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► **To cite this version:**

Yann Guédon, Jean-Michel Legave. Analyzing the time-course variation of apple and pear tree dates of flowering stages in the global warming context. *Ecological Modelling*, Elsevier, 2008, 219 (1-2), pp.189-199. <hal-00831805>

HAL Id: hal-00831805

<https://hal.inria.fr/hal-00831805>

Submitted on 7 Jun 2013

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1 Analyzing the time-course variation of apple and pear tree dates of flowering
2 stages in the global warming context

3

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13

14 Abstract

15 Over the last 40 years, perceptible advances in dates of flowering stages have been observed
16 in apple and pear trees growing in three cropping areas in France and one in Switzerland. The
17 time-course variation of dates of flowering stages was established for eight chronological
18 sequences. Our aim was to propose a statistical modelling framework for such sequences with
19 the objective of characterizing the relationship between flowering advances in fruit trees and
20 global warming. After an exploratory analysis, change-point models were applied to
21 multivariate and univariate sequences. The results clearly support the occurrence of a
22 significant abrupt change in the time-course variation of flowering dates at the end of the
23 1980s toward more frequent early dates, the most probable change instant being between
24 1988 and 1989. The coincidence between this abrupt change in phenological variations and
25 marked increases in temperature recorded particularly in France at the end of the 1980s led us

26 to consider the flowering advances in apple and pear trees as impacts of global warming. The
27 suddenness in the response to global warming could be explained by changes in rates for
28 completion of chilling and heat requirements, successively essential to the development of
29 floral primordia within buds. In all cropping areas, annual mean temperatures had suddenly
30 increased since 1988 (1.1-1.3°C), but including noticeable monthly differences. Particularly,
31 warming was clearly more pronounced in February and March (mean temperature increases
32 of 1.6°C) corresponding to the main period of heat requirements, than in November and
33 December (0.8°C) corresponding to the main period of chilling requirements. So marked
34 temperature increases during the heat phase would have suddenly resulted in more frequent
35 years with relatively short duration for completion of the heat requirements and consequently
36 more frequent early flowering years, despite some years with relatively long duration of
37 chilling requirements.

38

39 Key words: Change-point detection, Chilling requirement, Climate change, Fruit tree, Heat
40 requirement, Phenology.

41

42 Introduction

43 Global warming of the climate system is unequivocal, as is now evident from observations
44 of increases in average air temperatures in many parts of the world. Eleven of the last twelve
45 years (1995-2006) rank among the twelve warmest years since 1850. Mean temperature will
46 probably rise between 1.8°C and 4.0°C for the end of the 21st century, according to climatic
47 scenario (IPCC, 2007). As plant phenology is mainly influenced by temperature, climate
48 warming has caused renewed interest in phenological methods and observations. Long-term
49 phenological records at specific sites provide useful measures of species-level biological
50 responses to climate changes according to Schwartz (1999). A lot of phenological studies

51 focused on changes in natural systems (Parmesan and Yohe, 2003), while few studies dealt
52 with phenological changes in perennial horticultural crops (Schultz, 2000). Changes in tree
53 phenology have been observed in European countries where earlier onsets of leafing dates
54 were associated with global warming (Chmielewski and Rötzer, 2001). In fruit tree orchards,
55 changes in the timing of flowering phenology could have important impacts on production,
56 because of the indirect influences of phenology on spring frost damage, pollination and fruit
57 set efficiency (Cannell and Smith, 1986; Zavalloni et al., 2006).

58 Over the last forty years, similar evolutions toward an advance in dates of flowering
59 stages have been observed for several fruit species in distant countries in the northern
60 hemisphere and related to global warming (Omoto and Aono, 1990; Kai et al., 1993;
61 Chmielewski et al., 2004; Legave and Clauzel, 2006; Miller-Rhushing et al., 2007; Legave et
62 al. 2008). Nevertheless, it is less clear how these evolutions might be described to rightly
63 characterize the response to global warming and how they might be explained by changes in
64 temperature conditions during the flowering process. Thus, this study aimed to analyze the
65 time-course variation of dates of flowering stages through a statistical modelling approach
66 over ranges of years including the end of the 1980s when a marked increase in air temperature
67 has been recorded worldwide (IPCC, 2007). For this aim, we collected and analyzed long-
68 term chronological sequences of dates of flowering stages for apple and pear trees in three
69 cropping areas in France and one in Switzerland. After an exploratory analysis of these data,
70 we chose to estimate change-point models on the basis of these phenological sequences. It
71 was thus assumed that there were two periods within which the flowering dates follow the
72 same or nearly the same distribution and between which the flowering dates have different
73 distributions. This statistical modelling of phenological sequences was completed by an
74 analysis of temperature changes during the successive chilling and heat phases up to
75 flowering dates in the case of apple trees.

76 Materials and methods

77 *Plant material and temperature conditions*

78 The flowering data are issued from a French database (called 'PhénoClim') devoted to
79 fruit trees and vine. Flowering dates of one apple tree cultivar ('Golden Delicious') and three
80 pear tree cultivars ('Williams', 'Passe Crassane', 'Doyenné du Comice') were selected owing
81 to their economic importance. Dates of flowering stages are recorded since a long time and in
82 various locations in France for such main cultivars for various agronomic purposes like
83 parasitism control, breeding and modelling. Such dates are commonly assessed from
84 observations on several adult trees growing in long-term orchards managed by commercial
85 practices. The assessments of floral dates by experienced observers are made with an
86 inaccuracy of 2-3 days. Among the different phenological stages considered in past
87 observations, we selected stages that were subjected to reliable recording dates over the
88 longest ranges of years.

89 Thus, the date when about 10% of flower buds are opened (F1 stage) was chosen for apple
90 tree cultivar 'Golden Delicious', while the date when nearly 100% are opened (F2 stage) was
91 chosen for the three pear tree cultivars. F1 dates for 'Golden Delicious' were recorded during
92 different periods at three locations representative of the main cropping areas of France: from
93 1963 to 2006 at INRA research station near Angers (47° 28 N, 0° 33 W) in Pays de Loire,
94 from 1976 to 2002 at Domaine de Castang (grower farm) near Bergerac (44° 51 N, 0° 29 E)
95 in Aquitaine and from 1974 to 2006 at Ctifl professional station near Nîmes (43° 50 N, 4° 21
96 E) in Languedoc. Regarding F2 dates for pear trees, data were recorded mainly at Angers
97 from 1959 to 2006 for 'Williams' and 'Passe Crassane' and from 1972 to 2006 for 'Doyenné
98 du Comice'. Data were also recorded at Bergerac from 1972 to 2003 for 'Williams'. In
99 addition to French data, F2 dates collected for 'Williams' from 1971 to 2003 at the Agroscope
100 Changins-Wädenswil research station near Nyon in Switzerland (46° 24 N, 6° 14 E) were

101 used. This was achieved with the collaboration of Doctor Danilo Christen, in order to
102 compare French phenological sequences with one sequence representative of those collected
103 in another European country.

104 The temperature conditions of the four locations involved were studied on the basis of
105 mean daily temperature of 30 years (1973-2002) covering an appropriate period to highlight
106 temperature increases. The data were issued from databases managed by INRA in France and
107 Météo Suisse in Switzerland. Moreover, in order to analyse the change in flowering stage date
108 in relation to temperature changes, mean temperatures were assessed respectively during the
109 phase of chilling effects required to break bud endodormancy (Lang et al., 1987) and the
110 successive phase of heat effects required to active growth resulting in flower bud opening. To
111 do this, we determined the corresponding periods of these two phases for each annual
112 flowering process (chilling onset in the autumn of year $n - 1$ to heat completion in the spring
113 of year n). In practical terms, this analysis was applied to F1 stage of 'Golden Delicious' for
114 which previous work provided parameters to estimate a date of completion of the chilling
115 requirement for each year at each location (Legave et al, 2008). Moreover the 1st of October
116 of year $n - 1$ was found in France as an appropriate date to situate the onset of chilling effects
117 for each flowering year (n) and location (Bidabé, 1967). Thus, the mean temperature of the
118 chilling phase was calculated from this fixed date to the estimated date of chilling completion
119 for the flowering years 1976-2002 for which F1 dates were recorded at all three locations. The
120 mean temperature of the heat phase was calculated from the estimated date of chilling
121 completion to the observed F1 date for the same situations (year x location).

122

123 *Statistical models*

124 Multiple change-point models are used to delimit segments for which the data
125 characteristics are homogeneous within each segment while differing markedly from one

126 segment to another. In a probabilistic framework, the observed sequence of length T ,
 127 x_0, \dots, x_{T-1} is modelled by T random variables X_0, \dots, X_{T-1} which are assumed to be
 128 independent. In the following x_0^{T-1} is a shorthand for x_0, \dots, x_{T-1} .

129 We made the assumption of Gaussian multiple change-point models. Gaussian multiple
 130 change-point models differ in the parameters assumed to be constant within segments (i.e.
 131 between change points). This can be the mean or the mean and the variance. The two
 132 associated models are denoted by M_m (for mean), and M_{mv} (for mean/variance). For model
 133 M_m , we suppose that there exist some $J-1$ instants $\tau_1 < \dots < \tau_{J-1}$ (with the convention
 134 $\tau_0 = 0$ and $\tau_J = T$) such that the mean is constant between two successive change points and
 135 the variance is assumed to be constant:

$$136 \quad \text{if } \tau_j \leq t < \tau_{j+1}, \quad \begin{cases} E(X_t) = \mu_j, \\ V(X_t) = \sigma^2. \end{cases}$$

137 For model M_{mv} , the modelling of the variance is different since it is also affected by the $J-1$
 138 change points:

$$139 \quad \text{if } \tau_j \leq t < \tau_{j+1}, \quad \begin{cases} E(X_t) = \mu_j, \\ V(X_t) = \sigma_j^2. \end{cases}$$

140 The problem now is to estimate the parameters of these Gaussian multiple change-point
 141 models: the number of segments J , the instants of the $J-1$ change points $\tau_1, \dots, \tau_{J-1}$, the J
 142 within-segment means μ_j and, the global variance σ^2 (for model M_m) or the J within-
 143 segment variances σ_j^2 (for model M_{mv}). We shall adopt here a retrospective or off-line
 144 approach where change points are detected simultaneously. Let us denote by θ the set of
 145 mean and variance parameters. For model M_m , $\theta = \{\mu_0, \dots, \mu_{J-1}, \sigma^2\}$ while for model M_{mv} ,
 146 $\theta = \{\mu_0, \dots, \mu_{J-1}, \sigma_0^2, \dots, \sigma_{J-1}^2\}$. In a first step, we suppose that the number of segments J is
 147 known and the purpose is to obtain the optimal segmentation of the sequence into J segments.

148 We discuss in a second step the choice of J which can be put into a model selection
149 framework.

150 Once the change points have been fixed, the mean and variance parameters are estimated
151 by maximum likelihood. For model M_{mv} , we obtain the empirical mean and variance for each
152 segment:

$$153 \quad \hat{\mu}_j = \frac{\sum_{t=\tau_j}^{\tau_{j+1}-1} x_t}{\tau_{j+1} - \tau_j} \quad \text{and} \quad \hat{\sigma}_j^2 = \frac{\sum_{t=\tau_j}^{\tau_{j+1}-1} (x_t - \hat{\mu}_j)^2}{\tau_{j+1} - \tau_j}. \quad (1)$$

154 For model M_m , the estimated global variance is given by:

$$155 \quad \hat{\sigma}^2 = \frac{\sum_{j=0}^{J-1} \sum_{t=\tau_j}^{\tau_{j+1}-1} (x_t - \hat{\mu}_j)^2}{T}. \quad (2)$$

156 Then, if we denote by L_J the likelihood of a J -segment model, the estimation of the $J-1$
157 change points $\tau_1, \dots, \tau_{J-1}$, which corresponds to the optimal segmentation into J segments, is
158 obtained as follows:

$$159 \quad \hat{\tau}_1, \dots, \hat{\tau}_{J-1} = \arg \max_{0 < \tau_1 < \dots < \tau_{J-1} < T} \log L_J(x_0^{T-1}; \hat{\theta}),$$

160 with

$$161 \quad \begin{aligned} \log L_J(x_0^{T-1}; \hat{\theta}) &= -\frac{T}{2} (\log \hat{\sigma}^2 + \log 2\pi + 1) && \text{for model } M_m, \\ \log L_J(x_0^{T-1}; \hat{\theta}) &= -\frac{1}{2} \sum_{j=0}^{J-1} (\tau_{j+1} - \tau_j) (\log \hat{\sigma}_j^2 + \log 2\pi + 1) && \text{for model } M_{mv}. \end{aligned}$$

162 For this optimisation task, the additivity in j of the sum of squared deviations from the
163 means (see (2)) for model M_m , or the additivity in j of the log-likelihood for model M_{mv} (see
164 above) allows us to use a dynamic programming algorithm (Auger and Lawrence, 1989)
165 which reduces the computational complexity from $O(T^J)$ to $O(JT^2)$ in time.

166 The Gaussian multiple change-point models can be directly generalized to multivariate
167 sequences. In our context, the N variables correspond to different locations or to different

168 cultivars and the elementary random variables at a given time t are assumed to be
 169 independent. In the multivariate case, the log-likelihood of the J -segment model is given by:

$$170 \quad \log L_J(x_0^{T-1}; \hat{\theta}) = -\frac{NT}{2} (\log \hat{\sigma}^2 + \log 2\pi + 1) \quad \text{with} \quad \hat{\sigma}^2 = \frac{\sum_{j=0}^{J-1} \sum_{a=1}^N \sum_{t=\tau_j}^{\tau_{j+1}-1} (x_{a,t} - \hat{\mu}_{j,a})^2}{NT},$$

171 for model M_m and

$$172 \quad \log L_J(x_0^{T-1}; \hat{\theta}) = -\frac{1}{2} \sum_{j=0}^{J-1} (\tau_{j+1} - \tau_j) \sum_{a=1}^N (\log \hat{\sigma}_{j,a}^2 + \log 2\pi + 1) \quad \text{where} \quad \hat{\sigma}_{j,a}^2 \text{ is given by (1),}$$

173 for model M_{mv} . In the multivariate case, we introduce a supplementary model which is
 174 intermediate between models M_m and M_{mv} . In this new model denoted by M_{msv} (for
 175 mean/segment variance), the variance is common to the N variables within a segment. The
 176 log-likelihood of the J -segment model M_{msv} is given by:

$$177 \quad \log L_J(x_0^{T-1}; \hat{\theta}) = -\frac{N}{2} \sum_{j=0}^{J-1} (\tau_{j+1} - \tau_j) (\log \hat{\sigma}_j^2 + \log 2\pi + 1) \quad \text{with} \quad \hat{\sigma}_j^2 = \frac{\sum_{a=1}^N \sum_{t=\tau_j}^{\tau_{j+1}-1} (x_{a,t} - \hat{\mu}_{j,a})^2}{N(\tau_{j+1} - \tau_j)}.$$

178 Once a multiple change-point model has been estimated for a fixed number of segments
 179 J , the question is then to choose this number. Indeed, in real situations this number is
 180 unknown and should be estimated. In a model selection context, the purpose is to estimate J
 181 by maximizing a penalized version of the log-likelihood defined as follows:

$$182 \quad \hat{J} = \arg \max_{J \geq 1} \{ \log L_J(x_0^{T-1}; \hat{\tau}_1, \dots, \hat{\tau}_{J-1}, \hat{\theta}) - \text{Penalty}(J) \}$$

183 The principle of this kind of penalized likelihood criterion consists in making a trade-off
 184 between an adequate fitting of the model to the data (given by the first term) and a reasonable
 185 number of parameters to be estimated (control by the second term: the penalty term). The
 186 most popular information criteria such as AIC and BIC are not adapted in this particular
 187 context since they tend to underpenalize the log-likelihood and thus select a too large number
 188 of segments J . New penalties have therefore been proposed in this context; see for example
 189 Lavielle (2005) used in Picard et al. (2005), and Lebarbier (2005) and Zhang and Siegmund

190 (2007) used in Guédon et al. (2007). Zhang and Siegmund proposed a modified BIC criterion
 191 in the case of the univariate model M_m . This criterion is given by

$$192 \quad \text{mBIC}_J = 2 \log L_J(x_0^{T-1}; \hat{\tau}_1, \dots, \hat{\tau}_{J-1}, \hat{\theta}) - 2J \log T - \sum_{j=0}^{J-1} \log(\hat{\tau}_{j+1} - \hat{\tau}_j), \quad (3)$$

193 where

$$194 \quad \begin{aligned} \min_{0 < \tau_1 < \dots < \tau_{J-1} < T} \sum_{j=0}^{J-1} \log(\hat{\tau}_{j+1} - \hat{\tau}_j) &= \log(T - J + 1) \\ &\approx J \log T - (J - 1) \log T \quad \text{if } J \ll T, \\ \max_{0 < \tau_1 < \dots < \tau_{J-1} < T} \sum_{j=0}^{J-1} \log(\hat{\tau}_{j+1} - \hat{\tau}_j) &= J \log \frac{T}{J} \\ &= J \log T - J \log J. \end{aligned}$$

195 Hence each change point contributes between 1 and 2 dimensions to the penalty term
 196 (instead of systematically 1 dimension for each mean or variance parameter) and this penalty
 197 term is maximized when the change points are evenly spaced.

198 A model selection procedure leads generally to a unique solution. However, it could be of
 199 interest to rank the models allowing full consideration of other possible models. The posterior
 200 probability of the J -segment model M_J , given by

$$201 \quad P(M_J | x_0^{T-1}) = \frac{\exp\left(\frac{1}{2} \Delta \text{mBIC}_J\right)}{\sum_{k=1}^{J_{\max}} \exp\left(\frac{1}{2} \Delta \text{mBIC}_k\right)},$$

202 with

$$203 \quad \Delta \text{mBIC}_J = \text{mBIC}_J - \max_K \text{mBIC}_K,$$

204 can be interpreted as the weight of evidence in favour of the J -segment model (among the
 205 J_{\max} models).

206 For models M_{mv} and M_{msv} , the maximum log-likelihood of the J -segment model can be
 207 written as:

208
$$\log L_j(x_0^{T-1}; \hat{\tau}_1, \dots, \hat{\tau}_{j-1}, \hat{\theta}) = \max_{0 < \tau_1 < \dots < \tau_{j-1} < T} \sum_{j=0}^{j-1} \log f(x_{\tau_j}, \dots, x_{\tau_{j+1}-1}; \hat{\theta}_j)$$

209 where $\log f(x_{\tau_j}, \dots, x_{\tau_{j+1}-1}; \hat{\theta}_j)$ is the maximum log-likelihood of parameter $\hat{\theta}_j$ attached to
 210 segment $x_{\tau_j}, \dots, x_{\tau_{j+1}-1}$. It is often of interest to quantify the uncertainty concerning the instant
 211 of change points. In the case of a single change point, the posterior probability of entering the
 212 second segment at time τ_1 for $\tau_1 > 0$ is given by:

213
$$f(x_0, \dots, x_{\tau_1-1}; \hat{\theta}_0) f(x_{\tau_1}, \dots, x_{T-1}; \hat{\theta}_1) / \sum_t f(x_0, \dots, x_{t-1}; \hat{\theta}_0) f(x_t, \dots, x_{T-1}; \hat{\theta}_1),$$

214 This computation can only be performed for models for which the log-likelihood is additive in
 215 j (hence models M_{mv} and M_{msv} but not model M_m). This is the main justification of the
 216 introduction of the parsimonious model M_{msv} for multivariate sequences.

217

218 Results

219 *Exploratory analysis of temperature conditions*

220 In France, similar patterns were observed between the three locations regarding the annual
 221 evolution for monthly mean temperatures. However, for each monthly temperature, gradual
 222 ranges according to the latitude degree of location were obvious (data not shown). Thus,
 223 Angers is characterised by the coldest monthly temperatures with a mean annual temperature
 224 of 11.9°C and Nîmes the warmest (mean annual temperature of 14.5°C), while intermediate
 225 monthly temperatures are observed at Bergerac (mean annual temperature of 12.8°C).
 226 Changins is characterised by a relatively cold climate with a mean annual temperature of
 227 9.7°C.

228 Temperature increases have been clearly marked from the year 1988 in the three French
 229 growing locations as expressed by the comparison of means of annual temperatures between
 230 the two successive periods 1973-1987 and 1988-2002. The mean increases of annual

231 temperatures in the second period were +1.1°C at Angers, +1.2°C at Bergerac and +1.3°C at
232 Nîmes. A similar change has been obvious at Changins (+1.2°C during the period 1988-
233 2002). Nevertheless, these increases include noticeable monthly differences for the months
234 involved in the annual flowering process. Particularly, in France warming was clearly more
235 pronounced in the period February - March (mean temperature increases of 1.4-1.8°C
236 according to location), than in the period November - December (0.6-0.8°C).

237

238 *Exploratory analysis of the variability within the flowering dates*

239 The time-course variation of flowering dates was established for each of the eight
240 selected sequences (Figures 1, 2 and 3). This highlighted differences in flowering date
241 according to location and cultivar. For apple tree cultivar 'Golden Delicious', marked
242 differences are observed between the three regional sequences during the period 1976-2002
243 (Figure 1). The F1 date is consistently earlier at Nîmes than at Angers, while most of the time
244 an intermediate date is observed at Bergerac. The mean F1 dates for this period are April 22 at
245 Angers, April 14 at Bergerac and April 7 at Nîmes (8 days earlier at Bergerac than at Angers
246 and 7 days earlier at Nîmes than at Bergerac). The same range of variability in mean dates is
247 observed between the three locations when means are considered separately for the 1976-
248 1988 sub-period (April 25, April 19, April 11 respectively) and the 1989-2002 sub-period
249 (April 18, April 11, April 4 respectively). Such data clearly underline a constant influence of
250 location on the date of stage F1 for 'Golden Delicious' apple trees. The lower the latitude of
251 location, the earlier the flowering date in the apple tree growing area extending from North-
252 West to South-East of France.

253 For pear tree cultivar 'Williams', slight differences in the date of stage F2 are observed
254 between the two French locations of Bergerac and Angers during the period 1972-2003, while
255 later dates are clearly observed most of time at Changins in Switzerland (Figure 2). The mean

256 F2 dates for the period 1972-2003 are April 7 at Bergerac, April 9 at Angers and April 20 at
257 Changins. The differences in mean dates are unchanged when means are considered
258 separately for the 1972-1988 sub-period (April 11, April 13 and April 25 respectively) and the
259 1989-2003 sub-period (April 2, April 4 and April 15 respectively).

260 Differences in flowering date according to cultivar are highlighted by the comparison of
261 sequences of three pear tree cultivars growing at Angers during the period 1972-2006 (Figure
262 3). The F2 date is consistently earlier for 'Passe Crassane' than for 'Doyenné du Comice',
263 while 'Williams' shows an intermediate date most of the time. The mean F2 dates for the
264 period 1972-2006 are April 8 for 'Passe Crassane' and April 14 for 'Doyenné du Comice'.
265 This difference of 6 days is unchanged when means are considered separately for the 1972-
266 1988 sub-period (April 12 and April 18 respectively) and the 1989-2006 sub-period (April 3
267 and April 9 respectively).

268 The exploratory analysis clearly shows constant influences of location and cultivar on the
269 date of flowering stage. Nevertheless, as it is obviously apparent in the data (Figures 1, 2 and 3),
270 it was not possible to extract regularly decreasing trends (i.e. long-term changes in the mean
271 level) using various symmetric smoothing filters with different filter widths (results not shown)
272 Hence, we chose to apply multiple change-point models.

273

274 *Analysis of the changes in the flowering dates using multiple change-point models*

275 A multivariate sequence was built taking each location (three for apple tree cultivar
276 'Golden Delicious' and for pear tree cultivar 'Williams') or cultivar (three pear tree cultivars
277 growing at Angers) as a variable. Applying multiple change-point detection method to one of
278 these multivariate sequences consists then in detecting change points common to the
279 individual sequence (while the means are estimated for each segment and each variable, and
280 the global variance is estimated for model M_m , the variances are estimated for each segment

281 for model M_{msv} and for each segment and each variable for model M_{mv}); see Figures 1, 2 and
 282 3. Since the variances estimated for each segment and each variable are close, the modified
 283 BIC of Zhang and Siegmund (2007) always ranks the models from the more to the less
 284 parsimonious for a fixed number of segments i.e. M_m followed by M_{msv} and M_{mv} (results not
 285 shown); see the corresponding standard deviations estimated for the different 2-segment
 286 models in Table 1. We thus chose to focus on models M_m for the selection of the number of
 287 segments. The modified BIC favoured the 2-segment model for apple tree, cultivar ‘Golden
 288 Delicious’ and for pear tree, cultivar ‘Williams and the 3-segment model for pear tree at
 289 Angers (Table 2). In this last case, both the 2-segment and the 3-segment models are possible
 290 models according to their posterior probabilities. It should be noted that the penalty used in
 291 (3) is likely to slightly underpenalized the log-likelihood (and thus to select a too large
 292 number of segments) since this penalty was derived in the case where the global variance σ
 293 is known (instead of being estimated); see Zhang and Siegmund (2007).

294 In the case of the 2-segment models, we obtained the same instant for the change point
 295 (1988 \rightarrow 1989) in the three cases with a low uncertainty (posterior probability between 0.67
 296 and 0.87 for the change point 1988 \rightarrow 1989 computed using M_{msv} models; see Figure 4). The
 297 change-point magnitudes as given by the mean difference between the two segments
 298 $\hat{\mu}_{1,a} - \hat{\mu}_{0,a}$ are very similar (between -7.5 and -10; see Table 1). The sample autocorrelation
 299 function computed from the residual sequences obtained by subtracting the two successive
 300 segment means from the original sequences (Lavielle, 1998) showed that the residual
 301 sequences were stationary and close to white noise sequences (results not shown).

302 If all the data are gathered in a single multivariate sequence [apple tree, cultivar ‘Golden
 303 Delicious’ (Angers, Bergerac and Nîmes) and pear tree, cultivar ‘Williams’ (Angers, Bergerac
 304 and Changins), ‘Passe Crassane’ (Angers) and ‘Doyenné du Comice’ (Angers)], the 2-

305 segment model M_m is by far the best model with very few uncertainty (posterior probability
306 of 0.99 for this model; see Table 3) and there also remains almost no uncertainty for the
307 instant of the change point 1988 → 1989 with a posterior probability of 0.99.

308 At the opposite, on the basis of 2-segment models M_m estimated from univariate
309 sequences, the change point 1988 → 1989 was detected for all the apple and pear tree
310 sequences. On the basis of 2-segment models M_{mv} , the change point 1988 → 1989 was
311 detected for apple tree cultivar ‘Golden Delicious’ at Angers and Bergerac, pear tree cultivar
312 ‘Williams’ at Angers, Bergerac and Changins and pear tree cultivar ‘Doyenné du Comice’ at
313 Angers, but not for apple tree cultivar ‘Golden Delicious’ at Nîmes and pear tree cultivar
314 ‘Passe-Crassane’ at Angers (Table 4). Nevertheless, there is a strong consensus among the
315 univariate 2-segment models M_{mv} for the change point 1988 → 1989 since 1988 → 1989 is a
316 possible change point even for apple tree cultivar ‘Golden Delicious’ at Nîmes and pear tree
317 cultivar ‘Passe-Crassane’ at Angers (Table 4 and Figure 5). It should be noted that some of
318 the univariate sequences are longer than the multivariate sequences since only the common
319 range of years can be used to build multivariate sequences. However, this increase in length
320 of the univariate sequence does not compensate for the combination with another sequence in
321 terms of sample size for estimating change points.

322 Finally, despite usual yearly fluctuations, we may conclude that a change in the time-
323 course variation of flowering dates occurred abruptly at the end of the 1980s (1988 → 1989)
324 toward more frequent early dates. This evolution was similar for the eight sequences
325 analysed, regardless of the respective influences of location and cultivar (Figures 1, 2 and 3).
326 When the period 1976-2002 common to all sequences is considered to compare the advances
327 in flowering date (Table 5), this clearly highlights earlier mean dates of F1 and F2 stages
328 during the sub-period 1989-2002 in comparison with the sub-period 1976-1988, although

329 higher mean advances in pear tree (10-11 days for F2 stage) than in apple tree (by 7-8 days
330 for F1 stage) can be noted.

331

332 *Temperature changes related to flowering date changes*

333 Firstly, the changes in temperature during the chilling and heat phases for the three
334 locations regarding apple tree cultivar ‘Golden Delicious’ (Figures 6 and 7) were analysed
335 with the same approach used for the flowering dates. Multivariate sequences were built taking
336 each location as a variable for the ‘chilling temperatures’ and the ‘heat temperatures’. Since
337 the variances estimated for each segment and each variable are close, the modified BIC of
338 Zhang and Siegmund (2007) always ranks the models from the more to the less parsimonious
339 for a fixed number of segments i.e. M_m followed by M_{msv} and M_{mv} (results not shown); see
340 the corresponding standard deviations estimated for the different 2-segment models in Table
341 6. We thus chose to focus on models M_m for the selection of the number of segments. The
342 modified BIC favoured the 2-segment model for the chilling temperatures and the heat
343 temperatures (Table 7). We obtained the same instant for the change point (1987 → 1988) in
344 the two cases with a very low uncertainty (posterior probability of 0.94 in the chilling
345 temperature case, and of 0.93 in the heat temperature case for the change point 1987 → 1988
346 computed using M_{msv} models). The change-point magnitudes as given by the mean difference
347 between the two segments $\hat{\mu}_{1,a} - \hat{\mu}_{0,a}$ are very close for the three locations in the chilling
348 temperature case while they are more variable in the heat temperature case (Table 6 and
349 Figures 6 and 7). The sample autocorrelation function computed from the residual sequences
350 obtained by subtracting the two successive segment means from the original sequences
351 (Lavielle, 1998) showed that the residual sequences were stationary and close to white noise
352 sequences (results not shown).

353 On the basis of 2-segment models M_m estimated from univariate sequences, the change
 354 point 1987 \rightarrow 1988 was detected for all the chilling temperature sequences and for the heat
 355 temperature sequences at Angers and Nîmes.

356 Since a single change point was detected at one year apart in both the flowering date
 357 sequence for apple tree cultivar 'Golden Delicious' and the corresponding chilling and heat
 358 temperature sequences (and the ratios between the average absolute mean difference between
 359 the two segments and the global standard deviation $\sum_{a=1}^N |\hat{\mu}_{1,a} - \hat{\mu}_{0,a}| / N\hat{\sigma}$ are relatively close
 360 in the three cases; see Tables 1 and 6), the flowering date can be directly related to the
 361 corresponding chilling (respectively heat) temperature by a simple linear correlation
 362 coefficient. In the two cases, the correlation coefficients are largely below the threshold of -
 363 0.22 corresponding to the hypothesis of no correlation and clearly indicate negative
 364 correlation between the temperature and the flowering date. It should be noted that the heat
 365 temperature is far more correlated with the flowering date (correlation coefficient of -0.79)
 366 than the chilling temperature (-0.3).

367

368 Discussion

369 One difficulty with these data sets is the similar orders of magnitude of the mean
 370 difference between the two segments and the standard-deviation attached to each segment
 371 (see Table 1). Hence, the two underlying Gaussian distributions estimated for the two
 372 segments exhibit a large recovering. For instance in the case of two Gaussian random
 373 variables $X_0 \sim N(\mu_0, \sigma^2)$ and $X_1 \sim N(\mu_1, \sigma^2)$ with common variance σ^2 such that
 374 $\mu_0 - \mu_1 = \sigma$, we have $P(\mu_1 \leq X_0 \leq \mu_0) = P(\mu_1 \leq X_1 \leq \mu_0) = 0.34$ and
 375 $P(X_0 \leq \mu_1) = P(X_1 \geq \mu_0) = 0.16$.

376 Another source of difficulty lies in the relatively short length of segments (between 13
377 and 18; see Figures 1, 2 and 3). Assuming a segment length of 16, the confidence interval for
378 μ_j is roughly $\hat{\mu}_j \pm \hat{\sigma}/2$. Hence, our statistical analysis clearly supports the idea of abrupt
379 change of the dates of flowering stages at the end of the 1980s, but the statistical model (a
380 single change point between two stationary segments) is not fully validated because of the
381 quite short length of the segments in conjunction with the recovering of the two Gaussian
382 distributions estimated for the two segments.

383 Despite some statistical uncertainties, our analysis of phenological sequences and their
384 relationship with temperature changes provide elements for a right description and
385 explanation of the impact of global warming on apple and pear tree phenology in France. In
386 the case of apple tree ‘Golden Delicious’, the advances in flowering date have been similar
387 from North-West to South-East of France, i.e. without interaction with the location.
388 Moreover, the mean range in flowering advance (7-8 days) was similar to the mean difference
389 in flowering date between adjacent locations (6-8 days). Thus, as a result of the abrupt change
390 in flowering date, ‘Golden Delicious’ is now flowering at the northern location of Angers
391 within the same date range it was previously flowering further south at Bergerac. The same
392 relative change was observed between Bergerac and Nîmes (Table 5). For pear tree cultivars
393 growing at Angers, similar mean flowering advances were observed, i.e. without interaction
394 with cultivar. In comparison with apple tree ‘Golden Delicious’ in the same French locations,
395 pear tree cultivars showed higher mean flowering advances (10-11 days), exceeding the mean
396 difference between adjacent locations (2-3 days between Angers and Bergerac for
397 ‘Williams’). A similar higher advance (10 days) was also found for ‘Williams’ at Changins in
398 Switzerland. For each of the eight phenological sequences, there was a clear time coincidence
399 between the beginning of marked increases of annual temperatures and the most probable
400 instant (1988 → 1989, according to the statistical models) of abrupt change of flowering

401 dates. Thus, our results confirm a general impact of global warming in Europe toward earlier
402 flowering dates at the end of the 1980s (Chmielewski et al., 2004) and contribute to an
403 accurate characterisation of this impact (abrupt change, most probable change instant). In
404 addition, they suggest genetic differences in phenological response between apple and pear
405 trees, as already reported for cherry tree (Miller-Rhushing et al., 2007).

406 At present, such a phenological change do not affect fruit tree production, but it is
407 important to understand the mechanism by which climate warming exerts its influence,
408 especially because this was poorly investigated since the old works of Cannell and Smith
409 (1986). An interesting feature to explain is why the flowering advance would have been
410 expressed through an abrupt change and not in a progressive way. One explanation would lie
411 in different changes in the respective rates of completion of the chilling and heat
412 requirements. Indeed in the case of 'Golden Delicious' in France, previous works (Legave et
413 al., 2008) showed that a constant regional gradient of annual F1 dates (the latest dates at
414 Angers to the earliest dates at Nîmes) is determined by differences in length of the heat phase
415 (the longest at Angers and the shortest at Nîmes) since an inverse gradient of the dates of
416 chilling completion occurred constantly (the earliest at Angers and the latest at Nîmes).
417 Similarly, earlier F1 dates since 1989 at all three locations have been explained by a major
418 effect of warming in reducing the length of the heat phase (more frequent years with relatively
419 short lengths), in spite of noticeable trends, at the same time, toward some years with longer
420 lengths of the chilling phase (Legave et al., 2008). In agreement with these previous findings,
421 the present study clearly shows that the mean temperature during the heat phase has been the
422 main climatic factor determining the F1 date (the higher temperature, the earlier date), while
423 the mean temperature during the chilling phase has been a less important factor (poorly linked
424 to the F1 date). Indeed, the recent warming was non-uniform at all locations but particularly
425 pronounced in months corresponding to the heat phase (February and March particularly),

426 while warming was limited in months corresponding to the chilling phase (October to early
427 January). Moreover, the mean temperature during the heat phase clearly increased from 1988
428 to 1990 at Angers and Nîmes and more progressively at Bergerac (Figure 7). Then, from 1991
429 to 2002, the mean temperatures during the heat phase remained relatively high at all three
430 locations (particularly from 1994) in comparison with the mean temperatures prevailing
431 before 1988 (Figure 7). Such temperature changes led to a marked increase in the rate of
432 completion of the heat requirements since 1988 and can explain the abrupt change of
433 flowering dates. Nevertheless, as previously mentioned, climate warming also affected the
434 rate of completion of the chilling requirements which was clearly decreased in some years
435 (high temperatures during the chilling phase). In such cases, relatively long dormancy tended
436 to delay the flowering date despite the short length of the heat phase linked to a high rate of
437 completion of the heat requirements. This was markedly the case for the annual cycle 1987-
438 1988 characterized by relatively high temperatures at the end of chilling process (January
439 1988), particularly at Nîmes. Such a temperature feature at this time (Figures 6 and 7) can
440 explain that the most probable instant of abrupt change of flowering date is detected only
441 between 1988 and 1989, i.e. one year after the beginning of the marked warming in France
442 which started in 1988 as confirmed by our results .

443 For pear tree cultivars, we may suppose that abrupt change of flowering dates is
444 explainable in the same way as for apple tree 'Golden Delicious'. However, higher mean
445 advances in flowering dates for pear tree cultivars in same locations and periods suggest that
446 climate warming exerted a lower effect on the lengthening of dormancy in the case of pear
447 trees, due to their lower chilling requirements (Atkinson and Taylor, 1994).

448 Finally, it may be emphasized that cultivars of fruit trees have been suitable plants to
449 highlight climatic change factors during the recent climate warming in France (temperature
450 increases from autumn to early spring) as probably in other European countries. A first

451 advantage of fruit trees is due to the considerable longevity of cultivars (clone) permitting
452 analyses of phenological sequences over long terms. Another interesting feature lies in the
453 fact that their flowering process is highly linked to two temperature requirements, which
454 allows to highlight significant temperature changes during the different seasons. Therefore, it
455 is important to continue to collect and analyse flowering data for some main cultivars of fruit
456 trees, in order to detect new changes in main temperature factors and consequently select
457 cultivars adapted to possible phenological disorders in the future (Sunley et al., 2006).

458
459 The authors are grateful to Danilo Christen (SRA Changins-Wädenswil, André Bélouin (INRA
460 Angers), Catherine Miny (Domaine de Castang) and Vincent Mathieu (Ctifl Nîmes) for their
461 essential contribution to the collect of phenological data. Financial support is acknowledged
462 from INRA Mission on Climate Change (Bernard Seguin, INRA Avignon).

463

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530

531 Table 1. Apple tree, cultivar ‘Golden Delicious’ at Angers, Bergerac and Nîmes (1976-2002);
 532 pear tree, cultivar ‘Williams’ at Angers, Bergerac and Changins (1972-2003); pear
 533 tree cultivars ‘Williams’, ‘Passe Crassane’ and ‘Doyenné du Comice’ at Angers
 534 (1972-2006): estimated multivariate 2-segment model parameters ($\hat{\tau}_1 = 1989$ for
 535 models M_m , M_{msv} and M_{mv} in the three cases).

536

Sequence		$\hat{\mu}_{1,a} - \hat{\mu}_{0,a}$	$\hat{\sigma}_{0,a}$	$\hat{\sigma}_{1,a}$
apple tree, cv. ‘Golden Delicious’, 1976-2002	Angers	-7.46	7.49	7.66
	Bergerac	-7.97	7.99	5.85
	Nîmes	-7.67	5.89	7.33
	$\hat{\sigma}_j$		7.18	6.99
	$\hat{\sigma}$			7.08
pear tree, cv. ‘Williams’, 1972-2003	Angers	-9.54	8.47	7.19
	Bergerac	-9.33	7.48	7.84
	Changins	-9.97	6.25	6.04
	$\hat{\sigma}_j$		7.46	7.06
	$\hat{\sigma}$			7.27
pear tree, Angers, 1972-2006	Williams	-8.25	8.47	7.44
	Passe Crassane	-8.97	8.79	7.7
	Doyenné du Comice	-8.96	7.83	7.41
	$\hat{\sigma}_j$		8.37	7.52
	$\hat{\sigma}$			7.94

537

538 Table 2. Apple tree, cultivar ‘Golden Delicious’ at Angers, Bergerac and Nîmes (1976-2002);
 539 pear tree, cultivar ‘Williams’ at Angers, Bergerac and Changins (1972-2003); pear
 540 tree cultivars ‘Williams’, ‘Passe Crassane’ and ‘Doyenné du Comice’ at Angers
 541 (1972-2006): choice of the number of segments for multivariate models M_m .
 542

Sequence	J	$2\log L_J$	Free param.	mBIC $_J$	$P(M_J x_0^{T-1})$
apple tree, cv. ‘Golden Delicious’, 1976-2002	1	-567.93	4	-588.81	0.3
	2	-546.98	8	-587.34	0.62
	3	-532.86	12	-591.33	0.08
	4	-525.8	16	-601.77	0
pear tree, cv. ‘Williams’, 1972-2003	1	-688.11	4	-709.83	0
	2	-653.42	8	-695.48	0.71
	3	-635.57	12	-697.24	0.29
	4	-629.26	16	-710.19	0
pear tree, Angers, 1972-2006	1	-760.89	4	-783.06	0.01
	2	-733.19	8	-776.15	0.4
	3	-712.58	12	-775.38	0.58
	4	-702.38	16	-783.86	0.01

543
 544 Table 3. Apple tree, cultivar ‘Golden Delicious’ (Angers, Bergerac and Nîmes) and pear tree,
 545 cultivars ‘Williams’ (Angers, Bergerac and Changins), ‘Passe Crassane’ (Angers)
 546 and ‘Doyenné du Comice’ (Angers), (1976-2002): choice of the number of segments
 547 for multivariate model M_m .
 548

J	$2\log L_J$	Free param.	mBIC $_J$	$P(M_J x_0^{T-1})$
1	-1555.99	9	-1607.67	0
2	-1475.15	18	-1577.11	0.99
3	-1435.14	27	-1586	0.01
4	-1416.19	36	-1615.35	0

549

550 Table 4. Univariate 2-segment models M_{mv} : posterior change-point probabilities.

551

Cultivar	Location	Year range	1988 → 1989 probability	Maximum probability (change point)
Golden Delicious	Angers	1963-2006	0.23	0.21 (2002 → 2003)
	Bergerac	1976-2002	0.27	
	Nîmes	1974-2006	0.15	
Williams	Angers	1959-2006	0.24	
	Bergerac	1972-2003	0.27	
	Changins	1971-2003	0.46	
Passe Crassane	Angers	1959-2006	0.18	0.29 (1960 → 1961)
Doyenné du Comice	Angers	1972-2006	0.32	

552

553 Table 5. Mean dates of F1 stage (apple tree) or F2 stage (pear tree), expressed in calendar day

554 from 1st January, according to cultivar and location during the two successive

555 observation periods.

556

Cultivar	Location	Stage	Observation period	
			1976-1988	1989-2002
Golden Delicious	Angers	F1	115	108
	Bergerac	F1	109	101
	Nîmes	F1	101	94
Williams	Angers	F2	105	94
	Bergerac	F2	102	92
	Changins	F2	115	105
Passe Crassane	Angers	F2	104	93
Doyenné du Comice	Angers	F2	109	98

557

558 Table 6. Mean temperatures during the chilling and heat phases of the flowering process for
 559 cultivar ‘Golden Delicious’ at Angers, Bergerac and Nîmes (1976-2002): estimated
 560 multivariate 2-segment model parameters ($\hat{\tau}_1 = 1988$ for models M_m , M_{msv} and
 561 M_{mv} in the two cases).

562

Sequence		$\hat{\mu}_{1,a} - \hat{\mu}_{0,a}$	$\hat{\sigma}_{0,a}$	$\hat{\sigma}_{1,a}$
Chilling temperature	Angers	1	0.57	0.85
	Bergerac	1.08	0.67	0.91
	Nîmes	1.12	0.65	0.63
	$\hat{\sigma}_j$		0.63	0.81
	$\hat{\sigma}$			0.73
Heat temperature	Angers	1.28	0.62	0.95
	Bergerac	0.98	0.76	1
	Nîmes	1.77	0.9	0.91
	$\hat{\sigma}_j$		0.77	0.96
	$\hat{\sigma}$			0.88

563

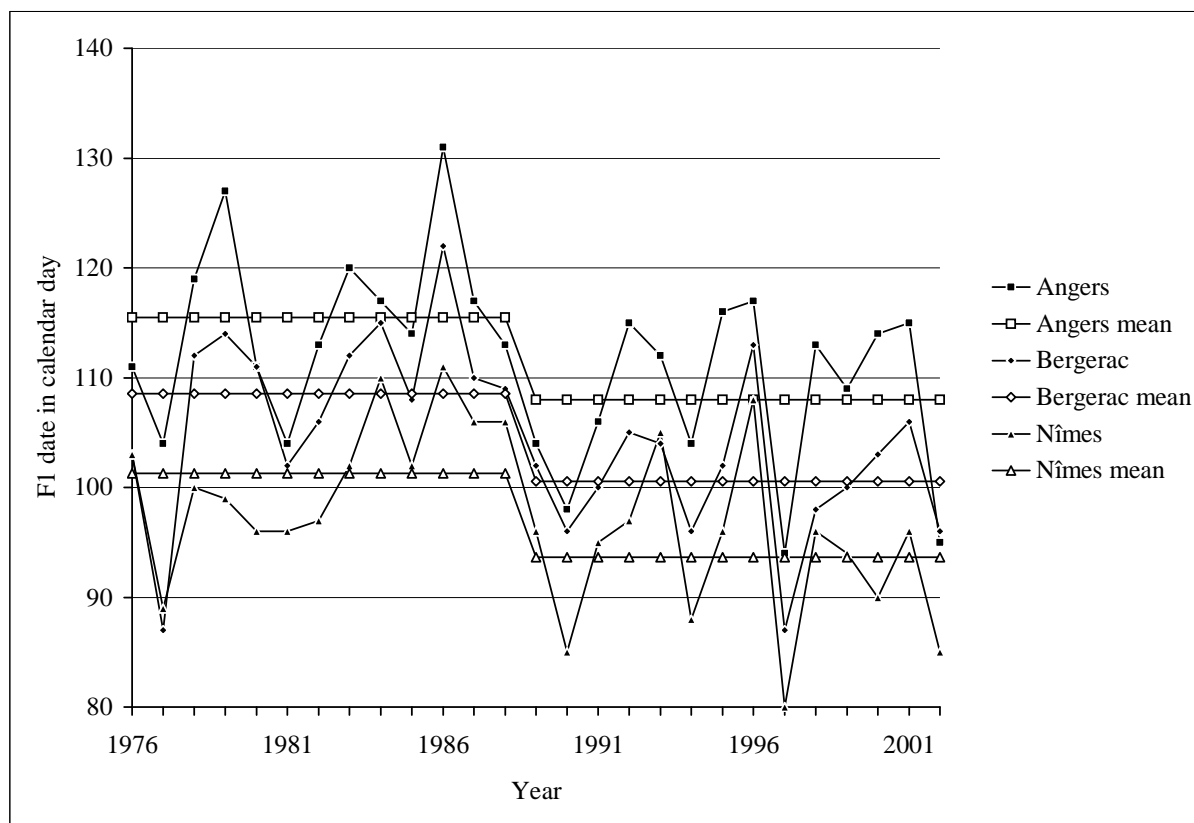
564 Table 7. Mean temperatures during the chilling and heat phases of the flowering process for
 565 cultivar ‘Golden Delicious’ at Angers, Bergerac and Nîmes (1976-2002): choice of
 566 the number of segments for multivariate models M_m .

567

Sequence	J	$2\log L_j$	Free param.	mBIC $_j$	$P(M_j x_0^{T-1})$
Chilling temperature	1	-213.78	4	-234.65	0
	2	-179.58	8	-219.92	1
	3	-174.02	12	-232.46	0
	4	-163.49	16	-240.5	0
Heat temperature	1	-247.44	4	-268.31	0
	2	-208.85	8	-249.2	0.53
	3	-199.11	12	-258.11	0.01
	4	-172.27	16	-249.46	0.46

568

569

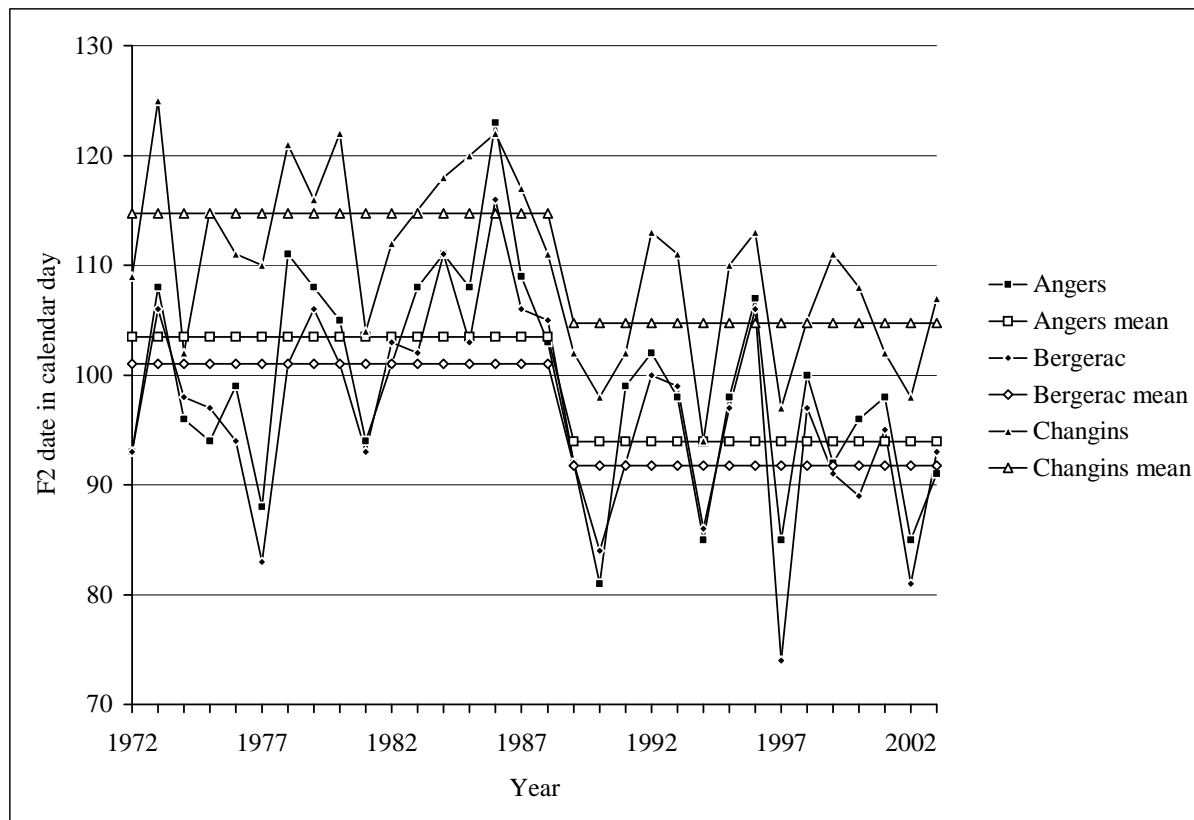


570

571 Figure 1. Segmentation of three chronological sequences of F1date for apple tree, cultivar

572 'Golden Delicious' at three locations.

573

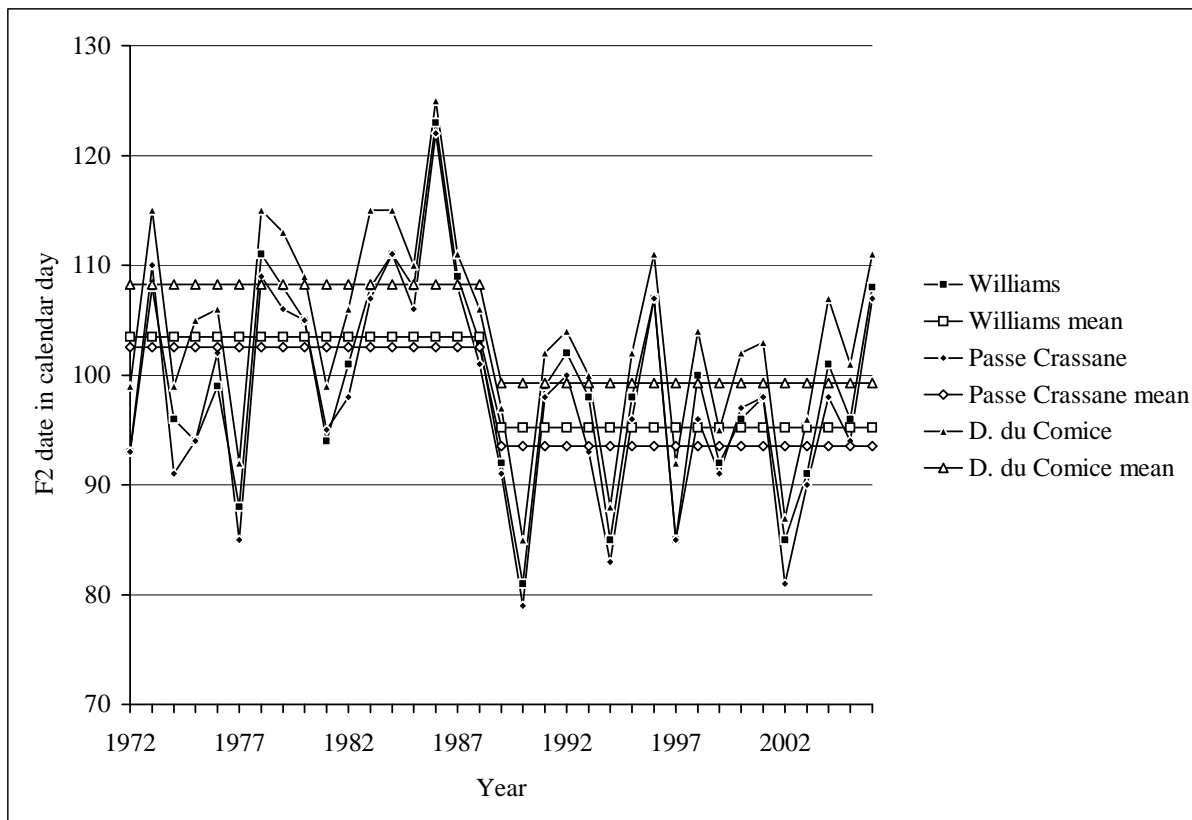


574

575 Figure 2. Segmentation of three chronological sequences of F2 date for pear tree, cultivar

576 'Williams' at three locations.

577

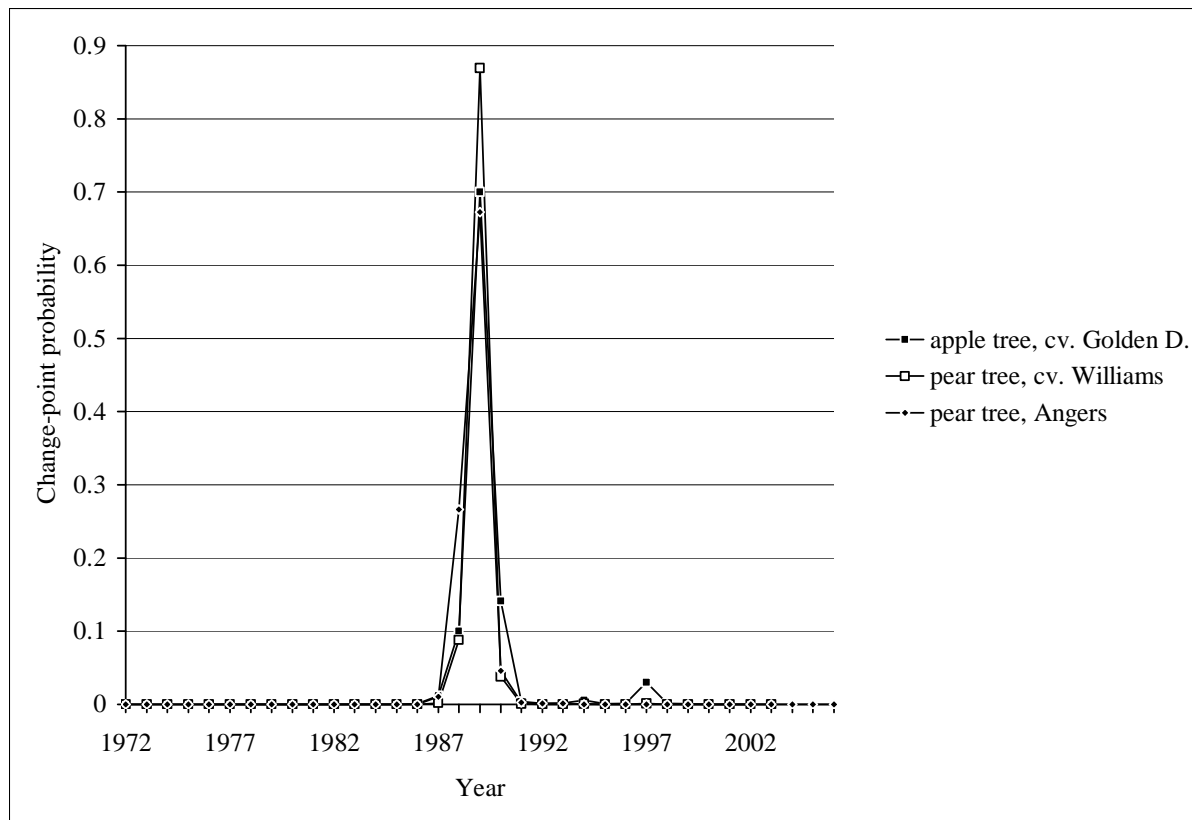


578

579 Figure 3. Segmentation of three chronological sequences of F2 date for three pear tree

580 cultivars at Angers.

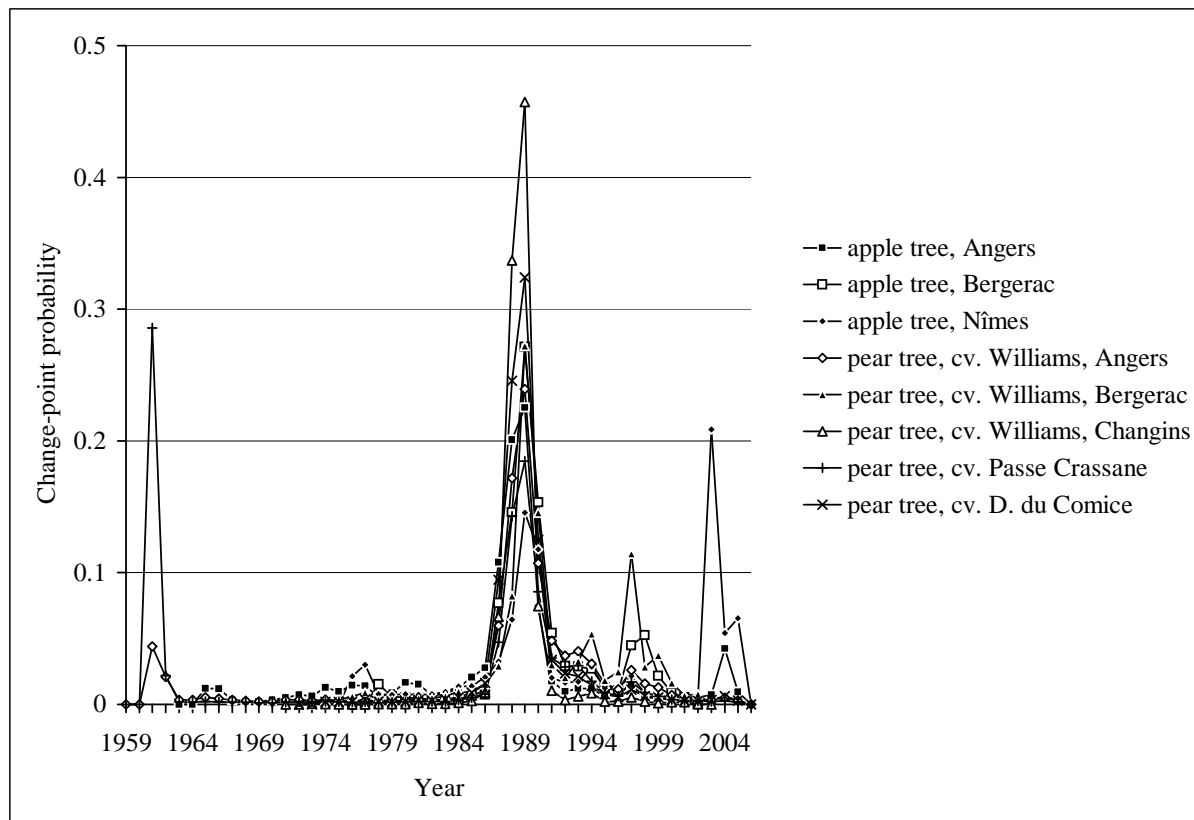
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582

583 Figure 4. Multivariate 2-segment models M_{msv} : posterior change-point probabilities.

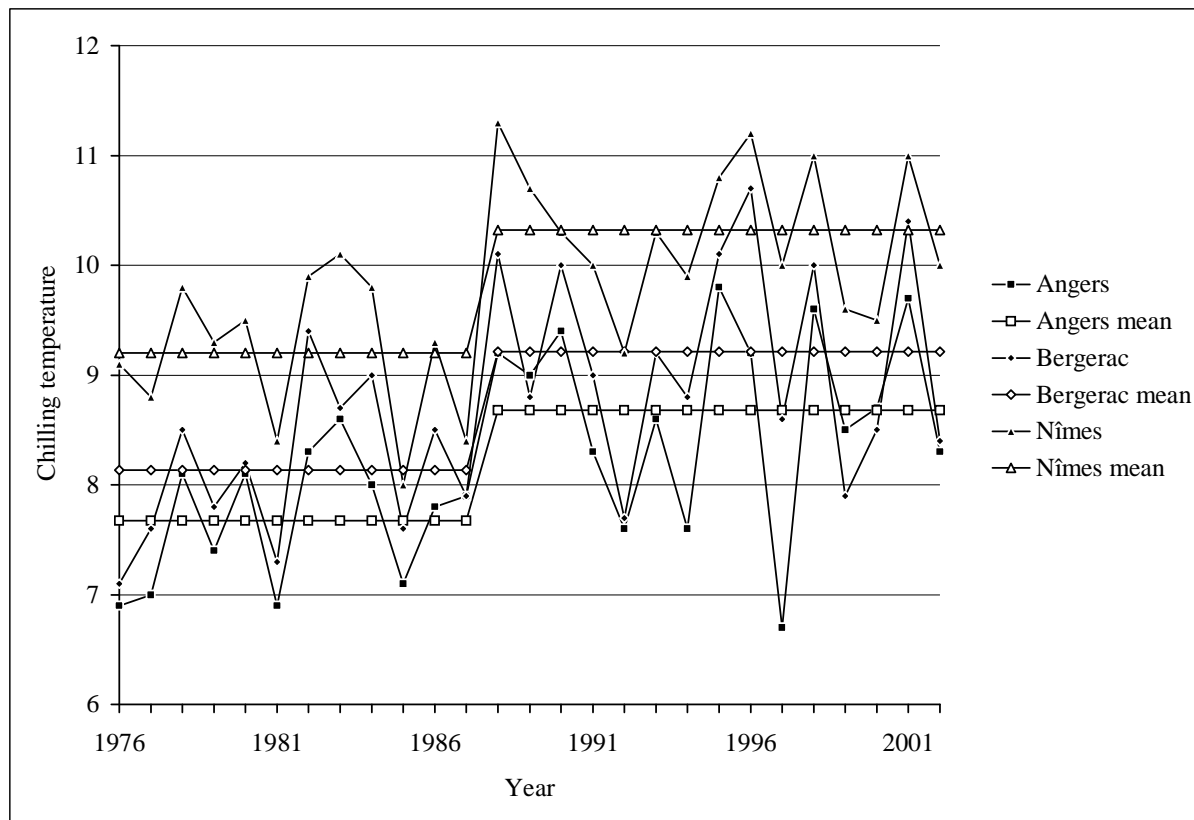
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585

586 Figure 5. Univariate 2-segment models M_{mv} : posterior change-point probabilities.

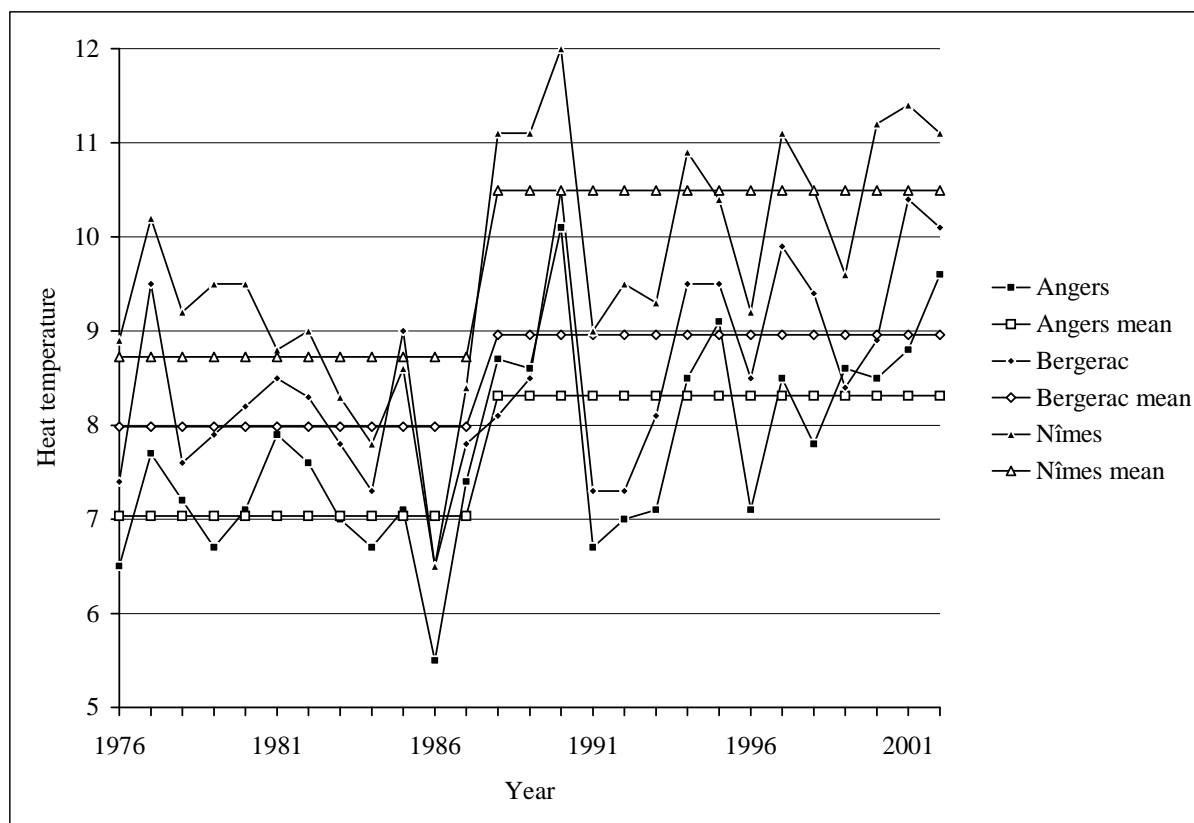
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588

589 Figure 6. Segmentation of three chronological sequences of mean temperature during the
 590 chilling phase of the flowering process for cultivar 'Golden Delicious' at three
 591 locations.

592



593

594 Figure 7. Segmentation of three chronological sequences of mean temperature during the heat

595 phase of the flowering process for cultivar 'Golden Delicious' at three locations.

596