Spatial characterization of recent hot summers in Japan with agro-climatic indices related to rice production

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Abstract

The spatiotemporal characteristics of high summertime temperatures, which can cause high-temperature injuries to rice, during the recent period of climatic variability (1978-2010) in Japan were analyzed and quantified by using daily gridded meteorological data with high spatial resolution and GIS data. Several indices based on heat-dose (defined as the cumulative temperature exceeding a certain threshold) were introduced to assess the impact of heat stress on rice production and quality. Specifically, we examined the utility of these indices for evaluating quality declines in rice. Time series of heat-dose indices based on maximum and minimum summertime temperatures showed that heat stress intensity increased remarkably from 1994. Moreover, high values of a heat-dose index based on a daily mean temperature exceeding 26°C during the 20 days after the heading date of rice showed a clear association with a decline in observed rice quality, whereas no clear relationship was apparent between decreased rice quality due to heat stress and average temperature. We also examined the effect of heat stress on spikelet fertility and ripening in the rice cultivar Koshihikari in four representative regions of Japan by using two indices, a heat-dose index based on a daily maximum temperature exceeding 35°C during 7 days around the heading date, and one based on a daily mean temperature exceeding 26°C during the 20 days after heading. The first index showed large interannual variability in the four regions because of its high dependence on the timing of heading.

Key words: Heat-dose, Heat stress intensity, Mesh Meteorological Dataset (NIAES), Rice planted area, Rice quality.

1. Introduction

The recent frequent occurrence of high summertime temperatures has attracted much attention because of the possible relationship to predicted global climate change. In Japan, hot summers have become frequent since the early 1990s. In 1994, most of the country experienced an extremely hot summer, and, in fact, the average temperature from June to August was the highest ever recorded. In 2007, a new record high temperature of 40.9°C for August was set in Tajimi, Gifu Prefecture, and also in Kumagaya, Saitama Prefecture, according to the Japan Meteorological Agency (JMA), (2008). Then, in 2010, a new record for highest average temperature from June to August was set (JMA, 2011), breaking the 1994 record. Extremely high summertime temperatures directly affect not only natural ecosystems but also human health and human economic activities such as energy consumption and crop production. In particular, the high temperatures of recent years have seriously affected rice production and quality.

Although it is difficult to determine whether the recent frequent occurrences of extreme high temperatures were caused by human-induced climatic change
(so-called global warming), such weather conditions are predicted to occur more frequently in the future (e.g., Intergovernmental Panel on Climate Change (IPCC), 2007). Therefore, both to address the serious problems from heat stress on rice productivity and quality that have already been encountered and to facilitate adaptation to projected global climatic changes, it is important to understand and characterize the high-temperature conditions that have already been experienced and their impacts on rice production.

Many previous researchers have investigated the impact of high temperature on rice productivity and quality. For example, Kawatsu et al. (2007) quantified changes in meteorological conditions and their effect on rice production and showed that rice quality declines as temperature increases during the early ripening period. Other studies investigated rice crop damage caused by the intense heat stress from the extreme high temperatures in August 2007 (Hasegawa et al., 2008; Ishimaru et al., 2008; Yoshimoto et al., 2008). The Ministry of Agriculture, Forestry and Fisheries (MAFF) of Japan has summarized findings of recent studies regarding damage to crops due to recent high temperatures and possible countermeasures (MAFF, 2006, 2008, 2011). The results of these studies can be used to establish a method for quantitative evaluation of the potential impact of meteorological conditions on rice production.

For spatial quantification of climatic or meteorological phenomena, it is reasonable to use gridded, spatially uniform meteorological data, rather than spatially heterogeneous data observed at multiple stations. Several studies have used gridded climatic and meteorological data to analyze and develop crop models for evaluating rice productivity and quality under different climatic conditions (e.g., Iizumi et al., 2009; Okada et al., 2009). Hayashi et al. (2001) introduced an index for quantifying the ripening of rice based on the relationship between mean temperature and cumulative solar radiation during the ripening period. The aim of these studies, however, was to develop a model for evaluating the impact of projected future climatic change on rice cultivation, and they did not explicitly address the spatial characteristics of the effects of heat stress on rice productivity and quality under current climatic conditions.

In this study, we introduced indices of heat stress, which can influence rice production and quality, and quantified the spatiotemporal characteristics of these indices during the summer. We focused on the months from June to September, the major growing season of rice, to clarify the effects of year-to-year variations in high temperatures during the recent period of climatic variability from 1978 to 2010. Then, we attempted to quantify how the spatial characteristics of heat stress intensity may have affected rice productivity and quality in relation to the seasonal phenological changes of rice based on the cultivation schedule. We also investigated the effects of yearly variation in heat stress intensity on a specific rice cultivar, Koshihikari. Koshihikari is a major rice cultivar in Japan because of its good eating quality; it was cultivated on 37% of the Japanese total rice cropping area in 2008 (MAFF, 2010).

A gridded daily meteorological data set with high spatial resolution developed by the National Institute for Agro-Environmental Sciences (NIAES) (Seino, 1993) was used for all analyses. We introduced several indices based on heat-dose (cumulative temperature exceeding a certain threshold; degree-days) to assess the impacts of heat stress on rice production and quality, and examined their utility for evaluating observed declines in the quality of rice under the recent hot summertime conditions.

In creating the gridded meteorological data set for our comparisons of yearly temperature changes, we did not consider the effects of land-use changes (e.g., urbanization) at observation sites (e.g., Nishimori et al., 2009; Fujibe, 2011; Kondo, 2011). We determined that it was not necessary to take into account such effects because our aim was only to clarify the spatial characteristics of high temperatures in relation to yearly meteorological variability, not to analyze long-term temperature trends.

2. Data and Methods

2.1 Study area and period

Our study area was the whole of the Japanese land area where rice is cultivated (Fig. 1). However, we excluded the Southwest Islands (Nansei Islands, i.e., the Ryukyu Archipelago) from some analyses because the agricultural systems used there differ from those used in mainland Japan. The Northern Territories (i.e., Southern Chishima Islands), where rice is not cultivated, were also excluded. The target period was from 1978 to 2010 (33 years). “Summer” was defined as the period from June to September, which corresponds to the major growing period of rice in Japan.
2.2. Mesh Meteorological Dataset (NIAES)

The gridded (mesh) high-resolution meteorological data ("Mesh Meteorological Dataset (NIAES)", hereinafter) used for this study were provided by NIAES and cover the land area of Japan from latitude 24°N to 46°N and from longitude 122°E to 146°E. This data set was created from daily observed meteorological data obtained at Automated Meteorological Data Acquisition System (AMeDAS) stations (AMeDAS is a high-resolution surface observation network developed by JMA) and Mesh Climatic Data 2000 (30-year average of monthly climatic data with a spatial resolution of 45° longitude and 30° latitude [approximately 1 km×1 km]; JMA, 2002). This data set is available on the gamsDB web system (NIAES, 2011) and consists of daily mean, maximum, and minimum temperatures, daily precipitation, daily shortwave radiation, and daily sunshine duration and covers the years from 1978 to 2011 (it is updated every year).

At grid cell without an observation station, daily temperatures were estimated using the following procedure: (1) several observation stations around the target grid cell are selected (generally 4 to 5 stations); (2) the differences between observed values on a given day and the normal value (30-year average) on the same day at the selected stations are estimated; (3) the average of the differences is calculated, weighted by the inverse of the distance between the center of the target grid cell and each of the selected stations; and (4) the averaged difference is added to the daily climatic value of the grid cell. Other meteorological elements such as precipitation and shortwave radiation are interpolated in the same way but using the ratio of the observed to the normal value instead of the difference in values. Seino (1993) describes this method for calculating meteorological values at grid cells without stations in more detail.

The sampling interval of temperature observation at AMeDAS stations for deriving daily maximum and minimum temperatures was changed in 2003 (all stations at the same time) and again in 2008 (from parts of stations subsequently); through 2002, they were extracted from hourly data (24 observations per day); from 2003 through 2007, they were determined using data collected every 10 minutes (144 observations per day); and since 2008, they have been extracted from data collected every 10 seconds (8640 observations per day) (JMA, 2008). To prevent any significant bias arising from these inconsistencies (e.g., Fujibe, 2004), we derived daily maximum and minimum temperatures from hourly data after the change in 2003, as well as before 2003, to use as reference data for creating the Mesh Meteorological Dataset (NIAES).

2.3 Other geographical data

2.3.1 Land-use data

Land-use information for each grid was obtained from “Land Use Mesh 2006”, National Land Numerical Information (Geographical Survey Institute, Ministry of Land, Infrastructure, Transport and Tourism of Japan, 2010)). In these data, land uses are grouped into 11 categories and the area that each category occupies within each individual grid is indicated. We grouped these 11 land uses into five land-use categories (paddy fields, other agricultural land, forest, urban, and other) and estimated the areal proportion of each of these five categories in each grid. Naturally, land uses likely changed during the target period of the present study (1978-2010), so to clarify the spatial pattern of climatic features among the years, we assumed land use to be invariable over time and used the data from 2006 for the entire period in our analysis. Table 1 show the area of each of the five land-use categories by region and the percentage contribution of each to the total area of each of the 11 regions (see Fig. 1 for the locations of the regions).

2.3.2 Administrative boundaries

Statistical data on rice productivity published by MAFF are summarized by sub-administrative regions called “sub-regions for yield statistics” ("sakugara-hyouji-chitai" in Japanese; SRYS, hereinafter). These regions are of sub-prefectural scale and are related to local administrative units (cities, towns, and villages).
Table 1. Area of each land-use category and its percentage area relative to the total area in each region.

<table>
<thead>
<tr>
<th>Region</th>
<th>Paddy (km²)</th>
<th>Agric.* (km²)</th>
<th>Forest (km²)</th>
<th>Urban (km²)</th>
<th>Others (km²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hokkaido</td>
<td>2339 (3.0%)</td>
<td>11983 (15.4%)</td>
<td>53167 (68.4%)</td>
<td>1662 (2.1%)</td>
<td>8598 (11.1%)</td>
</tr>
<tr>
<td>Tohoku</td>
<td>8119 (12.2%)</td>
<td>4010 (6.0%)</td>
<td>46505 (69.8%)</td>
<td>3087 (4.6%)</td>
<td>4895 (7.3%)</td>
</tr>
<tr>
<td>Eastern</td>
<td>4658 (14.5%)</td>
<td>3700 (11.6%)</td>
<td>14346 (44.8%)</td>
<td>5588 (17.5%)</td>
<td>3721 (11.6%)</td>
</tr>
<tr>
<td>Japan</td>
<td>4017 (15.9%)</td>
<td>477 (1.9%)</td>
<td>17236 (68.4%)</td>
<td>1633 (6.5%)</td>
<td>1840 (7.3%)</td>
</tr>
<tr>
<td>Koshin</td>
<td>1052 (5.8%)</td>
<td>1145 (6.4%)</td>
<td>13753 (76.4%)</td>
<td>872 (4.8%)</td>
<td>1179 (6.6%)</td>
</tr>
<tr>
<td>Tokai</td>
<td>2604 (8.9%)</td>
<td>1559 (5.3%)</td>
<td>19645 (67.2%)</td>
<td>3160 (10.8%)</td>
<td>2254 (7.7%)</td>
</tr>
<tr>
<td>Kinki</td>
<td>2785 (10.5%)</td>
<td>760 (2.9%)</td>
<td>18357 (69.0%)</td>
<td>2824 (10.6%)</td>
<td>1882 (7.1%)</td>
</tr>
<tr>
<td>Western</td>
<td>3396 (10.7%)</td>
<td>1075 (3.4%)</td>
<td>23762 (74.9%)</td>
<td>1654 (5.2%)</td>
<td>1831 (5.8%)</td>
</tr>
<tr>
<td>Chugoku</td>
<td>1540 (8.2%)</td>
<td>1101 (5.9%)</td>
<td>14045 (74.8%)</td>
<td>884 (4.7%)</td>
<td>1202 (6.4%)</td>
</tr>
<tr>
<td>Japan</td>
<td>4776 (12.0%)</td>
<td>3525 (8.8%)</td>
<td>25024 (62.7%)</td>
<td>2940 (7.4%)</td>
<td>3614 (9.1%)</td>
</tr>
<tr>
<td>Kyushu</td>
<td>49 (1.1%)</td>
<td>1008 (22.5%)</td>
<td>2606 (58.2%)</td>
<td>265 (5.9%)</td>
<td>546 (12.2%)</td>
</tr>
</tbody>
</table>

*Agric. Agricultural land use excluding paddy

To overlay them onto the Mesh Meteorological Dataset (NIAES), we re-distributed the SRYS data by the following process:

1. Local administration boundary data set ver. 6.2, polygonal data with city-level resolution, was obtained from ESRI Japan (http://www.esrij.com/products/gis_data/japanshp/japanshp.html);
2. the polygons were converted to grids with the same resolution as the grid used for the meteorological data;
3. each local administrative unit was assigned to its corresponding SRYS. In this process, the allocation of the local administrative units into SRYSs was fixed to match that in use in 2010 (note that this allocation changes every year).

The ESRI ver. 6.2 data set was modified to conform to the local administrative units of 2010 by using information about municipality boundary adjustments from the Ministry of Internal Affairs and Communications of Japan. All of Japan in 2010 was divided into 142 SRYSs. Data for other administrative units (prefecture and region) were prepared with the same spatial resolution. Region and prefecture administrative boundaries are shown in Fig. 1.

2.3.3 Agricultural statistical data

The yearly data set for rice production, which contains information on yield, quality, and the cultivation schedule (dates of transplanting, heading, and harvesting), was obtained from governmental crop statistics for the period from 1978 to 2010 provided by MAFF. These statistics are provided as the average of multiple survey points within each SRYS. Owing to the consolidation of municipalities, the SRYS allocations change from year to year, so for the purpose of constructing homogeneous time series, we aggregated the SRYS-based statistics of each year using the SRYS allocation of 2010. In Japan, rice is divided into four classes based on the proportion of well-matured grain: first, second, and third classes, and nonstandard. In this study, we used the proportion of first-class rice as the indicator of rice quality.

We used the original results of the multiple point survey provided by MAFF for the period from 2001 to 2005 for our analyses focusing on a specific cultivar (Koshihikari). The total number of survey points ranged from about 600 to 1200 each year for all of Japan except Hokkaido, and of those about 200 to 500 survey points were for the target cultivar Koshihikari.

2.4 Definition of agro-climatic indices

We introduced indices of heat stress, which can influence rice production and quality. The heat-dose (HD), defined as the cumulative temperature exceeding a certain threshold temperature ($HD = \sum (T - Tb)$, where $T$ is the daily observed temperature and $Tb$ is the base temperature), has often been used as an indicator of heat stress intensity for assessing the effect of temperature on crop production or quality (e.g., Rane and Nagarajan, 2004; Hasegawa et al., 2008). During rice development, extreme high temperatures (over 34-35°C) during the flowering period causes spikelet sterility (Satake and Yoshida, 1978; Kim et al., 2008).
resulting in a decrease in yield. In addition, high temperatures at night lead to yield reductions caused by increased respiration. In the present study, we used two HD values as indices of daytime and nighttime heat stress, daily maximum temperature above the threshold value of 35°C (HD_x35), and daily minimum temperature above the threshold value of 25°C (HD_n25), respectively. These two threshold values were decided by referring to the threshold of ‘the extremely hot day’ (mōsho-bi, in Japanese) and ‘the sultry night’ (netta-ya, in Japanese) established by JMA.

For analyses based on the growth stage of rice, we used heading date data for each year in each grid, as follows. First, time series of the heading date in each SRYS were determined from the crop statistics obtained as described above (section 2.3.3) and the date was assigned to each grid in the SRYS. In SRYSs in which multiple cultivars were grown, the heading date used was the typical date within the SRYS. The data for some SRYSs included early cultivation system statistics, but here we used only normal cultivation system data. Numerous previous studies have pointed out that rice production and quality are affected greatly by temperature during the ripening stage (e.g., MAFF, 2007). Morita (2008) reported that rice quality clearly declines when the daily mean temperature averaged over the 20 days after the heading date exceeds 26°C, and Wakamatsu et al. (2007) reported similar results. Based on their findings, Nagahata et al. (2006) had attempted to introduce a function of HD with the base of 26°C in daily average temperature as an indicator of heat stress intensity on rice quality. Given these findings, we first analyzed the interannual variation of averaged temperature during this period. Then, we examined the HD of daily mean temperature above the threshold temperature of 26°C (HD_m26) as an indicator of heat stress intensity during the early ripening stage of rice. At the same time, we estimated the cumulative solar radiation during the ripening period, which also affects the quality and productivity of rice. We defined the ripening period as the period from the heading date to the day when the cumulative daily mean temperature from the heading date reached 1000°C·day, referring to previous reports (e.g., MAFF, 2006).

Second, the analyses for Koshihikari were based on the multiple point survey data of heading date, whose availability was limited to the 5 years from 2001. We estimated the heading date for the entire target period (1978-2010) for each grid by using the model of developmental index (DVI) by Nakagawa and Horie (1995). The value of DVI is calculated by summing the daily development rate (DVR):

\[
DVI_t = \sum_{i=1}^{t} DVR_i
\]

where \(DVI_t\) is the DVI on day \(t\), and \(DVR_i\) is the DVR on the \(i\)-th day from emergence. The heading date is defined as the date when \(DVI\) first exceeds 2.

Daily DVR is calculated as a function of daily mean temperature \((T)\) and day length \((L)\) as follows:

\[
DVR = \frac{1}{G(1 + \exp(-A(T - Th)))} \quad (DVI < DVI^*)
\]

\[
DVR = \frac{\left(1 - P \exp(B \times \min(L - Lc, 0))\right)}{G(1 + \exp(-A(T - Th)))} \quad (DVI^* \leq DVI < 2)
\]

\[
DVR = \frac{1}{G(1 + \exp(-A(T - Th)))} \quad (2 \leq DVI < 3)
\]

where \(DVI^* = 0.45\), and \(A\), \(Th\), \(B\), \(Lc\), \(G\), and \(P\) are parameters whose values differ among cultivars and

<table>
<thead>
<tr>
<th>Parameters</th>
<th>(DVI &lt; DVI^*)</th>
<th>(DVI^* &lt; DVI &lt; 1)</th>
<th>(1 &lt; DVI &lt; 2)</th>
<th>(DVI &lt; 3)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>0.2366</td>
<td>0.2366</td>
<td>0.3797</td>
<td>0.118</td>
</tr>
<tr>
<td>Th</td>
<td>19.29</td>
<td>19.29</td>
<td>17.96</td>
<td>12.7</td>
</tr>
<tr>
<td>B</td>
<td>–</td>
<td>0.7453</td>
<td>0.5332</td>
<td>–</td>
</tr>
<tr>
<td>Lc</td>
<td>–</td>
<td>15.97</td>
<td>16.18</td>
<td>–</td>
</tr>
<tr>
<td>G</td>
<td>29.24</td>
<td>29.24</td>
<td>20.22</td>
<td>28.8</td>
</tr>
<tr>
<td>P</td>
<td>–</td>
<td>1</td>
<td>1</td>
<td>–</td>
</tr>
</tbody>
</table>
growing stages. The parameter values for each growth stage of Koshihikari are presented in Table 2. The initial value of DVI \((DVI_{ini})\) is derived as follows:

\[
DVI_{ini} = 0.087 \times RTPtp + 0.03681
\]

(3)

where \(RTPtp\) is leaf age at the transplanting. In the present study, we used \(RTPtp=3\). The transplanting date in each grid was derived by spatially interpolating the data observed at survey points by the nearest neighbor method. The transplanting dates for the 5-year period (2001-2005) were averaged by grid, and then the averaged date for each grid was used as the fixed transplanting date for that grid for the entire target period (1978-2010). The indices described above were calculated on the basis of the estimated heading date of Koshihikari. We also calculated HD_\(\text{x35}\) during the 7 days around the heading date to use as an indicator of heat stress affecting spikelet fertility (see Hasegawa et al., 2008).

3. Results

3.1 Overview of index values in relation to past summertime heat stress

First, we investigated the high summer (June to September) temperatures during the entire period from 1978 to 2010 by applying the heat stress indices introduced here. We examined the spatially integrated value of HD_\(\text{x35}\) (\(\text{°C} \cdot \text{day} \cdot \text{km}^{-2}\)) by land use in each year for all of Japan (Fig. 2a), eastern Japan (including Hokkaido) (Fig. 2b), and western Japan (excluding the Nansei Islands) (Fig. 2c) (see Table 1 for the regions included in eastern and western Japan). As Fujibe (2004) pointed out, remarkably large values compared with previous years were observed frequently beginning with the extremely high value in 1994. In eastern Japan, particularly large values were observed in 1995, 2001, 2007, and 2010. In contrast, the extremeness of the 1994 temperature (compared with other years) was much more apparent in western than in eastern Japan. In addition, the proportional contribution of urban areas to the spatially integrated HD_\(\text{x35}\) values was larger than that of the other land-use classes (see Table 1).

Similarly, we examined the yearly variation in the spatially integrated HD_\(\text{n25}\) value (Figs. 3a-c). Unlike the HD_\(\text{x35}\) results, the largest value was found in 2010 for all of Japan as well as for eastern and western Japan, although the value of this index was also large in 1994. Although no other years stand out as having remarkably large index values, overall, index values between 1994 and 2010 were higher than those before 1994. The contribution of urban areas to the total integrated HD_\(\text{n25}\) value of each year was remarkably large in eastern Japan (Fig. 3b). In contrast, the contributions of other land-use area were comparatively larger in western Japan (Fig. 3c). Comparison of the HD_\(\text{x35}\) and HD_\(\text{n25}\) results between eastern (Figs. 2b and 3b) and western Japan (Figs. 2c and 3c) showed that the impact of high minimum temperatures was larger in eastern Japan, and that of high minimum temperatures was larger in western Japan.

We then examined the spatial distribution of HD_\(\text{x35}\) from June to September and in July, August, and September in some typical hot-summer years (1994, 1995, 2001, 2007, and 2010) (Fig. 4). High values of HD_\(\text{x35}\) throughout the summer were found mainly in inland parts of the Kanto and Tokai regions, where
the coast, except in northern Japan. Areas of high urban and coastal areas and on small islands near affected in each month were not extremely large. Months of July to September, but the values and area areas with high values were found throughout the record for all of Japan from June to August was set, or September. In 2010, when a new mean temperature was limited to August, and was not observed in July years, whereas it was largest in July in 2001. In 2007, area with high values was largest in August in most year’s extremely large spatially integrated HD_x35 from the Kyushu to Tohoku regions, resulting in that however, areas with high values were widespread extremely high temperatures are common. In 1994, however, areas with high values were widespread from the Kyushu to Tohoku regions, resulting in that year’s extremely large spatially integrated HD_x35 values (Fig. 2). The monthly results show that the area with high values was largest in August in most years, whereas it was largest in July in 2001. In 2007, the remarkable expansion of the high temperature area was limited to August, and was not observed in July or September. In 2010, when a new mean temperature record for all of Japan from June to August was set, areas with high values were found throughout the months of July to September, but the values and area affected in each month were not extremely large.

We similarly examined the spatial distribution of HD_n25 (Fig. 5). High values were found mainly in urban and coastal areas and on small islands near the coast, except in northern Japan. Areas of high values were also found in inland areas surrounding the metropolises in Kanto and Tokai regions, especially in 1994 and 2010. In 2010, not only was the area with high values the largest but the values were very high, resulting in extremely large values of spatially accumulated HD_n25 in that year (see Fig. 3).

3.2 Heat stress on rice associated with the observed heading date

Using the observed heading dates in each SRYS, we calculated the average temperature and the HD_m26 value during the 20 days after heading, along with the cumulative solar radiation during the ripening period, for each grid. Then, we aggregated the values by region (Fig. 1) using spatial averages weighted by the proportion of paddy fields in each grid. Figure 6 shows time series of HD_m26 values in selected regions (Kanto, Hokuriku, Tokai, and Kyushu) and of observed rice quality (percentage of first-class rice) by prefecture within each region. In several years, high HD_m26 values corresponded to decreased rice quality. Particularly in 2010, when the highest HD_m26 value during the target period was found in many regions, a remarkable decrease in rice quality was reported for a large part of Japan (MAFF, 2011). Moreover, cumulative solar radiation and declines in rice quality were also apparently synchronous in some years.

Comparison of the relationship between HD_m26 during the 20 days after heading and rice quality with that between average temperature during that period and rice quality in Tokai and Kyushu regions (Fig. 7) suggests that the association between the decline in rice quality and heat stress intensity can be seen more clearly by using HD_m26 than by using the average temperature. The results for these two regions showed that low rice quality was associated with HD_m26 values larger than 20°C·day. On the other hand, these relationships seemed to be unclear in both HD_m26 and average temperature.

3.3 Heat stress on Koshihikari variety in relation to estimated heading date

Using the fixed transplanting dates (determined as described in section 2.4), the heading date of Koshihikari in each grid was computed for the period from 1978 to 2010. We examined calculated heading date anomalies relative to the heading date of a normal year (average of the 30 years from 1981 to 2010) in Kanto, Hokuriku, Tokai, and Kinki regions, where Koshihikari is the main cultivar for the regular cropping system (Fig. 8). The average heading dates
Fig. 4. Spatial distribution of HD_{x35} during the period from June to September (first column) and in July (second column), August (third column), and September (fourth column) for some typical hot-summer years (1994, 1995, 2001, 2007, and 2010).
Fig. 5. Spatial distribution of HD_n25 during the period from June to September (first column) and in July (second column), August (third column), and September (fourth column) for some typical hot-summer years (1994, 1995, 2001, 2007, and 2010).
in these four regions were 5 August, 7 August, 28 July, and 1 August, respectively. Reflecting the recent tendency toward high temperatures, the estimated heading dates tended to be earlier in 1994 and after than they were before that date. Moreover, the range of interannual variability seemed to be smaller during 1994-2010 than during 1978-1993.

HD_m26 during the 7 days around the heading date was calculated as an indicator of heat stress during the flowering period, which affects spikelet fertility in rice. Then, the area with values larger than 0°C-day (i.e., on at least one day the maximum temperature exceeded 35°C) was determined by region (Fig. 9). The years with large values differed among the four regions as follows: large values were found in 1994 and 2002 in Kanto; in 1978 and 1999 in Hokuriku; in 1995 and 2001 in Tokai; and in 1994 and 2001 in Kinki. HD_m26 during the 20 days after heading date, which can affect rice quality, was also calculated and the area where the value was larger than 20°C-day was determined by region in the same manner (Fig. 10). In Kanto region, the largest value was found in 2010, whereas in the other three regions, the largest values were found in 1994. Interannual variability in the area was larger in Kanto and Hokuriku regions than in Tokai and Kinki regions, and large areas with

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**Fig. 6.** Yearly variation in each of four regions of cumulative solar radiation within the ripening period (top graph in each group of three), HD_m26 during the 20 days after heading (spatial average weighted by the proportion of paddy fields in each mesh) (middle graph in each group), and observed rice quality (% of first class rice) by prefecture within each region (lower graph in each group).
Fig. 7. Relationships between HD_m26 during the 20 days after heading and rice quality (left), and those between averaged temperature during the same period and rice quality (right), in Tokai region (upper panels) and Kyushu region (lower panels).

Fig. 8. Calculated heading date anomalies relative to a “normal” year (average of 30 years: 1981-2010) in Kanto, Hokuriku, Tokai, and Kinki regions.

High HD_m26 were more frequent, and values were higher, in Tokai and Kinki regions than in Kanto and Hokuriku regions.
Fig. 9. Yearly variation in the total area with HD_x35 larger than zero during the 7 days around the heading date, in Kanto, Hokuriku, Tokai and Kinki regions. Each bar shows the proportional areas of four ranges of HD_x35 values.

Fig. 10. Yearly variation in the total area with HD_m26 larger than 20°C·day during the 20 days after heading, in Kanto, Hokuriku, Tokai and Kinki regions. Each bar shows the proportional areas of four ranges of HD_m26 values.
4. Discussion

We investigated the characteristics of recent high summertime temperatures by using heat stress indices. Within the target period (1978-2010), remarkable large values and large inter-annual variation of the heat stress due to daily maximum and minimum temperature, indicated by the spatially integrated HD_x35 and HD_n25 values respectively, were found after 1994 (Figs. 2 and 3). This feature seems to reflect the rapid change in large-scale situation of temperature in mid-1990s over Japan, as is pointed out in previous studies (e.g., Fujibe, 2004; Nishimori et al., 2009). The spatially integrated HD_x35 value was largest in 1994 (Figs. 2 and 4), whereas the spatially integrated HD_n25 value was largest in 2010 (Figs. 3 and 5). In 2010, high-temperature conditions were maintained for an extremely long period (from July to September), although the intensity of the heat stress due to maximum temperature was not very large compared with that in August 2007 and July 2001. Thus, the risk of rice productivity and quality losses due to high-temperature injury may be high even if the cropping schedule is modified to prevent the ripening period from coinciding with the predicted period of high temperatures (MAFF, 2011). On the other hand, in 2007, when a new extreme high temperature record was set in Japan, extremely large heat stress was found only in August. Similarly, in 2001, very high HD_x35 values were widespread, especially in Kanto region, but only in July. In these situations, serious high-temperature injury occurs if a rice growth stage with high-temperature sensitivity coincides with the period of intense heat stress.

We also examined indices of heat stress intensity around the heading date of each year. Many previous studies have reported that rice quality declines when the average temperature during the early ripening stage (20 days after heading) exceeds 26-27°C (MAFF, 2007). In the present study, we found that the rice quality is better related with HD_m26 index than mean temperature in Kyushu and Tokai regions. This finding implies that it may be reasonable to use HD_m26 during the 20 days after heading to evaluate the effect of high temperatures on rice quality at the prefectural scale. The index value of 20°C-day, which is equivalent to an average temperature of 27°C being maintained continuously during the 20 days, was the apparent threshold above which rice quality declined (Fig. 7). Of course, not only heat stress but also many other factors can cause declines in rice quality, as is apparent from the data: many low rice quality values are associated with low HD_m26 value (Fig. 7). Besides, it was found that high quality value were associated with high HD_m26 value in some regions. Low solar radiation also affects the quality of rice (Fig. 6). Furthermore, Yoshimoto et al. (2008) reported that panicle temperature, as calculated by their model (Yoshimoto et al., 2005), was a more effective indicator of heat stress than air temperature. In addition, Kuwagata et al. (2008) reported that water temperature also affects rice quality when the paddies are flooded. Further comprehensive analyses with respect to the relationships between rice quality and related meteorological or other environmental factors are required for discussion on the effectiveness of HD_m26.

We investigated two indices of heat stress related to quality in the specific rice cultivar Koshihikari. We used HD_x35 during the 7-day period around the estimated heading date as an indicator of the heat stress effect on spikelet fertility (Horie et al., 1995). The large interannual variability of the area with high values of this index among regions (Fig. 9) suggest that the existence of a heat stress effect on spikelet fertility depends greatly on the timing of heading. In Tokai region in 2007, where extremely high temperatures were observed only in August, only a small area was subjected to high heat stress (Fig. 9). It is therefore suggested that the heat injury to rice could have been avoided if the period of high temperature did not coincide with the flowering period. Although the validity of using HD_x35 in this way was not verified in this study, Hasegawa et al. (2008) reported a large positive correlation between the heat dose and spikelet sterility ($r^2=0.74$) when the threshold temperature was 34°C.

The interannual variability of the area with high HD_m26 values (Fig. 10) was large in Kanto and Hokuriku regions. The paddy field area in these regions is 4658 and 4017 km², respectively. Thus, 80% or more (by area) of the paddy fields were under heat stress. In Kanto region, 81% in 1994, 80% in 2007, and 87% in 2010, and in Hokuriku region, 87% in 1985, 98% in 1994, and 91% in 2010, were under heat stress. In contrast, in Tokai and Kinki regions, large areas showing high values was more frequent and the interannual variability was lower, particularly
from 1994. The explanation for the high values and low interannual variability in Tokai and Kinki regions may be that the heading date had been shifted to an earlier date, causing the early ripening stage to coincide with the period of high temperature. As a result, 80% or more of the paddy field area of Tokai region was under heat stress for 10 years and of Kinki region for 9 years.

5. Conclusion

We investigated the spatiotemporal characteristics of high summertime temperatures in Japan and their impact on rice cultivation during the recent period of climatic variability from 1978 to 2010 by using gridded meteorological data and GIS data. We introduce indices of heat stress intensity related to rice production and quality based on the heat-dose above a certain threshold value. We examined the utility of these indices for evaluating a quality decline in rice. As representative years with high summertime temperatures, we focused on 1994, 1995, 2001, 2007, and 2010, and analyzed the spatiotemporal characteristics of the high temperature occurrence. The major outcomes of our analysis are the following:

1. A remarkable increase in high temperature was confirmed from 1994, and the spatiotemporal characteristics of the high temperatures in each year were revealed.

2. The heat-dose based on daily mean temperatures exceeding 26°C may be the most useful of the indices examined for evaluating declines in rice quality because it considers temperatures higher than the average temperature.

3. For the specific cultivar Koshihikari, areas in which spikelet fertility and ripening of rice were affected by heat stress were estimated and the variability and intensity of the heat stress were characterized in representative regions.

In this study, we quantified the spatiotemporal pattern of high temperature areas using gridded meteorological data, thus avoiding the influence of heterogeneity in the spatial distribution of observation stations.

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