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REPORT

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Keywords: climate change, snow

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Norwegian Water Resources and Energy Directorate
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Preface

Snow depth and the extent of the seasonal snow cover in Norway are expected to decrease significantly in the future along with the warming of the climate. More precise knowledge of the future changes in snow conditions are of great interest to many sectors of the society, such as hydropower industry, winter tourism and recreation. This report presents new simulation results of future (2071-2100) average snow depth and snow line elevation for different regions and elevations of Norway. The new results are simulated by a dedicated snow model (seNorge) calibrated against historical snow data.

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Oslo, March 2018

Morten Johnsrud
Director

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Head of Section

Summary

Snow is an important part of life in the northern parts of the world. In Norway, for example, snow depth and the extent of the seasonal snow cover are expected to decrease significantly in the future along with the warming of the climate. Consequently, more precise knowledge of the future changes in snow conditions are of great interest to many sectors of the society, such as hydropower industry, winter tourism and recreation.

In this report, results of historical and future snow conditions (mainly focussing on snow depth) from the seNorge snow model (Saloranta, 2012; 2016) are presented. The main advantages of using the seNorge snow model are (1) that its parameters are specifically estimated on the basis of extensive historical snow data sets, (2) that its snow melt routine considers also solar radiation in addition to air temperature, and (3) that the model provides also results for snow depth (*SD*) and fraction of snow covered area (*SCA*), in addition to the snow water equivalent (*SWE*).

Results for the projected future average snow depth are presented for the 19 (number by the end of 2017) counties of Norway at different elevations and at the time of four different popular holiday seasons during the winter and spring. The results show, among others, that:

- For the four smallest counties around Oslo (Østfold, Vestfold, Oslo, Akershus) the greatest absolute changes in *SD* are seen in the highest elevation zone (500-600 m a.s.l., only present in Akershus and Vestfold), where a mean reduction of 20-60 cm is simulated in winter and spring (Christmas to Easter). Moreover, the snowline elevation rises by 100-300 m from 1971-2000 to 2071-2100, depending on the season.
- For the remaining larger 15 counties, the overall absolute changes in *SD* from 1971-2000 to 2071-2100 seem to be largest in the west coast counties (Rogaland to Møre og Romsdal) as well as in Nordland, where a mean reduction of over ~100 cm is seen in mid-winter and spring around 1000 m a.s.l. elevation. On the contrary, the overall smallest absolute changes in *SD* are seen in the inland counties of eastern Norway (Hedmark, Oppland, Buskerud), where the mean reduction in *SD* does not exceed ~50 cm.
- The rise in the wintertime (Christmas and winter holiday) snowline elevation from 1971-2000 to 2071-2100 is generally largest in the four west coast counties (Rogaland to Møre og Romsdal; a rise of 300-500 m) and smallest in the inland counties of eastern Norway (Hedmark, Oppland) as well as in northern Norway (Troms and Finnmark), where the wintertime rise in snowline elevation is only 100 m at most.
- In the springtime (Easter and Constitution day) the rise in snowline elevation from 1971-2000 to 2071-2100 is 200-400 m in most of the counties of Norway (except in Troms and Finnmark in the Easter, where rises of only 150 and 50 m are detected, respectively).

Such climate projections will naturally always contain several types of uncertainties. Some of these uncertainties are quantifiable, such as the uncertainty related to differences

in model algorithms and process parameterizations, which is in this report roughly estimated by showing results from three different climate model runs. Moreover, the snow depth over-/underestimation bias in the climate model runs in the historical period (1971-2015) is evaluated against best available high-resolution regional snow data (results from operational seNorge snow maps as well as from MODIS satellite images), and areas with potentially dubious model results are specifically highlighted.

1 Introduction

Snow is an inherent part of life in the northern parts of the world. In Norway, for example, each year more or less every region of the country experiences a wintertime snow cover. Snow is a prerequisite for many winter sport activities, and a challenge for traffic flow at airports and on roads and railways. The citizens are generally not indifferent to snow, and one can regularly read from media reports of current snow conditions, especially if there is exceptionally little or much snow on the ground. Snow conditions play also an important role in, among others, hydropower production planning, and in forecasting the risk of potentially disastrous floods, slush flows and avalanches.

Snow cover can respond rapidly to small changes in temperature due to the freeze/melt threshold of water at 0° C. Thus, the disappearing snow cover along the projected climate warming may be one of the most concrete and visible consequences of the climate change in the northern hemisphere.

The Norwegian Centre for Climate Services (NCCS; www.klimaservicesenter.no) provides many type of climate- and hydrology-related data that can be used e.g. in impact studies of changing climate on the society and environment. In a projected future climate, the length of the snow season is generally expected to decrease at lowland areas due to warmer temperatures. However, higher up on the colder hill and mountain areas of Norway the increased precipitation in a future climate can even result in more snow and little change in snow season length despite of the warming effect (Dyrrdal et al. 2013; Hanssen-Bauer et al., 2017).

The future climate projections of snow conditions for Norway, currently available at NCCS, are produced by the gridded HBV hydrological model (Wong et al., 2016). Climate model output of historical and future daily mean air temperature T [° C] and daily sum of precipitation P [mm], downscaled to 1×1 km resolution have been used as input forcing for the HBV model. The input data has also been bias-corrected using the observation-based seNorge v.1.1 gridded temperature and precipitation data (Wong et al., 2016). The climate model projections for these two basic variables (T, P) are considered relatively robust and well predictable, as compared to many other climate model output variables such as wind or cloudiness.

In this report, we present results of historical and future snow conditions (mainly focussing on snow depth) from an alternative snow model, the seNorge snow model (Saloranta, 2012; 2016). The main advantages of using the seNorge snow model are (1) that its parameters are specifically estimated on the basis of extensive historical snow data sets, (2) that its snow melt routine considers also solar radiation in addition to air temperature, and (3) that the model provides also results for snow depth (*SD*) and fraction of snow covered area (*SCA*), in addition to the snow water equivalent (*SWE*).

In this report, results for the projected future average snow depth are presented for the 19 (number by the end of 2017) counties of Norway (Figure 1) at the time of four different popular holiday seasons during the winter and spring. The new simulation results of snow conditions from the seNorge snow model, based on regional climate model (RCM) input forcing, are compared to the previous ones from the HBV model in order to highlight the effect of snow model choice and parameterization on the model results. The quality of the snow model results are also assessed against satellite images and against the operational seNorge2.0 snow maps, in order to highlight areas where the historical model results for snow may be dubious and have serious biases. Any such biases in the historical period (e.g. overestimated snow amount) may also be reflected in a projected future climate simulation.

2 Methods

2.1 The seNorge snow model

The snow simulation model applied in this study is the seNorge snow model (v.1.1.1; Saloranta, 2012; 2016), which is also used for operational snow mapping in Norway (www.seNorge.no). The input data requirements for the model are air temperature *T* [° C] and precipitation *P* [mm], and it is run with a daily time step in this study. The seNorge model consists of two main submodels, namely 1) the *SWE* submodel for snow pack water balance and 2) the snow compaction and density submodel for converting *SWE* to *SD*. The *SWE* submodel is independent of the snowpack compaction and density submodel, implying that *SWE* is not affected by snow density in the model.

Potential snow melt rates (M^*) are calculated using the extended degree-day snow melt rate equation (Hock, 2003):

$$M^* = b_0 T + c_0 S^* \qquad \text{, if} \quad T>0\ °\text{C} \qquad (1)$$

where T is air temperature, S^* is solar radiation, and where b_0 and c_0 are empirical parameters estimated from over 3000 daily melt rate observations from the Norwegian snow pillow network. Grid cell melt rates are also affected by the simulated *SCA*. The main model parameters are listed in Table 1.

2.2 The model input forcing data (temperature and precipitation)

The main simulations with the seNorge snow model are run with precipitation and air temperature data from three different regional climate model (RCM) runs, which have all been bias-corrected using the observation-based seNorge v.1.1 gridded temperature and precipitation data (Wong et al., 2016). The three RCMs are: (1) CNRM-CM5_SMHI-RCA4, (2) HADGEM2_SMHI-RCA4 and (3) MPI_SMHI-RCA4. The applied high-resolution regional model is the same in all these RCM runs, but they all have a different general circulation model (CNRM-CM5, HADGEM2, MPI) used as forcing at the regional model domain boundaries. The IPCC greenhouse gas emission scenario (representative concentration pathway, RCP) used in this study is the RCP4.5, which implies a slow increase of emissions until 2050, followed by emission reductions (Hanssen-Bauer et al., 2017).

Table 1. The nine main seNorge snow model parameters with their default values. Note that the parameters b_0, c_0 and f_{var} can have different values depending on whether the grid cell is located below or above the tree line (denoted by subscripts "*_f*" and "*_m*", respectively).

Parameters	Description	Default	Unit
r_{max}	maximum allowed weight fraction (W_L/ W_I) of liquid water in snowpack	0.1	[-]
T_S	threshold air temperature for rain/snow	0.5	[°C]
b_{0_f}	melt rate parameter (below tree line)	2.13	[mm d^{-1} °C^{-1}]
c_{0_f}	melt rate parameter (below tree line)	6.3 *	[mm d^{-1}]
f_{var_f}	spatial snow distribution parameter	0.25	[-]
b_{0_m}	melt rate parameter (above tree line)	1.81	[mm d^{-1} °C^{-1}]
c_{0_m}	melt rate parameter (above tree line)	10.9 *	[mm d^{-1}]
f_{var_m}	spatial snow distribution parameter	0.5	[-]
ρ_{nsmin}	minimum density of new snow	0.050	[kg L^{-1}]
η_0	coefficient related to viscosity of snow (at zero temperature and density)	7.6	[MN s m^{-2}]
C_5	coefficient for temperature effect on viscosity	0.1	[°C^{-1}]
C_6	coefficient for density effect on viscosity	24.3	[L kg^{-1}]

*c_0 is normalized to represent melt rates for a horizontal snow pack at the summer solstice at latitude 60 °N.

No further corrections of the RCM precipitation or temperature are made in the seNorge snow model simulations. These snow simulations are hereinafter referred as "seNorge-RCM" simulations.

In order to evaluate the quality of the seNorge-RCM simulations in the control period 1971-2000, two different reference snow data sets are used:

(1) The operational snow maps, simulated by the seNorge (v.1.1.1) snow model with observation-based seNorge2 temperature and precipitation grid data as input (Lussana et al. 2018; www.senorge.no; hereinafter referred as "seNorge2.0" simulations).

(2) Maps of *SCA* on 0.5x0.5 km resolution, based on MODIS satellite images in the period 2001-2015.

The seNorge2.0 snow maps have been thoroughly evaluated against the MODIS-SCA data (Lussana et al., 2018), and show good correspondence with the observed *SCA* in southern Norway, while in northern Norway the seNorge2.0 snow maps underestimate the observed *SCA* somewhat in the springtime period.

2.3 Calculation of the average snow conditions by elevation in the Norwegian counties

Since snow conditions normally vary significantly depending on the terrain elevation, the results of the snow simulations are here presented as long-term (30 years) median *SD* for different elevation zones for each of the 19 counties in Norway. All the 1x1 km grid cells within each county are assigned into their respective elevation zone bins (0-100, 100-200, 200-300 … 2400-2500 m above sea level (m a.s.l.)). A mean daily *SD* value is then calculated for each elevation bin. Finally, median *SD* values are calculated based on the 210 daily mean *SD* values picked out from a 7-day time window around a given date each year over a 30-year period (i.e. 30*7 =210). Figure 2 show these median snow conditions along elevation for the 19 counties in two different 30-year periods (1971-2000, 2071-2100), based on the seNorge-RCM simulations with the three different RCM forcings, in addition to the seNorge2.0 simulations functioning as a reference. The same procedure is applied also for variables *SWE* and *SCA*. The snow line elevation is defined as the elevation where the average *SCA* (e.g. in 1971-2000) exceeds 50 % (i.e. where half of the grid cells are snow-covered on average).

3 Results

3.1 Comparison and evaluation of the snow simulations in 1971-2015

The simulations from the three seNorge-RCM runs in the control period (1971-2000, blue lines in Figure 2) are generally coherent with each other, showing approximately similar *SD* vs. elevation profiles. However, when compared to results from the seNorge2.0 simulations (grey lines in Figure 2), considered as the reference dataset of regional *SD* in Norway in the same period 1971-2000, there is a clear tendency of the three seNorge-RCM runs to overestimate snow depth at higher elevations (above 500-1000 m a.s.l.) in the control period in most of the counties. This overestimation is, however, probably exaggerated in the northern Norway somewhat, as the reference data set (seNorge2.0 simulations) is known to underestimate *SCA* and precipitation in the northern Norway (Lussana et al. 2018). Moreover, the three seNorge-RCM runs generally underestimate snow depth at lower elevations (below ~1000 m a.s.l.) in the western Norway counties (Rogaland to Møre og Romsdal).

These under-/overestimation biases most likely originate from the bias-correction of the RCM input data (Wong et al., 2016), which was made using the previous version v.1.1. of the observation-based grid data set, known to overestimate precipitation and snow amounts in the mountains of southern Norway (Saloranta, 2012), and to have too warm wintertime temperatures along the west coast of Norway. This bias-tendency is also verified in Figure 3 where the simulated *SCA* (seNorge-RCM with CNRM-CM5_SMHI-RCA4 input forcing) is compared to the observed *SCA* based on MODIS satellite images in March-July 2001-2015.

A consequence of these under-/overestimation biases is that, if e.g. the simulated snow depth is largely overestimated by the seNorge-RCM in the control period (1971-2000), it is likely to be also overestimated in a future climate projection (2071-2100). Therefore, in order to highlight the areas where the over- or underestimation of *SD* is larger than 30 cm or 30 %, as compared to the reference dataset (i.e. the seNorge2.0 simulations), these dubious seNorge-RCM results are shown by dashed line in Figure 2, both for the control period and for the future projections.

As pointed out in Section 1, the future climate projections of snow conditions for Norway, currently available at NCCS, are produced by the gridded HBV hydrological model (Wong et al., 2016). The difference between *SWE* simulated by the HBV and seNorge snow models, both using the same RCM input forcing (CNRM-CM5_SMHI-RCA4) in 1971-2000 and 2071-2100 was studied, and Figure 4 exemplifies the often significant differences between the two models. The general tendency in many counties is that the HBV model simulates lower *SWE* than the seNorge model at all elevations. Since the input forcing is the same and the model structures are rather similar between the two models, this difference is likely associated with different snow model parameters values, as well as with the different snow melt algorithm used (degree-day vs. extended degree-day algorithms). The obvious weakness of the snow simulations from the HBV model is that the parameters of the hydrological model, including those of the snow module, have been optimized only against water discharge data. Consequently, no snow data has been used to calibrate the HBV snow model, as is the case with the seNorge snow model. Recently, the snow model intercomparison study by Skaugen et al. (2018) demonstrated that calibrating the snow melt temperature-index factor using runoff data only is not optimal for simulating correctly the snow coverage and dynamics of *SWE*.

3.2 Average snow depth in a future climate (2071-2100, RCP 4.5)

In a projected future climate with RCP 4.5 emission scenario, the countywise reduction in snow depth can be seen at different elevation levels in the *SD* vs. elevation profiles in Figure 2. The spread in the simulated future snow depth conditions between the three different seNorge-RCM runs using different input data is sometimes rather large. The future reduction in snow depth varies from county to county and is very dependent on the particular elevation level. However, none of the counties and different RCMs show a significant increase in average *SD* below 2000 m a.s.l. in 2071-2100 as compared to 1971-2000.

As an example of Figure 2 interpretation, e.g. in the county of Møre og Romsdal in the eastertime (the 7-day window around April 1) the future average (median) *SD* in 2071-2100 is zero below approximately 500 m a.s.l. in all seNorge-RCM runs. However, the seNorge-RCM runs in the control period (1971-2000) seem to underestimate *SD* by ~30 cm around 500 m a.s.l. as compared to the seNorge 2.0 reference data set. Therefore, the average snow line elevation in the future may be somewhat lower than the 500-700 m a.s.l. indicated by the seNorge-RCM runs. Higher up at 1000 m a.s.l., the average *SD* is reduced from ~200 cm in 1971-2000 to ~100 cm in two of the seNorge-RCM runs, and to ~60 cm in one of the seNorge-RCM runs (HADGEM2_SMHI-RCA4). Even higher up at 1500 m a.s.l. the seNorge-RCM results in the control period are flagged dubious due to likely overestimation (dashed line in Figure 2), since they show a *SD* of over 300 cm compared to the ~200 cm given by the seNorge 2.0 reference data set. Despite of the likely overestimation of absolute *SD* values, we can still consider the simulated change in SD from 1971-2000 to 2071-2100 here, which is a reduction of 90-160 cm depending on the particular seNorge-RCM run.

3.3 Changes in future snow depth - key findings and uncertainties

The mean reduction of snow depth (*SD*) from 1971-2000 to 2071-2100 at three different elevation zones (0-100, 500-600 and 1000-1100 m a.s.l.) is shown in Figure 5 for all the 19 counties of Norway. The values represent means of the changes simulated by the three different RCMs (see Figure 2).

For the four smallest counties around Oslo (Østfold, Vestfold, Oslo, Akershus) the greatest absolute changes in SD (Figure 5) are seen in the highest elevation zone (500-600 m a.s.l., only present in Akershus and Vestfold), where a mean reduction of 20-60 cm is simulated in winter and spring (Christmas to Easter). As these four counties are already in the current climate on average snow free around the middle of May (Constitution day), no further reduction in *SD* is possible in a future climate. The snowline elevation (not shown) rises by 100-300 m from 1971-2000 to 2071-2100, depending on the season.

For the remaining larger 15 counties (all spanning elevations over 1000 m a.s.l.) the overall absolute changes in *SD* from 1971-2000 to 2071-2100 seem to be largest in the west coast counties (Rogaland to Møre og Romsdal) as well as in Nordland, where a mean reduction of over ~100 cm (Figure 5) is seen in mid-winter and spring in the 1000-1100 m a.s.l. elevation zone. On the contrary, the overall smallest absolute changes in *SD* are seen in the inland counties of eastern Norway (Hedmark, Oppland, Buskerud), where the mean reduction in *SD* does not exceed ~50 cm. As a comparison, the highest detected mean reduction in Figure 5 is ~200 cm in Rogaland around the middle of May (Constitution day; 1000-1100 m a.s.l. elevation zone).

At the lowest elevation zone by the sea level (0-100 m a.s.l.) the reduction in *SD* is highest in the three northernmost counties (Nordland, Troms, Finnmark), where currently snow is often present even at the sea level due to the colder climate in these counties. The mean reduction of *SD* here is up to ~50 cm during the mid-winter and early spring time-windows (winter holiday and Easter).

The rise in the wintertime (Christmas and winter holiday) snowline elevation (not shown) from 1971-2000 to 2071-2100 is generally largest in the four west coast counties (Rogaland to Møre og Romsdal; a rise of 300-500 m) and smallest in the inland counties of eastern Norway (Hedmark, Oppland, Buskerud) as well as in northern Norway (Troms and Finnmark), where the wintertime rise in snowline elevation is only ~100 m at most. However, in the springtime (Easter and Constitution day) the rise in snowline elevation from 1971-2000 to 2071-2100 is 200-400 m in most of the counties of Norway (except in Troms and Finnmark in the Easter, where rises of only 150 and 50 m are detected, respectively).

The results in Figure 2 can be studied further in detail to assess the mean reduction in *SD* in different parts of Norway. It is important, however, to bear in mind that such climate projections will always contain several types of uncertainties.

The uncertainty in different climate model projections, arising from differences in model algorithms and process parameterizations, among others, is explicitly shown by plotting the three different seNorge-RCM runs in Figure 2 (previously, up to 10 different seNorge-RCM runs have been used (Wong et al., 2016)). In addition to this model-related uncertainty, there are several other reducible and irreducible uncertainties in such climate projections related e.g. to uncertainties in future greenhouse gas emissions (RCPs) and to the general complexity of the climate system, which may potentially produce unforeseen surprising behavior, not predicted by the models.

The over-/underestimation bias in *SD*, detected in the control period (Section 3.1), will also introduce uncertainty into the results of future *SD*. However, as pointed out in Section 3.2, despite of the over-/underestimation of absolute *SD* values, the simulated *change* in *SD* from 1971-2000 to 2071-2100 may still be a robust and realistic result.

3.4 Suggestions for future improvements

In order to improve the realism of the simulations of snow conditions in the historical and future climate, the results in this report suggest that it would be useful:

1. to select and use the least biased versions of observation-based gridded temperature and precipitation datasets (Lussana et al., 2018) in bias-correction of the RCM output;

2. to select and use a dedicated snow model (e.g. the seNorge snow model; Saloranta (2012; 2016)) of which parameters have been specifically optimized against extensive historical snow observations.

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Figures

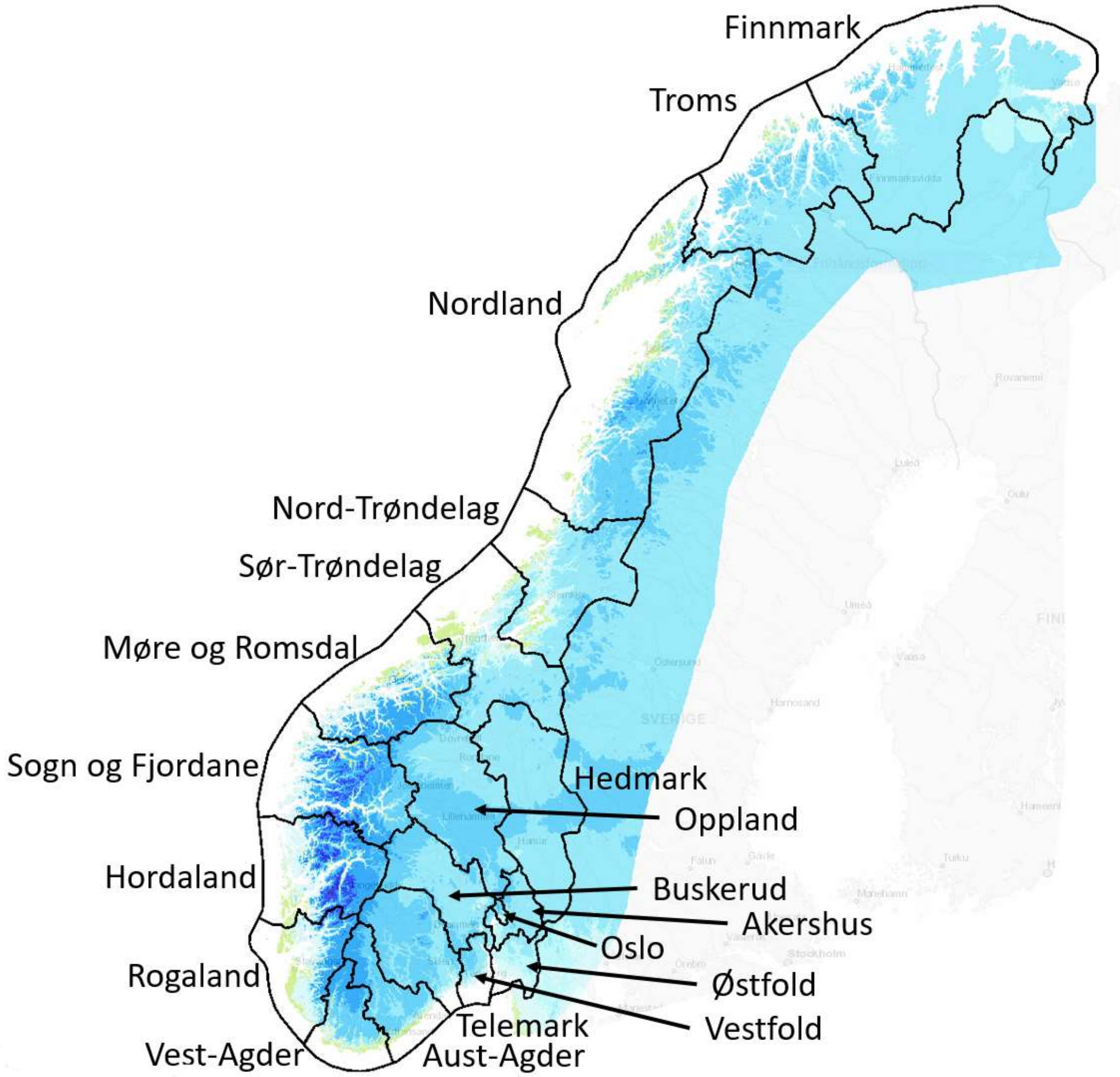


Figure 1. Example of a snow map (snow water equivalent, *SWE,* from www.xgeo.no) from 13. February 2018 simulated by the seNorge snow model. The 19 counties, for which results are summarized in Figure 2, are also shown.

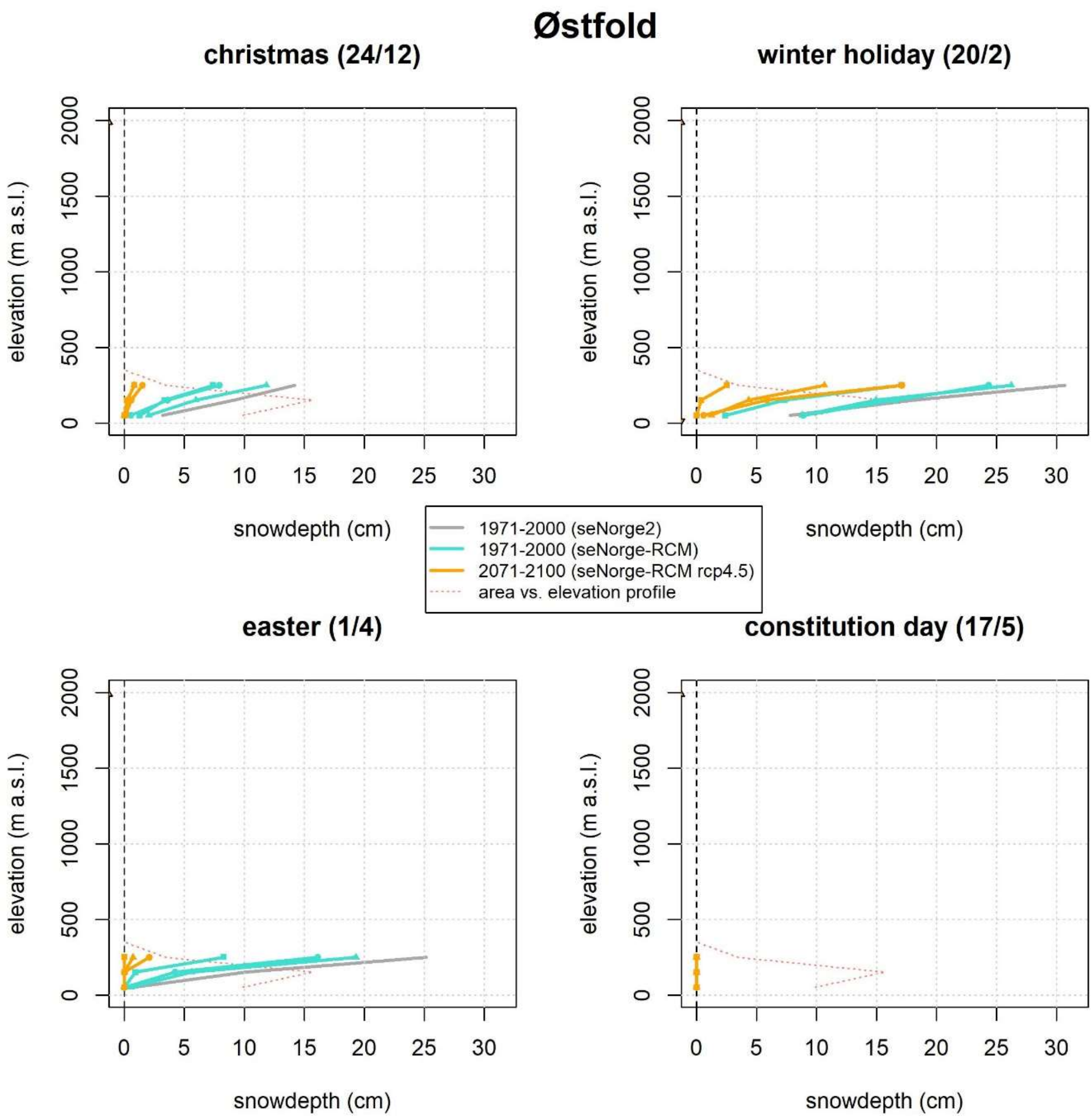
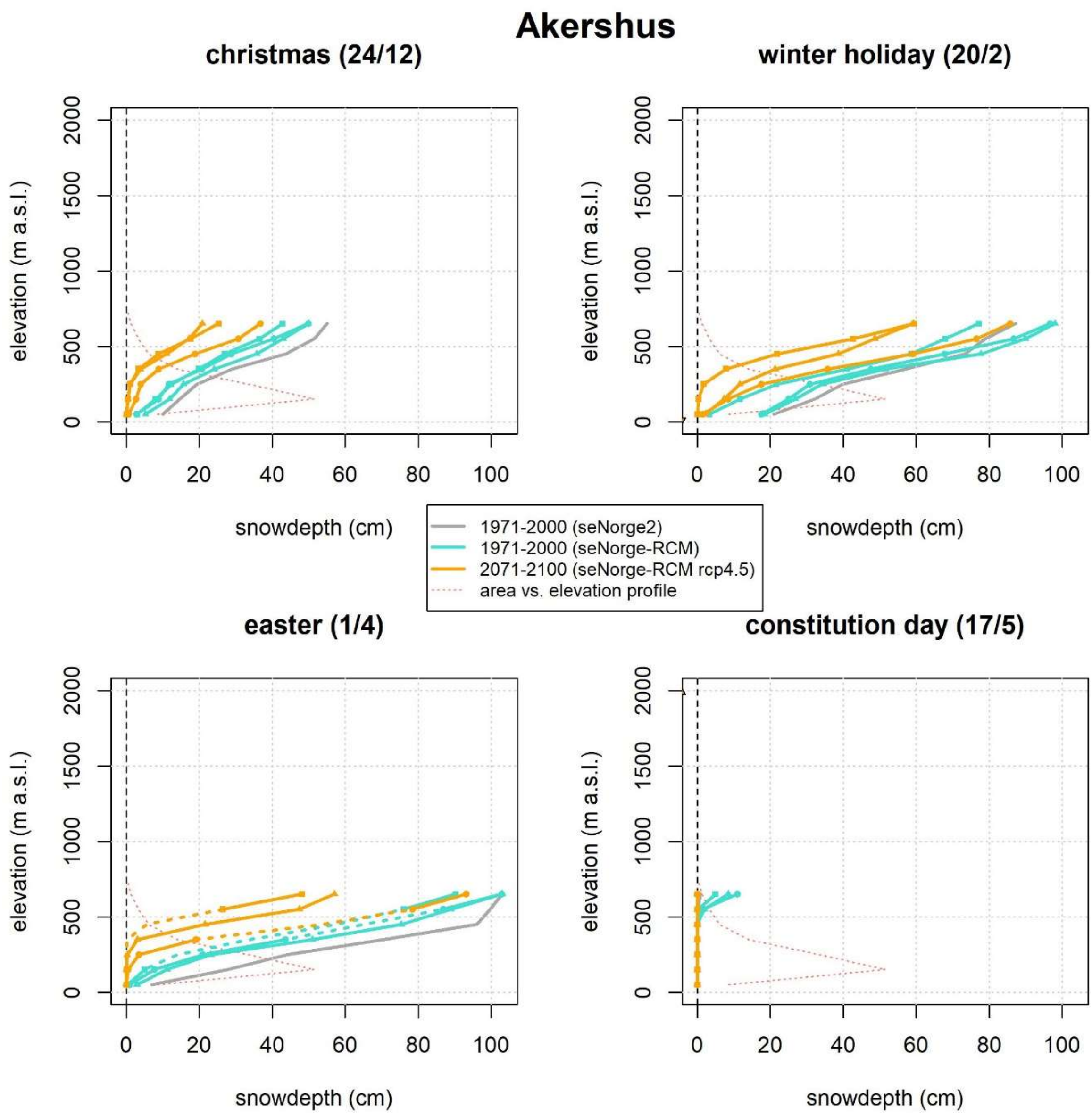


Figure 2. Climate projections for average snow depth (*SD*) along elevation in the 19 counties of Norway during four different winter/spring holiday seasons (7-day time-windows). Grey lines denote the results from the seNorge2.0 simulations (www.senorge.no; input forcing used is the seNorge2 observation-based grid data) in 1971-2000, representing the probably best available data of regional *SD* in Norway. Blue and orange lines denote results from the seNorge-RCM snow model in 1971-2000 and 2071-2100, respectively, where each line represents a different RCM used as input forcing (CNRM-CM5_SMHI-RCA4 (square markers), HADGEM2_SMHI-RCA4 (triangle markers), MPI_SMHI-RCA4 (circle markers)). The dashed portions of the lines (if any) denote possibly seriously biased seNorge-RCM snow model results, where the difference to the seNorge2.0 simulations (blue line compared to grey line) in 1971-2000 is more than 30 cm or 30 %. The thin dashed line denote the normalized area vs. elevation profile of the county. The results in 2071-2100 are based on the RCP 4.5 emission scenario.



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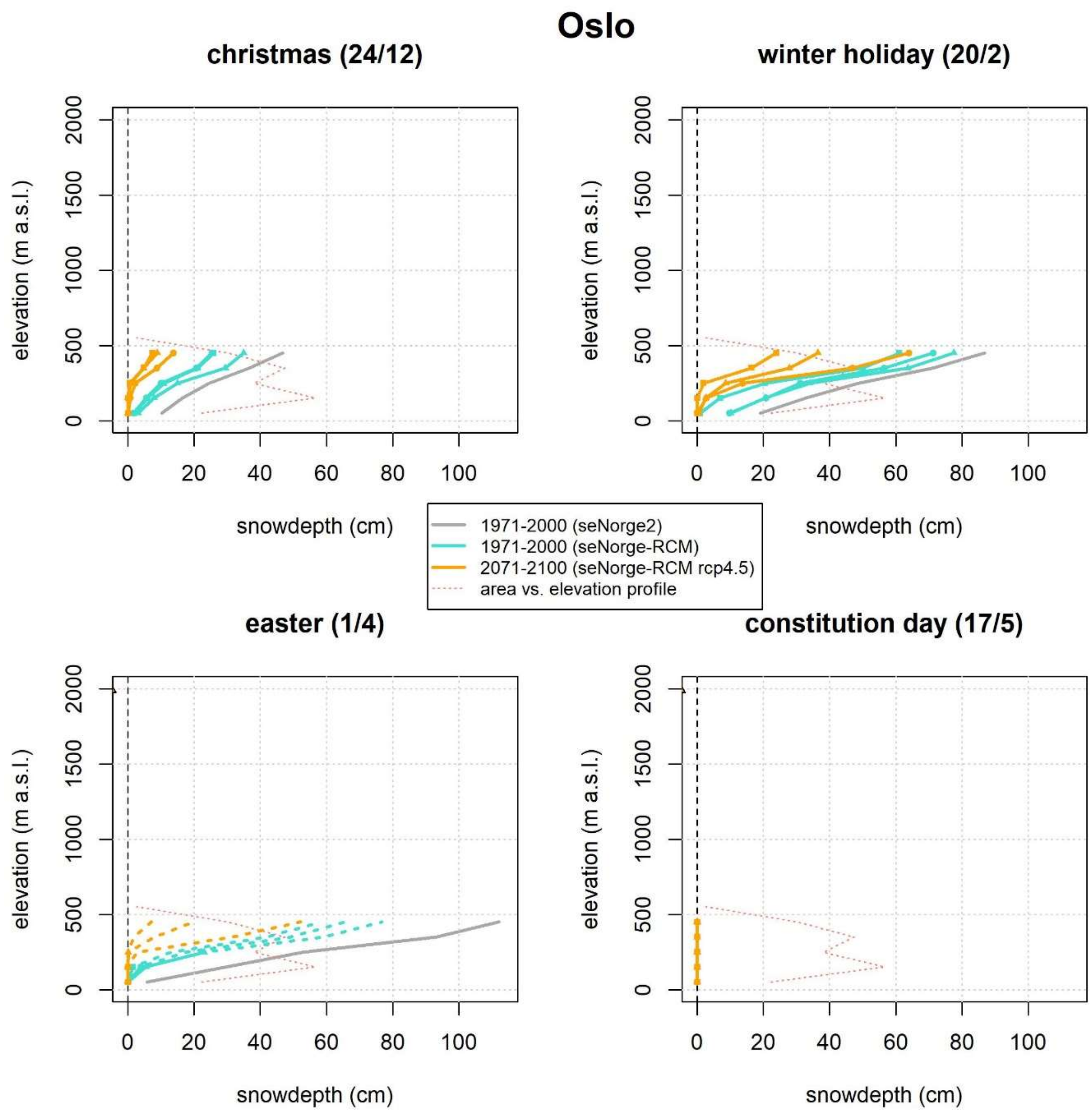

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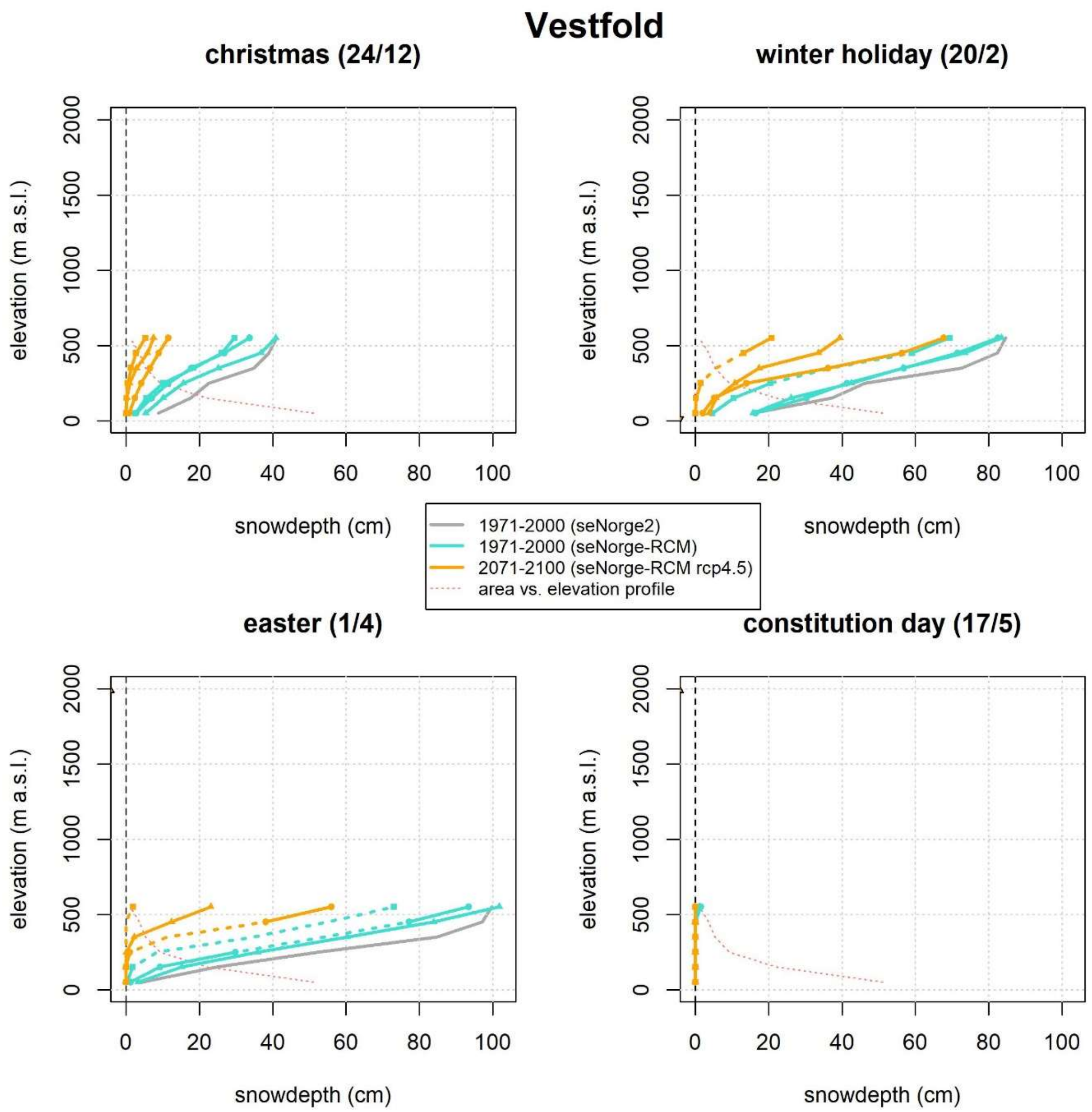

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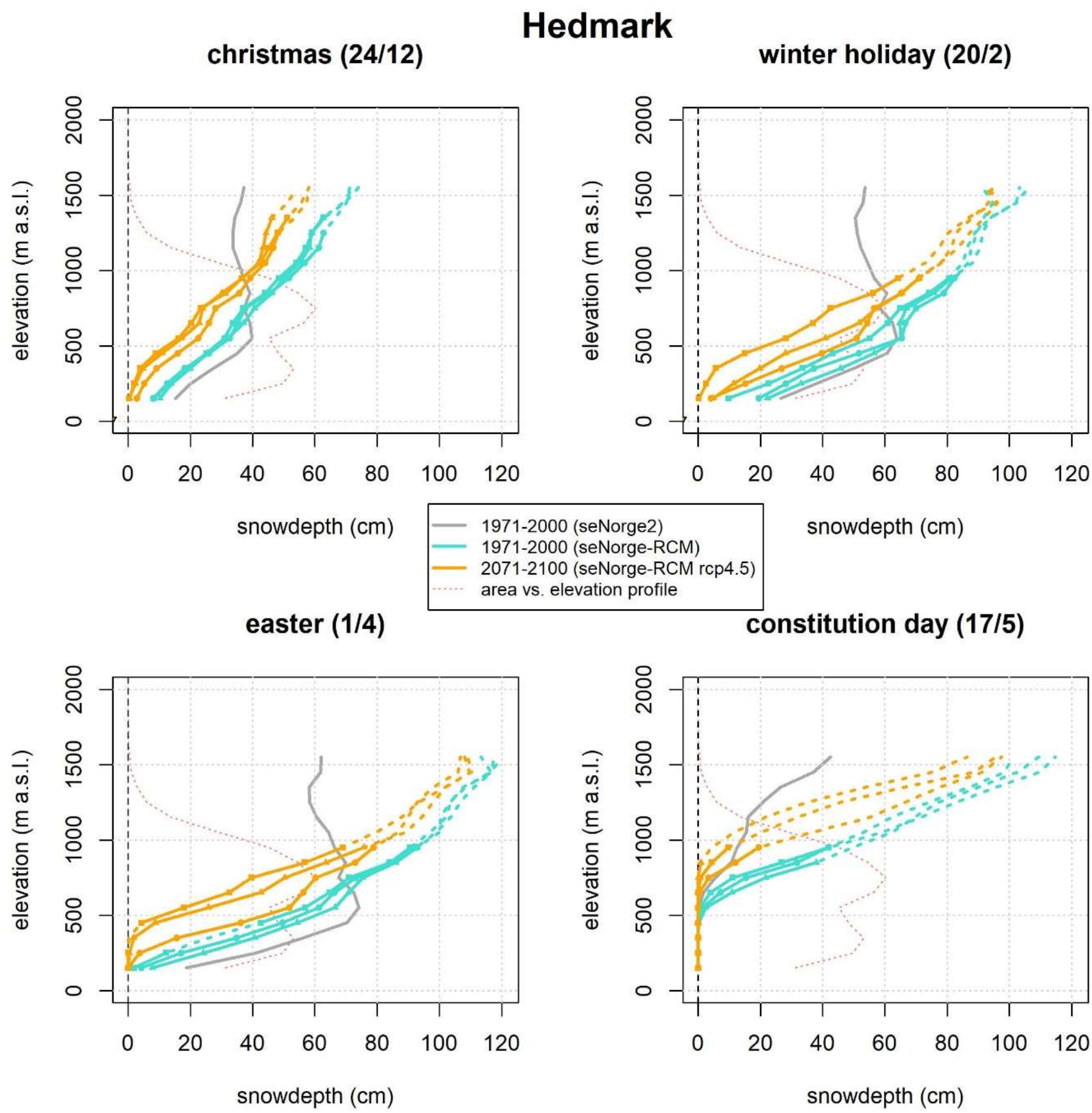

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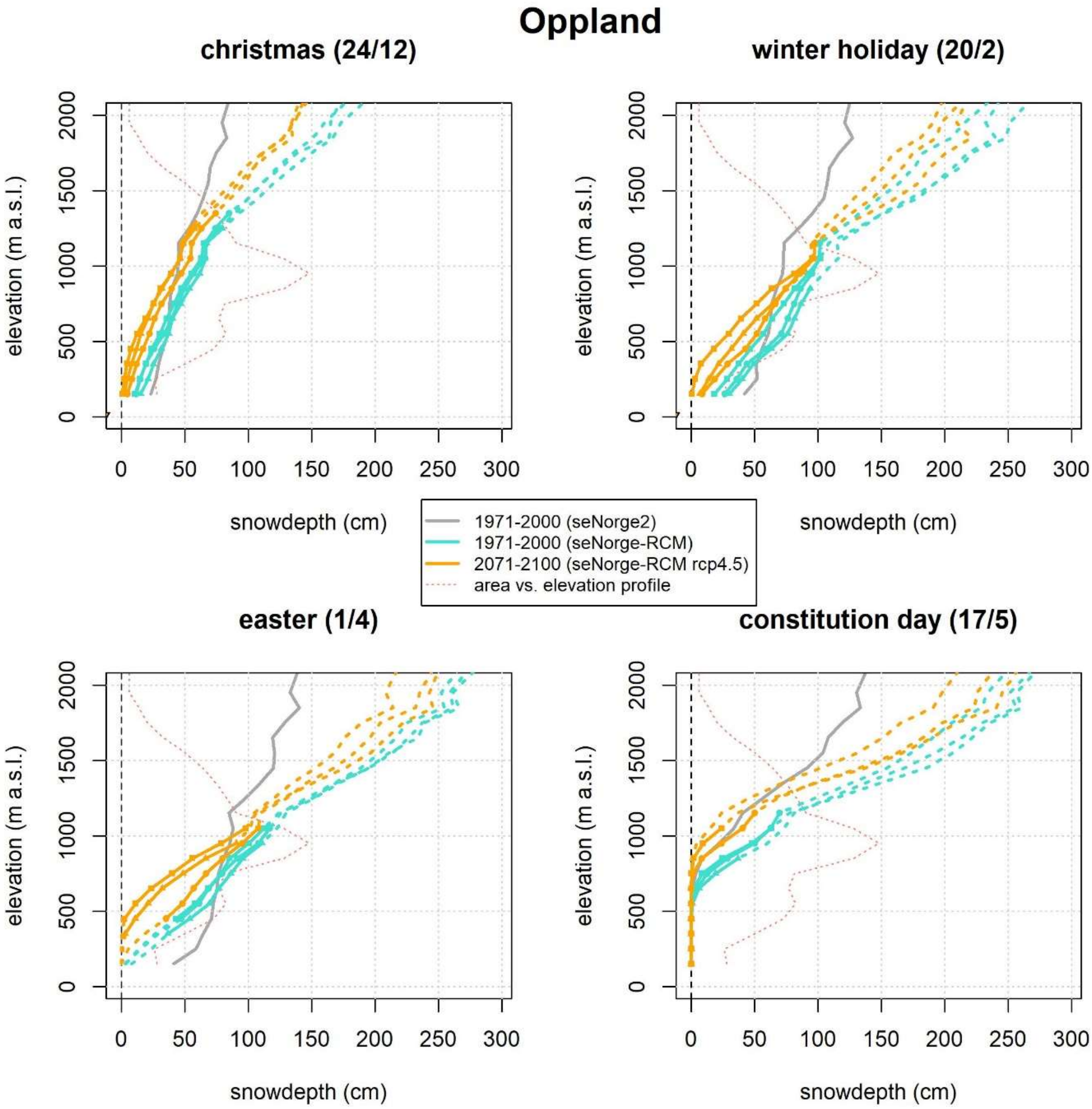

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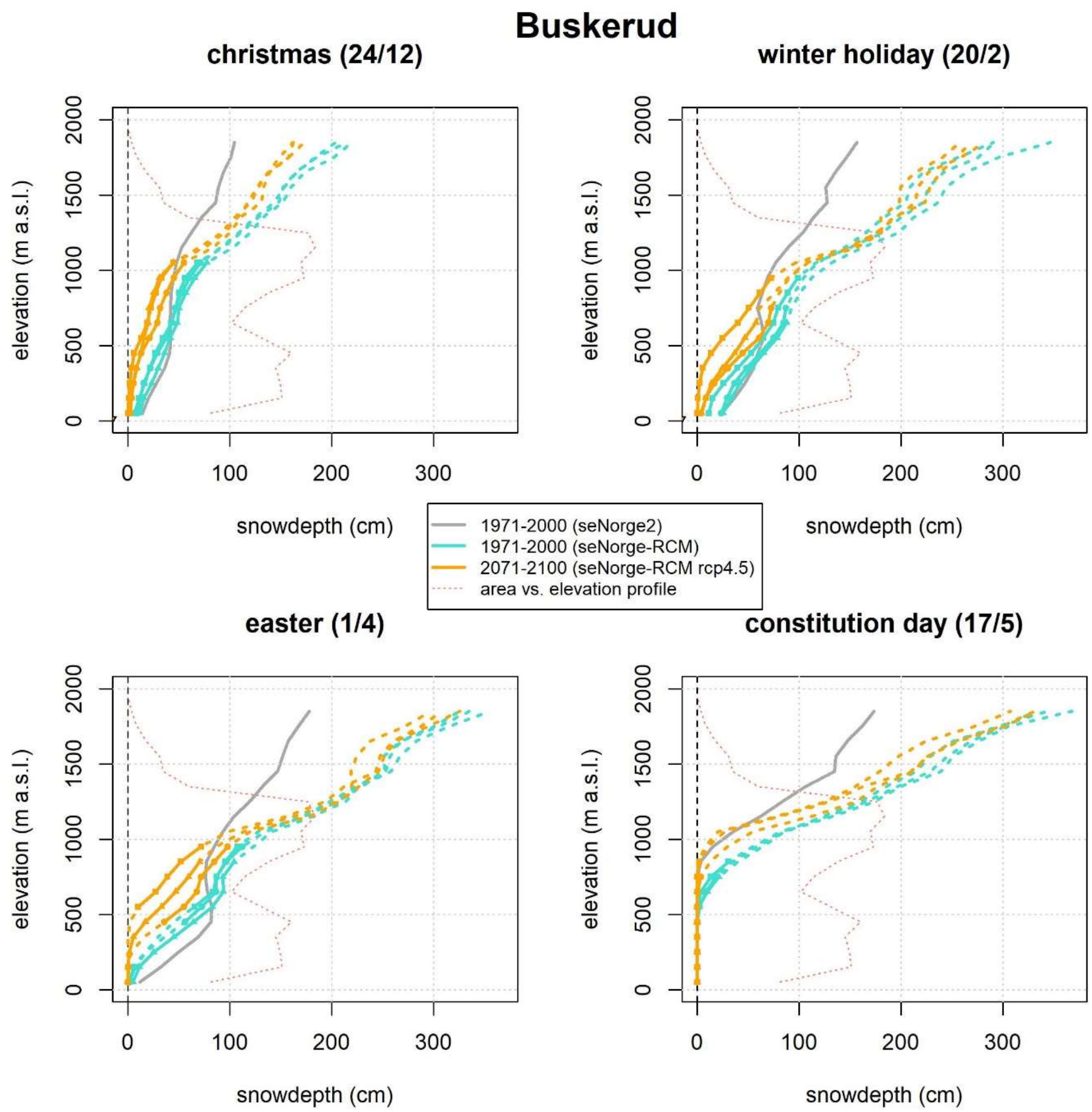

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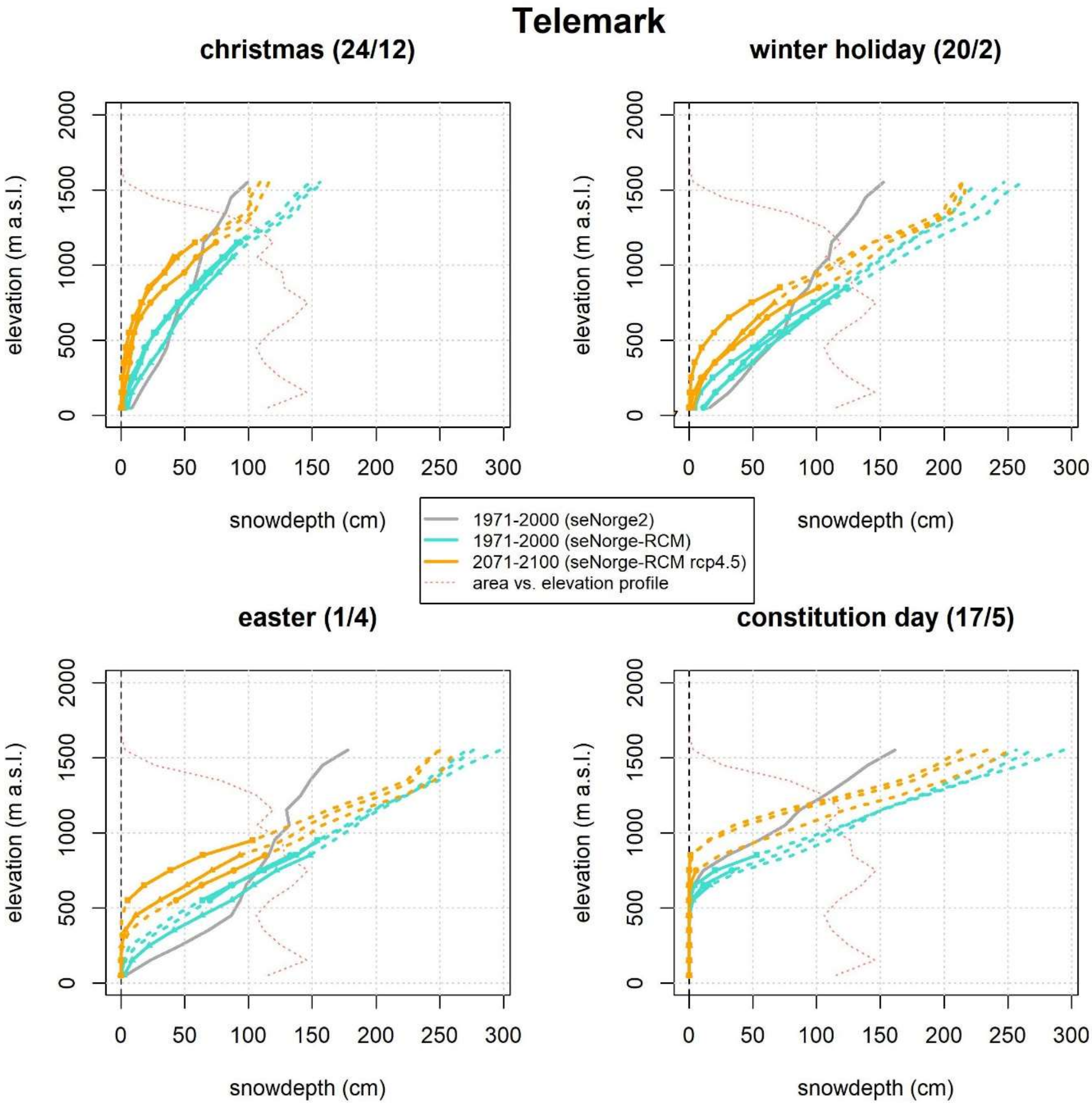
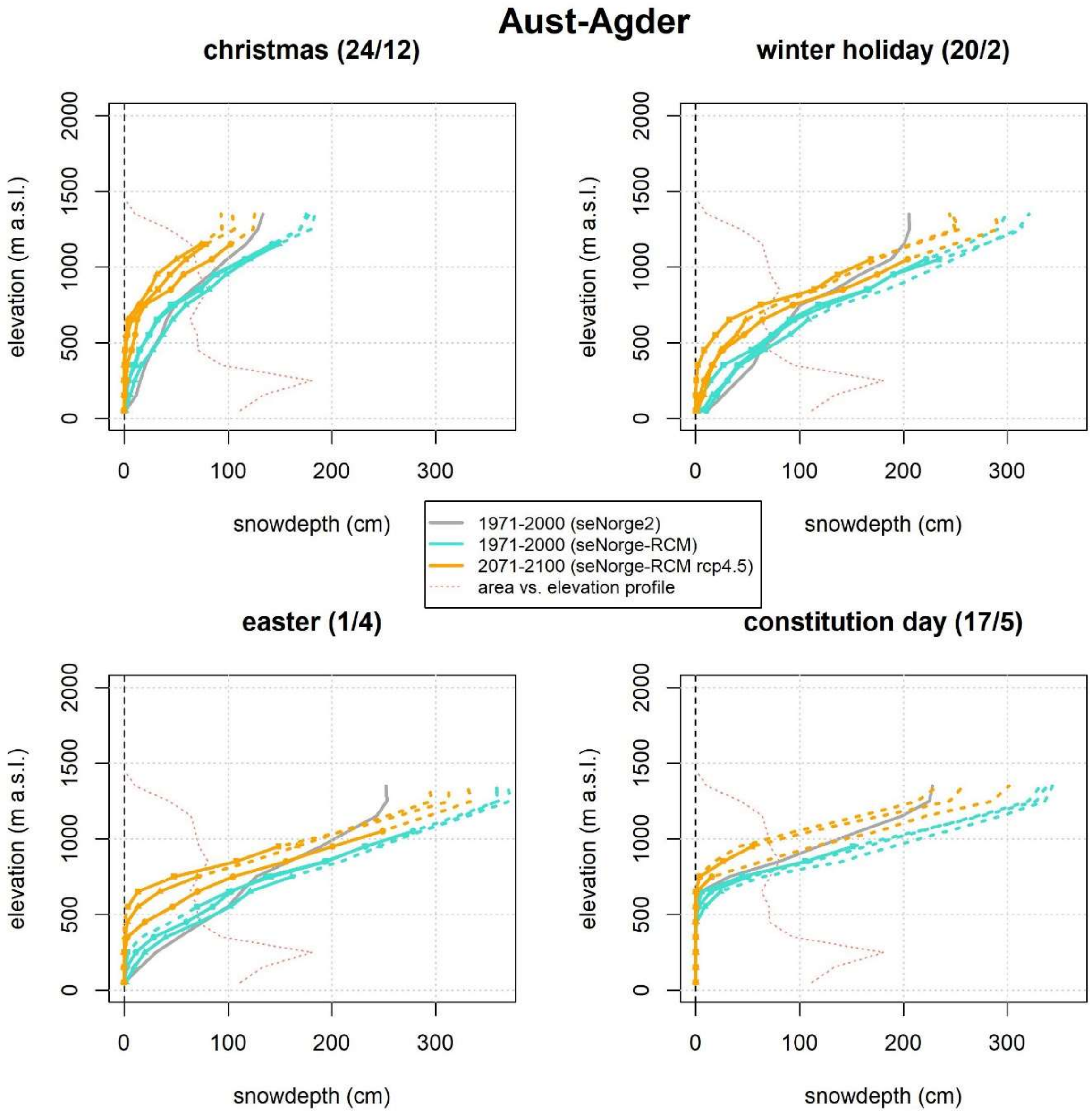


Figure 2. (continued)



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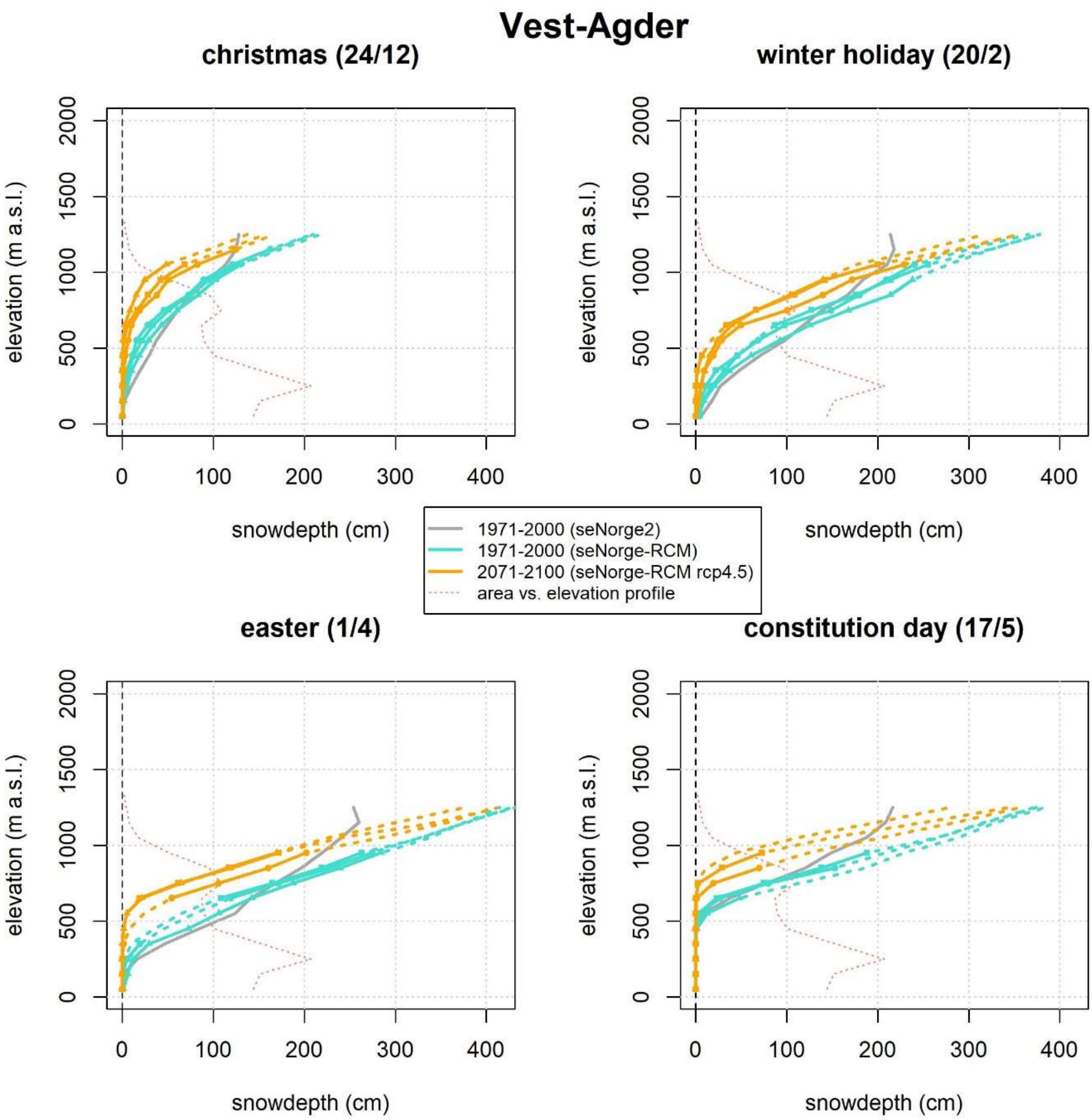

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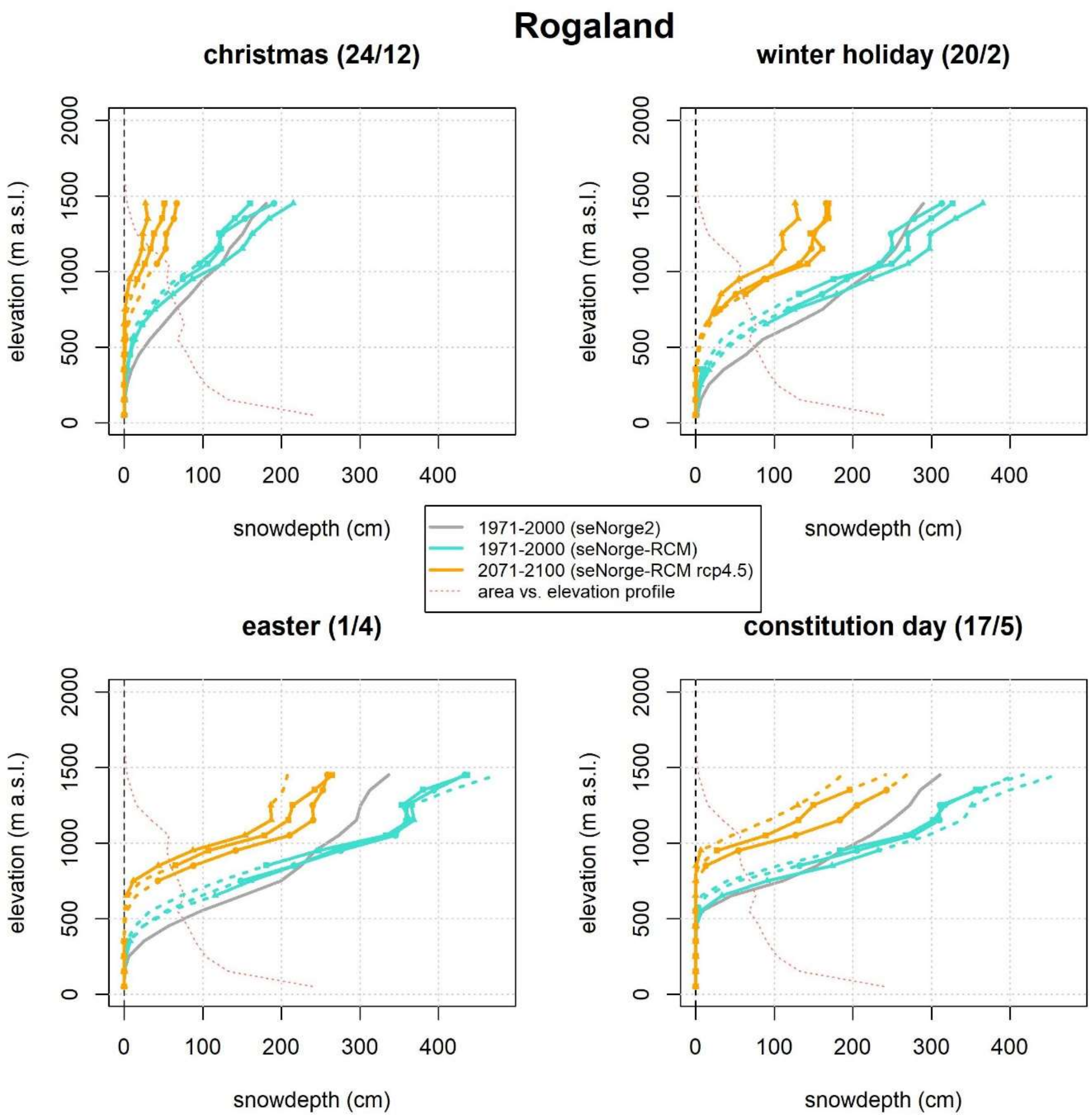

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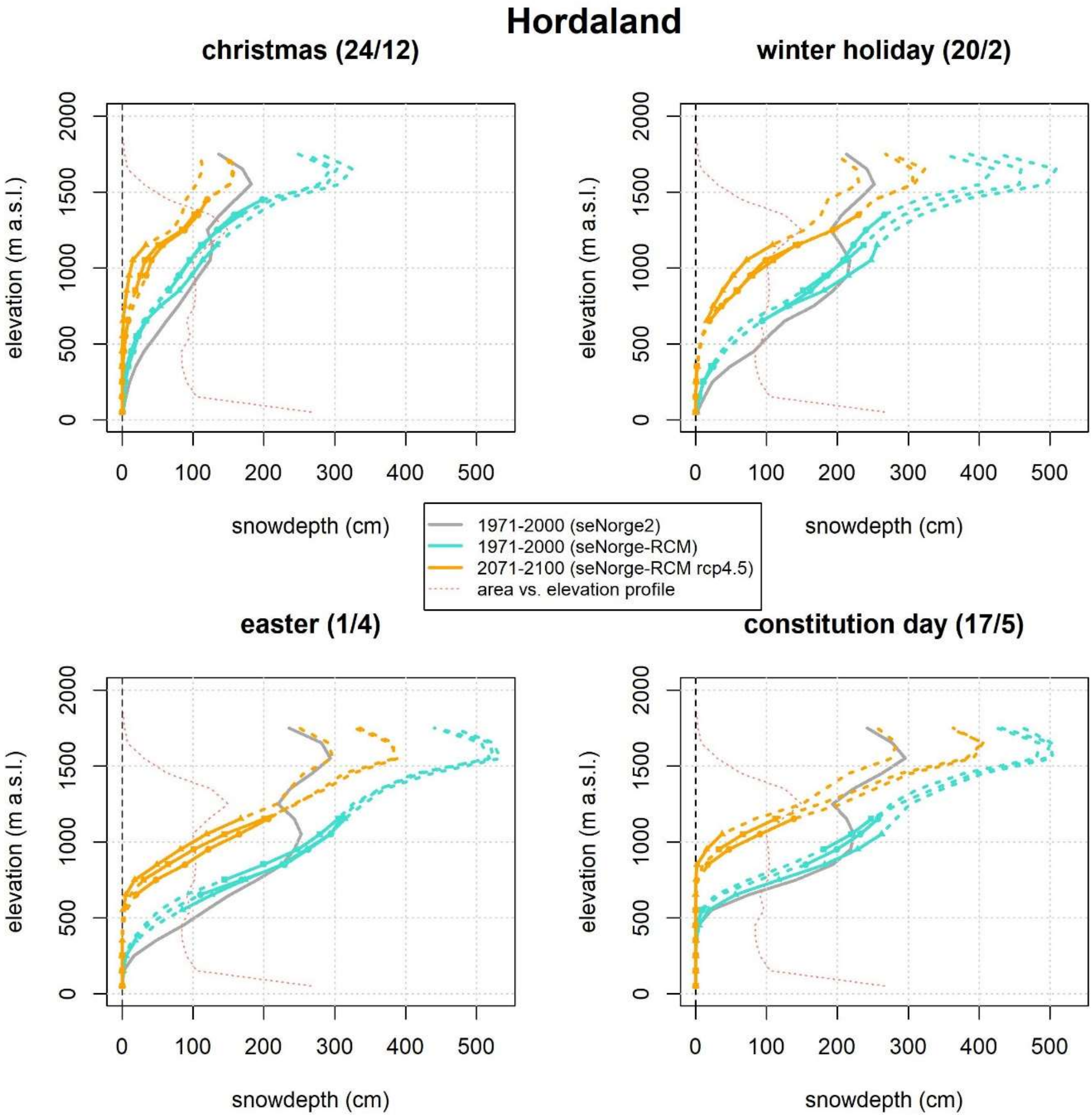

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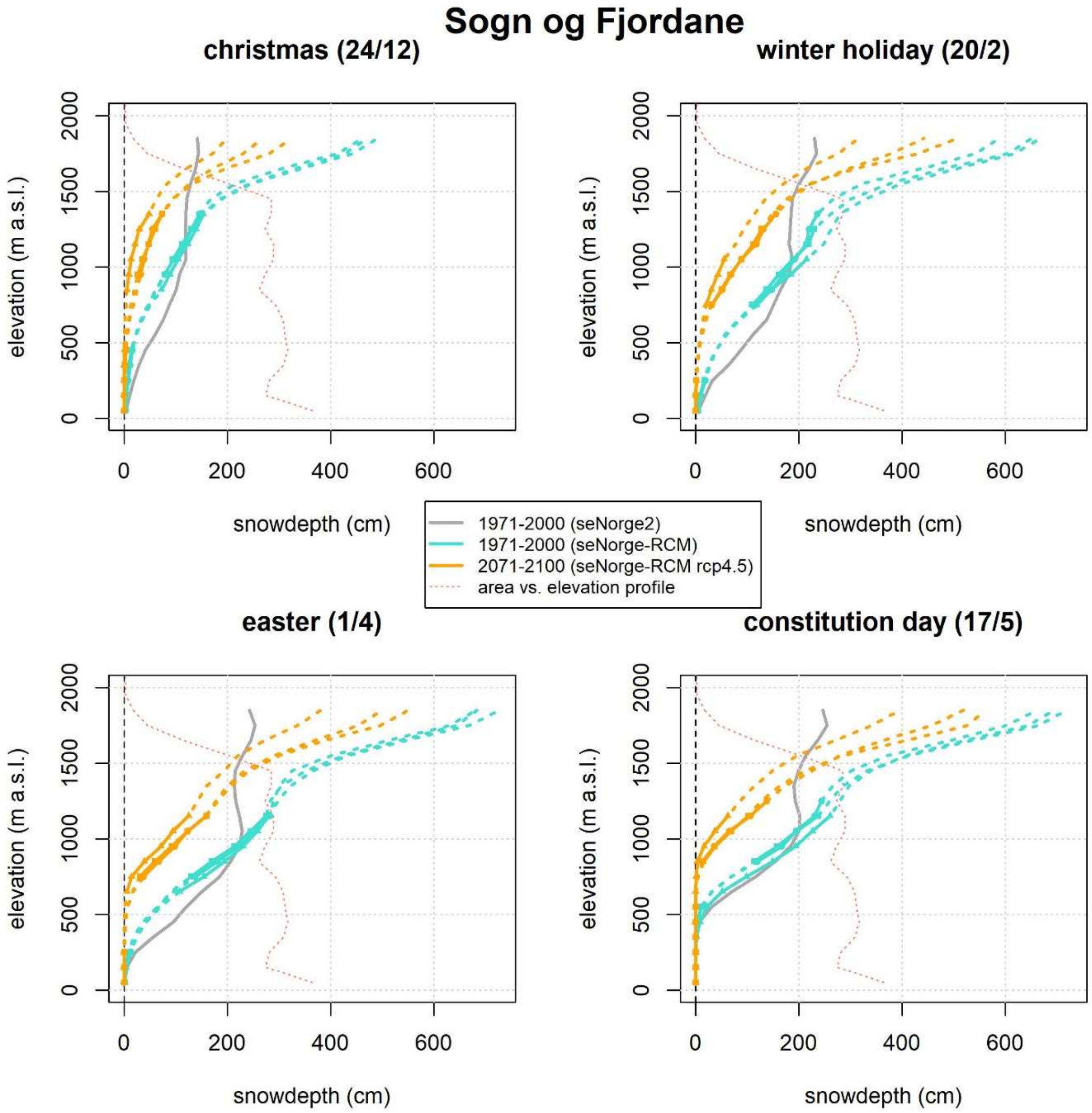

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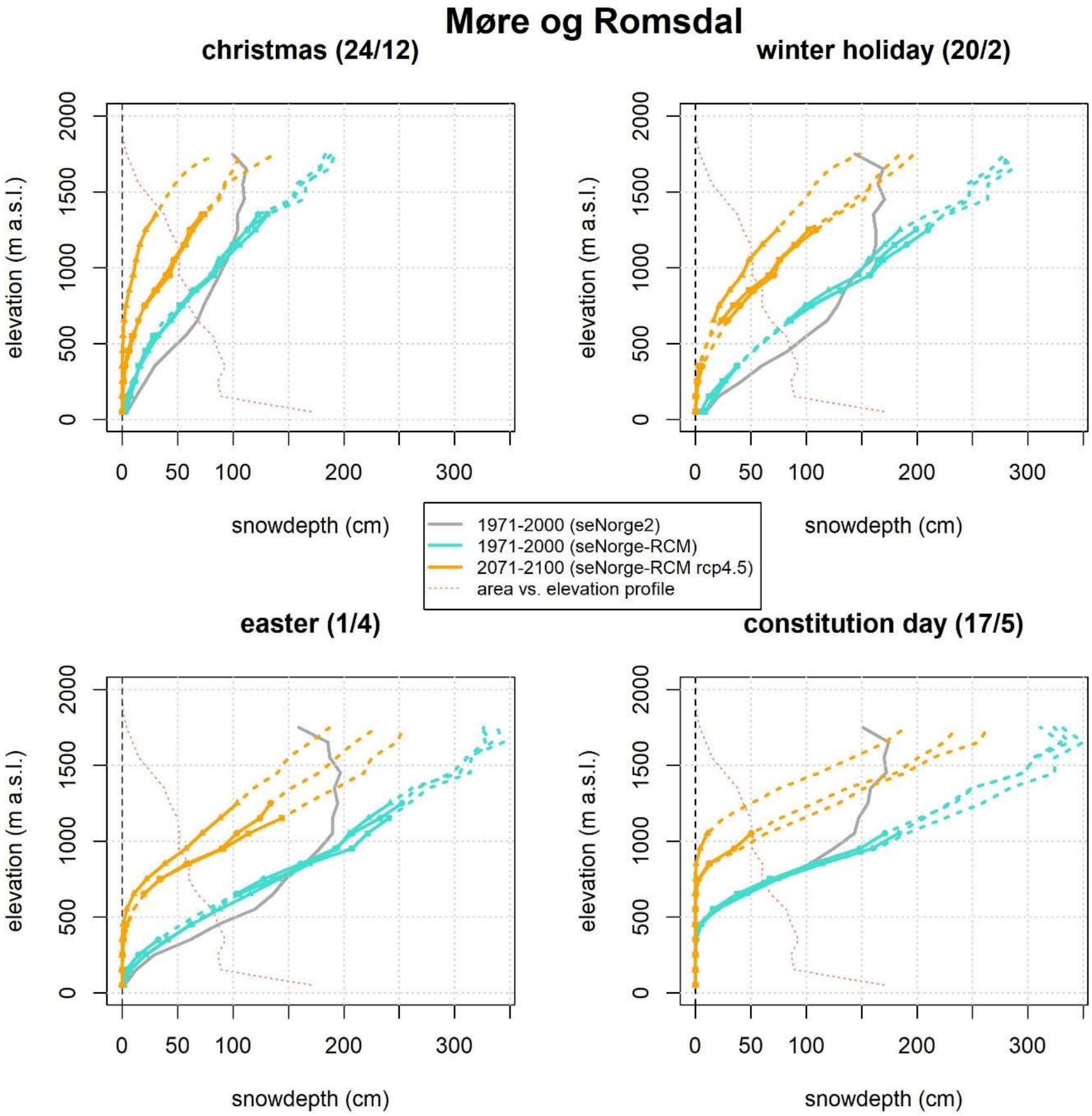

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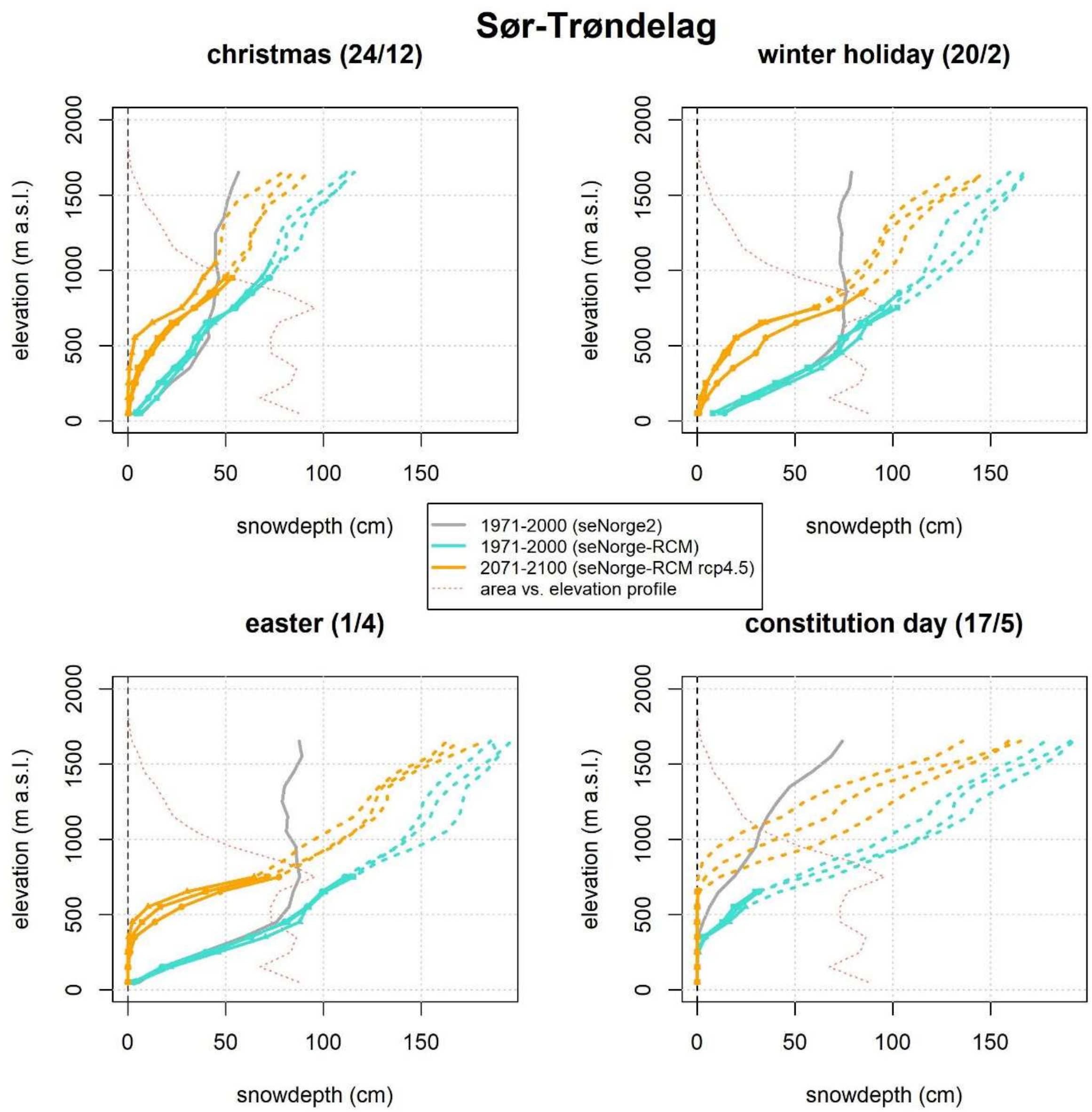

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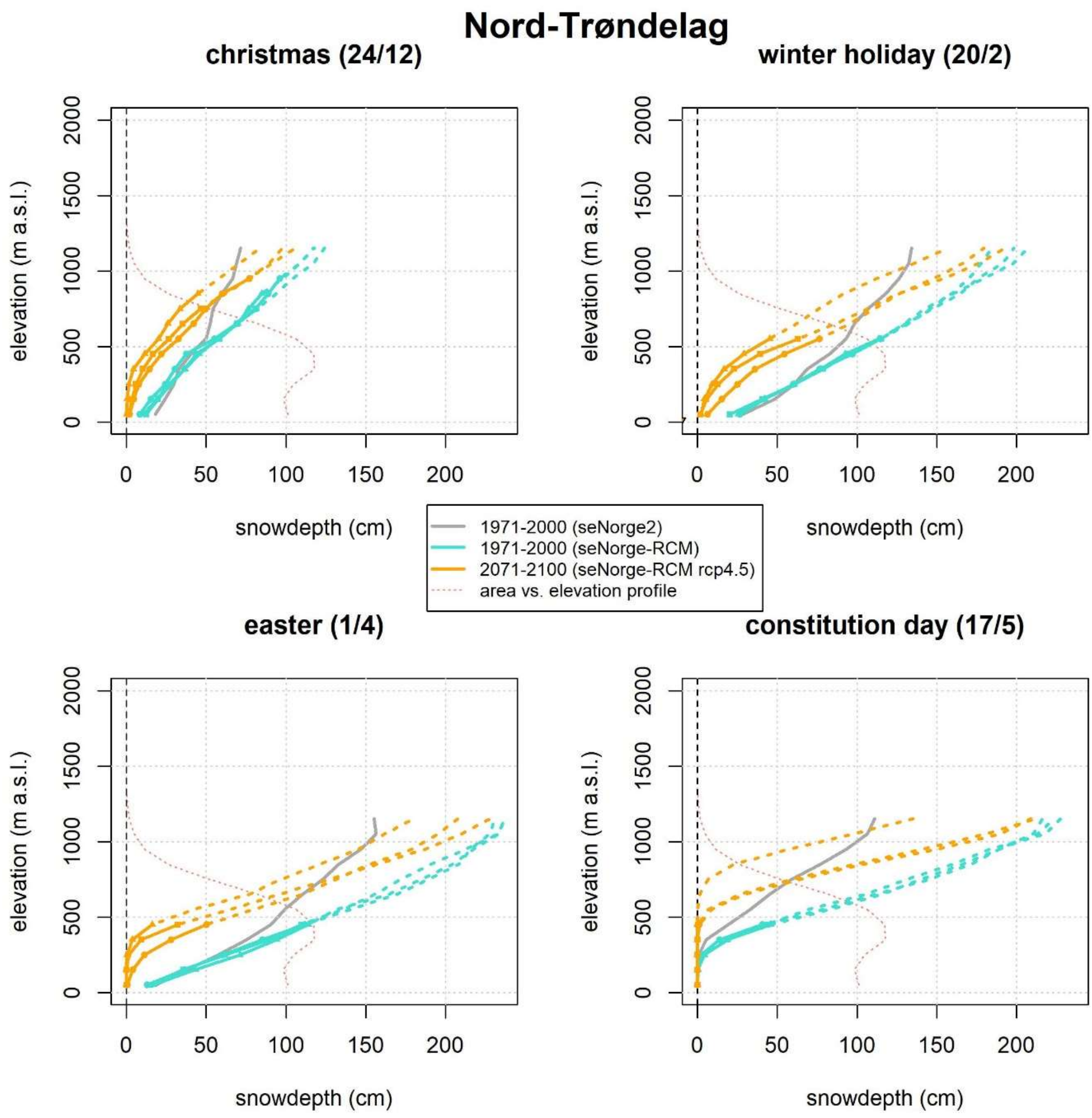

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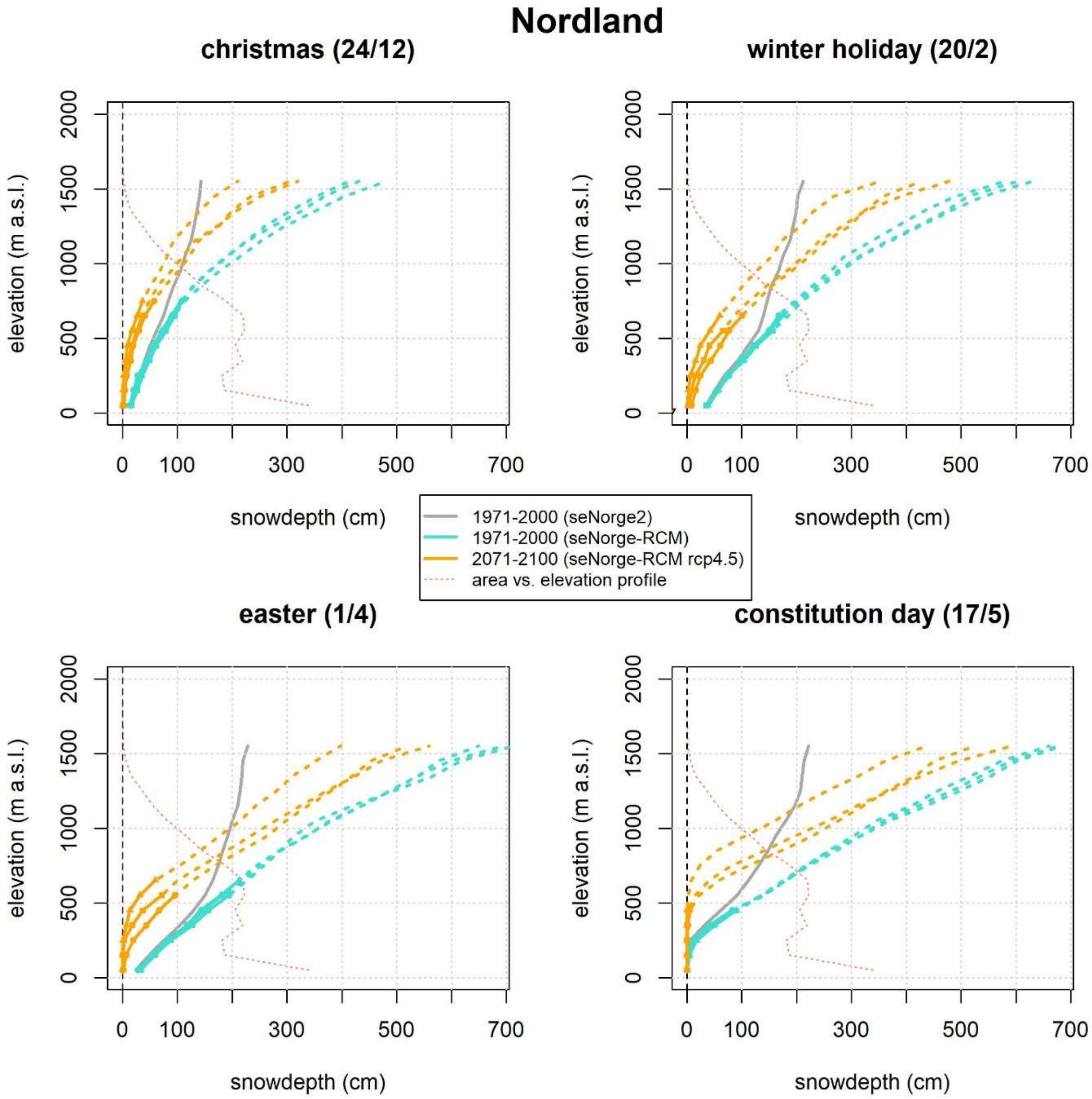

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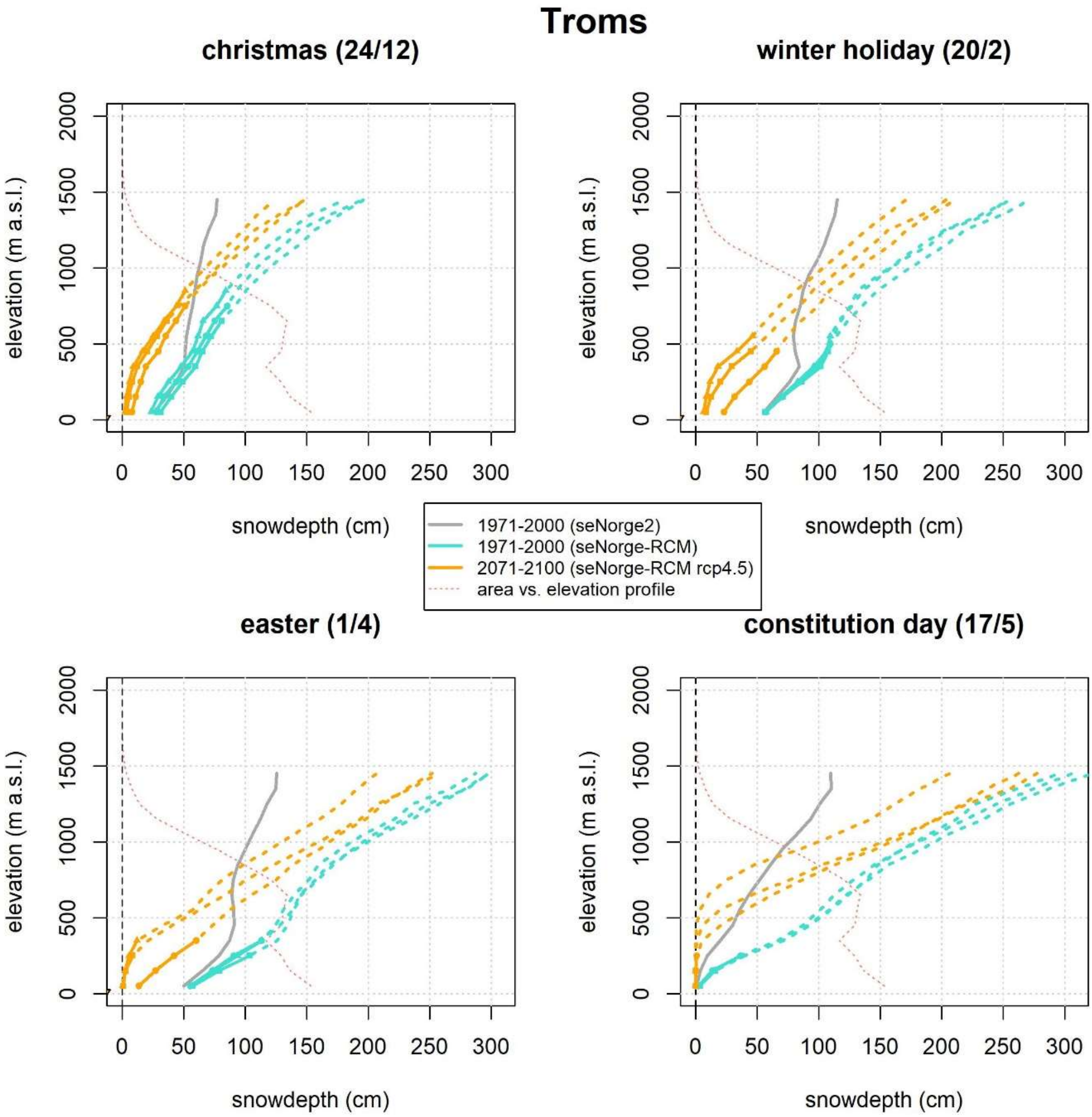

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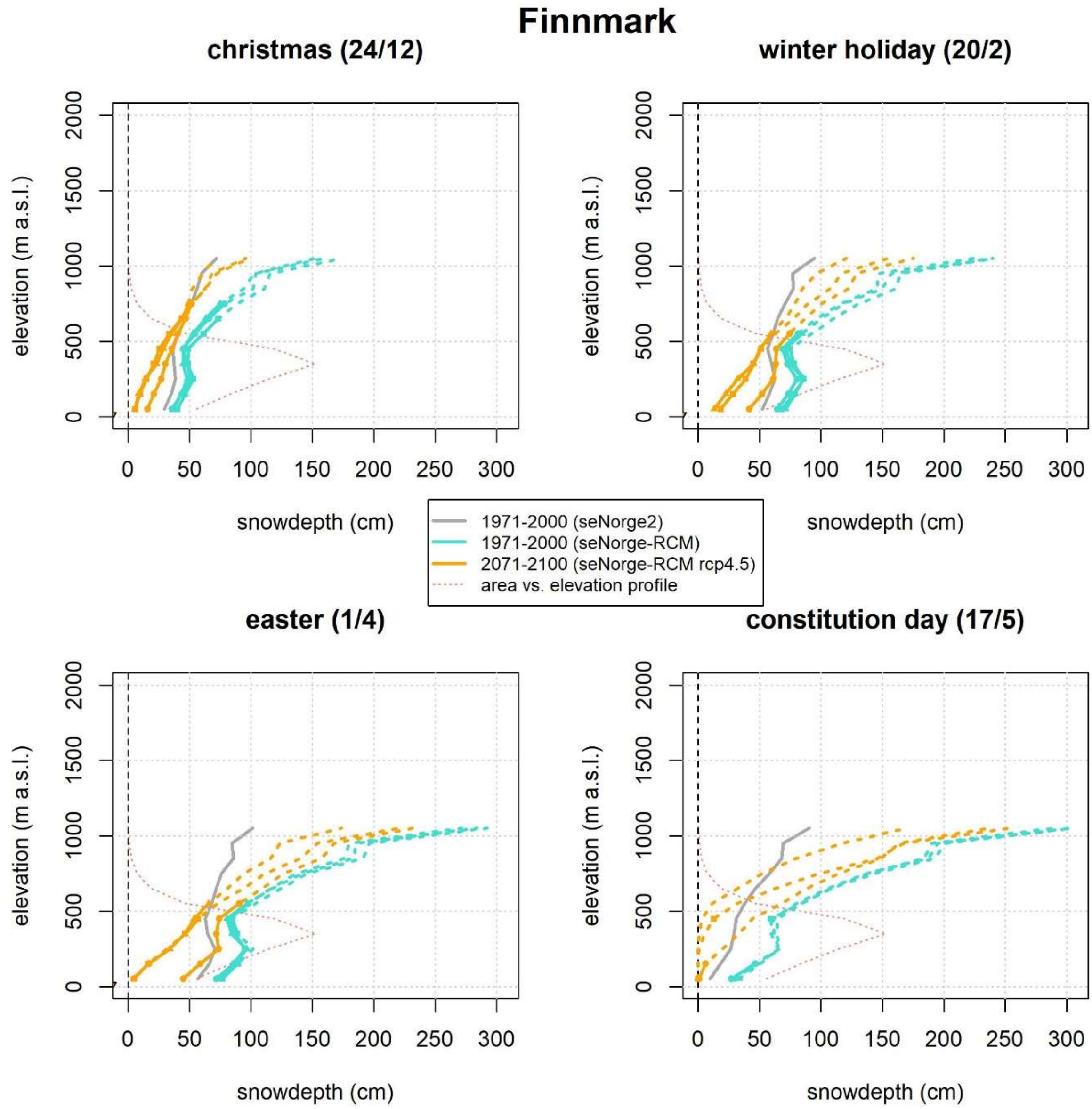

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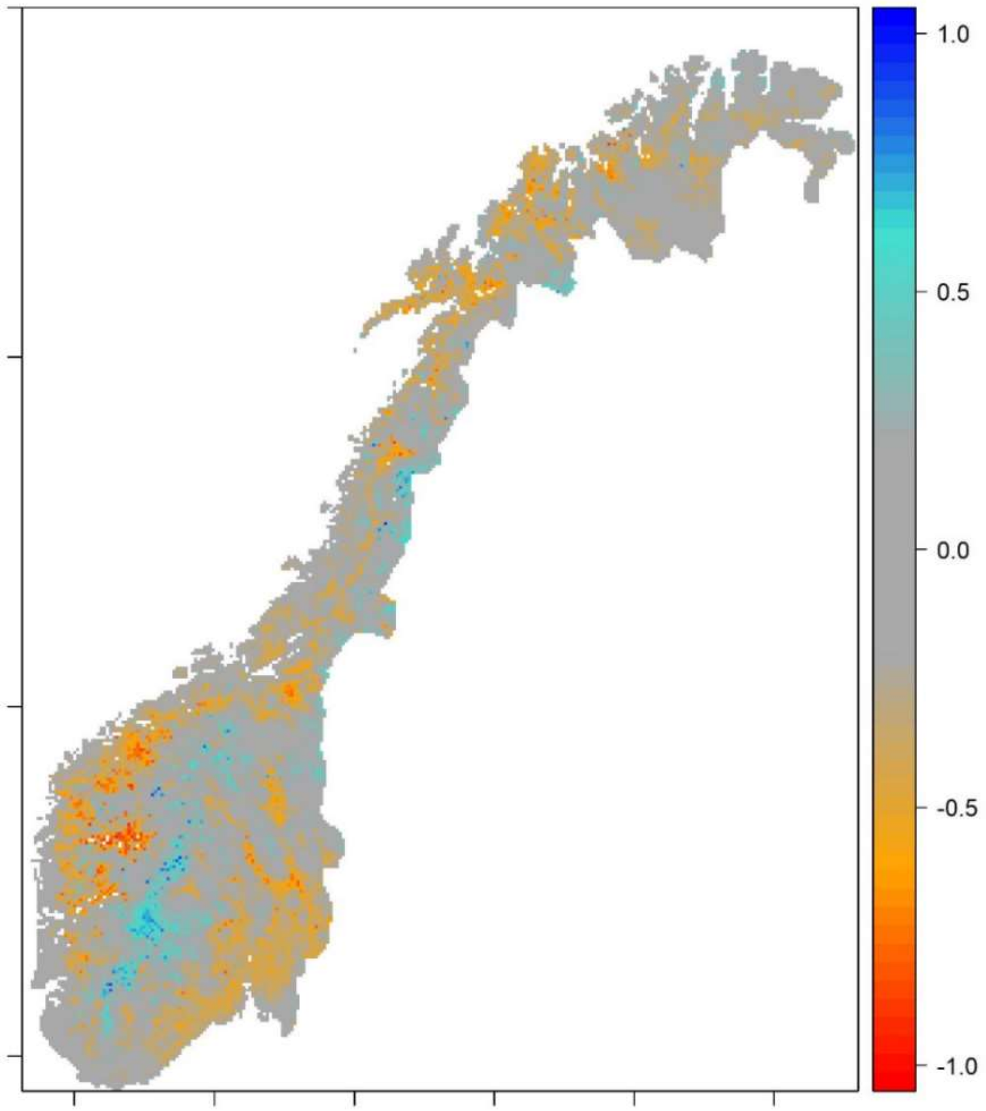

Figure 3. The bias index B (see Lussana et al., 2018) for simulated *SCA* (seNorge-RCM with CNRM-CM5_SMHI-RCA4 input forcing) based on MODIS satellite images in March-July 2001-2015. Positive (negative) values indicate model tendency to overestimation (underestimation) of *SCA* on average.

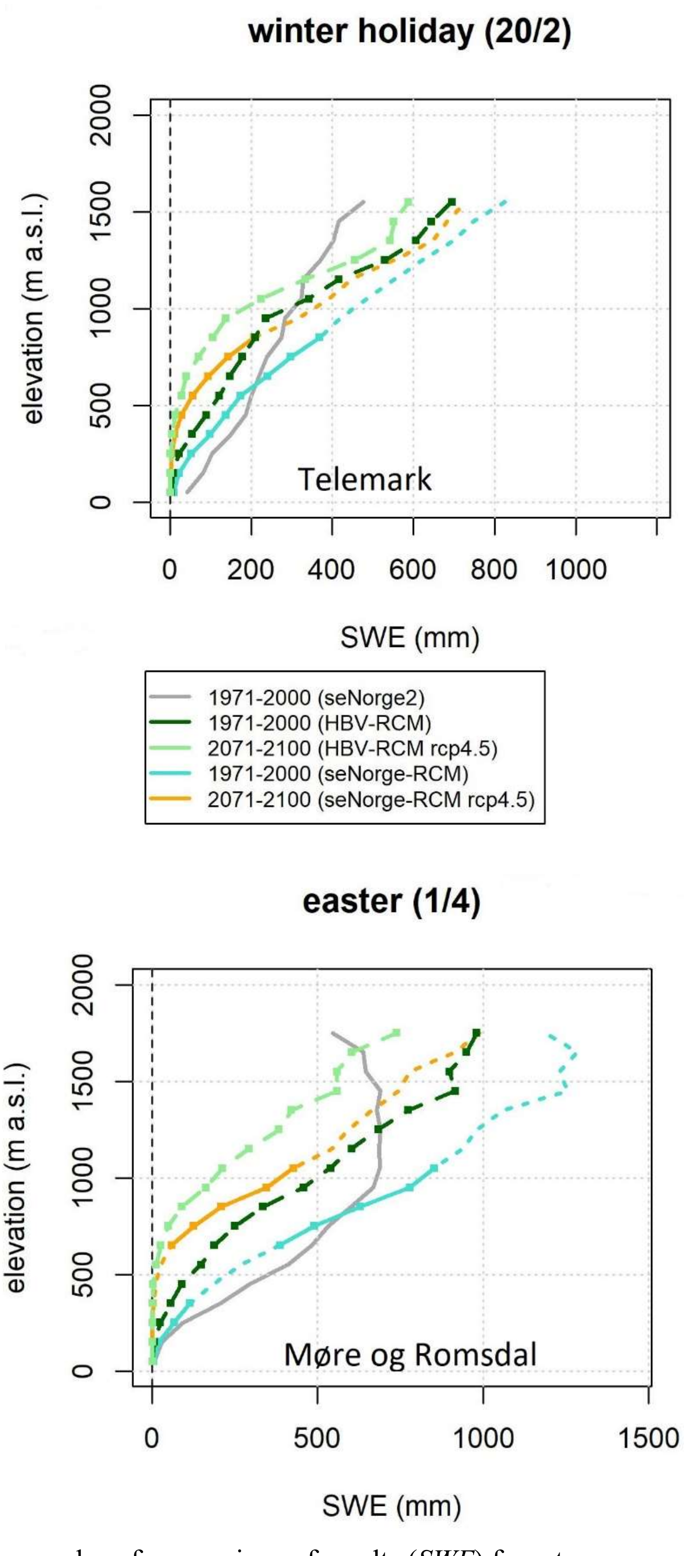

Figure 4. Two examples of comparison of results (*SWE*) from two snow models, HBV (green and light green lines) and seNorge (blue and orange lines), both using the same RCM input forcing (CNRM-CM5_SMHI-RCA4) in 1971-2000 and 2071-2100. The grey lines denote the results from the seNorge2.0 simulations in 1971-2000, as in Figure 2.

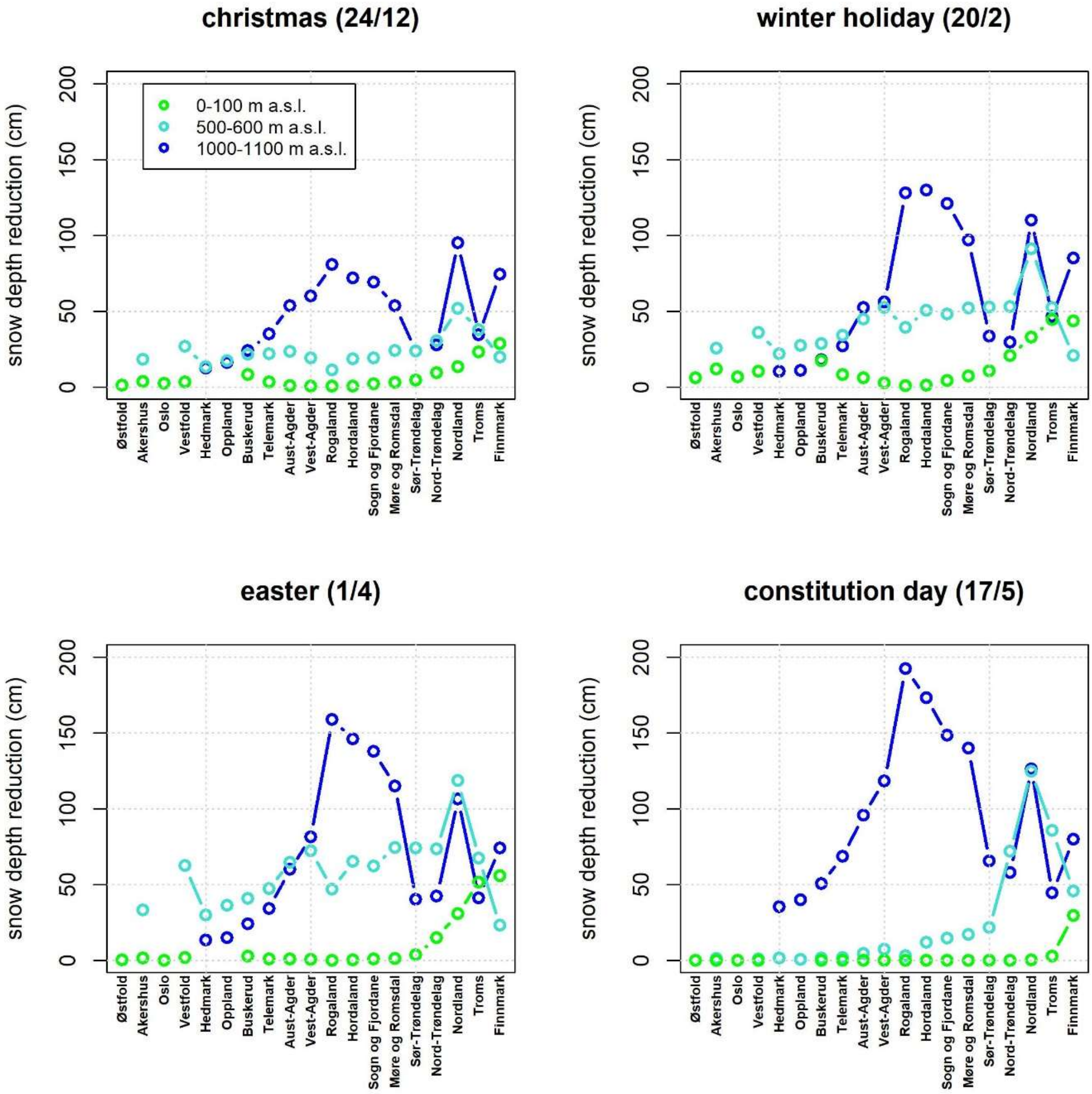

Figure 5. Mean reduction of snow depth from 1971-2000 to 2071-2100 at three different elevation zones (0-100, 500-600 and 1000-1100 m a.s.l.) in the 19 counties of Norway during four different winter/spring holiday seasons (7-day time-windows). The values are means of the changes simulated by the three different seNorge-RCM runs (see Figure 2).

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