DIRECT COMPARISON OF GLOBAL PRECIPITATION AND ATMOSPHERIC WATER VAPOR ISOTOPOLOGUE FROM SPACE AND MODEL

PERBANDINGAN PENGUKURAN ISOTOP PADA HUJAN DAN UAP AIR MENGGUNAKAN DATA SATELIT DAN IKLIM GLOBAL

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ABSTRACT

Stable isotopes in atmospheric water are important climatic tracers used to derive information on the moisture recycling, paleoclimate from ice cores, cloud physics, troposphere-stratosphere exchange, climate studies, hydrological cycle, etc. Some traditional methods to measure stable isotopes in the atmosphere are labor intensive and spatially limited. Nowadays, measurements of isotopes in the atmosphere are becoming visible using satellites to retrieve the data in one hand and using global climate models on the other hand. Therefore, this study has been carried out to compare the isotopes measurements using both the latest satellites measurements (SCIAMACHY and TES) and some global climate models (GissE, ECHAM, MUGCM) for direct comparison. The results from both satellites measurements and models simulations show that there are some isotope effects such as latitude effect, continental effect, and altitude effect. Interaction between surface and atmosphere can also be seen from the analysis. The stable isotopes comparison from satellites, models and ground observation is in a good agreement (±-100‰ The tropics and ±-260‰ The polar regions). The discrepancy of isotope from precipitation and water vapor also agrees well (-60‰ to -75‰ in tropics). In addition, a slope analysis from a correlation of total precipitable water and isotope ratio shows that measurements near from the surface is following Rayleigh-type rainout process and measurements in the middle troposphere is influenced by a mixing process.

Keywords: *Stable isotopes, atmospheric water, satellites measurements, GCM models, comparison*

ABSTRAK

Isotop stabil di atmosfer merupakan pelacak iklim yang penting yang dapat digunakan untuk memperoleh informasi dari daur ulang uap air, iklim paleo dari inti es, fisik awan, pertukaran lapisan troposfer dan stratosfer, pembelajaran iklim, siklus hidrologi, dan lain sebagainya. Beberapa metode tradisional untuk mengukur isotop stabil di atmosfer terbatasi oleh ketersediaan tenaga yang diperlukan dan luas jangkauan area yang bisa dicakup. Dewasa ini pengukuran isotop di atmosfer banyak dilakukan dengan menggunakan satelit dan model iklim global. Oleh karena itu, studi ini dilakukan untuk membandingkan hasil pengukuran isotop dengan menggunakan data satelit terbaru (SCIAMACHY dan TES) dan beberapa model iklim global (GissE, ECHAM, MUGCM). Hasil dari pengukuran satelit dan simulasi model menunjukkan adanya efek isotop seperti: efek lintang, kontinental, dan ketinggian. Interaksi antara permukaan dengan atmosfer juga terlihat dari hasil analisis. Perbandingan isotop yang diperoleh dari pengukuran satelit, simulasi model dan observasi menunjukkan hasil yang dapat diterima (±-100‰ di tropis dan ±-260‰ di daerah kutub), baik hasil antara isotop yang terdapat pada data hujan maupun isotop yang berada di uap air dengan perbedaan -60‰ sampai -75‰ di daerah tropis. Analisis kemiringan yang dilakukan juga menunjukkan bahwa hasil pengukuran di dekat permukaan bumi dipengaruhi oleh Rayleigh-type proses, sementara hasil pengukuran di lapisan tengah troposfer menunjukkan adanya pengaruh dari proses pencampuran uap air di atmosfer.

Kata kunci*: Isotop stabil, uap air di atmosfer, pengukuran satelit, model iklim global, perbandingan*

INTRODUCTION

Stable isotopes in atmospheric water are important climatic tracers used to derive information on the moisture recycling, paleoclimate from ice cores, cloud physics, troposphere-stratosphere exchange, climate studies, hydrological cycle, etc (Worden et al., 2006; Herbin, et al., 2007; Uemura, et al., 2008; Field, 2010). Some traditional methods to measure stable isotopes in the atmosphere use a mechanical cold trap device or tunable diode laser (TDL) absorption spectroscopy, which are installed in the balloon sounding, ship or aircraft observation vehicle but the measurements using those methods are labor intensive and spatially limited. Nowadays, measurements of isotopes in the atmosphere are becoming visible using satellites. However, only few measurements of water vapor in the lowest troposphere are available. The remotely sensed data are primarily focused in mid to upper stratospheric water vapor and lower stratosphere (Schmidt, et al., 2005). Only few measurements in troposphere are available.

The use of satellites to measure isotopic composition of water vapor has dramatically increased recently. There are some satellite sensors developed and dedicated to measure isotopes water vapor in the atmosphere such as: IMG (Interferometric Monitor for Greenhouse Gases) sensor on ADEOS (Zakharov et al., 2004; Herbin et al., 2007), TES (Tropospheric Emission Spectrometer) instrument on Aura (Worden et al., 2006, 2007), MIPAS (the Michelson Interferometer for Passive Atmospheric Sounding) instrument on Envisat (Payne, et al., 2007; Steinwagner et al., 2007, 2010; Lossow et al., 2011), and SCIAMACHY(Scanning Imaging Absorption Spectrometer for Atmospheric Chartography) measurements on Envisat (Frankenberg et al., 2009). Although those instruments have different characteristics such as wavelength, sensitivity, geometry viewing, the results from those measurements are complementary.

In contrast with the growth of satellites user, isotope-incorporated atmospheric general circulation models (AGCM) offer different approaches to understanding isotope ratio distribution such as: ECHAM AGCM (Hoffmann, 1998), GissE AGCM (Schmidt et al., 2005), MUAGCM (Brown et al., 2006), IsoGSM (Yoshimura et al., 2008), LMDZ-iso GCM (Risi et al., 2010), etc. Many models and studies compared the isotopes simulation results in precipitation with the GNIP data. On the other hands, only few studies have been carried out to compare the isotope water vapor data from satellite measurements with the results from model. Frankenberg et al., 2009 compared the SCIAMACHY deuterium measurements with IsoGSM model and afterward, Yoshimura et al., 2011 compared intensively the deuterium measurements from SCIAMACHY, TES and IsoGSM. Thus, this study compares the deuterium measurements from SCIAMACHY, TES and ECHAM.

This paper intensively shows a direct comparison of global isotopes data both in the precipitation and in the atmosphere from various isotopes measurement techniques starting from the space down to the earth and into your desk. "From the space down to the earth and into your desk", this means the global isotopes data are measured from satellites (space), in situ ground stations (down to the earth) and from the models simulation (into your desk). Two satellites data, some AGCM models and ground isotopes observation from IAEA database were used in this study for comparison. The comparison of satellites measurements with ECHAM-GCM has not been done before. Moreover, no studies compare their results with IAEA water vapor database.

The paper is organized as follows. The introduction part describes the importance of isotopes measurements, the past studies and why this study is performed. The second part discusses about the satellites (SCIAMACHY and TES), some AGCM models that have been used and in the end is isotopes in precipitation from IAEA networks. Chapter three, as the main part, is results and discussion. In this part the results are presented then followed by discussion, and finally, some conclusion can be drawn.

INSTRUMENTS AND METHOD

SCIAMACHY data

HDO data was retrieved using SCIAMACHY instrument aboard the European Space Agency (ESA)'s environmental research satellite ENVISAT with high sensitivity near the ground up to 10 km. SCIAMACHY has relatively high resolution (0.2 nm to 0.5 nm) and wide range coverage (240 nm to 1700 nm and in selected area between 2000 nm and 2400 nm). This high resolution and wide wavelength range makes SCIAMCHY able to detect many different gases, clouds and aerosols. The SCIAMACHY wavebands are UV-SWIR: 240-314, 309-3405, 394-620, 604-805, 785-1050, 1000-1750, 1940-2040 and 2265-2380 nm. In addition, SCIAMCHY has three different geometries, which are nadir, limb and sun/moon occultation. HDO data were retrieved using wavelength window ranging from 2355 to 2375 nm. The footprint resolution is 120 km by 30 km. HDO data retrieval was taking place from 2003 to 2005. The detail

information about the retrieval procedure and process can be found at Frankenberg et al., 2009.

TES data

TES (Tropospheric Emission Spectrometer) aboard Aura satellite is an infrared fourier transform spectrometer (FTS) that measures the spectral infrared (IR) radiances between 650 cm^{-1} and 3050 cm^{-1} in both a limb-viewing and a nadir mode. The resolution of IR radiance is 5.3 km by 8.4 km in the nadir viewing mode. In the nadir view, TES provides a vertical information of abundant atmospheric species not only HDO but also H_2O, O_3, CO and CH_4. HDO and H_2O profiles are obtained from TES thermal radiances between 1200 cm^{-1} and 1350 cm^{-1} (7400 to 8300 nm in wavelength). In this study, weighted mean values of the isotopic composition are calculated from heigth 550 and 800 hPa, where the HDO profiles are very sensitive. The data used in this study are from September 2004 to December 2009. The detail information about TES measurements can be found at Worden et al., 2006, 2007.

ECHAM model

ECHAM was developed in collaboration with the European Center of Midrange Weather Forecast (ECMWF) in Reading and the Max-Planck Institute for Meteorology in Hamburg. The ECHAM model used in this study has spatial resolution of 5.6° x 5.6° with vertical profiles from 1000 hPa to 0 hPa divided into 6 layers. ECHAM has an advantage compared with GISS model which ECHAM applied the semi-Lagrangian advection scheme to transport both active tracers (moisture and cloud liquid water) and corresponding passive tracers (moisture and the cloud water of isotopes). Two types of fractionation processes, equilibrium and nonequilibrium, are considered in the model. A disadvantage of this model is that ECHAM did not consider a fractionation during evaporation from land in its isotope module. The data used in this study is monthly data from 1971 to 2001. The detail information about ECHAM model can be found at Hofmann et al., 1998.

GissE GCM and MUGCM models

GissE GCM and MUGCM database can be downloaded from SWING website (http://www.bgc-jena.mpg.de/projects/SWING/). SWING (Stable Water Isotopes Intercomparison Group) has an objective to bring together an international intercomparison of current state-of-the-art water isotopes general circulation model and related observational isotopes data. In this website, isotopes data in precipitation from ECHAM, GissE, MUGCM and GNIP can be downloaded.

GISS model E known as GissE model has been developed by Schmidt (Schmidt et al., 2005). This new GissE model has some improvements compared with this predecessor. These improvements have been done on the cloud physics, surface boundary layer, and stratospheric circulation. The resolution of this model is relatively coarse 4° x 5° resolution. Most isotopes fractionation at a change of phase occurs at thermal equilibrium except: (1) surface evaporation from surface water uses a kinetic fractionation, (2) when condensing water vapor to ice, the kinetic efeect has been taking place, (3) kinetic fractionation factor has been used when evaporating liquid water into unsaturated air (Hoffmann et al., 1998; Schmidt et al., 2005). Moreover, this new version GissE model has two significant improvements which are the quadratic upstream scheme is involved and fractionation during condensation in a rising plume is performed. See Schmidt et al., 2005 for more detail information about this model.

The MUGCM (Melbourne University atmospheric General Circulation Model) is a spectral atmospheric model with R21 horizontal resolution (3.3° latitude x 5.6° longitude) and nine vertical levels in sigma coordinates. Moist convective, prognostic cloud fraction and two layers soil moisture scheme using a semi-Lagrangian transport scheme are included in this model. The isotopes tracer scheme is used in this model with the inclusion of equilibrium and kinetic isotopic fractionation. As described in Brown et al., 2006, evapotranspiration over land surface, ice, snow and frozen soil occurs without fractionation. Only over the ocean fractionation occurs during evaporation with kinetic effects from surface wind speed. Equilibrium fractionation in the atmosphere column to liquid occurs above -10°C and to solid below this temperature and Rayleigh fractionation is applied for solid condensate in case of convective precipitation (temperature below -10°C). Kinetic effects are included for all condensations if the temperature is below -20°C. See Brown et al., 2006 for more detail explanation about this model.

GNIP precipitation and water vapor network

The International Atomic Energy Agency (IAEA), in cooperation with the WMO, has long been operating the Global Network of Isotopes in Precipitation (GNIP) and recently, IAEA initiated effort not only to continue the measurements of isotopes data in precipitation but also to make isotopes water vapor data available through the group for Moisture Isotopes in the Biosphere and Atmosphere (IAEA-MIBA). For the moment, the water vapor data are only available from 10 countries (India, Portugal, Turkey, France, Brazil,

Egypt, Spain, Brazil, Morocco, Israel and Austria) while the precipitation data are available in many locations spreading over the World. The precipitation and water vapor isotope data can be downloaded from IAEA website (IAEA, 2005).

1 Data processing

All the HDO and Oxygen-18 data from observations and models are presented in delta deuterium (δD) and delta Oxygen-18 ($\delta^{18}O$) regarding to Vienna Standard Mean Ocean Water (VSMOW) expressed in permil (‰). Isotopic abundance for hydrogen and oxygen based on VSMOW standard is described as a follow:

$$R_{D/H} = \left(\frac{^2H}{^1H}\right)_{VSMOW} = 155.76 \pm 0.05\ x\ 10^{-6} \quad 1)$$

$$R_{18_O/16_O} = \left(\frac{^{18}O}{^{16}O}\right)_{VSMOW} = 2005.2 \pm 0.45\ x\ 10^{-6} \quad 2)$$

The isotopic abundance ratio is defined as $R = qHDO/qH_2O$, where q is the volume mixing ratio of HDO or H2O. This abudance ratio is also used for ^{18}O. Isotope composition is expressed as δD values, where:

$$\delta D\ permil = \left(\frac{R}{R_{SMOW}} - 1\right) x\ 1000 \quad 3)$$

Positive values indicate an enrichment of isotopes values compared to the standard. On the other hand, negative values indicate a depletion of heavier isotopes in the sample.

Since the water vapor and $\delta\ D$or $\delta^{18}O$ decrease with higher altitude, the average isotopes values from every layer use weighted mean values to compensate this altitude effect. The example weighted mean calculation for HDO is decribed as follows:

$$Weighted\ \delta D = \left(\frac{\sum_0^n (\delta D\ x\ H_2O)}{\sum_0^n H_2O}\right) \quad 4)$$

where $\delta\ D$is HDO values from every layer, H_2O is H_2O from every layers and n is a number of layers.

RESULTS AND DISCUSSION

The isotope data used in this study mainly is HDO since this data is available for all measurements. ^{18}O data is only available from models and ground stations while satellites only measure HDO due to wavelength limitless. Isotopes measurements in this paper divided into two types. First type is isotopes measurements in precipitation (HDO and ^{18}O) and second type is isotope measurements in water vapor (HDO only). Isotopes in water vapor are obtained from SCIAMACHY and TES satellites, ECHAM model, and from ground stations, whereas, isotopes in precipitation are obtained from GissE, MUGCM and ECHAM models, and from ground stations.

Comparison of average annual data

a) Isotope in water vapor

HDO data calculated from SCIAMACHY, TES and ECHAM are plotted on the world map (see Figure 1). The results from all of HDO measurements show that there is a strong latitude effect on HDO data. SCIAMACHY and the ECHAM model show stronger depleted in HDO in the higher latitude than TES because the TES measurement is less reliable in the higher latitude. The latitudinal mean δD was relatively large with values around -80 to -100‰ in the tropical region and it was decreasing down to -260‰ and more at higher latitudes. Humidity and temperature are the main parameters behind this latitude effect due to equilibrium and kinetic fractionation of isotopes in the atmosphere.

In the tropical area, there is a good agreement between the TES measurements and the ECHAM model. High enrichment of HDO shows in the whole Africa continent and South America, and Northern part of Australia while in Indonesia where the water vapor is higher, the enrichment of HDO is lesser. The higher evaporation processes from the land surface may likely trigger the enrichment of heavy isotopes in these regions and the less enrichment of HDO in Indonesia may be caused by the amount effect of isotopes (Dansgaard, 1964). The amount effect makes heavy isotopes leaving the cloud first as a precipitation and followed by the light isotopes. The SCIAMACHY measurements only show strong enrichment of HDO in the Amazon basin and Sahel area.

Latitudinal profile comparison in the tropical and sub-tropical region shows the overview of latitudinal effect (Figure 1 bottom right). This profile is an average latitude profile from longitude -180 degree to 180 degree. The average profiles from the measurements and model have the same pattern with strong enrichment of HDO in the tropical region and depleted in the sub-tropical regions. The maximum enrichment HDO in the tropical area is around -100‰ for TES and ECHAM while SCIAMACHY is around -130‰. The difference between measurements and model is greater in the sub-tropical regions than in the tropical regions, which are -50‰ in the northern hemisphere and -90‰ in the southern hemisphere. One should be noted that TES measurements are not reliable in the high latitude e.g. more than 45 degrees north and south (Worden et al., 2006).

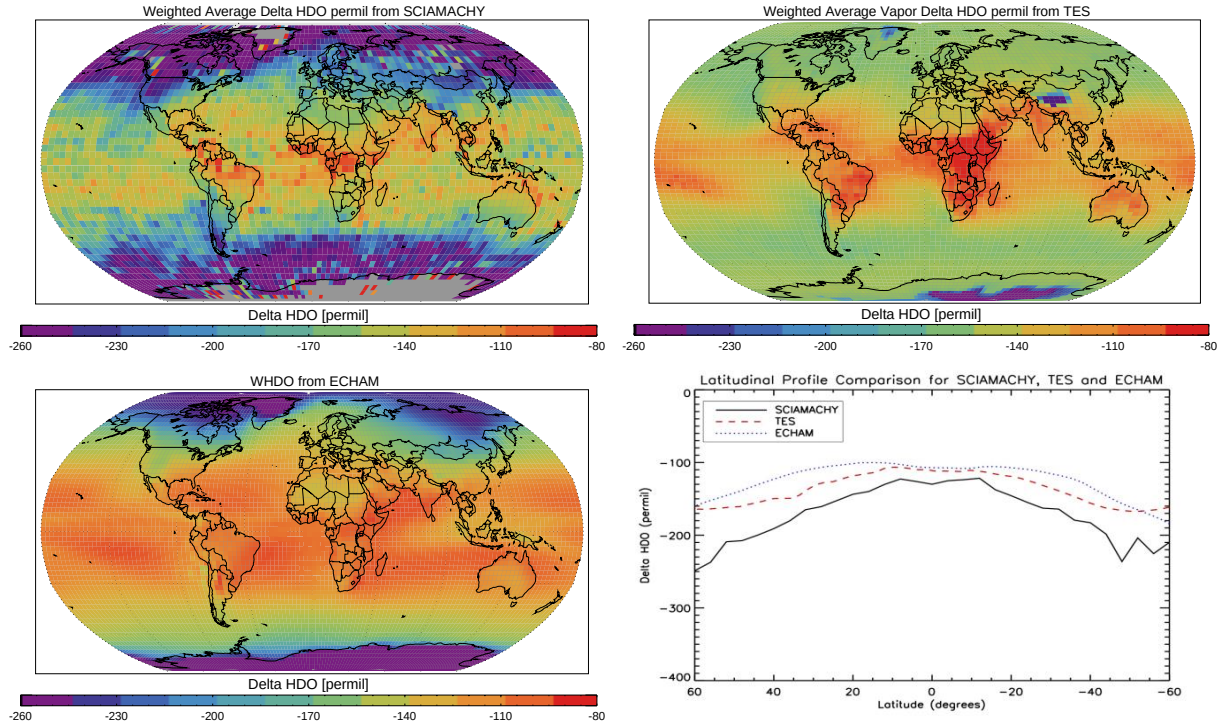

Figure 1 Annual average of weighted HDO in water vapor measured from SCIAMACHY, TES and ECHAM model; Latitudinal profile comparison in the tropical and sub-tropical region (bottom right).

In addition, continental effect and altitude effect are also observed in the results. Continental effect is observed in the North America and Eurasia continent while the altitude effect is strongly observed in the Andes Mountains and Himalayan for all measurements and in the Rocky Mountains for SCIAMACHY and ECHAM data. In contrast, Great Rift Valley in Africa does not give the altitude effect signature.

b) Isotope in precipitation

HDO and ^{18}O data in precipitation from the models are presented in Figure 2. The results from those models are comparable one to another except the HDO simulation from MUGCM. HDO simulation from MUGCM gives exceptional results, however, the ^{18}O result is acceptable. So far, there is no paper showing HDO results from MUGCM model even from the model creator.

Isotopes composition in precipitation simulated with the models also shows a latitudinal effect, altitudinal effect and continental effect. The water isotopes in precipitation in the tropical area are more enrich in heavy isotopes than in sub tropical or higher latitudes. Some depleted in heavy isotopes are also shown in mountainous area such as in Andes, Rocky Mountains and Himalayan. Continental effect is only shown in Central America and Eurasia. Moreover, ECTZ line in the tropic also can be seen clearly from the models. Isotopes data in Indonesia region are also depleted in heavy isotopes compared with the surrounding areas.

c) Comparison between isotopes in water vapor and precipitation from ECHAM model

From those models, only ECHAM model can simulate isotope composition in both water vapor and precipitation. Thus, the difference of HDO data in precipitation and water vapor can be made. Figure 3 illustrated this difference. The difference of HDO between water vapor and precipitation in tropic and sub tropic area is more or less -50‰ to -125‰. The big discrepancy occurs in Sahara, Sahel region, Amazon basin, Indonesia, and Europa while in Northern hemisphere, the discrepancy is very big especially in North America, Russia and North Asia.

The discrepancy in the tropical area over inland is more or less -75‰. It can be said that in tropical area, the HDO in water vapor is -75‰ depleted in heavy isotopes compared with precipitation. The enrichment of HDO value in the precipitation can be explained by diffusive exchange in the atmosphere due to heavy convective precipitation rate in the tropical area.

When precipitation rate increases, relative humidity increases and diffusive exchanges are more effective to re-enrich the precipitation (Dansgaard, 1964; Risi, 2008). Gedzelman (1994) also shows that in the convective rain, the isotope

value in precipitation is higher compared with stratiform precipitation. Moreover, TOGA COARE model results from Bony et al. (2008) also shows that if precipitation has HDO value more or less -30‰ then the HDO value in atmosphere (1000 hPa) is approximate -90‰ or we can say the difference is ±-60‰. This discrepancy is similar with ECHAM model which is ±-75‰.

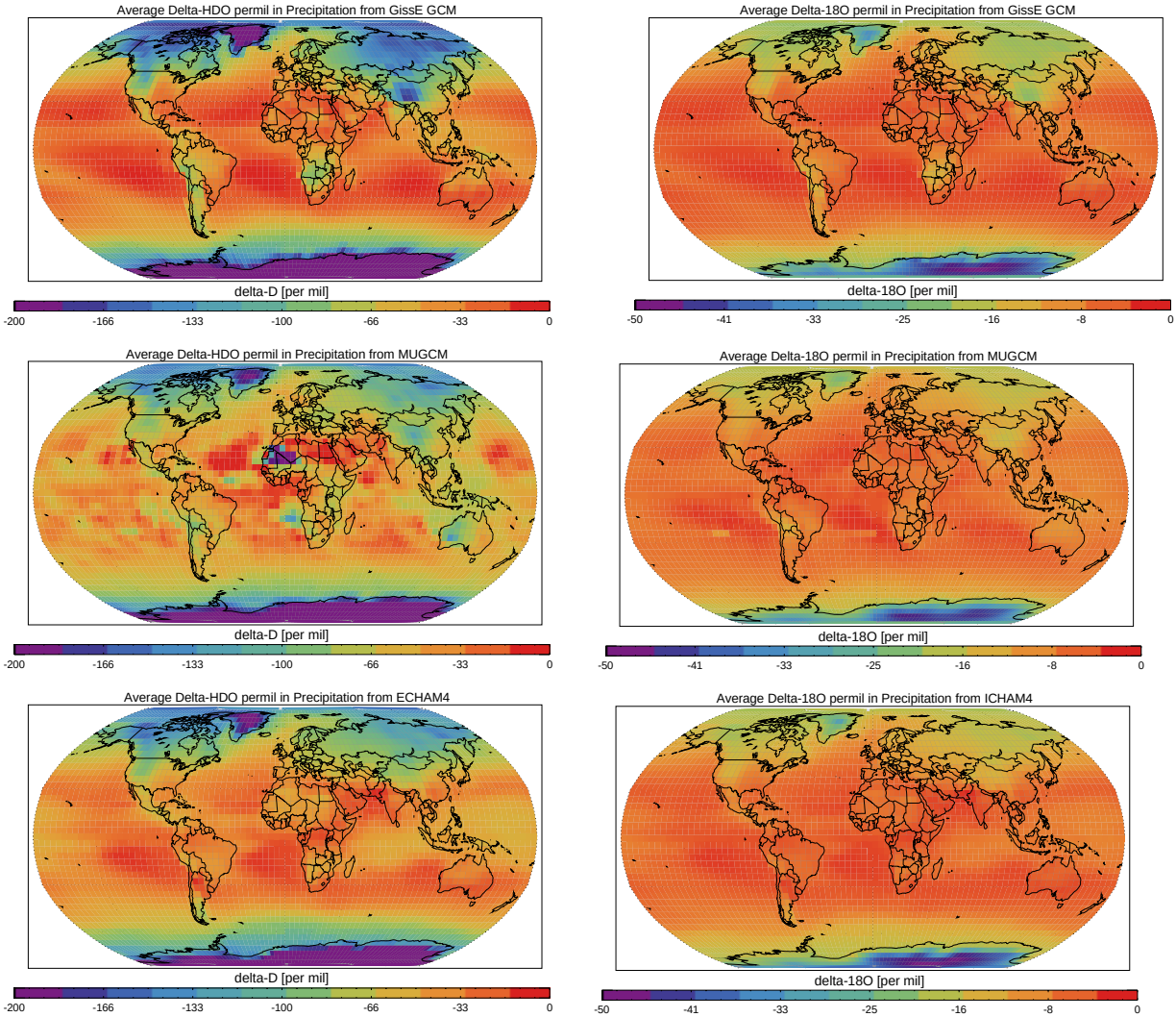

Figure 2 Annual average of HDO and ^{18}O in precipitation modeled from GissE, MUGCM and ECHAM models

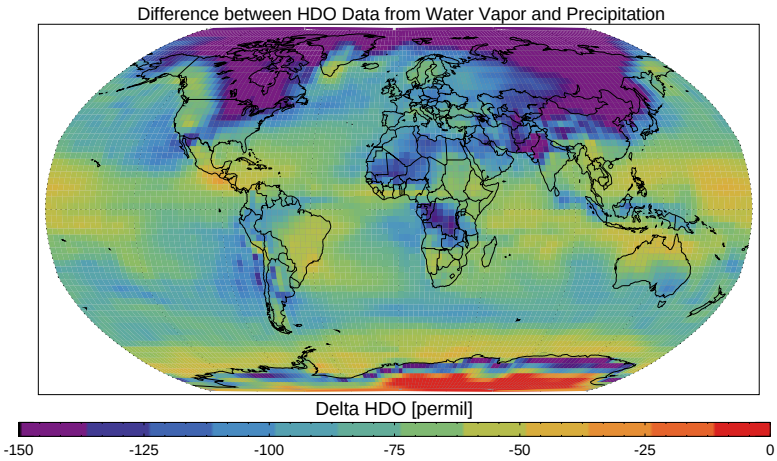

Figure 3 Difference between HDO in water vapor and precipitation (δD in water vapor-precipitation)

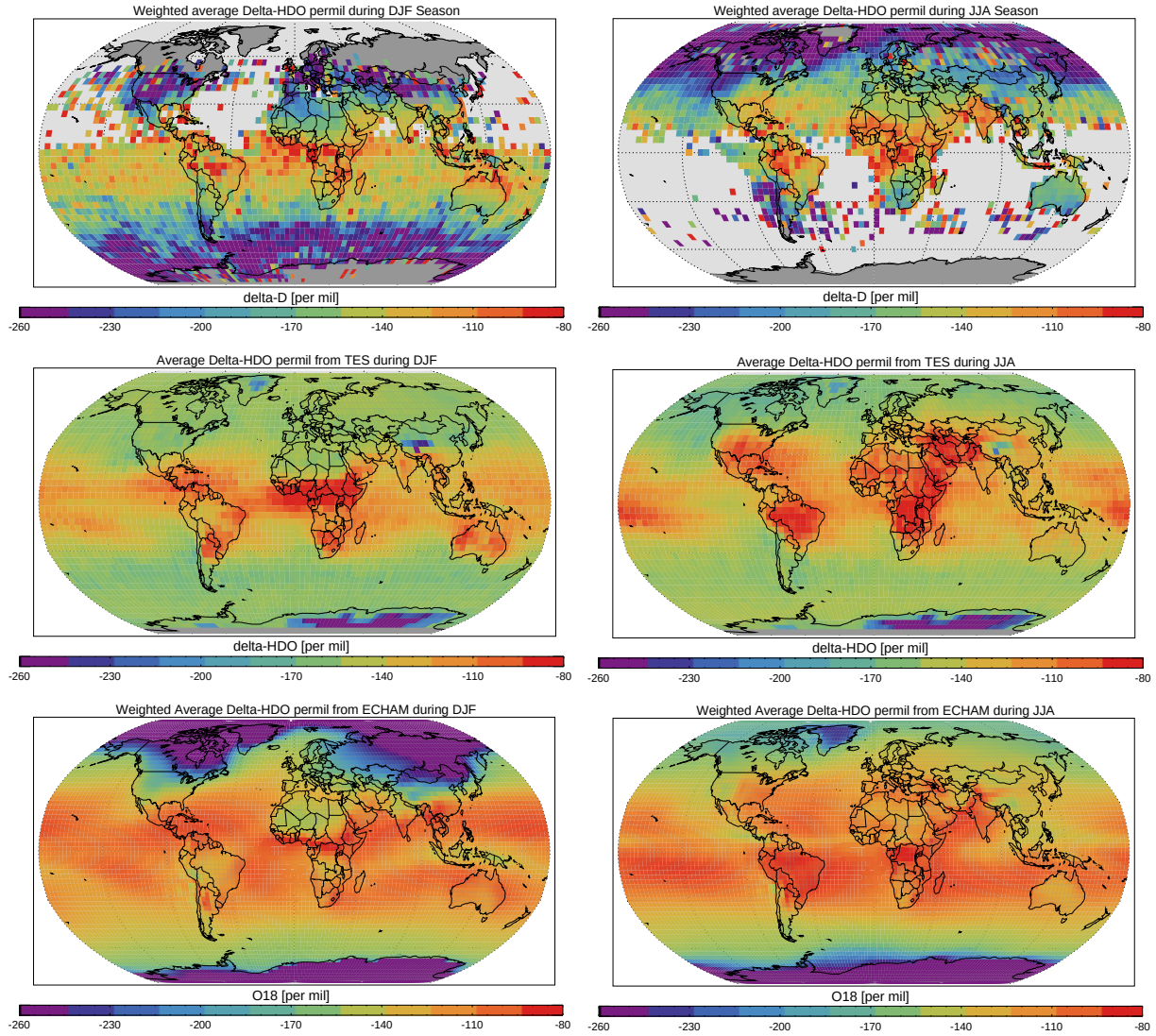

Figure 4 Seasonal variability during DJF and JJA from SCIAMACHY, TES and ECHAM

Comparison of seasonal variability

a) Isotope in water vapor

Seasonal variability from measurements and model is presented in figure 4 during summer period (JJA, June, July and August) and winter period (DJF, December, January and February). During winter season, the SCIAMACHY satellite is problematic to obtain more data in the Northern hemisphere especially above the ocean and it is vice versa during summer season. This problematic can occur due to the existence of reflecting low-level clouds, sun glint conditions or rough ocean surfaces (Frankenberg et al., 2009).

The most influence factor of SCIAMACHY measurements above the oceans is clouds. Without clouds, SCIAMACHY does not have a strong signal above the oceans (the albedo of water, i.e. the amount of reflection, in the 2.3 micron range is really low), so satellite cannot see any effect of the ocean surface. Measurements filter is also responsible for the absence of the data. SCIAMACHY data filter for clouds demands at least the relation between measured and priori should be greater or equal than 0.7. With high clouds this condition is not met, so such clouded scenes are rejected. With low-level clouds (up to 1 km), this condition is met. Thus all measurements above the oceans always contain such clouds. Moreover, the azimuthal and zenithal angle is responsible also for data absence in the North and South hemisphere.

SCIAMACHY measurements show that the enrichment of heavy isotope during winter and summer can be seen in the Africa especially Sahara and Sahel, North America area near to the Caribbean sea, most Middle East and most Asia continent especially India. The ocean surface and cloud cover problem in SCIAMACHY seemingly have no effect in TES measurements since TES is not sensitive near to the surface. Unlike

SCIAMACHY, TES measurements can cover the whole world during winter and summer measurements. The enrichment of heavy isotope during summer season from TES is visible in Central America, Amazon Basin, Sahara, South Europe, Middle East and small in Asia. The ECHAM model also shows the enrichment of heavy isotope globally. Almost the whole parts in the world are enriched in heavy isotope especially in the North Hemisphere.

Latitude and longitude comparison in Figure 5 gives a clear distinguish between satellites and model. The results from satellites and the model are in good agreement although SCIAMACHY results are lower than TES and ECHAM especially in the higher latitude. The fluctuation of HDO measurement from SCIAMACHY during summer in Southern hemisphere is caused by the absence of the data. The longitudinal profile shows clearly the discrepancy of sensitivity effect of the satellite measurements. SCIAMACHY results oscillate more compared with TES and model data because SCIAMACHY is very sensitive near to the ground. Surface roughness is one of the major factors influenced SCIAMACHY measurements.

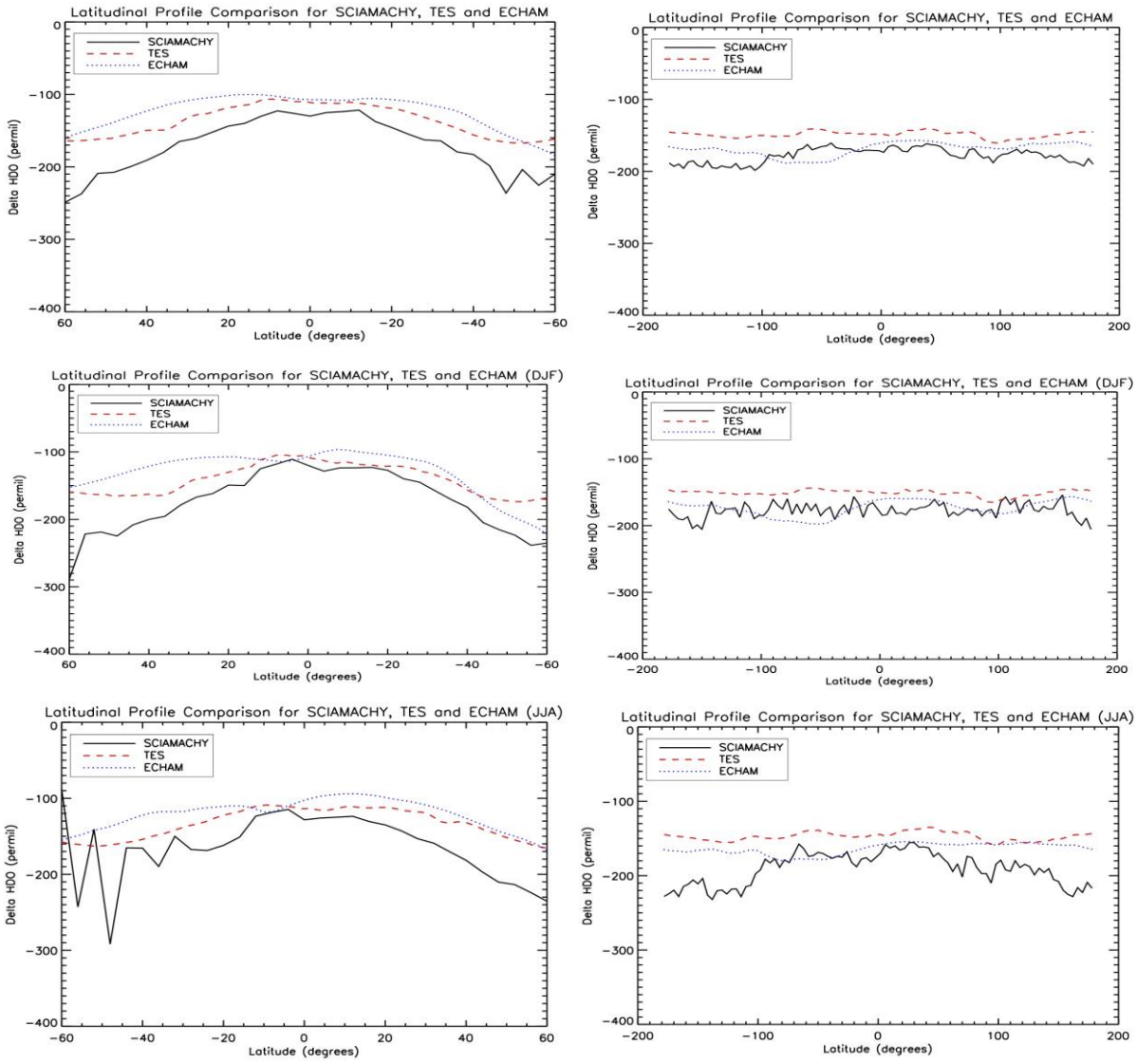

Figure 5 Latitudinal and longitudinal profile comparison for SCIAMACHY, TES and ECHAM. Left column is for latitudinal comparison and right column is for longitudinal comparison. Top, middle and bottom rows are for annual, DJF and JJA simulation respectively.

b) Isotope in precipitation

The isotope values during winter and summer in precipitation are also difference with more enrichment of heavy isotope during summer period (see Figure 6). The enrichment of heavy isotope during summer can clearly be seen in the Northern Hemisphere, Central America, Amazon Basin, Africa and Australia modeled from GissE GCM. Furthermore, ECHAM model shows the enrichment of heavy isotope in the Northern Hemisphere, Central America, South America, South Africa, Mediterranean, and Australia. On the other hand, the result from MUGCM on HDO data is not reliable for both winter and summer.

Tropical ECTZ line is seen in the GissE GCM model while in the ECHAM model, ECTZ line is not clearly visible. In some areas including Indonesia territory, both GissE-GCM and ECHAM show depleted in heavy isotope during summer. This phenomenon is contradictory with the enrichment concept during summer period. This phenomenon might be caused by a strong convective flow around ECTZ line where the flow from North and South meet and creates ECTZ line. See sub-chapter 3.1.3 for explanation about this phenomenon.

c) Relation between water vapor and HDO

Average of Total Precipitable Water (TPW) as a function of Ln water vapor has been plotted from the South to the North hemisphere for SCIAMACHY, TES, ECMWF (European Center for Medium Range Weather Forecast) and ECHAM (Figure 7, left). As expected, tropical area or also known as humid area has higher water vapor compared with sub tropical area or arid area. In general, the results from both satellites and models are match well. In detail, especially in the equator, the results from TES and ECHAM are close as like as the results from SCIAMACHY and ECMWF. The TPW is 4 measured by TES and ECHAM in the tropical area, while SCIAMACHY and ECMWF only measured 3.5. The Southern hemisphere has the lower TPW compared with the Northern hemisphere. This condition occurs due to the lower water vapor in the Southern Hemisphere where there is less continental and vegetation produced water vapor through evaporation and condensation from the land surface.

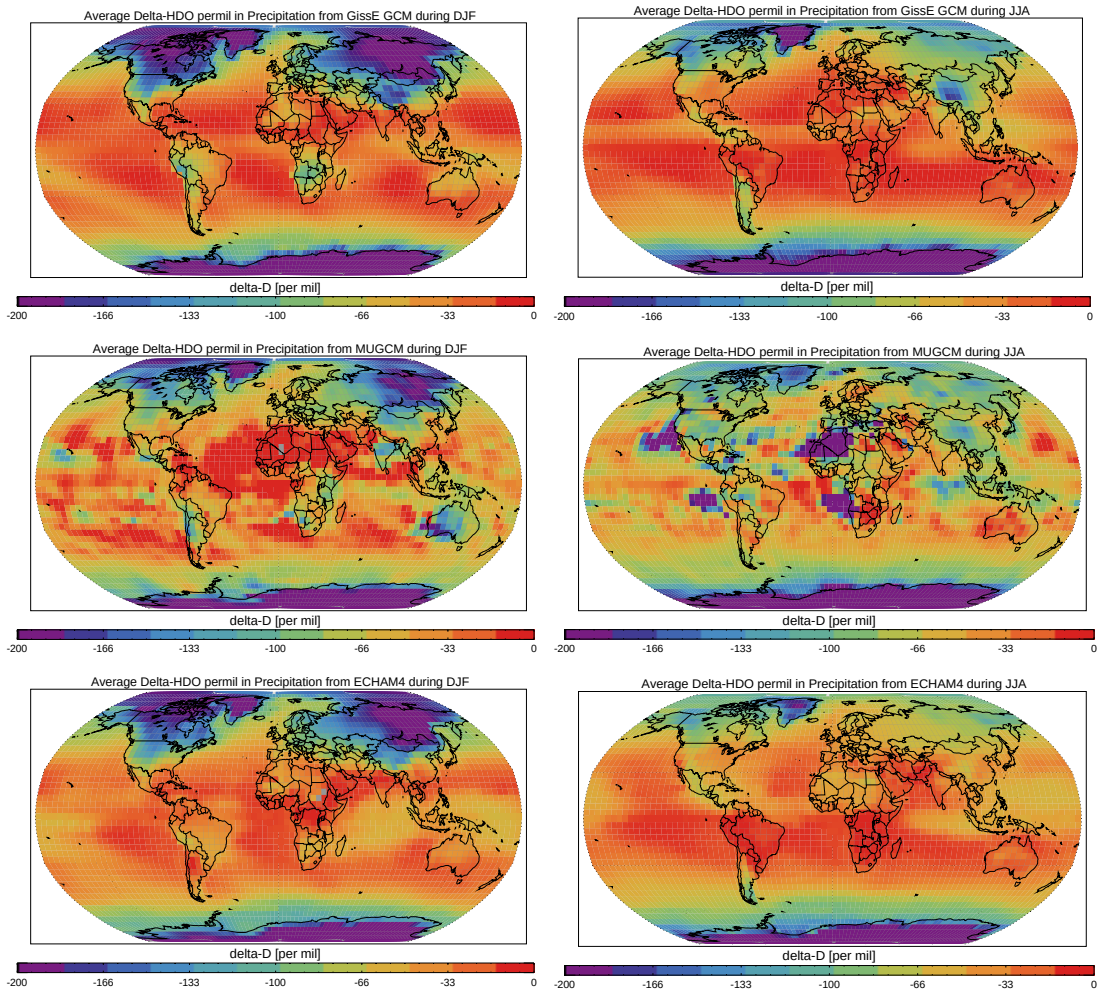

Figure 6 Seasonal variability during DJF and JJA in precipitation from GissE, MUGCM and ECHAM models

Figure 7 right presents the relationship between Ln water vapor amount (VMR) and Ln HDO and water vapor ratio from satellites and model in Sahel region. Sahel region has been chosen since SCIAMACHY has many measurements record over this region (> 8000 measurements). The correlation between water vapor amount (Ln H_2O) and changes of δD in the vapor phase (Ln(HDO/H_2O) or known as Ratio) represents a typical Rayleigh distillation process (Schneider et al., 2010; Yoshimura et al., 2011). This correlation performs a slope, which equals the fractionation factor minus 1 (α-1).

The slopes from SCIAMCHY, TES and ECHAM are 0.1095, 0.0227 and 0.0349, respectively. SCIAMACHY has a steeper slope compared with TES and ECHAM. This result is comparable with the result from Schneider et al. (2010) at two ground sites in Kiruna and Izana. From their study, they conclude that the slope is steeper at surface and decreased with height. The steeper slope from SCIAMACHY, however, is similar with a typical Rayleigh distillation process slope which is in between 0.08-0.15 depending on temperature (Majoube, 1971a, 1971b, Yoshimura et al., 2011). This SCIAMACHY slope corresponds to the Rayleigh-fractionation of temperatures 271.3K. While the temperatures from TES and ECHAM calculation are totally unacceptable (350.2K and 334.3K from TES and ECHAM, respectively). From this slope discrepancy, we can conclude that SCIAMACHY measurements are strongly influenced by Rayleigh-type rainout process and therefore, TES measurements may be influenced by a mixing process in the mid troposphere and not following the Rayleigh distillation process.

d) Time series data comparison

Daily data from satellites in year 2005, in a small particular area in Sahara, has been plotted for comparison both for HDO and TPW (see Figure 8). The average HDO data from SCIAMACHY is -136.5‰ while TES measured -125.4‰. Although the average values from SCIAMACHY and TES are close, the daily range value has a big discrepancy. SCIMACHY has data range between -270‰ and 30‰ and TES has data range between -180‰ and -70‰. The higher oscillation of HDO recorded by SCIAMACHY in the lower troposphere compared with TES in the upper troposphere shows that in the lower troposphere, the HDO data is strongly influenced by the higher temperature fluctuation in the surface during the day and the night. This temperature variation triggers the evaporation and condensation phase of water vapor as a result enrichment and depleted of heavy isotopes in the atmosphere.

TPW measurements from SCIAMACHY and TES are less fluctuates with range in between 1.5-3.5 and 2.5-4 for SCIAMACHY and TES, respectively. The maximum TPW occurs during summer period and the minimum value occurs in December and March for both measurements. These data are plotted based on the availability of the data. There are no measurements daily data in some months for TES indicated by a big gap between two measurements or a straight line in the graph.

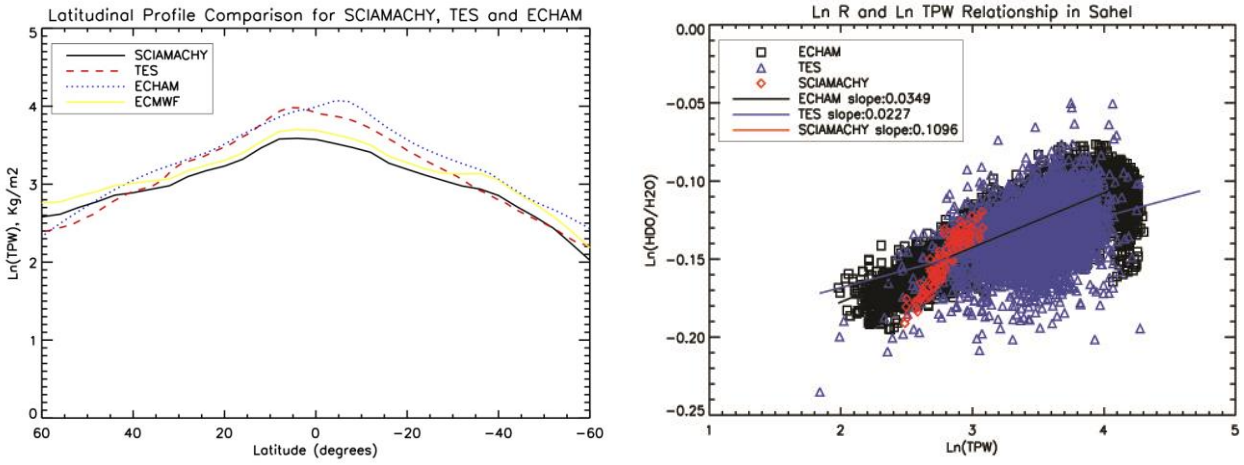

Figure 7 Average total precipitable water (TPW) comparison from North to South for SCIAMACHY, TES, ECMWF and ECHAM (left); HDO ratio and TPW relationship in Sahel region (right)

e) Comparison with IAEA database

Ground measurements of Isotopes in water vapor has been carried out by IAEA in 12 locations. The average HDO data from these location are compared with the data from satellites and model as presented in Figure 9. The data used from satellites and model are from the same month as observation. From this comparison we can see that the satellites data are agree well with the GNIP data. The GNIP data more enrich compared with the others data as a result from altitude effect. Isotopes are heavier near to the surface and its become more depleted in heavy isotopes along with the heigh increasing. Latitude effect also shown in this comparison. HDO in tropical areas e.g. India and South America are heavier compared with HDO in Europe. The isotope patterns from GNIP and satellites are identical. On the contrary, the isotope pattern from model is less fluctuative compared with GNIP and satellites.

In many places especially in tropical areas, the data produced by SCIAMACHY and TES agree well. On the other hand, the model results match well with satellites and observation only in some locations. The model results are fit with satellites in Manaus and Belem. Whereas, the model results are fit with observation in Ankara, Madrid and Vienna.

CONCLUDING REMARKS

From annual and seasonal analysis, it is seen that both models and satellites can capture the most important isotopes effects such as strong latitudinal effect over the hemisphere, continental effect, altitudinal effect. The ECTZ line is also shown in the models and measurements. The results from the models on precipitation data agree well except HDO results modeled from MUGCM. In addition, the results from Satellites and ECHAM model in water vapor are also in a good agreement although, in some results, the SCIAMACHY measurements underestimate compared with the others.

Comparison between water vapor and precipitation in the tropical areas from ECHAM model is consistent with TOGA-CORE model which has discrepancy ±-60‰. It can be said that in tropical area, the HDO in water vapor is -60‰ depleted in heavy isotopes compared with precipitation from TOGA-CORE model. ECHAM model in this study has discrepancy ±-75‰. This discrepancy between isotopes in preciptation and water vapor is caused by altitude effect where the isotopes become lighter along with the high increasing. Moreover, around these areas, the enrichment of heavy isotope is not following the fractionation concepts. The strong convective flow around ECTZ and rain re-evaporation are suspected performing this enrichment of heavy isotopes.

Slope analysis in Sahel shows that SCIAMACHY measurements, which is very sensitive near the surface, are strongly influenced by Rayleigh-type rainout process. In contrast, TES measurements and ECHAM which are very sensitive in the middle of troposphere are not followingthe Rayleigh distillation process. The results from TES and ECHAM might be influenced by atmospheric mixing process. Time series analysis also shows this discrepancy.

The satellites data and model agree well with the GNIP data. The GNIP data are more enrich compared with the others data as a result from altitude effect. Isotopes are heavy near to the surface and it is becoming more depleted in heavy isotopes along with the height increasing. Moreover, latitude effect is also shown in this comparison.

Despite sensitivity differences, the measurement results from SCIAMACHY can be used to support the measurement results from TES. SCIAMACHY data can be used for analysis near to the surface while TES data can be used for analysis in the middle of troposphere. Global climate models from this study also proved that the models are capable to simulate the isotope in the atmosphere together with the water vapor. Moreover, the isotope and water vapor data in the atmosphere can be used to provide the benchmark information for many analyses such as a study of hydrological cycle in the atmosphere. For future steps, it is recommended to do averaging kernel analysis and HDO bias correction analysis. This study compared the models and satellites results without using averaging kernel analysis. The comparison results between model and satellite will be more precise by using this analysis. HDO bias correction analysis is also important since HDO measurements from satellite is bias due to the uncertainties in the spectroscopic line strengths.

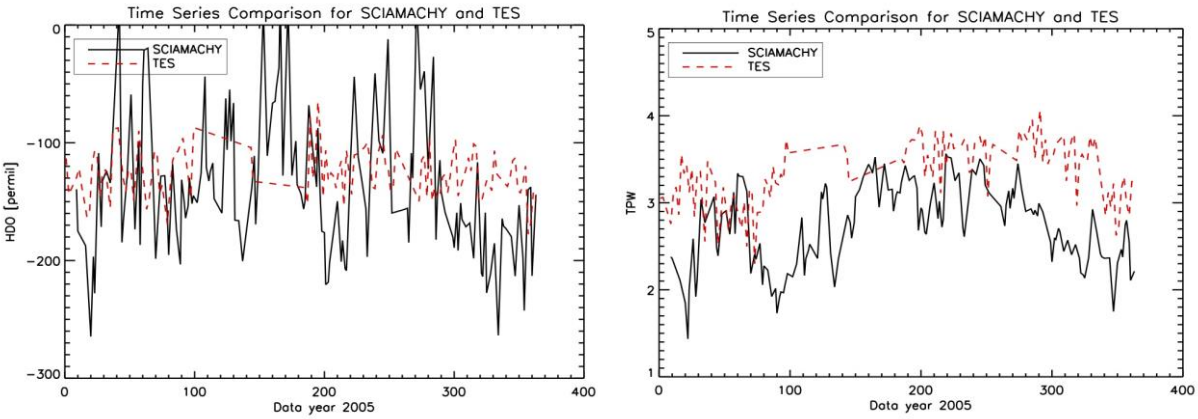

Figure 8 HDO time series data in year 2005 from SCIAMACHY and TES (left); TPW time series data in year 2005 from SCIAMACHY and TES (right). Both plots have been taken out from a small region in Sahara which is located in coordinate 20° N and 5° E.

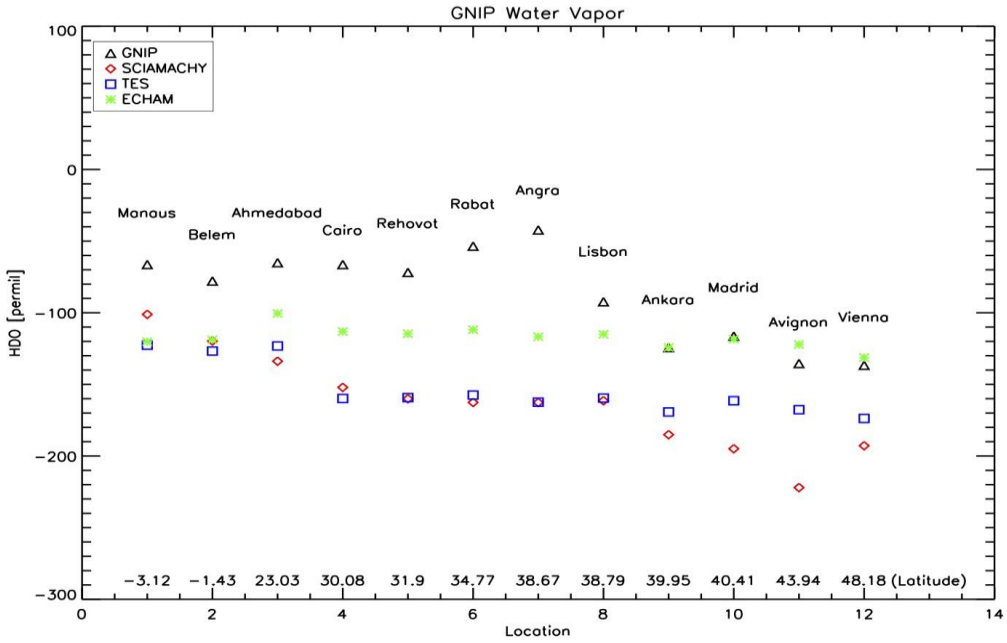

Figure 9 HDO comparison from GNIP-MIBA, SCIAMACHY, TES and ECHAM

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