OCL 2017, 24(1) D106
© T. Castel *et al.*, published by EDP Sciences, 2017
DOI: 10.1051/ocl/2017002

OCL Oilseeds & fats Crops and Lipids
Available online at:
www.ocl-journal.org

Topical issue on:
OIL- AND PROTEIN-CROPS AND CLIMATE CHANGE
OLÉOPROTÉAGINEUX ET CHANGEMENT CLIMATIQUE

RESEARCH ARTICLE – DOSSIER OPEN ACCESS

Frost stress evolution and winter pea ideotype in the context of climate warming at a regional scale

Thierry Castel[1], Christophe Lecomte[2], Yves Richard[1], Isabelle Lejeune-Hénaut[3] and Annabelle Larmure[2,*]

[1] Centre de Recherches de Climatologie, UMR Biogéosciences 6282 CNRS-Université de Bourgogne Franche-Comté, 6 Boulevard Gabriel, 21000 Dijon, France
[2] UMR 1347 Agroécologie, AgroSup, INRA, 17 rue Sully, BP 86510, 21065 Dijon cedex, France
[3] USC 1411 Institut Charles Viollette – Adaptation au Froid du Pois, INRA, Estrées-Mons, 80203 Péronne, France

Received 25 November 2016 – Accepted 11 January 2017

Abstract – Pea (*Pisum sativum* L.) is an important crop in temperate regions for its high seed protein concentration that is particularly sensitive to abiotic stresses. The abrupt temperature increase known as the "1987/1988 temperature regime shift" that occurs over Europe is questioning how winter pea will perform in the changing climate. This study assessed the winter frost damage evolution along from 1961 to 2015 in Burgundy-Franche-Comté by using: (1) daily observed and gridded regional temperature data and (2) a validated crop winter frost stress model calibrated for pea. This study shows a global decrease of the frost stress nevertheless resulting from a subtle balance between the decrease in its intensity and the increase of the number of events. The frost stress evolution patterns with warming depend on both plant frost resistance level and acclimation rate and are still sensitive to winter climate fluctuations. This study provides relevant information for breeding performant winter crop ideotypes able to moderate detrimental effects of climate change and offering new cropping opportunities in temperate regions.

Keywords: modeling / temperature abrupt shift / winter pea / frost resistance / Burgundy-Franche-Comté

Résumé – Évolution du stress gélif et idéotypes de pois d'hiver dans le contexte de changement climatique, à une échelle régionale. Le pois (*Pisum sativum* L.) est une culture majeure des régions tempérées implantée pour ses graines riches en protéines. Il est particulièrement sensible aux stress abiotiques. L'augmentation brutale des températures observée en Europe en 1987/1988 appelée "rupture climatique" questionne sur les performances future du pois d'hiver dans ce climat changeant. Cette étude évalue l'évolution des dégâts dus au gel de 1961 à 2015 en Bourgogne-Franche-Comté en utilisant (1) des données de températures observées et régionalisées et (2) un modèle de culture simulant le stress dû au gel hivernal, calibré et validé pour le pois. Les résultats montrent une diminution global du stress gel qui résulte néanmoins d'un équilibre subtil entre une diminution de son intensité et une augmentation du nombre d'événements. L'évolution du stress dû au gel dépend du niveau de résistance et de la vitesse d'acclimatation des plantes et reste sensible aux fluctuations du climat hivernal. Ces travaux fournissent des informations pertinentes pour la sélection d'idéotypes culturaux performants pour minimiser les effets négatifs du changement climatique et offrir de nouvelles perspectives pour les cultures d'hiver en climat tempéré.

Mots clés : modélisation / rupture des températures / pois d'hiver / résistance au gel / Bourgogne Franche-Comté

1 Introduction

In temperate climate, winter crops are the majority and frost damage is an important factor reducing crop yields, especially in regions where winter is regularly severe (Whaley *et al.*, 2004; Biarnès *et al.*, 2016). Recent researches show a temperature abrupt shift around 1987/1988 over France (Brulebois *et al.*, 2015), Europe (de Laat and Crok, 2013; Reid *et al.*, 2016) and more generally over large scale (Reid and Beaugrand, 2012; Xiao *et al.*, 2012). This warming has affected the Burgundy-Franche-Comté winter climate conditions (Castel *et al.*, 2014; Richard *et al.*, 2014). The effects of winter climate change on crops is however underrepresented (Kreyling, 2010) compared to studies on crop-related climate impact research during spring and summer seasons

* Corresponding author: annabelle.larmure@agrosupdijon.fr

(Trnka *et al.*, 2014; Moore and Lobell, 2014). In particular the paradoxical increase in spring freezing injury (observed/simulated) with warming for cold climate vegetation (Ball *et al.*, 2012; Auspurger, 2013) should be documented for winter crops.

The response of crops to winter temperature under a warming climate is indeed complex and varied. The acclimation process allows a plant to get more resistant to frost. It requires sufficient low temperature during sufficient time (Kacperska-Palacz, 1978). The opposite process "deacclimation" occurs when temperature rises. The main plant characteristics determining the frost resistance of winter crops are the variety, being more or less resistant to frost and having different acclimation rates and the plant stage (Roberts, 1979). The main environmental factor determining the frost response is the temperature. These ecophysiological processes have been synthesized in a predicting crop model for frost resistance (Lecomte *et al.*, 2003).

Adaptation is essential for moderating the detrimental effects of climate change on winter crops. The net effect of warmer climate is to advance maturity of many crops (winter cauliflower: Wurr *et al.*, 2004; wheat: Gate *et al.*, 2008; grapevine: Duchêne and Schneider, 2009). For the perennial species grapevine, Duchêne and Schneider (2009) suggested to anticipate the change in aromatic profiles of wines that could result from long term increasing temperatures. For wheat a major annual cereal crop, Gate *et al.* (2008) suggested that warmer winter will badly cripple frost sensitive varieties because of their low ability to acclimate. Without adaptation, Moore and Lobell (2014) predict for cooler regions in central France a decline in the agriculture production due to warming. Clearly, the adaptation options as suggested by Trnka *et al.* (2016) need the development of region-specific strategies.

The Burgundy-Franche-Comté region in France and the pea (*Pisum sativum* L.) are relevant models to identify levers of crop adaptation to winter frost with warming. Burgundy-Franche-Comté ranked among the main and largest farming regions in France. This region has recently encouraged agri-environmental practices including legume crops in cropping systems (Duc *et al.*, 2010). Pea is an important annual legume crop grown in temperate regions for its high seed protein concentration. It leads to environmental benefits thanks to its capacity to acquire nitrogen *via* atmospheric N_2 symbiotic fixation (Jensen and Hauggaard-Nielsen, 2003; Nemecek *et al.*, 2008), nevertheless it is particularly sensitive to abiotic stresses. By climate change, heat stress and drought are very detrimental to the yield, especially for spring pea (Brisson *et al.*, 2010; Vadez *et al.*, 2012). Breeders are now developing winter pea varieties, more likely to avoid these stresses occurring at the end of the crop cycle, because they flower earlier. However, the high level of frost risk in winter could limit the extent of peas even in a warming climate.

The aim of the paper is to analyze at regional scale the frost stress evolution for the winter pea crop to the abrupt warming observed in 1987/88 and the role of critical traits of the crop (representative of new pea varieties) in the sensitivity to frost. First, the warming for both minimum and maximum temperatures is assessed everywhere over Burgundy-Franche-Comté. After crop model validation, the study focuses on the analysis of the patterns of frost stress with time and their consequences for defining pea ideotypes. In the following sections, the main steps of the methodological approach are depicted and both interpolation method and characteristic of the frost model are detailed. The data records network and the physiography of the study area are also presented. Then performance of the spatial temperature interpolation and the validation of the frost model are evaluated. Finally, the results of the spatio-temporal evolution of the frost stress are showed and discussed.

2 Materials and methods

The evolution of pea frost stress with warming was determined by using a methodology described in Figure 1. The study was conducted in the eastern France over the Burgundy-Franche-Comté region (Fig. 2). Two types of *in situ* observed climate data (stations and grid) were used to feed a frost stress crop model parametrized for various genotypes of winter pea.

2.1 Climate observations and interpolation

The Burgundy-Franche-Comté region is located in eastern France and covers an area of about 48050 km^2. Land-use is mainly deciduous forests over the west part (*i.e.* Burgundy) and coniferous forests over the east part (*i.e.* Franche-Comté), pastures and croplands, superimposed on a rather complex terrain. Topography is chiefly characterized by two plains: the Paris Basin and the Saône plain. Low (the Morvan at Center West) and middle mountains (the Vosges, at North-East and Jura at East) are the first significant elevations encountered by mean westerly fluxes. As the Atlantic coast is located more than 500 km further west, semi-continental conditions prevail. Furthermore, topographical geometry favour meridional southerly fluxes. Those originating from the Mediterranean Sea are channelled along the Rhône and Saône valleys, between the Massif Central and the Alps, and further north between the Morvan and the Jura. Those originating from North or Central Europe are also channelled. Then, strong daily temperature variability is a feature of this climate. Stable atmospheric conditions often lead to thermal inversion with cold temperature over the plain that host crops and pastures. Even if the region offers good potential (soil, farmer practices, and economic opportunities) for the cultivation of peas, the winter climate is a major constraint that limits its development.

We used the daily surface temperature recorded by Météo-France over Burgundy-Franche-Comté since 1961. Daily maximal and minimal temperatures (October–March) were recorded by the Météo-France Station Network (MFSN) from 1961 to 2015 in order to analyse the impact of autumn and winter surface temperature warming at regional scale. The obtained dataset, with more than one hundred stations (among there thirty complete), permitted to accurately assess the temperature patterns at a daily time step. For this latter a spatial interpolation method that jointly uses the daily spatial autocorrelation of the temperature and their spatial correlation with both geographical (latitude and longitude) and environmental (relief) variables was used.

The values were interpolated on a 12-km grid, to obtain surfacic continuous information. For the day of interest all the available stations were used. An automated mapping based on a kriging with external drift (KED) method was used to interpolate both maximal and minimal temperatures (Fig. 1).

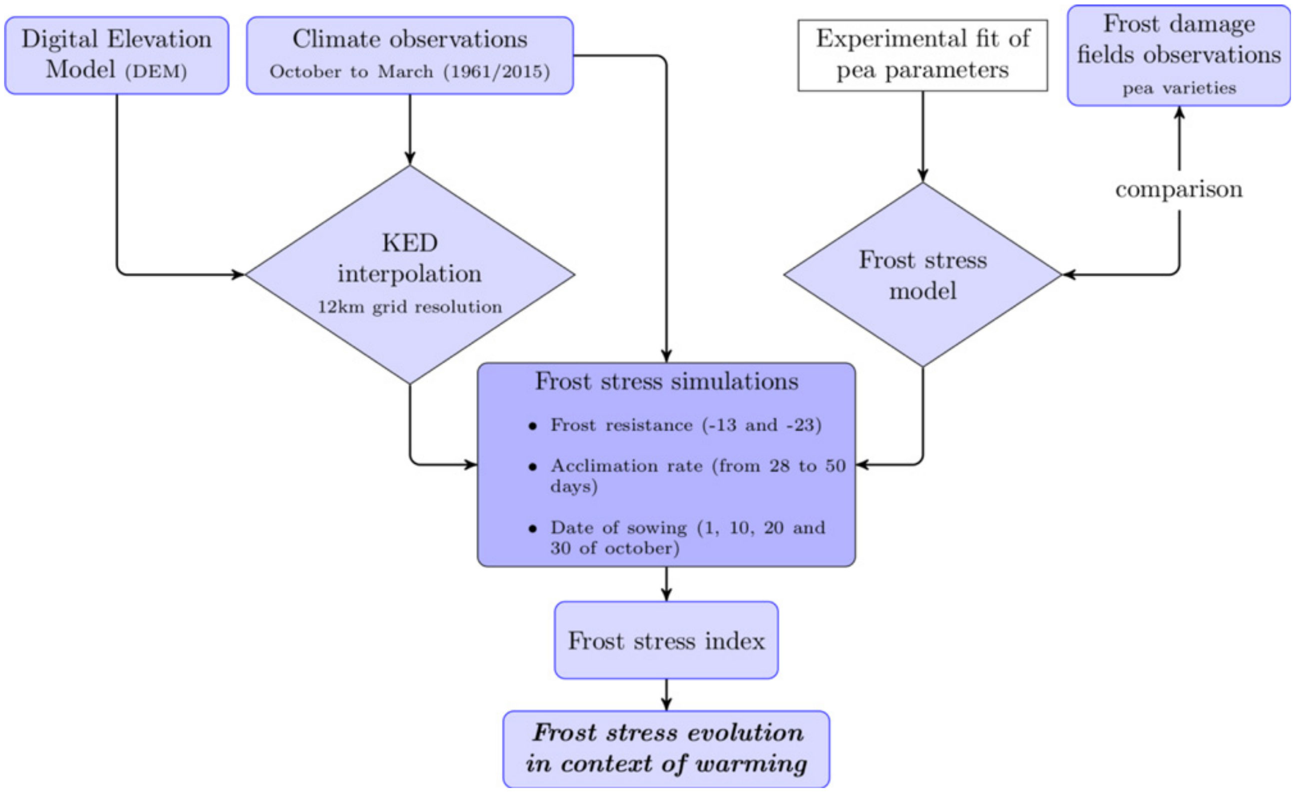

Fig. 1. Flow chart providing an overview of the methodological steps implemented in the framework of this study. The chart consists of two interrelated sections, pointing out for (right) parametrization and assessment of the frost stress model for winter pea crop and (left) daily climate data interpolation at 12-km-grid resolution from 1961 to 2015. KED is the kriging with external drift method which is similar to regression kriging (Hengl *et al.*, 2007). An automated interpolation based on the AUTOMAP R packages (R Core Team, 2016; Hiemstra *et al.*, 2009) has been used in this study.

The main advantage of KED is the ability to take into account trends present in the data (Lloyd, 2011). We choose the grid size of 12-km because the mean distance between stations is close (around 14 km). Note that for further studies it matches with the grid size of regional climate simulation (*e.g.* Boulard *et al.*, 2015). For each grid the longitude, latitude and height from Digital Elevation Model (DEM) were used as the first order external drift predictors (Fig. 1). We assume that the residuals are second order stationary with a constant mean and that the covariance is only determined by the distance vector, *i.e.* the lag. More details on the automatic variogram fitting may be found in Hiemstra *et al.* (2009). A station–gridpoint comparison was performed at seasonal scale to assess the quality of the interpolated data. The stations with less than 10% of missing data over the 1961–2015 period were compared with their nearest-neighbouring points. While all stations available each day were used in the interpolation process. Completed daily stations and gridded (interpolated) data were used to feed a parametrized winter frost stress model for pea crop.

2.2 Frost stress crop model and pea parameters

The crop model simulates a frost stress index for various combinations of the main traits of the pea crop, following the approach that was successfully implemented by Lecomte *et al.* (2003) for winter wheat. The main parameters of the crop model account for both varietal (frost resistance, acclimation rate and development stage) and cultural (date of sowing) pea traits. The model uses the minimum and maximum surface temperatures as input data.

Model parameters were estimated for pea from field experimental data collected in the INRA station Chaux-des-Près (located by the red cross in Fig. 2). This station is located at 879 m altitude in the Jura mountains, near the cold pole in France (see Lecomte *et al.*, 2003 for further description). The harsh conditions in this station make possible to observe regular frost damage on crops. The model makes it possible to calculate different frost stress criteria as the number of days with minimal temperature under the calculated resistance, the maximal difference between minimal temperature and resistance and the cumulative degree-days below the resistance value (frost stress index: see below).

The pea crop model was evaluated by a comparison of simulated frost stress indexes to observed frost damages in field (Fig. 1). The aim of this evaluation was firstly to validate the model and secondly to test if the frost stress index could be relevant to represent crop frost damage. The observed data were recorded over an experimental network of 13 trials over 4 years (2001, 2002, 2003 and 2005), 5 locations in France (Clermont-Ferrand, Colmar, Dijon, Lusignan and Mons) and for two varieties corresponding to two frost resistance traits (Térèse -8 °C and Champagne -23 °C). The observed frost damage is evaluated on a pea crop with a note from 0 (no damage) to 5 (death of all plants).

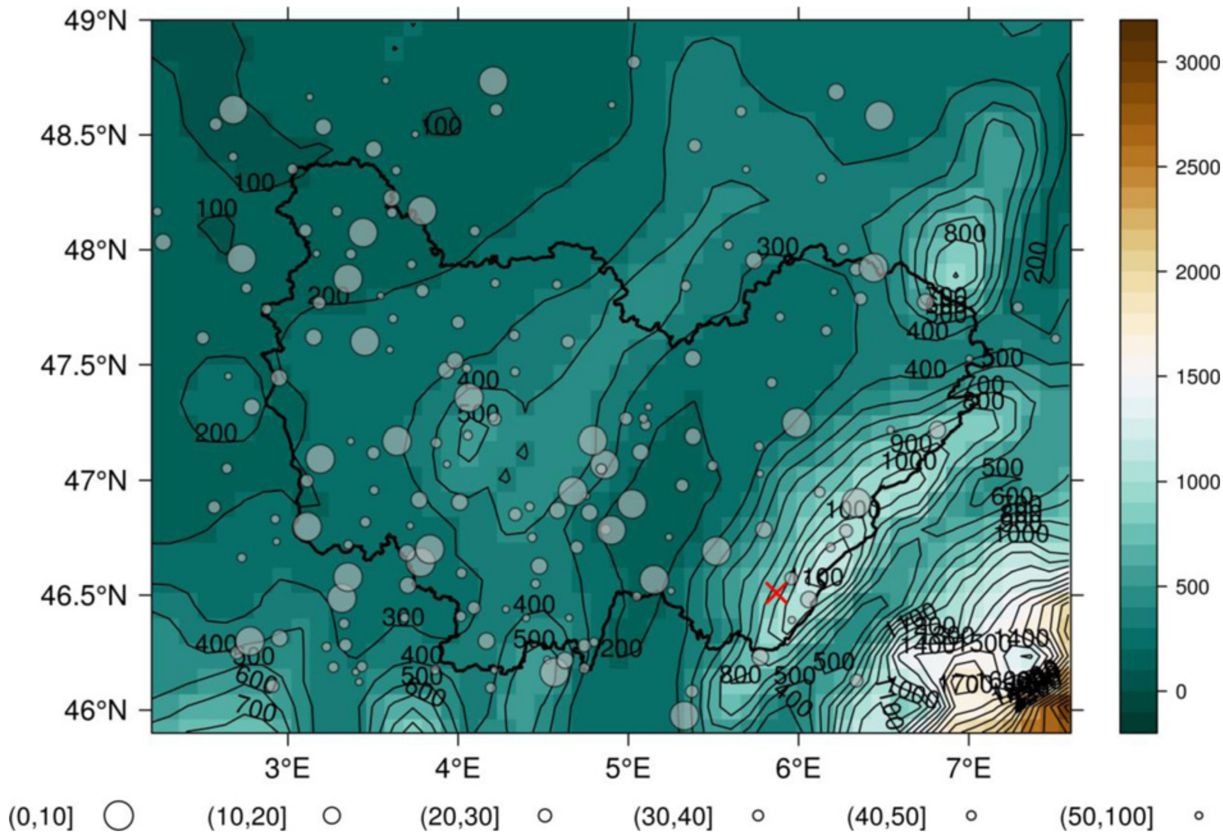

Fig. 2. Relief map of the Burgundy-Franche-Comté region (BLACK bold line) and location of the Météo-France climate stations (grey circles) used for both daily spatial interpolation of temperatures and computation of frost stress level. Note that the circle size is reversely proportional to the missing data in the climate series. Red cross corresponds to the pea crop experimental site located at Chaux-des-Prés. Altitude is given in metres above sea level. Elevated areas in the South-East of the map correspond to the Alps mountains.

This study focuses on three main parameters of the pea crop: (1) two frost stress resistance level (−13 °C and −23 °C), (2) twelve rates of acclimation (from 28 to 50 days) and (3) four dates of sowing during October (1, 10, 20 and 30) (Fig. 1). That corresponds to the simulation of 96 combinations computed for each year and each grid or station. All 12-km grids and stations with less than 10% of missing data were used to simulate frost stress index (Fig. 2). The simulated frost stress index was computed for autumn-winter period (principles depicted in Castel *et al.*, 2014). This computed frost stress index corresponds to the simulated cumulative sum of the degree-day of frost stress during winter.

3 Results and discussion

3.1 Temperatures interpolation

Figure 3 shows the inter-annual variability of the autumn-winter average temperatures (T_{min} and T_{max}) in Burgundy-Franche-Comté. Outliers points of systematic lowest temperatures (T_{min} or T_{max}) correspond to the coldest climate of the Jura and the Morvan mountains. These areas are less suitable for crop and are dedicated to grassland and forests. Very few cases of outlier points of highest temperatures (for T_{min} or T_{max}) are observed.

The results show an abrupt temperature warming in 1987/1988 with a warmer average temperature (+1.3 °C on T_{max} and +1.1 °C on T_{min}) from 1988 to 2014 than from 1961 to 1987. These results support recent works (Richard *et al.*, 2014; Brulebois *et al.*, 2015) conducted over Burgundy and France as well as over Europe (Reid *et al.*, 2016) and global scale (Reid and Beaugrand, 2012; Xiao *et al.*, 2012) that show an abrupt warming in 1987/1988. Our results show a higher warming for T_{max} than for T_{min}. This is a bit surprising because it is expected that greenhouse effect should lead to a stronger increase of the T_{min} (Lobell *et al.*, 2007).

The interpolated temperature data show very good performance and account for more than 94% and 98% of the observed inter-annual and spatial temperatures total variation (Tab. 1). The root mean squared error of prediction (RMSEP) is about 0.5 °C with an overall small absolute bias of 0.38 °C. As expected the 12-km resolution grid support of the interpolated data show lower amplitude and variability in the temperature indicating the difficulty to capture the local climate environment of the stations.

3.2 Frost stress simulation performance

The performance of the frost stress model is depicted in Figure 4. The experimental network for the crop model evaluation led to the largest possible range of frost damage note (from 0 to 5). The results show a good correlation between the frost stress index simulated by the model and the observed note of frost damage (coefficient of determination $R^2 = 0.76$, Fig. 4).

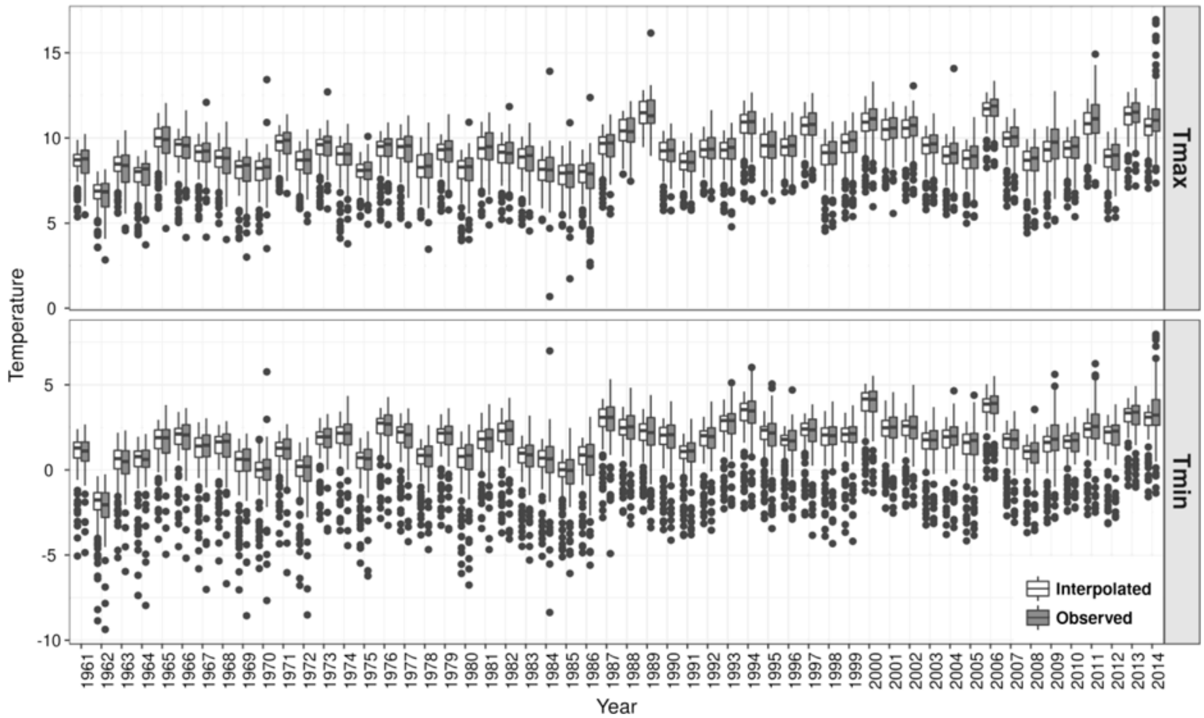

Fig. 3. Inter-annual boxplot of the October to March average minimal and maximal temperature in Burgundy-Franche-Comté for observed (station scale) and interpolated *i* (grid-scale) data. Each dot is the average T_{min} or T_{max} temperature of a station (observed) or its nearest grid point (interpolated). The dark bold line in the boxplot is the median. The two 'hinges' of the box are the first (Q1) and third quartile (Q3). The upper whisker is equal to: min(max(x), Q3 + 1.5 × IQR); the lower whisker is equal to: max(min(x), Q1 − 1.5 × IQR) where IQR is the inter quartile range equal to: Q3 − Q1, *i.e.* the box length. A point corresponds to an outlier which is defined as a data point that is located outside the fences ("whiskers") of the boxplot (*e.g.* outside 1.5 times the IQR range above the upper quartile and bellow the lower quartile).

Table 1. Summary of the statistics of the intercomparison performance between observed and interpolated climate data and frost stress simulations. R^2 is the coefficient of variation; RMSE is the root mean squared error; MAE is the mean absolute error; MBE is the mean bias error.

Variable	Temporal R^2	Spatial R^2	RMSE	MAE	MBE
Temperature	0.94	0.98	0.54	0.38	−0.14
Frost stress	0.88	0.89	13.22	6.52	−2.87

A non-linear relationship is clearly observed with the maximal damage level that is reached above the 90 cumulative degree-day of the frost stress index. A frost damage level of 5 indicates irreversible damage and the death of the plant. Up to 2, the frost damages are moderated while for levels of 3 and 4 the damages are severe. Hence, the simulated frost index (cumulative sum of the degree-day of frost stress) provides a relevant proxy for the observed frost damage. Thereafter we present and discuss the spatial and temporal frost damage evolution through the simulated frost stress index.

3.3 Evolution of the frost stress

The evolution of the frost stress follows the inter-annual variability of the surface temperatures. The simulation results show, for a pea variety with a frost resistance level of −13 °C that large outliers values (representing major frost stress of more than 300 °C) are observed until years 1987/1988 (Fig. 5). Whilst since 1988 the inter-annual variability of the frost stress index is clearly damped with lower outliers and median values (Fig. 5). This is an agreement with the abrupt temperature change observed at this date by recent studies (Richard *et al.*, 2014; Brulebois *et al.*, 2015; Reid *et al.*, 2016) which for the west part of Europe correspond to the 'start' of the surface warming. Similar results are observed when frost stress is derived from station or gridded climate data (Tab. 1) for both temporal (Fig. 5) and spatial patterns (not shown). Frost grid-based stress is however smoothed compared to station-based that may be attributed – as pointed in Figure 3 – to the capability of the gridded data to account for local climate conditions. Despite slight biases (Tab. 1), grid-based frost stress estimates is able to satisfactorily reproduce for various frost resistance levels the patterns of the pea frost stress. Consequently, grid-based frost estimates were used to simulate the evolution of pea frost stress with climate warming from 1961 to 2014.

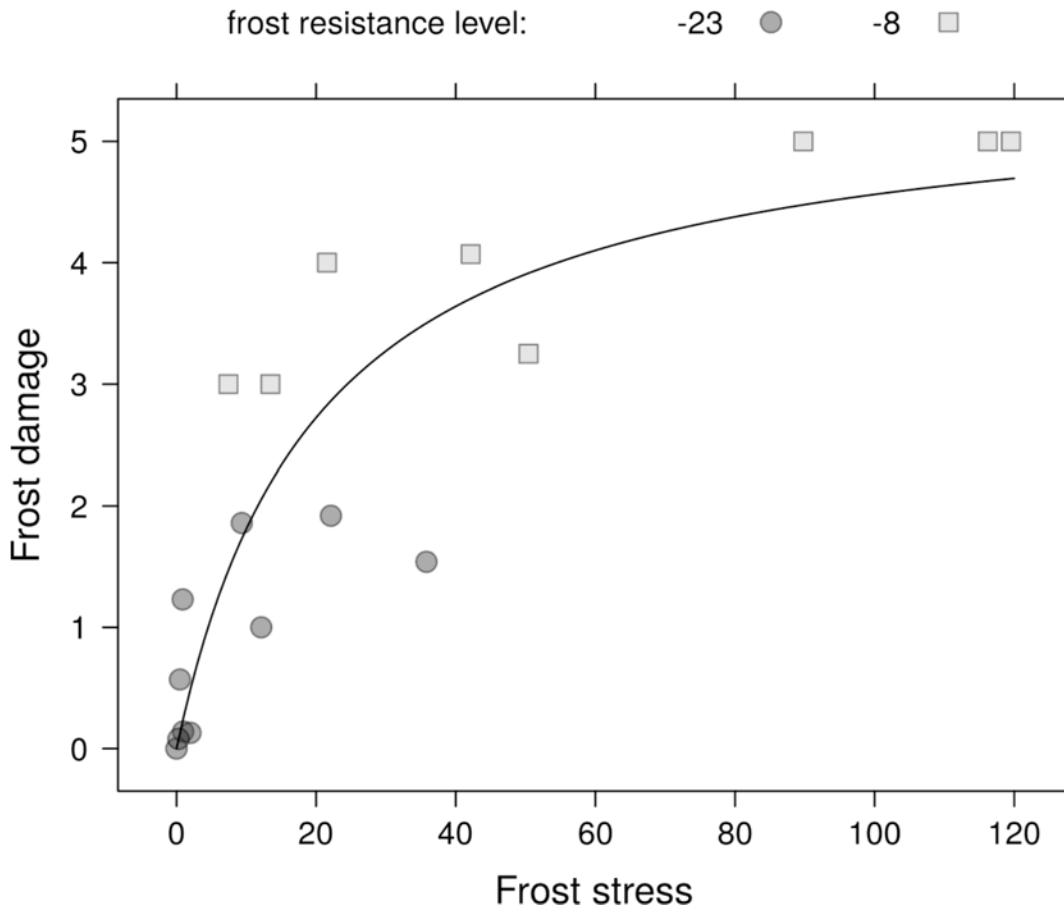

Fig. 4. Cumulative sum of the degree-day of frost stress *vs.* observed levels of frost damages for two varieties of pea (Champagne and Térèse). Frost damages are recorded over 13 experimental trials. The equation of the fitted model is: Frost damage = $a \times$ Frost stress/(b + Frost stress) with $a = 5.48$ and $b = 20.3$. The R^2 of the adjustment is 0.76.

3.4 Climate warming impact on the frost stress patterns

Figure 6 presents the probability density distribution of the frost stress index for both −13 °C and −23 °C levels of frost resistance as a function of the climate periods delimited by the 1987/1988 abrupt temperature shift. As expected a systematic decrease of the frost stress is observed between the two periods. The median values of the stress as well as the outliers are concerned by this trend. The range (distance between the first and the third quartile) of the stress level and the spread of the outliers are significantly reduced jointly with the median (mean) frost stress (results not shown). Hence, the median values of the frost stress reduce from 23 °C to 15 °C and from 2.1 °C to 1.9 °C for the −13 °C and −23 °C stress resistance varieties respectively. This demonstrates that the observed warming and its modalities that take place during the last 55 years have significantly impacted the occurring frost stress risk. Figure 6 shows that the significant decrease of the mean frost stress index mask an opposite and subtle changes. The decrease appears mainly driven by the collapse of the extreme values frost stress and consequently of the mean frost stress intensity. The results for the −13 °C frost resistance variety illustrate very well this behavior. On another hand, the density distributions show the increase of the probability that a frost stress event up to ~27 °C occurs. This suggests as quoted by Castel *et al.* (2014) an increase in the average number of frost stress events with climate warming. However, this increase does not balance the frost stress intensity decrease leading globally to a lower mean value of the frost stress index.

If the clear and large decrease of the average frost stress is attributable to the significant warming of both $T_{\min}$ and $T_{\max}$, the significant increase of the numbers of frost events partially supports the ‘paradoxical’ increase in freezing injury in a warming climate (Ball *et al.*, 2012). This ‘paradox’ has been documented for spring frost stress over forest (Auspurger, 2013; Rigby and Porporato, 2008; Rammig *et al.*, 2010) and wheat crop (Gu *et al.*, 2008; Zheng *et al.*, 2015) but to our knowledge few results concern winter frost stress over forest (Hänninen, 2006) and crops. Spring frost impact is for wheat attributable to the more rapid advance in development of crops to sensitive stages than the advance in last frost date (Zheng *et al.*, 2015). Whereas, winter observed and/or simulated frost damage are consistent with the role of temperature in mediating the acclimation/deacclimation process (Kalberer *et al.*, 2006; Pagter and Arora, 2013). This key process to acquire the frost resistance is modulated by acclimation rate (Rammig *et al.*, 2010) and date of sowing (Zheng *et al.*, 2012). Warmer surface temperature in winter causes decreases in both extent and duration of freezing tolerance. It may explain the

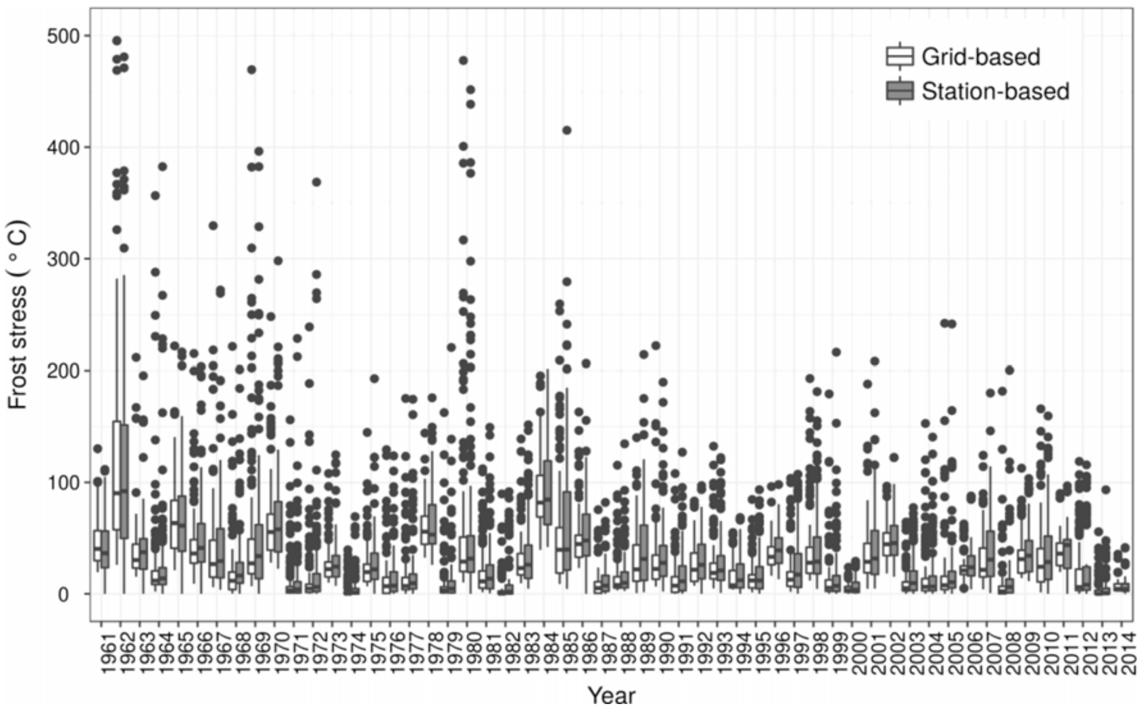

Fig. 5. Boxplot of the inter-annual frost stress index computed from observed (station) and interpolated (grid) climate data. The index is expressed as the cumulative sum of the degree-day of frost stress. The simulations concern the winter pea variety with a frost level resistance of −13 °C. A point corresponds to the results of one station (grid), one date of sowing and one rate of acclimation.

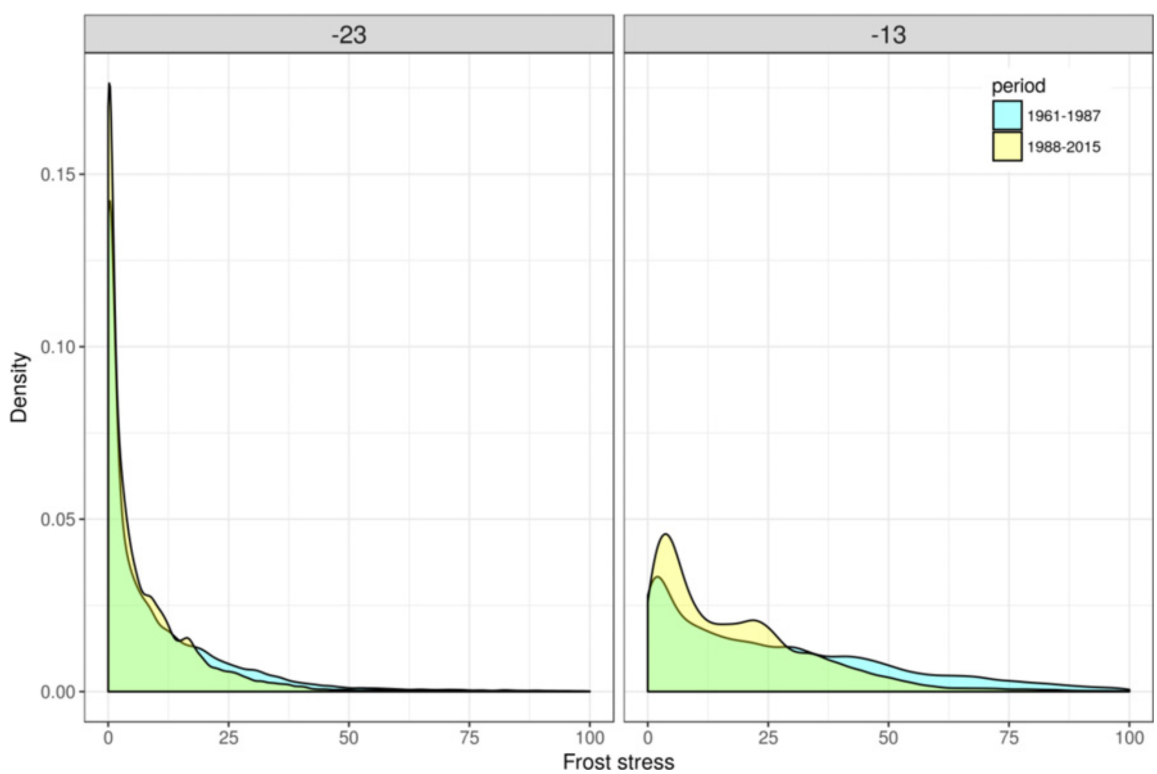

Fig. 6. Frost stress distribution before and after the 1987/1988 temperature shift and for the two stress resistance traits −13 °C and −23 °C and for all dates of sowing, for rates of acclimation. Green area corresponds to the common area of the two distributions. Cyan color indicates higher probability that frost stress index occurs during period 1961–1987 while for the yellow color it is the reverse. As the frost stress distributions are zero-inflated and left heavy-tailed, a robust Bayesian estimation following the method described in Kruschke (2013) is use to test the difference. The 95% Highest Density Interval (HDI) is a useful summary of where the bulk of the most credible values falls. When the difference is significant means that the 95% HDI interval does not include zero (no difference between periods).

Dossier

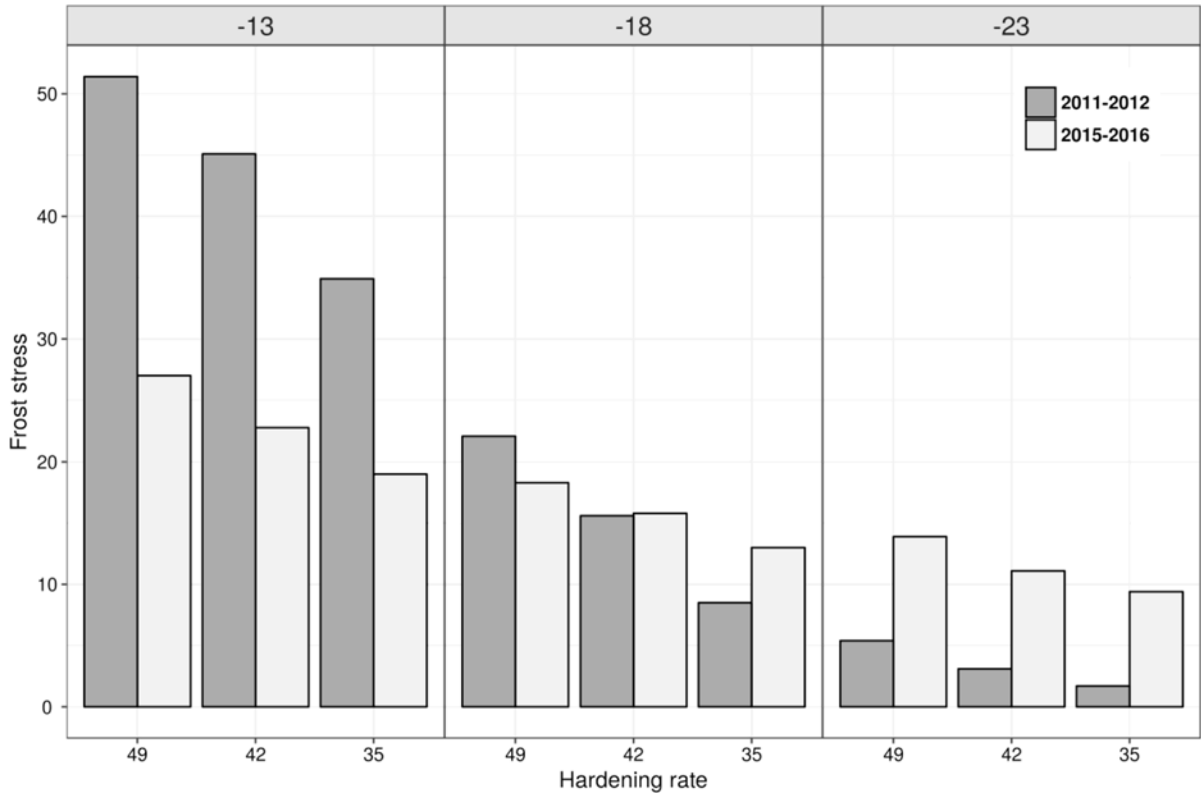

Fig. 7. Simulated frost stress index as a function of both frost resistance (−13 °C, −18 °C and −23 °C) levels and acclimation rates (35, 42 and 49 days) for 2011–2012 and 2015–2016 winters. The computation is conducted for Dijon place. The winter T_{min} and T_{max} showed contrasted fluctuations during January and February 2012 with an intense cold period of three consecutive weeks (observed minimal T_{min} of −15.7 °C the 5th of February) subsequent to a relative long warm period. Winter 2015–2016 experimented a minimal T_{min} of −9 °C the 24th of November 2015 with less fluctuations than winter 2011–2012. Note that the date of sowing is fixed the 25th of October.

increasing frost stress risk despite less extreme minimal temperature that reminds the seminal results of Cannell and Smith (1986). That is illustrated in Figure 7 for two recent winters (2011–2012 and 2015–2016) with relatively 'warm' mean temperatures (Fig. 3) and contrasted lower minimal temperature over the experimental site of −15.7 °C and −9 °C respectively. For the winter 2011–2012 simulated frost stress reaches up to 50 °C which is consistent with the catastrophic frost damage observed for in particular the winter wheat and pea crops over the Centre- and North-East part of France. The warm first part of the winter notably affects the acclimation process especially for the varieties with a long acclimation rate and low frost resistance level.

Hence the arising of a subsequent period in the first three weeks during February with minimal temperatures below −10 °C over the plain has caused irreversible frost injury to the crops. The results show that the plants were unable (slower or no accumulation of resistance) to reach their frost resistance level which increased their vulnerability. The effects of the abrupt temperature fluctuation reveal that both resistance level and acclimation rate are the main determinants of the frost crop damage. By contrast, with no abrupt change the temperature variance (not the mean – Rigby and Porporato, 2008) is for the winter 2015–2016 the strongest determinant of the frost damage that is supported by low difference as a function of crop traits. The results highlight the delicate balance of frost risk for crop in winter.

3.5 Spatial patterns of the changes of the frost stress

It is expected that the balance of frost risk is also related to the geography. The spatial pattern of the difference of the mean frost stress index between the two periods (Fig. 8) shows contrasted evolution as a function in particular of the physiography of the area. The correlation between the relief and the amplitude of the decrease of the frost stress index is observed. The highest part of the Jura mountains experienced the largest change in the frost stress reduction with a decrease (white area) larger than −50 °C. Best soil types for crops as the Saone plain (flat areas at low altitude with substantial proportion of deep and rich soil) show lower decreases with non homogeneous spatial patterns. The amplitude of the changes are here − as pointed above − related to the spatial patterns of minimum temperature (Zheng et al., 2015) with the occurrence of recurrent thermal inversions that favor the frost stress events in important cropping areas. High levels of both tolerance and acclimation rate seem required to best benefit to the winter crops (Rammig et al., 2010; Thorsen and Höglind, 2010). To this aim breeding for better frost tolerance is required. For these latter if frost level resistance is of primary importance, the rate of acclimation matters too (Fig. 8). Frost stress level decreases systematically with lower rate of acclimation whatever the frost resistance level (Fig. 8). The range of the acclimation rate effect is clearly frost resistance dependent. A relevant modelling at high spatial resolution of

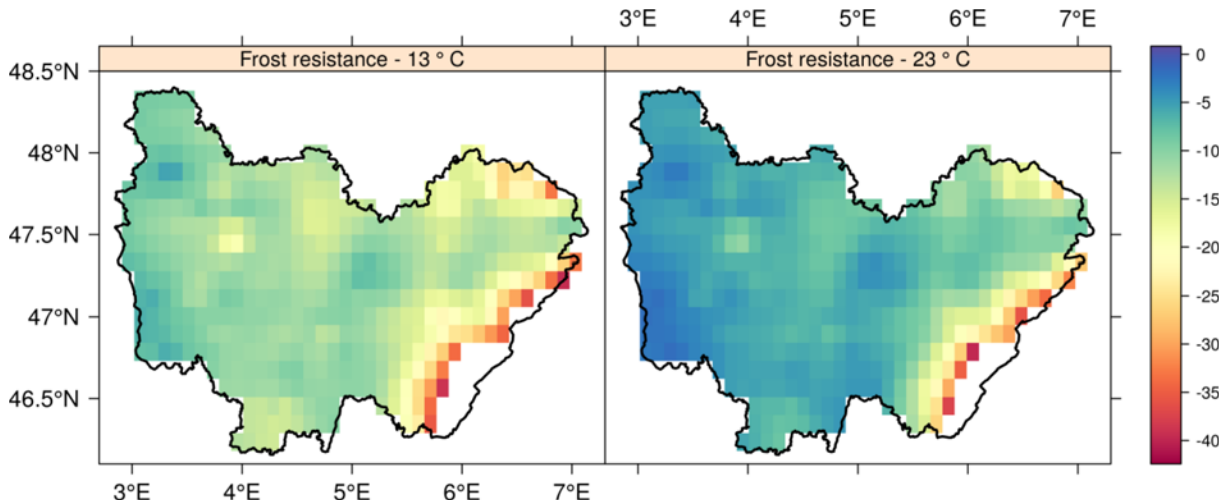

Fig. 8. Map of the difference between the average frost stress of each period (1988–2015 minus 1961–1987). White grids indicate that the difference is more than −50 °C which mainly correspond to the Jura and to a lesser extent to the Southern Vosges mountains.

daily climate change and more robust mimics of the acclimation/de-acclimation processes for crop are needed to account for both warming patterns (abrupt fluctuations, variance, geography) and pea traits (frost resistance level, acclimation rate, date of sowing) (Rammig *et al.*, 2010; Pagter and Arora, 2013).

4 Conclusion

Our results illustrate that the patterns of response of the winter pea crop to the observed winter warming are complicated by the dependence of the frost stress to a subtle balance between the crop traits and the spatio-temporal climate patterns. Our study takes advantage of more than thirty stations complete temperature records from 1961 to 2015, combined with supplementary stations with incomplete records along the same period. This permitted to produce daily map of minimum and maximum daily temperature for the whole period at 12-km resolution that reflected climate fluctuation in a realistic way for the Burgundy-Franche-Comté region in France. However, the 12-km grid resolution does not avoid the smoothing of extremes temperature that reduces the frost stress variability. The account of non-linear responses of physiological processes to warmer climate conditions observed since 1988 including extremes also enables realistic simulation of the frost stress. The frost index simulated by the crop model appears as a relevant proxy of the observed frost damage. The results from both observed and interpolated climate data are very similar. They show a significant decrease of the frost stress since 1988. This decrease hides the opposite trends of the frost stress intensity that is strongly reduced and the frost stress events which to a lesser extent significantly increase. The frost stress intensity changes clearly drive the whole decreasing trend. While subtle increase in the frost events support the 'paradoxical' increase in freezing injury in a warming climate that has been widely documented for spring and for the perennials vegetation such as forest (Hänninen, 1991, 2006; Rigby and Porporato, 2008; Ball *et al.*, 2012) in mid and high latitudes. The mechanisms of the spring frost increase is attributed to the hastening of bud burst that considerably increase the vulnerability to less extreme minimum temperature. By contrast, the winter frost damage is linked to the acclimation/deacclimation processes. In this case the exposure to the gradual appearance of the warmer low temperature results in delayed acclimation through slower accumulation of resistance (Woldendrop *et al.*, 2008) and decreases the frost resistance. Crop vulnerability seems also to be increased by mid-winter more frequent deacclimation to moderate elevation in temperature (~5 °C or less) in warmer climate (Kalberer *et al.*, 2006) and by the longer exposure of the crop to the fluctuating winter temperatures. The cases of 2011–2012 and 2015–2016 winters support the idea that far from alleviating the problem of frost due to higher average winter temperature, climate change may be limiting the productivity and the development of vegetal protein source from crop such as pea in cropping areas that offer great potential like the Burgundy-Franche-Comté region.

Finally, our results show that the account of the winter crop traits and the modalities of warming (geography, amplitude and temporal variability) jointly matter to better understand how winter climate warming will (i) affect change in frost risks evolution and (ii) reshape the climate areas leading to major changes in the agronomic potentialities. This is of primary importance to define new ideotypes with high level of frost resistance and short rate of acclimation to compensate the impact of projected warming. This necessarily implies better mimic of the climate variability at high temporal and spatial resolution. Both dynamical and/or statistical climate downscaling methods with new generation of crop stress models offer a promising way to regionalize abiotic stress for different radiative forcing trajectories.

Acknowledgements. Funds for this study were provided by the PSDR program INRA-Région Bourgogne (PROFILE and ProSys). This work was also supported by the Terres Inovia and Terres Univia-UNIP. We thank the CCUB cluster for the computations and the CRC team. We also thank the teams of the INRA Experimental Units in Dijon and Mons. The authors thank Météo-France, especially Annick Auffray and Denis Thévenin, who provided the temperature and precipitation data, as part of an agreement with the University of Burgundy.

References

Auspurger CK. 2013. Reconstructing patterns of temperature, phenology, and frost damage over 124 years: spring damage risk is increasing. *Ecology* 94 (1): 41–50.

Ball MC, Harris-Pascal D, Egerton JJG, Lenne T. 2012. The paradoxical increase in freezing injury in a warming climate: frost as a driver of change in cold climate vegetation. In: Storey KB, Tanino KK, eds. CABI (H ISBN 9781845938222), pp. 179–185 (chapter 12).

Biarnès V, Lecomte C, Lejeune I, Hascoët E. 2016. Pois d'hiver : la resistance au froid bientôt décryptée. *Perspect Agric* 436: 32–35.

Boulard D, Castel T, Camberlin P, *et al.* 2015. Capability of a regional climate model to simulate climate variables requested for water balance computation: a case study over northeastern France. *Clim Dyn* 46: 2689. DOI:10.1007/s00382-015-2724-9.

Brisson N, Gate P, Gouache D, Charmet G, Oury F-X, Huard F. 2010. Why are wheat yields stagnating in Europe ? A comprehensive data analysis for France. *Field Crops Res* 119 (1): 201–212.

Brulebois E, Castel T, Richard Y, Chateau-Smith C, Amiotte-Suchet P. 2015. Hydrological response to an abrupt shift in surface air temperature over France in 1987/88. *J Hydrol* 531 (3): 892–901. DOI:10.1016/j.jhydrol.2015.10.026.

Cannell MGR, Smith RI. 1986. Climatic warming, spring budburst and frost damage on trees. *J Appl Ecol* 23: 177–191.

Castel T, Lecomte C, Richard Y, Lejeune-Hénault I, Larmure A. 2014. Le réchauffement climatique diminue t-il le risque de dégâts de gel pour les cultures de climat tempéré ? Colloque AIC 2-5 juillet 2014, Dijon.

de Laat ATJ, Crok M. 2013. A late 20th century European climate shift: fingerprint of regional brightening ? *Atmos Clim Sci* 3: 291–300. DOI:10.4236/acs.2013.33031.

Duc G, Blancard S, Hénault C, *et al.* 2010. Potentiels et leviers pour développer la production et l'utilisation des protéagineux dans le cadre d'une agriculture durable en Bourgogne. *Innov Agron* 11: 157–173.

Duchêne E, Schneider C. 2009. Grapevine and climatic changes: a glance at the situation in Alsace. *Agron Sustain Dev* 25 (1): 93–99 <hal-00886271>.

Gate P, Blondlot A, Gouache D, Deudon O, Vignier L. 2008. Impacts du changement climatique sur la croissance et le développement du blé en France. *OCL* 15 (5): 332–336.

Gu L, Hanson PJ, Post WM, *et al.* 2008. The 2007 eastern us spring freeze: increased cold damage in a warming world ? *BioScience* 58: 253–262.

Hänninen H. 1991. Does climatic warming increase the risk of frost damage in northern trees ? *Plant Cell Environ* 14: 449–454. DOI:10.1111/j.1365-3040.1991.tb01514.x.

Hänninen H. 2006. Climate warming and the risk of frost damage to boreal forest trees: identification of critical ecophysiological traits. *Tree Physiol* 26: 889–898.

Hengl T, Heuvelink GBM, Rossiter DG. 2007. About regression-kriging: from equations to case studies. *Comput Geosci* 33 (10): 1301–1315.

Hiemstra PH, Pebesma EJ, Twenhöfel CJW, Heuvelink GBM. 2009. Real-time automatic interpolation of ambient gamma dose rates from the Dutch Radioactivity Monitoring Network. *Comput Geosci* 35: 1711–1721.

Jensen ES, Hauggaard-Nielsen H. 2003. How can increased use of biological N_2 fixation in agriculture benefit the environment ? *Plant Soil* 252: 177–186.

Kacperska-Palacz A. 1978. Mechanism of cold acclimation in herbaceous plants. In: Li PH, Sakai A, eds. Plant cold hardiness and freezing stress. Mechanisms and crop implications. Vol. 1. New York: Academic Press, pp. 261–272.

Kalberer SR, Wisniewski M, Arora R. 2006. Deacclimation and reacclimation of cold-hardy plants: current understanding and emerging concepts. *Plant Sci* 171: 3–16.

Kreyling J. 2010. Winter climate change: a critical factor for temperate vegetation performance. *Ecology* 91: 1939–1948. DOI:10.1890/09-1160.1.

Kruschke JK. 2013. Bayesian estimation supersedes the *t* test. *J Exp Psychol Gen* 142: 573–603.

Lecomte C, Giraud A, Aubert V. 2003. Testing a predicting model for frost resistance of winter wheat in natural conditions. *Agronomie* 23: 51–66.

Lloyd CD. 2011. Local models for spatial analysis. Boca Raton: CRC Press. http://www.crcpress.com/product/isbn/9781439829196.

Lobell DB, Bonfils C, Duffy PB. 2007. Climate change uncertainty for daily minimum and maximum temperatures: a model inter-comparison, *Geophys Res Lett* 34: L05715. DOI:10.1029/2006GL028726.

Moore FC, Lobell DB. 2014. Adaptation potential of European agriculture in response to climate change. *Nat Clim Change* 4 (7): 610–614.

Nemecek T, von Richthofen JS, Dubois G, Casta P, Charles R, Pahl H. 2008. Environmental impacts of introducing grain legumes into European crop rotations. *Eur J Agron* 28 (3): 380–393.

Pagter M, Arora R. 2013. Winter survival and deacclimation of perennials under warming climate: physiological perspectives. *Physiol Plant* 147: 75–87.

R Core Team. 2016. R: a language and environment for statistical computing. Vienna, Austria: R Foundation for Statistical Computing. URL: https://www.R-project.org/.

Rammig A, Jonsson AM, Hickler T, Smith B, Barring L, Sykes M. 2010. Impacts of changing frost regimes on Swedish forests: incorporating cold hardiness in a regional ecosystem model. *Ecol Model* 221: 303–313.

Reid PC, Beaugrand G. 2012. Global synchrony of an accelerating rise in sea surface temperature. *J Mar Biol Assoc.* 92 (7): 1435–1450. DOI:10.1017/S0025315412000549.

Reid PC, Hari RE, Beaugrand G, *et al.* 2016. Global impacts of the 1980s regime shift. *Glob Change Biol* 22: 682–703. DOI:10.1111/gcb.13106.

Richard Y, Castel T, Bois B, *et al.* 2014. Évolution des températures observées en Bourgogne (1961–2011). *Bourgogne Nat* 19: 110–117.

Rigby JR, Porporato A. 2008. Spring frost risk in a changing climate. *Geophys Res Lett* 35: L12703. DOI:10.1029/2008GL033955.

Roberts DWA. 1979. Duration of hardening and cold hardiness in winter wheat. *Can J Bot* 57: 1511–1517.

Thorsen SM, Höglind M. 2010. Modelling cold hardening and dehardening in timothy. Sensitivity analysis and Bayesian model comparison. *Agric For Meteorol* 150: 1529–1542.

Trnka M, Rötter RP, Ruiz-Ramos M, *et al.* 2014. Adverse weather conditions for European wheat production will become more frequent with climate change. *Nat Clim Change* 4: 637–643. DOI:10.1038/nclimate2242.

Trnka M, Hlavinka P, Semenov MA. 2016. Adaptation options for wheat in Europe will be limited by increased adverse weather events under climate change. *J R Soc Interface* 12 (112): 20150721. DOI:10.1098/rsif.2015.0721.

Vadez V, Berger J.D, Warkentin T, *et al.* 2012. Adaptation of grain legumes to climatic changes: a review. *Agron Sustain Dev* 32 (1): 31–44. DOI: 10.1007/s13593-011-0020-6.

Whaley JM, Kirby EJM, Spink JH, Foulkes MJ, Sparkes DL. 2004. Frost damage to winter wheat in the UK: the effect of plant population density. *Eur J Agron* 21 (1): 105–115.

Woldendrop G, Hill MJ, Doran R, Ball MC. 2008. Frost in a future climate: modelling interactive effects of warmer temperatures and rising atmospheric [CO_2] on the incidence and severity of frost damage in a temperate evergreen (*Eucalyptus pauciflora*). *Glob Change Biol* 14: 294–308.

Wurr DCE, Fellows JR, Fuller MP. 2004. Simulated effects of climate change on the production pattern of winter cauliflower in the UK. *Sci Horticult* 101 (4): 359–372.

Xiao D, Li J, Zhao P. 2012. Four-dimensional structures and physical process of the decadal abrupt changes of the northern extratropical ocean–atmosphere system in the 1980s. *Int J Climatol* 32: 983–994. DOI:10.1002/joc.2326.

Zheng BY, Chenu K, Dreccer MF, Chapman SC. 2012. Breeding for the future: what are the potential impacts of future frost and heat events on sowing and flowering time requirements for Australian bread wheat (*Triticum aestivum*) varieties ? *Glob Change Biol* 18: 2899–2914.

Zheng B, Chapman SC, Christopher JT, Frederiks TM, Chenu K. 2015. Frost trends and their estimated impact on yield in the Australian wheatbelt. *J Exp Bot* 66 (12): 3611–3623. DOI:10.1093/jxb/erv163.

Dossier

Cite this article as: Castel T, Lecomte C, Richard Y, Lejeune-Hénaut I, Larmure A. 2017. Frost stress evolution and winter pea ideotype in the context of climate warming at a regional scale. *OCL*, 2017, 24(1) D106.