Time trends and variations in mean and accumulated solar radiation for the ripening period of paddy rice in Kyushu for 1979-2007

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Abstract

A notable declining trend in the eating quality of rice panicles has been observed in Kyushu, Western Japan, since the 1990’s. As solar radiation is one of the factors determining eating quality, this study investigated the recent time trends and variations in the mean and accumulated radiation for the ripening period of paddy rice in Kyushu during the period 1979-2007. The 3-year running mean radiation data, which are dynamically downscaled reanalysis data using the non-hydrostatic regional climate model (NHRCM) with a grid interval of 20 km, were used for analysis after the validation. From a meta-analysis of governmental crop statistics, it was found that the ripening period (i.e., the period between heading and harvesting) in Kyushu was shortened by 10 days in a 29-year period and generally occurred between the end of August and early October in the 2000’s but between early September and the end of October in the 1980’s. The change in the length and timing of the ripening period resulted in decreased accumulated radiation for the period, although the mean radiation during the period increased as a result of the earlier timing of the ripening period. The empirical orthogonal function (EOF) analysis results showed that the earlier timing and shorter ripening period are the most dominant factors explaining the radiation change during the ripening period in Kyushu in the past three decades. In addition, a more westward extension in Pacific anticyclones and an associated change in the locations of precipitation that decreased the mean and accumulated radiation for the ripening period in the area were frequently observed in the 2000’s. These results indicate a more adverse radiation condition for paddy rice production in the 2000’s compared to the 1980’s and 1990’s.

Key words: Kyushu, Paddy rice, Regional climate model, Ripening period, Solar radiation.

1. Introduction

A notable declining trend in the eating quality of rice panicles has been observed in Kyushu, Western Japan, since the 1990’s (Morita, 2008; Okada et al., 2009). Additionally, the changes in the timing of phenological events of paddy rice, such as heading date, have been reported, at least, for Kyushu (Morita et al., 2010). Major reasons for the decline of rice quality are the occurrence of chalky grains, especially milky white grains (Morita, 2008), caused by such factors as an increase in the daily minimum temperature after heading, insufficient solar radiation, typhoons, and management factors (Matsushima and Manaka, 1957; Tsuchimori, 2003; Wakamatsu et al., 2007).

Despite the importance of solar radiation (hereafter referred to as radiation) conditions in determining the eating quality of rice panicles, few studies have been conducted to analyze the recent change in radiation conditions during the ripening period (i.e., the period between heading and harvesting) of paddy rice in Kyushu. One possible reason is the less dense observation network for radiation compared to that for other variables such as precipitation. While sunshine dura-
tion is observed in a dense observational network in Japan (e.g., the Automated Meteorological Data Acquisition System, AMeDAS), sunshine recorders have been changed several times since 1979, which has hindered scientists in understanding time trends in sunshine duration (Kondo et al., 1991).

One way to analyze the spatiotemporal change in radiation over Japan for the past few decades is to utilize reanalysis data dynamically downscaled by a fine-resolution regional climate model (RCM). While RCMs have a bias in their simulated variables, including radiation (Iizumi et al., 2010a, 2010b), they are a powerful tool to study physical mechanisms in regional climates (e.g., Fischer et al., 2007).

This study analyzed the recent time trends and variations in the mean and accumulated radiation during the ripening period of paddy rice in Kyushu in the years 1979-2007. In addition, this study analyzed the change in the timing and length of the ripening period for all of Japan as well as Kyushu. Instead of sparsely networked observation data, we used reanalysis radiation data dynamically downscaled using a non-hydrostatic RCM, the NHRCM (Saito et al., 2006; Ishizaki and Takayabu, 2009). The empirical orthogonal function (EOF) analysis method (Wilks, 2006) was applied to explore large multivariate data derived from the NHRCM, including radiation, yielding insights into the spatiotemporal variations exhibited in the radiation field over Japan during the ripening period in Kyushu.

2. Data and Methods

2.1 Data

For the validation of the modeled radiation, the observed radiation data for the period 1979-2007 were collected from the 55 surface observatories over Japan maintained by the Japan Meteorological Agency (JMA), where consecutive observations of radiation had been conducted (Fig. 1). In addition, we used the quality-controlled, high-resolution (0.05° × 0.05°) gridded daily precipitation APHRO_JP V1005 data (Kamiguchi et al., 2010) for Japan.

The modeled daily data for radiation, sea level pressure (SLP), and wind velocity at 850 hPa (UV850) with a grid interval of 20 km were derived from the NHRCM (Saito et al., 2006; Ishizaki and Takayabu, 2009). The initial and boundary conditions of the NHRCM were taken from the Japanese 25-year Reanalysis/JMA Climate Data Assimilation System (JRA-25/JCDAS) data (Onogi et al., 2007). The detailed settings for geographic domains, physical parameterizations and downscaling simulations are available from Iizumi et al. (2011).

The phenological data for paddy rice, such as heading and harvesting dates, for all prefectures of Japan, including the seven prefectures in Kyushu (Fig. 1) for the period 1979-2007 were obtained from the governmental Crop Statistics compiled by the Ministry of Agriculture, Forestry, and Fisheries, Japan (MAFF, 2010). Data averaged over the seven prefectures in Kyushu were used for the analysis.

2.2 Methods

We used EOF analysis (also known as principal component analysis) to detect the dominant spatiotemporal variation in the radiation field. The radiation data averaged over the ripening period in Kyushu were calculated for each year and then used for the analysis. In the EOF analysis, we first calculated the anomaly value of the modeled radiation data:

$$x' = x - \bar{x}$$  \hspace{1cm} (1)

where $$x'$$ is the anomaly value, $$x$$ is the yearly ripening-period mean radiation value, and $$\bar{x}$$ is the time mean
value. Then M-dimensional eigenvectors that are the linear combination of \( x' \) were calculated through the eigenvalue decomposition (Wilks, 2006):

\[
u_m = e_m^T x' = \sum_{k=1}^{K} e_{k,m} x_k
\]

where \( u_m \) is the \( m \)th principal component, \( e_m \) is the \( m \)th eigenvector, and \( x' \) is the K-dimensional anomaly data vector. The \( m \)th score, \( t_m \), which represents the similarity in the time variational pattern between \( e_m \) and \( x' \), was calculated as follows:

\[
t_m = u_m / \sqrt{\lambda_m}
\]

where \( \lambda_m \) is the \( m \)th eigenvalue.

Because each principal component, \( u_m \), is a linear combination of the original variables, \( x_k \), pairs of principal components and original variables will be correlated unless the eigenvector element, \( e_{k,m} \), relating them is zero. To gain the necessary information, we calculated the correlations between the principal component and the ripening-period mean radiation data (\( r_{u,x} \), called factor loading):

\[
r_{u,x} = \text{corr}(u_m, x_k) = e_{k,m} \cdot \sqrt{\lambda_m / s_{k,k}}
\]

where \( s_{k,k} \) is the variance of the ripening-period mean radiation data. The principal components, scores, and factor loadings were calculated for the accumulated radiation during the ripening period in Kyushu in a similar manner.

### 3. Results and Discussion

#### 3.1 Validation of the modeled radiation

For validation, we compared the modeled and observed radiation data prior to the EOF analysis. The correspondence between the monthly mean modeled and observed radiation at the 55 JMA observatories is illustrated in Fig. 2. The modeled radiation data are basically overestimated regardless of season (figure not shown), and there are relatively large discrepancies between the two datasets, especially in summer. Despite such biases, the calculated coefficient of determination (\( R^2 \)) value was 0.70, indicating a good correspondence between the two datasets in terms of the spatiotemporal variational pattern in radiation on a monthly scale over Japan.

While the validation of the modeled radiation data on a regional scale is not the purpose of this study, it is informative to show the limitation of the modeled radiation data. The correspondence between the two datasets on a regional scale is illustrated in Fig. 3, with Kyushu taken as an example. The \( R^2 \) value between the observed radiation averaged across the seven JMA observatories in Kyushu and the corresponding modeled data for the 29 years, both averaged over the ripening period in the area, was 0.29. This value is statistically significant, but the correspondence in the time variational pattern is not very high (Fig. 3a) (all significances in this study were tested at the 1% confidence level). Therefore, we applied the 3-year running mean to each dataset to get a better correspondence and then obtained the higher \( R^2 \) value of 0.61 (Fig. 3b). While we calculated the running mean on other time scales (i.e., 5-, 7-, and 11-year), the calculated \( R^2 \) values were almost the same as that in the 3-year case. Therefore, the time variation in the radiation field detected from the EOF analysis is not a true interannual variation, but a smoothed one.

#### 3.2 Changes in ripening period and radiation

The time changes in the length of the ripening period for five areas in Japan are shown in Fig. 4. Statistically significant decreasing trends in the ripening period length were found in the eastern and western parts of Japan (i.e., Kyushu, Kinki, Shikoku and Chugoku, and Kanto and Chubu). The decreasing trend in Kyushu was especially notable. The change in the timing and length of the ripening period and climatological daily mean temperature and radiation are shown in Fig.
In Kyushu, the ripening period was shortened by 10 days in the 29 years and generally occurred between the end of August and early October in the 2000’s, while it occurred between early September and the end of October in the 1980’s. When we took the beginning and final years during the 29 years as examples, the mean radiation for the ripening period in 2007 calculated from the regression lines was larger by 0.9 MJ m$^{-2}$ day$^{-1}$ ($14.6$ MJ m$^{-2}$ day$^{-1}$) than that in 1979 ($13.7$ MJ m$^{-2}$ day$^{-1}$) because of the earlier timing and shorter ripening period in 2007 (234-279 in day of year, DOY) compared to those in 1979 (244-299 in DOY). The mean temperature for the ripening period in 2007 (24.3℃) was also higher by 2.1℃ than that in 1979 (22.2℃) as a result of the gradual increase and interannual variation in temperature (JMA, 2011). By contrast, the accumulated radiation for the period decreased because of the shortened ripening period (Fig. 3): the accumulated radiation for the period in 2007 (599.1 MJ m$^{-2}$) decreased by 168.7 MJ m$^{-2}$ compared to that in 1979 (767.8 MJ m$^{-2}$).

### 3.3 Dominant spatiotemporal change and variation in radiation field

The factor loadings ($r_{u,\lambda}$) for the mean and accumulated radiation at each grid are illustrated in Fig. 6 and Fig. 7, respectively. For the mean radiation, the most dominant variational pattern (EOF1) appeared to increase the radiation over all of Japan (Fig. 6a), while the corresponding pattern for accumulated radiation appeared to decrease, with a central focus around Kyushu (Fig. 7a). The actual time variation of radiation can be reconstructed by multiplying each of the principal components by the score. For instance, the mean radiation over Japan will be higher than the long-term
mean value if the product of the principal component (represented by the factor loading) and the score is positive (e.g., for the period 2001-2007 in Fig. 6a and c). In contrast, a north-south variational pattern was detected as the EOF2 for both the mean and accumulated radiation. The EOF1 and EOF2 explained 51.4% and 16.5% of the total variance in the mean radiation, respectively (Fig. 6). Similar values were obtained for the accumulated radiation (Fig. 7). The EOF analysis results indicate that the time variation of radiation conditions around Kyushu can be attributed to the large-scale variation of radiation conditions over Japan, but not to the local variation around Kyushu.

The increasing trend in the EOF1 score ($t_m$) for the mean radiation and the decreasing trend in the EOF1 score for the accumulated radiation were both statistically significant. The correlation coefficient between the EOF1 score for the mean (accumulated) radiation and the time change in the ripening period length in Kyushu shown in Fig. 4 was $-0.78 (-0.54)$, indicating that the increase (decrease) in the mean (accumulated) radiation was strongly linked to the change in the ripening period.

To analyze the linkages between the mean radiation and other variables, we conducted a composite analysis.
For the mean radiation EOF2, we averaged the SLP and UV850 during the five years when the EOF2 score was high (low) to provide a composite image: this is referred to as the MEOF2HI (MEOF2LOW) mode. The particular five years were 1990, 2000, and 2004-2006 for the MEOF2HI mode and 1993-1997 for the MEOF2LOW mode, respectively. If we take the MEOF2HI mode as an example, the mode indicates the averaged status of the atmosphere when the mean radiation during the ripening period in Kyushu (represented by the EOF2) is lower than the long-term mean. In the MEOF2HI mode, a more westward extension in Pacific anticyclones was found compared to that in the MEOF2LOW mode (Fig. 8). The positive anomaly in Pacific anticyclones persisted in the MEOF2HI mode, suggesting the advection of water vapor from the south of Japan and the formation of a convergence zone around Western Japan. This indication was supported by the geographical pattern of a precipitation anomaly between the two modes depicted from the APHRO_JP data.

From the MEOF2HI mode, in which the mean radiation during the ripening period in Kyushu decreased, we can conclude that the second dominant spatiotemporal variation in the mean radiation is linked to the westward extension in Pacific anticyclones and an associated change in the location of precipitation. A similar conclusion can be gained from the accumulated radiation EOF2 (figure not shown). While the MEOF2HI mode occurred more frequently in the 2000’s than in the 1980’s and 1990’s, this change was...
not statistically significant at the moment of the analysis.

4. Conclusion

We investigated the time trend and variation in the mean and accumulated radiation for the ripening period of paddy rice in Kyushu, applying EOF analysis to the radiation data derived from the NHRCM. The validation results showed that the radiation data derived from the NHRCM were accurate enough to analyze the spatiotemporal change in radiation after calculating a 3-year running mean. While some sort of bias may be found in the RCM output, we believe that dynamically downscaled reanalysis data are useful to understand the atmospheric fields linked to the variation in a variable of interest (e.g., radiation) in a data-sparse area.

Based on the results of a meta-analysis of crop statistics, the ripening period in Kyushu was shortened by 10 days for the period 1979-2007, and the timing of the ripening period in the 2000’s was earlier than that in the 1980’s and 1990’s. While the mean radiation for the period increased, the accumulated radiation during the period significantly decreased. This suggests more adverse radiation conditions for paddy rice production in the 2000’s compared to those in the previous decades because of the lower activity of photosynthesis under the insufficient solar radiation conditions. The EOF analysis results showed that the earlier timing and shorter ripening period were the most dominant factors in the change in radiation conditions for the ripening period in Kyushu, while variations in atmospheric fields contributed, in part, to the deterioration of the radiation conditions in the area in the 2000’s. The adverse radiation conditions in the 2000’s could have been the cause of the decline in both rice quality and productivity in Kyushu. Modeling studies would be valuable to quantify the consequence of the adverse conditions, i.e., the decreased accumulated radiation, higher temperature, and their combination, on rice quality and productivity (e.g., Okada et al., 2011a, 2011b).

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