhouse effect and the logarithm of water content. The other type argues this statement stressing that there are many complicating mechanisms in the atmosphere, which make determination of positive feedback of water content effects on the whole atmosphere doubtful. The water vapour feedback in the lowest troposphere is positive, however the quantity of water vapour in the upper troposphere is not well-known, since it mostly depends on transport processes. For investigating the role of water vapour including the quantity in the upper troposphere it is best to use satellite data (Houghton, 1995).

The goal of this paper is to study the relationship between the water content of the atmosphere and the greenhouse effect determined with the help of effective temperature using solar constant data measured by satellites. First it is summarized what is known about the water content of the atmosphere illustrated by some observational data, *i.e.* some water vapour characteristics. Their seasonal distribution for the two hemispheres will be introduced, followed by the investigation of the relation between the greenhouse effect and the precipitable water.

2. Data-base and method

The effective temperature of the atmosphere is calculated on the basis of measured data. The daily values of the solar constants from November 1978 to April 1991 are available from the U. S. Department of Commerce. This data set includes values of 150 monthly solar constants, which makes the statistical investigation of the problem possible.

The relation between the solar constant and the effective temperature can be expressed by the following formula:

$$S(1-\alpha)\,\pi R^2 = \sigma T_e^4\, 4\pi R^2 \tag{1}$$

where S (W/m^2) is the solar constant, R is the radius of the Earth, α is albedo, and T_e is the effective temperature of the atmosphere. After some simplifications one obtains:

$$T_e = [S(1-\alpha)/4\sigma]^{1/4}, \tag{2}$$

where $\sigma = 5.76 \times 10^{-8}$ W/m^2 K^4 is the Stefan-Boltzmann constant.

3. The greenhouse effect of the atmosphere-Earth system

The knowledge of the temperature regime allows the determination of the greenhouse effect of the Earth-atmosphere system. The yearly course of the temperature of the Earth surface can be found in Rákóczi (1989).

If the intensity of the greenhouse effect is defined as the difference between the actual temperature and the effective temperature, first of all it is necessary to calculate the effective temperature for each month. The effective temperature can be determined by the Stefan-Boltzmann's law (2).

The solar constant is a parameter of the Earth and according to satellite measurements its value is 1372 Wm^{-2} in every month. The albedo has a yearly variation, with seasonal values based only on satellite measurements:

Winter: 0.309, Spring: 0.2906, Summer: 0.2878, Autumn: 0.310

By using the above albedo values and the measured solar constant, the effective temperature (T_e) can be determined. Its values are presented in Table 1. It can be seen that the surface temperature has s significant yearly variation, therefore the same statement can be made regarding the variation of the greenhouse intensity.

The highest value can be found in September and the minimum in January. The yearly average of the surface temperature is 288 K and for the effective temperature the yearly average was found to be 255 K. It is in accordance with the results mentioned earlier. The difference of these temperatures, *i.e.* the greenhouse intensity, is 33 K, which also agrees with the results of earlier investigations.

Table 1. Monthly variation of surface temperature (T_g)*, effective temperature* (T_e)*, greenhouse effect* ($T_g - T_e$) *and water content (Wc,* 10^{12} *t)*

Month	T_g (K)	T_e (K)	$T_g - T_e$	Wc
January	286.2	254.0	32.2	12.1
February	286.5	254.0	32.5	12.4
March	287.3	256.0	31.3	12.4
April	287.9	256.0	31.9	12.6
May	288.5	256.0	32.5	12.7
June	288,9	256.2	32.7	13.3
July	290,0	256.2	34.0	13.6
August	289.4	256.2	33.8	13.6
September	288.6	254.0	34.3	13.3
October	288.3	254.0	34.3	12.8
November	287.6	254.0	33.6	12.6
December	286.6	254.0	32.6	11.9
Average:	288.0	255.0	33.0	12.7

We have tried to look for correlation between these results and the water content of the atmosphere. The water content of the atmosphere is the mass of the water in a column between the surface and the 300 hPa level expressed in 10^{12} tons. These values are tabulated in the last column of Table I. It shows that there is a minimum in winter and a maximum in summer.

The computed dependence of the greenhouse intensity on the water content (Wc) is presented in Fig. 1. It can be seen that a logarithmic relation exists between these variables. The equation of the logarithmic function is the following:

$$T_g - T_e = 14.817 \ln (\mathrm{Wc}) - 4.7318$$

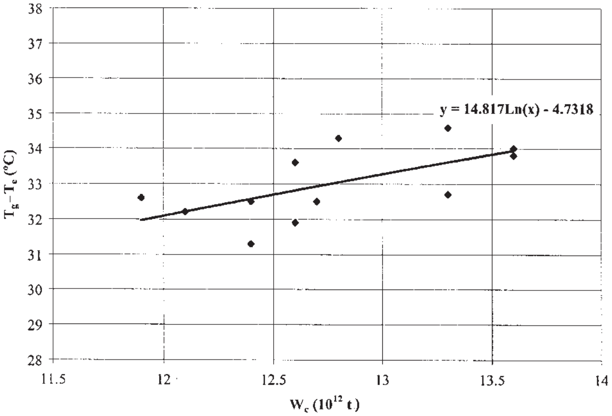

Figure 1. Relation between greenhouse effect ($T_g - T_e$) and the water content, Wc.

Based on this result it can be estimated how the intensity of the greenhouse effect might change if the water content changed *e.g.* by 10%. It is found that in the case of the increase of the water content by 10%, the greenhouse intensity would be 34.3 °C, so the change is 1.34 °C compared to the original value. It means that a higher or more intensive greenhouse effect can be expected than it is at present. Thus, if the water vapour content decreases by 10%, the greenhouse effect decreases by 1.6 °C.

5. Conclusions

Investigations and results can be summarized as follows:

a) On the basis of the references it seems that the humidity plays an important role in the greenhouse intensity.

b) Taking into account the seasonal variation of the albedo of the Earth-atmosphere system effective temperature (T_e) has been calculated.

c.) Making use of Rákóczi's earlier results concerning the ground temperature (T_g), greenhouse intensity had been determined ($T_g - T_e$). It was found that the greenhouse intensity also has yearly variation.

d) Knowing the values of the water content of the atmosphere (Wc), correlation analysis has been made between the greenhouse intensity and the water content. It was found that there is a logarithmic relation.

There is no doubt that the humidity of the atmosphere is a very important factor influencing the greenhouse intensity of the atmosphere. The greenhouse intensity can be characterized by calculating the effective temperature of the atmosphere. Since the monthly variation of the Earth surface temperature is known from former investigations, greenhouse intensity could have been calculated as the difference between the surface temperature and the effective temperature of the atmosphere. The greenhouse intensity also has a yearly variation. Humidity of the atmosphere can be characterized by its water content. The existing empirical logarithmic equation can be used for the estimation of the greenhouse intensity as a function of the potential changes of the water content. It was found that if the water content increases by 10%, it results in the increase of the greenhouse intensity by 1.34 °C. In the case of decrease of the atmospheric water content by 10%, the greenhouse intensity will decrease by 1.6 °C.

References

Cess, R. D. (1991): Positive about water feedback. Nature, **349**, 462–463.

Chahine, M. T. (1992): The hydrological cycle and its influence on climate. Nature, **359**, 373–379.

Duvel, J. P. and Breon, F. M. (1991): The clear-sky greenhouse sensitivity to a sea surface change. J. of Climate, **4**, 1162–1169.

Gaffen, D. J., Robock, A. and Elliot, W. P. (1992): Annual Cycle of Tropospheric Water Vapor. J. of Geophys. Res., **97**, No. D16, pp. 18, 185–18, 193.

Gutzler, D. S. (1993): Uncertainties in climatological tropical humidity profiles: Some implications for estimating the greenhouse effect. Journal of Climate, **6**, 978–982.

Hallberg, R. and Inamdar, K. (1993): Observations of seasonal variations in atmospheric greenhouse trapping and its enhancement at high sea surface temperature. Journal of Climate **6**, 920–931.

Houghton, J. T., Meira Filho, L. G., Callander, B. A., Harris, N., Kattenberg, A. and Maskell, K. (editors) (1995): Climate Change 1995. The Science of Climate Change. Published for the IPCC. Cambridge, University Press.

Johnson, F. S. (1954): The solar constant. Journal of Meteorology, **11**, No. 6, 431–439.

Lindzen, R. S. (1990): Some uncertainties regarding water vapor's role in climate sensitivity. Paper presented at the Workshop on the Role of Water Vapor in Climate Processes, Oct. 29–Nov. 1, 1990, NASA/Goddard Inst. of Space Studies, Easton.

Manabe, S. and Wetherald, R. (1967): Thermal equilibrium of the atmosphere with a given distribution of relative humidity. J. of Atmos. Sci., **24**, 241–259.

Rákóczi, F. (1989): Annual variation of some selected meteorological elements on the two hemispheres. Zeitschrift für Meteorologie, B**39**, H**4**, 193–201.

Raval, A. and V. Ramanathan, (1989): Observational determination of the greenhouse effect. Nature, **342**, pp. 758–761.

Rind, D., Chiou, E.-W., Chu, W., Larsen, J., Oltmans, S., Lerner, J., Mc. Cormick, M. P. and McMaster, L. (1991): Positive water vapor feedback in climate models confirmed by satellite data. Nature, **349**, 500–503.

Sellers, W. D. (1969: Physical Climatology, Chicago–London.

Shine, K. P. (1991): On the cause of the relative greenhouse strength such as halocarbons. Journal of the Atmospheric Sciences, **48**, 1513–1518.

Shine, K. P. and Sinha, A. (1991): Sensitivity of the Earth's climate to height dependent changes in the water vapor mixing ration. Nature, **354**, 382–384.

Sinha, A. (1995): Relative influence of lapse rate and water vapor on the greenhouse effect. Journal of Geophysical Research, **100**, D3, 5095–5103.

Slingo, A. and Schrecker, H. M. (1982): On the shortwave radiative properties of stratiform water clouds. Quarterly Journal of Royal Met. Society, **108**, 407–426.

Stephens, G. L. (1990): On the relationship between water vapour over the oceans and sea surface temperature. Journal of Climate, **3**, 634–645.

Stephens, G. L. and Greenwald, T. J. (1991): The Earth's radiation budget and its relation to atmospheric hydrology. 1. Observations of the clear-sky greenhouse effect. J. Geophys. Res., **96**, 15311–15326.

Stephens, G. L., Randall, D. A., Wittmayer, I. L. and Dazalich, D. A. (1993): The Earth's radiation budget and its relation to atmospheric hydrology. 3. Comparison of observations over oceans with GCM. J. Geophys. Res., **98**, 4931–4950.

United States Department of Commerce (1991): Solar Geophysical Data Comprehensive Reports. No. 564, Part II. for the period from 16 November 1978 through 30 April 1991.

Wuebbles, D. J., Jain, A. K., Patten, K. O. and Grant, K. E. (1995): Sensitivity of direct global warming potentials to key uncertainties. Climatic Change, **29**, 265–297.

SAŽETAK

Vodena para i efekt staklenika

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Proučene su količina i uloga vodene pare u atmosferi. Za procjenu efektivne temperature atmosfere Stefan-Boltzmannovim zakonom korištena je vrijednost solarne konstante izmjerena satelitom Nimbus-7 na kanalu 100. Efekt staklenika definiran je kao razlika između temperature na površini i efektivne temperature atmosfere. Izračunata je godišnja varijacija intenziteta efekta staklenika, te je nađena logaritmička veza između intenziteta efekta staklenika i količine vodene pare u atmosferi.

Ključne riječi: efekt staklenika, vodena para

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