Future risk of frost on apple trees in Japan

Yoshimitsu Masaki[1]

Abstract

We investigated the spring frost risk over the main apple production areas in Japan under future climates using multiple sets of global circulation models and scenarios. Frost risk was judged by the daily minimum air temperature. Apple phenology was estimated with a phenology model under future meteorological conditions. Since spring cold hardiness of apple trees depends on the phenophase, we took the effect into consideration by decomposing the season into three phenophases. April temperatures are projected to increase by 0.5–2 °C for 2031–2050 and 1.5–6 °C for 2081–2100 relative to that of 1981–2000, depending on the climate models and scenarios. Spring phenology will advance by 10 days or more for the highest temperature increase case for 2081–2100. Frost risk will not monotonically change with the future temperature increase. For the scenario with the temperature increase by 1–2 °C in spring, corresponding to the medium temperature increase case among our simulation cases, frost risk will be maximized in the southern Tohoku region and central highlands, where frost risk is relatively high under the current climates. Frost risk will tend to decrease for the highest temperature increase case. During bud break to foliation, apple trees will be in highest frost risk under future climates.

1 Introduction

Agriculture is largely controlled by weather conditions. Since each plant has its own suitable temperature range for growth, both high and low temperatures beyond this range can deteriorate the growth or even damage the plant. As fruit trees are grown under open air and live for decades, farmers should consider whether the environment is suitable for the trees both now

✉ Yoshimitsu Masaki
  ymasaki@hirosaki-u.ac.jp

[1] Hirosaki University, Hirosaki, Japan

and for some decades in the future. Orchards with less agrometeorological risk will be beneficial for fruit production for decades after the trees are planted.

Apple, classified as a temperate fruit, is intrinsically cultivated in cool climates. The world's main apple production areas are distributed along the colder side of temperate climate zones or highlands at low latitudes. The world apple production is estimated as 83 million tons in 2017, with China, the USA, Turkey, Poland, and India leading in production (Food and Agriculture Organization 2019). Japan produced 735 thousand metric tons of apples in 2017 (ranking 19th in the world), with its production geographically concentrated in the Tohoku region (ca. 37°–42° N) and central highlands because of suitable climate conditions (Fig. 1). The production in the Tohoku region and Nagano Prefecture (in central highlands) amounts to 96% of the national production (Ministry of Agriculture, Forestry and Fisheries 2018). Climate change in this region potentially threatens apple production in the future as warming climates may raise agrometeorological risks (e.g., incompletion of dormancy, sunburn, frost injury, changes in phenology, disorders in fruit skin color). However, few quantitative assessments on such risks have so far been made for this region. This hinders the action to make adequate adaptation plans to alleviate climate impacts on apple production in this region. Sugiura et al. (2007) made a questionnaire survey on observed influence of climate change on fruit-tree cultivation in each prefecture as of 2003. For apple, late frost (responded from 4 prefectures of 47) is the third most common influence, next to disorders in fruit skin color (11 prefectures) and fruit softening (7 prefectures). Interestingly, according to the survey, opposite changes were reported: 3 prefectures responded an increase of frost risk, whereas 1 prefecture responded a decrease. This fact indicates that frost risk makes a contrast to other risks that will change in one direction (e.g., an increase in sunburn, not a decrease). Since measures against future frost risk are not simple, impact assessment of climate change on frost risk of apple is necessary.

Frost injury is one of the major concerns of apple production worldwide. If the trees meet an unseasonably cold spell in spring, buds or flowers will be severely damaged. Under future climates, both increasing and decreasing risks have been reported (Chmielewski et al. 2005; Eccel et al. 2009; Kaukoranta et al. 2010; Hoffmann and Rath 2013; Vitasse et al. 2018; Unterberger et al. 2018). For example, in Styria, Austria, constant or increasing risk was reported (Unterberger et al. 2018), whereas in Trentino, Italy, constant or decreasing risk was reported (Eccel et al. 2009). Hoffmann and Rath (2013) showed frost risk will unlikely increase in Germany. Reported regional differences in frost risk motivated us to conduct this study: In which region will future frost risks of apple increase (decrease) in Japan? Will these change trends continue until the end of this century? Will these changes be irrelevant of time or future scenario? Such information will also help farmers to make a future plan of fruit-tree cultivation. Put simply, warming climates should reduce the frost risk. However, warming climates will also advance the phenophase of the apple. Thus, to assess future frost risk, we should consider the compound effects of exposure in cold spells and advancement of phenology.

Apple trees can tolerate severe cold environments well below –10 °C in winter; however, the cold hardiness gradually weakens in the course of phenological development in spring. This is known as dehardening or acclimation. However, a constant temperature criterion (–2.2 °C in Unterberger et al. 2018) or multiple constant temperature criteria for different significance level (0 °C and 2 °C in Hoffmann and Rath 2013; –4 °C, –2 °C, and 0 °C in Chmielewski et al. 2005; –3 °C, –1 °C, and + 1 °C in Eccel et al. 2009) have been adopted for judgment of frost injury throughout spring phenology. Since spring apple phenology is still in the process of dehardening, the temperature criteria for frost injury should change with the
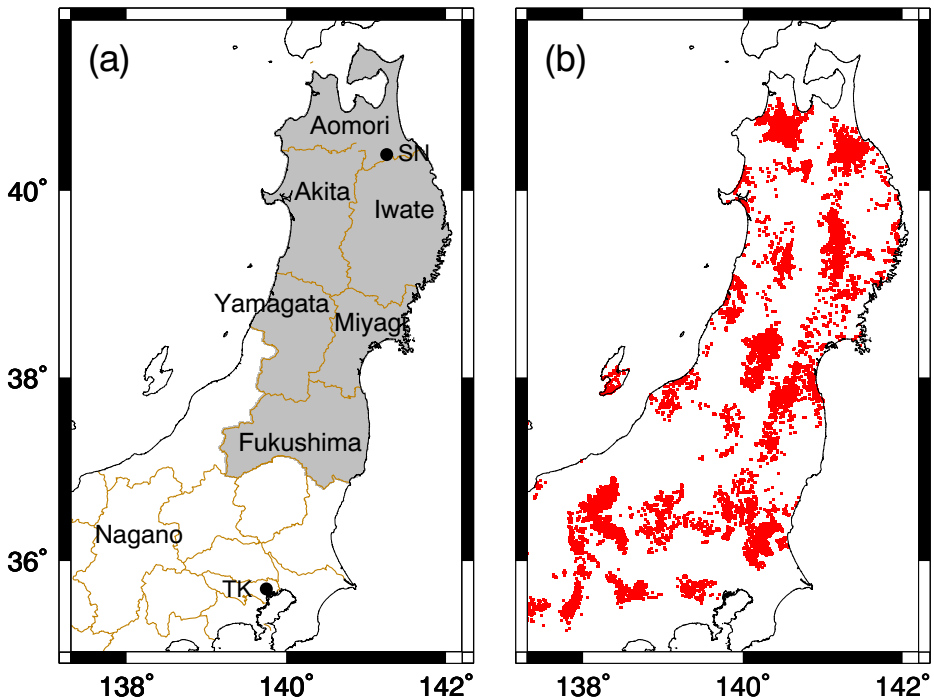
Fig. 1 (**a**) Analysis area. Six prefectures in Tohoku region (shaded; Aomori, Akita, Iwate, Yamagata, Miyagi, and Fukushima Prefectures) and Nagano Prefecture in central highlands are shown. Tokyo (TK) and Sannohe (SN) are also indicated. (**b**) Apple orchard distribution used in this study

phenophase. In this study, we took this point into consideration by using the results of laboratory experiments in the literature.

In this study, we evaluated the impacts of climate change on frost risks for apples under future climates at a high geographical resolution in the main apple production areas in Japan. We decomposed spring phenology into three phenophases and set different temperature criteria for frost injury for each phenophase. We aimed to clarify future frost risk in the main apple production areas by considering a possible range of future climate scenarios.

2 Methods

2.1 Analysis area

The analysis area (Fig. 1a) is the northeastern part of Japan, covering the current major apple production areas. We specified the geographical distribution of apple orchards (Fig. 1b) at a resolution of ca. 1 × 1 km as meshes satisfying two criteria: (i) apple production in a municipality (subdivision of the prefecture, i.e., city, town, and village) amounted to 1 metric ton or more in 2006 (in 2004 for Niigata Prefecture) according to the agricultural census data (Ministry of Agriculture, Forestry and Fisheries 2005, 2007), and (ii) the land use was classified as orchard in 1987 according to the National Land Numerical Information (Ministry of Land, Infrastructure, Transport and Tourism 1988). Although the obtained

distribution is a bit overestimated in suburb areas near Tokyo due to contamination of other fruit-tree crops, this reproduces a reliable distribution of current apple production areas at a fine resolution. Both surveys were made decades ago, but the latest ones covering each municipality are necessary at a high geographical resolution.

2.2 Climate projection data

By taking uncertainties in climate projection into account, comparisons of projected climates across multiple models or methods are desirable. In this study, we assessed frost risk using every combination of two global circulation models (GCMs) and two climate scenarios in terms of representative concentration pathways (RCPs; see van Vuuren et al. 2011). A GCM simulates atmospheric (and oceanic) circulation and their status at a global scale, based on physics. RCPs give future trajectories that include greenhouse gas concentration and land-use change. Radiative forcing in W m^{-2} in the year 2100 is labelled. Among four standardly adopted RCPs, RCP2.6 and 8.5 were used in this study.

Two GCMs, MIROC5 and MRI-CGCM3 (hereafter, MIROC and MRI, respectively), were chosen from higher and lower members of future temperature increase around Japan, respectively, and chosen among GCMs included in the Coupled Model Intercomparison Project Phase 5 (CMIP5). Therefore, together with the two RCPs, we can estimate the upper and lower bounds of the possible uncertainty range of climate models.

We utilized downscaled datasets compiled for domestic impact assessment of climate change at a high geographical resolution of ca. 1 × 1 km. National Agriculture and Food Research Organization (NARO) provided such datasets based on a simple bias correction method to adjust the mean and deviation of the daily values to those of observation for 1981–2000 using the 1 × 1 km meshed climate database.

The analysis periods were 1981–2000 (the reference period), 2031–2050, and 2081–2100. Since dormancy in winter must be evaluated in an apple phenology model, we started phenology calculations using meteorological data from September of the previous year, well before the start of dormancy. We used the daily meteorological elements (mean, maximum, and minimum temperatures) for the analysis.

2.3 Phenology model

Apple phenology was estimated by a compound model of chill unit (CU) and growing degree hours (GDH) developed by Ito (2019). He revised Asakura's (2011) phenology model and improved the accuracy. We briefly explain the model in this section and in the Supplementary material. We focused on the cultivar "Fuji" in this study because it is the most popular cultivar in Japan (53.3% of the total apple production in 2018; Ministry of Agriculture, Forestry and Fisheries, 2019).

Apple requires a certain amount of cold in winter for completing dormancy. In this study, the completion of endodormancy was judged by the accumulation of a given amount of CU. The phenological development was modeled by GDH, with rapid growth under high temperatures. GDH was accumulated with a reduced rate (see the factor g as defined in Supplementary material) from just before the completion of endodormancy and with a full rate after the completion. Ito (2019) improved the accuracy by replacing a temperature-dependent function in evaluation of CU and by revising parameters of GDH (see Supplementary material).

Since future climate projection data are at a daily interval, we have to estimate hourly temperature from available projection data. Seino et al. (1981) proposed a scheme to estimate hourly temperature from the daily maximum and minimum temperature data by fitting a sum of powers of sine functions. This scheme is suitable for evaluating time duration above/below a certain threshold temperature, but estimated hourly temperature data are completely symmetrical about the noon. We modified the original scheme of Seino et al. (1981) in order to take the minimum and maximum temperatures at 3 h and 15 h by translating the function along the time axis and smoothly connect the hourly temperature data to the adjacent days.

We estimated bud break, foliation, blooming, and flower abscission dates with this phenology model. Prior to the main analysis, we checked the reproducibility of the phenological prediction using on-site meteorological data by comparing the observed phenology at five experimental orchards in the analysis region. In order to fit the observation, we revised or newly determined the GDH criteria for achieving each phenophase (see Sects. S1 and S2 in the Supplementary material).

2.4 Judgment of frost injury

Apple trees gradually lose cold hardiness in a warming phase from winter to spring (dehardening). Thus, susceptibility to frost injury depends on the phenophase. We set the threshold temperature for each phenophase and judged frost injury when the daily minimum air temperature reached or fell below the threshold. Two thresholds for different significance of frost injury were adopted.

2.4.1 Frost risk 0.5 criteria (FC)

Sakuma et al. (2013) determined the tolerance temperature for deciduous fruit trees from a laboratory experiment by examining the health of twigs bearing flower buds after a 1-h freezing treatment. They defined frost injury risk when 30% of flower buds were damaged by frost because farmers cannot recover from such frost injury without economic loss (e.g., by thinning flowers/fruits). Thus, this criterion gives frost risk accompanied by economic loss. They derived the probability of 30% bud injury risk by fitting a logistic curve as a function of the temperature. The temperature giving the probability of 0.5 was adopted for our thresholds (see Table 1). We call it the frost risk 0.5 criteria (FC hereafter) in this study. Although Sakuma et al. (2013) more finely classified phenophases (bud break stage, –3.7 °C; initial stage of foliation, –2.3 °C; bud exposure stage, –2.2 °C; bud coloration stage, –2.2 °C; blooming to full bloom stages, –2.5 °C; and flower abscission stage, –2.0 °C), we simplified the criteria by

Table 1 Temperature criteria for frost injury. We judged frost injury when the daily minimum air temperature gets to or below the criteria. *FC* frost risk 0.5 criteria, *SC*: safety temperature + 2 °C criteria. For detail, see text

Phenophase	Temperature criteria [°C]	
	FC	SC
Phenophase 1: bud break to foliation	–3.7	–0.1
Phenophase 2: foliation to blooming	–2.2	–0.1
Phenophase 3: blooming to flower abscission	–2.5	+0.5

aggregating multiple phenophases to create the ones in Table 1 because only four phenophases can be estimated by the phenology model (Sect. 2.3).

2.4.2 Safety temperature + 2 °C criteria (SC)

Fukushima Prefecture (2019) recommends farmers to take preventive action (e.g., oil-burning heaters, smoke, aspersion irrigation) to protect fruit crops from frosts based on tree body temperature. If we suppose atmospheric temperature is higher than the tree body temperature by 2 °C due to nighttime radiative cooling, we determined another set of temperature criteria (safety temperature + 2 °C criteria, SC hereafter) for frost risk by adding 2 °C to the original criteria (Table 1). SC is also based on a 1-h exposure to the temperature environments.

We note that the temperature threshold of SC is higher than that of FC because SC is a criterion for preventive action for safety, whereas FC is a criterion accompanied by economic loss due to frost injury. Thus, the number of days satisfying SC is larger than that satisfying FC.

2.5 Pseudo-warming experiment

The magnitude of climate change impacts sometimes shows nonlinearity with the temperature increase. Similar impacts can be expected for cases of the same temperature increase, irrelevant of future warming scenarios or pathways. In such cases, it is informative to describe how the impacts change with the temperature increase, instead of the combination of GCMs and RCPs.

For this purpose, we made so-called pseudo-warming experiment. Temperature data sets (27 sets) were artificially produced by simply adding a constant level of warming (at 0.25 °C interval up to 6.5 °C) to the daily temperature data of MIROC for 1980–2000. We similarly calculated apple phenology (Sect. 2.3) and examined the frost risks with FC and SC (Sect. 2.4) for each level of warming.

3 Results

3.1 Future temperature change

In comparison with the annual mean temperature for 1981–2000 (Fig. S1), future annual mean temperature (Fig. S3) was projected to increase by 2–3 °C with MIROC and 1 °C with MRI under both RCPs for 2031–2050. For 2081–2100, MIROC showed an increase by ca. 2–3 °C and 6–7 °C under RCP2.6 and 8.5, whereas MRI showed an increase by ca. 1–2 °C and 4 °C, respectively. Therefore, MIROC under RCP8.5 for 2081–2100 showed the highest increase of the annual mean temperature among all the cases examined. The future temperature increase with MIROC was prone to be overestimated a bit, according to the data provider (by M. Nishimori, personal communication).

Spring climates directly affected both spring phenology and cold spells. Mean temperature in April (Fig. S4) showed a smaller increase than the annual mean temperature. A temperature increase for 2031–2050 ranged between 0.5 °C and 2 °C over most of the analysis region. For 2081–2100, the smallest and largest increases in mean temperature in April are ca. 1.5 °C under RCP2.6 with MRI and 5–6 °C under RCP8.5 with MIROC.

3.2 Future change in phenology

Due to warming climates, springtime apple phenology will advance in future (Figs. 2, 3, S5, and S6). Using MIROC, the phenology will advance by ca. 2–3 and 5 days in the coastal and inland areas of Tohoku region for the case with a future temperature increase by ca. 1–2 °C in April (both RCPs for 2031–2050 and RCP2.6 for 2081–2100). Retardation of phenology was seen in the current southern edge of apple orchard distribution because completion of chill requirement delayed. Warm winters due to global warming meant dormancy was incomplete. For the highest temperature increase case under RCP8.5 for 2081–2100, phenology was advanced by 10 days or more in the inland area of Tohoku region. On the other hand, retardation due to incompletion of dormancy also expanded to coastal areas of this region. Using MRI, the advancement was smaller than with MIROC. Retardation of phenology was geographically limited in the southern edge of the current apple orchard distribution only under RCP8.5 for 2081–2100.

3.3 Future change in frost risk

First, the number of frost-risk days per year for 1980–2000 is shown in Figs. 4 (FC) and 5 (SC). When we used FC, the number of frost-risk days was less than 1 day per year for most of the area. Nagano Prefecture and the southern part of Tohoku region showed a relatively high
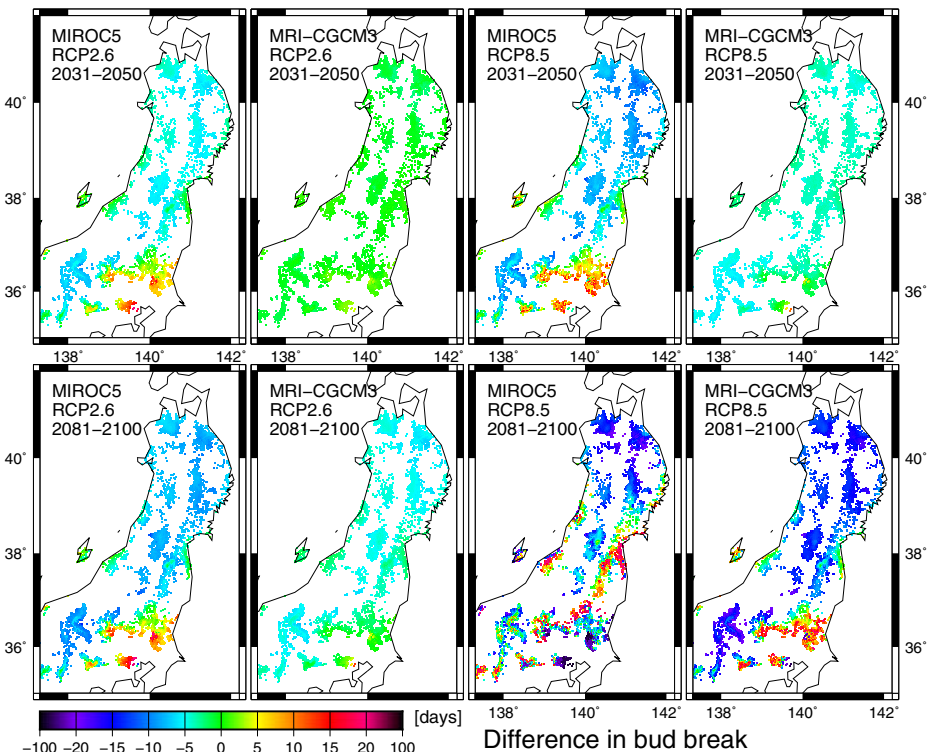

Fig. 2 Future changes in bud break date (relative to 1981–2000) over the apple orchards studied. Information on GCM, RCP, and analysis period is embedded on each panel
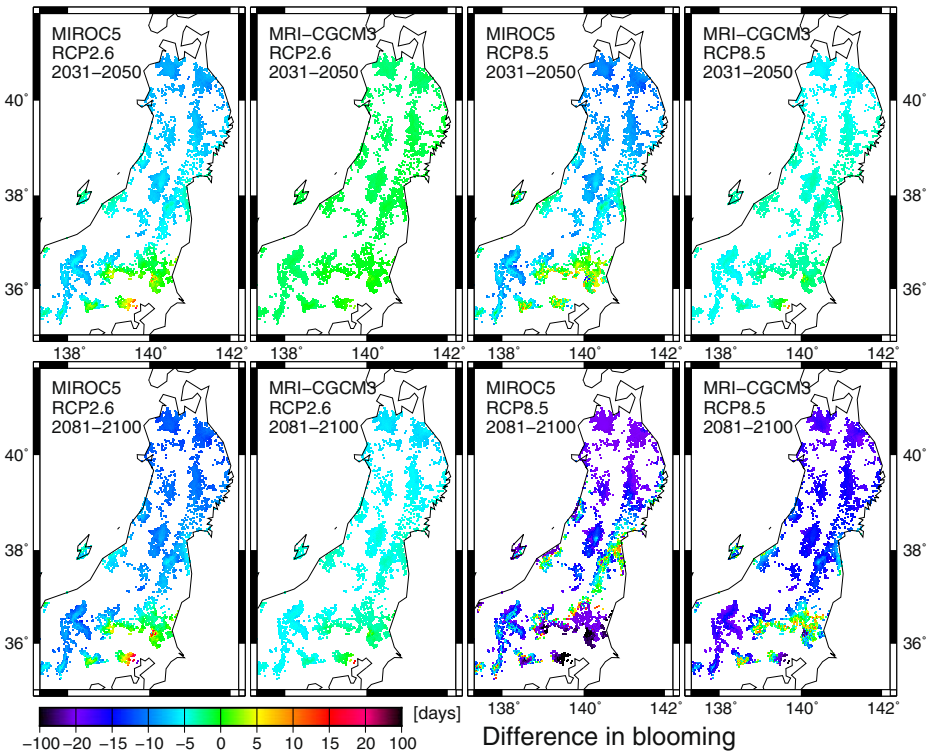
Fig. 3 Future changes in blooming date (relative to 1981–2000) over the apple orchards studied. Information on GCM, RCP, and analysis period is embedded on each panel

value (ca. 2 days per year). Frost risk mostly occurred in Phenophases 1 and 2. Using SC, more frost-risk days were detected than FC. Some inland sites showed 5 to 10 days of frost risk per year. In general, the central highlands and the southern part of Tohoku region tended to have the highest frost risk.

Even if the number of days was small, please note that this was the annual mean value. Over 20 years, the annual values were detected 20 times. In particular, since FC gives the risk of economic loss due to frost injury, even a couple of days during 20 years can be serious enough for farmers. Besides, taking year-to-year variation into consideration, the number of frost-risk days will fluctuate around the mean value; if some years may be free of frost risks, other years may have more frost days than the mean value.

Next, future change in the frost-risk days with FC is shown in Fig. 6. Decreasing trends dominated over the analysis area; however, increasing trends were also detected in some areas. For example, using MIROC, future frost risk will increase in central highlands and the southern part of Tohoku region for the case of a future temperature increase by ca. 1–2 °C in April (both RCPs for 2031–2050 and RCP2.6 for 2081–2100). Interestingly, under the highest temperature increase case of RCP8.5 for 2081–2100, the increasing trend disappeared. Using MRI, future frost risk will decrease in most of the analysis area.

With SC (Fig. 7), the overall tendency of future change was similar to that of FC, but with different magnitudes. The area of increasing frost risk largely expanded to most of the central highlands and the southern part of Tohoku region, especially with MIROC. MRI showed a
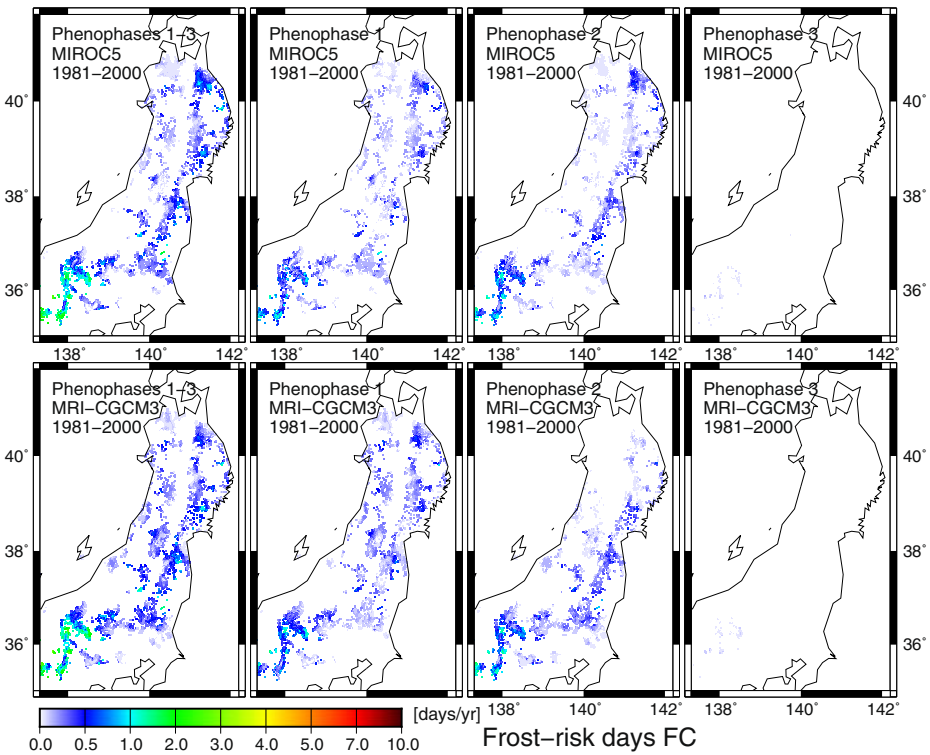
Fig. 4 Number of frost-risk days evaluated with FC for 1981–2000 over the apple orchards examined. The value is given as days per year. The upper and lower panels are results with MIROC and MRI. From left to right, total days during the three phenophases and days during each phenophase from 1 to 3 are shown

decreasing trend in most areas but an increasing trend was also detected. SC also showed decreasing trends under RCP8.5 for 2081–2100 in most areas.

3.4 Which phenophase is more susceptible to frost injury?

As shown in Figs. 4 and 5, the number of frost-risk days is highest in Phenophase 1 and lowest in Phenophase 3. Please note that the duration of each phenophase is different (Table S2). Phenophase 2 is of the longest duration. Although the duration of Phenophase 1 is shorter than that of Phenophase 2, more frost days are detected during Phenophase 1 than Phenophase 2.

Distribution of daily minimum temperatures at an example site in the course of the season provides some explanation (Fig. 8). Sannohe is a relatively high frost-risk site in the Tohoku region (see Fig. 4 with Fig. 1), even in historical records (e.g., Kuryu et al. 1977). Due to the advancement of phenology, future distribution shifts earlier as a whole. For 2031–2050, a certain amount of data lies below the criteria, especially in early DOY for both Phenophases 1 and 2. In each phenophase, the first half of the duration is more susceptible to frost injury than the last half because low temperatures are more frequent in the seasonal course of warming. However, typically seen under RCP8.5 for 2081–2100 with MIROC, the distribution shifts earlier and also upward, especially in Phenophases 1 and 2. Even though the phenology will advance, the temperature during the corresponding phenophases will increase well above the frost injury criteria. Thus, the frost risk will decrease for the highest temperature increase case.
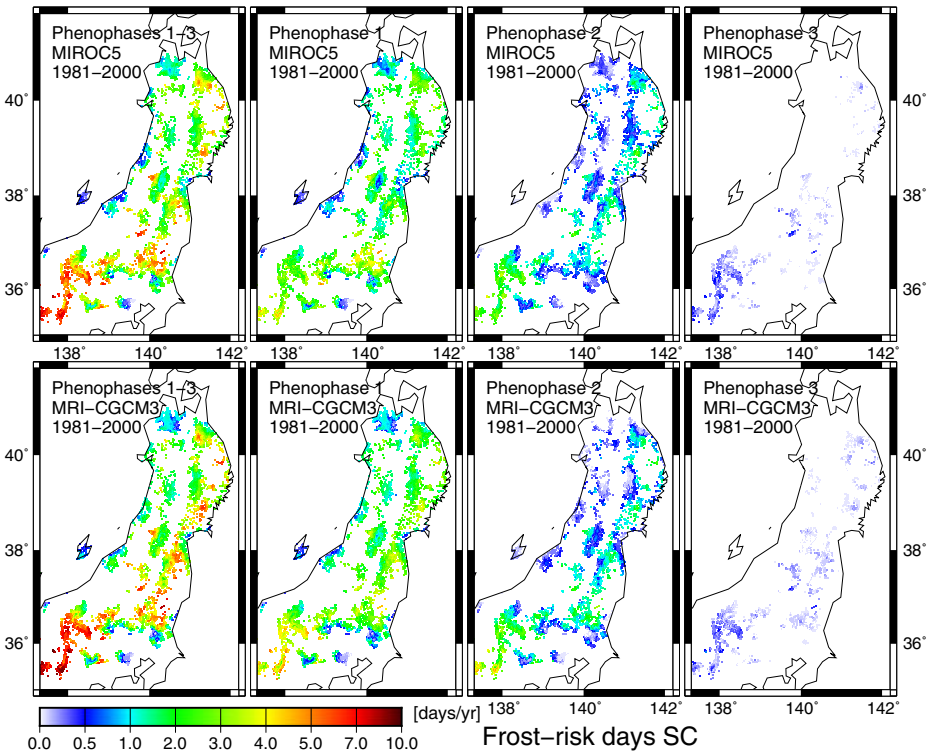
Fig. 5 Number of frost-risk days evaluated with SC for 1981–2000 over the apple orchards examined. The value is given as days per year. The upper and lower panels are results with MIROC and MRI. From left to right, total days during the three phenophases and days during each phenophase from 1 to 3 are shown

3.5 Which level of temperature increase will maximize frost risk?

Future frost risk will increase up to the medium temperature increase cases but tend to decrease for higher temperature increase cases. Then, which level of temperature increase will maximize the future frost risk? Figure 9 shows the results from pseudo-warming experiment.

The total number of frost-risk days over Phenophases 1–3 will reach a maximum in most areas when the temperature will increase by up to 1 °C. In some inland areas (e.g., the northern part of Tohoku region for FC and the southern part of Tohoku region for SC), the frost-risk days will reach the maximum when the temperature increases by ca. 2–3 °C. By deconstructing the period into each phenophase, for Phenophase 1, frost risk will be highest when future temperatures will increase by 2–3 °C in Nagano Prefecture and the southern inland area of Tohoku region. Over the northern part of Tohoku region, frost risk will be highest when future temperatures will increase by 2–4 °C for Phenophase 2 and by >5 °C for Phenophase 3. However, the contribution of Phenophase 3 remains subtle even in the future climates because the number of frost-risk days during Phenophase 2 is extremely small in comparison with the other phenophases.

We note that the temperature increase in the pseudo-warming experiment does not completely coincide with the climate projection by GCMs. The future temperature increase in the pseudo-warming experiment is assumed to be constant, independent of the season, over
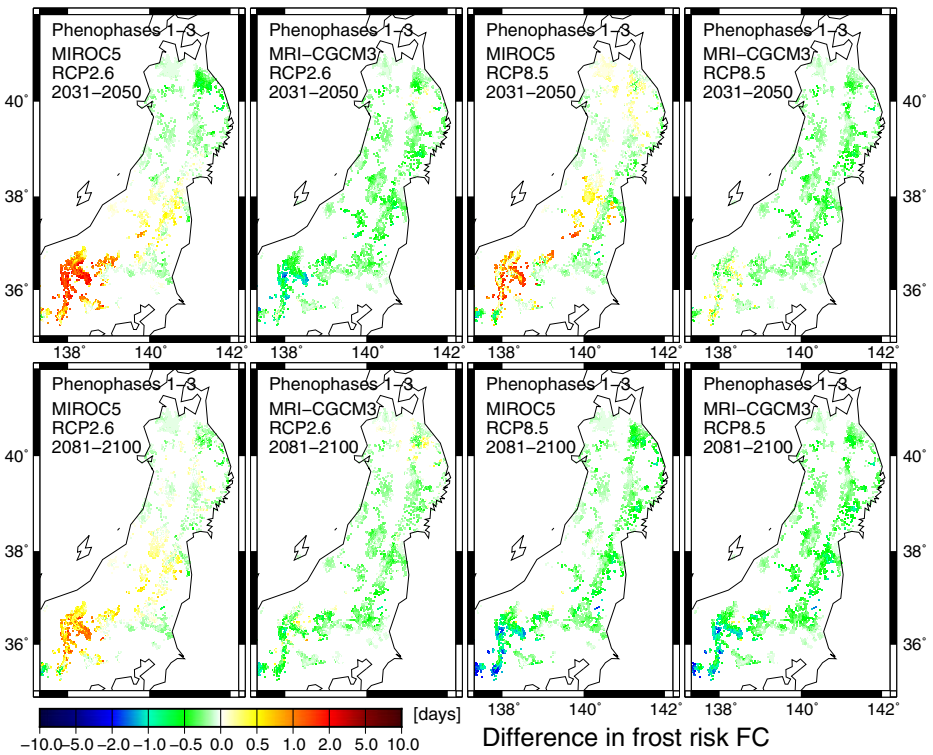
Fig. 6 Future changes in frost-risk days evaluated with FC (relative to 1981–2000) over the apple orchards examined. The value is given by days per year. Information on GCM, RCP, and analysis period is embedded on each panel

the analysis area, whereas the temperature increase projected by GCMs is seasonally and geographically different, as you would expect from differences between Figs. S3 and S4.

4 Discussion

4.1 Interpretation of frost analysis

Risks of future frost for apple cultivation do not seem simple nor straightforward, as both increasing and decreasing changes were detected among different RCPs and locations. At some sites, frost risks will increase in the near future but will tend to decrease after that. By taking an uncertain range of future projected climates into consideration, measures for climate adaptation must be fine-tuned for each site. If future frost risk decreases for any projection case, the current measures for frost protection will work even in the future.

By introducing different temperature criteria for frost injury among the three phenophases (Table 1), differences in frost-risk days were clarified among them. Even though the temperature criteria were lowest for Phenophase 1, the detected frost-risk days were largest (Figs. 4 and 5) in most of the area because the rate of increase in the daily minimum temperature in a seasonal course was steeper than that for in the temperature criteria of frost injury. It is advantageous for practical assessment of frost risk to adopt different temperature criteria among phenophases because if we
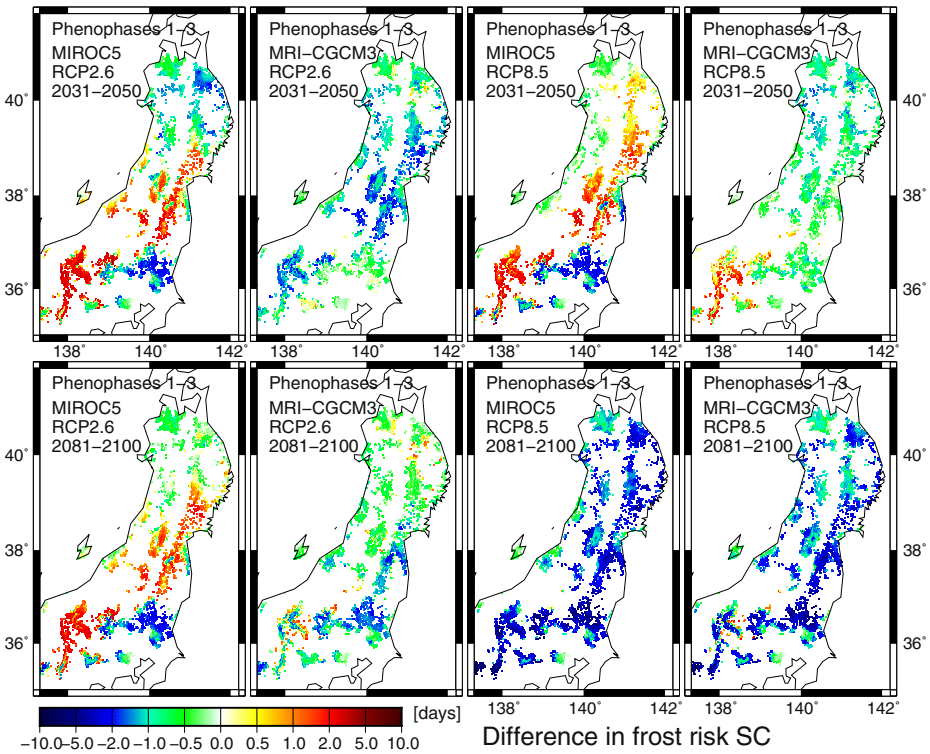
Fig. 7 Future changes in frost-risk days evaluated with SC (relative to 1981–2000) over the apple orchards examined. The value is given by days per year. Information on GCM, RCP, and analysis period is embedded on each panel

used a constant temperature criterion throughout the season, the number of frost-risk days would be overestimated during Phenophase 1 or underestimated during Phenophase 3.

Figure 9 shows that future frost risks will be maximized at a certain level of spring temperature. Aside from year-to-year variation, we can simply assume that future temperatures will increase with the year (at least until this mid-century) under global warming. Therefore, sites painted in blueish colors in Fig. 9 imply that frost risk is currently at the maximum or approaching the maximum in the very near future, whereas in sites painted yellow to reddish colors, frost risks will increase until the conditions reach the turnover temperature.

In this study, the pseudo-warming experiment provides fruitful insights into which level of temperature increase will maximize future frost risk. The experiment helps us to interpolate future climates projected with certain sets of RCPs and GCMs. Fortunately, since this study primarily uses temperature indices for both phenology calculation and frost-risk judgment, the experiment can be successful. In contrast, if an impact assessment model uses meteorological elements which mutually depend on other elements, the pseudo-warming experiment could not reproduce future environments because only temperature-dependent impacts can be evaluated.

Although frost risk itself does not necessarily mean that the site is unsuitable for apple cultivation, farmers must pay for additional expenses (e.g., for oil-burning heaters) to protect orchards from frost. In contrast, a decrease in frost risks (like the case of RCP8.5 with MIROC for 2081–2100) does not simply mean apple cultivation is beneficial and free of agrometeorological risks because other risks (e.g., sunburn risk in summer) should also be considered.
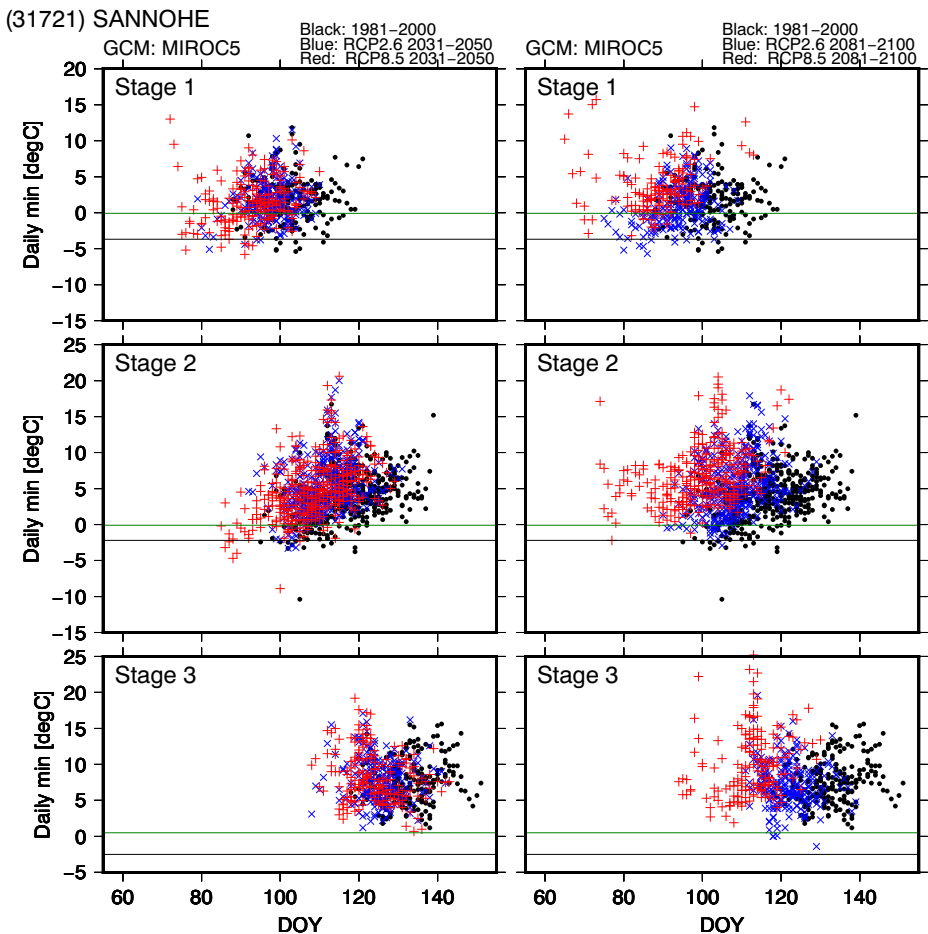
Fig. 8 Daily minimum temperature distribution for each phenophase over 20 years at Sannohe (see Fig. 1). Temperature criteria of FC and SC are shown by black and green horizontal lines. Panels on the left and right columns show results for 2031–2050 and 2081–2100. Blue and red crosses represent the projected climates under RCP2.6 and 8.5, respectively. Black dots represent the current climate (1980–2000) as a reference. A horizontal distribution range gives an approximate duration of each phenophase

4.2 Building an adaptation plan

To avoid unmitigated risks of climate change, plans for adaptation have been widely discussed in today's society. The current standard climate conditions for apple production in Japan are summarized in Sect. S3 in the Supplementary material. When we consider apple cultivation in new lands, we should carefully examine beforehand whether they are suitable for the fruit crops from the viewpoint of agrometeorological risks. It is meaningless to adapt to global warming by relocating orchards to new areas where frost risks will increase under future climate conditions. An impact assessment similar to this study will be helpful for building an adaptation plan without taking an unwilling new risk under climate change. However, few impact assessments of climate change have been made for apple production in Japan, except for the pioneering work of Sugiura and Yokozawa (2004). This is in clear contrast to staple
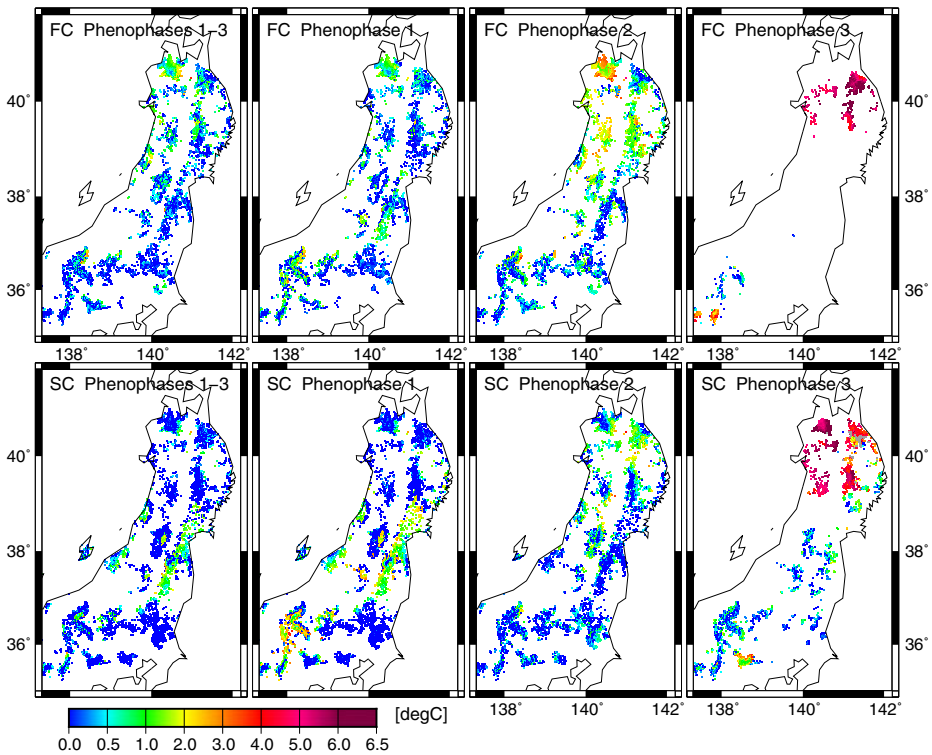
Fig. 9 Temperature increase to maximize frost-risk days via pseudo-warming experiment over the apple orchards examined. Temperature criteria of FC (upper panels) and SC (lower panels) were used. In cases of no frost days for any temperature increase (0–6.5 °C), the mesh is painted white. When non-zero frost days are unchanged for any temperature increase, the mesh is painted gray

food crops (i.e., rice) for which many impact assessments have been made. At least, a sufficient amount of information on future climate impacts is indispensable to form the basis of discussion for a practical adaptation plan. In fact, this study is targeting only to the cultivar "Fuji." Information on future climate impacts on other cultivars is also important for understanding differences between cultivars. Moreover, other meteorological risks on apple production (e.g., sunburn) should be evaluated before making an adaptation plan.

Between fruit-tree and herbaceous crops, there are fundamental differences in adaptation planning. (1) Relocation of apple orchard requires a decadal timespan until the same level of yield will be obtained. (2) Since phenophases of fruit-tree crops are primarily governed by meteorological (i.e., open air) conditions, it is difficult to intentionally modify phenophases of fruit-tree crops as for herbaceous crops (e.g., by shifting transplanting dates or by accelerating phenophase in a greenhouse).

Sustainability of local agricultural industries under climate change will also be important for the coming decades. For example, Hirosaki City, known as a major apple production city in Japan, produces a fifth of Japan's apple production (Ministry of Agriculture, Forestry and Fisheries 2007). Our results showed that future frost risk is relatively low in the city; however, other meteorological risks have not been evaluated yet. Consideration of possible risks from various points of view is helpful for sustainable agriculture in massive production areas.

5 Conclusion

Future change in spring frost risk over the main apple production area in Japan shows different sensitivity to the future temperature increase. The southern part of Tohoku region and central highlands show an increase in frost risk for the medium temperature increase case, but this turned to a decrease for a warmer case. Advancement of spring phenology due to warm climates can be more than 10 days for the highest temperature increase case. In the early phenophase from bud break to foliation, apple trees are at their highest vulnerability to frost risk even under future climates.

Warming climates do not simply decrease frost risk in the future. Some parts of the current apple production area will experience higher frost risk compared with that of today for some future climate scenarios. For adaptation to climate change, relocation of the orchard or a change of crops (from apples to other crops or vice versa) can be one option. In order to avoid taking new risks by adaptation, possible agrometeorological risks should be assessed beforehand. Since future warming paths cannot be uniquely predicted beforehand, we should understand the possible range of future agrometeorological risks and prepare several options corresponding to every warming scenario to ensure sustainable apple production in this region.

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