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Future climate change impacts on apple flowering date in a Mediterranean subbasin

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ABSTRACT

Chilling temperatures are important in apple and other fruit production because they are needed to break full dormancy, which is a prerequisite for effective and synchronous bud-break and flowering. Temperature increase related to climate change could lead to inadequate chilling in certain areas, which could affect the suitability for some species or cultivars to survive or yield in that location. The aim of this study was to estimate how climate change could affect flowering date and, consequently, feasibility of the most significant apple cultivars in the lower Fluvià subbasin (correspondent to the Protected Geographical Indication "Poma de Girona"). The estimations are based on a chilling and forcing requirements approach for each apple cultivar in this region, through a statistical analysis. The chilling-forcing sequential model, together with meteorological projections based on two climate change scenarios (B1 and A2), were used to estimate apple flowering dates along the 21st Century. Results show, in general, that apple cultivars could suffer delays on flowering date since the mid century and they could present serious disorders as a consequence of insufficient chilling in the long term in A2 scenario, which could affect crop feasibility in the region.

1. Introduction

In temperate climates, the buds of deciduous fruit trees are dormant during the autumn and winter (Lang et al., 1987). Deciduous fruit trees enter this dormant stage to survive winter conditions and avoid cold weather damage (Faust et al., 1991; Saure, 1985). It is commonly assumed (Cesaraccio et al., 2004; Fenell, 1999; Legave et al., 2008; Rea and Eccel, 2006) that this rest period is composed of an endodormancy phase followed by an ecodormancy phase: after accumulating enough winter chilling, endodormancy ends and is followed by ecodormancy (Lang et al., 1987), when flower bud development initiation depends on heat accumulation, or forcing in phenology literature.

Hence, chill requirements are needed to overcome endodormancy, and reaching a heat or forcing requirement is needed to bloom. These requirements have been widely used to model the dates for blooming and overcoming dormancy (Campoy et al., 2012 and see review in Campoy et al., 2011b). These parameters are considered to be cultivar-specific and are useful for predicting the probability of the successful adaptation of a cultivar to a pre-determined environment (Campoy et al., 2012; Fenell, 1999)

Campoy et al. (2011b) propose to determine the potential of certain areas to support growing fruit cultivars according to their chill requirements, based on data from the network of stations maintained by meteorological services and long-term predictions of temperature changes. This potential would serve growers to establish, at the proper time, orchards adapted to future changing environmental conditions.

Chilling temperatures are important in apple and other fruit production because they are needed to break full dormancy, which is an essential prerequisite for effective and synchronous bud-break and flowering (Erez, 2000; Saure, 1985). A common symptom for sub-optimal chilling is poor and protracted bud-break, which can lead to extended and partial flowering, followed by poor fruit set and final yield (Sunley et al., 2006).

Therefore, the knowledge of the chill requirement of a cultivar has significant practical and economic impacts on the control,

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Abbreviations: BBCH, biologishe bundesanstalt bundessortenamt and CHemische industrie; GDH, growing degree hour; CP, chill portions; CR, chill requirement; HR, heat requirement; CR_{10}, percentile 10 of estimated CR; PGI, protected geographical indication; RCP, representative concentration pathways.

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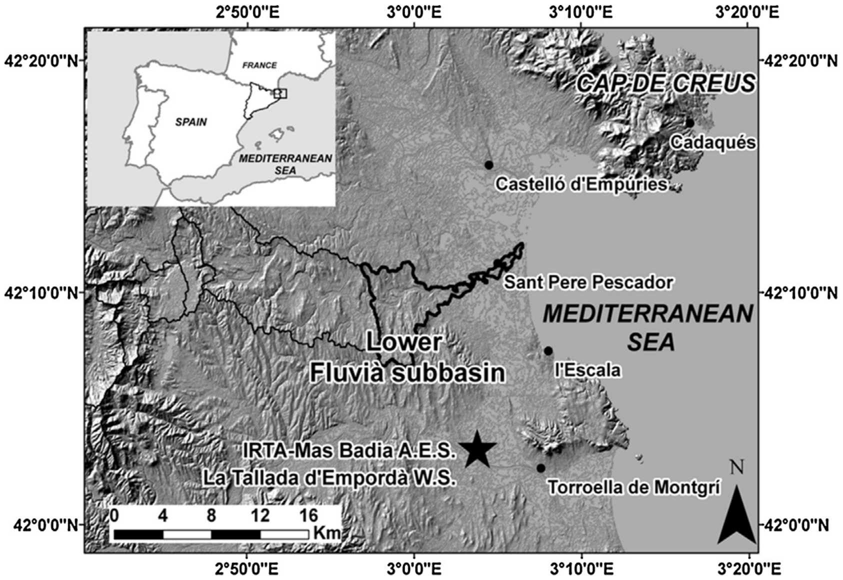

Fig. 1. Location map of the study area, the lower Fluvià subbasin. Black Star indicates location in the map of IRTA-Mas Badia Agricultural Experimental Station and La Tallada d'Empordà Weather Station.

Source: Department of Agriculture, Catalonian Governenment (DAAM, 2013a,b).

maintenance and production of woody plants (Fenell, 1999). Predicting when dormancy period ends is important for growers, as global warming could lead to inadequate chilling in certain areas, which could affect the suitability for some species or cultivars to survive or produce in that location (Cesaraccio et al., 2004).

It is commonly known that rising temperatures are a first order factor driving phenological disorders (see review in Campoy et al., 2011b; Legave et al., 2013) such as changes in phenological phases timing or duration, flowering anomalies, disorders in cross-pollination and plant-insect interactions, changes in plant diseases and pests patterns, higher frost risk or changes in fruit quality and maturation, that could affect crop production and trade (see review in Campoy et al., 2011b; Legave et al., 2013; Cesaraccio et al., 2004).

Mediterranean climate is characterized by a double stress (hot and dry summers and rainy cold and very cold winters) with a high level of variability along the geographical locations and years (SMC, 2012; Terradas and Savé, 1992). In general, projections by the end of the century for the Mediterranean basin show greater increases in annual mean temperature comparing to the global world mean (IPCC 2007, 2014). Global warming might reduce ecodormant phase in some species, advancing their phenology, but in other species, the effect could be deficient dormancy release, resulting in a delay of phenology (Campoy et al., 2011b), which could directly impact on yield formation processes and so on final crop yield (Chmielewski et al., 2004; Lobell and Asner, 2003). In Catalonia an increase in temperature between 1.1 °C and 1.4 °C during the period 1950–2008 has been observed (Martín-Vide et al., 2010), and climate change projections based in A2 and B1 scenarios (IPCC, 2007) would suppose a global increase in temperature of 4 °C and 2.6 °C by the end of the Century (2081–2100), respectively (Calbó et al., 2010). New RCP scenarios (IPCC, 2014) keep basically the same spectrum of projections for the Mediterranean basin in terms of temperature behavior.

Catalonian region, NE Spain, is one of the main apple growing regions in Spain with about 11000 ha in surface, supposing 40.4% of the apple growing surface all over Spain. 'Golden Delicious' cultivars reach 52.2% of the apple surface distribution by cultivar in Catalonia, 'Gala' 16.5%, 'Fuji' 10.1%, 'Granny Smith' 6.7%, 'Cripps pink' 3.4% and 'Red delicious' 8% (MAGRAMA, 2012).

The aim of this study was to analyze how climate change could affect dormancy phase release and, consequently, flowering time of some apple cultivars in a certain region of NE Spain (Fluvià river lower course subbasin) based on the establishment of a cultivar-specific chilling and forcing requirements approach for this region.

2. Material and methods

2.1. Study area

The study area (Fig. 1) was the Fluvià river lower course subbasin (delineated in Savé et al., 2012 see also Lopez-Bustins et al., 2013 and Pascual et al., 2014), located at the Northeast of the province of Girona (NE Spain). The subbasin has an area of 36.14 km^2 and 0, 57 to 162 m sea level elevation (minimum, mean and maximum, respectively). The average annual mean, maximum and minimum temperatures are 14.9 °C, 20.5 °C and 9.4 °C, respectively, and the average annual rainfall is 694 mm. The study area temperature details are described in Table 1 for winter and spring months.

Part of the study area belongs to the PGI 'Poma de Girona', which is a relevant apple growing area (approximately 2260 hectares, 20% of apple surface in Catalonia; DAAM, 2012) in NE Spain because of its history, quality production and territory links, being the pattern cultivar distribution very close to the whole Catalonian pattern.

2.2. Phenological and meteorological data

Flowering dates were recorded as the anthesis of 50% of the flowers: F2 stage (Fleckinger, 1945), correspondent to stage 65 in

Table 1
Study area (Fluviá, Subbasin 13) temperature details. Winter temperature consider as the mean of December, January and February. Spring temperature is the mean of March–May. The means was calculated from daily data temperature regionalized for subbasin 13 using SWAT Model for the period 1984–2008 (reference period).

	Winter			Spring		
	January	February	March	April	May	June
T mean (°C)	7.9	9.3	11.3	13.0	17.0	20.8
T max (°C)	13.2	15.0	17.0	18.6	22.4	26.2
T min (°C)	2.5	3.7	5.6	7.4	11.5	15.3

Table 2
Mas Badia A.E.S. temperature details. Winter temperature consider as the mean of January, February and March. Spring temperature is the mean of April–June. This means was calculated for the period 1992–2013 coincident with the period of the available phenological data.

	Winter			Spring		
	January	February	March	April	May	June
T mean (°C)	7.2	7.9	10.7	13.2	17.1	20.7
T max (°C)	13.1	13.7	16.4	18.7	22.4	25.9
T min (°C)	2.2	2.6	5.0	7.6	11.5	15.1

(Source: La Tallada d'Empodà Weather Station, Meteorological Service of Catalonia)

the international BBCH code. Data recording was performed by the IRTA-Fruit production Program in the IRTA-Mas Badia Agricultural Experimental Station (42° 03′N 3° 03′E, elevation 15 m; Fig. 1) with an average annual mean, maximum and minimum temperature of 15.9 °C, 21.7 °C and 9 °C, respectively, (winter and spring monthly temperature details described in Table 2; see Fig. S1 in supplemental material) and an average annual rainfall of 663 mm. This Experimental Station is located 13 km away the study area.

The records were taken for 9 apple cultivars well represented in the area ('Golden Smoothee', 'Golden Reinders', 'Early Red One', 'Brookfield Gala', 'Aporo', 'Red Chief', 'Fuji Chofu 2′, 'Granny Smith' and 'Pink Lady') during the period 1992–2013 (Table 3; see Figs. S2 and 3 in supplemental material).

In addition, we obtained hourly temperature records from La Tallada d'Empordà Weather Station (Agrometeorological network, Meteorological Service of Catalonian Government) located in the IRTA-Mas Badia facilities, for the period (1992–2013).

2.3. *Flowering date modeling*

The model used in this study in order to simulate flowering date is characterized by a sequential chill-forcing model (Ashcroft et al., 1977) based on the assumption that chilling and heating temperatures have successive and independent effects, respectively, on the endodormancy release and ecodormancy phase that leads to bud break and blooming (Legave et al., 2013).

2.3.1. *Chilling and forcing models*

Chilling phase was simulated by using the Dynamic Model developed by Fishman et al. (1987). This model determines chill exposure by counting "Chill Portions" (CP) based on an interactive effect of temperature that takes into account the synergic effect of cold and moderate temperatures on chill accumulation and the final reach of endodormancy break (Fishman et al., 1987).

Forcing phase was performed using growing degree hour model (Richardson et al., 1975) taking 4.5 °C as base temperature. All temperatures above 25 °C are assumed to equal 25 °C; thus the greatest possible accumulation for any hour is 20.5 GDH.

2.3.2. *Estimating endo- to ecodormancy shift date*

To estimate CR and HR from temperature data, three chronological dates must be fixed first: (i) chill accumulation start date, (ii) the date considered the end of endodormancy and (iii) the date when F2 stage is reached (Couvillon and Erez, 1985). The first date is fixed on the day when effective chill accumulation begins, after 1st October, the end of summer in the Northern Hemisphere, prior to the arrival of chilling temperatures (Campoy et al., 2011b; Legave et al., 2013). Starting date has no effect on the chilling accumulation as long as no CP is banked before the starting date. F2 stage date is fixed by visual observation. A direct observation of endodormancy end is not possible due to the lack of external signs. Estimations under laboratory conditions have been deemed to be of low practical significance with regard to fruit trees under orchard conditions because the environmental variables are unnaturally constant, rather than fluctuating (Dennis, 2003; Luedeling et al., 2009a). So we chose the use of the statistical method of Alonso et al. (2005) to estimate the mean date from endo- to ecodormancy shift. This method is based on the different influence of warm and cold temperatures on flowering date depending on their impact on dormancy phases: heat accumulation during the forcing phase would advance flowering; hence, a negative correlation would be expected between temperature in this phase and flowering date. On the contrary, temperature would be positively correlated with flowering date during the chill phase. As a sequential chill-forcing model is assumed, the onset of the forcing phase is determined by the end of the chill phase.

Thus, following Alonso et al. (2005), daily maximum, minimum, and mean temperatures were averaged day by day over different time periods (running means for the subsequent 5,10,15,20, 25 and 30 days intervals) and correlated with flowering dates expressed as day-of-year number for each apple cultivar in every phenological year from 1st October until 28th February. After Alonso et al. (2005) the endo- to ecodormancy shift (endodormancy breaking date), was considered to be the day when the first statistically significant correlation occurs in a continued presence of negative correlations coefficients (Fig. 2).

2.3.3. *Establishing cultivar-specific chill and heat requirements*

During the period time 1992–2013, meteorological and phenological data were randomly divided in two similar sized groups to (i) *parameterize* CR and HR and (ii) *evaluate* the model (Bellocchi et al., 2010). The total number of years in each group depended on the available data for that cultivar.

CR values were calculated for every cultivar in 7 to 11 phenological years in the period 1992–2013 as the number of CP accumulated by the date of endodormancy break according to the Dynamic Model (Fishman et al., 1987). HR was calculated by counting GDH accumulation from the next hour after CR had been completely satisfied, till F2 stage date.

Results for every year were averaged for each cultivar to obtain an approach of the cultivar-specific CR and HR in this region (Alonso et al., 2005; Luedeling et al., 2013).

Table 3
Summary of Mas Badia phenology records (F2 stage; Fleckinger, 1945), seasons and sample size per cultivar.

Cultivar	Mean flowering date[a]	Seasons	Sample size (seasons)
'Pink Lady'	11th April (±1.7)	1999–2013	15
'Brookfield Gala'	12th April (±1.4)	1997–2013	17
'Granny Smith'	12th April (±1.8)	1992–2013	22
'Fuji Chofu 2'	12th April (±1.6)	1995–2002;2005–2006;2008–2013	15
'Golden Smoothee'	17th April (±1.7)	1992–2002;2008–2013	17
'Early Red One'	14th April (±1.4)	1992–2010	19
'Red Chief'	14th April (±1.6)	1992–2012	21
'Aporo'	9th April (±2.4)	2000–2007;2009–2013	13
'Golden Reinders'	20th April (±1.5)	1994–2013	20

[a] Mean flowering date correspondent to the phenology record period. Value in brackets is the standard error.

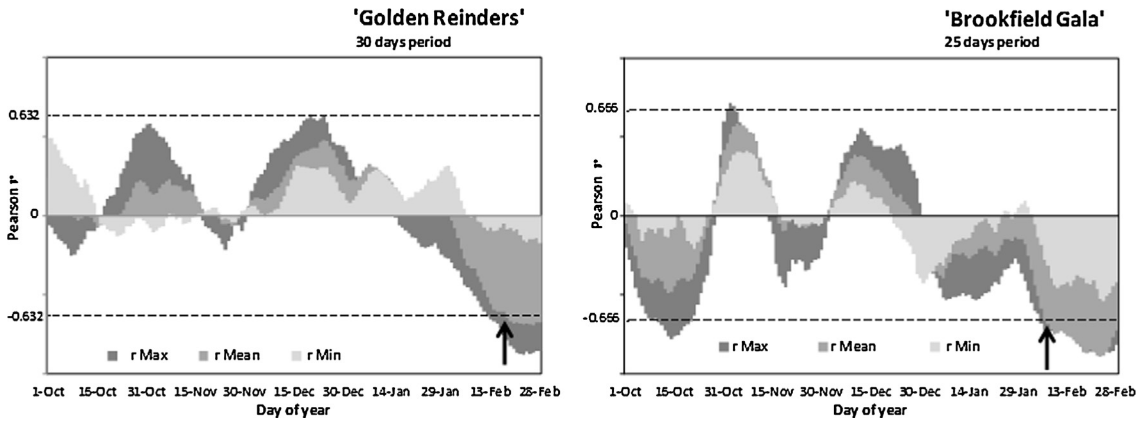

Fig. 2. Establishing shift date between endo- and ecodormancy, e.i., endodormancy breaking day, in the case of 'Golden Reinders' and 'Brookfield Gala' cultivars, by analyzing the day by day evolution of Pearson correlation coefficients (r) between flowering dates and average temperatures of subsequent 20 day interval (r mean, with mean temperatures; r min, with minimum temperatures; r max, with maximum temperatures) during 7–11 phenological years between the period 1992–2013, depending on the available data for each cultivar. The arrows indicate the first negative significant correlation coefficient obtained with the mean temperature and, consequently, dormancy breaking date. Discontinuous line represents r value with $p = 0.05$.

2.4. Model evaluation

The accuracy of the model was evaluated by estimating, from the CR and HR established previously, the theoretical flowering dates for each cultivar for the 6 to 11 remaining years between 1992 and 2013 not having been used for the construction of the model. Estimated dates were compared with those obtained in Mas Badia Agricultural Experimental Station for those years.

The calculated statistics were: root mean square error (RMSE, mean distance between simulation and measurements), model efficiency (EF, proportion of variation explained by the model) and least-squares coefficient of determination (R^2) (Bellocchi et al., 2010).

2.5. Simulation of future apple flowering dates in two climate change scenarios

After model evaluation, cultivar-specific CR and HR were used to estimate theoretical future flowering dates of each cultivar for three different periods: short term (2009–2030), mid term (2031–2075), long term (2076–2100), plus a reference period (1984–2008), as defined in Savé et al. (2012). The years composing the reference period had been chosen because these last 25 years presented the most comprehensive meteorological records in the Fluvià watershed.

The future flowering date estimations were performed using climate projections data for two climate change scenarios, A2 and B1, defined by the 4th assessment report of the Intergovernmental Panel for Climate Change (IPCC, 2007) according to the expected evolution of greenhouse gases and anthropogenic aerosols emissions that depends on the future demographic, economic and technological development. A2 scenario implies a medium-high emissions level and, contrarily B1 scenario represents a low emissions level. For the lower Fluvià watershed, these scenarios suppose an increment of mean annual temperature in 2.2 °C for the B1 and in 3.3 °C for the A2 at the end of the 21st Century (2076–2100; Savé et al., 2012). Although the philosophy behind the scenarios of IPCC4 and 5 is different, A2 and B1 are broadly comparable to RCP8.5 and RCP4.5, respectively, in terms of overall forcing (Box 2.2 IPCC, 2014).

The climate projections for the Fluvià watershed were performed by combination of downscaled climate (general circulation model, GMC: ECHAM5/MPI-OM (Marsland et al., 2003; Roeckner et al., 2003) plus MM5 dynamic regionalization carried out by the Catalonian Meteorological Service (SMC) to a high temporal and spatial resolution of 6 h and 15 km; Barrera-Escoda and Cunillera, 2011) and watershed hydrological model (Soil and water Assessment Tool, SWAT) that allows spatial distribution of the meteorological parameters along the watershed at subbasin level. To estimate future flowering dates we used daily temperature data (maximum, minimum, mean) from the climate change projections for the 13th subbasin described in Savé et al. (2012). Since the Dynamic and GDH models require hourly temperature data input, idealized daily temperature curves with an hourly resolution were constructed from the projected daily maximum and minimum temperatures as proposed by Linvill (1990).

For the projected long-term period, when insufficient chilling problems are expected, a minimum chill requirement (CR_{10}) was estimated as the 10% quantile of the resulting CR estimated over the phenological years used to build the model. This metrics define the minimum CR which was achieved to successfully complete endodormancy phase in 90% of the years (1992–2013) used for the model parameterization. In other words, in only 10% of the years endodormancy was broken before reaching CR_{10}. It can be interpreted as the minimum threshold CR to consider for each apple cultivar to grow in this location.

3. Results

3.1. Endo- to ecodormancy shift date

Table 4 shows mean dormancy break date estimated for each cultivar. Daily mean temperature and the longest time periods (20,

Table 4
Mean dormancy breaking date establishment in each cultivar studied. All results correspond to models using daily mean temperature. The column Period represents the periods of subsequent days to calculate day by day average temperature (maximum, minimum and mean). N is the number of years used in correlations between temperature and flowering date.

Cultivar	Period	N	Dormancy breaking date
'Pink Lady'	–	8	–
' Brookfield Gala'	25	9	07-Feburary
'Granny Smith'	30	11	12-Feburary
'Fuji Chofu 2′	20	7	13-Feburary
'Golden Smoothee'	30	10	10-Feburary
'Early Red One'	30	9	14-Feburary
'Red Chief'	20,25	10	15-Feburary
'Aporo'	20,25	7	13-Feburary
'Golden Reinders'	30	10	18-Feburary

Table 5
Model evaluation: root mean square error (RMSE), model efficiency (EF) and R^2 (Student's test, $^{*}p < 0.05$, $^{**}p < 0.01$, $^{***}p < 0.001$) values for the best model of each cultivar by using cultivar-specific CR and HR calculated for this region. N_E is the number of observations or years (flowering date) used in model evaluation.

Cultivar	RMSE	EF	R^2	*P*-value Paired *t*-test	N_E
'Brookfield Gala'	2.94	0.69	0.75^{**}	0.74	7
'Granny Smith'	4.86	0.61	0.75^{***}	0.04	11
'Fuji Chofu 2'	3.14	0.69	0.77^{**}	0.24	8
'Golden Smoothee'	2.85	0.78	0.80^{**}	0.55	7
'Early Read One'	2.85	0.75	0.78^{***}	0.61	10
'Red Chief'	2.73	0.83	0.88^{***}	0.127	11
'Aporo'	5.69	0.57	0.90^{**}	0.05	6
'Golden Reinders'	3.01	0.77	0.78^{***}	0.78	10

Table 6
Cultivar-specific CR and HR (±Standard Deviation). CR is expressed in CP. HR is expressed in GDH. N_c is the number of observations (years) used in CR and HR parameterization.

Cultivar	CR	HR	N_c
'Brookfield Gala'	62.5 (±5.6)	9229.7 (±881.8)	9
'Granny Smith'	63.9 (±5.7)	8930.1 (±1072.0)	11
'Fuji Chofu 2'	64.0 (±5.2)	9025.2 (±561.2)	7
'Golden Smoothee'	65.0 (±6.9)	10144.5(±1366.6)	10
'Early Read One'	65.6 (±6.1)	9199.9 (±1019.5)	9
'Red Chief'	66.4 (±5.8)	9076.2 (±1135.8)	10
'Aporo'	66.4 (±7.8)	7416.2 (±687.4)	7
'Golden Reinders'	68.4 (±5.9)	10272.5(±1031.8)	10

25, even 30 days) generally gave the highest significantly negative correlation coefficients. However, quite often it was not evident which model fitted best the data used for model parameterization: we chose the temperature average (mean, maximum, minimum) and the time period giving the best validation statistics for flowering date estimation (lowest RMSE, highest EF, highest R^2; Bellocchi et al., 2010; Table 5). After this process, daily mean temperature was the best predictor in all cases. Best time period was more variable although always in the range 20–30 days, and in some cases, as 'Aporo' or 'Red Chief', more than one time period defined the same dormancy breaking date (Table 4).

In 'Pink Lady' we did not find any significant negative correlation between mean, maximum or minimum temperature and flowering date in any time period. Therefore, no CR and HR could be established, no model could be adopted and no estimations for future climate conditions could be made.

3.2. *Model evaluation*

Table 5 summarizes statistics values in the validation model. Most RMSE values for the model best fitting each cultivar are below 4 days. 'Brookfield Gala' model presented the best validation statistics (2.94 days). These RMSE values are similar to others in the literature for apple and other fruit trees blooming or budburst modeling studies and can be considered fairly precise for this kind of models (Luedeling, 2012): 4–6 days (Legave et al., 2013), 1.2–6.3 (Rea and Eccel, 2006) and 3.2–5.7 (Hoffmann and Rath, 2013) for apples, 4 days for peach trees (Miranda et al., 2013) and even wider ranges (4.7–29.8) for pear, cherry and kiwifruits (Cesaraccio et al., 2004).

Model efficiency (EF) values, in general, were high, explaining roughly 60 to 80% of the variability (Table 5). All the cultivar models in this study accomplished the conditions established by Chung et al. (2000) to judge results as satisfactory: model efficiency >0.3, R^2 >0.5 and *P*-value of the paired *t*-test between the observed and simulated values >0.025.

3.3. *Cultivar-specific chill and heat requirements*

We obtained cultivar-specific CR and HR (Table 6). CR values did not vary much between cultivars: 62.5 to 68.4 CP, which corresponds to a maximum difference of 9 days to accumulate these CP in the reference period (Fig. 3). CR_{10} was 5 to 6 CP lower than CR in most cultivars, a quite homogeneous difference.

Although no clear relationship could be found between CR and HR of the different cultivars, 'Golden Reinders' showed the highest CR, CR_{10} and HR values. However, 'Golden Smoothee' presented the second highest HR but an average CR.

3.4. *Climate change flowering date simulations*

The flowering trends during the base period 1992–2013 showed no flowering date change (Fig. S2 and 3 in supplemental material), as no trend can be seen in the temperature data for the same period either (Fig. S1 in supplemental material).

The results of the simulations for future apple flowering dates over the studied region along the 21st century for both climate change scenarios are presented in Fig. 3 for each apple cultivar in this study, except for 'Pink Lady' because we could not fit a proper model. Results showed that flowering date in most cultivars would experience light or no changes in B1 scenario in the short and mid term, with no clear tendency as changes ranged from +2 to −2 days with respect to the reference period.

During the long-term period (2076–2100) in the low emissions scenario (B1), flowering date was delayed in all cultivars respect to the reference period (5–10 days). In spite of the great decrease in the number of forcing days (18–22 days less than the reference period), which would advance flowering date, this was largely overcompensated by the delay in achieving CR, because of an increase in both the number of days with no CP accumulation (+15) and the number of days needed to sum-up the need CP (+10–15). This pattern could already be observed in the short and mid term, but delays and advancements compensated each other there.

A2 scenario presented similar figures to the reference period in the short term due to the characteristics of this scenario, with delays of no more than one day; but in the mid term delays between 3 and 8 days could be observed. These delays rised to more than two weeks by the end of the century. The pattern observed in B1 scenario was here exacerbated, with delays of more than a week both in the beginning of CP accumulation and in the time needed to complete CP accumulation partially compensated by advancements in fulfilling HR. The phases related to CR achievement grew to almost three weeks and about a month, respectively, in the long term, not being compensated by shortenings of about two weeks in the forcing phase. However, the most prominent result in the simulations was the appearance in long-term period for A2 scenario of a high number of years in which CR could not be completely fulfilled (hence, flowering would be compromised) due to the rising temperatures. Consequently, the results of flowering delay for this period must be taken carefully and both figures (flowering delay and number of years with no CR achievement) should be considered: for instance, 'Golden Reinders', the cultivar with the highest CR in the study, presented only 8 days of delay; but it was the cultivar that presented more years not fulfilling CR, 72% of the period.

As CR was calculated as an average, roughly 50% of the years used to parameterize the model would not fulfill CR in the date established by our method, so for the long-term period we calculated a minimum chill requirement (CR_{10}) as the 10% quantile of the resulting CR estimated over the phenological years used to

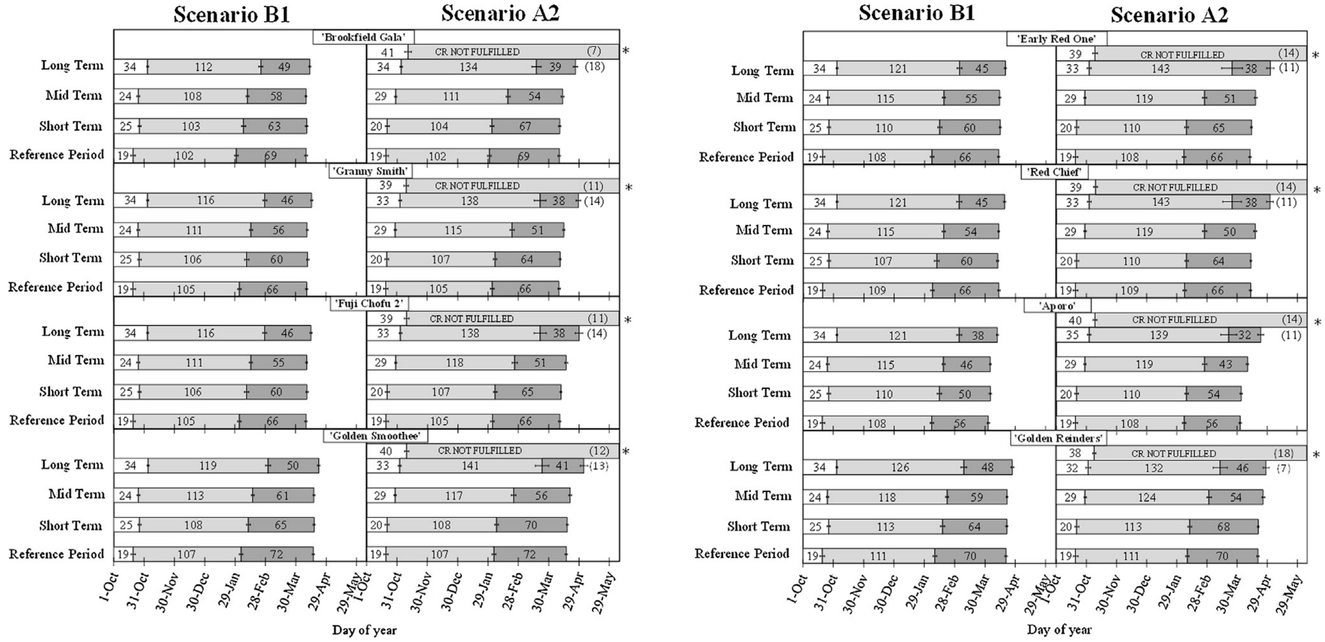

Fig. 3. Sequential time representation of the chilling and heat proceedings from 1st October to F2 in each cultivar according to each term and climate change scenarios: B1 (left) and A2 (right). White strips, days from 1st October without no CP accumulation, light color strips represent winter chill days from the day the first CP is accumulated to the day CR is fulfilled and dark color strips represent heat accumulation days from CR achievement to F2 stage. Numbers inside each bar, are number of days in each process. All data are averaged through the corresponding term. Bars at the end of each strip represent only standard error of the mean of the results of each year in a period (short, mid and long term and reference period), represent only variability of the projected period in achieving each phase. These bars do not represents the phenology model RMSE or uncertainties related to climate projections. Numbers in brackets in the long term period strips represent the number of phenological years that did not satisfy CR in the bar marked with * and years that did satisfy CR in the unmarked bar.

build the model (endodormancy was broken before reaching CR_{10} in only 10% of the years). Results showed (Table 7) that when CR_{10} was used as chill requirement in the models, the number of years that would not fulfill this requirement in A2 scenario decreased largely by 6 years in most of the cultivars but still represented 25% of the period. In the case of 'Golden Reinders', a reduction was also observed, but still 10 years (40% of the period) would not achieve CR and would presumably present flowering problems.

4. Discussion

The estimation of theoretical future flowering dates for apple trees of several cultivars in the Fluvià river lower course subbasin (PGI "Poma de Girona") for three different periods along the 21st century yielded both flowering date delays and advancements in the several scenarios and periods studied. Some authors have published flowering apple advancements during the recent past in France (Legave et al., 2008), Germany (Blanke and Kunz, 2009; Chmielewski et al., 2004), Japan (Fujisawa and Kobayashi, 2010), North Italy (Eccel et al., 2009) and Central Europe (Legave et al., 2013). Moreover, other studies have verified flowering advancements in the recent past for apple together with pear and other temperate fruits in South Africa (Grab and Craparo, 2011), Australia (Darbyshire et al., 2013), New Zealand (Clothier et al., 2012), Germany (Blanke and Kunz, 2009; Estrella et al., 2007), France (Guedon and Legave, 2008), and Central Europe (Menzel et al., 2006). Other studies using climate model projections showed also advancements of apple or other temperate fruits: apple in North Italy (Eccel et al., 2009) and Germany (Hoffmann and Rath, 2013), fruit trees in general in Central Europe (Trnka et al., 2011), grapevine in France for the end of the Century (García de Cortázar-Atauri, 2006) and in Australia for mid century (Webb et al., 2007; Darbyshire et al., 2014). On the other hand, other authors found delays in the beginning of chill accumulation and fulfillment of CR, which should lead to later flowering (Luedeling et al., 2013).

The advancements or delays in flowering might be linked to the specific CR of the species or cultivars and the winter chilling accumulation of the study area (Campoy et al., 2011b). In cold regions as North-Central Europe a flowering advancement is produced because of winter chill is not a limiting factor for reaching flowering and heat is accomplished faster because of future or recent warming effects. Consequently, in these cold areas, the spring frost risk may substantially increase because full bloom could advance at a faster rate than spring frosts retreat (Darbyshire et al., 2013), although Eccel et al. (2009) proposed that the frost risk will not differ greatly from its present level in climatic contexts similar to North Italy. However, in Mediterranean fruit-growing areas blooming may be affected in the future by excessive delays in chilling satisfaction because chill accumulation would be limited and the satisfaction of CR for high-chill cultivars would be incomplete (Campoy et al., 2011b; Legave et al., 2013) delaying flowering date despite a faster heat phase.

In our case, both advancements and delays in the estimated flowering date included an increase in the days needed to fulfill

Table 7
Minimum threshold cultivar-specific CR (CR_{10}) values, in CP, and number of years in the long-term simulations (2075–2100) with no CR fulfillment (NnoCR) for this location.

Cultivar	Long term simulations with minimum CR	
	CR_{10}	N_{noCR}
'Brookfield Gala'	57.3	6
'Granny Smith'	57.3	6
'Fuji Chofu 2'	58.2	6
'Golden Smoothee'	56.4	6
'Early Red One'	59.2	6
'Red Chief'	60.2	6
'Aporo'	58.9	6
'Golden Reinders'	63.0	10

CR (both in days needed to accumulate the first CP, and in days needed to accumulate the required CP), and a reduction in the time needed to achieve HR. Mostly in the short term in the B1 scenario, the combination of delay in CR fulfillment and shortening in HR achievement resulted in a slight or no advancement of the flowering date, but in the rest of the cases, the result was a longer time to blooming. Hence, although some delays and advancements were in the same range of the RMSE of model validations, the general picture was retardation in flowering date that increased along the century and presented the highest delays in the A2 scenario. Moreover, according to our results, a large number of years on the last quarter of the 21st century (between 28 and 72% depending on the cultivar) would present winters that would not fulfill CR, which would turn apples in an unsuitable crop for the lower course of the Fluvià watershed. Similar results were obtained by Darbyshire et al. (2014) for apple in Australia. From a different approach, (Luedeling et al., 2009b) obtained a similar conclusion: they defined the concept of safe winter chill (minimum winter chill accumulated in 90% of the years) and applied it to climate projections along the 21st century according to different IPCC (2007) scenarios in California's Central Valley. They found that safe winter chill decreased along the century all over the valley for all the scenarios. In their study, the scenario presenting the highest climate change (A2) resulted in climatic conditions that would make high-chill species like apple unsuitable crops to grow in California's Central Valley at mid and end 21st century.

As the CR not being fulfilled in A2 projections for the end of the 21st century was an average CR, we calculated a minimum chill requirement (CR_{10}) to get a minimum estimation of non-CR-compliant years. This parameter is, in a sense, a reversal of the safe winter chill concept (Luedeling et al., 2009b), and should be understood as a conservative lower threshold below which a species or cultivar would be unsuitable to grow in the studied area. The cultivar-specific CR_{10} values could be successfully satisfied in some years in the long-term period when insufficient chilling fulfillment was obtained when using averaged CR. However, even with this reduction, chilling requirements (CR_{10}) would be unsatisfied in 25% of years of the last quarter of 21st Century in A2 scenario in almost all cultivars in this region. Moreover, probably long before they experience this incapability to comply with chilling requirements some cultivars would be confronted with challenges related with fruit quality at maturity, including changes in textural and taste attributes (Sugiura et al., 2013) and exposure to sunburn (Wünsche et al., 2004).

The purpose of this work is to offer an objective baseline to apple growers in northern areas of the Mediterranean basin in order to develop adaptive strategies to climate change, based on different agronomical options (Clothier et al., 2012). However, it should be noted that this work relays on several hypothetical assumptions. First of all, just one climate model was used, as this is the only one available which had been regionalized to a high resolution for the area of study. According to Barrera-Escoda and Cunillera (2011) the ECHAM5/MPI-OM is one of the best models for future projections of the climate for Catalonia, where the study area is included, among all the models considered in the IPCC (2007), because it is one of the global models that best reproduces the current climate of the Earth under the known radiative forcing (Ulden and Van Oldenborgh, 2006), especially in the Mediterranean area (Altava-Ortiz, 2010). Moreover, the use of ECHAM5/MPI-OM allowed us to take advantage of the MM5 dynamic regionalization downscaling performed by the SMC to a high spatial and temporal resolution, necessary in areas with complex orography such as Catalonia or the Mediterranean region, where orographic precipitation or convective phenomena affect the local climate (Barrera-Escoda and Cunillera, 2011). On the other hand, we included two contrasted emission scenarios in our climate projections, B1 and A2, to encompass a range of future storylines, which reduces the associated uncertainty. We believe this is equivalent to Hoffmann and Rath (2013) approach, who obtained similar results for apple after combining 7 phenological models and 13 climate projections (climate model plus regionalization combinations), although in a single IPCC scenario (A1B): a decrease in blossom frost risk compatible with CP accumulation delay, but and advancement in flowering phases well-suited to the northern localization of their study (Lower Saxony, Germany).

A second assumption is implicit in the method used to estimate flowering dates (Alonso et al., 2005). This method assumes that cultivar-specific chill and heat requirements are genetically determined, but estimations of these cultivar-specific parameters are not constant around the world: other factors such as latitude, elevation or climatic conditions during endodormancy inception can affect their value (Campoy et al., 2011a). However, we estimated CR and HR specifically for the territory were the cultivars were growing, with both meteorological and phenological data. Although the relationship between chill and heat requirements and a specific area of the earth could change with time, this is a problem that no study based on projections in time could overcome. Another feature of this method is the use of a statistical approach to establish a common day for endodormancy end from which CR and HR are derived. Luedeling et al. (2013) noted that this kind of statistical approaches cannot produce definitive estimates of CR and HR, though they can provide an indication of these and help improve projections of climate change impacts on well-established cultivars in a region. This might be the reason for the lack of success in the case of cv 'Pink lady', although the lower number of data available for this cultivar can also be the cause. Despite the case of 'Pink Lady', delineation of chilling and forcing phases was clear and easy for the rest of cultivars studied.

Finally, the sequential model specifically assumes that the plant copes with chill and heat requirements in two consecutive phases. For the chill phase, we used the Dynamic Model because of the higher credibility of projections with this model (Luedeling et al., 2011; Darbyshire et al., 2013). Some other models also perform reasonably well (Luedeling et al., 2011) – or even better in non Mediterranean areas (Maulión et al., 2014) – in reproducing observed flowering patterns, but their suitability for climate change projections has been questioned (Luedeling, 2012). Although Darbyshire et al. (2013, 2014) suggested that the sequential modeling may need improvement, especially in the context of climate projections, and they advocated for more field and laboratory work to validate and define in a better way both chilling and forcing procedures, they also noted that the sequential model composed by the Dynamic chilling model and GDH growth model dominated the best performing models across all the data series in their study. However, Harrington et al. (2010) proposed a new general concept of chilling and forcing requirements in which low chilling can be compensated by high forcing. Although their model is also compatible with our results of date flowering stability in the short and mid term, the philosophy behind is different: in our case, longer periods to achieve CR are compensated by short durations of the HR phase, while in the case of Harrington it is heat accumulation itself that compensates for poor winter chilling. Pope et al. (2014) recently reported, for three *Prunus dulcis* cultivars, a large overlap of the kind proposed by Harrington et al. (2010): models accounting for chill accumulation until approximately 75% of the heat requirement had been met fit best to the data. If these models are correct, then the delays obtained in this study, and especially the existence of non-CR-compliant years by the end of the century might not stand. Indeed, Darbyshire et al. (2014) also found many runs of their models tests in which chill requirements were not met, and concluded that the likelihood of these results depended on how well the structure of the sequential model reflected the underlying physiology.

Notwithstanding these methodological uncertainties associated with the assumptions of the different steps of the process, the results of the study could pose a strong challenge to the apple growers of the lower Fluvià subbasin as the fulfillment of CR could become more and more difficult along the 21st century for the tested apple cultivars. Furthermore, this problem would affect very similarly to all cultivars, as CR estimations were quite similar for all of them. This similarity in CR is probably related to their fitting to similar climate conditions (NW Mediterranean, NE coast of the Iberian Peninsula).

Some alternatives to manage this situation could go through the redistribution of cultivars to near locations with colder winter, both northward or uphill, or the use of new cultural practices (Campoy et al., 2011b) such as: (i) applications of rest breaking agents to avoid or reduce the negative consequences of an insufficient chill accumulation but with the negative ecological impact associated; (ii) over-tree sprinkling of water and the subsequent evaporation to reduce bud temperature by several degrees, which is very limited in this geographical area due to low and/or irregular water availability, (iii) shading to reduce temperature during the isolation hours or (iv) dormancy avoidance in which the potential for continued growth is allowed by moderate temperatures through strong stimulus before the induction of endodormancy such as defoliation and drought and subsequent irrigation. A final option would be a shift to low-chilling apple cultivars with commercial quality (Carter, 2007; Labuschagne et al., 2002) or to different crops more suited to the region new conditions. In the first case, applying the concept of safe winter chill (Luedeling et al., 2009b), a value of 48CP was obtained for the period 2076–2100 for the lower Fluvià subbasin (data not shown), which would constitute the upper threshold for CR of candidate cultivars in this region. Adaptation to climate change effects on agriculture is an important challenge for growers (OCCC, 2012; Clothier et al., 2012) as short-term adjustments in tree cultivars are very costly and would be a severe economic blow to many growers (Luedeling, 2012). As changes will probably happen anyway as growers try to cope with the real changes they perceive, be them related to climate change, economic perspectives, or social expectations, it would be helpful to improve modeled projections of climate change effects in agriculture in order to develop efficient adaptation strategies at mid and long term that can be combined with other sources of decision by growers.

5. Conclusion

Chill and heat requirements of the major apple cultivars in the lower Fluvià subbasin were quite similar, corresponding to their fitting to similar climate conditions. In general, the cultivars could suffer delays on flowering date since the mid century and they could present serious disorders as a consequence of insufficient chilling by the end of the century in A2 scenario, which could affect crop feasibility in the region.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.agwat.2015.06.013.

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