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Reducing vulnerability of rainfed agriculture through seasonal climate predictions: A case study on the rainfed rice production in Southeast Asia

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ABSTRACT

Rainfed rice production needs to contribute more to the current and future world food security due to the increasing competition for limited water supplies including irrigation water. However, it is vulnerable to climate variabilities and extremes hence the utilization of climate predictions is crucial. In this study, the predictive accuracy and applicability of a seasonal climate predictions (SINTEX-F) were evaluated for rainfed rice areas where climate uncertainties are main constraints for a stable and high production. Outputs from SINTEX-F such as daily rainfall, maximum and minimum air temperatures, and wind speed were tested for Indonesia and Lao PDR through the cumulative distribution function-based downscaling method (CDFDM), which is a simple, flexible and inexpensive bias reduction method through removing bias from the empirical cumulative distribution functions of the GCM outputs. The CDFDM outputs were compared with historical weather data. Obtained results showed that discrepancies between SINTEX-F and the historical weather data were significantly reduced through CDFDM for both sites. ORYZA, an ecophysiological rice growth model that simulate agroecological rice growth processes, was used to evaluate the applicability of the SINTEX-F for grain yield predictions. Obtained results from on-farm field validation showed that the predicted grain yield was close to the actual grain yield that was obtained through optimum sowing timing given by the predictions. A normalized root mean square error between predicted and actual grain yield showed satisfactory model fit in predictions. This implies that SINTEX-F was applicable for improving rainfed rice production through CDFDM. However, CDFDM has a limitation in orographic precipitation, the high-resolution daily weather data or a sophisticated special interpolation method should be considered in order to improve the representation of the geographical pattern for the parameters derived from CDFDM.

1. Introduction

According to the Fifth Assessment Report from IPCC, the average combined land and ocean surface temperature increased globally by 0.85° C during the period 1880 to 2012. As a result, more extreme weather events such as droughts and floods occurred more frequently than before and crop yields have been negatively affected (IPCC, 2014). This change in climate causes serious problems in agriculture, especially in rainfed environments where crop production's water supply highly depends on rainfall.

Seasonal climate predictions are useful for decision making in agriculture (Meza et al., 2008) and many application studies have been carried out on various crops for predictions. Wheat yield predictions were evaluated at the local and regional scale and adequate predictability was reported by Cantelaube and Terres (2005) and Marletto et al. (2007). Semenov and Doblas-Reyes (2007) also evaluated the seasonal climate predictions in wheat yield predictability and they reported a limitation of skill score for higher latitude areas like Europe and New Zealand. Ines and Hansen (2006) presented a method of application for seasonal climate predictions through bias-correction to be suitable to predict maize yield in semi-arid Kenya. Application of seasonal climate predictions in agricultural management increased average gross margins for maize farmers in Kenya (Hansen et al., 2009). Roudier et al. (2012) also quantified the economic value of seasonal climate predictions in millet production in Niger and they found that the seasonal climate predictions are effective at the time of bad years. The

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study of Malherbe et al. (2014) emphasized the use of the global coupled model to expect crop yield prediction outperformed. Despite these promising results in the application of seasonal climate predictions in crop yield predictions and agricultural decision making, no study has evaluated the applicability of seasonal climate predictions on rice production at the local scale in Asia, where the granary of world rice production and supply exist.

Rice is one of the major staples feeding around 3.5 billion people in the world. According to the projection, 560 million tons of rice is needed by 2035 to feed the world population which requires an increase of 120 million tons of rice production compared with the one in 2010 (GRiSP (Global Rice Science Partnership), 2013). Irrigated rice is the major ecosystem for world rice supply; however, the production should be diversified through other ecosystems like rainfed rice in order to deal with an increasing pressure brought about by the competition for limited water (Wassmann et al., 2009). Rainfed areas account for 33% of the total rice production area in the world but it provides only 19% of world rice production because its yield is low, only 2.3 t ha^{-1} on the average, which is lower than that for irrigated rice at 5.0 t ha^{-1} (GRiSP, 2013). Improving productivity in rainfed rice is imperative not only to enhance food supply for current and future demand but also to alleviate constraints for irrigated rice according to the world and regional climate change contexts.

Rainfed rice farming has high uncertainty in terms of the start and end of the rainy season, rainfall amount, and duration (Mackill et al., 1996). The probability of occurrence of abiotic stresses such as drought is also high during the growth period and their effect, particularly at critical growth stages, could cause substantial damage to the growth and nutrient use of the rice plant. Optimum time for sowing is essential to avoid adverse effects and for rice growth to occur under optimum flowering (Fukai, 1999) hence the application of seasonal climate predictions in crop models is one of the ways to make rainfed rice production more adaptive to climate change (Abedullah, 1998; Lansigan et al., 2000).

This study aimed to evaluate the applicability of seasonal climate predictions in rainfed rice areas of Southeast Asia, where the granary of world rice production and supply exist. In order to achieve this goal, we evaluated (1) the predictive accuracy of seasonal climate predictions at the local scale and (2) the applicability of seasonal climate predictions in a crop growth model for rice yield prediction.

2. Materials and methods

2.1. Study areas

In order to evaluate the predictive accuracy of seasonal climate predictions in wide areas of designated region, Indonesia and Lao PDR were selected as target countries to represent low and relatively high latitudes in the region.

Rice is the staple for Indonesia and Laos PDR, where per capita consumption is 127.4 kg year^{-1} and 165.5 kg year^{-1}, respectively (GRiSP, 2013). Rainfed is one of the dominant ecosystems for rice production in both countries and this study targeted Central Java province in Indonesia and Savannakhet province in Lao PDR that account for 30% and 40% of the total rice area in each country, respectively (Amien and Las, 2000; Linquist and Sengxua, 2001). The most critical constraint in rice production in these provinces is drought stress (Schiller et al., 2006; Boling et al., 2016) that causes a water shortage during the crop growth period, resulting in yield loss. Average grain yield in rainfed rice is 3.5 t ha^{-1} on the average for direct-seeded rice and 1.2 t ha^{-1} on the average for transplanted rice in Central Java (Wihardjaka et al., 1999) and 2.4 t ha^{-1} on the average for wet-season rice in Savannakhet (Linquist and Sengxua, 2001).

2.2. Global coupled model and statistical downscaling

The Scale Interaction Experiment–Frontier Research Center for Global Change (SINTEX-F), which is a relatively high-resolution ocean–atmosphere coupled general circulation model to simulate the climatology and El Niño Southern Oscillation (ENSO) in the tropical Pacific (Luo et al., 2008) was used for this study. ENSO is highly correlated with South Asian monsoon through regulating the length of the rainy season (Goswami and Xavier, 2005); hence, predicting this climate mode is crucial for agriculture, especially for rice production in tropical Asia. The SINTEX-F is a GCM which has a predictability of ENSO at 9–12 months lead times with a resolution of 1.1°× 1.1° (Luo et al., 2008) and provides daily weather parameters such as rainfall, maximum and minimum air temperature, wind speed. The outputs from SINTEX-F can't be directly applied for a crop model in specific areas because of its systematic error (bias), hence a dynamic or statistical downscaling is necessary for adaption study (Iizumi et al., 2011). The cumulative distribution function-based downscaling method (CDFDM), which is a bias reduction downscaling method to calibrate GCM daily data, was used to remove systematic errors through the empirical cumulative distribution functions (CDFs) of the SINTEX-F outputs and observed data (Iizumi et al., 2010, 2012). The CDFDM is an inexpensive method compared with the dynamical models and other sophisticated statistical models, and flexible to apply various daily variables, including daily mean, maximum, and minimum temperature, precipitation, solar radiation, relative humidity, and wind speed (Iizumi et al., 2011).

The outputs from SINTEX-F were obtained from Japan Agency for Marine-Earth Science and Technology (JAMSTEC) for the designated grids (S6.2, E110.3 for Central Java, N16.5, E105.1 for Savannakhet) and the period from 1982 to 2014 with a 9-month lead time. The parameters were minimum and maximum air temperature (°C), precipitation (mm d^{-1}), and wind speed (m/s). The data on wind speed from SINTEX-F was at 10 m above ground; thus, correction was made by using the following formula by Rosenberg et al. (1983):

$$u1 = u_2 \, ln\left(h_1/z\right) \Big/ ln\left(h_2/z\right)$$

where u_1 is wind speed (m/s) at 2 m, u_2 is wind speed (m/s) at 10 m, h_1, h_2 and z are 2, 10, and 0.05, respectively.

Data on locally observed long-term weather is one of the required datasets for CDFDM to obtain the empirical CDFs from daily SINTEX-F outputs and observed weather data within targeted grid. The data on locally observed long-term weather were acquired from the Indonesian Agricultural Environment Research Institute for Central Java and the Department of Meteorology and Hydrology of Lao PDR for Savannakhet. The periods of the datasets for Central Java were from 1987 to 2013, and the one for Savannakhet was from 1982 to 2013.

In order to evaluate the performance of CDFDM, mean error (ME) was computed using following formula;

$$\mathrm{ME} = \frac{1}{n}\sum_{i=1}^{n}(Pi - Oi)$$

where, Pi is outputs of SINTEX-F or CDFDM, Oi is observed weather data (Walther and Moore, 2005).

2.3. Evaluation of applicability of SINTEX-F to rainfed rice areas

To evaluate the applicability of the seasonal climate predictions for grain yield prediction of rice varieties, ORYZA, an ecophysiological rice growth model that simulates the growth and development of rice under potential, water-limited, and nitrogen-limited conditions (Bouman and van Laar, 2006), was used for the simulation of designated varieties at