TEMPEX: Developing spatial layers of climatic temperature extremes: Final report in the BAFU-WSL program “Forests and Climate Change”

Report

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Publication date:
2018-08

Permanent link:
https://doi.org/10.3929/ethz-b-000311157

TEMPEX Final Report

Developing spatial layers of climatic temperature extremes

A project funded by the BAFU-WSL program on
"Forests and Climate Change" in Switzerland

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Ein Projekt-Schlussbericht aus dem Forschungsprogramm «Wald und Klimawandel» von BAFU und WSL
(www.wsl.ch/wald_klima)

Projektlaufzeit: 1.7.2014 bis 31.12.2016.

Zitierung

Zimmermann, N.E.; Wüest, R.O.; Schmatz, D.R.; Gallien, L., 2016. TempEx Final Report: Developing spatial layers of climatic temperature extremes. Birmensdorf, Eidg. Forschungsanstalt für Wald, Schnee und Landschaft WSL; 12 Seiten.

Im pdf-Format zu beziehen über www.wsl.ch/wald_klima

Project Summary

In this project we calculated eight indices of temperature extremes and a compound index of frost frequency after leaf flush, which was tuned to four different species and calculated in a prognostic mode. The eight indices extracted from downscaled climate data, scaled to NFI plots (1 x 1 km NFI 1 network) in Switzerland for current and projected future climates, included the following: (1) the absolute annual minimum temperature; (2) absolute annual maximum temperature; (3) the annual number of frost days (Tmin < 0°C); (4) the annual number of frozen days (Tmax < 0°C); (5) the annually largest diurnal temperature range; (6) the mean annual diurnal temperature range; (7) the annually longest period of continuous frost days (Tmin < 0°C); (8) the annually longest period of continuous frozen days (Tmax < 0°C).

All nine measures generated here indicate that the projected climate trends are affecting the temperature extremes as much as they do the temperature means. The extremes decrease at a rate comparable to temperature means, and the climatic conditions become gradually suitable to species that are less tolerant to low temperature extremes. By the end of the 21st Century, the climate barely reaches conditions represented as the cold limit of Mediterranean species (30-year mean of annual absolute minimum temperatures of ca. -6 °C on the Swiss Plateau). Since the climate is fluctuating quite considerably, and because the trajectory barely reaches this threshold towards the end of the 21st Century, it is not very likely that truly mediterranean species will already find suitable habitats then. Rather, sub-mediterranean and warm-temperate species will be the preferred choice for adaptive and active forest management practice. It remains to be considered that the indices presented here do not include drought, which represents another important constraint for the choice of suitable tree species.

Caution is needed when interpreting the presented results. First, we only use data from one scenario (A1B), whereas there is uncertainty as to which of the usually four scenarios used is actually most suitable for describing the future trajectory of the climate. Second, we only use data from three regional climate models (CLM, RCA30, RegCM3) that are all fed by data from the same global circulation model (ECHAM5). This means that only a small variety of possible futures is explored. Finally, we had to request new versions of the obtained data from Meteotest due to errors found during the processing. While we think that most problems are solved now, we are not completely the currently used data is error-free, as we still found some patterns that are counter-intuitive. Some of this may originate from the RCM data, though.

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Introduction

Climate has long been accepted as being a major driver of plant species distribution, but also of growth, regeneration and – especially the variability and extremes in climate – mortality (Humboldt & Bonpland 1805; Shugart 1984; Woodward 1987). The world is currently undergoing a comparably rapid shift in climate means and its variability (IPCC 2007, 2013). This has consequences for the Earth's vegetation, as many species start to respond to these on-going changes (Parmesan & Yohe 2003; Walther *et al.* 2005; Walther *et al.* 2002). Much attention has been and is given to the drought related increase in mortality events, which naturally occur at the trailing edge of species' ranges as a consequence of an increase in temperature, vapour pressure deficits and soil humidity, with its cascading effects on secondary causes of mortality (Breshears *et al.* 2009; van Mantgem *et al.* 2009). However, we observe also a slow and steady migration of many species towards higher altitudes or latitudes (Gehrig-Fasel *et al.* 2007; Lenoir *et al.* 2008; Parmesan *et al.* 1999), which can be attributed to a change in temperature-related control of the upper (cold-constrained) distribution limit of species.

Tree species have also started to respond to these changes. While we observe significant changes at the (usually drought-constrained) trailing edge in some species and some locations (Allen *et al.* 2010; Breshears *et al.* 2009; van Mantgem *et al.* 2009), there is only a weak signal currently observable at the upper or northern range edge (Gehrig-Fasel *et al.* 2007; Woodall *et al.* 2009). One reason for this slow upward and northward movement is the slow reduction in cold-temperature related extremes and means (Körner *et al.* 2016). In order to better understand the effect of temperature on upward or poleward movement of trees, and to understand the change in habitat suitability just north of (or at higher elevation than) the current range, it is important to track the temperature related variability and extremes. Zimmermann et al. (2009) have demonstrated that climate (including temperature) extremes significantly influence species ranges. Having such variables at hand for analyses allows for a better assessment of the likely consequences of climate change on tree species ranges.

There is clear evidence for a temperature control of poleward and upper range limits. On the one hand, the treeline has been shown to be clearly summer temperature limited (Gehrig-Fasel *et al.* 2007; Körner 1998; Körner & Paulsen 2004). In addition, the upper limit of broad-leaved deciduous tree species is also clearly limited by temperatures, namely the absolute minima of temperatures during the leave-flush period (Körner *et al.* 2016; Lenz *et al.* 2013; Zimmermann *et al.* 2016). Furthermore, it has been shown that the boreal poleward and the upper alpine limit of tree species are position according to the same ranking among tree species and following similar temperature constraints, indicating that different biotic environments do not much affect the temperature control of the cold limit in tree species (Randin *et al.* 2013), a fact that is not only valid for trees but also for other plants (Pellissier *et al.* 2013).

We can summarize from these findings, that the poleward and upward movement of tree species most likely is controlled by warming of summer temperatures in general, and the release in cold extremes in specific. Due to the fact that extremes are rare, the release is not likely to occur linearly, and the advance of tree species to higher or more poleward sites is likely a very slow

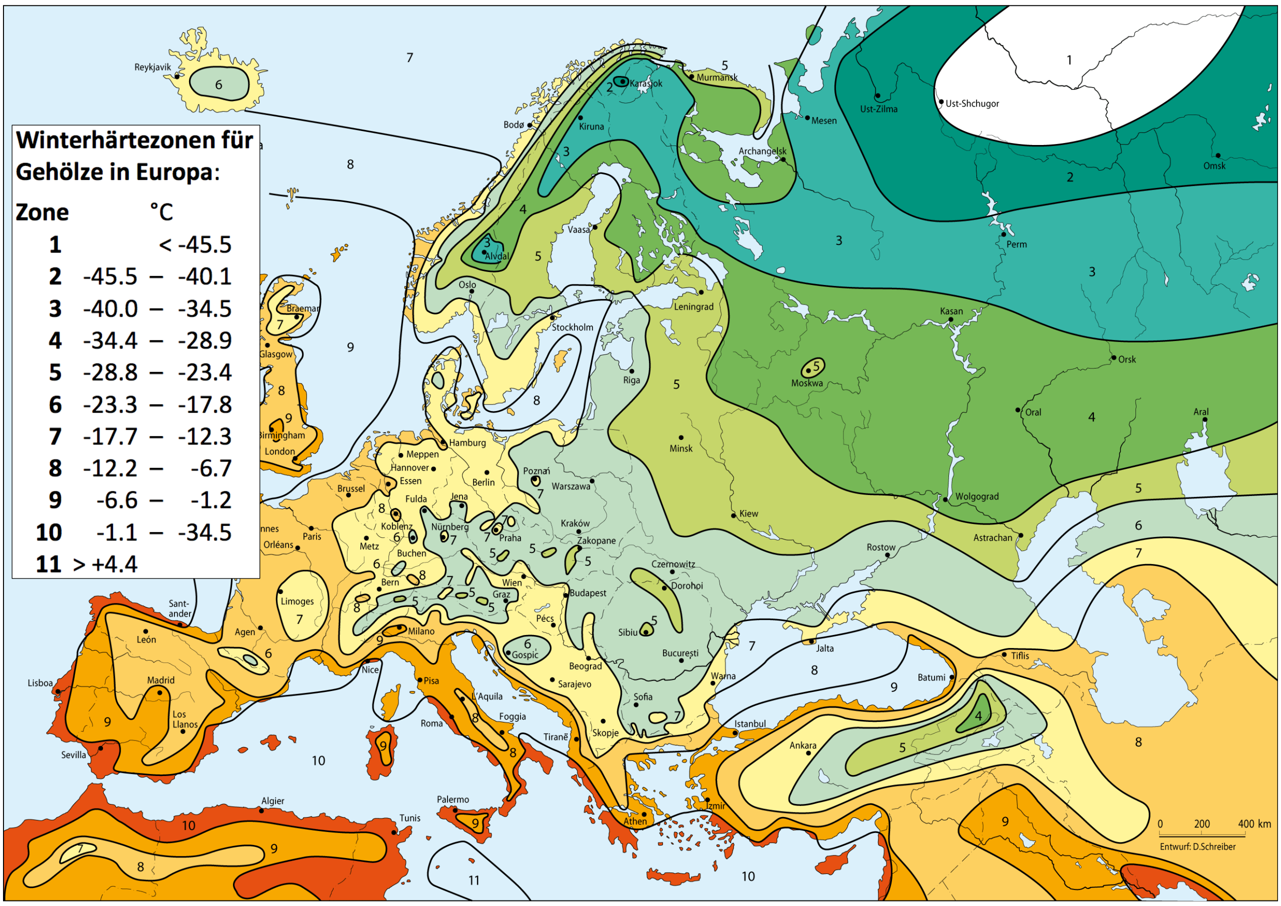

Figure 1*: Plant Hardiness Zones, originally developed by the US Dept. of Agriculture, represent the average annual extreme temperatures (daily minimum temperatures), and not the absolute lowest temperature ever observed.*

process. Trees do not only need to be able to regenerate, but also to survive the sapling age and mature to adult trees. Several studies have demonstrated how slow this upward and poleward migration actually is. Gehrig-Fasel et al. (2007) have shown that the upward shift in treelines is much slower than can be expected from the general warming trend, and only amounts to few meters per year as a maximum rate. In the Polar Ural mounts, a region untouched by humans, the upward shift of treelines has also shifted only very marginally, with open and closed forests climbing only 41 m and 23 m during the period from 1910 to 2000 (Shiyatov *et al.* 2007). In both studies, the simultaneous temperature change during the study periods suggests a much (2-5x) higher upward shift, which indicates the time lag in the re-adjustment to the rising temperatures.

It is not only the boreal or temperate, but also the (sub-) mediterranean species that will benefit from warming temperatures. It is crucial that the winter minima do not fall on average below -12 °C for many submediterranean tree species. the winter hardiness of mediterranean trees is even higher, namely -6 to -1 (for meso- and thermo-mediterranean species), and the same species cannot tolerate a longer duration of frozen soils (Bärtels 2001; Figure 1). Many mediterranean species do not tolerate absolute extremes below -10 to -15 °C.

It is therefore important to understand the evolution of low temperatures under climate change. For many species though, it is not simply the absolute minimum temperature that governs its response to climate change (as it may tolerate generally low temperatures) but rather the total amount of thermal energy above a threshold below which no growth is possible. This threshold is generally set to 5.5 °C for trees (Woodward 1987), and the index is called "degreedays of the growing season" (DDEG). Other important indices relate to the maximum temperature or to the number of freezing (minimum temperature is below 0 °C) or frozen (maximum temperature is below 0 °C) days. Finally, a complex form of analysing temperature effects is to address the frost events around the leaf flush date of trees. This requires individual models for the flush dates, which is not available for many tree species.

Here, we present a range of temperature related maps and indicators of temperature extremes. These can be used to assist the judgement what areas might become suitable to more (sub-) mediterranean and warm-adapted species, and by when. This is relevant for species that are currently not adapted in these regions and require that climate is less cold-extreme than it currently still is. We present results from three climate models that all follow the A1B scenario, as was decided to use in phase 2 of the FOEN and WSL organized "forest and climate change" program.

Project objectives

Research objectives

The major goal of the TempEx (*Developing spatial layers of climatic temperature extremes*) was to develop state-of-the-art temperature based climate extreme data layers in order to support the adaptation of the management to projected future climates in the forests of Switzerland. This information is important to enhance our knowledge about future climate trajectories and how it might affect our forests and the management of them. It is also important for integrating the results form previous projects into a synthesis of the forest and climate change program towards a support tool for Swiss foresters. The layers are based on downscaled daily climate data for Switzerland at a ca. 1 km spatial resolution made available by Meteotest for 3 different regional circulation models (RCMs) originating from the ENSEMBLES EU project and the Swiss report on the climate development by the end of 2100, termed CH2011 (2011).

RESULTS 1: *Absolute minimum temperatures*

The absolute minimum temperature in Switzerland is expected to change considerably, and increasing by more than 5°C on average across all three RCMs used (Fig. 2; Appendix A1.1). The trend is similar in all four elevational bands. The spatial patterns of the RCA30 model differ from the other two and do not seem to look very reliable (Appendix A1.1, first row), although in the temporal trend graph there is no obvious deviation from the other two models. The CLM model projects slightly higher warming trends than the other two models. On the other hand, the RCA30 is clearly the one with the lowest projected warming trend.

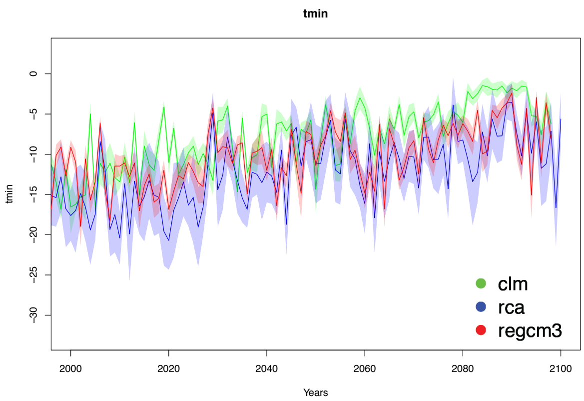

***Figure 2**: Absolute annual minimum temperature simulated from three different RCM models over Switzerland for the elevation band <500m. Variations around the mean trend reflect the values from all pixels falling into this elevation band.*

The evolution of the absolute minimum temperature reaches values by the end of the Century that become clearly suitable for submediterranean, and partly even mediterranean species. After 2070, absolute low temperatures rarely fall below -15 °C, even for the "coldest" RCA30 model on the lowest altitudinal band. Even above 1200 m, the values are warmer than currently below 500 m for two models, but not for RCA30, indicating that many temperate species will be able to grow at higher altitudes.

RESULTS 2: *Absolute maximum temperatures*

Like absolute minimum temperatures, the absolute maximum temperatures in Switzerland are projected to increase considerably and >5 °C on average across all three models (Fig. 3; Appendix A1.2). The CLM model clearly projects a warming in temperature maxima that is clearly higher than that of the two other models. This trend is most clearly visible in the lower two elevation bands and is much weaker above 800 m (Appendix A1.2, rows 3-4).

As illustrated in Figure 4, the CLM model projects a slight decrease in the absolute temperature maxima for the first period (2020-2049), whereas for all other periods and for the two other

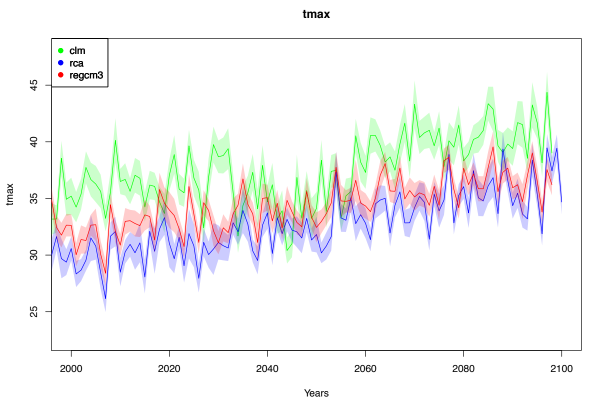

***Figure 3**: Absolute annual maximum temperature simulated from three different RCM models over Switzerland for the elevation band 500-800 m. Variations around the mean trend reflect the values from all pixels falling into this elevation band.*

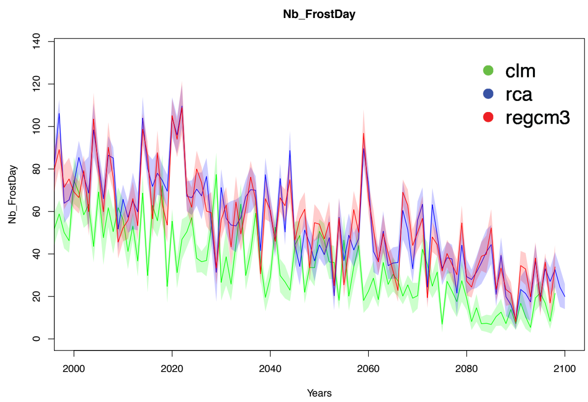

***Figure 5**: Temporal trend of the number of frost days simulated from three different RCM models over Switzerland for the elevation band <500m. Variations around the mean trend reflect the values from all pixels falling into this elevation band.*

models, the absolute temperature maxima are always projected to increase compared to today (1981-2010).

This cooling is, however very low only, and the trend in both directions is below 1 °C. We therefore can assume that the absolute maximum temperatures are very similar as under the current climate for this CLM model. For the other two models, the warming trends are also very low for the period and only increase afterwards (Appendix A2.2).

RESULTS 3: *Number of frost days*

The number of days with frost is expected to dramatically decrease in Switzerland by the end of the century (Appendices A1.3 & A2.3). Specifically, at lowest altitudes (below 500 m) and on the Swiss Plateau, the decrease is proportionally strong (Figs. 5 & 6), the decrease amounts to ca. 40-50 days, which reduces the frost days from ca. 70 as of today to below 20-30 for the elevational band below 500 m (Fig. 5).

This reduction by >50% is strong, and it is strongest for the CLM model, while the two other models remain at slightly higher values (Fig. 6). Such a decrease in frost days will allow more sub-mediterranean and mediterranean species to survive on the Plateau.

RESULTS 4: *Number of frozen days*

The number of frozen days follows a very similar pattern (Appendices A1.4 & A2.4) as that of the number of frost days. There is one significant exception, though. The number of frozen days (days with Tmax below freezing) remains particularly high in some periods throughout the 21st Century, but decrease much more rapidly otherwise (Fig. 7) compared to the number of frost days (Fig. 5). This indicates the number of days with complete freezing will be reduced even more strongly than the number of frost days. Yet, it also means that some extended frozen periods still remain. However, towards the end of the 21st Century, these periods of frozen days are reduced to almost 0, even at altitudes between 800-1200 m, and clearly even more so below 800 m in altitude. This trend is true for all three models (Fig.7).

Most models project a warming in all future periods, with the exception of the CLM model, which projects a slight increase in the number of frozen days during the first period until 2020-2049 for low altitudes in the Ticino (Fig. 8).

This trend is very weak only, and likely not statistically significant. After 2080, the projections predict very few frozen days only at lowest altitudes, indicating almost mediterranean conditions.

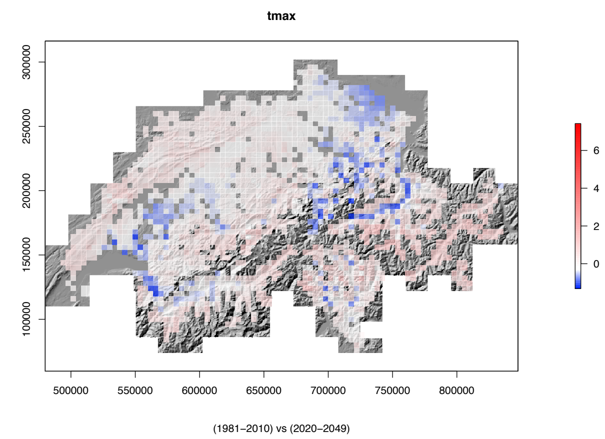

***Figure 4**: Anomalies in absolute annual maximum temperature simulated from the CLM model for the mean over the period 2020-2049 relative to the current climate (mean over 1981-2010). Blue shades indicate lower temperatures than today, while red colors indicate warmer temperatures compared to today.*

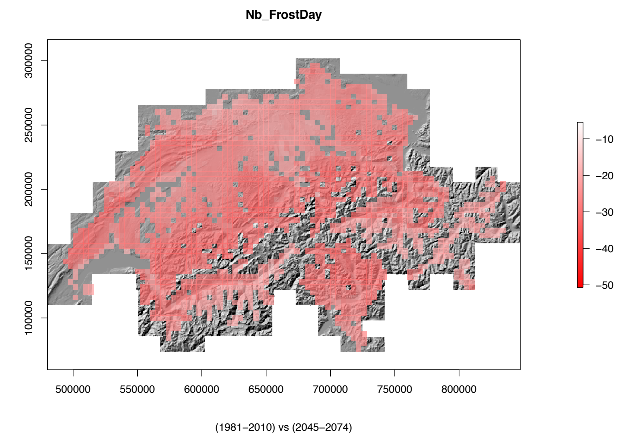

***Figure 6**: Anomalies in the number of frost days simulated from the RegCM3 model for the mean over the period 2070-2099 relative to the current climate (mean over 1981-2010). Blue shades indicate lower temperatures than today, while red colors indicate warmer temperatures compared to today.*

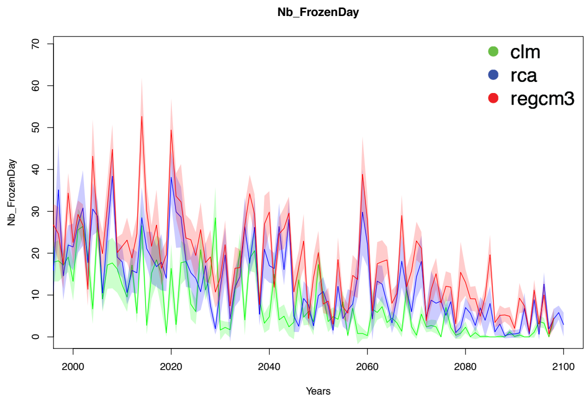

***Figure 7**: Temporal trend of the number of frozen days simulated from three different RCM models over Switzerland for the elevation band 500-800m. Variations around the mean trend reflect the values from all pixels falling into this elevation band.*

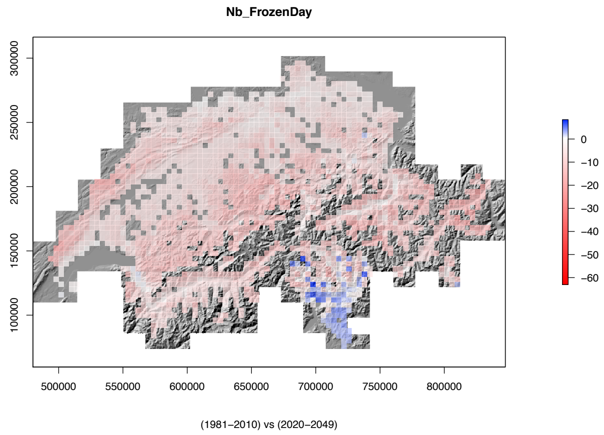

***Figure 8**: Anomalies in the number of frozen days simulated from the CLM model for the mean over the period 2020-2049 relative to the current climate (mean over 1981-2010). Blue shades indicate lower temperatures than today, while red colors indicate warmer temperatures compared to today.*

RESULTS 5: *Maximum of temperature range*

The maximum temperature range is an indication of thermal continentality vs. oceanity. The higher the diurnal temperature range, the more continental is the climate. The projected trends are very low, meaning that the climate is not projected to become clearly more continental (Appendix A1.5). However, the spatial patterns of the maps of maximum diurnal temperature range (Appendix A2.5) differ clearly among the models and are partly rather weird. The RCA30 model is (again) very different from the other two models, with very strange peaks in diurnal temperature ranges in Western Switzerland and in Northern Grisons (two quite different climates). On the other hand, the two other models are more similar, but differ in the Central Jura mountains, where the patterns have almost completely opposing numbers (Appendix A2.5). We do not illustrate figures here and refer to the appendices.

RESULTS 6: *Mean of temperature range*

Quite similar to the trend in annual maximum diurnal temperature range, the annual mean in the diurnal temperature range has almost no projected trend (Appendix A1.6). The spatial patterns are more similar among the models (Appendix A2.6). This indicates that – hidden in the data – there is likely some inconsistency in the data that only become visible as one extracts the absolute extremes.

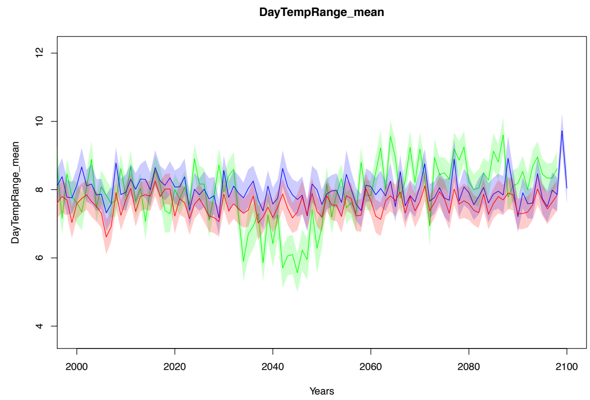

***Figure 9**: Temporal trend of mean daily temperature simulated from three different RCM models over Switzerland for the elevation band <500m. Variations around the mean trend reflect the values from all pixels falling into this elevation band.*

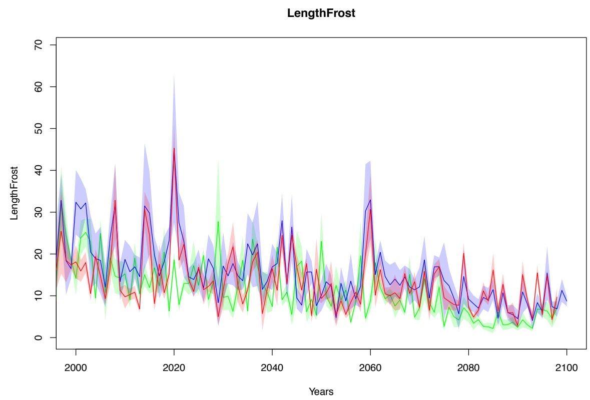

***Figure 10**: Temporal trend of the length of the annually longest stretch of continuous daily frost simulated from three different RCM models over Switzerland for the elevation band <500m. Variations around the mean trend reflect the values from all pixels falling into this elevation band.*

The temporal trends, although there is almost none, show one strange feature for the CLM model (Fig. 9). In all elevational bands, but most clearly in the band below 500 m in elevation, the CLM model shows strongly decreased mean diurnal temperature ranges between 2030 and 2050, and then increased ranges after 2060. Towards the end of the century, these values are higher than those of the other two models.

RESULTS 7: *Length of continuous frost days*

The annual length of the longest stretch in continuous frost days (stretch of days that all have Tmin<0.0°C) is projected to decrease considerably. Yet, all three models project that during the first part of the 21st Century, there is a burst in continuous frost ca. every 5 years. After the first 20-30 years, these burst in continuous frost are much reduced and approach 0 towards the end of the century, specifically for lower altitudes (Fig. 10). Above 1200 m, the trend is a bit different. Here, the variability remains more or less equally high, and despite a slight reduction in the overall length of continuous frost towards the end of the 21st Century, there are still considerable frost periods projected by all three models (Appendix A1.7).

The projected spatial anomalies reveal a decrease in frost length for all three models steadily throughout the 21st Century and at all altitudes. This will – again – provide conditions under which specifically mediterranean species are more likely to survive than when longer stretches of frost events occur. The decrease in the length of frost periods is projected to be higher at high altitudes than at low altitudes (Appendix A2.7).

RESULTS 8: *Length of continuous frozen days*

The trends in the annually longest stretch in continuous frozen days (stretch of days that all have Tmax>0°C) are very similar to those of the length of continuous frost days (Appendix A1.8). Since the patterns are so similar, we do not illustrate these here and refer to the appendix. The only difference to the frost periods is that the frozen days still have peaks all the way to the 2060s.

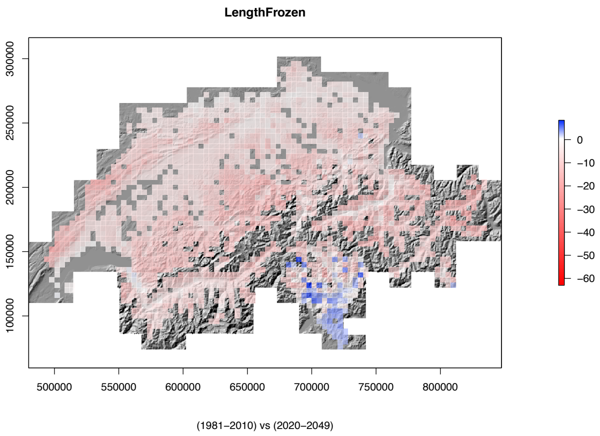

***Figure 11**: Anomalies in the mean length of the annually longest stretch of frozen days simulated from the CLM model for the mean over the period 2020-2049 relative to the current climate (mean over 1981-2010). Blue shades indicate lower temperatures than today, while red colors indicate warmer temperatures compared to today.*

The CLM model – again – predicts some longer stretches of continuous frozen days in the Ticino in the first period of 2020-2049 compared to today (Fig. 11). As in earlier examples (e.g. the annual number of frost days), the change is rather marginal and most regions do not exhibit a very strong shift by the mid Century (Appendix A2.8). Only after ca. 2050 the length of frozen days is more strongly reduced. The three models agree on the fact that the biggest reductions in the continuous periods of frozen days occur mostly at higher altitudes.

The meaning for plants is similar as that for stretches of frost days. However, for most plants sensitive to frost, it is actually the periods of frozen days that affect plant growth and survival more clearly. If days only marginally get below freezing during the nights, it might not result in frozen soils. If, however, a time period never exhibits days above freezing, then the soil is most likely turning frozen and this may have a strong effect on frost sensitive species.

RESULTS 9: *Frost frequency during leaf flush*

The number of frost days during leaf flush is also becoming reduced towards the end of the 21st Century for all four species evaluated (*Fagus sylvatica, Quercus robur, Picea abies, Pinus sylvestris*). For this, the flush date was modelled with species-specific parameters on an annual basis using the daily climate data, and then the frequency of frost events was extracted for the 40 days following the modelled leaf flush dates. The three climate models are in quite high agreement, with CLM usually exhibiting slightly lower numbers of frost days following leaf flush (Fig. 12; Appendix A3.1) for beech.

For almost all models and periods, the frost frequency is projected to decrease towards the end of the 21st Century. The only exception to this rule is, as in previous examples, the first

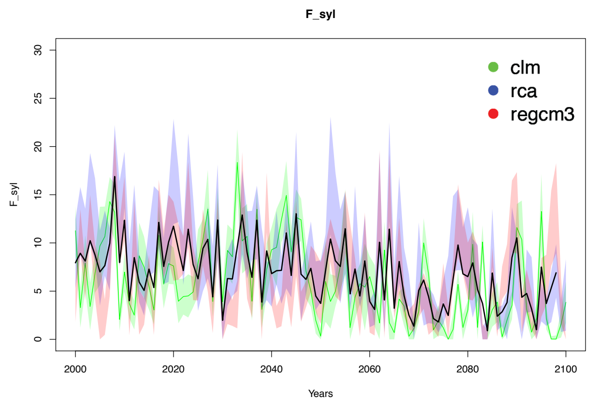

***Figure 12**: Temporal trend of mean daily frost frequency during the leave flush period of Fagus sylvatica simulated using data of three different RCM models over Switzerland for the elevation band <500m. Variations around the mean trend reflect the values from all pixels falling into this elevation band.*

period (2020-2049) for beech, which is expected to see an increase in frost frequency following leaf flush for the whole Swiss Plateau and the Jura mountains (Appendix A4.1). Again, the degree of increased frost frequency is rather small (up to 1 day maximum), meaning that we do not take this as an indication of much change compared to today (1980-2010).

The species most at risk in the elevational belt it usually occupies is Picea abies (Appendix A3.3, forth row >1200 m). This is as expected, since spruce is most frost tolerant among the four modelled species.

For most species, a decrease in frost frequency following leaf flush will not strongly affect its behavior. Rather it indicates that the species will be able to colonize higher altitudes, where the frost frequency still is the same as today.

The spatial patterns of some of the anomalies in the frequency of frost following leaf flush exhibit strange results for the period of 2020-2049 for basically all four species. However, this is possibly mostly an effect of coloring, with slightly positive values having a different color than slightly negative ones. The real difference in numbers is in fact very small, and may be visible too strongly now.

Management implications

The general reduction in frost related and the increase in heat related extremes have been observed from data of all climate models. Only the first period of 2020-2049 seems – at least for the CLM model, seem to sometime show an increase in some frost related indices.

This generally means that the warming trend that can be observed from changes in annual average temperatures is mirrored by an even stronger reduction in extremes over the course of the 21st Century. This generally means that an active and adap-tive forest management is supported by the changes in extremes. During the course of the 21st Century, not only do the mean temperatures raise, but also the extremes raise at least at the same rate, so that planting more warm adapted, heat demanding species are not (much) threatened by still prevailing low temperature extremes.

More specifically, many submediterranean species (*Quercus cerris*, *Ostrya carpinifolia, Fraxinus ornus, Acer opalus*, etc.) will find suitable habitats (at least if the climate is not too humid but rather slightly drier than today at the same time) and even some rela-tively cold tolerant meso-mediterranean species (*Quercus ilex, Phillyrea* spp.*, Arbutus unedo, Pinus halepensis*) will likely just start to find suitable temperature conditions. For thermo-mediterranean species (*Quercus suber*, *Olea europaea*), the climate is still too cold, even by the end of the 21st Century. The habitat suitability models for Central European tree species from the PorTree project of the FOEN-funded "Forest and Climate Change" Program presented in Zimmermann et al. (2014) and (2016) suggest that *Quercus ilex* will barely find yet suitable climates in Switzerland by the end of the 21st Century (using climate means in the models). The cli-mate models however suggest that the Swiss Plateau with now 30-year means in ab-solute annual Tmin values of ca. -12 °C will exhibit temperatures of -6 °C by the end of the 21st Century. The thermal limit of the winter hardiness zone for mediterranean vegetation is -6.6 °C as a cold limit. This underlines the fact that mediterranean trees might just make it, but that risks are still comparably high. It is therefore clear, that safe management will not make use of truly mediterranean, but rather sub-mediterranean and warm tempe-rate tree species.

It is also clear that beech will continue to climb higher altitudes in the northern Pre-Alps of Switzerland. A warming of 3 °C translates to a 600 m upward shift in the elevational distribution of a species. Since the projected temperature increase from models under the A1B scenario total to ca. 4.5-5.0 °C on aver-age compared to the pre-industrial mean, especially for the mountain regions (Zimmermann *et al.* 2014), the shift in the upper limit of beech will reach 900-1000 m, thus reaching the current forest treeline in this region. Since most of this region is currently colonized by spruce, and since beech does not regenerate well in acidic soils under a spruce canopy, the upward shift in beech will require support through management. However, spruce will likely not be fully threatened in these regions and can likely be kept to the end of the 21st Century above 1200 m, as it has been planted on the Swiss Plateau at warmer sites than its natural habitat.

The upward movement of spruce beyond the current treeline will likely be extremely slow. There are +/- well-developed soils up to ca. 150 m above the treeline, meaning that this zone can be colonized rather easily by many tree species from lower altitudes. Yet, above this zone, the soils are mineral and undeveloped, and a migration to even higher altitudes is not easily possible without significant human support.

The presented results only refer to temperature extremes, and not to water related (e.g. drought) extremes. It is clear that management decisions have to consider drought as a factor as well, and this was not a responsibility in the presented project.

Concluding remarks

The temporal and spatial patterns extracted for temperature extremes are more or less as expected. In general, the low temperature extremes are projected to fade away to milder values at least at the same pace as we can expect from temperature mean values.

We have to bear in mind that these trends are taken from models that are all based on the same climate change scenario (A1B). This cautions the use of the presented data as a certainty. We know that some recent trends in CO_2 increase and in the increase of global annual temperatures rather follow the more extreme A1FI or A2 scenarios, meaning that the rate of change might even be more severe by the end of the 21st Century. While the A1B scenario was a rather extreme one in the fourth IPCC assessment report (IPCC 2007), the new rcp8.5 scenario used in the fifth IPCC assessment report (IPCC 2013) is clearly more extreme than any scenario used in the fourth report, and is only balanced with even much milder sce-narios, such as rcp2.6. This means that there is considerable uncertainty as to which scenario is actually valid for use in adaptive and active forest management.

Another uncertainty comes from only using three RCMs in all analyses as was decided by the program committee for this research program. Usually, it is important to use more than simply 3 models (and more than one scenario). It is not clear, to what degree the three models reflect the variability of all possible models for this scenario. It is possible, that the three scenarios provided here (all based on the ECHAM 5 global GCM input to the RCMs) are rather on the high end with regards to the amount of expected warming (and reduction in frost-related extremes). Using other GCMs as input to RCMs such as e.g. the CCSM30 GCM would have changed some of the patterns found here. ON the other hand, using the HadCM3 GCM as input might have lead to even more extreme values.

Finally, some uncertainty remains with regards to the downscaled data obtained for analyses of extremes, as previous versions were prone to some errors (Appendix A5).

Methods brief

Below, we provide a short description of the methods used. Most methods are rather simple. Yet, considerable processing time was required because daily temperatures had to be brought to a common format first, and then required time-consuming processing to extract annually the extremes statistic.

Origin of climate data

The climate data used originate from MeteoSwiss for current climates and from the Ensembles EU project for 3 regional climate models (RCMs) that were downscaled to fine spatial resolution by Meteotest (Remund *et al.* 2016). The data was provided for all sites of NFI1 and NFI2. The data contained minimum, maximum and average daily temperature, amongst others. The data were provided in different formats, partly one file per one NFI plot. Data from the following three climate models were made available by Meteotest: (1) CLM, RCA30, and RegCM3. These three RCMs were all fed at the boundary of the simulation region of Europe by data from the global circulation model ECHAM5. For the three climate models, data from the A1B scenario were provided, as the Ensembles project hardly simulated any other scenarios at RCM resolution.

Data extraction and processing

Prior to analyses, we had to import all data into a common data format. We chose the NetCDF format, which is commonly used for storing climatological data. This format is flexible as it can be read and written from the statistical environment R.

Description and processing of "extremes" variables

Below, we describe the definition and extraction of the processed temperature indices. These were stored first as time series per NFI plot, and then aggregated to maps for four 30-year periods, namely for 1981-2010 (i.e. current), 2020-2049, 2045-2074, and 2070-2099. The latter three periods were often re-presented in the form of anomalies compared to the first (current) period, thus indicating to what degree and with what spatial patterns the expected changes in climates are projected by the three climate models. Temporal trends were calculated for elevation bands <500m, 500-800m, 800-1200m, >1200m.

Tmin: for each year, we extracted the absolute lowest daily minimum temperature value for each NFI plot and stored it as a value annually. For mapping spatial patterns, we averaged the absolute *Tmin* values over 30 years each for all NFI plots. Therefore, the 30-year value stored is the mean and not the absolute minimum over this period.

Tmax: for each year, we extracted the absolute highest daily maximum temperature value for each NFI plot and stored it as a value annually. For mapping spatial patterns, we averaged the absolute *Tmax* values over 30 years each for all NFI plots. Therefore, the 30-year value stored is the mean and not the absolute maximum over this period.

Nb.FrostDays: for each year, we extracted the number of frost days for each NFI plot and stored it as a value annually. For mapping spatial patterns, we averaged the *Nb.FrostDays* values over 30 years each for all NFI plots. A frost day is a day for which Tmin falls below 0 °C.

Nb.FrozenDays: for each year, we extracted the number of frozen days for each NFI plot and stored it as a value annually. For mapping spatial *Nb.FrozenDays* patterns, we averaged the values over 30 years each for all NFI plots prior to mapping. A frozen day is a day for which Tmax remains below 0 °C.

T-range.max: for each year, we extracted the daily temperature range and recorded and stored the largest temperature range per year for each NFI plot. For mapping spatial *T-range.max* patterns, we averaged the values over 30 years each for all NFI plots prior to mapping. Therefore, the 30-year value stored is the mean over all yearly maximum values, and not the absolute maximum over this period.

T-range.avg: for each year, we extracted the daily temperature range and recorded and stored the mean temperature range per year for each NFI plot. For mapping spatial *T-range.avg* patterns, we averaged the values over 30 years each for all NFI plots prior to mapping. Therefore, the 30-year value stored represents the mean over all yearly mean values.

Len.Frost: for each year, we determined the longest period of continuous frostdays for each NFI plot and stored it as a value annually. For mapping spatial patterns, we averaged the values of *Len.Frost* over 30 years each for all NFI plots. Therefore, the 30-year value stored per NFI plot is the mean longest period over 30 years. A frost day is a day for which Tmin falls below 0 °C.

Len.Frozen: for each year, we determined the longest period of continuous frozen days for each NFI plot and stored it as a value annually. For mapping spatial patterns, we averaged the values of *Len.Frozen* over 30 years each for all NFI plots. Therefore, the 30-year value stored per NFI plot is the mean longest period over the 30 years. A frozen day is a day for which Tmax remains below 0 °C.

<u>Calculation of frost frequency after leaf flush</u>

In order to determine the leaf flush data of tree species in a prognostic mode, we implemented the model of Hammel & Kennel (2001). The method is based on findings of Menzel & Fabian (1999), first calculates the species-specific required number of "cold-days", and once this threshold is reached it calculates the species-specific heat-index (warm days) required for a species to flush the leaves. The cold days are needed to avoid a flushing of leaves in a warm stretch during the early winter. The report by Hammel and Kennel provides species specific parameters for four important tree species, namely: *Fa-gus sylvatica*, *Quercus robur*, *Picea abies*, and *Pinus sylvestris*.

We implemented this method in R and calculated the leaf flush dates for each species and NFI plot. After this, we calculated to what number of frost days in the 40 days following the calculated leaf flush date for each NFI plot. For mapping spatial patterns in the frost days following leaf flush, we aver-aged the annual frost frequency values over 30 years each for all NFI plots.

<u>Illustration of temporal and spatial patterns in climate extremes</u>

Time series graphs per altitudinal band illustrate the trajectory of annual extremes (e.g. absolute temperature minimum per year) for all NFI plots falling in the respective elevational band. The mean trend is illustrated by a bold colored line, while the light shade of the same color represents the variability around the mean as derived from all NFI plots per elevational band. The three colors per graph illustrate the different trajectories as derived from the three RCMs

The maps illustrate the 30year mean or extremes of the yearly indices per location. A location (or pixel) in the map is generated by aggregating all NFI plots within a neighborhood of ca. 2.5 x 2.5 km. This aggregation to a larger area (then usually represented by an NFI plot allows for better visualization of the fine-grained patterns. The mean or extreme values per 30-year period per NFI plots are averaged to represent the 2.5 km pixels size in the graphs.

All analyses and illustrations were generated in the R statistical environment (R Core Team 2016).

References

Allen CD, Macalady AK, Chenchouni H, *et al.* (2010) A global overview of drought and heat-induced tree mortality reveals emerging climate change risks for forests. *Forest Ecology and Management* **259**, 660-684.

Bärtels A (2001) *Enzyklopädie der Gartengehölze: Bäume und Sträucher für mitteleuropäische und mediterrane Gärten* Verlag Eugen Ulmer, Stuttgart.

Breshears DD, Myers OB, Meyer CW, *et al.* (2009) Tree die-off in response to global change-type drought: mortality insights from a decade of plant water potential measurements. *Frontiers in Ecology and the Environment* **7**, 185-189.

CH2011 (2011) Swiss Climate Change Scenarios CH2011, p. 88. C2SM, MeteoSwiss, ETH, NCCR Climate, and OcCC, Zürich, Switzerland.

Gehrig-Fasel J, Guisan A, Zimmermann NE (2007) Tree line shifts in the Swiss Alps: Climate change or land abandonment? *Journal of Vegetation Science* **18**, 571-582.

Hammel K, Kennel M (2001) Charakterisierung und Analyse der Wasserverfügbarkeit und des Wasserhaushalts von Waldstandorten in Bayern mit dem Simulationsmodell BROOK90. Forstliche Forschungsberichte München. Heinrich Frank, München, p. 148.

Humboldt Av, Bonpland A (1805) *Essaie sur la Géographie des Plantes; Accompagne d'un Tableau des Régions Equinoxiales*, Paris.

IPCC (2007) *Climate Change 2007: Impacts, Adaptation and Vulnerability: Working Group II contribution to the Fourth Assessment Report of the IPCC* Cambridge University Press, Cambridge, UK and New York, NY, USA.

IPCC (2013) *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* Cambridge University Press, Cambridge, UK and New York, NY, USA.

Körner C (1998) A re-assessment of high elevation treeline positions and their explanation. *Oecologia* **115**, 445-459.

Körner C, Basler D, Hoch G, *et al.* (2016) Where, why and how? Explaining the low temperature range limits of temperate tree species. *Journal of Ecology* **104**, 1076-1088.

Körner C, Paulsen J (2004) A world-wide study of high altitude treeline temperatures. *Journal of Biogeography* **31**, 713-732.

Lenoir J, Gégout J-C, Marquet PA, de Ruffray P, Brisse H (2008) A significant upward shift in plant species optimum elevation during the 20th century. *Science* **320**, 1768-1771.

Lenz A, Hoch G, Vitasse Y, Korner C (2013) European deciduous trees exhibit similar safety margins against damage by spring freeze events along elevational gradients. *New Phytologist* **200**, 1166-1175.

Menzel A, Fabian P (1999) Growing season extended in Europe. *Nature* **397**, 659.

Parmesan C, Ryrholm N, Stefanescu C, *et al.* (1999) Poleward shifts in geographical ranges of butterfly species associated with regional warming. *Nature* **399**, 579-583.

Parmesan C, Yohe G (2003) A globally coherent fingerprint of climate change impacts across natural systems. *Nature* **421**, 37-42.

Pellissier L, Brathen KA, Vittoz P, *et al.* (2013) Thermal niches are more conserved at cold than warm limits in arctic-alpine plant species. *Global Ecology and Biogeography* **22**, 933-941.

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

Randin CF, Paulsen J, Vitasse Y, *et al.* (2013) Do the elevational limits of deciduous tree species match their thermal latitudinal limits? *Global Ecology and Biogeography* **22**, 913-923.

Remund J, von Arx G, Gallien L, *et al.* (2016) Klimawandel in der Schweiz – Entwicklung waldrelevanter Klimagrössen. In: *Wald im Klimawandel. Grundlagen für Adaptationsstrategien* (eds. Plüss A, Augustin S, Brang P), p. pp. 199-221. Haupt, Bern, Stuttgart, Wien.

Shiyatov SG, Terent'ev MM, Fomin VV, Zimmermann NE (2007) Altitudinal and horizontal shifts of the upper boundaries of open and closed forests in the Polar Urals in the 20th century. *Russian Journal of Ecology* **38**, 223-227.

Shugart HH (1984) *A Theory of Forest Dynamics: The Ecological Implications of Forest Succession Models* Springer-Verlag, New York.

van Mantgem PJ, Stephenson NL, Byrne JC, *et al.* (2009) Widespread Increase of Tree Mortality Rates in the Western United States. *Science* **323**, 521-524.

Walther GR, Hughes L, Vitousek P, Stenseth NC (2005) Consensus on climate change. *Trends in Ecology & Evolution* **20**, 648-649.

Walther GR, Post E, Convey P, *et al.* (2002) Ecological responses to recent climate change. *Nature* **416**, 389-395.

Wohlgemuth T, Gallien L, Zimmermann NE (2016) Verjüngung von Buche und Fichte im Klimawandel. In: *Wald im Klimawandel. Grundlagen für Adaptationsstrategien* (eds. Plüss A, Augustin S, Brang P), p. pp. 115-135. Haupt, Bern, Stuttgart, Wien.

Woodall CW, Oswalt CM, Westfall JA, *et al.* (2009) An indicator of tree migration in forests of the eastern United States. *Forest Ecology and Management* **257**, 1434-1444.

Woodward FI (1987) *Climate and plant distribution* Cambridge University Press, Cambridge.

Zimmermann NE, Normand S, Psomas A (2014) PorTree Final Report, p. 24. Swiss Federal Research Institute WSL, Birmensdorf.

Zimmermann NE, Schmatz DR, Gallien L, *et al.* (2016) Baumartenverbreitung und Standortseignung. In: *Wald im Klimawandel. Grundlagen für Adaptationsstrategien* (eds. Plüss A, Augustin S, Brang P), p. pp. 199-221. Haupt, Bern, Stuttgart, Wien.

Zimmermann NE, Yoccoz NG, Edwards TC, *et al.* (2009) Climatic extremes improve predictions of spatial patterns of tree species. *Proceedings of the National Academy of Sciences of the United States of America* **106**, 19723-19728.

The following is a compilation of the time series on temperature extremes indices for four altitudinal bands (0-500 m; 500-800 m, 800-1200 m, >1200 m) represented by three regional climate models (CLM; RCA30; RegCM3) for the A1B scenario. The data for extracting these temperature extremes indices was provided by MeteoTest. The following indices have been compiled here: Tmin: 30-year average of annual absolute minimum temperatures; Tmax: 30-year average of annual absolute maximum temperatures; Nb.FrostDays: 30-year average of yearly number of frost days; Nb.FrozenDays: 30-year average of yearly number of frozen days; Len.Frost: 30-year average of annual longest stretch of continuous frost days; Len.Frozen: 30-year average of annual longest stretch of continuous frozen days. The appendix lists eight indices, which are listed below:

List of temperature extremes indices:

Tmin: Absolute minimum temperature

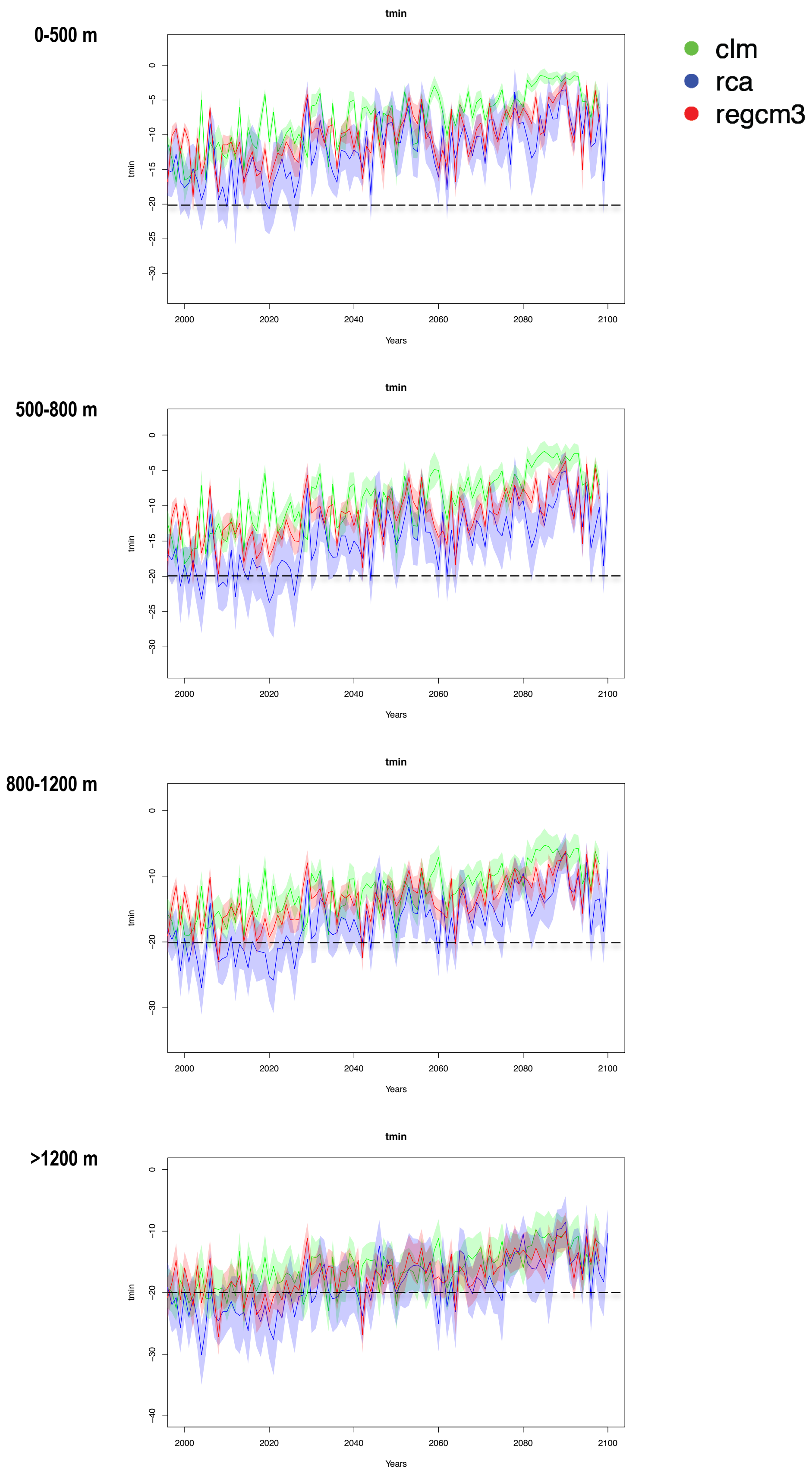

Figure A1.1*: Time series of absolute minimum temperature for 3 different RCMs. Red shades: RegCM3; Blue shades: RCA30; Green shades: CLM.*

Tmax: Absolute maximum temperature

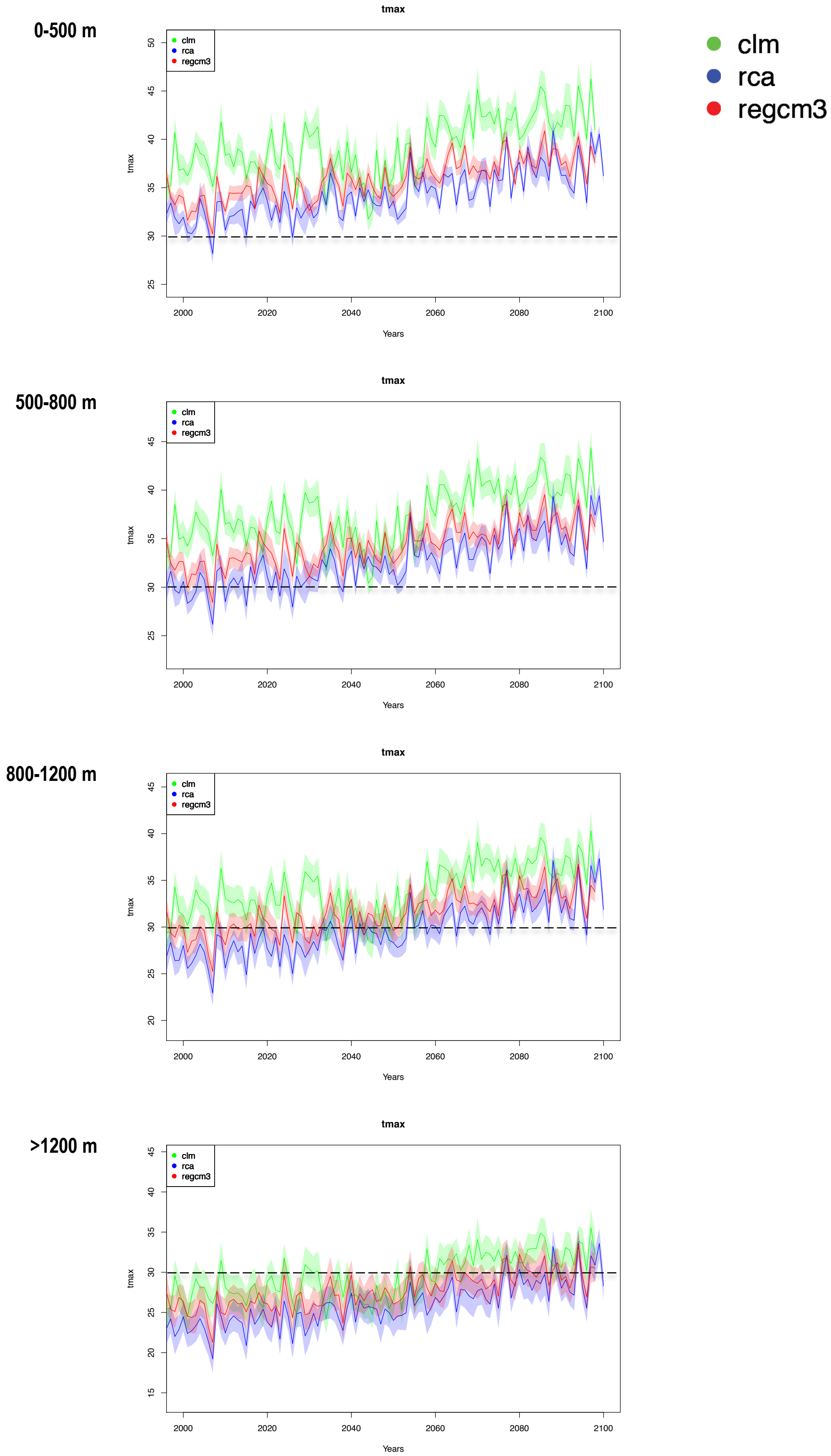

Figure A1.2: *Time series of absolute maximum temperature for 3 different RCMs. Red shades: RegCM3; Blue shades: RCA30; Green shades: CLM.*

Nb.FrostDays: Number of days with frost

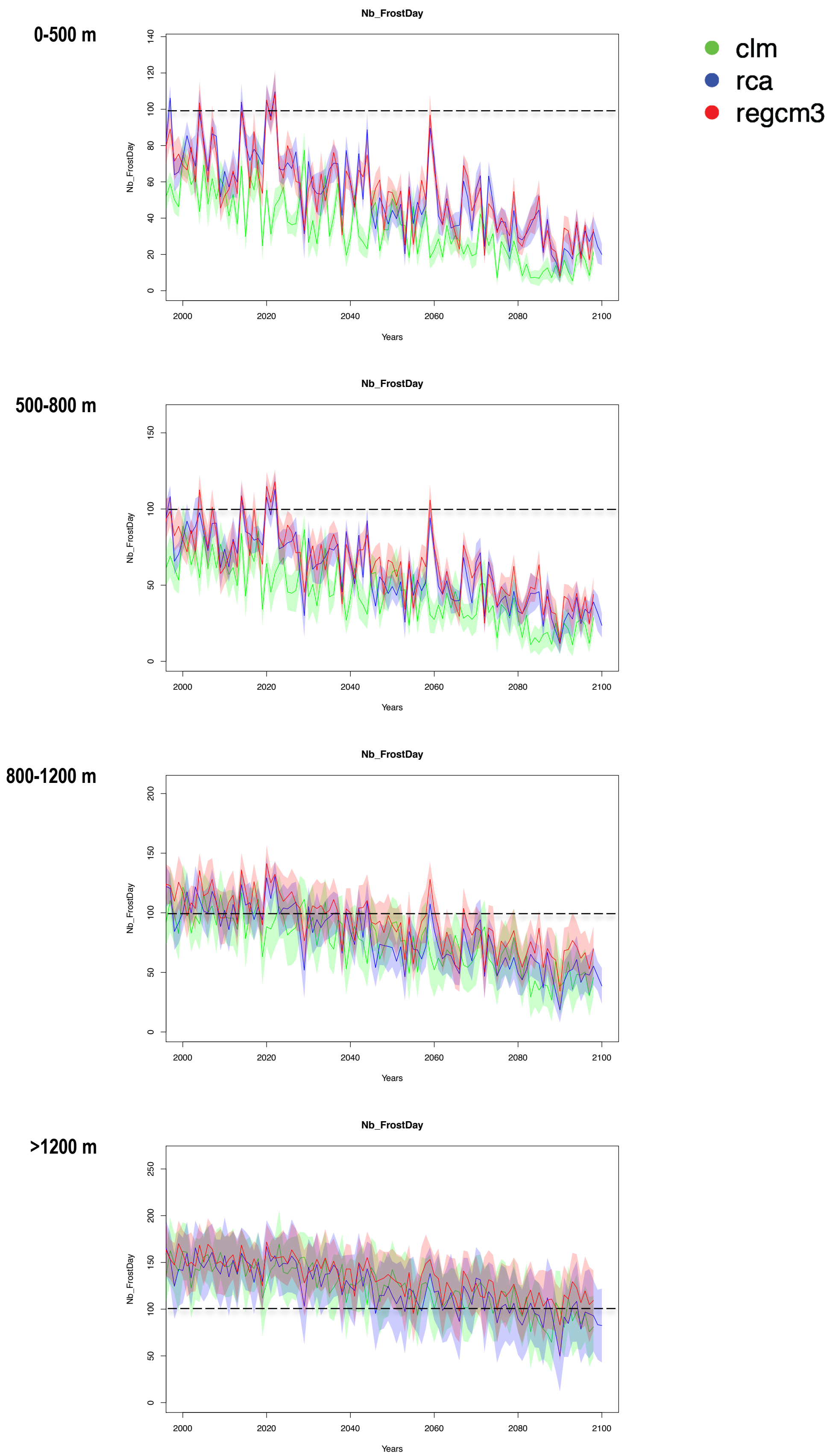

***Figure A1.3**: Time series of the number of days with frost for 3 different RCMs. Red shades: RegCM3; Blue shades: RCA30; Green shades: CLM.*

Nb.FrozDays: Number of frozen days (no thawing)

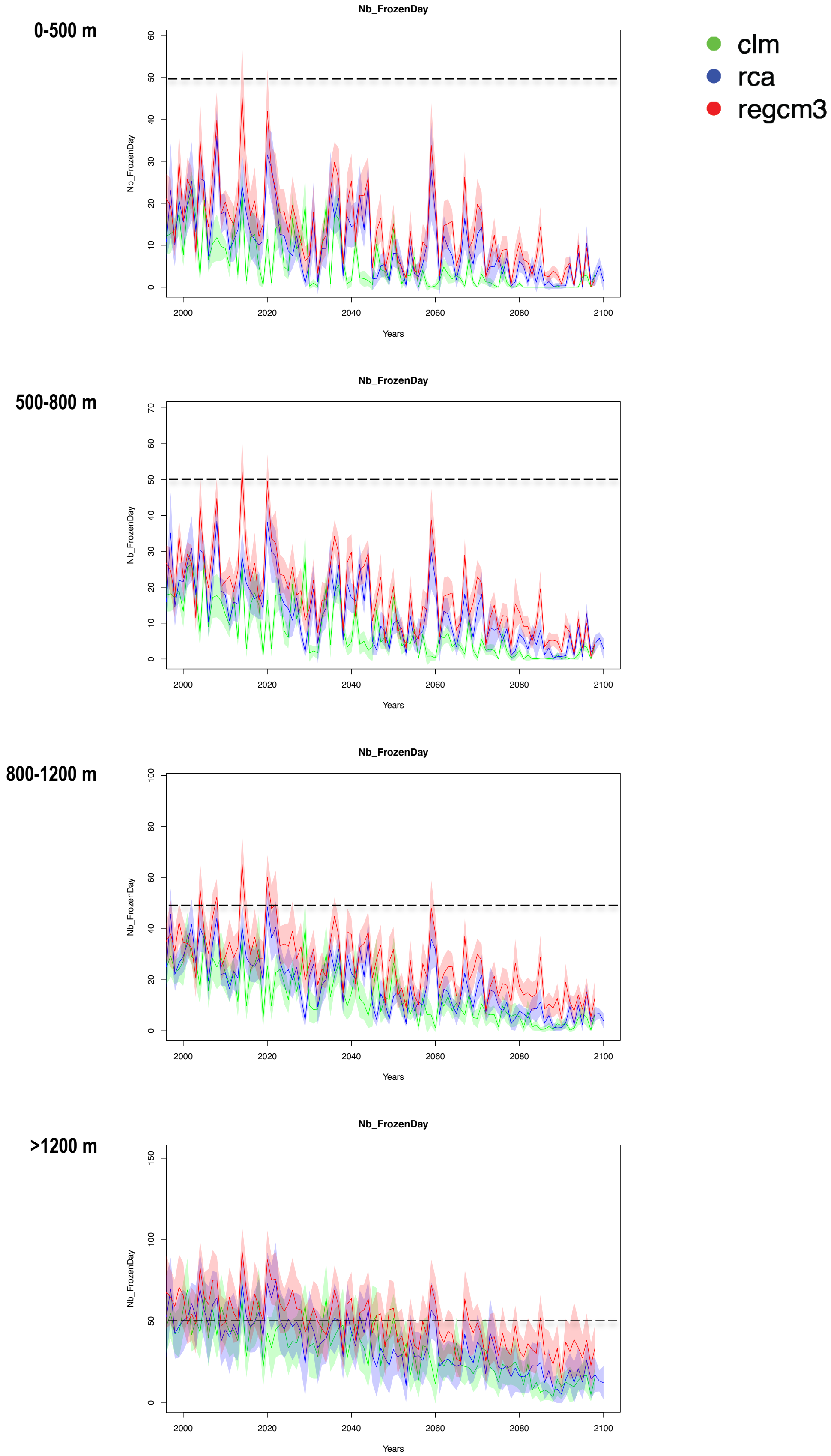

***Figure A1.4**: Time series of the number of frozen days (no thawing) for 3 different RCMs. Red shades: RegCM3; Blue shades: RCA30; Green shades: CLM.*

T-Range.max: Monthly maximum of the diurnal temperature range

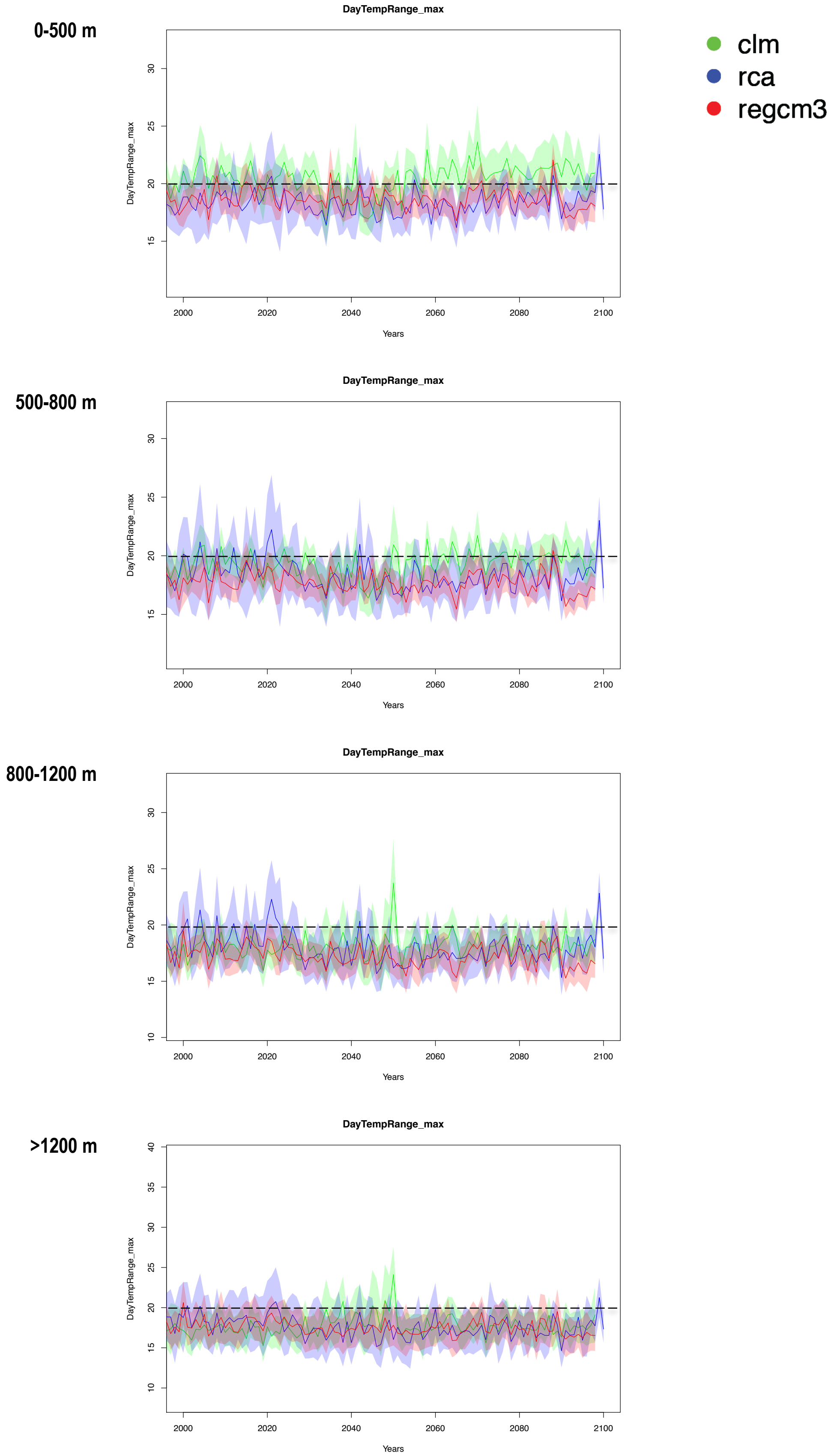

Figure A1.5*: Time series of the monthly maximum of the diurnal temperature range for 3 different RCMs. Red shades: RegCM3; Blue shades: RCA30; Green shades: CLM.*

T-range.avg: Monthly mean of the diurnal temperature range

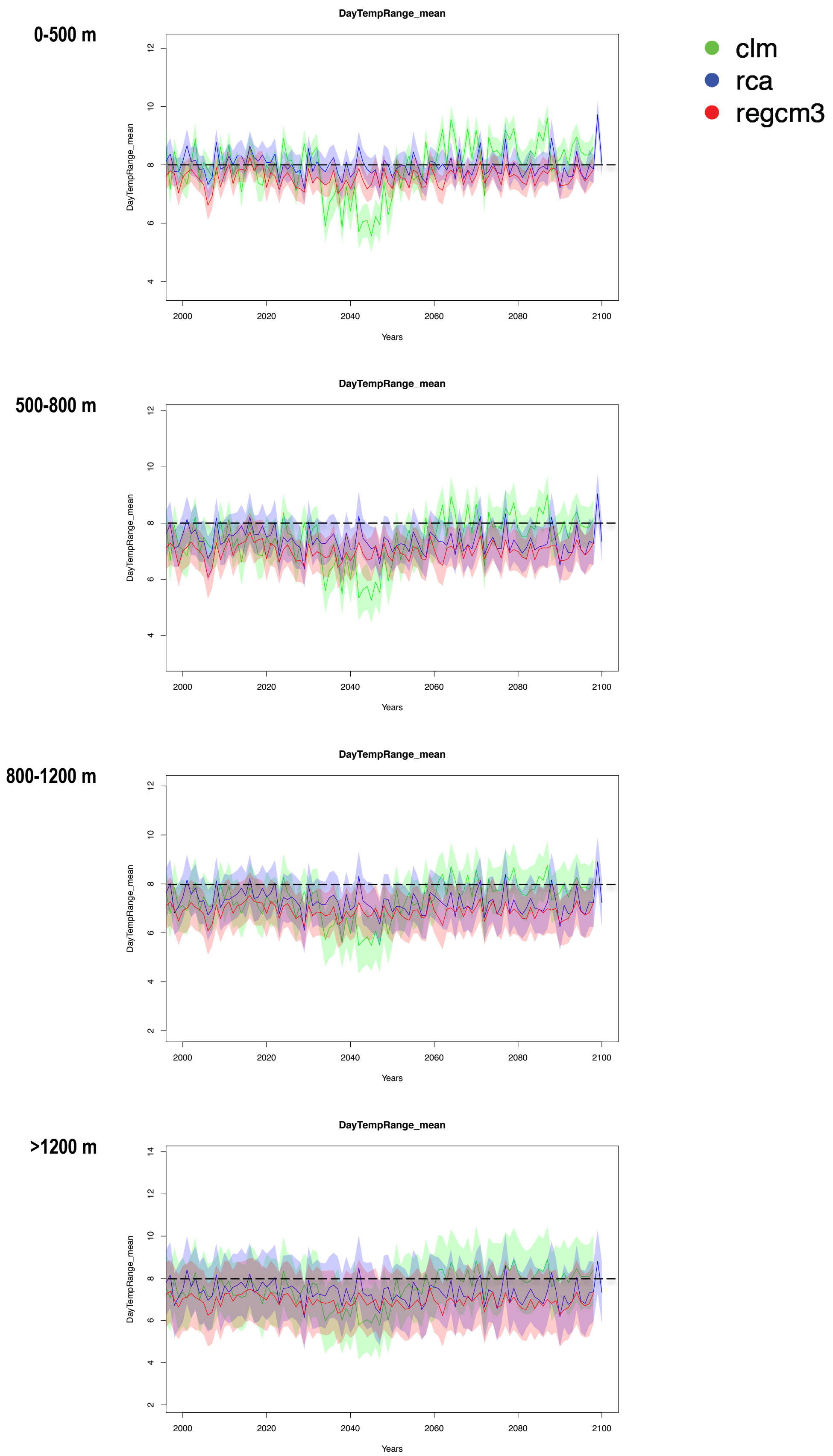

***Figure A1.6**: Time series of the monthly mean of the diurnal temperature range for 3 different RCMs. Red shades: RegCM3; Blue shades: RCA30; Green shades: CLM.*

Len.Frost: Mean length of longest annual stretch of frost days (daily freezing)

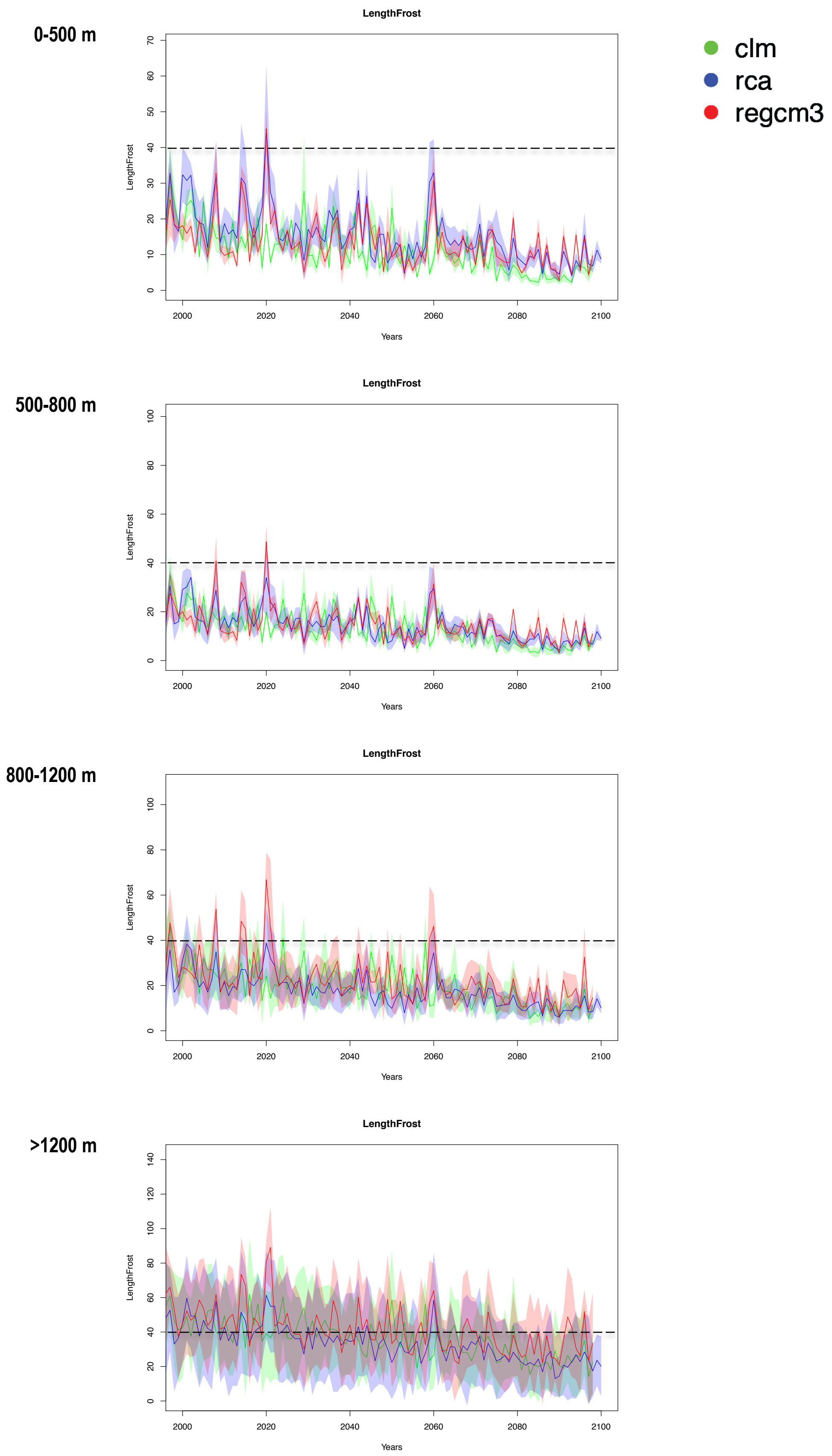

Figure A1.7*: Time series of the length of the longest period with frost per year for 3 different RCMs. Red shades: RegCM3; Blue shades: RCA30; Green shades: CLM.*

Len.Frozen: Mean length of longest annual stretch of frozen days (no thawing)

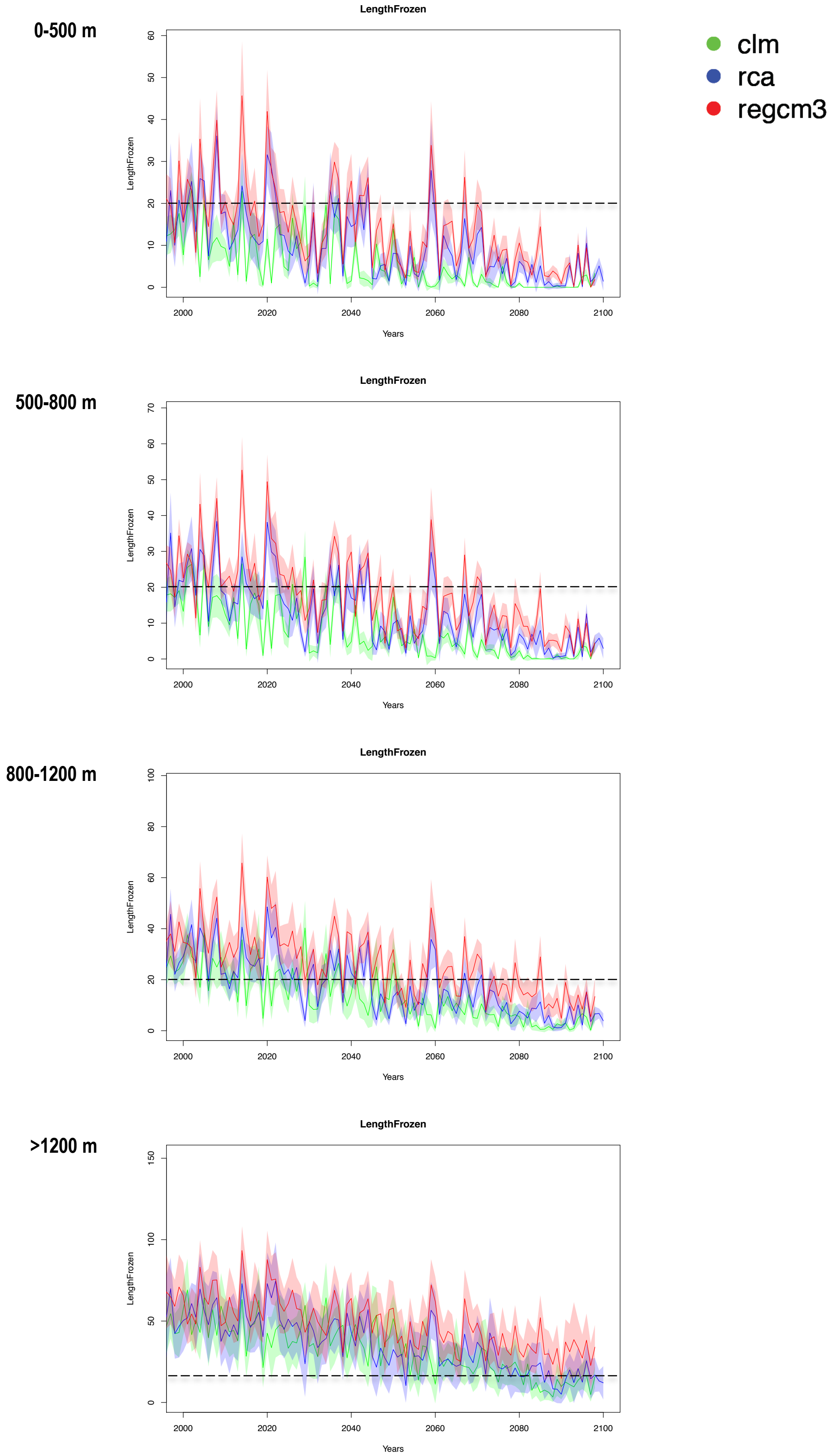

***Figure A1.8**: Time series of the longest frozen period per year (no thawing) for 3 different RCMs. Red shades: RegCM3; Blue shades: RCA30; Green shades: CLM.*

The following is a compilation of the spatial patterns on temperature extremes indices and anomalies thereof for current climate (means or extremes for the period 1981-2010 and for three periods of projected future climate, namely 2020-2045, 2045-2074, and 2070-2099. The projected future climate is represented by three regional climate models (CLM; RCA30; RegCM3) for the A1B scenario. The data for extracting these temperature extremes indices was provided by MeteoTest. The following indices have been compiled here: Tmin: 30-year average of annual absolute minimum temperatures; Tmax: 30-year average of annual absolute maximum temperatures; Nb.FrostDays: 30-year average of yearly number of frost days; Nb.FrozenDays: 30-year average of yearly number of frozen days; Len.Frost: 30-year average of annual longest stretch of continuous frost days; Len.Frozen: 30-year average of annual longest stretch of continuous frozen days. Maps were generated by aggregating all LFI sites within a 2.5 x 2.5 km wndow for better visibility. The appendix lists eight indices, which are listed below:

List of temperature extremes indices:

TMIN: Absolute minimum temperature

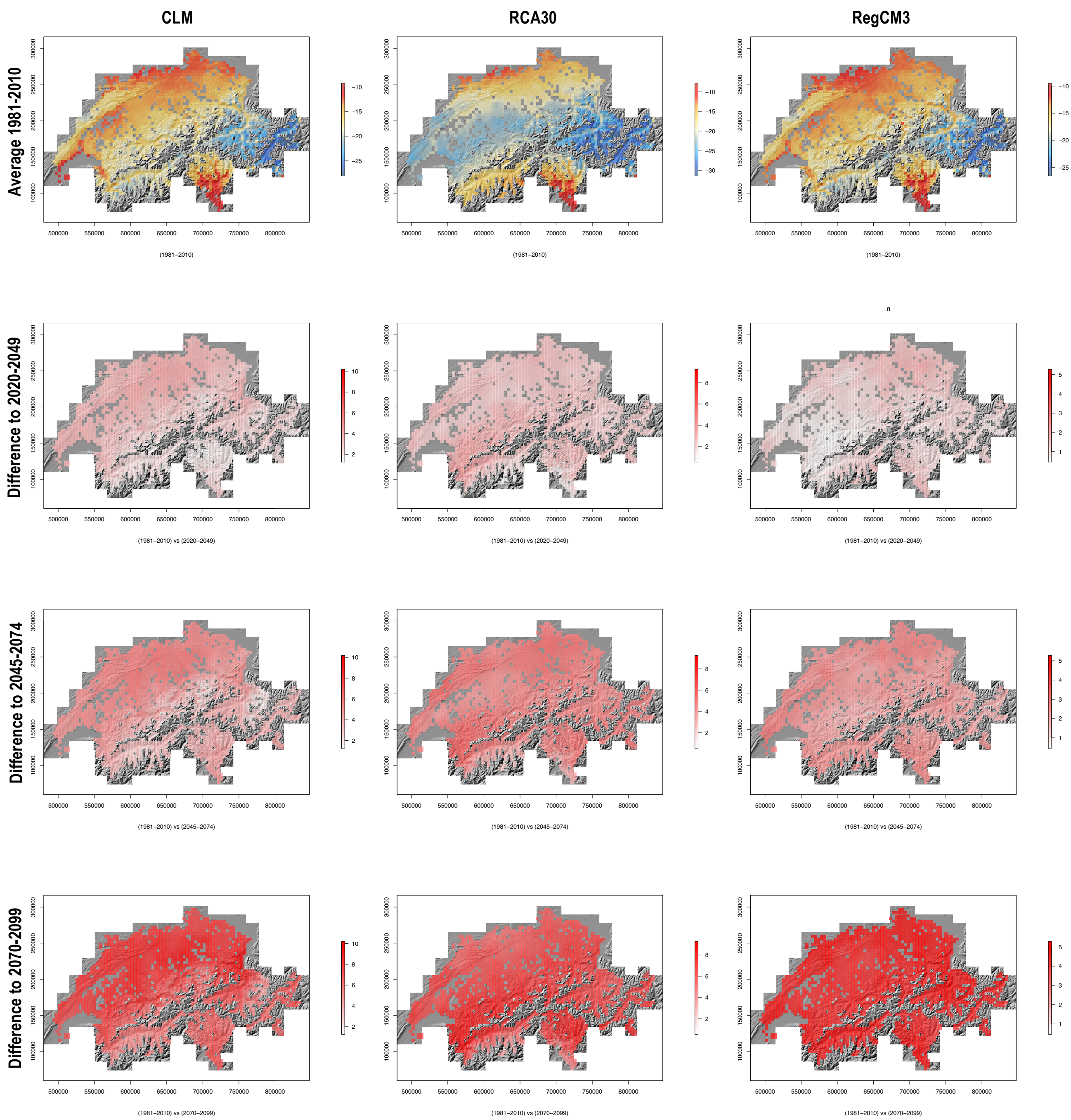

***Figure A2.1**: Absolute minimum temperature patterns and anomalies for 3 different RCMs in Switzerland.*

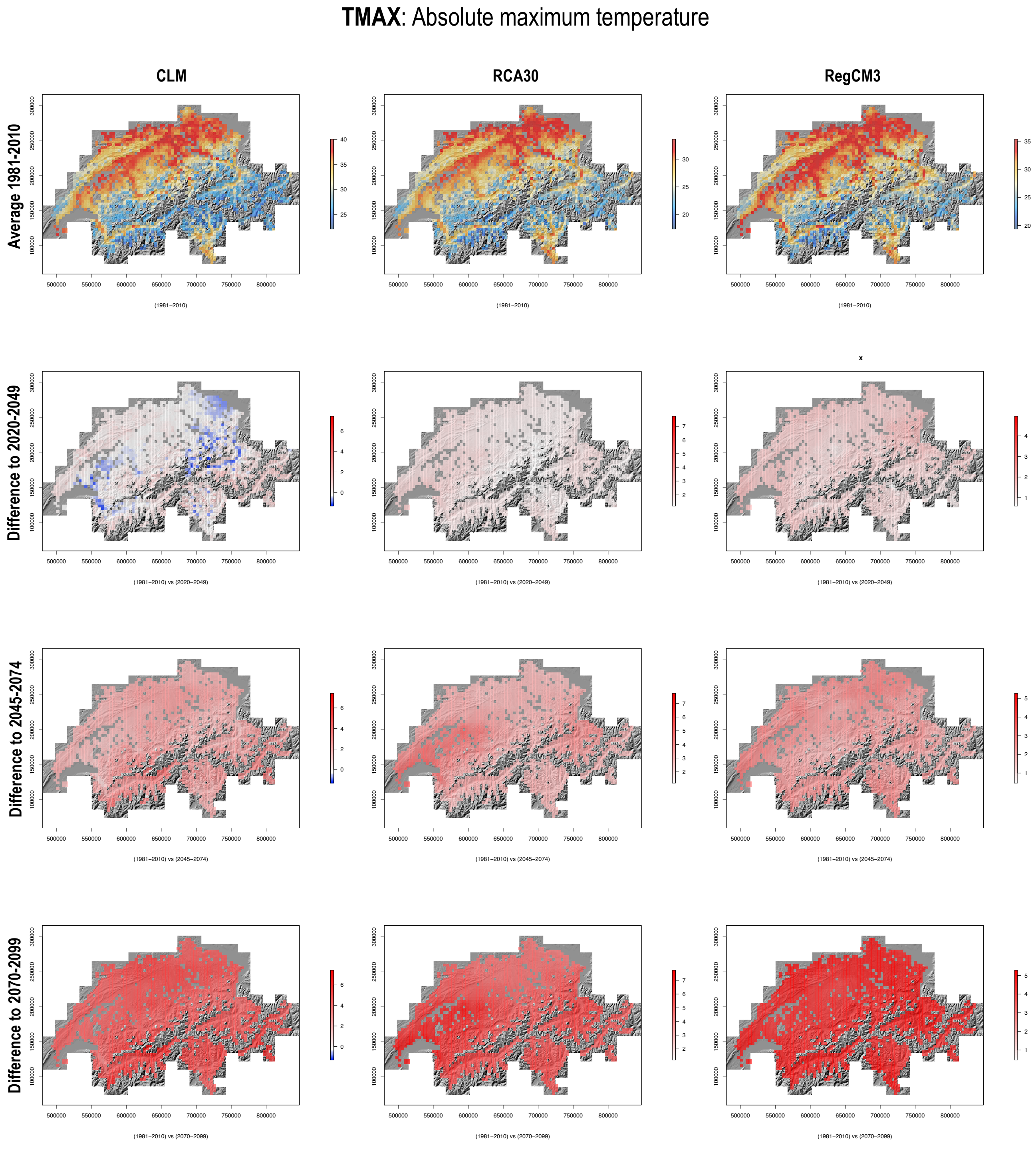

***Figure A2.2**: Absolute maximum temperature patterns and anomalies for 3 different RCMs in Switzerland.*

Nb.FrostDays: Mean number of frost days per year

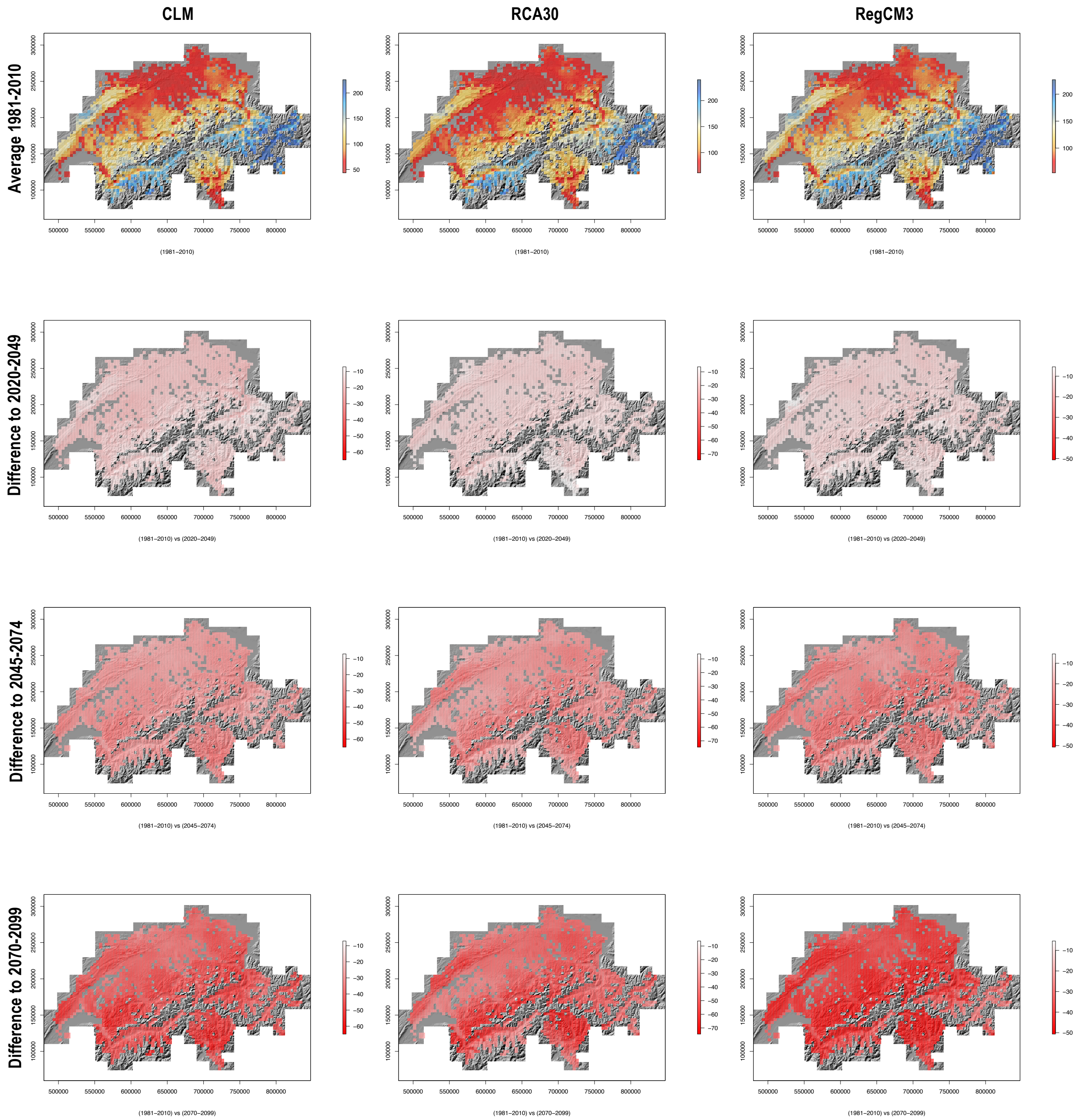

Figure A2.3*: Yearly mean of number of frost days (Tmin < 0°C) patterns and anomalies for 3 different RCMs in Switzerland*

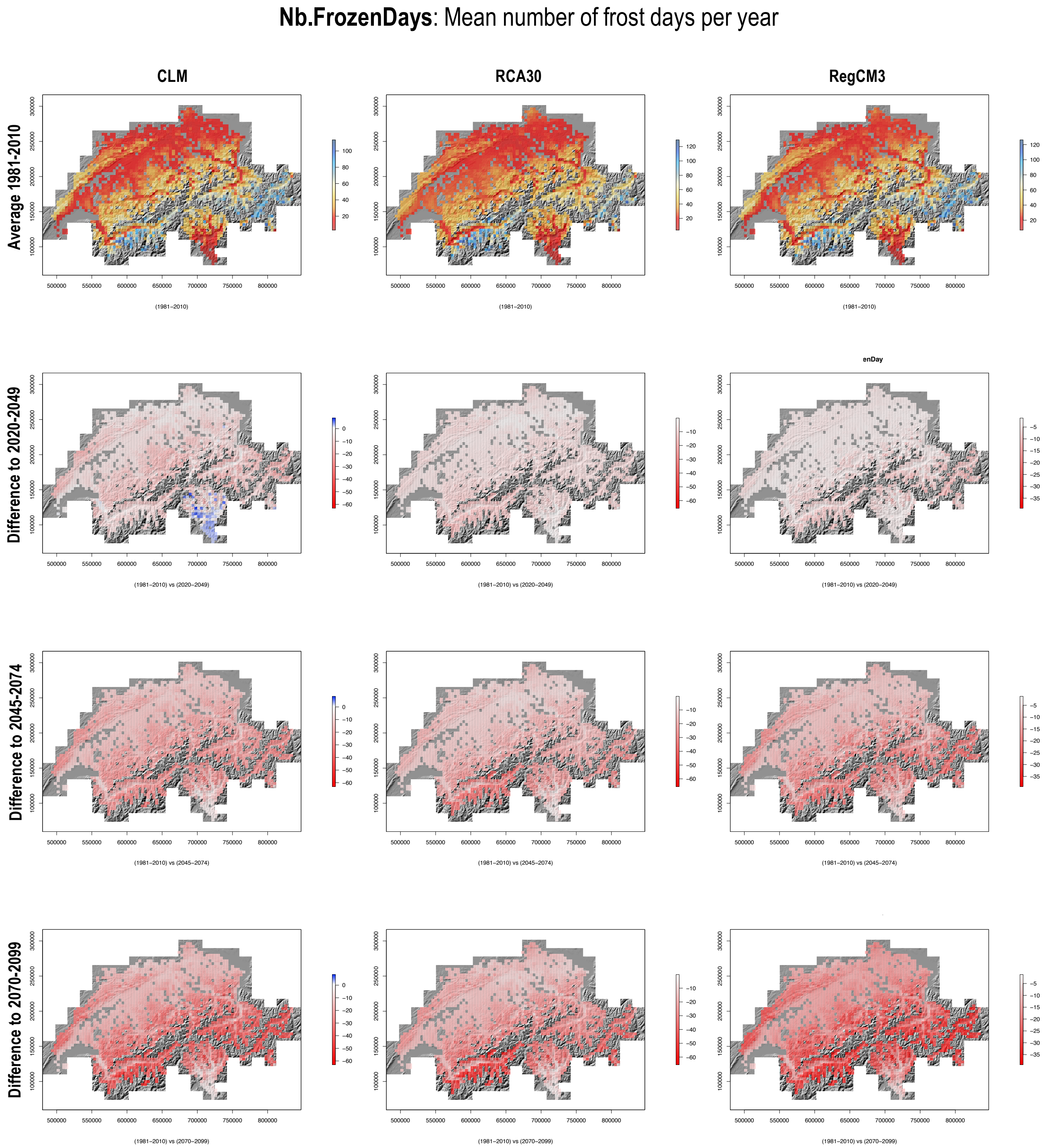

Figure A2.4*: Yearly mean number of frozen days (Tmax < 0°C) patterns and anomalies for 3 different RCMs in Switzerland*

T-range.max: Maximum diurnal temperature range

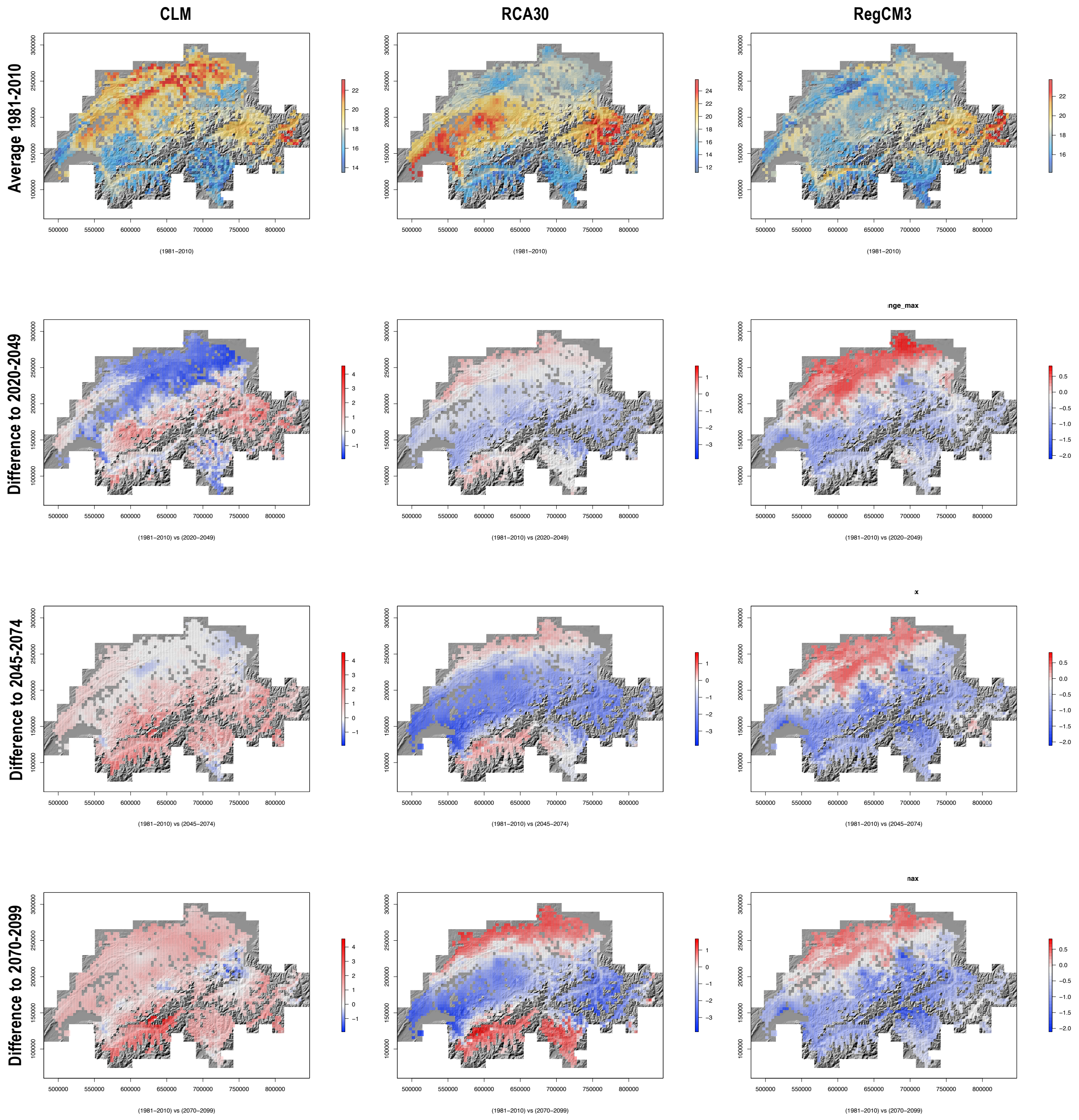

Figure A2.5*: Mean yearly maximum of diurnal temperature range patterns and anomalies for 3 different RCMs in Switzerland*

T-range.avg: Average diurnal temperature range

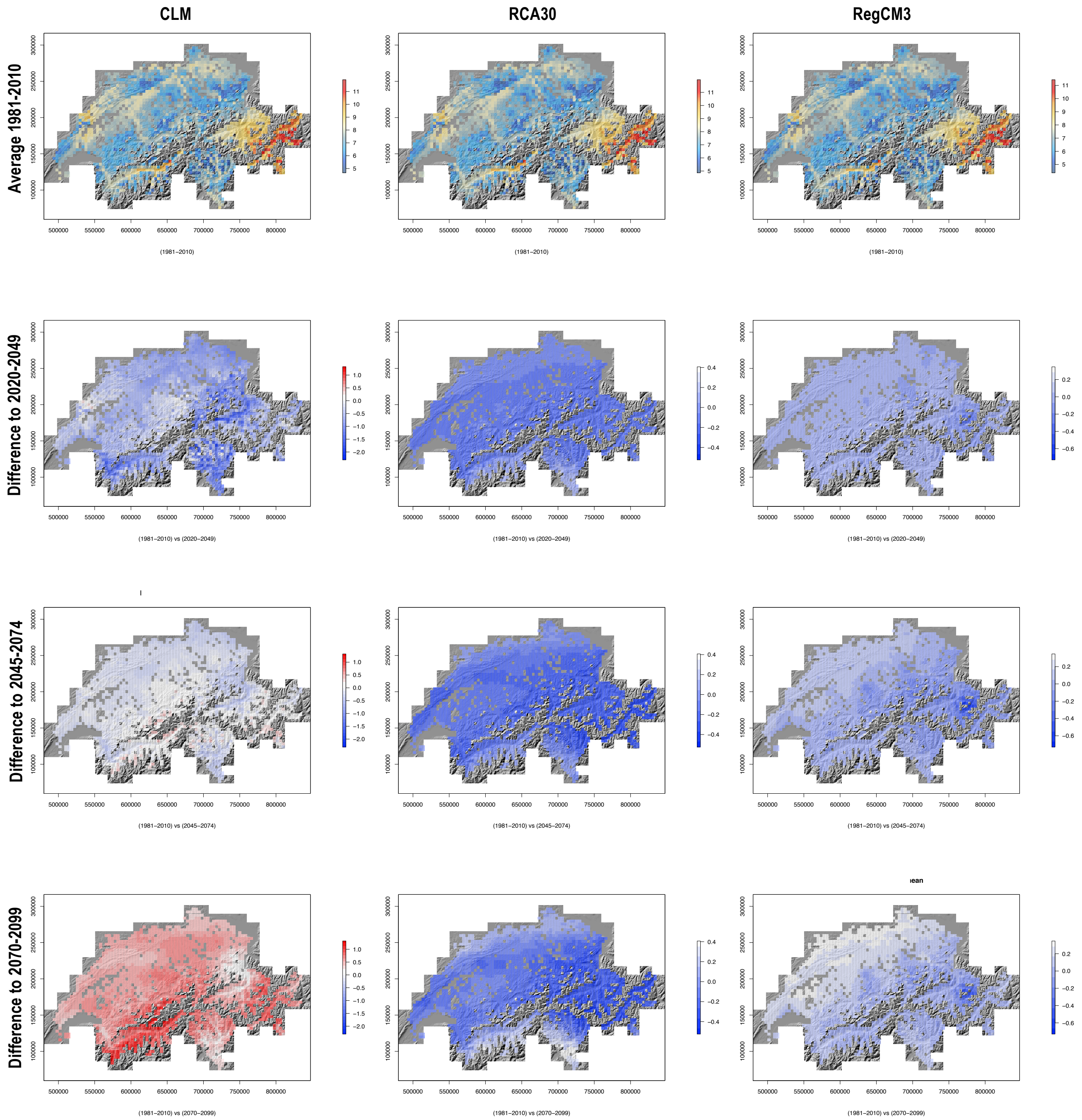

***Figure A2.6**: Mean yearly average of diurnal temperature range patterns and anomalies for 3 different RCMs in Switzerland*

Len.Frost: Mean of annual longest stretch of continuous frost days

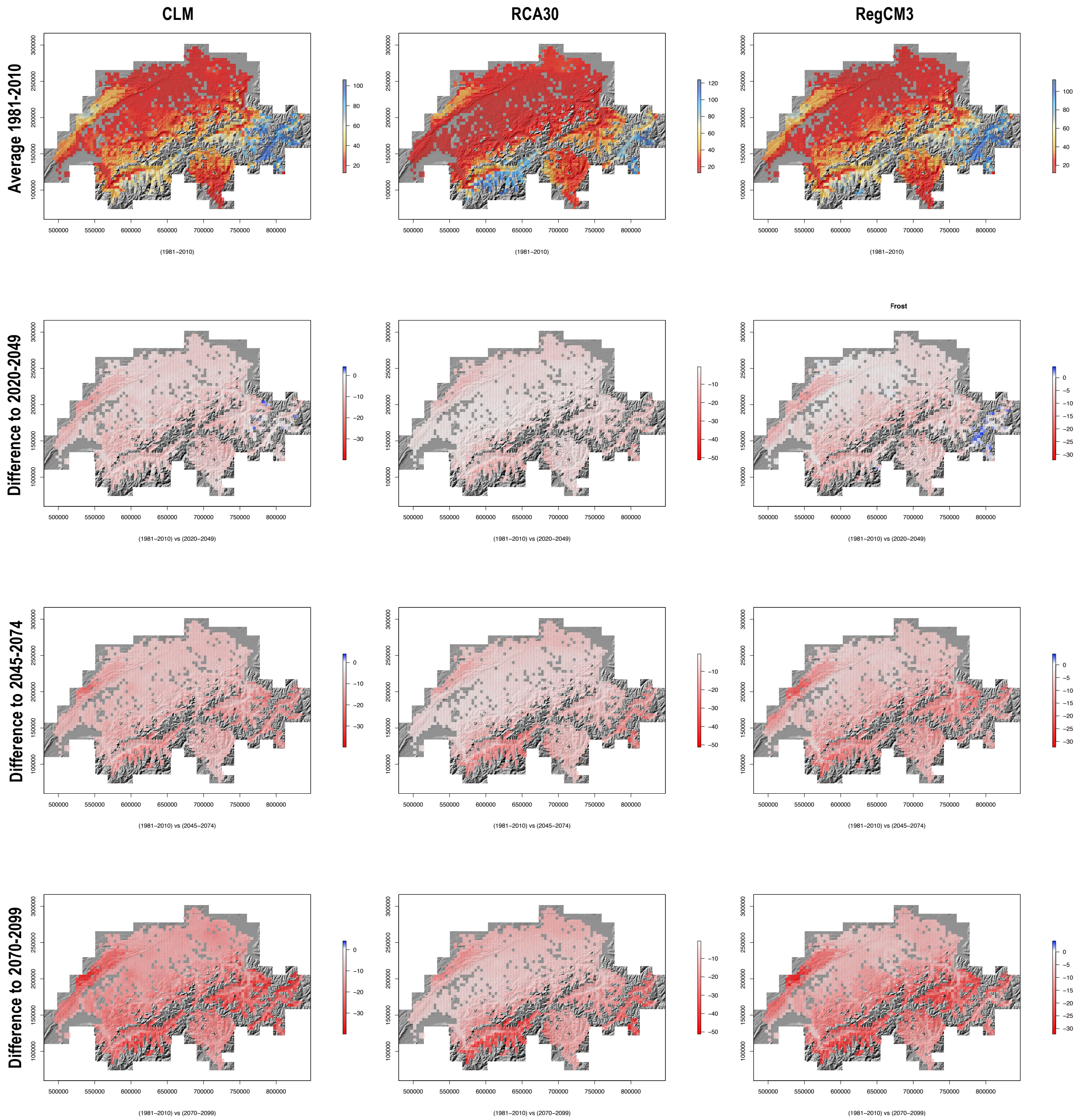

***Figure A2.7**: Mean of annual longest stretch of continuous frost days for 3 different RCMs in Switzerland.*

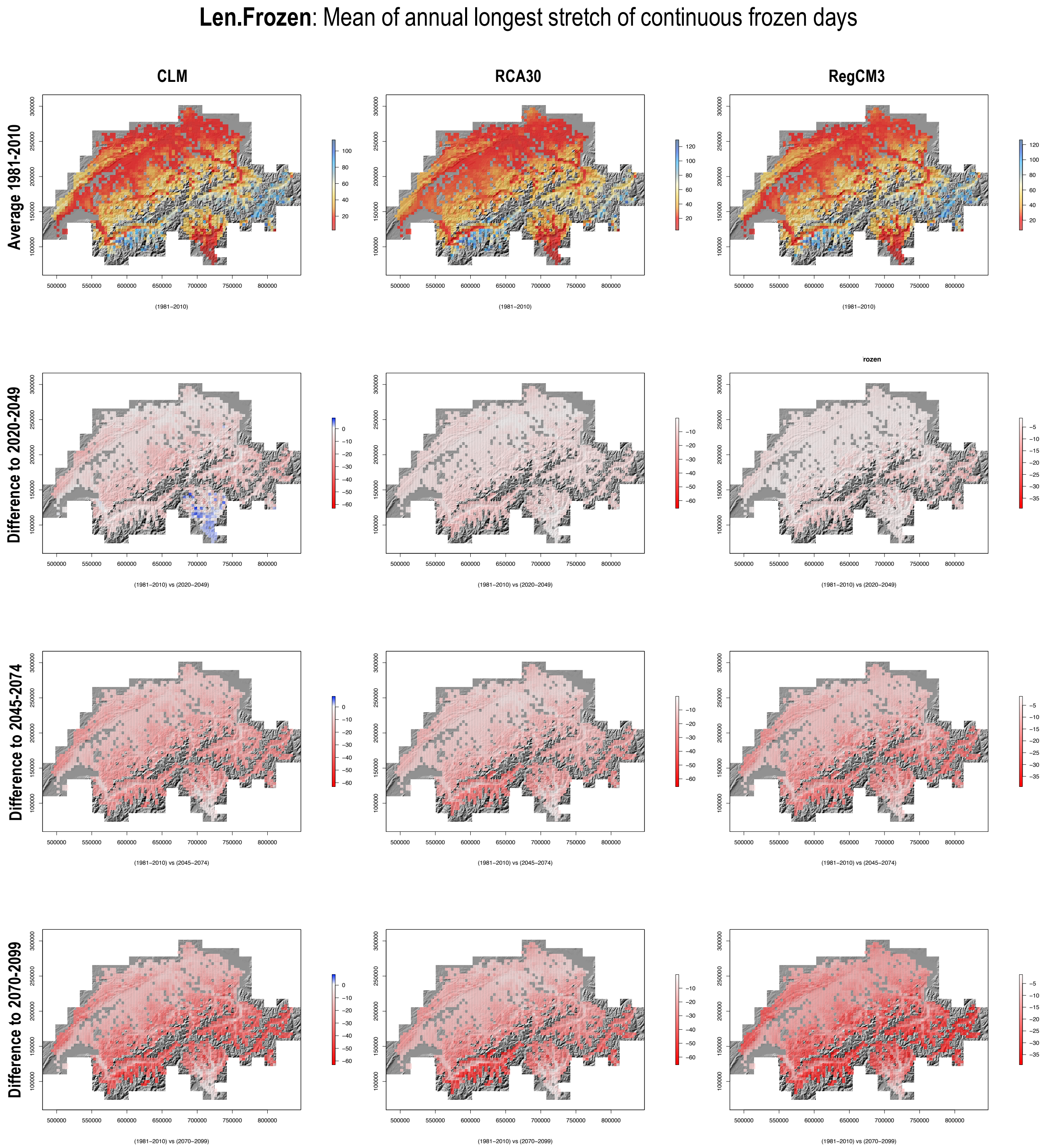

***Figure A2.8**: Mean of annual longest stretch of continuous frozen days for 3 different RCMs in Switzerland.*

The following is a compilation of the temporal patterns on the risk of frost frequencies during leaf flush in four tree species for four altitudinal bands (0-500 m, 500-800 m, 800-1200 , and >1200 m). The projected future climate is represented by three regional climate models (CLM; RCA30; RegCM3) for the A1B scenario. The data for extracting these temperature extremes indices was provided by MeteoTest. The methods for modelling leaf flush dates are presented in the TempEx final report. The leaf flush frost risks have been calculated for the following four tree species: *Fagus sylvatica*, *Quercus robur*, *Picea abies*, *Pinus sylvestris*. The appendix lists the patterns and anomalies for the four species:

List of species with leaf flush frost risk patterns:

Fagus sylvatica: frost frequency during the leaf flush period

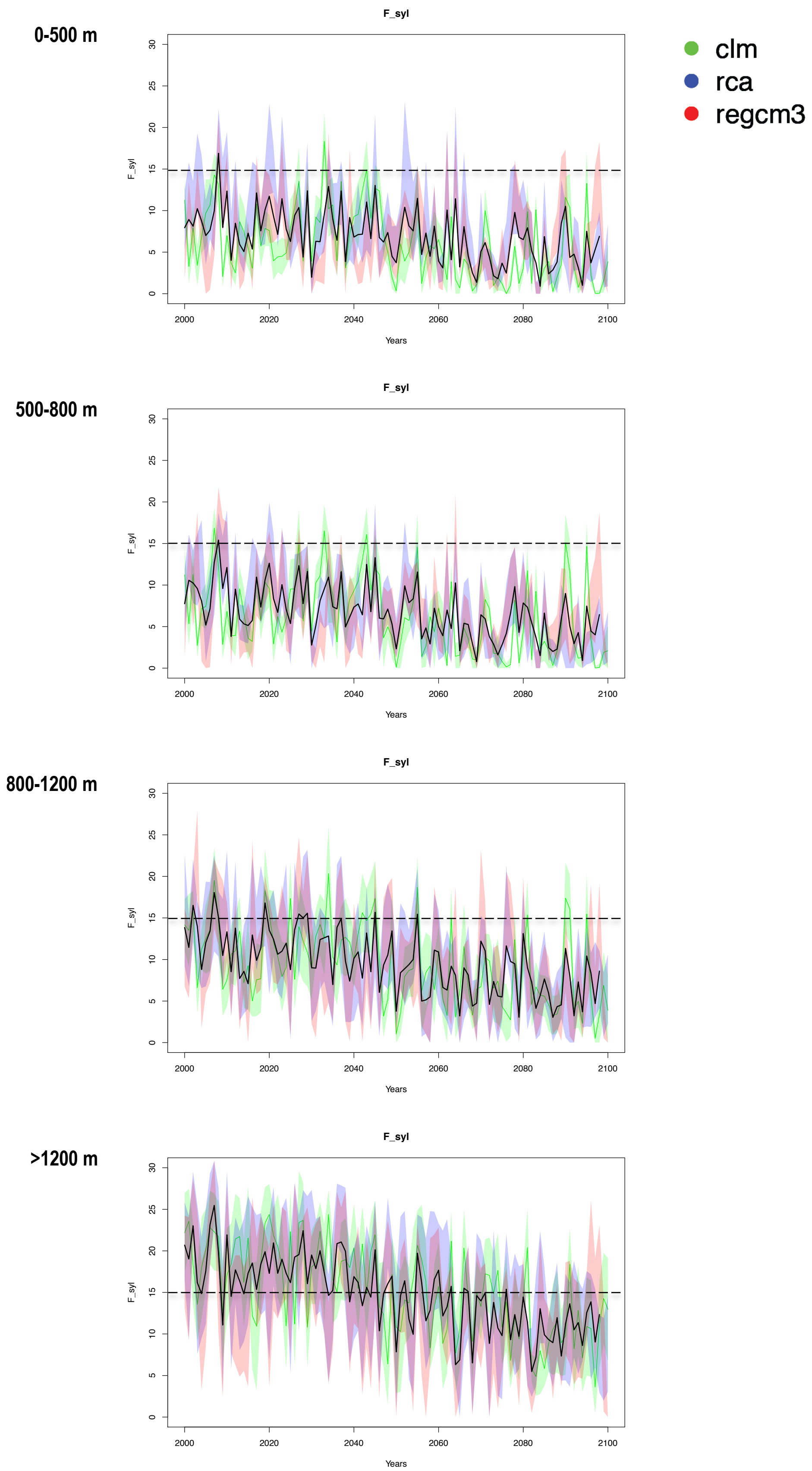

Figure A3.1: *Temporal patterns in frost frequency during leaf flush in Switzerland for four altitudinal bands. Red shades: RegCM3; Blue shades: RCA30; Green shades: CLM. The bold black line indicates the ensemble mean trend among the three RCMs used.*

Quercus robur: frost frequency during the leaf flush period

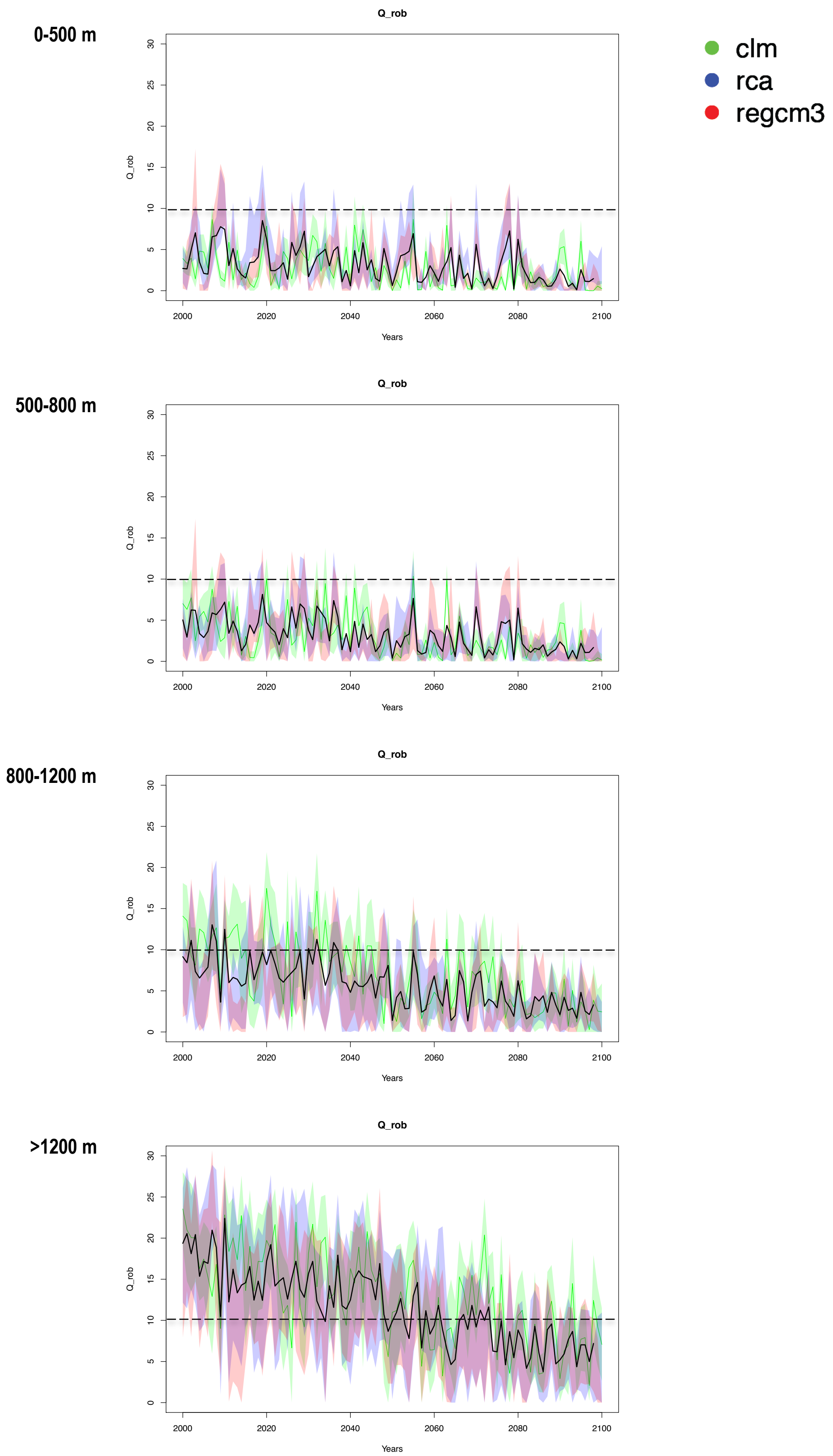

Figure A3.2: *Temporal patterns in frost frequency during leaf flush in Switzerland for four altitudinal bands. Red shades: RegCM3; Blue shades: RCA30; Green shades: CLM. The bold black line indicates the ensemble mean trend among the three RCMs used.*

Picea abies: frost frequency during the leaf flush period

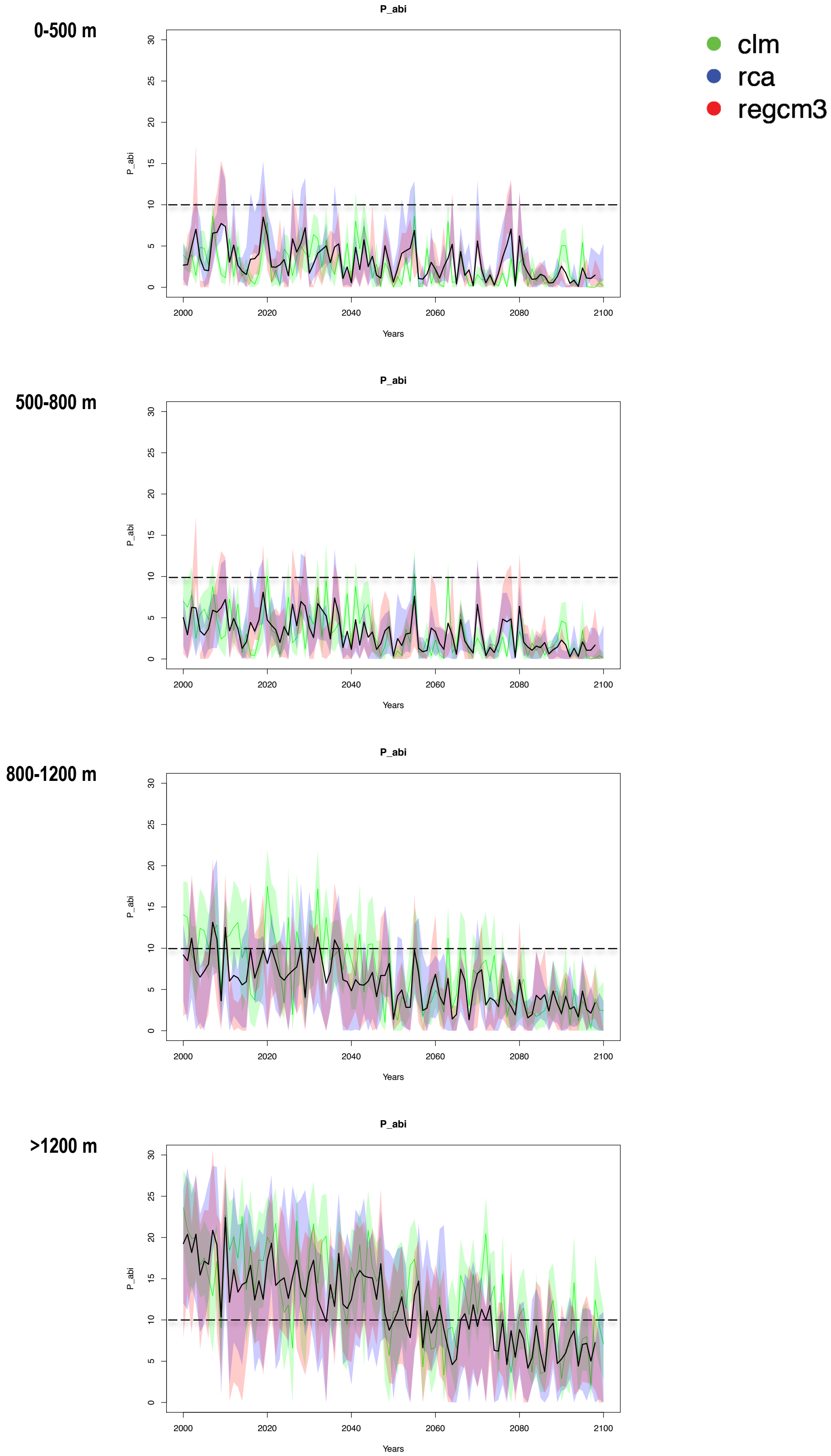

***Figure A3.3**: Temporal patterns in frost frequency during leaf flush in Switzerland for four altitudinal bands. Red shades: RegCM3; Blue shades: RCA30; Green shades: CLM. The bold black line indicates the ensemble mean trend among the three RCMs used.*

Pinus sylvestris: frost frequency during the leaf flush period

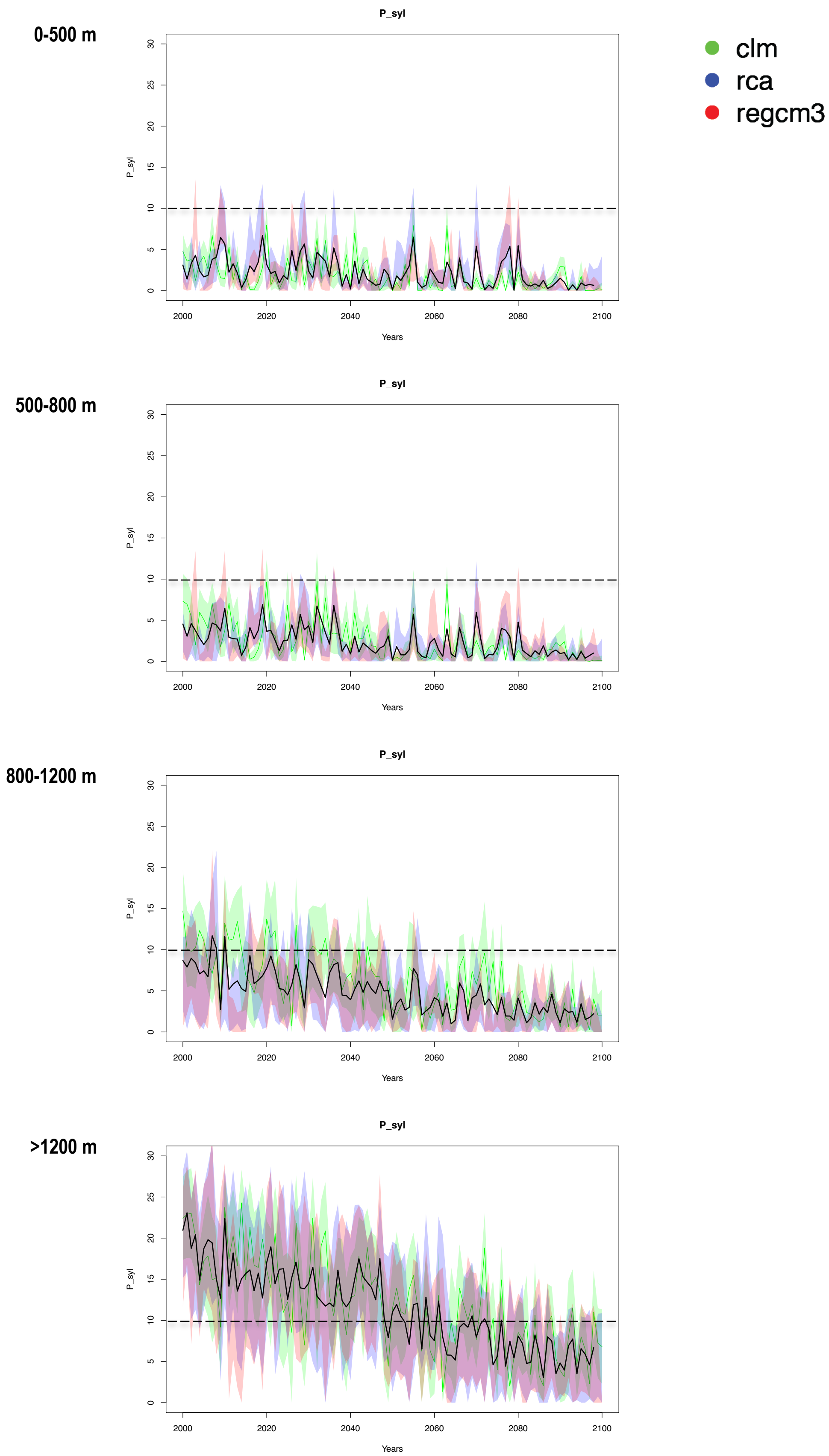

Figure A3.4: *Temporal patterns in frost frequency during leaf flush in Switzerland for four altitudinal bands. Red shades: RegCM3; Blue shades: RCA30; Green shades: CLM. The bold black line indicates the ensemble mean trend among the three RCMs used.*

The following is a compilation of the spatial patterns on the risk of frost frequencies during leaf flush in four tree species and anomalies thereof for current climate (means annual frequency for the period 1981-2010 and for three periods of projected future climate, namely 2020-2045, 2045-2074, and 2070-2099. The projected future climate is represented by three regional climate models (CLM; RCA30; RegCM3) for the A1B scenario. The data for extracting these temperature extremes indices was provided by MeteoTest. The methods for modelling leaf flush dates are presented in the *TempEx* final report. The leaf flush frost risks have been calculated for the following four tree species: *Fagus sylvatica*, *Quercus robur*, *Picea abies*, *Pinus sylvestris*. Maps were generated by aggregating all LFI sites within a 2.5 x 2.5 km window for better visibility. The appendix lists the patterns and anomalies for the four species:

List of species with leaf flush frost risk patterns:

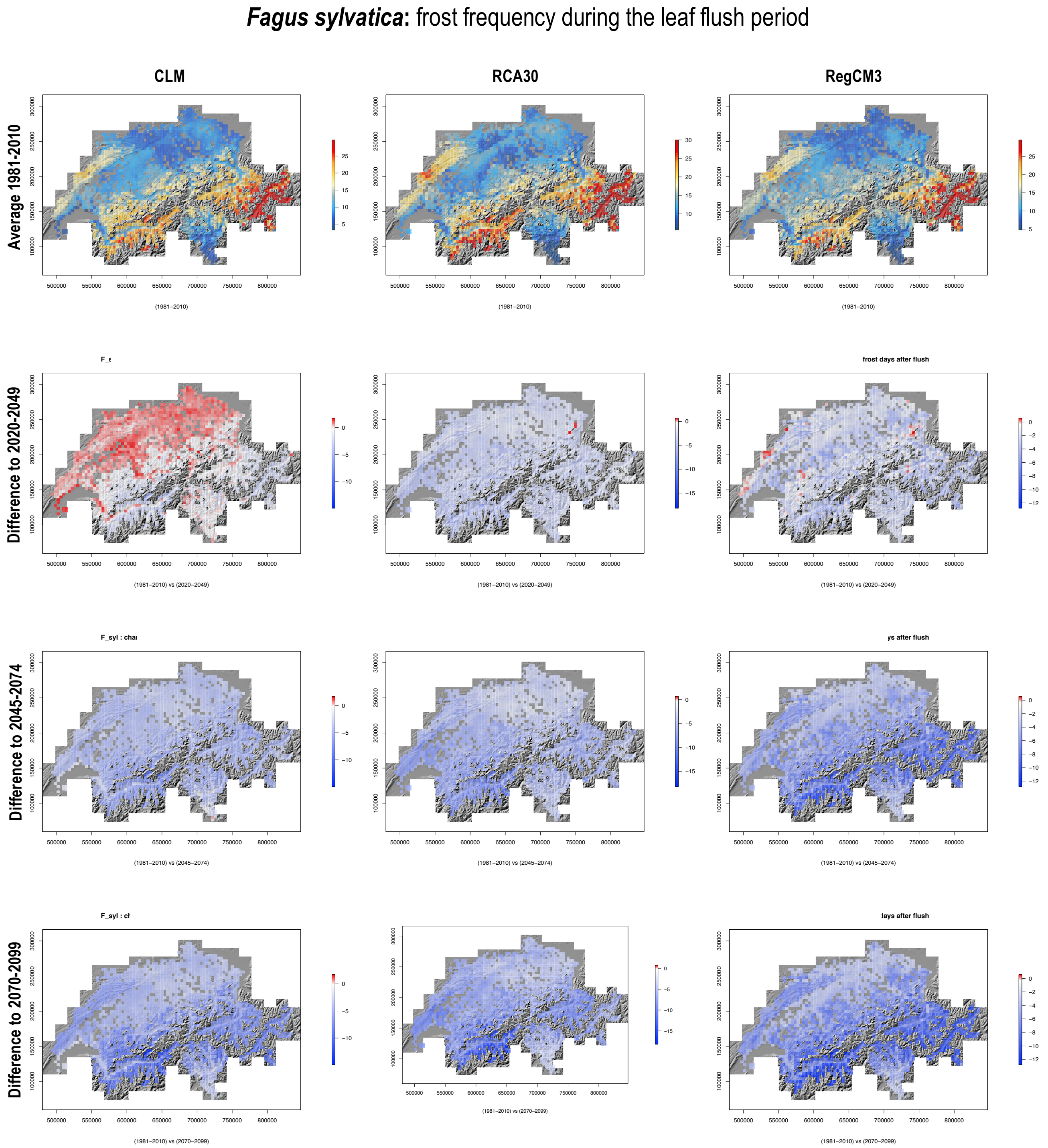

Figure A4.1*: Spatial patterns (row 1) and anomalies (rows 2-4) in frost frequency during leaf flush.*

Quercus robur: frost frequency during the leaf flush period

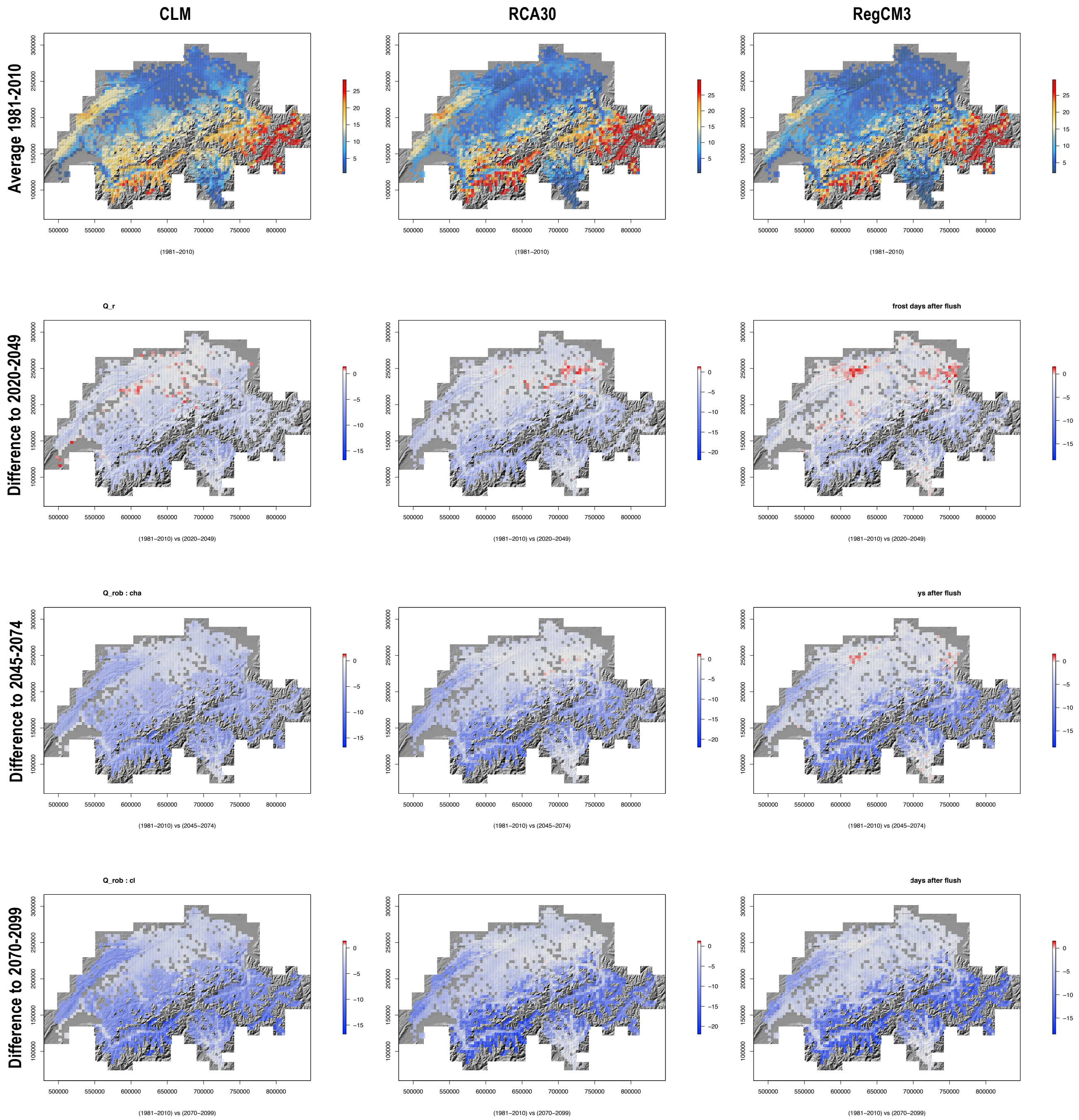

Figure A4.2: *Spatial patterns (row 1) and anomalies (rows 2-4) in frost frequency during leaf flush.*

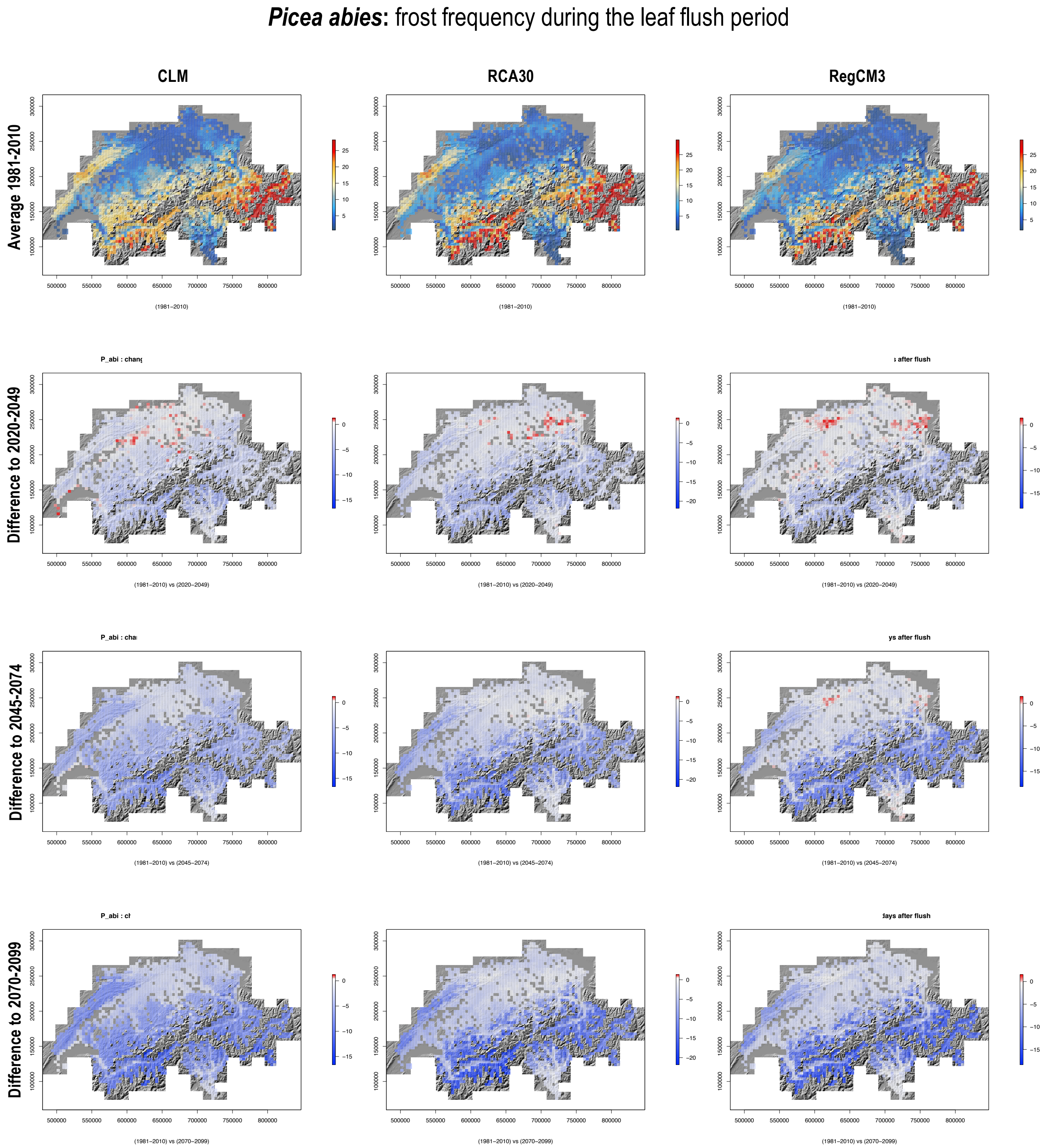

Figure A4.3*: Spatial patterns (row 1) and anomalies (rows 2-4) in frost frequency during leaf flush.*

***Pinus sylvestris*: frost frequency during the leaf flush period**

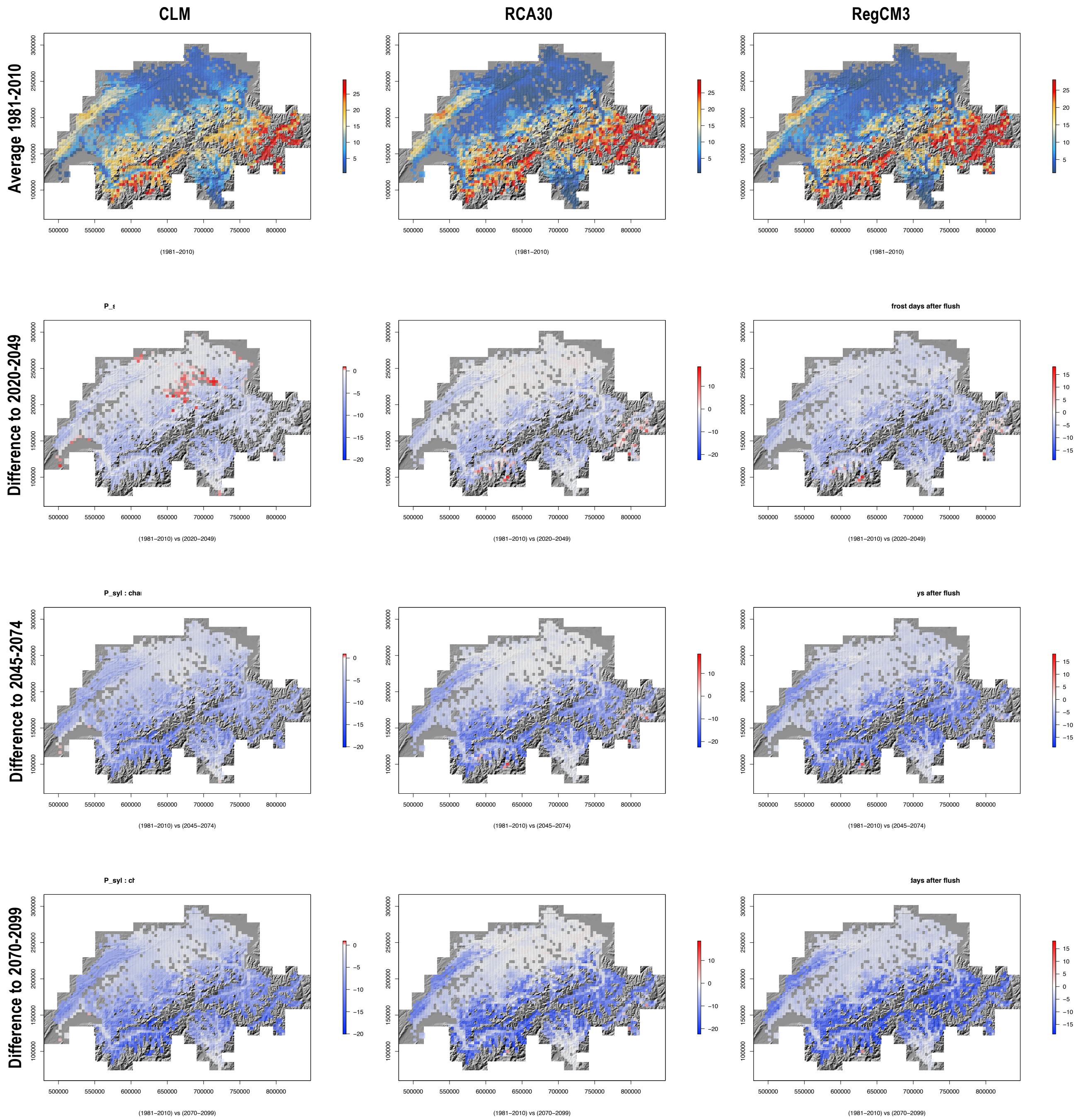

***Figure A4.4**: Spatial patterns (row 1) and anomalies (rows 2-4) in frost frequency during leaf flush.*

Appendix A5: Some spatial error structures of earlier data versions

Examples of errors found in earlier data versions

Here, we address some uncertainties in earlier versions of the data delivered by Meteotest. The first version was prone to errors, and also the second version still contained significant errors. These errors were hard to detect, since it only concerned data of single days. Meteotest claimed that these data were already erroneous in the original RCM coarse resolution (18x18 km) data they downscaled. We are routinely using the same data, and were not able to detect these errors. Our RCM data seemed to have been error-free. Because only some few daily maps were erroneous we could not easily detect the errors. Yet, the derived extremes statistic then became erroneous, and we detected some errors only after the time-consuming processing of all indices. Figure A5.1 illustrates some of the problems we found even in the second delivery of the data. Next to the strange patterns, some extreme outliers were detected, such as Tmax values of 486.3 and 1552.8 °C. The last (third) delivery was improved and we didn't find the same very strong errors any more. Yet, there were still patterns in the data that we found strange and it meant that we calculated monthly averages of single-day absolute extremes instead of using these single-day extremes. By this, we reduced the effect of remaining possible errors. In another application, we also abstained from using effects of single-day absolute climate extremes from analyses, such as in those on forest regeneration (Wohlgemuth *et al.* 2016). We think that bay calculating means of annual (single-day) absolute extremes, most errors were now removed or avoided to propagate and we find that the general trends reproduced from the models are fine. Yet, after having found errors repeatedly means that we could not be completely certain that all errors were found and that the calculations based on these data are all without errors.

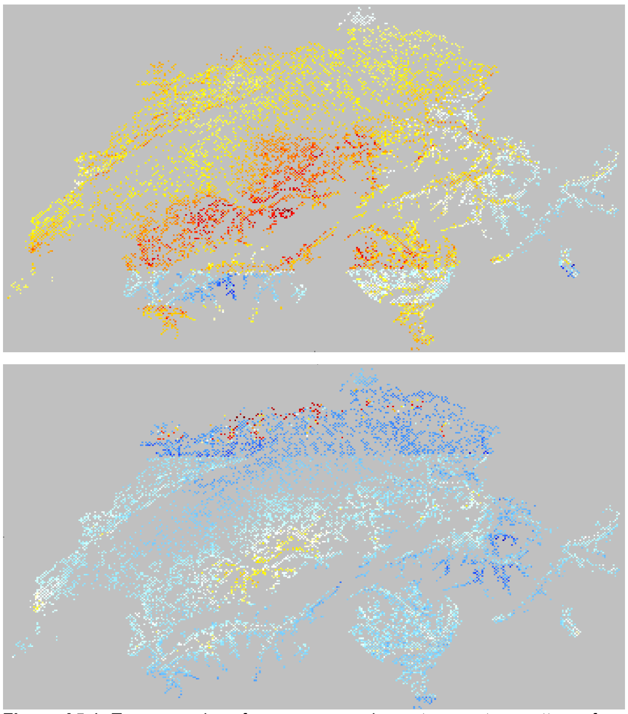

Figure A5.1*: Two examples of erroneous maximum temperature patterns from two different days obtained in the 2nd delivery of data from Meteotest. The strange patterns appeared in 2033 and faded by summer 2034. Not only were there strong striping patterns that are clearly wrong. In addition, the temperatures were generally warmer at higher altitudes and lower in low altitudes. This pattern is not caused by temperature inversion (as there is none included in RCMs, and because it was found throughout all of Switzerland). Finally, it is visible that few single cells had illogically high or low values compared to adjacent cells. Red colors indicate high, blue colors low temperatures.*