



Increasing risks of apple tree frost damage under climate change

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Abstract

Anthropogenic climate change is affecting agriculture and crop production. The responses of horticultural and agricultural systems to changing climatic conditions can be non-linear and at times counter-intuitive. Depending on the characteristics of the system, the actual impact can arise as a result of a combination of climate hazards or compound events. Here, we show that compound events can lead to increased risk of frost damage for apple fruit trees in Germany in a 2 °C warmer world of up to 10% relative to present day. Although the absolute number of frost days is declining, warmer winters also lead to earlier blossom of fruit trees, which in turn can lead to regionally dependent increased risks of the occurrence of frost days after apple blossom. In southern Germany, warmer winters may also lead to an increase in years in which apple yield is negatively affected by a lack of sufficient amount of cold days to trigger the seasonal response of the trees. Our results show how cropping system responses to seasonal climate can lead to unexpected effects of increased risk of frost damage as a result of warmer winters. An improved understanding of ecosystem responses to changes in climate signals is important to fully assess the impacts of climate change.

Keywords Apple tree · Climate change · Weather extremes · Compound weather events

1 1 Introduction

The relatively linear response of global mean temperatures to anthropogenic greenhouse gas emissions leads to a complex pattern of changes in local and seasonal

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climatic conditions (IPCC 2013; Saeed et al. 2018). Changes on the seasonal scale can play an important role for the response of eco- and agricultural systems (Porter et al. 2014). To assess the risks arising from changing climate conditions on a system or sector, the characteristic responses of that system need to be incorporated (Sillmann et al. 2018), as impacts may be highly sensitive to even minor changes in the climate hazard. In particular, a climate hazard may arise from the interaction of multiple climate variables or compound hazards over time (Zscheischler et al. 2018).

Horticultural crops, e.g., apple trees, are sensitive organisms, and their yield strongly depends on each year's climatic conditions. Apple trees are especially vulnerable during their blossom period when a few frost days can lead to vast yield reductions (von Storch and Claussen 2012). Moreover, the internal clock of apple trees that triggers blossom depends on various factors as the temperature history during winter and spring and the change in day length.

Apple tree blossoming is triggered by sufficiently long warm periods (forcing requirement) after dormancy which can be characterized by a sufficient number of chill units (chilling requirement). For different apple varieties, these two requirements differ in terms of lengths and required temperatures. If the chilling requirements are not fulfilled, great yield reductions can be expected (Luedeling 2012). In Germany, dormancy has been neglected in the past, because chilling requirements are often already reached at the beginning of the year (Luedeling et al. 2009). Particularly sub-tropical regions, however, are already facing the challenge of not meeting the chilling requirements, fostering dormancy research.

Although the phenological properties are not fully understood yet, there are reasons to believe that climate change will impact apple yields in the future (Augsburger 2013). Global warming impacts frost risks on apple trees through generally warmer air temperatures in late winter and early spring (see Fig. SIIa). On the one hand, frost days are projected to become rarer in a warmer climate (Fig. SIIb). On the other hand, it has been shown that global warming leads to earlier apple tree blossom due to warmer late winter and spring temperatures (Fujisawa and Kobayashi 2010; Grab and Craparo 2011). Thus, frost risk might increase as the start of apple blossom might more frequently happen before the last frost days of spring.

Such an extremely damaging series of frost nights occurred in Europe in April 2017 leading to overall economic losses of €3.3bn (Faust and Herbold 2018). After a relatively warm spring, fruit trees and wine crops were already in an advanced budding phase and thus, especially vulnerable to frost. Vitasse and Rebetez (2018) found that this frost event in 2017 was unprecedented since 1864 for parts of Switzerland and southern Germany. In the observational record, they could, however, not identify a trend towards an increased frost risk in these regions.

Whether global warming increases the risk of frost damages strongly depends on regional aspects of climate change and the phenological properties of the studied crop. Therefore, in addition to locally trustworthy climate projections, a model of phenological processes is required to project changes in growing periods for the crop. Different semi-statistical phenological models for the apple blossom date have been proposed. These models vary in the complexity of the implementation of the chilling and forcing requirements. When applied to the stationary climate the models were calibrated to, they perform quite well. However, when tested on different climate conditions outside of the range of the climate they were calibrated to, the response of the different models is contradictory (Luedeling 2012).

Case studies projecting future changes in frost risk using climate models have been conducted and often times concluded that no robust trend could be identified. This can be due to a canceling out of shifts in blossom dates and the decrease in frost days, but it could also be a result of sparse statistics for the analysis of generally rare frost damages. In this study, we will exclude the latter issue by using the large ensemble HAPPI simulations for current climate (2006–2015) as well as a 1.5 °C and 2 °C climate (Mitchell et al. 2017). With 800 years per scenario (20 10-year runs for each of the 4 models), we are able to make reasonable statistical statements about changes in the frequency of relatively rare frost events after blossom. We use bias-corrected climate simulations which is especially important when analyzing processes characterized by fixed temperature thresholds.

2 2 Methods

2.1 2.1 HAPPI simulations

We analyze daily temperatures in 4 atmosphere-only global circulation models (MIROC5, NorESM1, CAM4-2degree, and ECHAM6). Simulations are run under the HAPPI (“Half a degree Additional warming, Prognosis and Projected Impacts”) protocol (Mitchell et al. 2017) with three climate scenarios: a current climate forced by observed ocean and sea ice coverage conditions of 2006–2015 (about 0.9 °C warming compared to pre-industrial levels) and two 10-year future scenarios representing a 1.5 °C and a 2 °C world above pre-industrial levels. Ocean surface temperature patterns for the future scenarios are obtained by adding the respective warming patterns from CMIP5 simulations on the observed patterns from 2006 to 2015. Sea ice coverage patterns are projected by fitting historic sea ice coverage to ocean surface temperatures and applying this regression to the projected ocean surface temperatures. For each 10-year scenario and each model, 20 runs are analyzed. These 800 years per scenario allow for a reasonable statistic of rare events.

2.2 2.2 Bias correction using EWEMBI reanalysis

For model evaluation, we use the EWEMBI reanalysis (Lange 2016) that has also been used for bias correction in the Inter-sectoral Impact Model Intercomparison Project (ISIMIP).

As the used phenological models rely on absolute temperature thresholds and parameters, we apply a trend-preserving bias correction to the HAPPI simulations. This bias correction technique first adjusts monthly means and then the daily variability around the monthly mean to the reference dataset (EWEMBI) over the reference period (2006–2015) without influencing projected trends (Hempel et al. 2013).

2.3 2.3 Phenological models

We use two phenological models explained and calibrated by Chmielewski et al. (2011): one simple forcing model and one parallel chilling-forcing model. The regions for which the models have been calibrated are shown in Fig. 1.

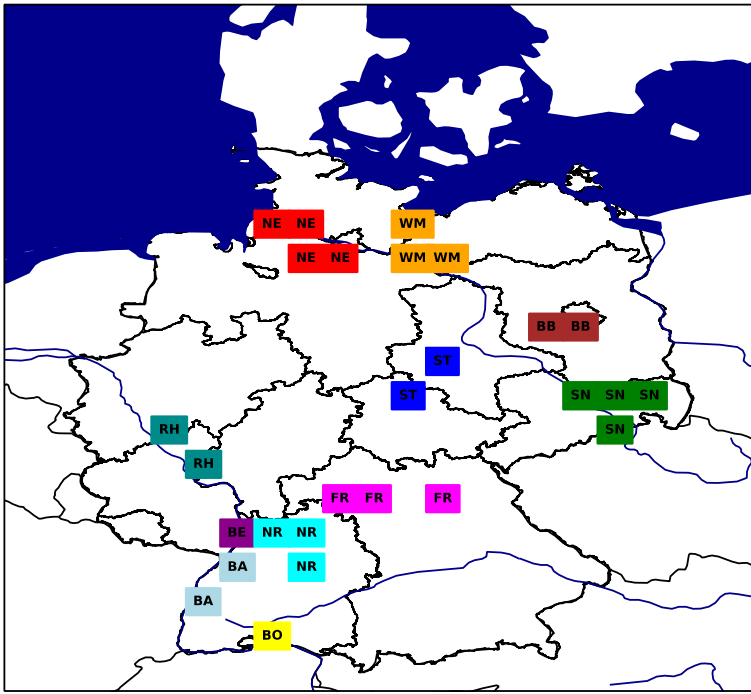


Fig. 1 Apple cultivation regions in Germany: phenological models have been calibrated for each of the different regions (distinguishable by different colors) by Chmielewski et al. (2011). The model parameters for the regions are listed in Table 1

The *forcing model* cumulates forcing units on days with daily mean temperatures T_i above the base temperature for forcing $T_{BF} = 3.3^\circ\text{C}$ from January 1 onwards. The current state of forcing S_F can be expressed as

$$S_F(t) = \sum_{i=1}^t \begin{cases} 0 & \text{if } T_i \leq T_{BF} \\ \frac{28.4}{1 + e^{(-0.185 (T_i - T_{BF} - 18.4))}} & \text{if } T_i > T_{BF} \end{cases}$$

Blossom is predicted to start when the state of forcing S_F reaches the forcing criterion F_{force}^* . We use the parameters fitted by Chmielewski et al. (2011) (see Table 1). Figure 2a illustrates the functioning of the simple forcing model.

Following Chmielewski et al. (2011), we consider days with temperatures below 7°C as contributing to the *chilling requirement*. As an indication of the amount of chilling days required by apple trees in each region, we take the threshold they identify in the parallel chilling-forcing model (see parameter C^* in Table 1). The methodology is displayed in Fig. 2b.

In the *parallel chilling-forcing model*, chilling units as well as forcing units are accumulated from August 1 onwards. The chilling state S_C is the sum of all days with temperatures below the chilling base temperature $T_{BC} = 7^\circ\text{C}$

$$S_C(t) = \sum_{i=1}^t \begin{cases} 0 & \text{if } T_i \geq T_{BC} \\ 1 & \text{if } T_i < T_{BC} \end{cases}$$

Table 1 Model parameters for the simple forcing and the parallel chilling-forcing model. All parameters have been fitted by Chmielewski et al. (2011). Forcing and chilling base temperatures are location independent. For the forcing model, the forcing base temperature is $T_{BF} = 3.3 \text{ }^\circ\text{C}$ and for the parallel chilling-forcing model the forcing and the chilling base temperatures are $T_{BF} = 2.8 \text{ }^\circ\text{C}$ and $T_{BC} = 7 \text{ }^\circ\text{C}$

Region	Forcing model F_{force}^*	Parallel chilling-forcing model			
		a	b	k_m	C^* (days)
BE	161.0	1030.2	0.0	0.43	71
FR	135.0	768.12	-0.0002	0.31	100.0
BA	147.0	815.41	-0.0001	0.31	83.0
BB	144.0	1003.63	-0.0001	0.36	62.0
WM	152.0	824.89	-0.0001	0.3	83.0
BO	124.0	758.68	0.0	0.4	116.0
NE	157.0	1151.63	-0.0003	0.42	57.0
ST	148.0	947.51	-0.0004	0.34	79.0
SN	150.0	1026.39	-0.0003	0.37	66.0
NR	147.0	951.76	-0.0005	0.37	81.0
RH	159.0	868.5	0.0	0.26	73.0

The effectiveness of forcing units rises with the amount of accumulated chilling days and the forcing state S_F is defined as:

$$S_F(t) = \sum_{i=1}^t \begin{cases} 0 & \text{if } T_i \leq T_{BF} \\ \left(K_m + \frac{1-K_m}{C^*} S_C \right) (T_i - T_{BF}) & \text{if } T_i > T_{BF} \end{cases}$$

with C^* being the chilling criterion, T_{BF} the forcing temperature threshold, and K_m a model parameter. Blossom is predicted to start when the state of blossom S_F reaches the forcing criterion:

$$F_{parallel}^* = a \exp^b S_C(t)$$

All model parameters are listed in Table 1, and the functioning of the model is visualized in Fig. 2c. Chmielewski et al. (2011) fitted the above described models for eleven regions in Germany (see Table 1 and Fig. 1).

2.4 2.4 Frost risk

We analyze frost risk by counting the years with frost days after the modeled blossom date. We define frost days as days with a minimal daily temperature below 0 °C.

3 Results

In the historic climatology, the forcing model predicts the first blossom day for the second half of April (compare Fig. SI2). Blossom starts earlier in eastern and southern Germany and later in the north. Frost days after blossom are rarer in northern Germany than in southern Germany where 20% of all years' frost days happen after blossom. For both, the day of blossom and the amount of years with frost days after blossom, the bias corrected HAPPI ensemble reproduces the EWEMBI reanalysis well.

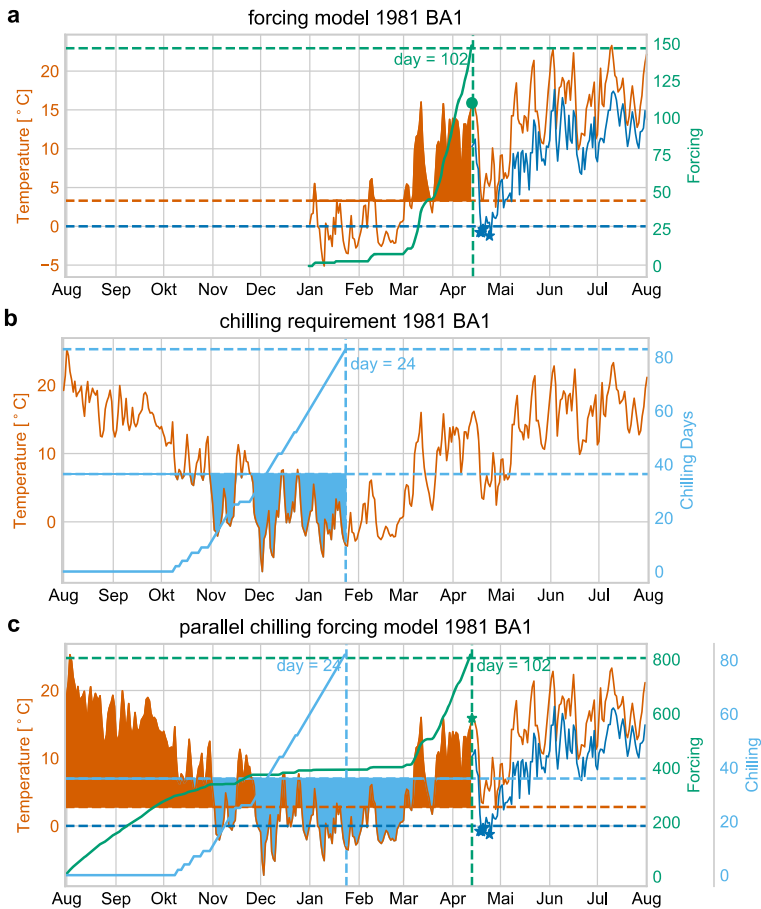


Fig. 2 Simple forcing model (a): daily mean temperature (red) and daily minimum temperature (blue) for a grid cell in Baden (Southwest Germany) for 1981. Data from EWEMBI. From January onwards, days with temperatures above the forcing base temperature $T_{BF} = 3.3^\circ\text{C}$ contribute to the forcing (green). The start of blossom is predicted for the day when the forcing threshold is reached (day 102). Frost days after blossom are indicated by blue stars. Evaluation of the chilling requirement (b): from August 1 onwards, days with temperatures below the chilling base temperature $T_{BC} = 7^\circ\text{C}$ are accumulated. The chilling requirement is fulfilled when the chilling threshold is reached (day 24). Parallel chilling-forcing model (c): from August 1 onwards, days with temperatures below the chilling base temperature T_{BC} are accumulated (light blue). In parallel, forcing units are accumulated (green). Note that forcing units become effective after the chilling requirement is fulfilled. The start of blossom is predicted for the day when the forcing threshold is reached (day 102)

As shown in Fig. 3a, HAPPI models project blossom to start 10 days earlier in a 2°C world as compared to the recent past (2006–2015). The shift is rather homogeneous with strongest shifts (11 days) in northern Germany and weakest shifts (9 days) in eastern Germany. At all locations, MIROC5 projects the strongest shift which is in average 3 days longer than in NorESM1.

This shift in blossom day leads to a consistent increase in frost risk in parts of northern, central and southern Germany and mixed projections elsewhere (Fig. 3b). For eastern and western Germany, there is low model agreement on changes in frost risks with NorESM1 and CAM4-2degree projecting a decrease, while MIROC5 and ECHAM6 project an increase in frost risk.

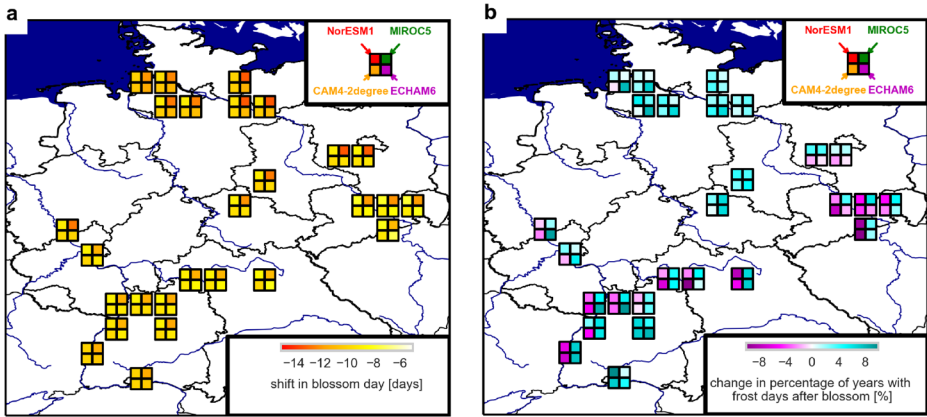


Fig. 3 Simple forcing model: shift in blossom day (a) and relative change in frost risk (b) in a 2 °C world as compared to current climate (2006–2015) in the HAPPI ensemble. Individual model projections are shown by a square at each location: NorESM1 (top left), MIROC5 (top-right), CAM4-2degree (bottom left), and ECHAM6 (bottom right)

The simple forcing model assumes that the chilling requirement is always fulfilled by January 1. But a rise in winter temperatures also affects the cumulation of chilling units and could thereby influence the start of blossom through the chilling requirement. Figure 2b shows a simple evaluation of chilling unit accumulation. In the climatological mean, the chilling criterion is reached in February in most locations (see Fig. S13a). The Bodensee region (southern German region bordering Switzerland) is the only area where the chilling criterion isn't reached in about 5% of the years in the reference period (Fig. S13b).

The accumulation of winter chill is projected to be hampered in the 2 °C scenario. As compared to current climate, apple trees are projected to have accumulated around 10 days less by end of January (Fig. 4a). Consistently, the chilling criterion is reached 10 days later in most locations (Fig. 4b). In some locations especially in southern Germany, this results in an increase in the frequency of years where the chilling requirement is not reached at all (Fig. 4c). This is also reflected by an extreme prolongation of the average chilling period length for some regions in southern Germany (Fig. 4b).

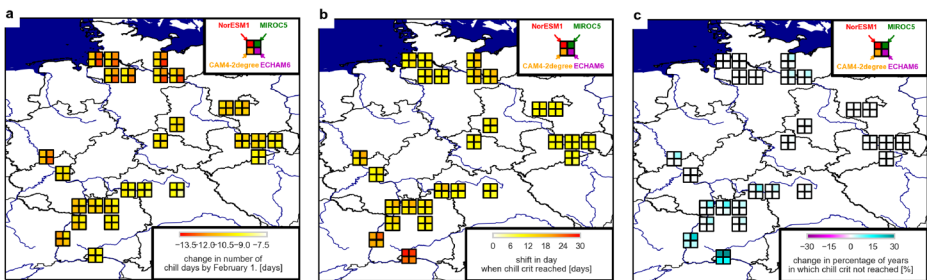


Fig. 4 Chilling requirement. a Change in the amount of chilling days accumulated by February 1 in a 2 °C world as compared to current climate (2006–2015) in the HAPPI ensemble. b Shift in day when chilling requirement is fulfilled (same scenarios). Years where the chilling criterion is not reached are filled with May 1. c Relative change in years in which the chilling requirement is not fulfilled (same scenarios). Individual model projections are shown by a square at each location: NorESM1 (top left), MIROC5 (top right), CAM4-2degree (bottom left), and ECHAM6 (bottom right)

Chilling days are projected to become less abundant all over Germany, but only in southern parts this seems to become critical as apple trees are already today at the edge of not getting enough winter chill. In other regions, there seems to be enough headroom for winter chill, such that global warming of 2 °C does not seem to endanger winter chill. At higher warming levels, winter chill might also be at risk in other regions.

Finally, we test a phenological model that considers both processes of chilling and forcing in parallel as shown in Fig. 2c. For the historic scenario, the blossom day is predicted for the second half of April as in the forcing model (compare Fig. SI4 and Fig. SI2). Also, the amount of frost days after blossom resembles closely the results from the forcing model.

As in the simple forcing model (Fig. 2a), blossom days are projected to be around 11 days earlier in the 2 °C scenario (Fig. 5a). However, the parallel chilling-forcing model projects stronger regional differences with shifts up to 19 days in southern Germany.

For some grid-cells in northern Germany, a decrease in frost risk is projected by the parallel chilling-forcing model (Fig. 5b) while the forcing model projects an increase in frost risk. Although the averaged projected shift in blossom day is nearly identical in both models (less than 1 day difference) in 20% of the years, the model projections differ by a week for northern Germany. Thus, considering the temperature history from autumn onwards leads to stronger shifts in different years than when only forcing from January onwards is considered. This results in a different projection of frost risks and highlights again the importance to analyze frost risks as a compound weather event rather than analyzing shifts in blossom days and occurrence of frost days in spring separately.

The strongest increase in frost risk is projected for southern Germany with 25% increase at the most southern grid-cell next to the Bodensee. For this grid-cell also, the strongest change in winter chill has been projected. The strong signal at this grid-cell could be explained by climate conditions being already close to relevant phenological thresholds today. However, noting that the parallel chilling-forcing model has a relatively low prediction skill in the historic validation at this location (Chmielewski et al. 2011) questions the reliability of climate change projections in this context.

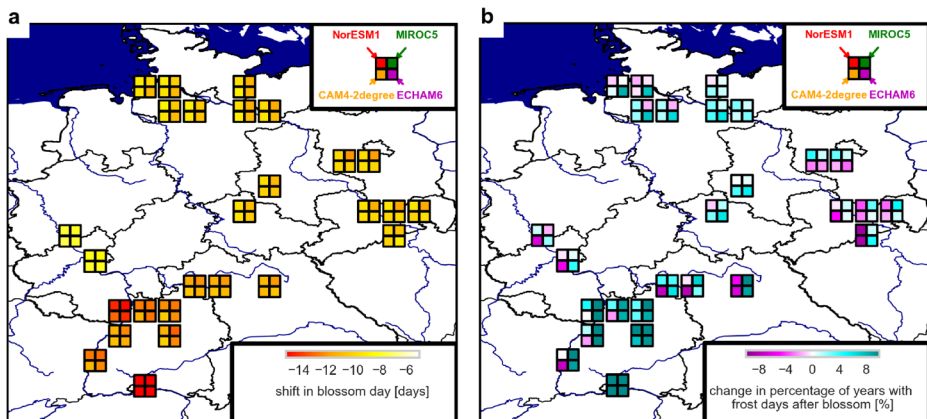


Fig. 5 Parallel chilling-forcing model: shift in blossom day (a) and relative change in frost risk (b) in a 2 °C world as compared to current climate (2006–2015) in the HAPPI ensemble. Individual model projections are shown by a square at each location: NorESM1 (top left), MIROC5 (top right), CAM4-2degree (bottom left), and ECHAM6 (bottom right)

Frost risks are lower in the 1.5 °C than in the 2 °C climate scenario. As shown in Fig. S15, additional increases in frost damages with an additional 0.5 °C warming are most pronounced in southern Germany, especially in the parallel chilling-forcing model. In some regions as in northern Germany, the signal is partially mixed with some models projecting lower frost damages in the 2 °C scenario than in the 1.5 °C scenario.

4 Summary and discussion

We analyze the effect of global warming on the date of apple blossom by running two phenological models on large ensemble atmosphere-only HAPPI simulations for a 1.5 °C, and 2 °C world as well as the recent past (2006–2015). Both, the simple forcing model and the parallel chilling-forcing model project a robust shift towards 10 days earlier blossom start in the 2 °C scenario as compared to the recent past. In some regions, this leads to an increase in risk of frost damages after blossom. Additionally, in the 2 °C world, the risk of not fulfilling the winter chill before spring increases in southern Germany.

With this study, we demonstrate how global warming can lead to counter-intuitive responses by sensitive organisms: although frost days are projected to become less frequent in a warmer climate, the risk of frost damages on apple trees could increase in certain regions. This is due to the importance of the timing of certain weather events rather than their frequencies or intensities. In this case, the probability of frost days after a relatively warm late-winter increases, and thereby the probability of frost days after apple blossom.

The forcing model used to project the date of blossom is a strong simplification of the actual processes influencing the start of blossom. In this model, it is assumed that winter chill is always fulfilled January 1. We, therefore, also test a more holistic model that models chilling and forcing processes considering the whole temperature history from autumn to blossom. The results of this model do not differ significantly apart from a stronger signal in southern Germany, where the risk of not reaching the chilling criterion is also higher. This is to some extent unexpected, as warmer winter temperatures could delay apple blossom by delaying an effective forcing process. In the parallel chilling-forcing model, forcing only becomes really effective after a sufficiently long chilling period but the increased forcing temperatures seem to dominate this aspect.

The especially strong signal in southern Germany is surprising as for this region a critical delay in the achievement of the chilling criterion is projected. Note that winter chill not only affects the starting date of blossom but that insufficient winter chill can also reduce apple yields (Luedeling 2012). Thus, the critical hampering of winter chill in combination with an increased frost risk in southern Germany is a reason for concern.

While there is some evidence that frost days within the growing season become more frequent as growing seasons lengthen (Liu et al. 2018), many case studies have shown insignificant trends or contrasting results. For northeastern Germany, a decrease in frost risks for apples has been found for a 3 °C warmer world (Hoffmann and Rath 2013). For northern Italy, no significant change in frost risk for apples is projected (Eccel et al. 2009). For northeastern USA, Wolfe et al. (2018) found a small increase in frost risks for the next decades and a decrease in frost risks for the second half of the century. For sweet cherries, Chmielewski et al. (2018) found no change in frost risk in Berlin and a small decrease at a location in southwestern Germany. For grapevine in the Swiss Rhine valley, Meier et al. (2018) conclude that depending on the region the risk of spring frost damages might either decrease or increase. For fruit trees in Switzerland, Vitasse et al. (2018) confirm that the change in risk

varies regionally arguing that it has only increased in higher elevations. Jeong et al. (2018) project that the risk of frost damages on kiwi fruits in Korea remains mostly unchanged under global warming.

Our study showing a tendency towards an increase in frost risk in most regions in Germany and uncertain results in the remaining regions is broadly in agreement with the other studies that highlight a large variety of results depending on regions, climate models, and studied levels of climate change. While many studies are confronted with a weak signal to noise ratio, our analysis of large ensemble climate simulations delivers reasonably large statistics. In many regions, however, the four analyzed climate models project contradicting changes in frost risks. Also, the necessity of simplified empirical models for the estimation of blossom days is a challenge for climate change studies in this field (Chmielewski et al. 2018). Up to date, the phenological processes that govern apple blossom are not fully understood. We have based our analysis on models that have shown acceptable performance for a range of different climate conditions over Germany (ranging from an average DJF temperature of 3 °C in the north-western Germany to 0 °C in eastern Germany). However, in a 2 °C world, climate conditions will lie partly outside of their calibration range in particular for southern Germany.

Our results, therefore, should be interpreted with caution indicating potential future risks rather than providing fully reliable projections. More research and improved horticultural models are needed to improve projections of future risk.

Nevertheless, our results highlight the importance of considering the complexity of sensitive environments when estimating climate change impacts. Although blossom days are projected to shift all over Germany, frost risk only increases in some regions. Our results are of wider relevance not just to apple trees, but also to other economically important horticultural crops, such as, for example, grapes, cherries, or other fruits that in principle are vulnerable to frost damages.

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