Long-term changes in rice development in Southern Brazil, during the last ten decades

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Abstract – The objective of this work was to test long-term trends in the duration of rice development phases in Santa Maria, RS, Brazil. The duration from emergence to V3 (EM-V3), emergence to panicle differentiation (EM-R1), emergence to anthesis (EM-R4), and emergence to all grains with brown hull (EM-R9) was calculated using leaf appearance and developmental models for four rice cultivars (IRGA 421, IRGA 417, EPAGRI 109, and EEA 406), for the period from 1912 to 2011, considering three emergence dates (early, mid, and late). The trend of the time series was tested with the non-parametric Mann-Kendall test, and the magnitude of the trend was estimated with simple linear regression. Rice development has changed over the last ten decades in this location, leading to an anticipation of harvest time of 17 to 31 days, depending on the cultivar maturity group and emergence date, which is related to trends of temperature increase during the growing season. Warmer temperatures over the evaluated time period are responsible for changing rice phenology in this location, since minimum and maximum daily temperature drive the rice developmental models used.

Index terms: *Oryza sativa*, development rate, global warming, growing season, maturity group, modeling, phenology.

Alterações de longo prazo nas fases de desenvolvimento de arroz no Sul do Brasil, nas últimas dez décadas

Resumo – O objetivo deste trabalho foi verificar a tendência de longo prazo na duração de fases do desenvolvimento do arroz em Santa Maria, RS. A duração da emergência ao V3 (EM-V3), da emergência à diferenciação da panícula (EM-R1), da emergência à antese (EM-R4) e da emergência a todos os grãos com casca marrom (EM-R9) foi calculada com os modelos de aparecimento de folhas e de desenvolvimento, para quatro cultivares de arroz (IRGA 421, IRGA 417, EPAGRI 109 e EEA 406), no período de 1912 a 2011, com três datas de emergência (cedo, intermediária e tardia). A tendência da série temporal foi testada com o teste não paramétrico de Mann-Kendall, e a magnitude da tendência foi estimada com regressão linear simples. O desenvolvimento do arroz modificou-se ao longo das últimas dez décadas neste local, o que levou à antecipação de 17 a 31 dias na época de colheita, dependendo do grupo de maturação da cultivar e da data de emergência, o que foi relacionado a tendências de aumento na temperatura durante a estação de crescimento. O aumento da temperatura no período avaliado é responsável por modificar a fenologia do arroz neste local, uma vez que as temperaturas mínima e máxima guiam os modelos de desenvolvimento de arroz utilizados.

Termos para indexação: *Oryza sativa*, taxa de desenvolvimento, aquecimento global, estação de crescimento, grupo de maturação, modelagem, fenologia.

Introduction

Global warming has been in the agenda of most of the scientific debates. According to the Fourth Assessment Report (AR4) of the Intergovernmental Panel on Climate Change (2007), global mean temperature has increased by 0.76ºC since pre-industrial times as a consequence of the steady increase in greenhouse gases, mainly CO_2, resulting from anthropogenic activities. The trend of increasing temperature has been more pronounced during the last 50 years (Intergovernmental Panel on Climate Change, 2007), which coincides with the increasing high-carbon energy-based economy of developed and developing countries, and with the warm phase of the Pacific Decadal Oscillation (PDO) from the middle of the 1970's to the end of the 1990's (Streck et al., 2011a).

In southern Brazil, particularly in the state of Rio Grande do Sul, increases in temperature during the 20th century have been reported, with greater increase observed in the minimum rather than in the maximum temperature. For instance, in the 1960–2002 period, the annual average minimum temperature increased from 0.5 to 0.8ºC per decade, whereas maximum temperature increased 0.4ºC per decade (Marengo & Camargo, 2008). In the 1913–2006 period, the increase in minimum temperature was 0.17ºC per decade, and there was no trend in maximum temperature (Sansigolo & Kayano, 2010).

Plants respond finely and are tuned to changes in the environment, mainly in terms of development rate. Phenology is an important part of plant ecology for studying changes in the development cycle of plants and ecosystems, and is a surrogate measure for climate change, particularly in locations where meteorological data are not available, referred to as phenoclimatic measures (Cleland et al., 2007). In subtropical and temperate regions, natural ecosystems and perennials (trees in streets and fruit trees in orchards) green up in spring (due to leaf unfolding and flowering), especially in response to temperature in late winter and early spring. Therefore, global warming may be tracked through plant phenology (Wang et al., 2008; Körner & Basler, 2010).

Annual agricultural crops are also highly sensitive to temperature, considering that the developmental phases are strongly temperature-dependent. In warmer climates, the daily rate of crop development increases, reducing the duration of growth period, which ultimately has the potential to decrease crop yield (Wheller et al., 1996; Streck & Alberto, 2006; Walter et al., 2010). Earlier flowering and maturity of crops in the Northern Hemisphere have been reported over the last five decades and associated with warmer temperatures in winter and spring (Hu et al., 2005; Menzel et al., 2006; Tao et al., 2006; Estrella et al., 2007; Wang et al., 2008). However, some authors argue that long-term changes in crop phenology are more driven by changes in farm management practices and by the adoption of new technologies, mainly new cultivars, than by past climate change (Craufurd & Wheller, 2009). Therefore, studies based on long-term data on the onset of phenological events in agricultural crops may have some confounding factors built in. To eliminate these confounding factors, a more appropriate approach would be to use crop development models, well calibrated for local genotypes, and run them over the long-term temperature series. By doing this, cultivars and farming practices are detrended and kept constant throughout the past decades.

Soybean, maize, and rice are the three main agricultural crops cultivated in the state of Rio Grande do Sul, Brazil. About 60% of the rice produced in the country is grown in approximately 1 million hectares of flooded irrigated lowlands in Rio Grande do Sul (Reunião técnica da cultura do arroz irrigado, 2010). A typical timeline for rice production in the state is sowing in the spring (October and November) and harvesting in late summer/early fall (February and March). From harvesting to sowing in the next growing season, the rice paddies are kept as fallow. Over the last 40 years, the timing of rice harvest in Rio Grande do Sul has been shifted from late April and May to February and March, partly due to an anticipation of sowing time from November–December to October–November and to field management practices during the fallow period, such as no-tillage sowing and pre-germinated sowing (Reunião técnica da cultura do arroz irrigado, 2010). Moreover, global warming may also have played a crucial role in the anticipation of rice harvesting time in Rio Grande do Sul State during the last decades.

The objective of this work was to test for long-term trends in the duration of the rice developmental phases in Santa Maria, RS, Brazil.

Materials and Methods

The experiment was carried out in Santa Maria, RS, Brazil (29º43'S and 53º43'W, at a 95-m altitude). This location is representative of a major rice (*Oryza sativa* L.) growing area of the state, known as Depressão Central (Reunião técnica da cultura do arroz irrigado, 2010). Rice development cycle was divided into four developmental phases: emergence to three fully expanded leaves (EM-V3), emergence to panicle differentiation (EM-R1), emergence to anthesis (EM-R4), and emergence to all grains with brown hulls (EM-R9), according to the Counce phenological scale (Counce et al., 2000). The V3 stage was chosen because it is the recommended time for the onset of flood-irrigating rice paddies and for the first application of nitrogen side dressing (Reunião técnica da cultura do arroz irrigado, 2010). At the R1 stage, the number of spikelets per panicle is set and the nitrogen side dressing is applied for the second time (Reunião técnica da cultura do arroz irrigado, 2010), whereas at R4 the number of grains per panicle is set.

The EM-V3 phase was simulated using the Streck leaf appearance model (Streck et al., 2008):

$$LAR = LAR_{max12} \times f(T) \times f(C) \quad (1),$$

in which: LAR is the daily leaf appearance rate (leaves per day); LAR_{max12}, is the maximum daily leaf appearance rate of the first two leaves (leaves per day); f(T), is a temperature response function; and f(C), is a chronology response function.

The EM-R1, EM-R4, and EM-R9 phases were simulated with the Wang & Engel model (Wang & Engel, 1998) adapted for rice by Streck et al. (2011b):

$$r = r_{max,v} \times f(T) \quad (2)$$

$$r = r_{max,r} \times f(T) \quad (3)$$

$$r = r_{max,gf} \times f(T) \quad (4),$$

in which: r is the daily development rate; $r_{max,v}$, $r_{max,r}$ and $r_{max,gf}$ are the daily maximum development rates during the vegetative, reproductive, and grain filling phases, respectively; and f(T) is a temperature response function.

The f(T) in equations (1) to (4) and the f(C) in equation (1) are dimensionless response functions that vary from zero to one. The f(T) is a beta function:

$$f(T) = [2(T - T_{min})^{\alpha}\times(T_{opt} - T_{min})^{\alpha} - (T - T_{min})^{2\alpha}]/(T_{opt} - T_{min})^{2\alpha} \quad (5)$$

for $T_{min} \leq T \leq T_{max}$,

and $f(T) = 0 \quad (6)$

for T < Tmin or T > Tmax;

$$\alpha = \ln2/\ln[(T_{max} - T_{min})/(T_{opt} - T_{min})] \quad (7),$$

in which: T is the air temperature; and T_{min}, T_{opt}, and T_{max} are the cardinal temperatures (minimum, optimum, and maximum) of 11, 26, and 40ºC, respectively, for LAR. Cardinal temperatures for r are genotype and development phase-dependent, and are given in Streck et al. (2011b). The function f(T) was calculated using daily minimum (TN) and maximum (TX) air temperatures as the values of T, and the resulting daily values of f(T) were averaged (Streck et al., 2011b).

The f(C) in equation (1) is given by (Streck et al., 2008):

$$f(C) = 1 \quad (8)$$

for HS< 2, and

$$f(C) = (HS/2)^{-0.3} \quad (9)$$

for HS≥2,

in which HS is the main culm Haun Stage. The Haun Stage is defined as the number of fully expanded leaves plus a fraction length of the uppermost expanding leaf to the penultimate leaf at the shoot whorl. The HS is calculated as: $HS = \Sigma\, LAR$, and the V3 stage is considered as the day when HS = 3, i.e., when there are three fully expanded leaves on the main culm. The developmental stage (DS) is zero at emergence, 0.4 at R1, 1.0 at R4, and 2.0 at R9, and is calculated as $DS = \Sigma r$.

Four rice cultivars were evaluated: IRGA 421, IRGA 417, EPAGRI 109, and EEA 406. These cultivars, from the *indica* and *japonica* subspecies, were selected due to their different development cycles. They were released at different times, rendering wide and different cropping scenarios. IRGA 421, IRGA 417, and EPAGRI 109 are modern, semi-dwarf cultivars of the *indica* subspecies, released in the late 1990s and early 2000s. They are currently grown in the state of Rio Grande do Sul, with very early, early, and late development cycles, respectively. EEA 406 is an old, tall, broad-leaf cultivar, of the *japonica* subspecies, released and widely grown in Rio Grande do Sul in the 1950s and 1960s (Streck et al., 2011b).

The coefficient LAR_{max12} in equation (1) is genotype-dependent, and the values for the four rice cultivars used in the present study are 0.351, 0.349, 0.326, and 0.277 leaves per day for IRGA 421, IRGA 417, EPAGRI 109, and EEA 406, respectively (Streck et al., 2008). Likewise, the coefficients $r_{max,v}$, $r_{max,r}$, $r_{max,gf}$, and the cardinal temperatures in equations (2) to (7) are also genotype-dependent, and the values for the four rice cultivars used in the present study are given in Streck et al. (2011b).

The effect of the photoperiod on the development of the evaluated rice cultivars was tested when the WE model was calibrated by Streck et al. (2011b), but no significant photoperiod effect was found. Therefore, no photoperiod effect on rice cultivar development was considered (equations 2 to 4). Furthermore, even though the R9 stage may sometimes be difficult to identify in the field and the post-flowering phase is less sensitive to temperature in some rice genotypes (Van Oort et al., 2011), the development model, during the grain filling phase (equation 4), assumes a temperature response similar to that of the other developmental phases (equations 2 and 3).

Daily TN and TX time series of the meteorological station of the Instituto Nacional de Meteorologia

(Brazilian National Weather Service) at Santa Maria, RS, from the 1912/2013 to the 2010/2011 growing season, were used to run the models, considering three emergence dates in each growing season: 10/17, 11/18, and 12/15 for the cultivar IRGA 421; 10/16, 11/10, and 12/5 for the cultivar IRGA 417; and 10/6, 10/21, and 11/4 for cultivars EPAGRI 109 and EEA 406. These dates were selected for early, mid, and late plant emergence according to the recommended sowing period for each cultivar, which varies from 10/1 to 12/10 (Reunião técnica da cultura do arroz irrigado, 2010). For each emergence date within each growing season, the duration (days) of the EM-V3, EM-R1, EM-R4, and EM-R9 development phases was computed. When there were gaps (missing data) in the TN and TX time series before any of the development phases was completed, the simulation was stopped and the model was run for the next emergence date or growing season, so that only completed development phases, with observed TN and TX, were used.

The trend of the time series of the duration of the development phases was tested with the non-parametric Mann-Kendall (MK) test (Original MK and Modified MK – the latter was used if autocorrelation was detected with the RUN test), and the magnitude of the trend was estimated with simple linear regression (Sansígolo & Kayano, 2010), at 5% probability.

Results and Discussion

During the simulation period (October to April), monthly average minimum and maximum temperature series had an increasing trend of minimum temperature in all months, except April (no significant trend), and there was a decreasing trend of maximum temperature in January and February. The other five months had no significant trend in monthly average maximum temperature. The increase in minimum temperature was 0.25, 0.25, 0.23, 0.17, 0.18, and 0.16ºC per decade in October, November, December, January, February, and March, respectively, and the decrease in maximum temperature was 0.13 and 0.16ºC per decade in January and February. The monthly average minimum and maximum temperature series of three of these months (October, December, and February) are plotted in Figure 1.

The time series of the duration of each development phase in each emergence date for the rice cultivars IRGA 421, IRGA 417, EPAGRI 109, and EEA 406 were registered (Figures 2 to 5). The number of growing seasons in which the development phases were not completed, due to missing TN or TX data during the 1912–2011 period, varied from 2 (2.04%) to 30 (30.61%), depending on emergence date, development phase, and cultivar.

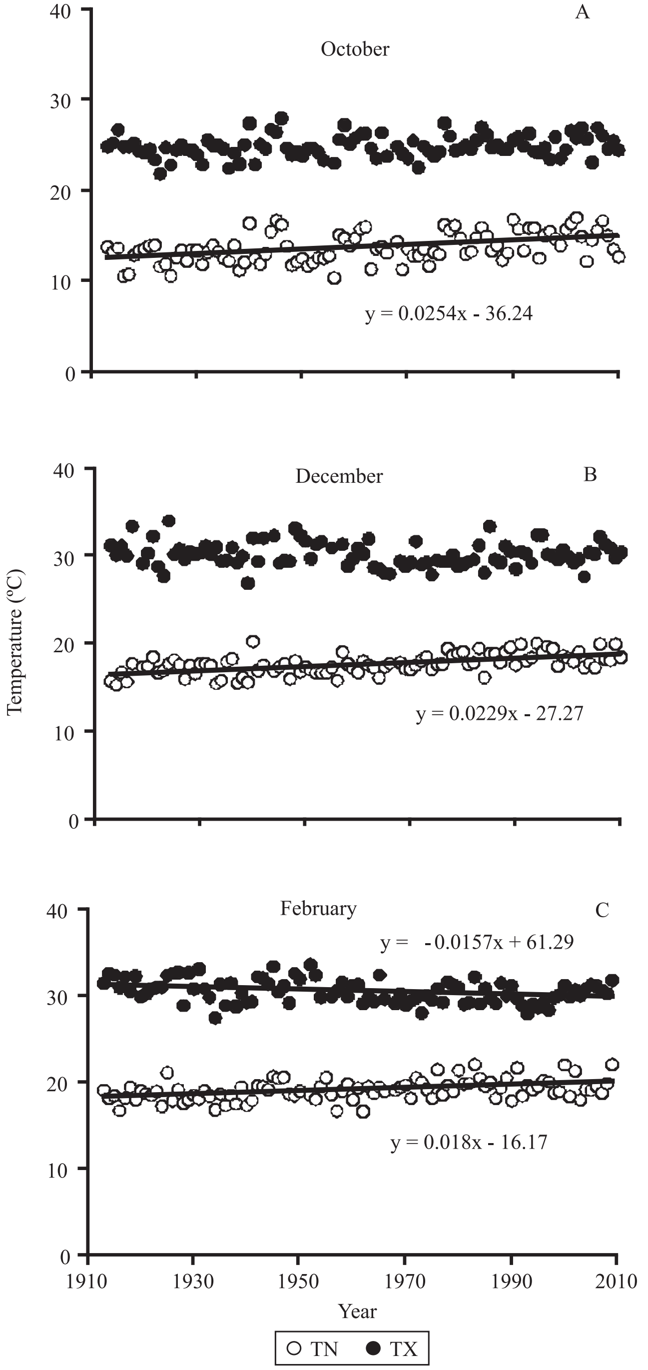

Figure 1. Time series of monthly average minimum (TN) and maximum (TX) temperatures in October (A), December (B), and February (C) during the simulation period.

Within a growing season, the duration of all development phases decreased from early to late emergence in all cultivars, which is realistic since both TN and TX increase as sowing is delayed throughout the recommended period for rice in this location. Among cultivars, the duration of the development phases increased in the sequence IRGA 421<IRGA 417<EEA 406<EPAGRI 109, which is also realistic and consistent with the developmental cycle of these four rice cultivars (Reunião técnica da cultura do arroz irrigado, 2010). These results indicate that the LAR (equation 1) and the r models (equations 2 to 4) are appropriate for the present study.

The MK test indicated a significant negative long-term trend (decrease) for all time series (developmental phases, emergence dates, and cultivars). These results

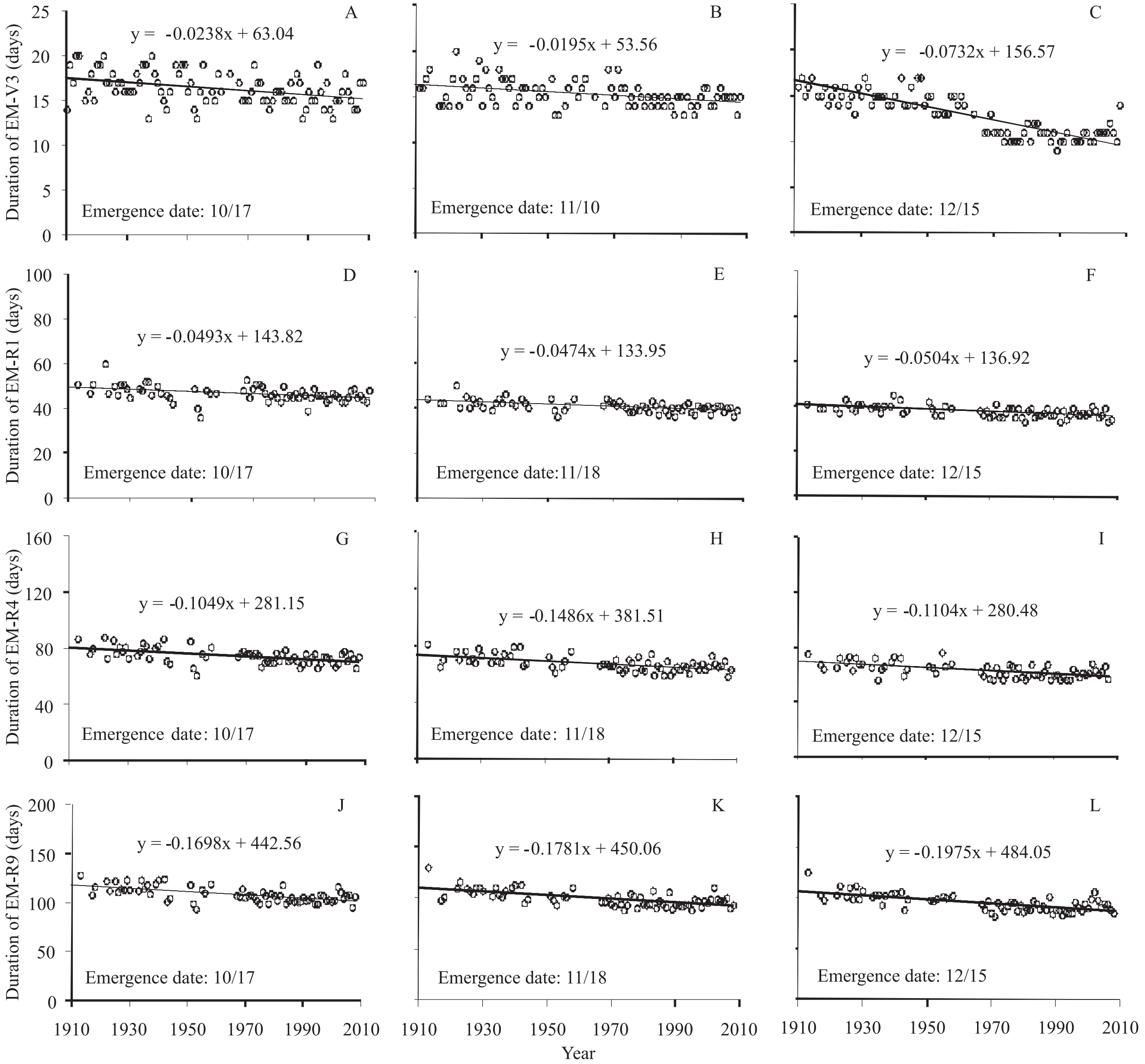

Figure 2. Duration from emergence to expansion of the third leaf (EM-V3), emergence to panicle differentiation (EM-R1), emergence to anthesis (EM-R4), and emergence to all grains with brown hulls (EM-R9) of the rice cultivar IRGA 421 as a function of years, during the 1912–2011 period (1912/1913 to 2010/2011 growing seasons) in Santa Maria, RS, Brazil, in three emergence dates (month/day): 10/17 (A, D, G, J), 11/18 (B, E, H, K), and 12/15 (C, F, I, L).

indicate that development rates in rice have increased over the past one hundred years in this subtropical location. The magnitude of the decreasing trend, which is given by the slope of the linear regression of the duration of the development phase against years, was significant for all time series (development phases, emergence dates, and cultivars). Linear regressions are shown in order to provide the magnitude of the trends for each time series (Figures 2 to 5).

Among development phases, the decrease (slope) was lower (less negative) for earlier ones (EM-V3) and increased (became more negative) for later ones, indicating a steady increase in the development rate throughout the rice development cycle. Among

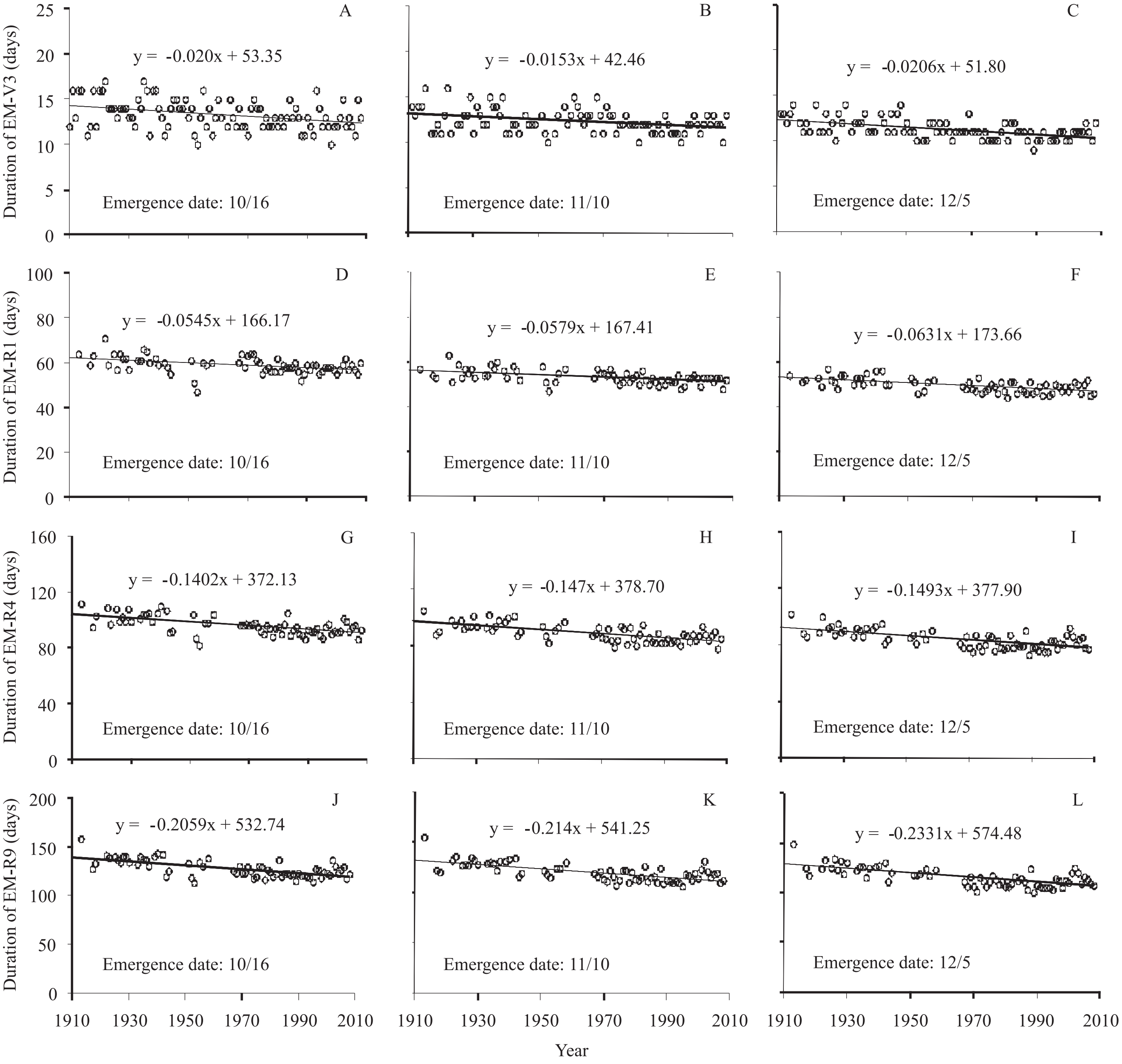

Figure 3. Duration from emergence to expansion of the third leaf (EM-V3), emergence to panicle differentiation (EM-R1), emergence to anthesis (EM-R4), and emergence to all grains with brown hulls (EM-R9) of the rice cultivar IRGA 417 as a function of years during the 1912–2011 period (1912/1913 to 2010/2011 growing seasons) in Santa Maria, RS, Brazil, in three emergence dates (month/day): 10/16 (A, D, G, J), 11/10 (B, E, H, K), and 12/5 (C, F, I, L).

emergence dates, the decrease (slope) increased (became more negative) from early and middle to late emergence dates, indicating that the increase in the development rate was more pronounced when the development cycle started and took place during late spring/early summer (November and December). Among cultivars, the slope usually increased (became more negative) in the sequence IRGA 421<IRGA 417<EEA 406<EPAGRI 109, i.e., proportionally to the length of the development cycle (early to late cultivars), indicating that the increase in the development rate occurred throughout the entire growing season.

For the EM-V3 phase (Figures 2 A, B, and C to 5 A, B, and C), the decrease varied from 0.1 day per decade (cultivar EEA 406 in the 10/21 emergence date) to 0.7 day per decade (IRGA 421 in the 12/15 emergence

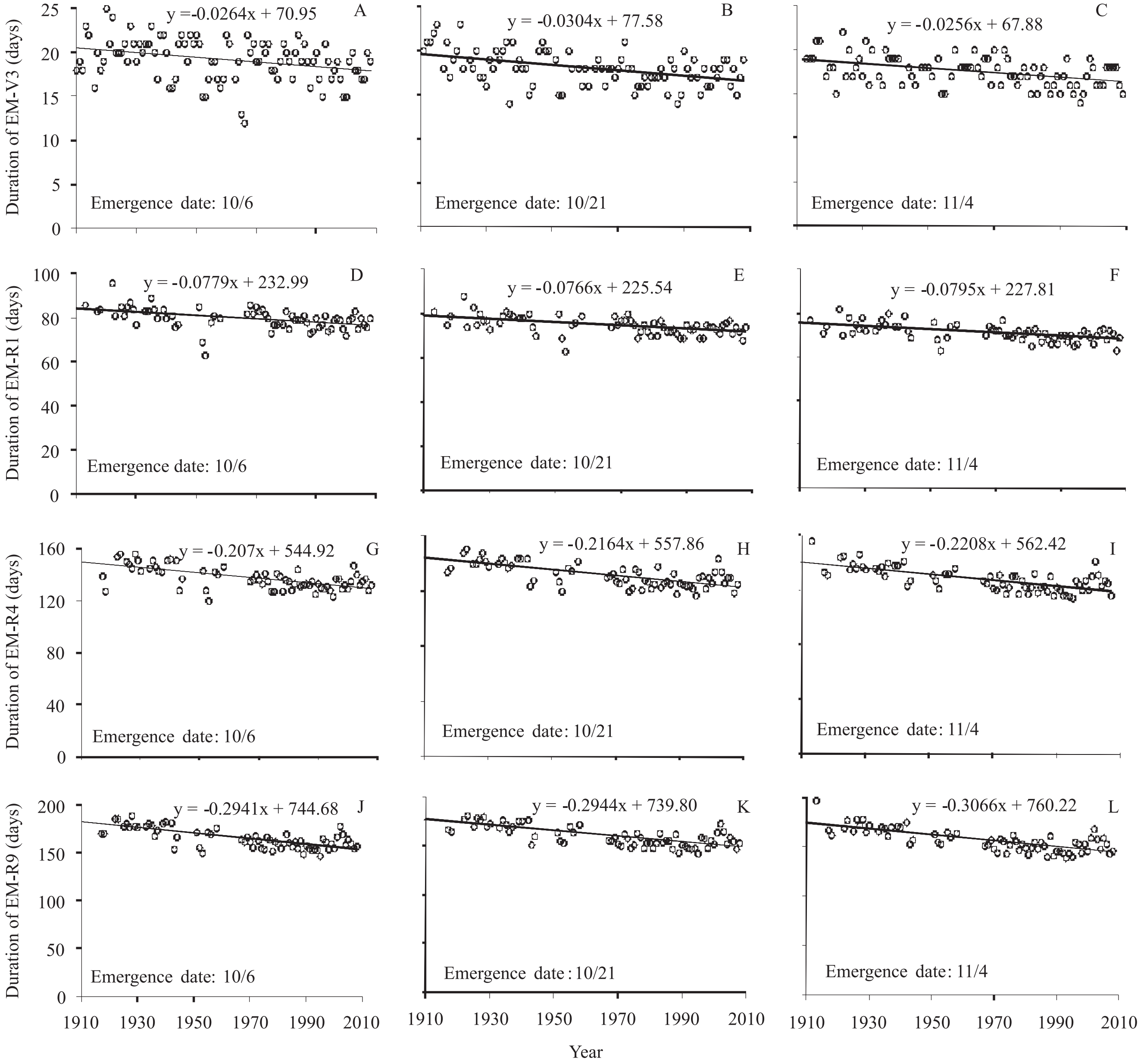

Figure 4. Duration from emergence to expansion of the third leaf (EM-V3), emergence to panicle differentiation (EM-R1), emergence to anthesis (EM-R4), and emergence to all grains with brown hulls (EM-R9) of the rice cultivar EPAGRI 109 as a function of years during the 1912–2011 period (1912/1913 to 2010/2011 growing seasons) in Santa Maria, RS, Brazil, in three emergence dates (month/day): 10/6 (A, D, G, J), 10/21 (B, E, H, K), and 11/4 (C, F, I, L).

date). For the EM-R1 phase (Figures 2 D, E, and F to 5 D, E, and F), the duration decrease varied from 0.5 day per decade (IRGA 421 in the 11/18 emergence date) to 0.8 day per decade (EPAGRI 109 in the 11/4 emergence day), whereas for the EM-R4 phase (Figures 2 G, H, and I to 5 G, H, and I), the duration decrease varied from 1.0 day per decade (IRGA 421 in the 10/17 emergence date) to 2.2 days per decade (EPAGRI 109 in the 11/4 emergence date). For the EM-R9 phase (Figures 2 J, K, and L to 5 J, K, and L), the duration decrease varied from 1.7 day per decade (IRGA 421 in the 10/17 emergence date) to 3.1 days per decade (EPAGRI 109 in the 11/4 emergence date). The increase in the slope of linear regressions from early to late emergence dates in each phase (for example, Figures 2 A, B, and C) can be attributed to the fact that November and December

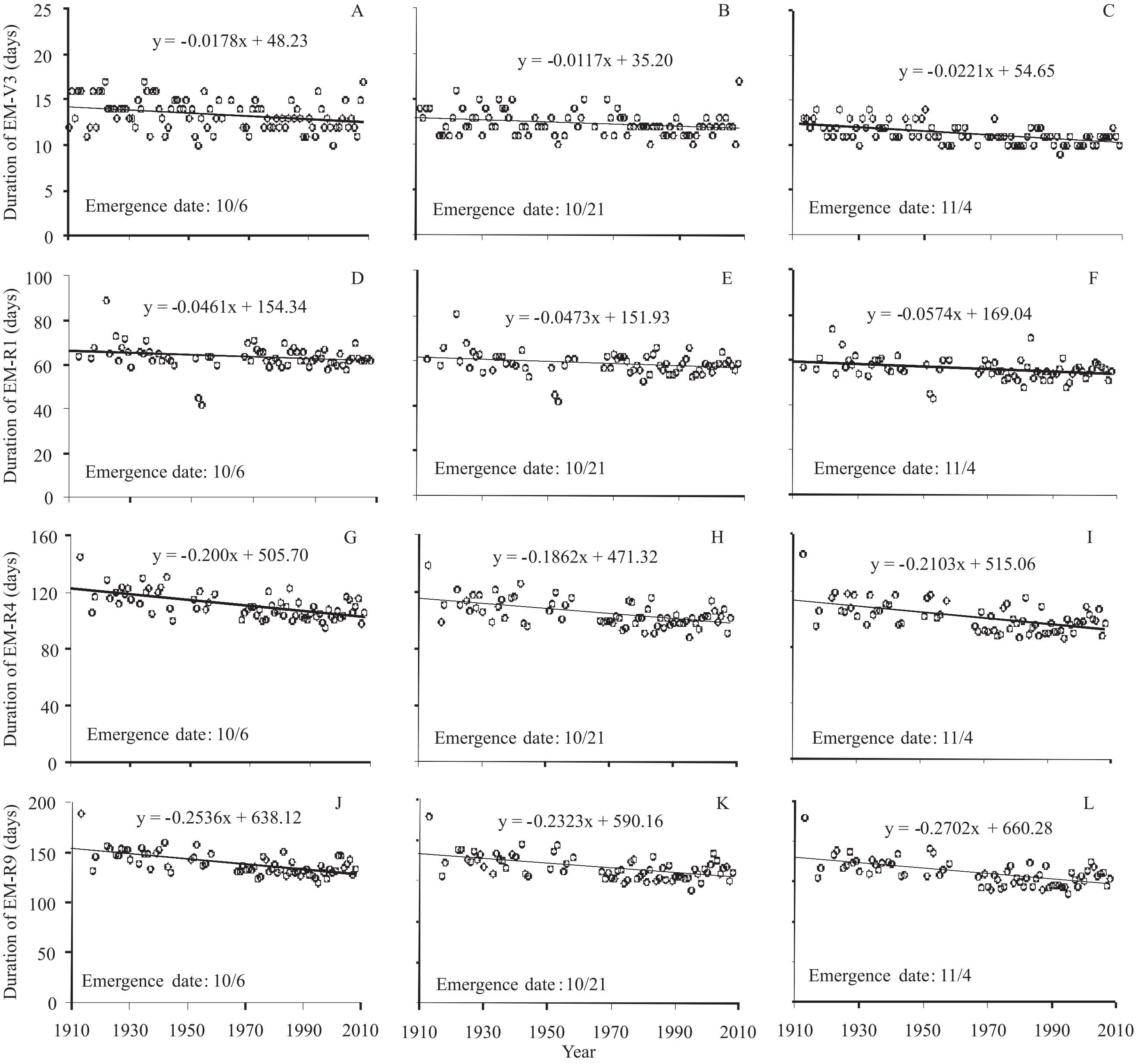

Figure 5. Duration from emergence to expansion of the third leaf (EM-V3), emergence to panicle differentiation (EM-R1), emergence to anthesis (EM-R4), and emergence to all grains with brown hulls (EM-R9) of the rice cultivar EEA 406 as a function of years during the 1912–2011 period (1912/1913 to 2010/2011 growing seasons) in Santa Maria, RS, Brazil, in three emergence dates (month/day): 10/6 (A, D, G, J), 10/21 (B, E, H, K), and 11/4 (C, F, I, L).

had the highest increase in minimum temperature (0.25 and 0.23ºC per decade, Figure 1 B). In October, the increase in minimum temperature was also high (0.25ºC per decade), but temperatures were not as high as in the summer (Figure 1 A). Therefore, the development rate was lower and so was the contribution to the decrease in duration of the development phases.

Considering that the period of the temperature time series is almost one hundred years long (98 growing seasons = 1912/1913 to 2010/2011), the anticipation of the R9 stage (which is close to the harvest date) was of 17 to 31 days since the 1912/1913 growing season, depending on the cultivar maturation group (very early to late) or sowing time (early to late), i.e., from half to one month. The anticipation of harvesting time in rice farms in a subtropical environment, such as the Rio Grande do Sul State, is currently beneficial for farmers for several reasons. First, harvesting rice in February and March allows grains – maturing when atmospheric vapor pressure deficit (VPD) during daytime is high (1.5 to 2.5 kPa) – to be harvested close to optimal moisture (20–22%) and combine harvesters to work more hours per day, taking advantage of the longer photoperiod and less foggy mornings, when compared to April and May. Second, due to higher evapotranspiration, combine harvesters can work better over dry soil during harvest, which increases their efficiency in comparison to working over water-saturated and flooded soil. Third, ratoon management after rice harvesting is better performed during the fall (end of March and April) than during winter time, when soil is usually water-saturated.

For other development phases, the anticipation in timing is also important for field management practices. For instance, for the V3 stage, anticipation over one hundred years was of 1 to 7 days, i.e., the recommended time for the onset of flood irrigation and the first nitrogen dressing were anticipated by up to one week. For the R1 stage, the anticipation in one hundred years was of 5 to 8 days, which means that the second nitrogen dressing was anticipated by a week. Anthesis (R4 stage) anticipation in the one hundred-year period was of 10 to 22 days, reducing the risk of spikelet sterility due to low temperatures (below 15°C) during late summer and early fall (Buriol et al., 1991).

The approach used here to evaluate long-term trends in crop phenology differs from that of previous studies (Hu et al., 2005; Menzel et al., 2006; Tao et al., 2006; Estrella et al., 2007). The latter use observed phenology data, with consequent changes in technology, whereas the adopted development model has the unique advantage of being technology-change independent, a good example of how computer models can help to advance the understanding on the response of agroecosystems to past climate. The LAR and r models used in the present study have been previously calibrated and validated for local modern and old rice cultivars (Streck et al., 2008, 2011b). In addition, these models were built based on the state-of-the-art knowledge on rice development and on its response to driving environmental variables, since these models use the multiplicative approach and a non-linear temperature response function to represent the genotype vs. environment interaction. Moreover, the daily crop development rate is calculated in the models taking into account, separately, the minimum and the maximum daily temperatures, which is important as daily minimum temperature usually increases more than daily maximum temperature in Rio Grande do Sul, including the municipality of Santa Maria, since 1912 (Marengo & Camargo, 2008; Sansigolo & Kayano, 2010; Streck et al., 2011a). Therefore, the long-term simulated rice development observed in the present study can be considered realistic.

According to the literature, global warming has already been affecting the phenology of natural ecosystems, perennials, and agricultural crops in the Northern Hemisphere (Cleland et al., 2007; Wang et al., 2008; Craufurd & Wheeler, 2009; Körner & Basler, 2010). In Santa Maria, RS, Brazil, an increase in both minimum and maximum temperatures (0.1 to 0.7ºC) has been reported during the 1960–2002 period only during winter (June–July–August) and summer (December–January–February) (Marengo & Camargo, 2008), whereas significant positive trends were detected in minimum temperature during winter (1.8ºC per 100 years), spring (1.8ºC per 100 years), summer (1.9ºC per 100 years), and fall (1.5ºC per 100 years), with a significant decrease (-0.6ºC per 100 years) in maximum temperature during summer for the 1913–2006 period (Sansigolo & Kayano, 2010). The earlier harvesting time of rice in Rio Grande do Sul, during the recent decades, has probably been driven by changes in technology, such as earlier cultivars and sowing (Reunião técnica da cultura do arroz irrigado, 2010). The obtained results indicate that warmer temperatures over the past one hundred years have also played a significant role in the anticipation of harvesting time in rice in the central region of Rio Grande do Sul. Considering the increase in temperature over the last one hundred years in the entire state of Rio Grande do Sul (Sansigolo & Kayano, 2010), the trend of increasing rice development rates is also expected.

An important management practice that has increased rice yield in the state of Rio Grande do Sul since the mid 1990s is the anticipation of the sowing date (Reunião técnica da cultura do arroz irrigado, 2010). This close relationship between earlier sowing and higher crop yield has a physiological background, since earlier planting increases the time in which plants can make better use of competing resources, such as solar radiation and water (Kucharik, 2006). If the development phases in rice continue shortening in the future, there may be a negative impact on rice yield in the coming decades, due to a shorter growing period in a warmer climate (Walter et al., 2010). These results corroborate warnings raised in the AR4 (Intergovernmental Panel on Climate Change, 2007) that agriculture is highly vulnerable to climate change and global warming.

Conclusions

1. Changes in rice development over the last ten decades in Santa Maria, RS, Brazil, are related to warming trends during the growing season, leading to an anticipation of harvest time of 17 to 31 days, depending on the cultivar maturation group and emergence date.
2. Warmer temperatures over the evaluated time period are responsible for changing rice phenology, since minimum and maximum daily temperature drive the rice development models used.

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