RESEARCH PAPER

CORRELATION OF DROUGHT RELATED TO ENSO AND WATER ISOTOPES IN INDONESIA

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Received: ….. (left blank) Revised: ….. (left blank) Accepted: ….. (left blank)

Abstract

ENSO affects mainly the hydrological cycle and produces in particular droughts during El Niños and floodings during La Niñas, respectively. Here, the ECHAM 4 IsoGCM model has been used to simulate drought conditions over Indonesia by computing two drought indices, SPI and SPEI, which are commonly used in the empirical studies. The ECHAM model allows the computation of water isotopologues, which are a key tracer of the regional and global water cycle. The correlation of drought and water vapor isotopologues during ENSO events shows that the ECHAM 4 model is capable to simulate the ENSO associated droughts realistically. The SPI index reproduces the extreme droughts in Indonesia such as the year 1994, where there were 19817 ha paddy fields damaged. On the other hand, SPEI and Nino-3 index only show severe drought due to low evapo-transpiration. The correlation of drought indices and water isotope is remarkably good (R^2 = -0.926), whereas, the correlation of drought indices and Nino-3 is weak (R^2 = -0.436). The correlation of local Nino-3 index and global HDO_v shows a strong correlation over Indonesia, pointing to the isotopic amount effect as a dominant factor for the regional isotope signature.

Keywords: Drought, ENSO, isotope, GCM model, correlation

INTRODUCTION

General Background

It is known that in Indonesia prolonged dry and wet periods are mainly connected to ENSO variability. ENSO (El Nino-Southern Oscillation) is a quasi climate oscillation between two states, La Niña and El Niño. An El Niño event is associated with anomalously warm sea surface water temperatures (SST) in the tropical eastern Pacific Ocean (the coast of Peru). The Southern Oscillation refers to major changes in surface pressure gradients over the entire Pacific, which results during an El Niño (La Niña) event in anomalously high (low) surface pressures in the tropical western Pacific and over Indonesia. Because of its large associated SST patterns, and numerous associated teleconnection pattern affecting temperature, precipitation and circulation anomalies, ENSO is considered as the dominating source of inter-annual variability.

Different methods and climatological indices have been developed to measure the strength of drought, such as PDSI (Palmer drought severity index) (Palmer, 1965; Alley, 1984), a modification of PDSI called SC-PDSI (Self-calibrating Palmer Drought Severity Index) (Wells et al., 2004), SPI (Standardized Precipitation Index) (Mckee et al., 1993), and SPEI (Standardized Precipitation Evaporation Index) (Vicente-Serrano et al., 2009). These methods, especially PDSI, are robust and have been widely used in many countries as national drought indicators. In this study, the magnitudes of droughts in Indonesia were calculated using SPI and SPEI indices and compared with observations. In a following step, the results from both indices will be compared with the simulated isotopes in precipitation and atmospheric water vapor isotopologues (HDO/H_2O).

The modeling was done using the ECHAM 4 IsoGCM model (Hofmann et al., 1998), a general circulation model equipped with an isotope module allowing the computation of all related fractionation processes between the different water isotopes in function of the simulated climate. Some other studies analyzed the correlation of ENSO and water isotopes using GCMs (e.g. vuille and Werner, 2005; Tindall et al., 2009). However, no study correlates the strength of drought with ENSO, the isotopic composition of water vapor, and the isotopic composition of precipitation both simulated by GCM. Thus, this study has an objective to study the correlation of droughts and ENSO, and their consequences for the water isotopic signature in the region of Indonesia.

METHODS

To describe drought severity in the region of Indonesia two well-established indices, SPI and SPEI, were used. The ECHAM 4 model simulated the monthly precipitation and temperature data used in the analysis. Validation of the model performance to realistically reproduce ENSO related drought events in Indonesia have been carried out using the same indices computed with meteorological data from Empang (1967-2006) and Gunung Mas (1978-2012) stations. The averaged indices from both stations then were compared with the model result of the two grids point including the corresponding climatological stations. In addition, documentary on the area of paddy fields affected by droughts has been collected to confirm the droughts occurrences. Exceeded probability analysis for droughts and floodings has been performed using the Gumbel distribution.

Furthermore, we analyze the isotopic compositions of water vapor (HDO_v) and precipitation (HDO_p) computed by the ECHAM 4 model, and from IAEA-GNIP (International Atomic Energy Agency-Global Network of Isotope in Precipitation) network observations in permil notation ($^o/_{oo}$). Correlation analysis of model and observations was performed between the drought indices and Nino-3 index, drought indices and isotopic composition of water vapor and precipitation, and between Nino-3 index and isotopic composition of water vapor and precipitation. The correlation of local Nino-3 index with global SPI and HDO used F-Test statistical analysis with confidence interval of 10%.

Nino-3 Index

The Niño 3 index is an average of the sea surface temperatures (SST) in the region of 150 degrees West to 90 degrees West (longitude) and 5 degrees North to 5 degrees South (latitude) (see Figure 1). When the index is positive (red), waters are warmer than normal and when the index is negative (blue), waters are cooler than normal. El Niño occurs when the water is much warmer than normal for a sustained period of time and vice versa for La Niña. Strong El Niño events occurred in years 1972, 1982 and 1997.

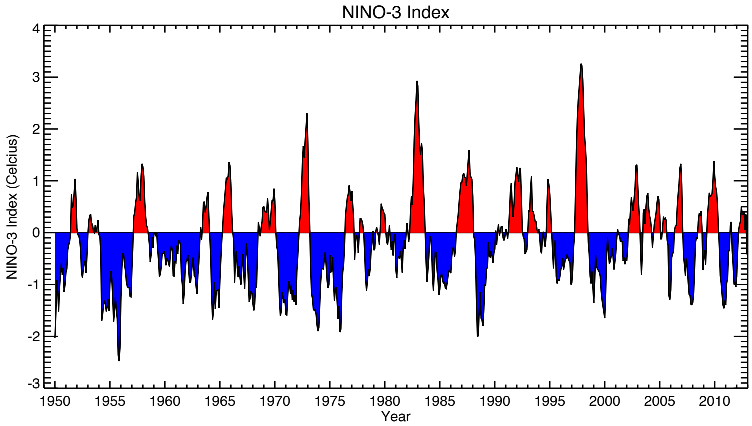

Figure 1. Nino-3 index from January 1950 to December 2012 obtained from NASA (National Aeronautics and Space Administration)

Drought Indices

The SPI drought index is based on standardized precipitation data and was developed by McKee et al., 1993. Unlike PDSI, SPI was designed to quantify a precipitation deficit at different time scales. The advantages of SPI index are it is simple, spatially consistent (invariant) in its interpretation, does not need a fixed time scale, and only precipitation data is required (McKee et al., 1993; Vicente-Serrano et al., 2009). However, the SPI method does not include evapo-transpiration and does not reach on temperature changes.

The SPEI method is originally based on the SPI procedure using monthly precipitation and temperature data but adds a simple procedure to estimate evapo-transpiration (Thornthwaite method). However, Sheffield et al., 2012 demonstrates that the choice of the Penman-Monteith evapo-transpiration method replacing the Thornthwaite method leads to remarkably different results, in particular concerning the relation between global warming the last 40 years. A typical drought classification scheme based on SPI and SPEI index can be seen in Table 1. The SPI and SPEI computations require a long-term monthly precipitation record with minimum 30 years of measurements length. Detailed information about SPEI method can be found in Vicente-Serrano et al., 2009.

Table 1. Classification of drought based on SPI and SPEI index.

Index	Classification	Probability
> 2	Extremely wet	2.3
1.5 to 1.99	Very wet	4.4
1 to 1.49	Moderate wet	9.2
0 to 0.99	Mildly wet	34.1
0 to -0.99	Mild drought	34.1
-1 to -1.49	Moderate drought	9.2
-1.5 to -1.99	Severe drought	4.4
-2 <	Extreme drought	2.3

ECHAM 4 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 is a state of the art general circulation model, which was used within the CMIP4 model intercomparison study. Here we use the model in T42 spectral resolution with 6 vertical layers. The model was “nudged” by a specifically developed spectral nudging technique. This procedure guaranties a good representation of the specific past weather situation since the simulated wind fields are close to observational based on ERA40 reanalysis. The detailed information about ECHAM model can be found in Hoffmann et al., 1998.

RESULTS AND DISCUSSION

Precipitation and water isotopes simulated from ECHAM

The amount of precipitation and isotopic composition of water vapor and precipitation were simulated by the ECHAM 4 model (Figure 2). Amount and global pattern of precipitation simulated by ECHAM is in a good agreement with the measurements from TRMM satellite (Tropical Rainfall Measuring Mission), in particular within the ITCZ and the West Pacific Warm pool.

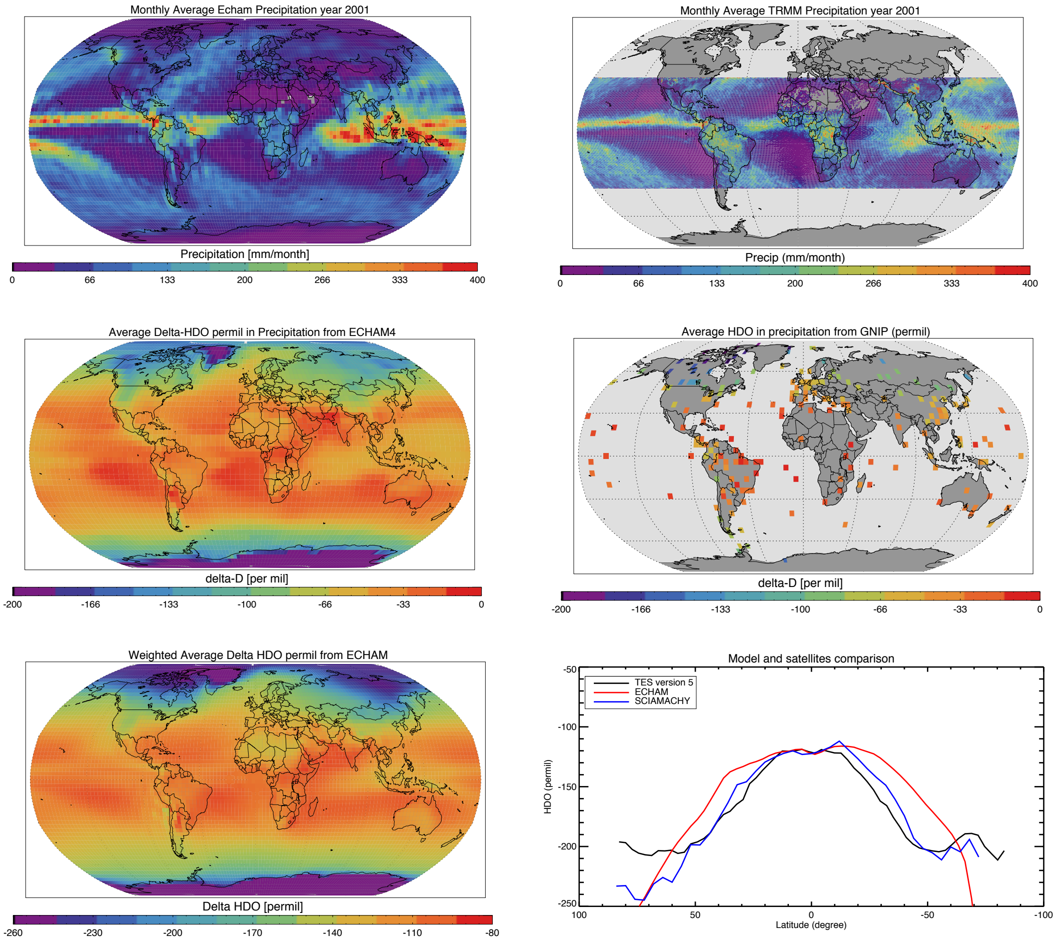

Figure 2. Comparison of the simulated precipitation and TRMM observation (top), the simulated HDO_p and GNIP observation (mid), and latitudinal comparison of the simulated HDO_v and satellites measurements (bottom).

The simulated HDO_p agrees well with the GNIP network, and reproduces in particular the latitudinal gradient of the water isotope with the enriched signals in the Tropics and more depleted signal in higher latitude. Moreover, the HDO_v simulated from ECHAM also agrees with the measurements from the TES version 5 (Tropospheric Emission Spectrometer) (Worden et al., 2012) and SCIAMACHY (Frankenberg et al., 2009) satellite datasets, especially in the tropics. The strong isotopic latitude effect mainly a result of the corresponding latitudinal temperature gradient is seen from the results. A stronger bias of the remote sensing data in polar region is evident because the satellite is less sensitive. A detailed comparison of model results and measurements is not presented here since this is beyond the scope of this study. In general, the model climatology is in good agreement with existing datasets.

Droughts analysis

SPI and SPEI drought indices over Indonesia were calculated using model results and observations to validate (Figure 3). The simulation period was carried out from the years of 1978 to 2001 in order to have the same data length within ECHAM and the observations. SPEI index from observations was not calculated due to the lack of continuous temperature data.

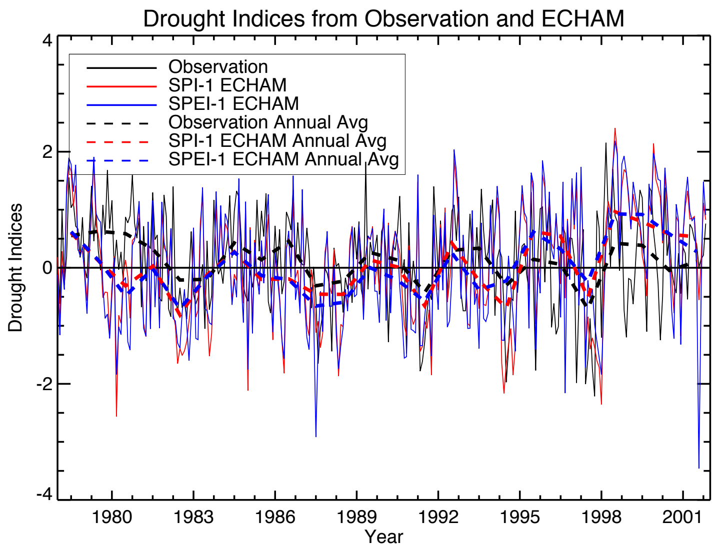

Figure 3. Drought indices analysis from observation and ECHAM

The comparison of droughts analysis from GCM and observation agrees well, although the model slightly overestimates the observations in one year (e.g year 2000), and underestimates in another year (e.g. 1980). However, overall, the ECHAM model can reproduce a drought signature (frequency, severity, etc) similar to the observations. The results from SPI and SPEI analysis in Indonesia region are close. This is due to the temperature effects to SPEI by adding the computation of evapo-transpiration comparably small over Indonesia. The SPEI therefore produces a quite different result to the SPI index if there is an extreme temperature deviation. For example, the cold temperature in year 1994 lowers the SPEI value relative to the SPI.

Correlation of drought and ENSO

Figure 4 left shows the occurrences of dry and wet conditions during El Niño and La Niña related to a Nino-3 index. For this plot, we used SPI-6 and SPEI-6 to match the drought results with the duration of ENSO events from the increasing point to the peak (±6 months). Overall, the drought indices are anti-correlated to the Nino-3 index that is a positive Nino-3 index associated to drought conditions, and it shows as negative values in the drought indices. This anti-correlation is more visible during strong ENSO events such as the 1982-1983 and 1997-1998 El Niños. Both well-known El Niños years produced droughts with exceeding probability more than 10%. However, for the year of 1988 during La Niña, both the model and observations show a negative signal, indicating a drought condition during La Niña.

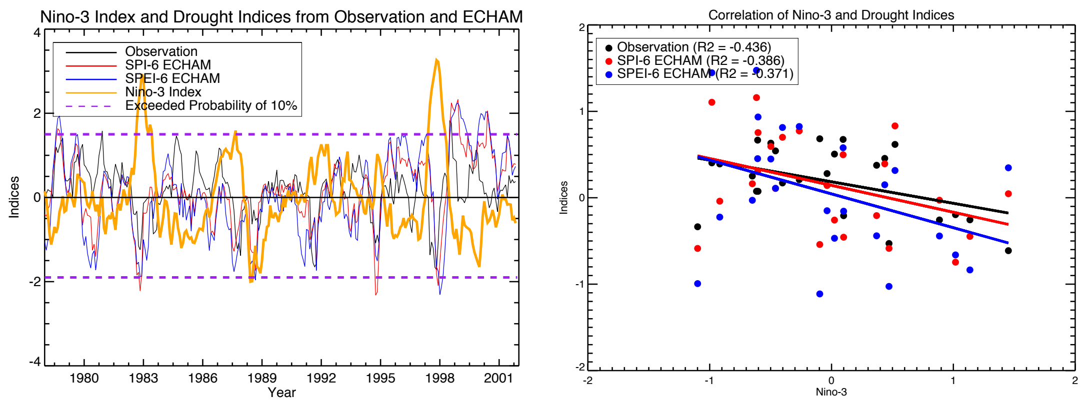

Figure 4. SPI-6, SPEI-6 and Nino-3 index plot (left), and a correlation of annual average Nino-3 Index and annual average SPI, annual average SPEI from observation and ECHAM (right).

To check the consistency of drought related to ENSO, a number of paddy field areas affected by droughts was collected from 1989 to 2001 in Central Java. There is no data in the year of 1988, thus we cannot validate the drought in this year. Based on the data, the highest number of paddy field affected by droughts occurred in 1991 and 1994, with affected areas of 18928 ha and 19817 ha, respectively (Adidarma et al., 2006). The Nino-3 index during the extreme droughts in these years only shows an index value of ±1, while the SPEI values show severe droughts for both years. Surprisingly, the SPI value in year 1994 shows an extreme drought with index value more than 2 (exceed the probability of occurrences 10%), in a good agreement with the largest area of paddy field affected by drought. A large precipitation deficit triggered the extreme drought since the SPI index is only based on precipitation data. In contrast, SPEI index shows only severe drought because the evapo-transpiration flux was also low (low temperature).

For a better overview on the relationship between droughts and ENSO, the drought indices have been plotted against the Nino-3 index (Figure 4 right). The results show that the observation has higher correlation coefficient (R^2 = 0.436) than ECHAM (R^2 = 0.386, 0.371 for SPI and SPEI, respectively). Generally, there is no strong correlation between the strength of ENSO and the droughts denoted by drought indices in Indonesia. The El Niño and La Niña events are not always followed by droughts or floodings in Indonesia, respectively.

Correlation of drought and water isotopes

The correlation of SPI and Nino-3 index with HDO, in relation with the isotopic amount effect and ENSO events, is presented in Figure 5. A strong anti-correlation between HDO and SPI due to the isotope amount effect is seen in annual data in the Indonesia region with an R^2 value of -0.926. The anti-correlation signal between SPI and HDO is caused by the significant isotope amount effect since in convective events the precipitation amount is inversely related to the water isotopic composition of the rain (Dansgaard, 1964). The lower SPI values (dry) and the enriched HDO values are dominated by El Niño events, and it is conversely for La Niña.

The correlation of Nino-3 index and HDO becomes slightly weakened (R^2 = 0.738) compared to the correlation of SPI and HDO. In addition, there is a positive correlation between Nino-3 and HDO since positive values of Nino-3 mean drought or dry condition. The weakened correlation of Nino-3 and HDO might be caused by the time lag of dry/wet condition. One should note that Nino-3 index is based on the temperature anomaly in the Central-East Pacific Ocean, whereas the location of study is over Indonesia region (West Pacific). In addition, Indonesia is located between two different climatic conditions, Indian Ocean and Pacific Ocean.

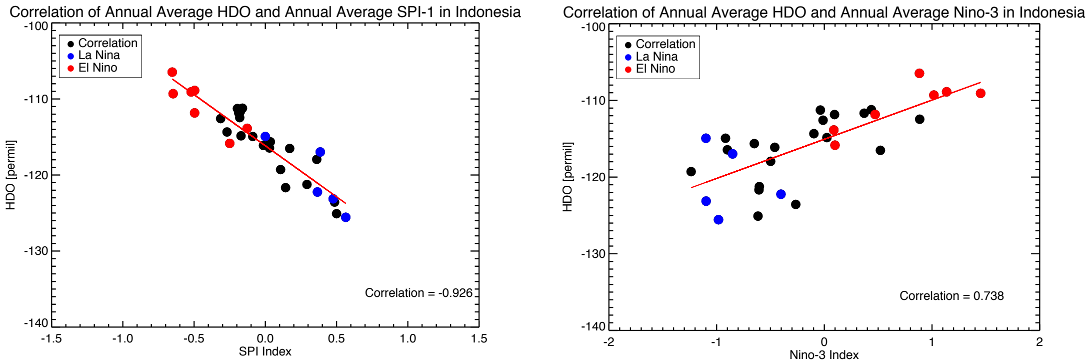

Figure 5. A Correlation of SPI-1 and HDO (left), and a correlation of Nino-3 index and HDO (right) in Indonesia (averaged grids from 5N to 10S, 100E to 135E).

Global correlation and the isotope amount effect

Correlation of local Nino-3 index on global SPI and HDO_v from ECHAM were simulated (Figure 6). The simulation of Nino-3 and HDO_v results in an ENSO pattern, with a strong correlation in the region of Indonesia in one hand, and a strong anti-correlation in the Eastern-Central Pacific Ocean on the other hand as a result of the isotope amount effect. It is opposite for the correlation of Nino-3 and SPI index. During high ENSO, Indonesia region is dry and Pacific Ocean is wet. As a consequence, the HDO_v values in Indonesia are enriched due to the dry condition and the HDO_v values in the Pacific Ocean are depleted due to the wet condition.

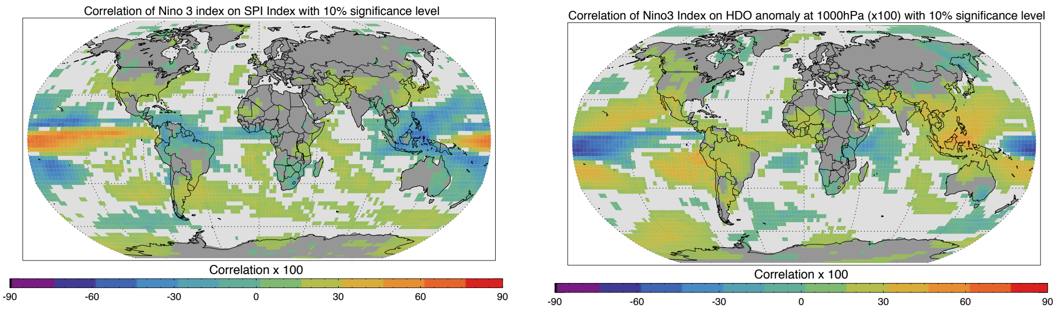

Figure 6. A correlation of local Nino-3 index on global SPI index (left), and local Nino-3 index on global HDO_v (right) from ECHAM at 1000 hPa nudged 1971-2001. F-test statistical analysis was applied with confidence interval 10%. Correlation was multiplied by 100 as percentage values of correlation.

CONCLUSION AND RECOMMENDATION

The results of the droughts analysis using the ECHAM 4 model are realistic. The SPI drought index can be used as a good agricultural drought indicator in Indonesia since the dominant factor related to drought in Indonesia is precipitation. The highest number of paddy field affected by droughts in year 1994 confirms the SPI result with the probability of occurrences more than 10%. There is no strong correlation between the strength of ENSO, denoted by Nino-3 index, and the droughts, denoted by drought indices in Indonesia.

Stable water isotope, on the other hand, is a good climatic indicator for droughts and floodings events compared to Nino-3 index. The correlation of SPI index and water isotope is remarkably good (-0.926), and for Nino-3 index and water isotope is quite good (0.738). Global correlation of drought indices and HDO_v show that there is a strong anti correlation in Indonesia and correlation in the eastern Pacific Ocean. In contrast, the correlation between Nino-3 Index and HDO_v shows an opposite result, which is in agreement with the anti-correlation of ENSO and drought indices. The anti correlation of drought indices and HDO_v points to the isotopic amount effect as a dominant factor for the regional isotope signature not only on a seasonal but also on an inter-annual scale.

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