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Assessments of current and future suitability of heat conditions for apple growing in Norway

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SAMMENDRAG/SUMMARY:

The commercial apple production in Norway is limited to the small regions along the fjord areas in the southwest part of the country and around lakes or near the sea in the southeast part with favorable climate. Due to the rapid rate of climate change over the recent decades, it is expected that suitable heat conditions for apple growing will expand to the areas that previously were too cold. This study analyses the heat suitability of past, present and future climate for six commercial apple varieties in Norway (Discovery, Gravenstein, Summerred, Aroma, Rubinstep, and Elstar). The methodology for identifying favorable heat conditions is developed using meteorological and phenological observations from the Ullensvang orchards and applied on a high-resolution gridded datasets of temperature observations and climate projections. The assessment indicates that with increasing temperatures, heat conditions suitable for cultivation all six apple varieties are expanding. The surfaces with favorable heat conditions for less heat-demanding varieties increased threefold over the last 60 years. In the period 2011-2020, heat suitable climate for cultivating at least one of the considered apple varieties is found at 15% of the analyzed territory, while 2.5% was suitable for growing all six varieties. In the future, the favorable areas will advance from south and southeast northwards and inland in the eastern region, along the west and northwestern coastline towards higher latitudes, and along continental parts of fjords. The fastest expansion of heat suitable conditions is expected for less heat-demanding varieties. The findings of this study show an increasing potential for apple production in Norway that are relevant for strategical planning of climate change adaptation measures within the sector. Weather related risks, such as the risk from damaging low temperatures, drought and extreme precipitation were not considered.

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Preface

The fruit production in Norway is in the south part of the country having the most favorable climate. The main locations are along the fjord areas in the southwest part of the country and around lakes or near the sea in the southeast part of the country. Due to a short and relatively cool growing season in Norway, the commercial fruit production is limited to grow the fruit species apple, pear, European plum and sweet cherry. For sweet cherry, the same cultivars as in the rest of the world can be grown, developing large yields of good quality. However, for the three other crops and especially apple and pear only early season cultivars in countries further south can be managed properly and give good quality fruits.

Climate change giving higher temperatures and longer growing seasons have some positive sides from the agronomic view. This study is focused on processing phenological data for six apple varieties from NIBIO Ullensvang orchards, western Norway. Weather and climate conditions under which they are cultivated are represented with data from NIBIO Ullensvang meteorological station. Collected phenological data are for the period 2003-2020. Derived thresholds for heat conditions, required for growing of those cultivars, are applied over the southern part of Norway, to assess spatial distribution of favorable heat conditions for apple growing. Their change under climate changing conditions was also assessed and discussed.

The main goal of this study was to investigate the relationship between climate and phenology parameters on growth and development of Norwegian apple cultivars. The overall aim is the increase the production based on Norwegian grown apples of high quality.

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Lofthus, 07.08.23

Mekjell Meland

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1 Introduction

Apple (*Malus domestica* Borkh.) originated from the central Asia and it travelled a long journey, along the Old Silk Roads, to reach fertile soils of Europe and North America. It is one of the most important temperate fruit species, being second fruit grown worldwide (after bananas). Its production is ~93 million tons, where China produces ~46 million tons (49% of world production). An estimated economic value of apple production is over $47 billion (FaoStat, 2023). Large gene pools, successful production in both northern and southern hemispheres, different appearance, pleasant aroma and taste, low prices, good transportability, less fruit deteriorating, and year-round storage are making apple one of the most popular snack fruits. Besides eating fresh, it can be used for making juice, food pastes, jellies, concentrate, marmalade, jams, compotes, tea, wine, dried fruits, cider and as well as other products (Patocka et al., 2020). Nutritional qualities, which depend on cultivar, rootstock, cultural and growth conditions, plant nutrition, storage and processing together with biotic and biotic stresses, especially during the maturation of the fruits are highly appreciated and so popular by consumers (Meike et al., 2022). The most important chemicals are carbohydrates, organic acids, minerals, phenolic compounds, vitamins, volatile organic compounds, dietary fibers, pectin, chlorophyll, and carotenoids (Delgado-Pelayo et al., 2014; Fotirić Akšić et al., 2020; Fotirić Akšić et al., 2022; Horvacki et al., 2022; Zhang et al., 2010). Seeds, waste from juice processing, have up to 27% of oils rich in fatty acids, carotenoids and tocopherols (Fotirić Akšić et al., 2021). Due to the high antioxidant activity apples are preventing cancers, cardiovascular diseases, asthma, Alzheimer’s disease, obesity and diabetes and improving gastrointestinal health and pulmonary function (Hyson, 2011; Hyun and Jang, 2016).

Due to the large number of bred cultivars, apple could be considered as very adaptable species. The largest area where apples are grown are limited to the latitude range of 25 to 52° N, so from Poland (with often winter freeze damage) to Egypt (inadequate winter chilling for fruit bud development), with Washington State, USA, on west, which production can be described with stress and fruit sunburn and in the East in Japan (Jackson, 2003). Due to the large quantity of oceans in the southern hemisphere, and their moderation of the climate, apple production is successfully done in South Africa, Brazil, Argentina, Chile, Australia and New Zealand. Of course, apples are grown beyond this range if the regions have favorable climate; heated with warm water masses (Norway) or cooled down in places with subtropical climate. Besides, using low chill cultivars, dormant breaking and deleafing chemicals can spread apple production further south. Regarding temperatures, the areal of apple growing is spreading from places with -40°C (Northern China and Siberia) up to subtropic and tropic regions of Indonesia and Columbia (near the equator) where two harvests are produced in a single year (Janick and Moore, 1996). According to Charles-Edwards (1982) the average means temperature decreases by 0.45 °C while the relative seasonal amplitude in temperature increases by 0.015 °C per degree of latitude per degree of latitude from 10 to 55°.

Temperature is the most important limiting factor for apple production. Late frosts in the spring and low temperatures in late autumn and winter are drawing the line where apple production can be organized. Apples can withstand temperatures up to -40°C, but in most cases the rootstock is the one that is killed with winter freezing. Due to the direction of hardiness process, the trunk is the last to get hardy. Flower buds and roots are more sensitive than shoots, and the cambial tissue more sensitive than the xylem tissue. Under natural conditions, twigs can survive to -38°C but even the hardiest rootstocks can only survive to -18°C (Potapov, 1999). The consequence of winter freezing is the darkening of the xylem, stem dieback, frost splitting of tree-trunks (winter sun-scald or south-west injury), and crown and root injury, together with coming pathogens, can kill the tree completely. Not only low temperatures in mid-winter can damage the tree, but also, mild temperatures in mid-winter followed with low temperatures can affect tree survival. Winter or spring low temperatures can kill dormant vegetative or flower buds which affect only yields of the coming crop. Besides this, many other physiological processes connected with the apple tree development depend on temperature. Flower bud initiation, flower time, leafing time, lateral shoot growth, lateral shoot numbers, number of leaves which develop on new shoots, fruit colour, harvest time, leaf senescence and abscission in autumn are in the function of temperature (Johnson and Lakso, 1985; Zhu et al., 1997; Curry, 1997). Apple flower development starts 2.5 days earlier per degree of lower latitude between 43 °N and 65 °N (Wagenmakers, 1991). According to Benmoussa et al., (2017) and Santos et al. (2018) two main thermal factors are influencing fruit development in temperate climatic regions, and those are chilling and forcing. After fulfilling a chilling period during winter, growth and development are driven by forcing. During spring forcing becomes stronger than chilling and tree starts to bloom. Of course, heat accumulation is needed for adequate blooming and fruit ripening (Rodriguez et al., 2020; Cho et al., 2021). At 12 °C flowering seems to be limited by low temperature depression of growth and leaf production, while at 27 °C, flowering is blocked by inhibition of the floral initiation itself. Intermediate temperatures of 18–21 °C, on the other hand, seem to satisfy the requirements for both processes (Heide et al., 2020). The apple net photosynthesis is optimal on temperatures between 15 °C and 30 °C, while a maximum is on the 20 °C (Lakso et al., 1999). Apple photosynthesis at 10 °C is 70–80% of the maximum at optimal temperature, while at 30 °C to 40 °C, it is near zero.

Besides temperature, rainfall is also very important ecological factor that directly influences apple production. Both excessive and lower rainfall is harmful to apple growth. Temperature and precipitation strongly influence physical and chemical reactions properties of the soil. Climate also determines a vegetation cover which in turn influences soil development. Precipitation also affects horizon development factors like the translocation of dissolved ions through the soil (Slingo, 2009). Under moderate drought, flower bud formation can often be reduced, but under severe drought this process can be fully inhibited. In contrast, if the apple trees are under the low, (45–55%) in contrast to high (80–100%), relative humidity nine weeks from full bloom, the differentiation of apple buds toward floral types is increasing from 12% to 54% (Tromp, 1984). Drought can cause a significant reduction and damage in photosynthesis and chlorophyll degradation (Bhusal et al., 2018). With large negative influence on apple physiological processes in case of drought, high rainfall increases the incidence of fungal diseases, especially apple scab, while cloudy cover is reducing the available solar radiation.

Climate change may impact agriculture/horticulture/livestock/fish and consequently food supply. Both agricultural as well as horticultural crops are under the direct and indirect effect of the global climate change (Arundhati and Bhagat, 2020). Since temperature is considered the most important atmospheric factor for crop phenological and physiological development, climate change is a major threat (Fraga and Santos, 2021). Climate change is likely to reduce productivity due to high temperatures during flowering and fruit growth, and fruit sunburn and cracking is likely to increase (Gitea et al., 2019; Fraga and Santos, 2021).

Climate change can lead to extreme weather events such as the occurrence of spring frosts, cold waves and frequent hailstorms, lack of sufficient chilling hours, lack of sufficient soil moisture, poor pollination, low yield, occurrence of new insect pests and diseases, altered blooming and harvesting time and bad impact on fruit quality (Arundhati and Bhagat, 2020). Temperature (with solar radiation) and precipitation are the major climatic factors affecting apple growth and yield (Pu et al. 2008; Fujisawa and Kobayashi 2011). Qu et al., (2013) showed that decreased winter temperatures, spring frosts, and high temperatures and aridity in summer and autumn are major meteorological factors limiting the growth of apple trees. Eccel et al. 2009 demonstrated that the flowering and maturity stages of apple are the most sensitive phenophases when climate changes have the biggest impact. On the other hand, Li et al. (2020) proved that temperature, wind speed, precipitation, evaporation, and active accumulated temperature, and especially in spring, had the highest effect on apple production.

Lately, a sharp decrease on overall precipitation especially during winters has been noticed (Jethi et al., 2016). Snowfall is considered important for climatologically and hydrological conditions because it maintain the soil radiation balance. Change in snowfall pattern alters the timing of bearing, blossoming of the apple, affecting fruit yield and quality (Vedwan and Rhoades, 2001). Decrease in snowfall (with shorter duration of snow cover) and rainfall and temperature increase are making that sufficient chilling hours are not met. This affects the flowering and fruit set. In the lights of climate change, if temperature rises 1 °C it will shorten the period of leaf appearance to ripening in apple trees by 2 days, but if it rises 3 °C it would shorten the vegetation for 4-5 days (Belliveau et al., 2007). The apple tree requires 1200-1500 hours of chilling below 7°C depending on the type of cultivar. Chilling hour less than 1000 leads to low yield with poor quality (Rai et al., 2015). A slight increase in temperature can reduce the chilling hours, which can delay the flowering or alter the flower bud differentiation (Verma, et al., 2016). All of this is indicating that higher altitudes, earlier unsuitable due to extreme cold conditions, are now becoming suitable for apple cultivation. Biodiversity shift has also been reported by Sugiura and Yokozawa (2004) predicting that the favorable regions to cultivate apples in Japan will gradually move northwards by 2060 due to the impact of global warming.

In some regions, earlier blooming and higher temperatures during maturation periods can also influence changes in taste and texture in some apple cultivars which can lower acid concentration and fruit firmness (Sugiura et al. 2013). Pan and Shü (2007) observed that a slight increase in day and night temperature may reduce the amounts of soluble sugars, amino acids, proteins and starch in apple. Finally, Sen et al. (2015) established that increase in the maximum temperature for January, February, March, October, December, minimum temperature for October and November and rainfall of November may cause reduction in the productivity. In the light of this, weather impacts both crop yield quantity and quality and thus a driving force of farm income volatility (Lesk et al., 2016).

In colder climates, the persistent temperature increase could create opportunities for cultivating new species or varieties in regions where it was previously impossible due to the limiting climatic factors (Hanssen-Bauer et al., 2017). Although Norway has a long tradition of apple growing, its commercial production is limited by insufficient heat during the vegetation period spanning from May to September (Røen, 1998).

The fjord areas of western Norway have a marinate climate, with relatively cool summers and mild winters. Western winds that are usually coming from the Atlantic Ocean are bringing clouds, rain, and wind throughout the year. Majority of the rainfall appears during the wintertime, mostly as rain. The growth period from May to September can be relatively dry and all orchards have trickle irrigation for supplying the trees with enough water during the and summer. Due to this maritime climate where orchards are located near to water not freezing over, the orchards rarely suffer from winter frost and blossom frost. The only problem is lower summer temperatures which are limiting the length of the vegetation season, large yields and good fruit quality. The production is mainly located in the municipalities (from southwest to south north) Hjelmeland, Ullensvang. Sogndal, Gloppen and Stryn). In southeast Norway, areas where fruit production is conducted have a more pronounced continental impacts on climate, with colder winters and warmer summers. Severe winter frost is possible and, when snow cover is absent it can damage or kill the trees or the rootstocks. From time-to-time spring frost during blossom time can happened especially during springs having early flowering. At the southeast side the main production is in the municipalities Midt-Telemark, Øvre Eiker, Lier and Drammen.

Average global surface air temperature for the period 2011–2020 was 1.1 °C higher compared to preindustrial times, and the trend of increase has accelerated since the 1980s (IPCC, 2021). The increase in the temperature is more pronounced over the northern hemisphere, and especially at the higher latitudes. Under global warming impact, heat conditions in Norway are becoming more favorable for development of diverse agricultural production, because of the expansion of growing season and increasing growing season temperature (Hanssen-Bauer et al., 2015). Relatively fast change of climate conditions requires improvement of knowledge on spatial distribution of areas where heat conditions become sufficient for growing of different cultivars.

Adaptation to climate change considers the implementation of actions specific to region and sector because of the different changes in frequency and intensity of climatic impact-drivers and other climate hazards, and their impacts (IPCC, 2022a). Actions are mainly designed to reduce risks from negative impacts of climate change, and to ensure the sustainability of the resilience to climate change under future climate change. In some areas climate change could provide an opportunity to expand agricultural production, if climate change and impacts are well studied and actions well planned.

In this study, change of the climate heat potential for apple growing in Norway has been assessed. The chosen indicator to assess this impact is the change in surface areas with favorable heat conditions for apple growing in the period of 1961–2020, and for the future periods until 2100, using high-resolution observed gridded datasets on temperature (observed and projected with multi-model ensemble).

To be able to approximately determine areas where the heat conditions are sufficient for growing of different cultivars, it is necessary to develop a relation between phenological development and heat conditions, usually expressed through developed bioclimatic indices which are generated using surface air temperature data (for example for Norway, Bhandari 2022). There are different approaches to determine heat conditions required for achieving different phenological stages, depending on the availability of data and required simplicity of methodology (easy to calculate). For example, some used calculation of chilling and heating units to include importance of the rest period for the growing season on-set, but also discuss on the large spans of the determined thresholds (Luedeling et al. 2011; Fadon et al., 2020; Ruiz and Campoy 2007; Djaman et al. 2021). In case of full set of observed data for some phenological stage is available for long term period, sums of active temperatures can be used to define average date of the on-set of each phenological stage (for example, Ruml et al. 2010, Ruml et al. 2011, Vukovic et al., 2022). Others, who are targeting ripening and harvest dates, simply accumulate active daily temperatures from fixed base temperature value (for example, Łysiak 2012 and 2022). In this study, considering availability of phenological data and the final goal (determining lower thresholds for favorable heat conditions for apple growing), chosen methodology is based on: (a) determining base temperature for full blooming date, which is calculated as the growing season start date according to WMO (WMO, 2009), and (b) determining threshold for sum of active temperatures (growing degree days) required from full blooming to harvest.

After determining the required heat conditions for apple growing, the methodology was transferred to the whole south part of Norway, which includes the domain 4.4°E-12.9°E and 58°N-65.2°N (regions: Western Norway, Southern Norway, Eastern Norway, Trøndelag). Calculation was applied on the set of interpolated daily data on resolution 0.01°x0.01°. Input data for interpolation are from EOBS database on resolution 0.1°x0.1°. Applying the derived criteria for apple growing over the period 1961-2020 produced the assessment on the rate of expansion of areas where heat conditions are favorable for apple growing. In order to assess future heat suitability for apple growing by the end of the 21st century, determined heat requirements are applied to the downscaled dataset of an ensemble of 10 climate models, under the IPCC RCP8.5 (IPCC, 2021) scenario. This scenario is chosen because the climate change represented by the multi-model ensemble results by the mid-century period (2041-2060) according to this scenario well reflect the range of outcomes of the climate conditions with both, RCP4.5 and RCP8.5 (scenarios used in adaptation planning). This means that the ranges of ensemble values obtained for mid-century period with these two scenarios in major part overlap. Under RCP4.5 in the second half of the 21^{st} century stabilizes, which means that main climate characteristics are close to ones in the mid-century period. Under RCP8.5 changes continue to accelerate. The main goal is to provide the assessment for the mid-century period which is considered as relatively certain according to current global mitigation policies. Outputs of this analysis are maps of favorable heat conditions for apple growing for different climate periods and for different varieties. Spatial data were further processed to assess the rate of expansion of surfaces for less and more heat-demanding varieties.

Results provide strong evidence on the rapid progression of heat favorable conditions for apple growing in Norway, and suggest the need for the zoning of potential apple growing areas including climate change information.

The workflow in this study is organized as follows: (1) determining the criteria for the calculation of the optimal heat conditions required for growing, based on the full blooming and harvest dates of six apple varieties (Discovery, Gravenstein, Summerred, Aroma, Rubinstep, and Elstar); (2) the interpolation of gridded daily temperature data in high resolution for the selected domain; (3) the application of the derived criteria for six varieties over the domain to map areas with heat favorable conditions for their growing in the periods from 1961 to 2020; (4) the assessment of surface areas with such conditions for each decade in the period of 1961–2020 and the analysis of their change; (5) summarizing the results derived for each variety in two groups— surface area change with heat conditions favorable for growing at least one variety (with minimum heat requirements) and with heat conditions favorable for growing any variety (including ones with higher heat demands); (6) the application of the derived criteria for six varieties over the domain to map areas with heat favorable conditions for their growing in the future climate periods from 2021 to 2100 under RCP8.5; and (7) summarizing the results derived for each variety for the future climate periods.

Material from this Report has been used in published papers: (1) Vuković Vimić et al. (2023) which provides the methodology for derivation of the phenological criteria, mapping of heat favorable conditions for apple growing during the period 1961-2020, and observed climate change impact on change of zones with heat favorable conditions, and (2) Vujadinović Mandić et al. (2023) which provides the analysis of future climate change and change of zones with heat favorable conditions for apple growing until the end of the 21st century.

2 Materials and methods

2.1 Phenological data

Phenological data for six apple varieties were collected from the Ullensvang orchards and used for determining heat conditions required for fruit development, until harvest. Phenological observations were available for the period 2003-2020. According to the extended BBCH-scale (Hack et al. 1992; Meier, 2001), the coding scheme for phenological stages, number of years with available observations for each phenological stage are given in the Table 2.1, along with harvest dates availability.

Table 2.1. List of varieties and number of available data for each phenological stage in the period of observations 2003-2020 and harvest data; Full blooming (FB, yellow) and harvest (HAR, orange) are chosen for further determining the criteria for heat conditions for apple growing; FB+HAR (green) is number of years with available data on both, FB and HAR.

Variety/ BBCH-scale	Discovery	Gravenstein	Summered	Aroma	Rubinstep	Elstar
51	13	10	11	16	6	8
52	12	12	10	13	9	5
53	16	13	11	16	8	8
54	14	13	14	13	6	8
55	8	8	6	6	8	4
56	14	13	14	15	7	9
57	10	10	12	12	5	5
58	6	5	2	4	2	1
59	8	9	11	7	4	7
60	12	9	11	10	2	9
61	3	5	1	3	2	2
62	2	4	6	3	1	2
63	3	6	1	7	2	1
64	5	8	5	3	2	2
65 (FB)	17	17	17	16	6	11
66	1	5	0	2	0	2
67	12	15	13	9	3	4
68	7	9	8	8	2	4
69	9	10	11	9	4	7
70	3	7	4	3	1	0
71	4	2	3	1	1	1
72	4	5	7	5	4	1
73	1	1	0	0	1	0
74	3	3	3	0	1	0
HAR	16	5	14	18	13	11
FB+HAR	15	4	13	16	3	4

Harvest (HAR) date is used as a mark for the end of the fruit development. Harvest dates for the individual varieties are based on main ripening criteria such as fruit colour (ground and blush colour), starch content and fruit firmness.

For purpose of this study, *full blooming* (FB) is chosen as an initial phenological stage, which marks the definite start of the plant's vegetative development. For this phenological stage dates were available for most of the years, or for the stages before and after, which enabled filling the missing data for full blooming. Since the data on fruit development were scarce, and there were no data for the dates of completed fruit development, *harvest* (HAR) date is used as a mark for the end of the fruit development. Harvest dates for the individual varieties are based on main ripening criteria such as fruit colour (ground and blush colour), starch content and fruit firmness. Harvest may be greatly impacted by the decision of the producer. Harvesting may be implemented before or well after the ripening (Laaksonen et al., 2017). For this reason it is expected to obtain larger uncertainty in the criteria derived for harvest dates than for the full blooming dates.

2.2 Short description of the cultivars

Figure 2.1. Discovery. Photo: M. Meland

Discovery. English cultivar (Worcester Pearmain x Beauty of Bath). Relatively dwarfing and compact growth and the yields are moderate. Nice looking, attractive fruits covered by red surface colour and tasteful. Harvest end of August/beginning of September. Tolerant to the diseases scab and mildew.

Figure 2.2. Gravenstein. Photo: O. Frøynes

Gravenstein. Old Danish cultivar grown for more than two hundred years. The tree has vigorous growth, give large yields and large fruits. It has some sports with red surface colour. Susceptible to diseases like scab and mildew. Tasteful fruits with good balance of sugar and acid. Harvest time is mid-September.

Figure 2.3. Summerred. Photo: F. Maas

Summerred: Canadien cultivar. Result of free pollination of a crossing from McIntosh x Golden Delicious. Very productive variety and thinning is mandatory. The fruit has red surface colour and harvests second half of September. The tree is susceptible to diseases.

Figure 2.4. Aroma. Photo: M. Meland

Aroma: Swedish cultivars. Parents are Filippa x Karen Schneider. It has several coloured strains (sports) and is the main commercial cultivar in Norway. Comes fast into production and gives large yields. Ripening in beginning of October. Thinning is required. Can be stored to end of January.

Figure 2.5. Rubinstep. Photo: O. Frøynes

Rubinstep: (Pirouette®) from Czech Republic. Parents are Clivia x Rubin. Abundant flowering and ripening is about one week later than Aroma. Comes fast into production and gives large yields of good quality. Can be stored to March.

Figure 2.6. Elstar. Photo: M. Meland

Elstar: Origin from The Netherlands. Parents are Golden Delicious x Ingrid Marie. Trees are vigorous and precocious cropping. Several strains are available with red surface colour. Harvest time is second half of October. Tasteful fruit and good for storage.

2.3 Meteorological data

2.3.1 Meteorological observations in Ullensvang

Meteorological data used for determining the criteria for heat conditions for apple growing, in this study, are from the local meteorological station at NIBIO Ullensvang (daily data for the period 2001-2020). Climate values of average monthly temperature and monthly accumulated precipitation for the period 2001-2020 and for the later decade 2011-2020 are given in Figure 2.7. Annual values and values for the growing season (May-September) are given in the Table 2.2. The latter decade, 2011-2020 is somewhat warmer than the climate period 2001-2020. Average annual temperature is 8.9°C, and average growing season (May-September) temperature is 14.3°C. Accumulated precipitation also increased, and for the period 2011-2020 average annual accumulated precipitation is 1870 mm and average for growing season is 541 mm. Under global warming in the future, it is expected for temperature further to rise. Conditions related to precipitation and water availability will not be considered due to the lack of information for quantifying the limitations they may have to apple production.

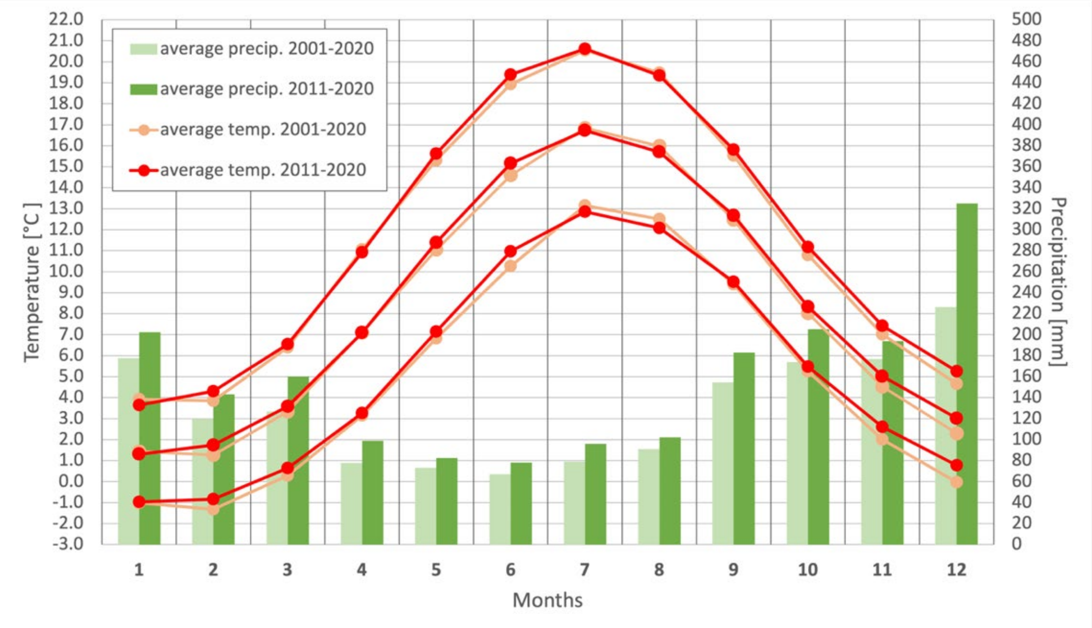

Figure 2.7. Average monthly temperature (maximum – upper pair of lines; mean – middle pair of lines; minimum – lower pair of lines) for the climate period 2001-2020 (orange) and for the latter decade 2011-2020 (red), and average monthly accumulated precipitation for the climate period 2001-2020 (light green) and for the decade 2011-2020 (dark green), for Ullensvang.

Table 2.2. Average temperature (mean Ts, maximum Tx, minimum Tn) and average accumulated precipitation for growing season (GS, May-September) and annual values (ANN) derived from Ullensvang station.

	Temperature						Precipitation	
	GS			ANN			GS	ANN
	Ts	Tx	Tn	Ts	Tx	Tn		
2001-2020	14.2	18.0	10.4	8.7	12.0	5.0	464	1544
2011-2020	14.3	18.2	10.5	8.9	12.2	5.3	541	1870

2.3.2 Gridded meteorological data for Norway

To be able to apply the derived criteria for the heat conditions needed for apple cultivation in the chosen domain in Norway, meteorological data for the selected region were necessary. EOBS database with spatial lat-lon resolution of 0.1°x0.1° was chosen (daily data; Cornes et al. 2018). Daily data from the EOBS database were interpolatied on higher resolution of 0.01°. Note that the quality of interpolated data depends on the availability of observations.

Domain for which the study was done (4.4°E-12.9°E and 58°N-65.2°N) is presented in Figure 2.8 (right panel), in the following text referred to as “south part of Norway”, and includes the regions: Western Norway, Southern Norway, Eastern Norway, and western part of Trøndelag. As a showcase, in Figure 2.9 are given values for average annual temperature and accumulated precipitation for 2011-2020 derived from the EOBS dataset.

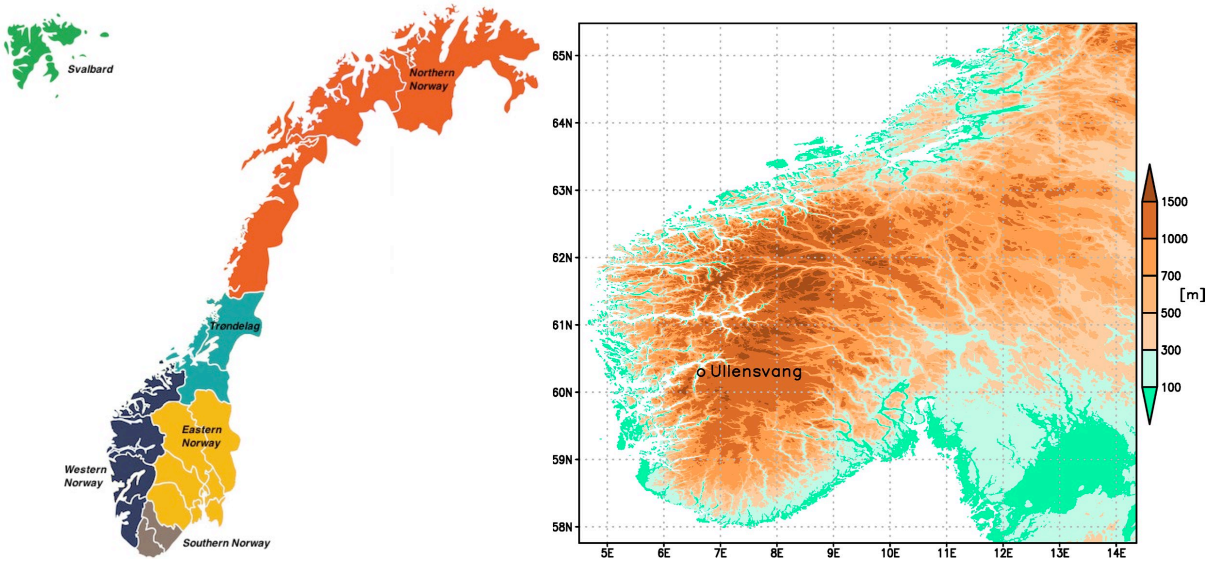

Figure 2.8. Regions in Norway (left, taken from: www.touropia.com/regions-in-norway/), domain for data interpolation and zoning of favorable heat conditions for apple growing (right) with altitudes and location of the Ullensvang orchards.

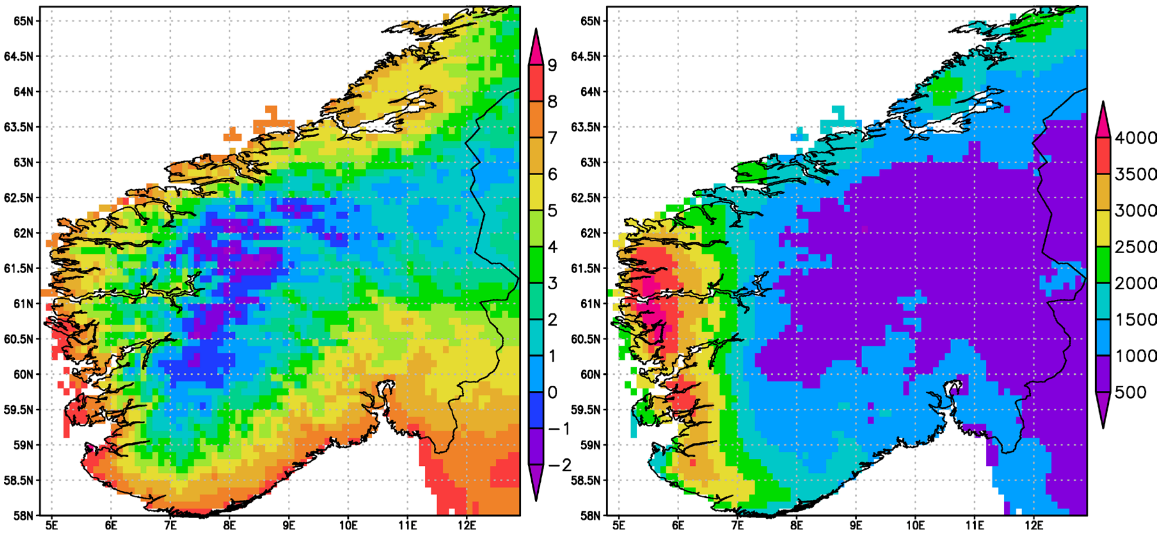

Figure 2.9. Average annual temperature (left; in °C) and accumulated precipitation (right; in mm) for the period 2011-2020, derived from EOBS database.

2.3.3 Downscaling of gridded meteorological data

Temperature data from the EOBS database were downscaled from 0.1°x0.1° resolution to 0.01°x0.01°. Data were interpolated for each day. The methodology applied is the method of successive corrections (Cressman, 1959). This method is in use usually for numerical weather forecast purposes and represents optimal combination of simplicity, computational efficiency and quality of the obtained interpolated data. It is used for the climate analysis in project of the national viticulture zoning in Republic of Serbia (Ivanisevic et al., 2015), zoning of fruit production and identifying risks for fruit growing (Djurović et al., 2020; Vujadinovic Mandic et al., 2022). This methodology also can be used for obtaining interpolated observations for the purpose of climate models bias correction (Vukovic et al., 2015).

2.4 Methodology for finding the criteria for heat conditions needed for apple growing

2.4.1 Methodology for determining heat conditions for full blooming

To find biological minimum or, frequently called the base temperature, for full blooming for each variety, following methodology was implemented: assumption was made that it is between 9°C and 15°C; for each temperature value within this interval and step of 0.1°C, FB date was calculated using each temperature value (total 41 temperature values) as the base temperature for each year; average calculated and observed dates were compared; temperature which was used to predict average FB date closest to the observed one was adopted as the base temperature.

According to the WMO indices (WMO, 2009), growing season start is defined as the end date of the first of appearance in the year of the six consecutive days above the base temperature. Here, for the stage of the growing season start is considered full blooming. FB date was calculated according to this approach – when the first time from the beginning of the year appears period of six consecutive days with average daily temperature above the base temperature, the sixth day of this period is the date of the FB. For the years with available observed FB was calculated difference between average observed and predicted FB for each base temperature. The base temperature for which the difference between average predicted and observed FB date was smallest was chosen as the base temperature for FB. Base temperatures for FB were determined for each variety.

In the period of year when blooming occurs, temperature is increasing fast with date, as can be seen in Figure 2.10 (left panel). How fast is changing base temperature with date, average for 2001-2020, derived from Ullensvang station data, is presented in Figure 2.10 (right panel). During the period when FB usually occurs for selected varieties (approximately between 130 and 160 day of year) average daily temperature changes approximately about 4°C. Heat conditions of the location are such, so that the base temperature of 10°C is achieved around 135th day of year in average, and of 12°C about 145th day of year. This means that the thresholds for base temperature are changing fast with the date, which is the consequence of rapid temperature increase during spring.

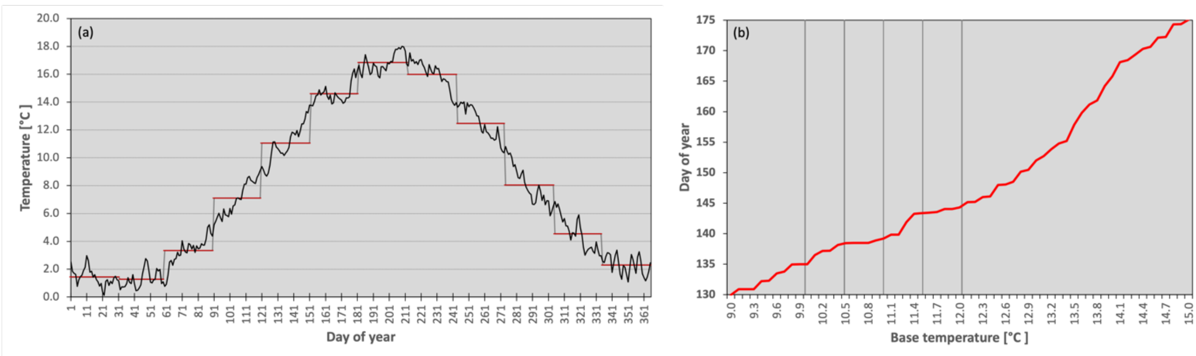

Figure 2.10. Average daily temperature and monthly temperature (left) and change of the base temperature with date (vertical lines mark 10°C, 10.5°C, 11°C, 11.5°C and 12°C, respectively), derived from the data from Ullensvang station, for the period 2001-2020.

2.4.2 Methodology for determining heat conditions for harvest

Heat conditions required to reach harvest (HAR), assuming it is close to the date of fully developed fruits, are determined using accumulated temperatures. For each variety, for the years which had available date of FB and HAR are calculated as a sum of temperatures above determined base temperature (so called "sum of active temperatures" – SUMT), until the harvest date. Two heat conditions were chosen to predict harvest date, average SUMT (sumta) and minimum SUMT (sumtn).

The values of SUMT varied depending on the year much more than between the varieties within one year.

2.5 Methodology for zoning of Norway for apple growing based on heat requirements

For each variety the most suitable base temperature (Tb) and sum of active temperatures (SUMT) required to be collected between FB and HAR were obtained. Those two conditions were applied over the whole domain, in each grid point. Following steps were applied for each grid point:

(1) FB date was calculated: starting from the beginning of the year was calculated first appearance of the six consecutive days above determined threshold value (base temperature - Tb), the sixth day was chosen as FB date,

(2) from calculated FB date accumulation of temperatures above threshold value starts and at the date when the accumulated value reaches determined threshold (predefined sum of active temperatures) – that date was chosen as harvest date (assuming it is close to biological ripening),

(3) if these heat criteria were possible to reach in each year of the chosen period of years – the areas that belongs to that grid point is considered as the areas with favorable heat conditions for apple growing.

This is repeated for each grid point, to derive a map of areas with favorable heat conditions for each variety.

Since all verities have their own heat requirements, to be able to provide a rather general (representative) map(s) of favorable heat conditions for apple growing, following condition were applied:

- minimum heat requirements for apple growing: if in the grid point are favorable heat conditions at least for one variety – area which belongs to that grid point has favorable heat conditions for apple growing.

- heat requirements for growing of any apple variety: if in the grid point are favorable heat conditions for all varieties – area which belongs to that grid point has favorable heat conditions for growing of any apple variety.

2.6 Future climate data

In order to assess hydro-climatological impacts of climate change across complex orography and coastline of Norway, the Norwegian Center for Climate Services created a national dataset of high-resolution spatially interpolated and bias-corrected daily outputs of 10 combinations of global and regional climate models selected from the EURO-CORDEX database (Wong et al., 2016). The list of chosen regional models, alongside with their driving global climate models (GCMs), is given in Table 2.3. The national dataset is produced at the spatial resolution of 1x1 km (0.0219° longitude x 0.0088° latitude) and it is available for download at https://klimaservicesenter.no. The simulations used in this study are done under the IPCC RCP8.5 scenario, which foresees the continual increase in greenhouse gasses concentrations by the end of the century. This scenario was selected following the adaptation planning recommendations in Norway (Meld. St. 33, 2013). Although this scenario is widely used in the future climate change impact studies and policy evaluations (Pielse et al., 2021), it assumes very high fossil fuel emissions in the second half of the century, which are evaluated as less likely (IPCC, 2022b).

Daily fields of mean temperatures from the national dataset were used to determine the change in average mean vegetational temperature, average sum of growing-degree days above 10°C from May 1st to September 30th, and suitability of heat conditions for 6 apple varieties following the criteria found in this study, resulting from the above explained procedure.

Results are analysed in three 20 years long future periods: near future (2021-2040), mid-century (2041-2060) and end of the century (2081-2100); and compared to the referent period 1971-2000. All calculations are done for each model and presented are median of the ensemble, as well as 25th and 75th percentile (where it is suitable), in order to address the uncertainty of the projections.

Table 2.3. List of global (GCM) and regional (RCM) climate models used in this study.

GCM	RCM
CNRM	CCLM
CNRM	RCA
ECEARTH	CCLM
ECEARTH	HIRHAM
ECEARTH	RACMO
ECEARTH	RCA
HADGEM	RCA
IPSL	RCA
MPI	CCLM
MPI	RCA

3 Results and discussion

3.1 Base temperature for apple varieties

Differences between average predicted (calculated) and observed full blooming (FB) date, for base temperatures from 9°C to 15°C with interval 0.1°C, for each variety in Ullensvang, are given in Figure 3.1. The temperature for which is the difference between average predicted and observed dates is smallest is selected for the base temperature (Tb). In the Table 3.1 are given values of the selected Tb for each variety. As discussed before, this means; starting from the beginning of the year, first time the period of 6 consecutive days with mean daily temperature above Tb appear, sixth day of this period is a full blooming date. By applying this methodology for calculating FB date is expected to obtain "predicted" average date of FB close to the average "real" (observed) FB date. Difference between average predicted dates and average observed dates for all varieties have difference less or equal to 2, when chosen Tb is used for calculation of predicted dates. This confirms that derived Tb values and methodology for calculation of full blooming date well represent average observed dates.

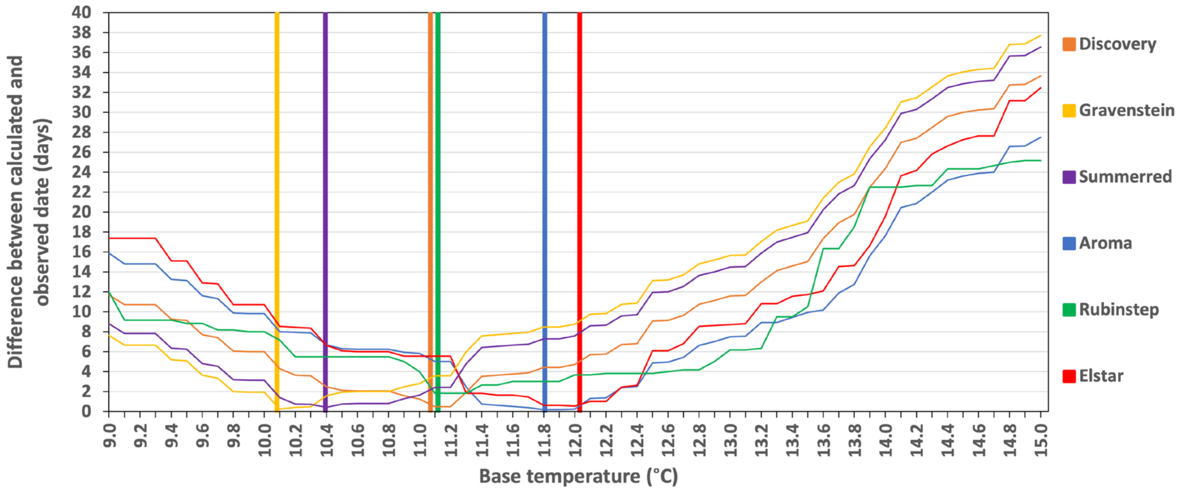

Figure 3.1. Difference between average predicted and observed full blooming date for the whole range of assumed base temperatures (9°C to 15°C with interval 0.1°C), for each variety, and selected base temperatures for each variety (vertical lines) for which is the smallest difference between predicted and observed dates.

Table 3.1. For each variety number of available observations of full blooming (FB), average observed date of FB, selected base temperature (Tb) for FB and difference between average predicted (using selected Tb) and observed FB date.

Variety	Number of years with observed FB	Average observed date		Selected base temperature (Tb) [°C]	Difference between predicted and observed FB date [days]
		day of year	date		
Discovery	17	143	22.5.	11.1	0
Gravenstein	17	139	18.5.	10.1	0
Summerred	17	140	19.5.	10.4	0
Aroma	16	147	26.5.	11.8	0
Rubinstep	6	144	23.5.	11.1	2
Elstar	11	148	27.5.	12.0	1

3.2 Heat required for fruit development

To determine heat requirements for fruit development to full size (ripening), when they are ready for harvest, it is required to have observed dates of ripening. Here are used dates of harvest for each variety which is based on ripening criteria for optimum harvest dates for direct marketing and storing. Available dates for harvest for all varieties are given in Figure 3.2. In Table 3.2 are given average, earliest and latest harvest dates for each variety, derived from available data.

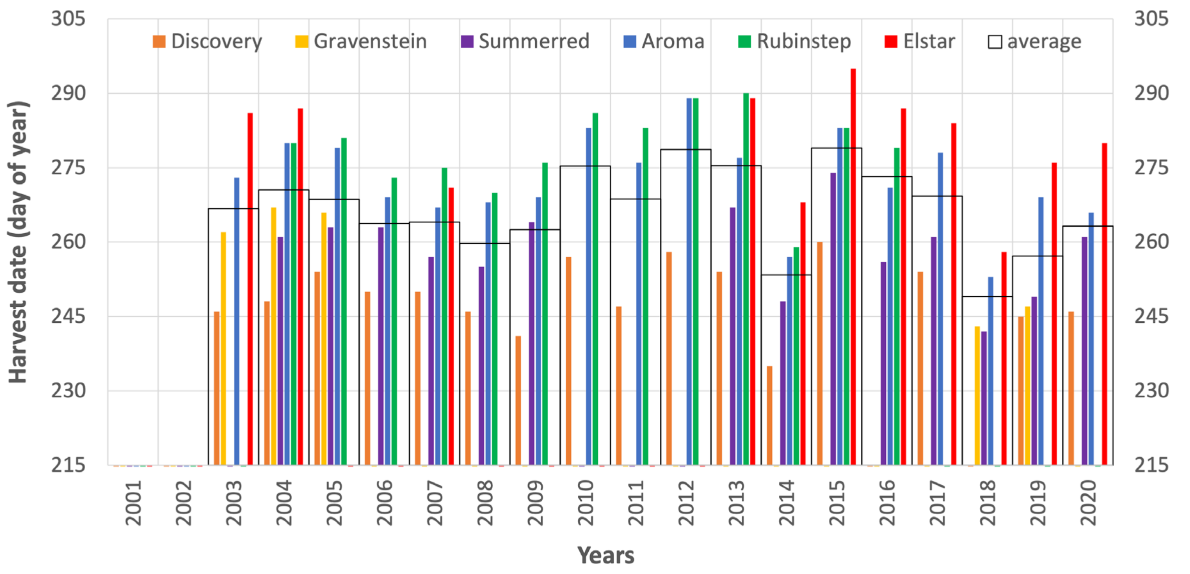

Figure 3.2. Available dates when the harvest was done for each variety in units "day of year", from NIBIO Ullensvang orchards.

Table 3.2. Dates when harvest was conducted: number of years in the period 2001-2020 with available data for full blooming and harvest in the same year (all data on harvest dates), average date (in "day of year"), earliest date (minimum day of year), latest date (maximum day of year), and difference between maximum and minimum dates; for Ullensvang.

	Number of years	Average date	Earliest date (min)	Latest date (max)	Max-min
Discovery	15 (16)	249	235	260	25
Gravenstein	4 (5)	257	243	267	24
Summered	13 (14)	259	242	274	32
Aroma	16 (18)	273	253	289	36
Rubinstep	3 (13)	279	259	290	31
Elstar	4 (11)	280	258	295	37

For each variety, for each available year "sums of active temperatures" (SUMT) from full blooming (FB) date to the harvest date (HAR) are calculated. Active temperatures are mean daily temperatures above the base temperature. Sums of active temperatures are calculated for each variety and for each year, for which exist observed dates of FB and HAR. They are given in Figure 3.3. Unfortunately, in one year both, FB and HAR dates, are available for lesser number of years, which means that is expected for derived criteria for determining the harvest date to have larger uncertainties.

As can be seen from Figure 3.3, there is a large difference in sums of active temperatures for different years, which can be the consequence of using harvest date instead the date of physiological ripening, meaning that harvest date is impacted by the human decision when to harvest, and physiological ripening may occur much earlier. This assumption is also supported by the fact that in years with higher values of sums of active temperatures, it was the case for all varieties. Variations of SUMT from year to year are mostly larger than variations in sums between different varieties. The fact that harvest is more determined by the date (time of year) than by weather conditions is supported also by the data on temperature. For example, average May-September temperature (approximately growing season period for fruits in Norway) was higher than average in years for which are derived higher sums of active temperatures (most pronounced in 2006, 2014, 2016, 2018), and for years with average temperature lower than average are derived lower sums of active temperatures (2003, 2005, 2007, 2012, 2015). In Figure 3.4 are given anomalies for average May-September temperatures for each year with respect to the average May-September temperature for the period 2001-2020.

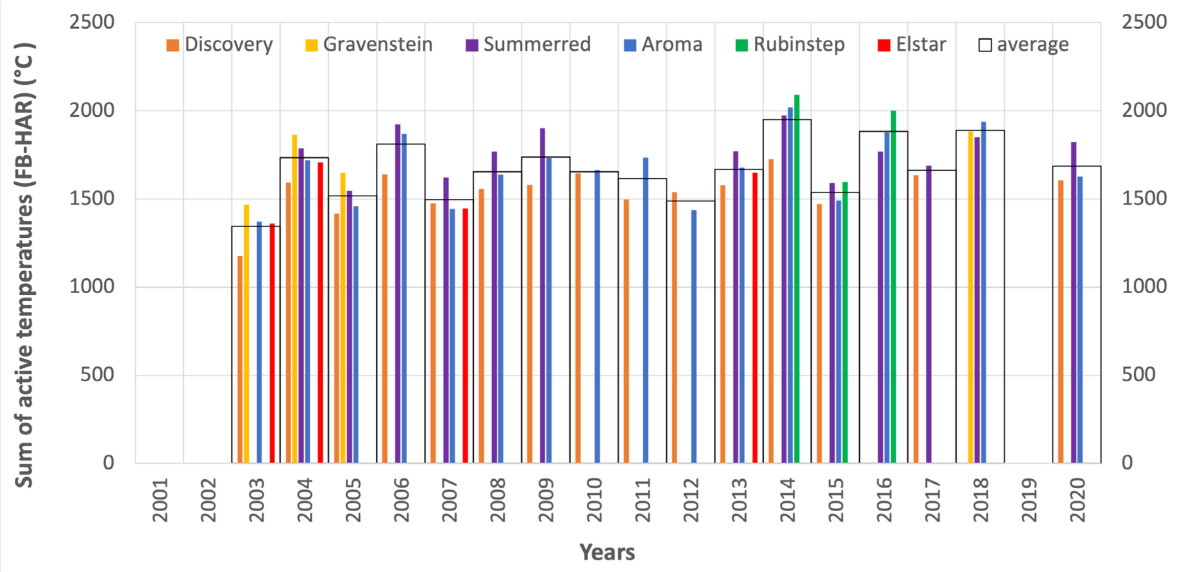

Figure 3.3. Sums of active temperatures for each variety and each year with available observations of both, FB and HAR dates, and average sums of active temperatures for all varieties with available data for each year.

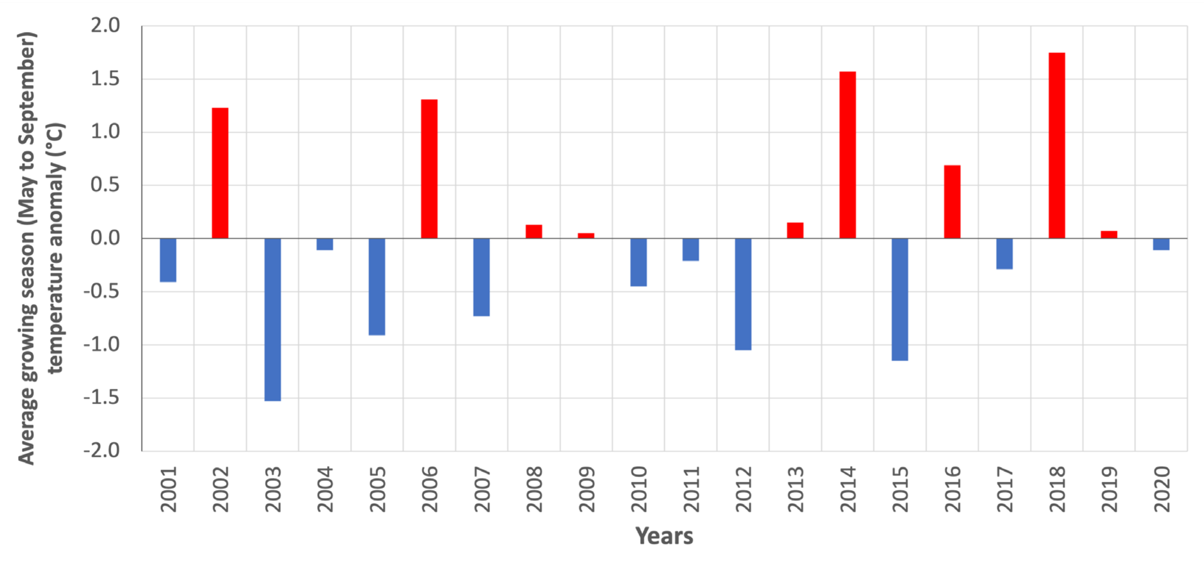

Figure 3.4. Anomalies of average temperature for May-September for each year with respect to the average temperature for May-September for the period 2001-2020, for Ullensvang.

The heat conditions required to achieve ripening and harvest, starting from the FB phenological stage, are to be determined by threshold for the sum of active temperatures (SUMT) for each variety. Calculation of harvest date was done using three thresholds for SUMT values: average (sumta), maximum (sumtx) and minimum (sumtn), for each variety, for each year. From the beginning of the year first was calculated FB using chosen Tb for each variety, and from FB date are calculated SUMT.

The date for which the difference of calculated SUMT and threshold SUMT is the smallest is selected as harvest date. The results are given in Figure 3.5.

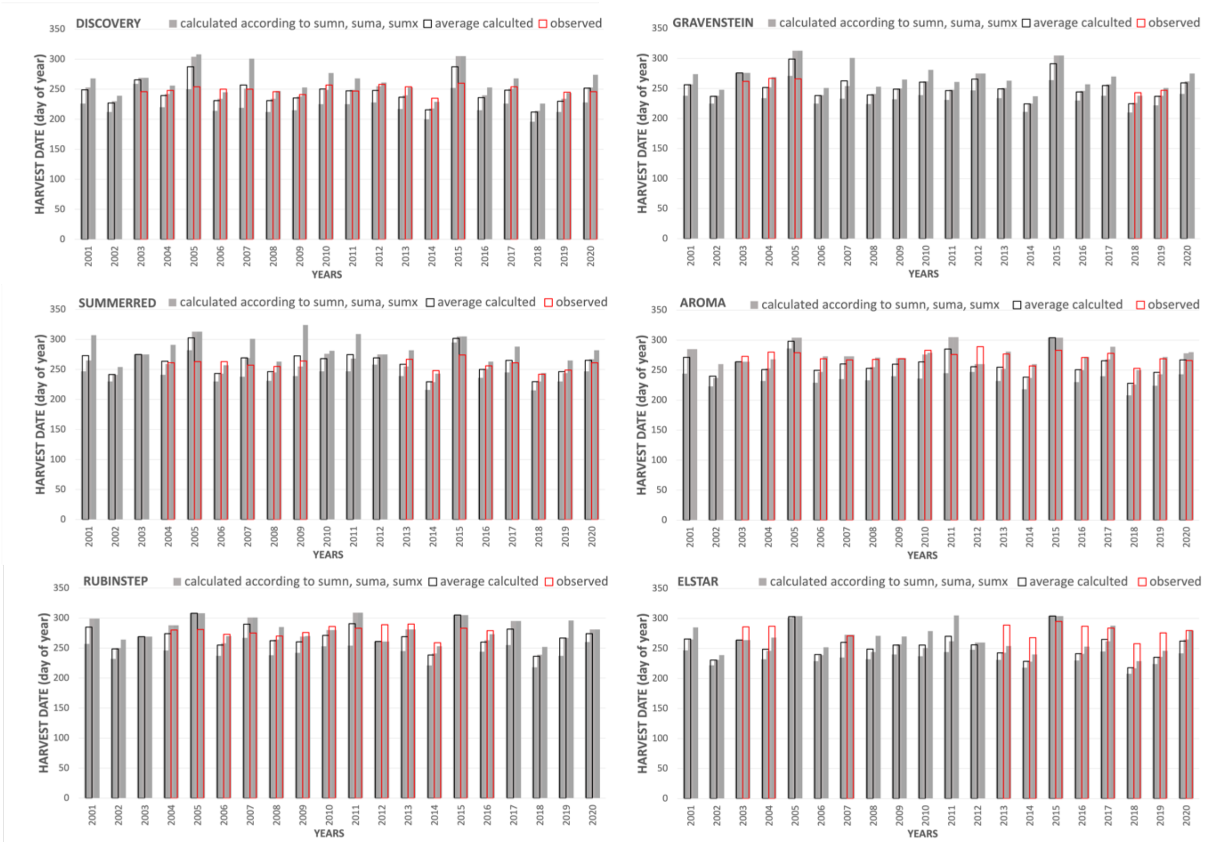

Figure 3.5. Harvest dates calculated using threshold values for SUMT (*suma, sumtx, sumtn*; in grey), average calculated date (black) and the real (observed) harvest date (red)

Difference between average predicted and observed harvest date is smallest when *sumta* is used as a threshold for SUMT. For all varieties, except for Elstar (els), average HAR dates are well represented. Considering the large variability of harvest dates between the years (approximately in the range 25-35 days is a difference between earliest and the latest harvest dates), predicted average dates using threshold *sumta* can be considered well represented.

The heat conditions fulfill the *sumta* threshold could be too strict, and both thresholds will be used in further work, *sumta* and *sumtn*. This can be justified by the following assumption: earliest harvest date was conducted closest to the ripening phenological stage, when SUMT was equal to *sumtn*. One remark should be kept in mind, and that is for varieties which have marginal heat requirements, meaning that they are bordering with maximum heat capacity of the growing site, derived thresholds for heat requirements have larger uncertainties. Good example is Elstar, for which derived heat conditions probably underestimate heat conditions required for growing of this variety, which is visible from largest difference between average predicted and real harvest date. Thresholds are derived from only 4 years of data. Increasing number of data would certainly provide more information for generating more reliable assessments on heat requirements.

3.3 Summary of determined methodology for assessing favorable heat conditions for apple growing

As a summary for further work, the following methodology is accepted for the mapping of favorable heat conditions for apple growing. For each variety and for each year (using values summarized in Table 3.3):

- to determine **full blooming date (FB)** as a sixth day of the first appearance in the year of the period with six consecutive days above the base temperature;
- to calculate **sum of active temperatures (SUMT) -** accumulate average daily temperatures above base temperature (Tb), from FB date until the threshold value is reached;
- **thresholds for SUMT** are determined here as *sumta* and *sumtn*;
- if it is satisfied ***SUMT* ≥ *threshold SUMT*** (in this case for both, *sumta* and *sumtn*) heat conditions in that year are favorable for apple growing;
- repeat **for each year**;
- if **in all years the condition is fulfilled** – the location has favorable heat conditions for growing of that apple variety.

Table 3.3. Summary for derived thresholds for calculation of favorable heat conditions for apple growing, for each variety: base temperature (Tb), and threshold values for sums of active temperatures - average heat requirements represented with *sumta*, and minimum heat requirements represented with *sumtn*.

Variety	Tb	*sumta*	*sumtn*
Discovery	11.1	1542	1177
Gravenstein	10.1	1716	1467
Summerred	10.4	1771	1547
Aroma	11.8	1669	1372
Rubinstep	11.1	1896	1597
Elstar	12.0	1541	1361

3.4 High-resolution daily temperature data

Using the EOBS data set with daily temperature data, interpolation of data is done on daily level for the period 1961-2020 on 10 times higher resolution, i.e. on resolution of 0.01°. Interpolated daily data enable application of the methodology developed for assessing favorable heat conditions for apple growing. For example, in Figure 3.6 average values for the warmest decade 2011-2020 are given from the EOBS data and from the high-resolution data. Considering the complex orography of Norway and that agricultural production is situated in areas with favorable climate features in relatively small-scale areas, high-resolution data enable higher reliability of the assessment of spatial distribution of zones with favorable heat conditions.

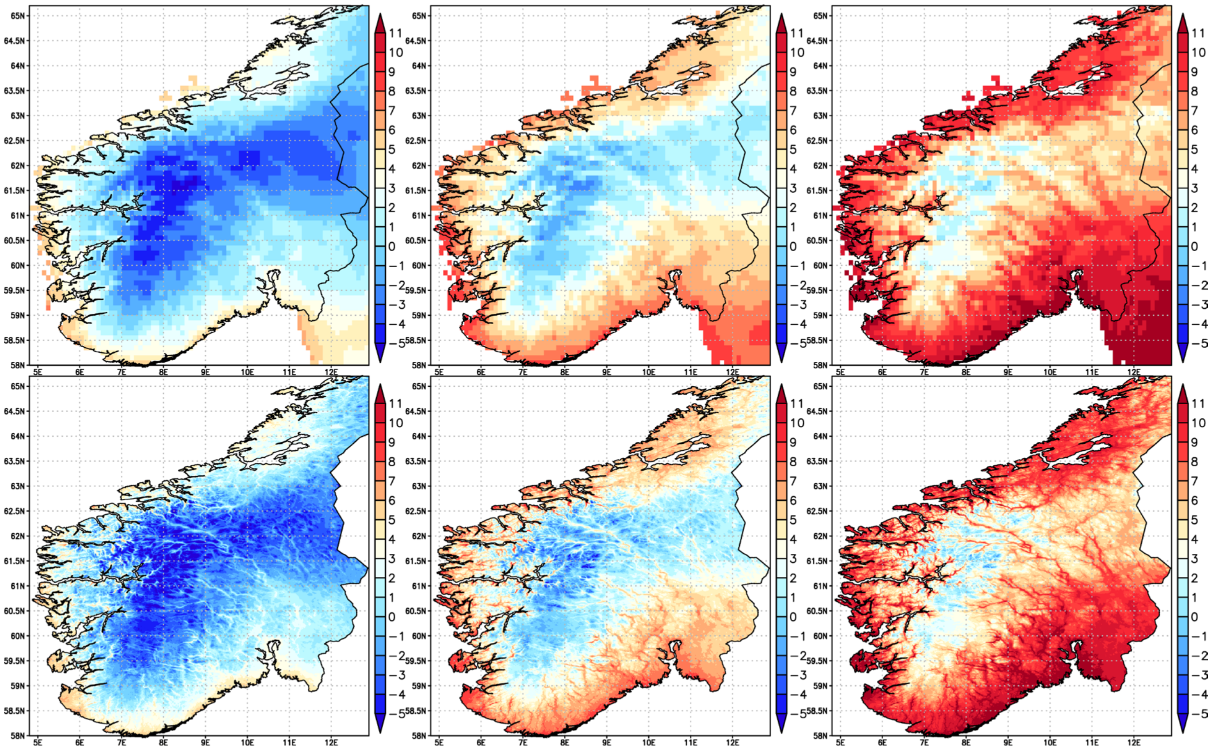

Figure 3.6. Average minimum (left), mean (middle), and maximum (right) daily temperature from EOBS (upper panels) and from interpolated (high resolution) daily data (lower panels), for the period 2011-2020.

3.5 Zoning of south part of Norway according to heat requirements for apple growing

3.5.1 Results for the period 2011-2020

When applying the methodology summarized in Chapter 3.3., and applying the calculation for the period 2011-2020, maps are developed for each variety, using both thresholds for sum of active temperatures between full blooming and harvest date (SUMT): minimum SUMT (*sumtn*) and average SUMT (*sumta*). Results obtained for each variety are given in the Appendix (Chapter A1), along with the percent of areas such heat conditions are fulfilled in different number of years.

If the heat conditions are fulfilled in all years (10 years), the area is suitable for apple growing (in all maps marked with red colour). If the area has fulfilled thresholds for heat conditions in less, but close to, 10 years, it could mean some of the following: (a) the area with favorable heat conditions is of lesser spatial scales (smaller size) than the grid box of data from which mapping is performed (0.01°x0.01°) which is common in areas where steep terrains are present, (b) the area could reach favorable heat conditions in the near future climate under continuing global warming), and (c) local meteorological measurements are not in the international exchange, and thereby not included in the EOBS dataset, from which high-resolution interpolation is made, so that local-scale climate is not visible.

Results derived for each variety (Chapter A1) show that for varieties with higher demands for heat during the growing season (Elstar, Aroma, Rubinstep) heat conditions are fulfilled over the area lesser than 5% of the selected domain, Summered between 6% and 7%, and for varieties with lesser demands for heat for fruit development, favorable heat conditions are fulfilled over the 10% of the domain (about 11% for Gravenstein and 15% for Discovery). These results are obtained <u>using *sumtn* as a threshold</u> for SUMT. <u>Using *sumta* as a threshold</u> significantly decreases the surface area with favorable heat conditions, so that for Discovery fraction of surface area with favorable conditions is only about 3.8%, for Gravenstein 2.4%, and for other varieties less than 1%. This indicates that using *sumta* as a threshold for SUMT could be too restrictive and overestimate required heat conditions required for apple growing. This is further discussed in the following assessment of rather general heat requirements for apple growing.

To represent general capacity to grow apples, two summary maps are derived from results derived for each variety separately, as was discussed in Chapter 2.4:

- *favorable heat conditions for apple growing*; a map with areas where heat conditions are favorable for at least one variety (if heat conditions are fulfilled at least for one variety, the areas have potential for apple growing)
- *favorable heat conditions for growing of any apple variety*: a map with areas where heat conditions are favorable for all varieties (if heat conditions are fulfilled for all varieties, the area has potential for growing any of studied apple varieties)

Results derived using heat conditions defined according to *sumtn* are given in Figure 3.7 and Table 3.4, and results derived using more strict heat conditions *sumta* are in Figure 3.8 and Table 3.5.

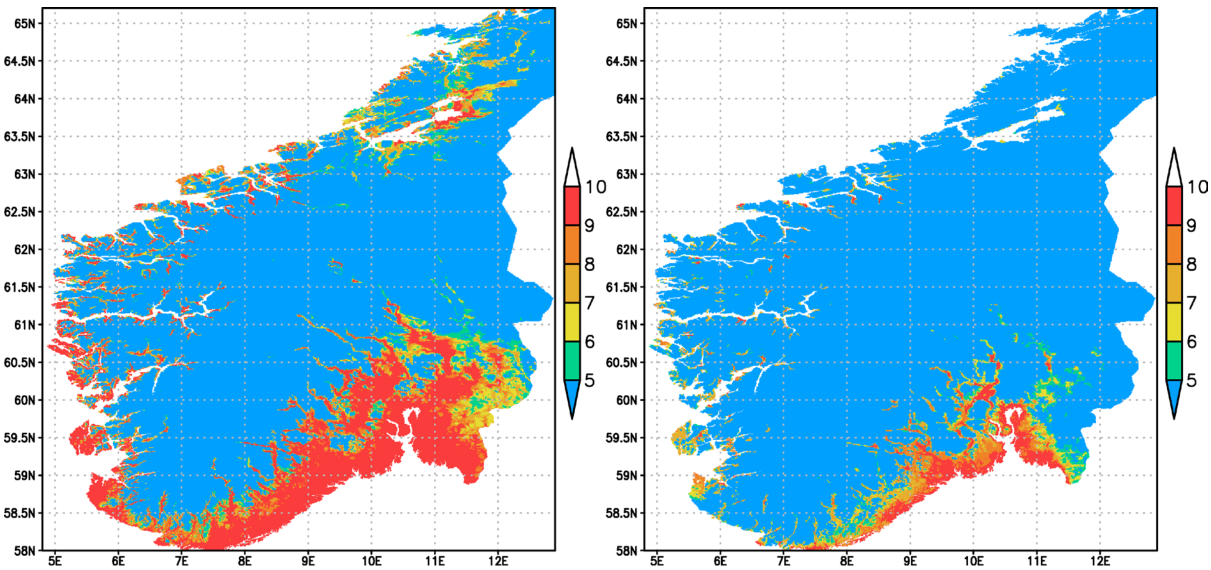

Figure 3.7. Number of years in which heat conditions are fulfilled at least for one variety (left), and for all varieties (right) in the period 2011-2020, using *sumtn* for heat threshold; in blue are areas which have in ≤ 5 years fulfilled heat conditions, in green reached required heat conditions in 6 years, in yellow in 7, etc., and in red are given areas which fulfilled required heat conditions in all 10 years.

Table 3.4. Percentage of total land area for which mapping is performed (179042.6 km ^{2}) where are heat conditions achieved none of the years (0), in one or more years (1≤), in two or more years (2≤), etc., and in all (10) years during the period 2011-2020, derived using *sumtn* as heat threshold, when heat conditions are fulfilled at least for one variety (one), and for all varieties (all).

	0	1 ≤	2 ≤	3 ≤	4 ≤	5 ≤	6 ≤	7 ≤	8 ≤	9 ≤	10
one	50.8	49.2	41.8	38.8	36.2	33.8	30.1	26.5	23.2	19.1	15.1
all	70.5	29.5	22.6	19.6	16.8	13.9	11.3	9.2	7.3	4.5	2.6

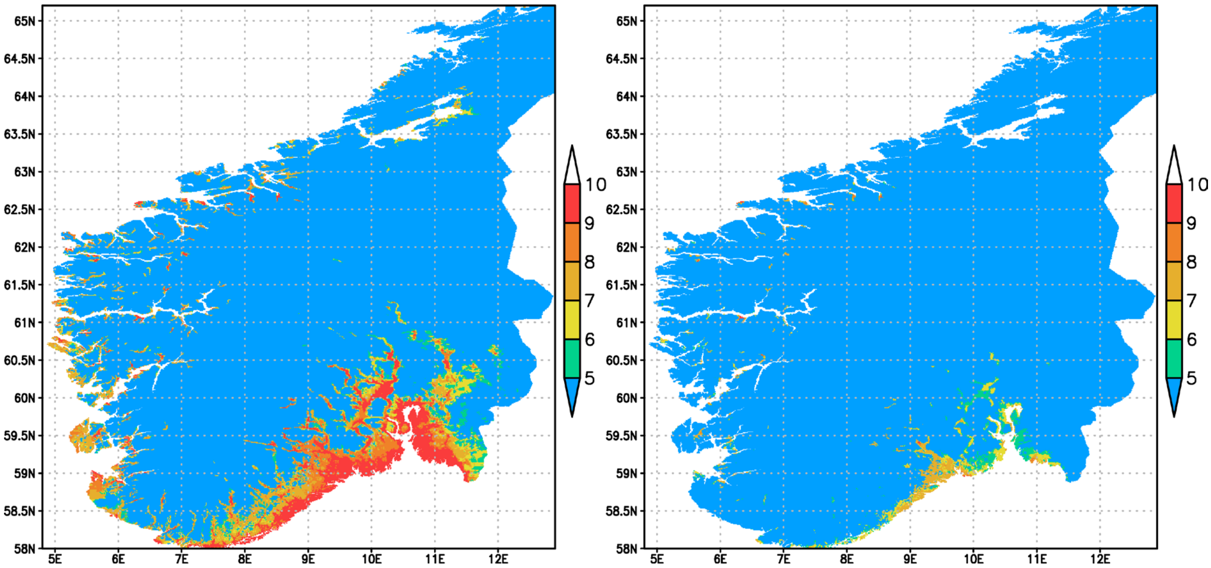

Figure 3.8. Number of years in which heat conditions are fulfilled at least for one variety (left), and for all varieties (right) in the period 2011-2020, using *sumta* for heat threshold; in blue are areas which have in ≤ 5 years fulfilled heat conditions, in green reached required heat conditions in 6 years, in yellow in 7, etc., and in red are given areas which fulfilled required heat conditions in all 10 years.

Table 3.5. Percentage of total land area for which mapping is performed (179042.6 km 2) where are heat conditions achieved none of the years (0), in one or more years (1≤), in two or more years (2≤), etc., and in all (10) years during the period 2011-2020, derived using *sumta* as heat threshold, when heat conditions are fulfilled at least for one variety (one), and for all varieties (all).

	0	1 ≤	2 ≤	3 ≤	4 ≤	5 ≤	6 ≤	7 ≤	8 ≤	9 ≤	10
one	65.74	34.26	26.77	23.38	20.73	17.96	15.25	13.02	10.65	6.29	3.87
all	83.39	16.61	11.13	7.69	5.51	4.09	3.10	1.96	0.96	0.06	0.01

According to the obtained results using *sumtn* as a threshold, heat conditions are favorable for growing of apples in the selected domain "south part of Norway" over 15.1% percent of territory, and for growing of any apple variety over 2.6%. In additional 4% (19.1% in total) heat requirements for apple growing are fulfilled in 90% of years (for this chosen period 2011-2020 it means 9 of 10 years), and over additional 15% (30.1% in total) in 60%-90% of years (6 to 9 years of the period 2011-2020). Those areas could reach heat potential for apple growing under future climate.

According to the results using *sumta* as a threshold (more limiting threshold in heat requirements), heat conditions are favorable for growing of apples in the selected domain "south part of Norway" over 3.9% percent of territory, and for growing of any apple variety over 0.01%. Heat requirements are fulfilled in at least 60% of years (in the period 2011-2020 at least 6 years) over 15.2% of territory for apple growing.

More limiting threshold (*sumta*), most probably overestimate heat requirements for apple growing as was already discussed, since it is derived as an average value of SUMT for each variety from harvest dates and could underestimate surface areas which can implement apple growing. For this reason, in further analysis is used threshold according to the *sumtn* values, derived for each variety.

3.5.2 Comparison with past periods

How important is to develop the relations between phenological development and meteorological conditions, and their use in assessing the capacities for growing of different cultivars, will show the analysis of the change of surface areas favorable for growing under accelerated climate changes.

Change of the average temperature for the whole domain is given in the Figure 3.9. Given values represent the difference between average temperatures, for the whole domain, for each decade in the period 1961-2020 and average for the period 1961-2020. Presented anomalies show continuous and rapid, especially since the late 20th century, increase of temperature, which enabled increase of surface areas with favorable heat conditions for apple growing. In the Table 3.6 are given values of average temperatures and anomalies for each decade, with respect to the two base periods, 1961-2020 (the whole past period for which data were analysed, as in Figure 3.9) and 1971-2000 (base period chosen for the climate change analysis in Hanssen-Bauer et al., 2015, and in the following text where future climate is discussed). Note that in time the EOBS dataset had different input of observations from Norway which could impacts the EOBS data quality and thereby quality of interpolated high-resolution data used here, so that these assessments not necessarily are the same as some assessments derived from the national data. The trend of temperature increase, for which is here assumed that is well represented with used dataset, is the most important for implementation of comparison of heat capacities for apple growing in different periods.

According to the used (interpolated) data, average temperature for the selected domain of "south part of Norway" increased by 1.1°C with respect to the average temperature for the period 1971-2000, and decades were becoming warmer from mid-20th century until near past (2011-2020). Smallest increase was in highest altitudes (not shown here), and higher in lower altitudes, which can be explained by using more heat on snow melt in higher altitudes and not for surface and air heating.

How much temperature increase impacted change of surface areas with favorable heat conditions for apple growing is given in Figure 3.10 and in Table 3.7. Spatial maps are given in the Appendix (Chapter A2). During the first three decades of the period 1961-2020, surface area when at least one variety of considered varieties can be grown according to the heat conditions required during growing season (condition is fulfilled in all 10 years of a decade) is in the range 4.5-7.5%, in the last decade of 20th century the surface increased to about 8.4%, and during 21st century over 15%. Surface area where heat conditions for all varieties are fulfilled increased from well below 1% to about 2.6%. Increase in surface areas where heat conditions are fulfilled in certain number of years is also increasing, meaning that other surfaces are increasing heat potential toward favorable for apple growing, and may reach such heat requirements in the future. Increase is pronounced in the 21st century. Surface areas where heat requirements for apple growing are not fulfilled in any year (not even extremely warm) are decreasing, from about 70% of the territory to about 50% of the territory. Areas with favorable heat conditions spread to the north part of domain for the varieties with lesser demands for heat during the fruit development.

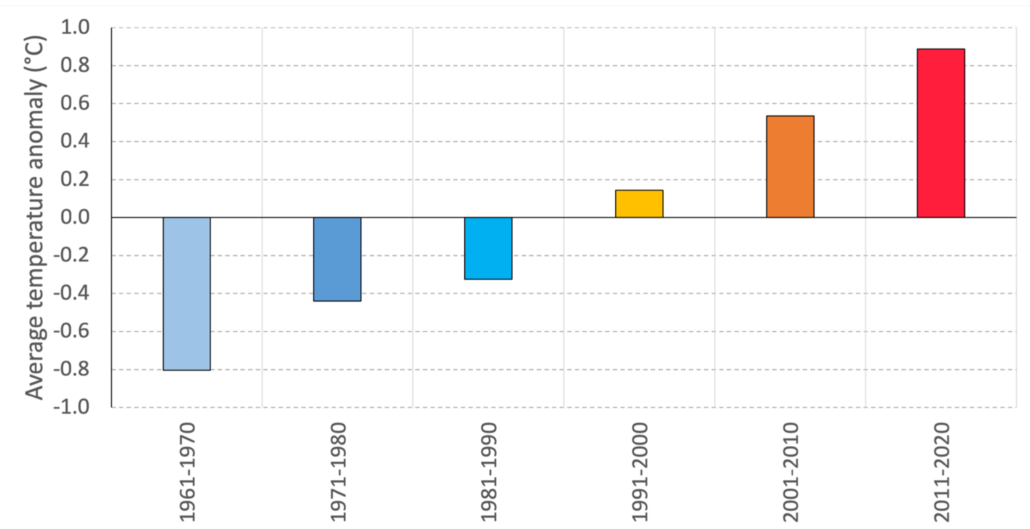

Figure 3.9. Anomalies of average temperature for the whole domain for each decade, compared to the average temperature for the period 1961-2020.

Table 3.6. Average temperature for the whole domain for each decade (Tave), anomalies of average temperature compared to the values for 1961-2020 (Tan 6120) and for 1971-2000 (Tan 7100).

	Tave	Tan 6120	Tan 7100
1961-1970	1.8	-0.8	-0.6
1971-1980	2.2	-0.4	-0.2
1981-1990	2.3	-0.3	-0.1
1991-2000	2.8	0.1	0.4
2001-2010	3.2	0.5	0.7
2011-2020	3.5	0.9	1.1

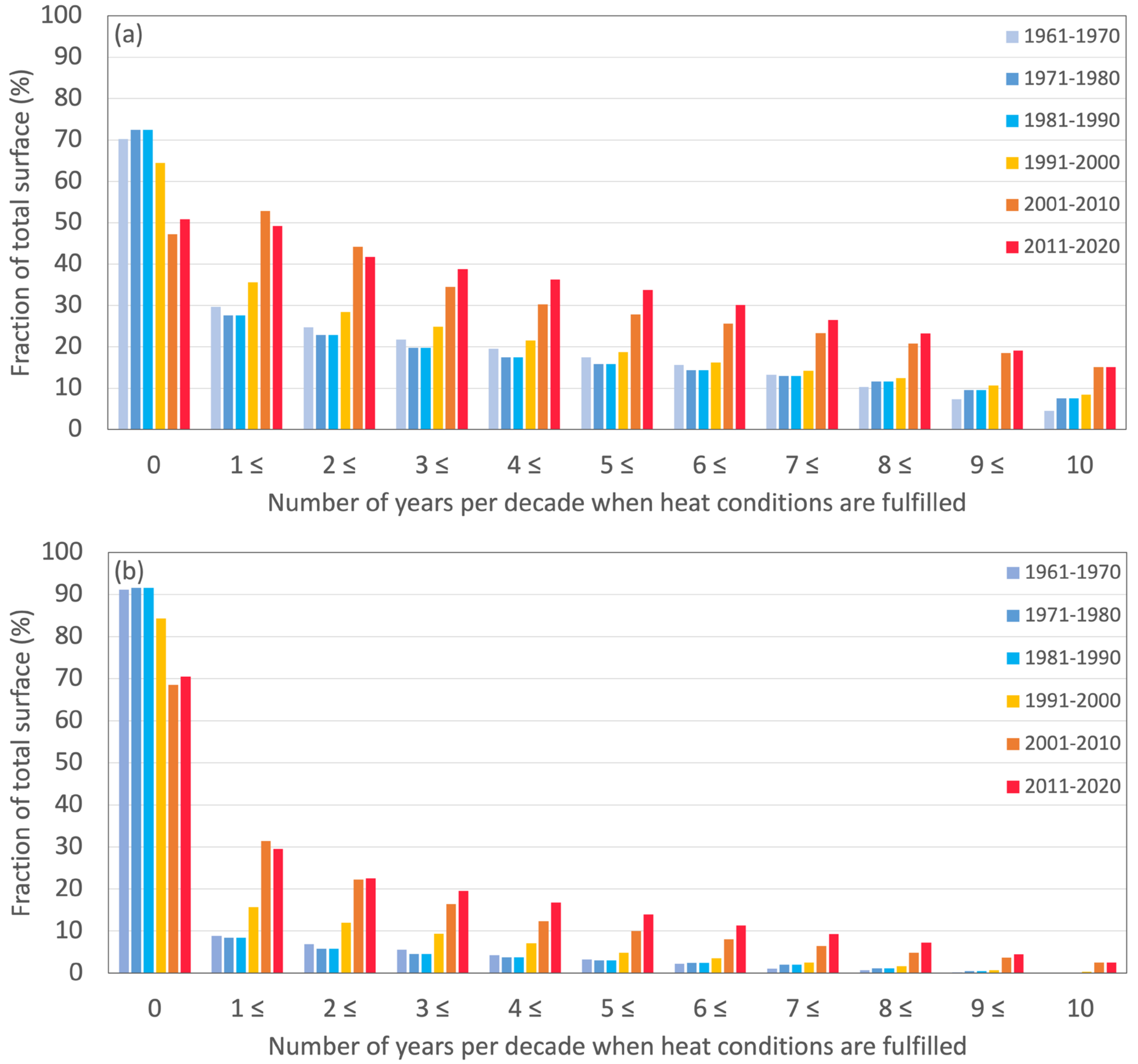

Figure 3.10. Percentage of total surface area of the domain when zero years fulfil minimum required heat conditions (0), when the condition is fulfilled at least in one year (1 ≤), at least in two years (2 ≤), etc., and when the condition is fulfilled in all years (10), for each decade during the period 1961-2020. Upper panel (a) gives results for surface areas where at least one variety fulfil the condition, and lower panel (b) when all varieties fulfil the condition. Colours which represent results for chosen decades are the same as in Figure 3.9.

Table 3.7. Percentage of total surface area of the domain when zero years fulfil minimum required heat conditions (0), when the condition is fulfilled at least in one year (1 ≤), at least in two years (2 ≤), etc., and when the condition is fulfilled in all years (10), for each decade during the period 1961-2020. Results are for surface areas where at least one variety fulfil the condition (one), and when all varieties fulfil the condition (all). Colours which represent results for chosen decades are the same as in Figure 3.9 and Figure 3.10.

1961-1970										
	0	1 ≤	2 ≤	3 ≤	4 ≤	5 ≤	6 ≤	7 ≤	8 ≤	9 ≤	10
one	70.28	29.72	24.71	21.78	19.53	17.53	15.59	13.32	10.32	7.32	4.48
all	91.15	8.85	6.91	5.56	4.29	3.29	2.23	1.06	0.69	0.21	0.01
1971-1980											
	0.00	1 ≤	2 ≤	3 ≤	4 ≤	5 ≤	6 ≤	7 ≤	8 ≤	9 ≤	10.00
one	72.44	27.56	22.84	19.75	17.50	15.81	14.36	13.02	11.58	9.59	7.54
all	91.59	8.41	5.75	4.58	3.77	3.07	2.51	1.96	1.10	0.52	0.12
1981-1990											
	0.00	1 ≤	2 ≤	3 ≤	4 ≤	5 ≤	6 ≤	7 ≤	8 ≤	9 ≤	10.00
one	70.30	29.70	24.48	21.88	19.30	17.58	15.45	13.44	11.48	7.22	4.54
all	87.56	12.44	10.12	7.26	5.76	4.83	4.13	2.60	1.45	0.18	0.05
1991-2000											
	0.00	1 ≤	2 ≤	3 ≤	4 ≤	5 ≤	6 ≤	7 ≤	8 ≤	9 ≤	10.00
one	64.43	35.57	28.37	24.82	21.53	18.70	16.16	14.20	12.43	10.68	8.43
all	84.32	15.68	12.02	9.33	7.12	4.87	3.58	2.58	1.61	0.73	0.33
2001-2010											
	0.00	1 ≤	2 ≤	3 ≤	4 ≤	5 ≤	6 ≤	7 ≤	8 ≤	9 ≤	10.00
one	47.23	52.78	44.15	34.50	30.27	27.81	25.65	23.30	20.73	18.52	15.12
all	68.54	31.46	22.21	16.44	12.38	10.01	8.04	6.46	4.86	3.71	2.59
2011-2020											
	0.00	1 ≤	2 ≤	3 ≤	4 ≤	5 ≤	6 ≤	7 ≤	8 ≤	9 ≤	10.00
one	50.85	49.15	41.77	38.77	36.24	33.76	30.13	26.51	23.20	19.12	15.06
all	70.53	29.47	22.57	19.58	16.78	13.93	11.33	9.24	7.28	4.53	2.58

Change of surface fraction with respect to the base period 1971-2000 is given in Figure 3.11. In the figures are marked areas which did not fulfilled the heat requirements for apple growing in all years in the 1971-2000 but did in 2011-2020, which means that those areas achieved heat conditions required for growing apples because of the temperature increase.

In case that the heat the conditions are fulfilled in all years (areas have heat potential) for at least one variety the following change happened: increase of the surface in 2011-2020 compared to the 1971-2000 is 248%; during the period 1971-2000 surface areas with favorable heat conditions was 7750 km ^{2} and in 2011-2020 26969 km ^{2}. If the condition is that the heat conditions are fulfilled in all years for all varieties: such surfaces were almost non-existent during the 1971-2000 (29 km ^{2}), but in 2011-2020 their total surface is 4612km ^{2}.

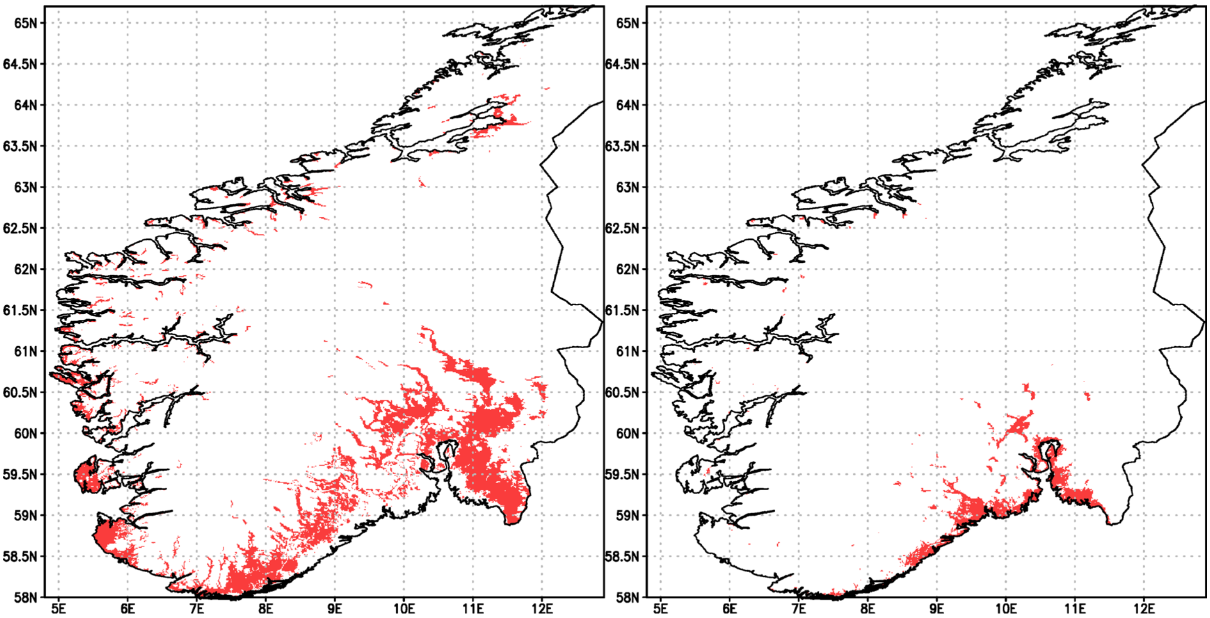

Figure 3.11. Areas with favorable heat conditions for apple growing in 2011-2020, which were not suitable during the base period 1971-2000, if the condition for at least one variety is fulfilled (left) and for all varieties (right). This anomaly shows the expansion of areas with favorable heat conditions in 2011-2020, with respect to the 1971-2000.

3.6 Impact of future climate change

3.6.1 Temperature and heat accumulation change

Anomalies of the mean temperature for the period May-September and accumulated growing-degree days above 10°C for the same fixed periods, for three future periods in comparison to the referent period (1971-2000), under the RCP8.5 scenario, are presented in Figures 3.12. and 3.13. According to the ensemble median, the mean vegetational temperature in the period 2021-2040 is expected to increase from 1 to 1.5°C across the domain, with an increase between 0.5 and 1°C in high mountains, and an increase between 1.5 and 2°C locally along the coastline and in the north and northwest of the domain. In the period 2041-2060, the mean vegetational temperature anomaly is expected to range between 1.5 and 2°C in the largest part of the domain. The smallest change (from 1 to 1.5°C) is anticipated along the coast and at high mountains in the west, while changes above 2°C are projected locally in the north, northwest hinterland and southeast inland areas. Projected changes are the largest for the end of the century (2081-2100), when the anomalies between 4 and 5°C are expected in the largest part of the domain, and between 3 and 4°C along the coastline.

Ensemble median accumulated growing-degree days are projected to increase between 100 and 200°C across most of the domain in the period 2021-2040, while in the north, along the northern and northwestern coast, and in the western hinterland, the increase is up to 300°C. In the period 2041-2060 accumulated growing-degree days are expected to increase between 200 and 300°C in almost all regions of the domain, except the western coast, where the expected change is below 200°C. In the period 2081-2100 the projected increase is between 600 and 700°C, between 500 and 600°C along the coast, and above 700°C locally in inland regions and in north of the domain.

The range of ensemble's 25th and 75th percentile of the anomaly, representing the uncertainty of the results, increases over time both for the mean vegetational temperature and the accumulated growing-degree days. It is more pronounced in continental parts of large fjords in the western and northwestern regions, as well as in the north.

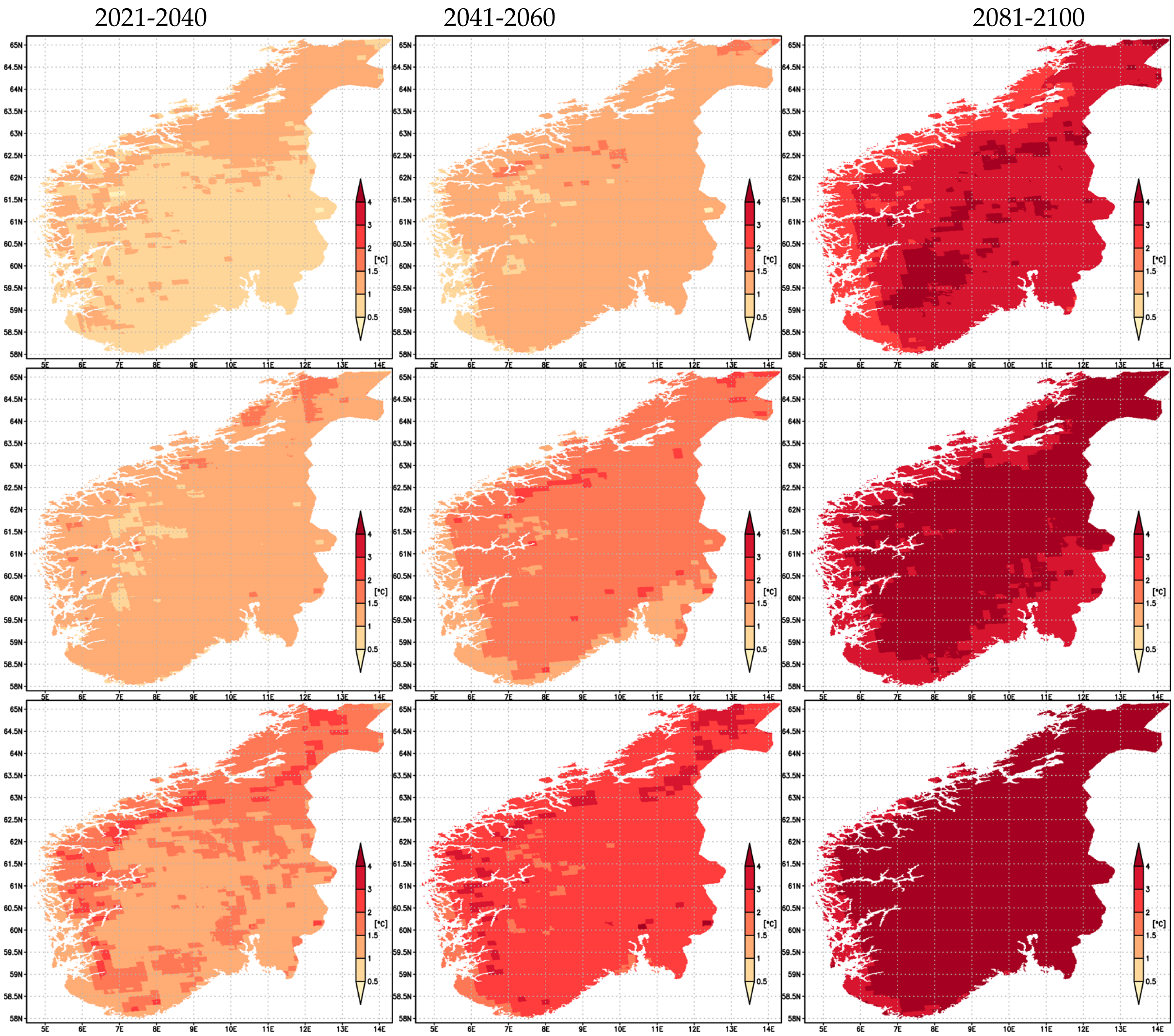

Figure 3.12. Median (middle row), 25th (upper row) and 75th (bottom row) percentile of the ensemble for the average anomaly of the mean temperature from May 1st to September 30th for 2021-2040 (left column), 2041-2060 (middle column) and 2081-2100 (right column) in comparison to the referent period 1971-2000, under the RCP8.5 scenario.

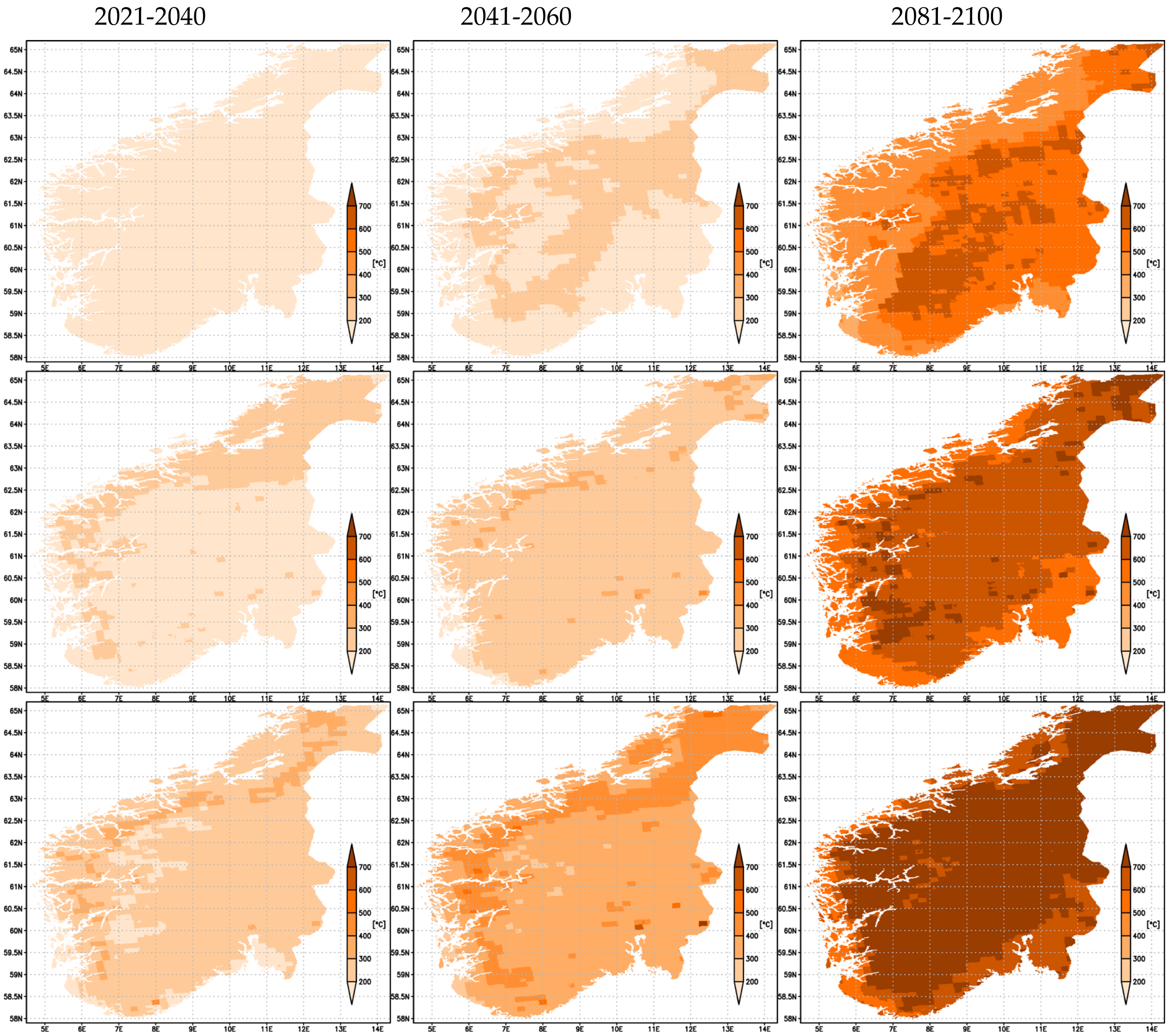

Figure 3.13. Median (middle row), 25th (upper row) and 75th (bottom row) percentile of the ensemble for the average accumulated growing-degree days from May 1st to September 30th for 2021-2040 (left column), 2041-2060 (middle column) and 2081-2100 (right column) in comparison to the referent period 1971-2000, under the RCP8.5 scenario.

3.6.2 Future zoning

Based on the previously established criteria of favorable heat conditions for cultivating 6 apple varieties, areas with these criteria fulfilled in at least 70% of years in a period (i.e. 14 years out of 20) were located. Areas with the fulfilled criteria for at least one variety in at least 5 models (i.e. the half from all models in the ensemble) are marked in blue in Figure 3.14, while those with fulfilled criteria for all 6 varieties are denoted in red. In the referent period, favorable heat conditions for cultivating all 6 of considered apple varieties were not found anywhere in the domain, but criteria for at least one variety were met only in the southern and southeastern coastline and some locations along the fjord in the western coast. The ensemble median was able to accurately identify 7 out of 9 areas where apple production is currently located. The only exceptions were the two northernmost locations, Stryn and Gloppen, which could not have been captured by the ensemble median.

In the period 2021-2040 most of the areas where in the referent period at least one variety fulfilled the criteria will be suitable for growing all 6 considered varieties. Areas in which at least one variety could be grown are going to spread inland (northward) in the south and southeast, as well as along the western coastline and its fjords, and locally in fjords in the north and northwest of the domain. In the period 2041-2060 areas in the south and southeast suitable for growing all 6 varieties will expand further into the continent, as well as some smaller coastal areas in the west and some fiords in the northwest of the domain. At the same time, the areas suitable for at least one variety will spread further along the western and northern coastline, inland in south and southeast, but it will also appear northern of 63.5°N, especially along the fjord and coastline. In the period 2081-2100 regions suitable for cultivating all 6 varieties will cover a wide area in the south, southeast and east, most of the western and northwestern coastline and fjords, as well as northern areas of the domain. Regions northern than 63°N are going to be suitable for growing at least one variety.

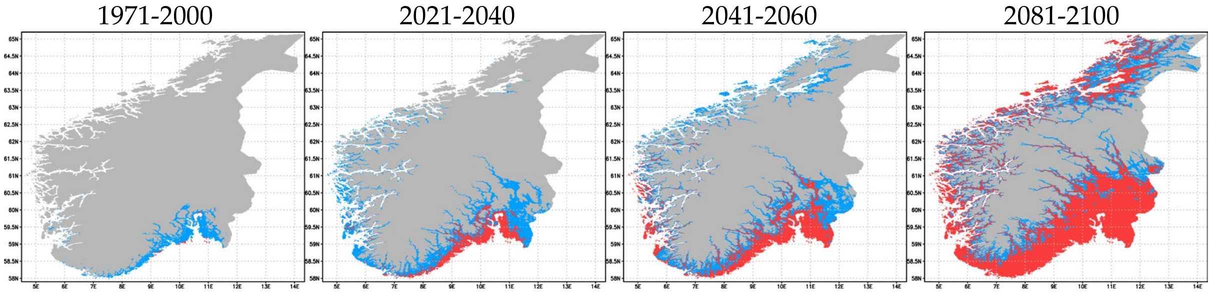

Figure 3.14. Areas in which is the heat condition criteria fulfilled for at least 70% of years during the period for 5 or more models are designated in blue, while areas where the criteria are met for all 6 considered varieties are in red. Maps are for different time periods, starting from the referent period (1971-2000) on the left, 2021-2040, 2041-2060, and 2081-2100 on the right.

Areas with suitable heat conditions for growing each of the considered apple varieties according to the ensemble median, in the referent and three future periods are noted in red in Figure 3.15, while surfaces (km ^{2}) of those areas according to the 25th, median and 75th percent values are given in Table 3.8. In the referent period heat conditions suitable for growing Discovery was found at the largest area (12.497 km ^{2}), followed by Garvenstein (7.924 km ^{2}), while climate favorable for Rubinstep covered the smallest area (340 km ^{2}). Heat conditions were met for all six varieties along the southern and southeastern coast and Oslofjord, while Discovery and Gravenstain could also be grown in some locations in the western coast.

In the period 2021-2040, the potential areas of cultivating Aroma, Elstar and Rubinstep are located along the southern and southeastern coast, around lakes in the southeast and locally in the western coast and its fjords. Summered shows potential expansion to the western coast and its fjords, while Gravenstein and Discovery will be potentially suitable for cultivating along the northwestern and northern coastline, with largest potential surfaces of 31.252 and 38.956 km ^{2} respectively.

In the period 2041-2060 heat conditions suitable for growing Aroma, Elstar and Rubinstep will expand northward in the south and southeast, along the western coast and locally in some fiords in the west and northwest. Areas suitable for cultivating Gravenstein and Discovery will spread northern of 63°N, potentially covering 49.036 km ^{2} and 59.150 km ^{2} respectively.

By the end of the century (2081-2100), under the scenario RCP8.5, even varieties that are more heat-demanding, Aroma, Elstar and Rubinstep, will potentially expand northern of 63°N, while Gravenstein and Discovery could cover 104.697 km ^{2} and 147.446 km ^{2} respectively.

Uncertainties in this climate change assessment arise from the selection of the greenhouse gasses concentration scenario, climate models and heat requirements criteria. To account for uncertainties related to future greenhouse gasses concentrations, multiple scenarios should be used. The choice of the scenario in this study was based on the adoption of the RCP8.5 scenario for adaptation planning in Norway (Meld, 2013). However, ranges of projected temperature changes across an ensemble of climate models often overlaps across different scenarios. For the ensemble used in this assessment, projected temperature change ranges for Norway under the RCP8.5 partially overlaps with those under the RCP4.5 by 2080, and median ensemble value under the RCP4.5 falls into the lower half of the ensemble range under the RCP8.5 up to 2050, while after 2080 these two ranges diverge (Hanssen-Bauer et al., 2017). Projected temperature changes under both scenarios have the same character but develop with different rate. Therefore, expected temperature changes at the end of the century under the RCP4.5 are comparable to the changes in the mid-century projected under the RCP8.5 (Hanssen-Bauer et al., 2017), while differences at the end of the century are substantial. Therefore, for long-term planning it is recommended to update this assessment using other scenarios as well.

Uncertainty related to model selection mainly originate from the parameterizations of complex or small-scale processes within the models. To assess it, an ensemble of multiple models can be used, and the range of its results should be analyzed alongside the median values. The ensemble used in this study consists of 10 combinations of 5 different global and 4 regional climate models.

Finally, the uncertainties originating from the choice of heat requirements criteria in this study were minimalized by employing criteria developed using time series and meteorological observations in Norwegian climate (Ullensvang). The fact that the ensemble median was capable to identify locations with heat favorable conditions within the referent period indicated that the last two sources of uncertainty are adequately mitigated.

Table 3.8. Surface (km ^{2}) of areas in the domain where the climate is suitable for growing considered apple varieties. Estimates are done according the 25th, median and 75th percentile of the ensemble of climate models for the referent (1971-2000) and three future periods.

Period/ Variety		Discovery	Gravenstein	Summerred	Aroma	Rubinstep	Elstar
1971-2000	25th perc.	10.831	6.835	2.787	908	201	590
	median	12.497	7.924	3.417	1.222	340	823
	75th perc.	15.400	9.444	4.154	1.843	532	1.308
2021-2040	25th perc.	32.735	26.732	16.448	9.416	6.029	7.818
	median	38.956	31.252	20.695	13.102	8.607	10.964
	75th perc.	49.699	40.768	29.404	21.342	15.625	18.508
2041-2060	25th perc.	47.681	40.368	29.543	20.434	15.868	17.722
	median	59.150	49.036	35.713	27.119	21.122	24.779
	75th perc.	71.453	61.929	48.411	37.826	31.733	35.280
2081-2100	25th perc.	94.903	85.679	72.473	62.048	54.716	58.402
	median	115.358	104.697	90.524	78.514	72.518	75.360
	75th perc.	147.446	136.320	121.228	109.276	101.366	105.261

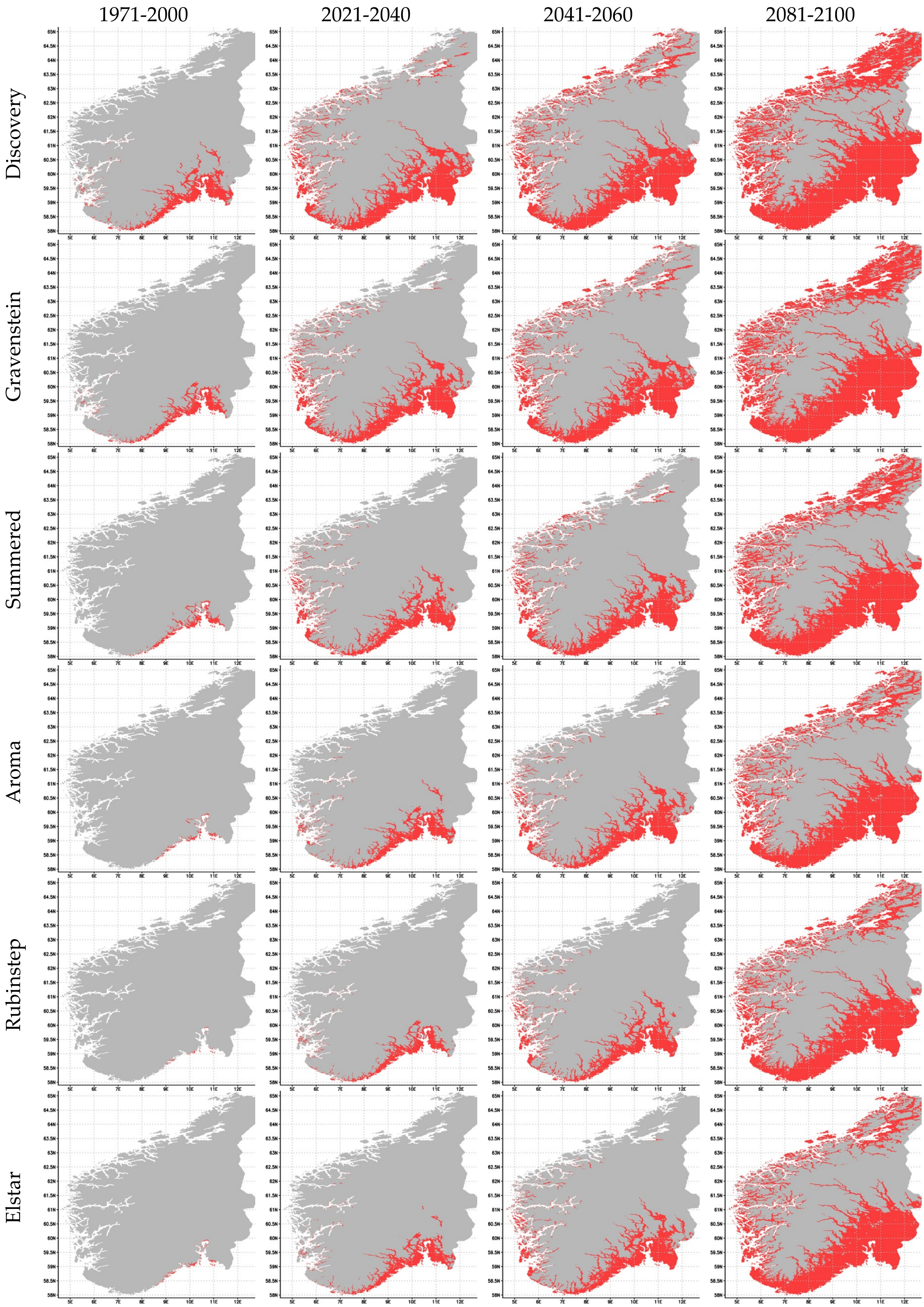

Figure 3.15. Areas in which the heat criteria are fulfilled for at least 70% of years during the period for 5 or more models are designated in red. From the left to the right, first column is for the referent period (1971-2000), second column for the period 2021-2040, the third column for the period 2041-2060, and the last column for the period 2081-2100. In rows are presented results for different varieties.

This study is limited to the analysis of heat conditions previously found to be necessary for cultivating common apple varieties. It does not involve the analysis of soil types, land cover, or the weather-related risks, which are critical information for planning of apple production at the local level. However, some conclusions about future impacts of weather-related risks can be drawn from the available literature. Although in many fruit production regions insufficient accumulation of chilling units during dormancy is a significant concern (Fraga and Santos, 2021), in Norway, even with the projected temperature increase, this is not expected to be a problem (Meld, 2013.). The risk of low temperatures during dormancy will decrease which could enable the cultivation of new varieties (Meld, 2013.). However, the risk of spring frost requires further analysis due to the shift of blooming, the most vulnerable development phase, towards earlier dates. The maximum daily temperatures during vegetation are not expected to increase enough to pose a considerable risk to the production (Hanssen-Bauer et al., 2017).

The primary future concern for apple production in Norway is likely to be an increase in precipitation, which may enhance occurrence of insects and diseases, inhibit pollination and affect activities in orchards. According to the projections, annual precipitation in the regions relevant for future apple production is expected to increase by 8% (under the RCP4.5) to 17% (under the RCP8.5) by the end of the century, while the number of days with heavy precipitation is estimated to double (Hanssen-Bauer et al., 2017). This may result in a larger share of intensive events and less of moderate and weak precipitation in the total accumulated water. Long term observations indicate increasing trends in seasonal precipitation across these regions, ranging from 1.2 to 2.5% per decade during winter, from 0.1 to 2.7% per decade during spring, from 0.4 to 1.6% per decade during summer, and from 1 to 3% per decade during autumn (Hanssen-Bauer et al., 2017). This requires further analysis of future precipitation change within sensitive periods such as blooming and pre-harvest. Nevertheless, it is important to consider the high uncertainty of models' precipitation projections, as well as large spatial heterogeneity of precipitation over the complex terrain such is Norway.

4 Conclusions

This study presents a methodology for the assessment of climate change impact on heat conditions for apple cultivation. Available phenological and meteorological observations were collected from the NIBIO Ullensvang orchards for the period 2001-2020. Phenological data were collected for the six apple cultivars Discovery, Gravenstein, Summered, Aroma, Rubinstep and Elstar. Data were processed to determine the base temperature for full blooming and the threshold for the sum of temperatures above the base temperature, which represent heat requirements of the variety to achieve stage of ripening after which harvest could be carried out.

Derived criteria and thresholds were applied over the chosen domain of southern part of Norway, which includes Western Norway, Southern Norway, Eastern Norway, and western part of Trøndelag, to determine zones where the heat conditions are favorable for apple growing. . Spatial mapping was done using EOBS daily temperature data, which was interpolated at a 10 times higher resolution (lat-lon 0.01°x0.01°). Obtained results show that, in the period 2011-2020, 15.1% of the area is suitable for apple growing, with 2.6% having heat potential for growing of all varieties, including ones with higher demands for heat.

Increasing temperatures lead to an expansion of surface areas with favorable heat conditions for apple growing, with the area increasing by approximately 2.5 times compared to the period 1971-2000. The expansion rate is even greater in surfaces with heat potential for growing of all varieties, including those with the highest heat demands. The heat conditions required for fruit development during the growing season for varieties with lesser demands for heat spread towards the north in the Trøndelag region.

Climate change projections under the RCP8.5 shows that areas suitable for cultivating all six considered apple varieties will continue to increase. The spread is expected to occur in three general directions: (1) northwards (inland) in the south and southeast, (2) along the western and northwestern coastline towards higher latitudes, and (3) along continental areas of fjords.

Over the next 20 years, heat conditions along the western and northwestern coast and fjords will become suitable for cultivating at least one of the apple varieties, while areas around the Oslofjord and along the south and southeastern coast will be favorable for all six varieties.

By the middle of the century, heat conditions will be adequate for cultivating all six apple varieties in the south and southeast coast, expanding inland in the southeastern part of the country, as well as along the western coastline and locally along continental areas of fjords in the western and northwestern region.

By the end of the of the century, all six varieties could potentially be grown in the large area of the eastern and southeastern region, along the western and northwestern coastline and fjords, as well as north of 63.5°N. The Discovery and Gravenstein varieties, which require less heat, are expected to have the fastest and largest expansion.

Reliability of the presented methodology can be increased by including additional phenological data from multiple sites and years. Furthermore, the mapping can be sensitive to the quality of available meteorological data. Therefore, incorporating data from additional meteorological observation sites can enhance the accuracy of interpolated data and thereby improve the quality of the zoning. The presented methodology can also be extended to other cultivars, provided that phenological data are available, preferably with meteorological observations close to the growing sites.

Presented zoning of areas with favorable heat conditions for apple growing includes the assessment of heat capacity during the growing season available for plants development. However, weather risks, such as the risk from damaging low temperatures, drought and extreme precipitation, were not considered. Besides, the zoning of potential growing areas should also include information on land cover and soil properties, which would provide information on whether the surface is available for cultivating and if the soil has appropriate characteristics (e.g. composition, depth, etc.).

This assessment, due to its high spatial resolution, may be useful for strategic planning and developing climate change adaptation measures in apple production. The findings can help in identifying suitable locations for new experimental and commercial orchards, developing policies to support apple production in specific areas, maximizing the potential benefits of the changing climate, and promoting sustainability through efficient use of natural resources and reduced environmental impacts.

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Appendix

A1. Mapping of spatial distribution of favorable heat conditions for apple growing for 2011-2020

Results derived for each variety according to different thresholds for SUMT, *sumtn* and *sumta*, are given in Figures A1.1 and Figure A1.2, respectively. Tables showing percentage of surface of areas which fulfil heat conditions in certain number of years, according to both SUMT thresholds, are given in Table A1.1 and Table A1.2.

Table A1.1. Percentage of total land area for which mapping is performed (179042.6 km ^{2}) where are heat conditions achieved in none of the years (0), in one or more years (1≤), in two or more years (2≤), etc., and in all (10) years during the period 2011-2020, for each variety; derived using *sumtn* as heat threshold, for each variety.

	0	1 ≤	2 ≤	3 ≤	4 ≤	5 ≤	6 ≤	7 ≤	8 ≤	9 ≤	10
Discovery	51.2	48.8	41.6	38.6	36.1	33.7	30.1	26.3	22.9	19.1	15.0
Gravenstein	55.2	44.8	37.6	34.8	31.7	28.3	25.2	22.7	20.4	15.0	11.4
Summerred	61.2	38.8	31.4	28.5	25.4	22.2	19.2	16.8	14.7	9.5	6.6
Aroma	66.9	33.1	26.0	23.6	20.5	17.6	14.3	12.2	9.6	7.2	4.6
Rubinstep	69.7	30.3	23.0	19.8	17.1	14.3	11.8	9.7	7.8	4.6	2.6
Elstar	68.4	31.6	24.5	22.0	19.0	16.1	12.9	10.8	8.4	6.3	3.9

Table A1.2. Percentage of total land area for which mapping is performed (179042.6 km ^{2}) where are heat conditions achieved in none of the years (0), in one or more years (1≤), in two or more years (2≤), etc., and in all (10) years during the period 2011-2020, for each variety; derived using *sumta* as heat threshold, for each variety.

	0	1 ≤	2 ≤	3 ≤	4 ≤	5 ≤	6 ≤	7 ≤	8 ≤	9 ≤	10
Discovery	67.2	32.8	25.5	22.5	19.5	16.4	13.8	11.6	9.6	6.1	3.8
Gravenstein	67.7	32.3	26.2	22.3	19.8	17.6	15.0	12.8	10.0	4.5	2.4
Summerred	72.7	27.3	21.3	17.4	15.1	12.9	10.6	8.7	6.4	2.2	0.9
Aroma	79.5	20.5	14.7	11.3	9.0	6.6	5.2	3.8	2.7	1.0	0.3
Rubinstep	83.1	16.9	11.2	7.7	5.5	4.1	3.1	2.0	1.0	0.1	0.01
Elstar	75.7	24.3	17.5	14.4	11.8	8.9	7.0	5.7	4.4	2.5	0.9

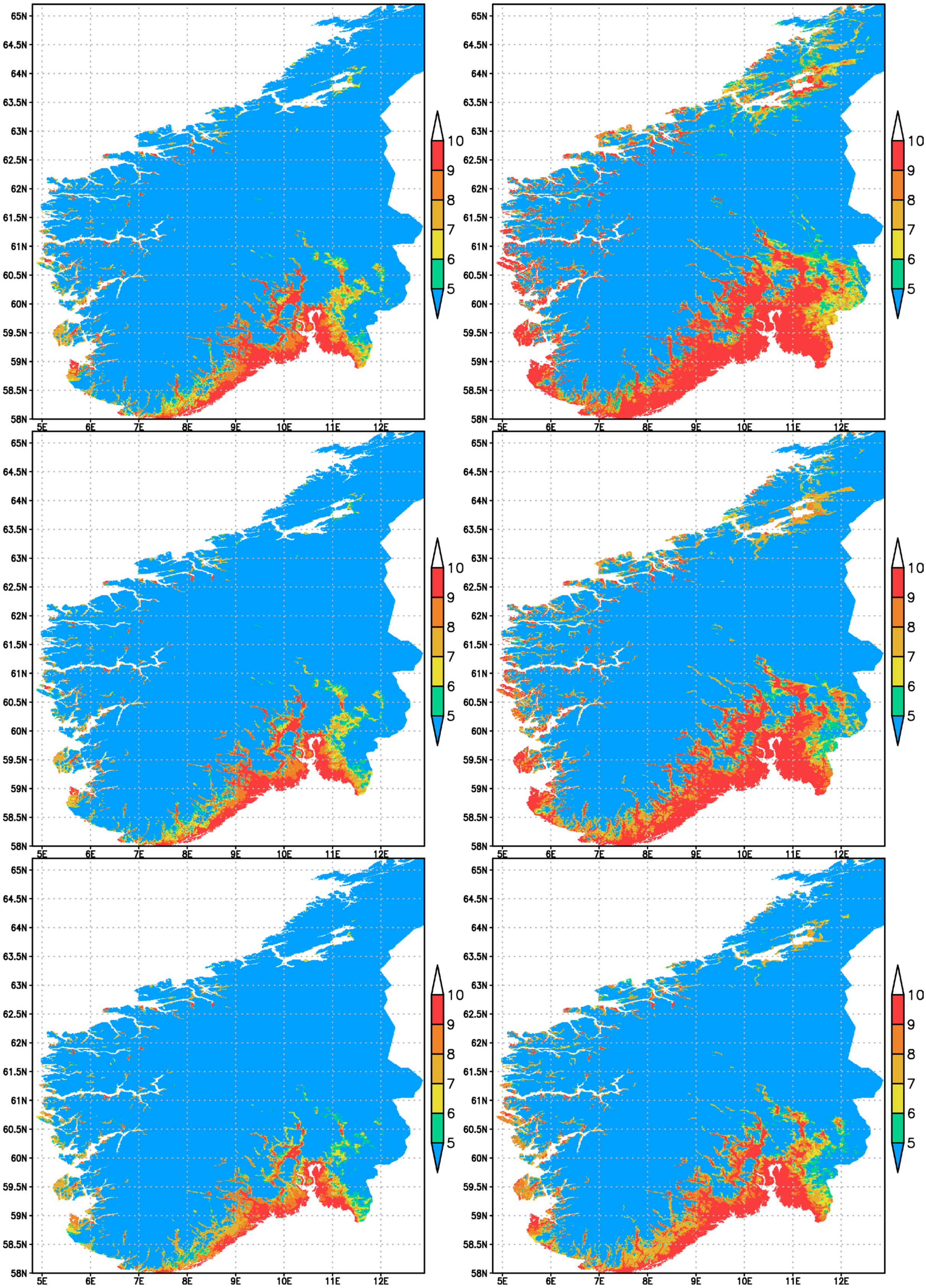


Figure A1.1. Number of years in 2011-2020 when heat conditions were achieved for each variety: Aroma (upper left), Discovery (upper right), Elstar (middle left), Gravenstein (middle right), Rubinstep (lower left), and Summerred (lower right), using sumn for heat threshold; in blue are areas which have in ≤ 5 years fulfilled heat conditions, in green reached required heat conditions in 6 years, in yellow in 7, etc., and in red are given areas which fulfilled required heat conditions in all 10 years.

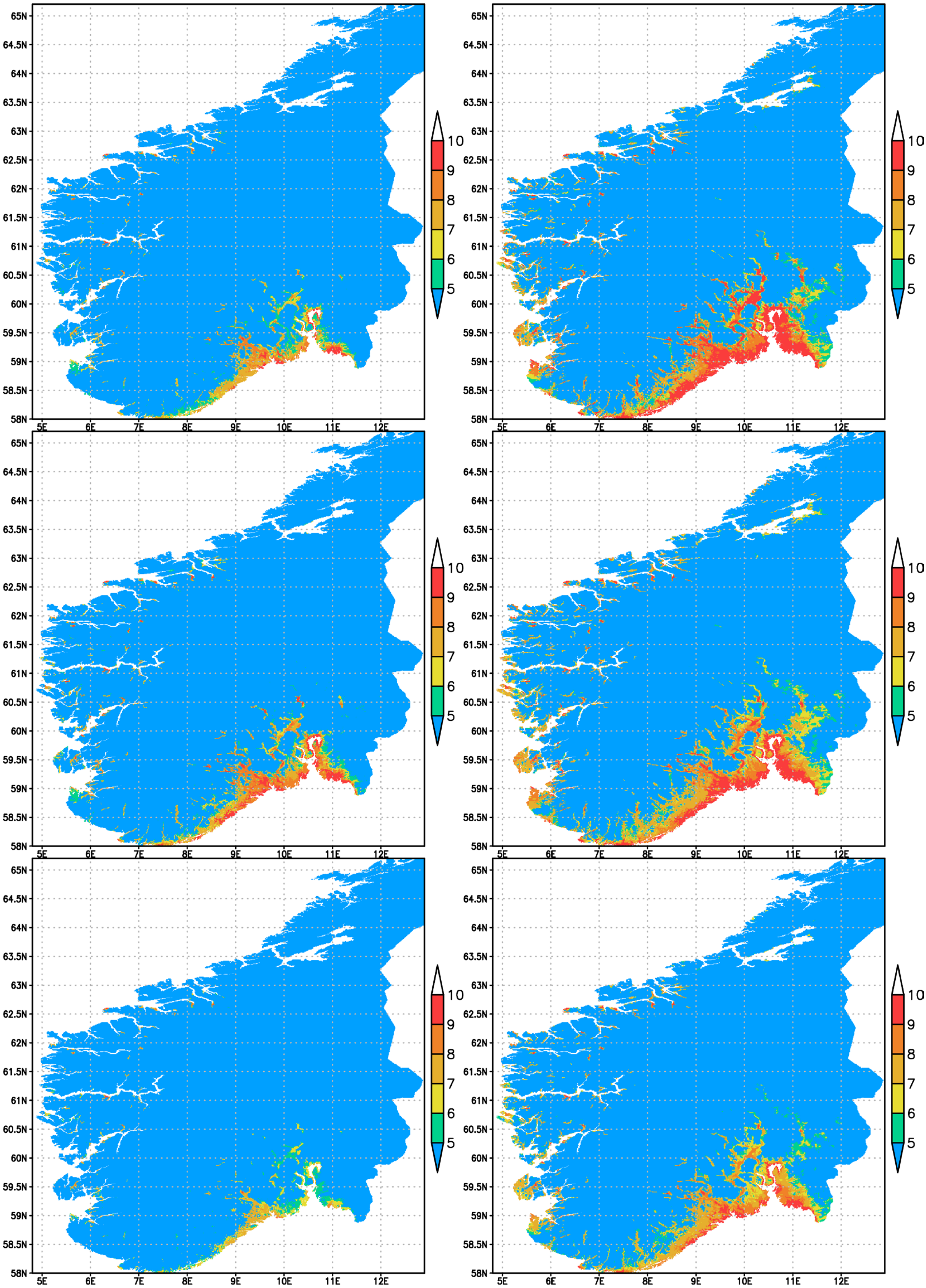
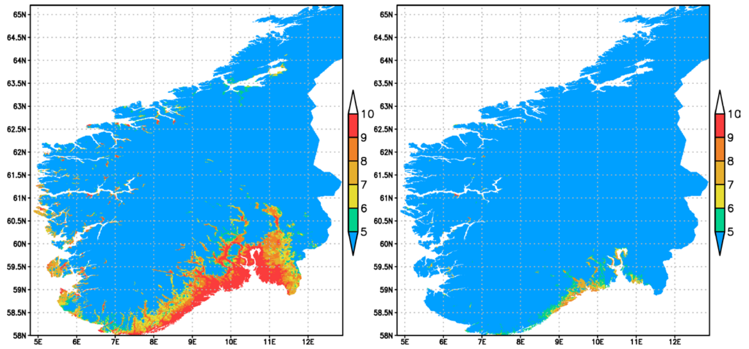


Figure A1.2. Number of years in 2011-2020 when heat conditions were achieved for each variety: Aroma (upper left), dis (upper right), Elstar (middle left), Gravenstein (middle right), Rubinstep (lower left), and Summerred (lower right), using suma for heat threshold; in blue are areas which have in ≤ 5 years fulfilled heat conditions, in green reached required heat conditions in 6 years, in yellow in 7, etc., and in red are given areas which fulfilled required heat conditions in all 10 years.

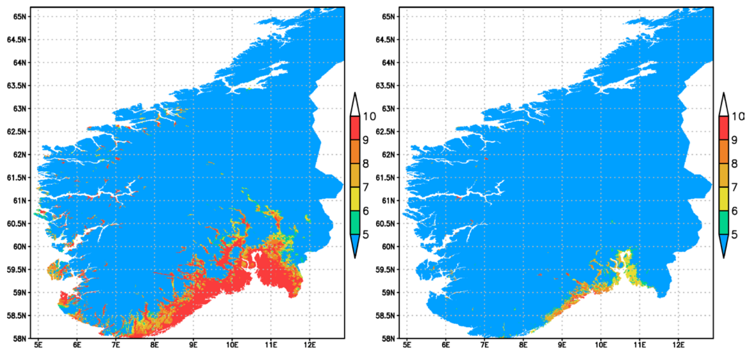
A2. Mapping of spatial distribution of favorable heat conditions for apple growing for past periods

Maps shown in Figures A2.1 and A2.2 show the expansion of areas when heat conditions for apple growing are fulfilled in certain number of years for each decade in the period 1961-2020. These data are supplement to the Figure 2.11 and Table 2.9 in the main text.

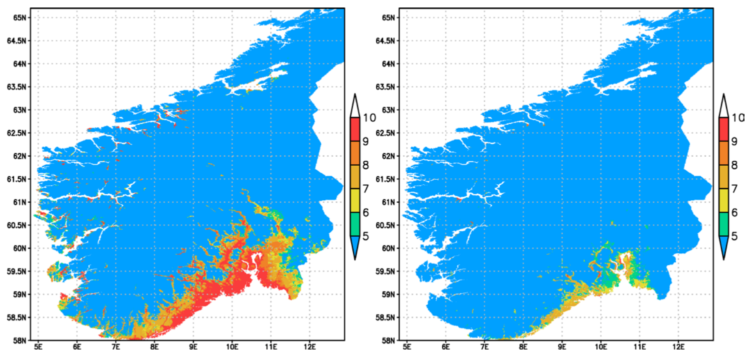
1961-1970



1971-1980



1981-1990



1991-2000

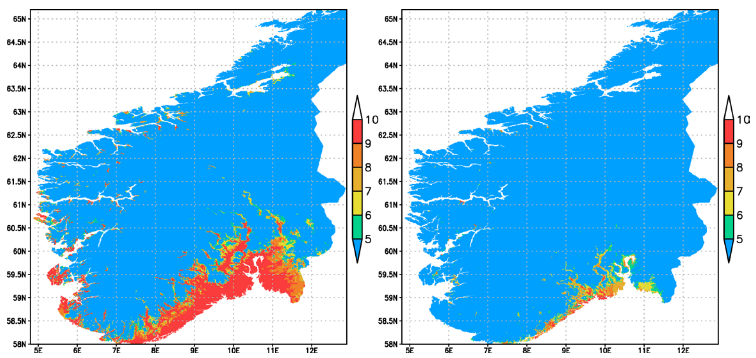


Figure A2.1. Number of years in different decades in the 20th century when heat conditions were achieved at least for one apple variety (left) and for all apple varieties (right); using sumn for heat threshold; in blue are areas which have in ≤ 5 years fulfilled heat conditions, in green reached required heat conditions in 6 years, in yellow in 7, etc., and in red are given areas which fulfilled required heat conditions in all 10 years.

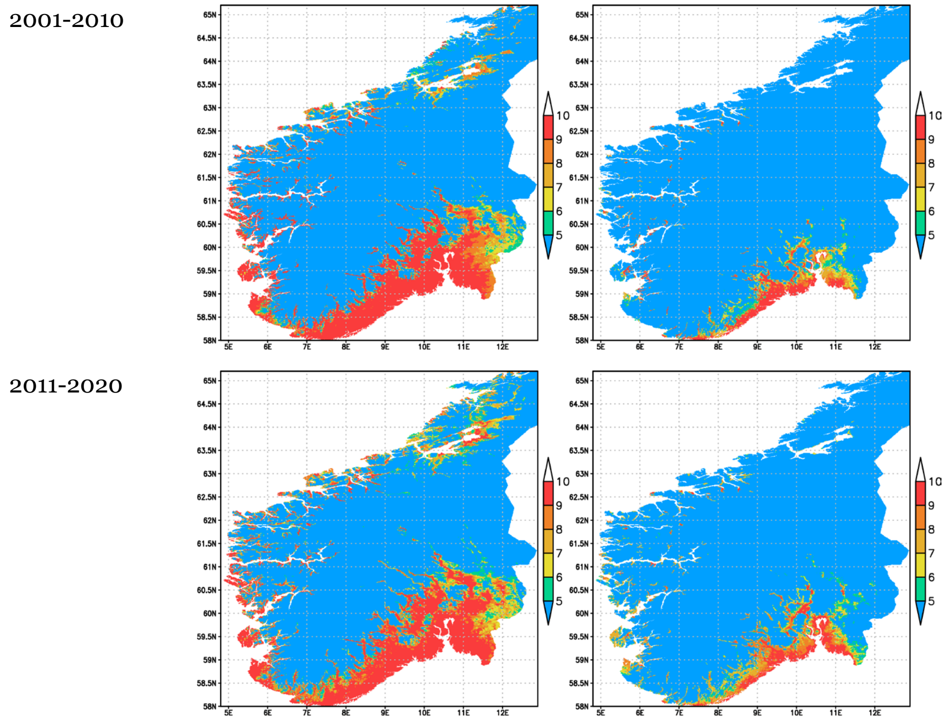


Figure A2.2. Number of years in decades 2001-2010 and 2011-2020 when heat conditions were achieved at least for one apple variety (left) and for all apple varieties (right); using sumn for heat threshold; in blue are areas which have in ≤ 5 years fulfilled heat conditions, in green reached required heat conditions in 6 years, in yellow in 7, etc., and in red are given areas which fulfilled required heat conditions in all 10 years.

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Cover photo: The apple cultivar ‘Gravenstein’ in full full bloom. Photo: Oddmund Frøynes

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