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Table 1 Suppl. Global climate models from the *CMIP5* ensemble incorporated in the *LARS-WG* weather generator. Scenarios are based on *RCP4.5* representative concentration pathways.

| | Research Centre | Country | Global climate model | Grid resolution |
|---|---|---|---|---|
| 1 | The Centre for Australian Weather and Climate Research | Australia | ACCESS1-3 | 1.25° × 1.88° |
| 2 | Beijing Climate Center | China | BCC-CSM1.1 | 2.77° × 2.81° |
| 3 | Canadian Centre for Climate Modelling and Analysis | Canada | CanESM2, | 2.77° × 2.81° |
| 4 | Centro Euro-Mediterraneo sui CambiamentiClimatici | Italy | CMCC-CM | 0.74° × 0.75° |
| 5 | CNRM-GAME &Cerfacs | France | CNRM-CM5 | 1.40° × 1.40° |
| 6 | Australia's Commonwealth Scientific and Industrial Research Organisation | Australia | CSIRO-MK36 | 1.85° × 1.88° |
| 7 | EC-Earth consortium | Europe | EC-EARTH | 1.125° × 1.125° |
| 8 | Goddard Institute for Space Studies | USA | GISS-E2-R-CC | 2.00° × 2.50° |
| 9 | UK Meteorological Office | UK | HadGEM2-ES | 1.25° × 1.88° |
| 10 | Institute for Numerical Mathematics | Russia | INM-CM4 | 1.50° × 20° |
| 11 | Institute Pierre Simon Laplace | France | IPSL-CM5A-MR | 1.27° × 2.50° |
| 12 | University of Tokyo, National Institute for Envir. Studies, Japan Agency for Marine-Earth Science &Technology | Japan | MIROC5 | 1.39°×1.41° |
| 13 | University of Tokyo, National Institute for Envir. Studies, Japan Agency for Marine-Earth Science &Technology | Japan | MIROC-ESM | 2.77° × 2.81° |
| 14 | Max-Planck Institute for Meteorology | Germany | MPI-ESM-MR | 1.85° × 1.88° |
| 15 | Meteorological Research Institute | Japan | MRI-CGCM3 | 1.11° × 1.13° |
| 16 | National Centre for Atmospheric Research | USA | NCAR-CCSM4 | 0.94° × 1.25° |
| 17 | National Centre for Atmospheric Research | USA | NCAR-CESM1-CAM5 | 0.94° × 1.25° |
| 18 | Norwegian Climate Centre | Norway | NorESM1-M | 1.90° × 2.50° |

Table 2 Suppl. Overview of the indicators used to define grassland relevant agroclimatic indicators in this study.

| Indicator name | Acronym/unit | Description |
|---|---|---|
| 1. Mean annual temperature | 2. Tavg<br>3. [°C] | Mean annual temperature based on complete daily data for the given period. The calculation of the daily mean was based on averaging daily maximum (Tmax) and minimum (Tmin) temperature measured under standard conditions (in a shelter) at 2 m height over a grass surface. |
| 4. Sum of temperatures above 10 °C;<br>5. | TS10<br>6. [°C] | Mean of annual accumulated temperature sum (growing degree days) above 10 °C during the frost-free period of the year |
| 7. Number of tropical days | 8. Tropical days<br>9. [$d \cdot year^{-1}$] | Mean of annual number of days per year with Tmax[1] above 30 °C |
| 10. Mean annual sum of precipitation | 11. Precipitation<br>12. [mm] | Mean annual sum of precipitation based on daily precipitation data for the given period. |
| 13. Annual mean of the climatological water balance | Water balance<br>14. [mm] | Difference between mean annual sum of precipitation and mean annual sum of potential evapotranspiration. Daily ETr estimates were based on the Penman-Monteith method (Allen *et al*. 1998) using the SoilClim model (Hlavinka *et al*. 2011) |
| 15. Number of days with limited topsoil water availability | Reduced soil moisture<br>16. [$d.year^{-1}$] | Number of days with limited soil water availability[1] (soil water content in the top 40 cm of the soil below 50 % of maximum water holding capacity) as calculated by the SoilClim model (Hlavinka *et al*. 2011) |
| 17. Number of days with frost | 18. Frost days<br>19. [$d. year^{-1}$] | Mean of annual number of days per year with the Tmin[3] below 0 °C per year |
| 20. Number of days with snow cover | 21. Snow days<br>22. [$d.year^{-1}$] | Mean of annual number of days with the snow cover[4] more than 3 cm deep. |
| 23. Effective global radiation | EGR<br>24. [$MJ.m^{-2}.year^{-1}$] | The mean annual sum of the effective global radiation estimated as the sum of daily global radiation on days when the mean air temperature exceeded of 5 °C (without snow cover or frost occurrence) and when there plants were not limited by lack of water (ETa[5]/ETr[6] > 0.4). |

Notes:

[1]The $T_{max}$ maximum daily temperature was measured 2 m above ground.

[2]The soil moisture was calculated assuming three cuts per year for grassland surface assuming a soil water-holding capacity of 0,27 m and a maximum rooting depth of 1.3 m. For number of days only soil moisture in the topsoil, *i.e.* 0-0.4 m was considered.

[3]The $T_{min}$ minimum daily temperature was measured 2 m above ground; thus, the actual grass temperature might be even lower.

[4]The snow cover was estimated using a model validated by Trnka *et al*. (2010).

[5]The $ET_a$ refers to the actual evapotranspiration calculated for winter wheat assuming a soil water-holding capacity of 0,27 m and a maximum rooting depth of 1.3 m.

[6]The $ET_r$ refers to the same crop surface as 1 but for reference evapotranspiration; the crop parameters were set according to Allen *et al*. (1998)

Table 3 Suppl. Overview of the adverse weather condition definitions used in this study.

| Indicator name | Expected effect on grasslands | Indicator description – situation must occur at least once per season to be counted |
|---|---|---|
| 25. Frost with no snow | Symptoms including leaf chlorosis; burning of leaf tips to cut back plant growth or even to plant death | Event is triggered when $T_{min}$[1] is equal to or below -20 °C for at least one day with no or very limited snow cover[2] (less than 1 cm of freshly fallen snow) |
| 26. Late frost | Its occurrence after loss of the winter-hardiness leads to leaf chlorosis, burning of leaf tips, floret sterility, damage to lower stem and consequently medium to severe yield losses | Event is triggered when the $T_{min}$[1] is equal to or below -2 °C after the start of a window, determined as the period when the mean air temperature is continuously above 10 °C (for at least 5 d) and does not drop below 10 °C for more than 2 d in a row |
| 27. Snow suffocation | | Event is triggered when the $T_{max}$[3] temperatures are above 10 °C with snow cover is above 3 cm and less than 30 cm and this situation lasts more than 10 d |
| 28. Excess snow | Snow mold occurrence, high mortality and low quality of the grass | Event is triggered when the snow cover above 10 cm continuously covers the ground for at least 60 d in the given winter (October - April) or within this period, snow cover of at least 3 cm lasts for 90 d |
| 29. Extremely wet early season | Restricts growth and reduces yield through the occurrence of diseases, nitrate leaching, waterlogging and root anoxia | Event is triggered if the soil moisture[4] is at or above the field capacity for more than 60 d from January till May 31. Days with a mean temperature below 3 °C are not counted |
| 30. Extremely wet late season | Restricts growth and reduces yield through the occurrence of diseases, nitrate leaching, waterlogging and root anoxia | Event is triggered if the soil moisture[4] is at or above the field capacity for more than 60 d from June 1 till October 31. Days with a mean temperature below 3 °C are not counted |
| 31. Early season heat stress | Causes partial or complete sterility of the florets with a severe effect on yield | Event is triggered when the $T_{max}$[3] is above +31 °C for at least 2 d during the period from April to June. |
| 32. Late season heat stress | Speeds up development and decreases yield until the growth stops, resulting in a substantial yield reduction | Event is triggered when the $T_{max}$[3] is above +35 °C for at least 3 d during the period from June to October |
| 33. Severe early drought | Causes a severe reduction of growth or plant dieback | Event is triggered if $ET_a$[5]/$ET_r$[6] is less than 0.15 for at least 10 consecutive days between January 1 to May 31$^{st}$. Days with a mean temperature below 3 °C are not considered for period January 1 and May 31 |
| 34. Severe late drought | Causes a severe reduction of growth or plant dieback | Event is triggered if $ET_a$[5]/$ET_r$[6] is less than 0.15 for at least 10 consecutive days between June and October |
| 35. Severely dry season | Causes severe reduction of growth or plant dieback | Event is triggered if $ET_a$[5]/$ET_r$[6] is less than 0.15 for at least 21 d during the period January to December; the days with a mean temperature below 3 °C are not considered |

[1]The $T_{min}$ minimum daily temperature was measured 2 m above ground; thus, the actual grass temperature might be even lower.
[2]The snow cover was estimated using a model validated by Trnka *et al*. (2010).
[3]The $T_{max}$ maximum daily temperature was measured 2 m above ground.
[4]The soil moisture was calculated assuming three cuts per year for grassland surface assuming a soil water-holding capacity 0,27 m and a maximum rooting depth of 1.3 m.
[5]The $ET_a$ refers to the actual evapotranspiration calculated for winter wheat assuming a soil water-holding capacity of 0,27 m and a maximum rooting depth of 1.3 m.
[6]The $ET_r$ refers to the same crop surface as 1 but for reference evapotranspiration; the crop parameters were set according to Allen *et al*. (1998)

Table 4 Suppl. Overview of the projected shifts of the agroclimatic conditions based on the HadGEM GCM model for the period 2041 - 2060 for grassland sub-regions defined in the Fig. 1*C* together with the set of general and *Festuolium sp.* specific breeding recommendations.

| Sub-region | Expected climate conditions for the subregion (Fig. 1) | Breeding recommendation (general): | Breeding recommendation (*Festulolium*) |
|---|---|---|---|
| 1a | Increase of mean temperatures by 2.1 °C; large increase of TS10 out of all zones and major increase in tropical days (to 79 per year); major decrease of precipitation by 15 %, further deepening of the water balance deficit from -557 mm to -733 mm leading to major decrease of effective global radiation which becomes even lower than those in zone V; substantial increase in the heat and drought stress | Non-dormant alfalfa with increased usage of short-term ryegrasses and *Festulolium* (*Lolium*-types of LmFa) on arable land (sowing in autumn - cutting in spring) | LmFa (*Lolium*-types) |
| 1b | Increase of mean temperatures by 2.2 °C; largest increase of TS10 out of all zones and major increase in tropical days (to 79 per year); basically no change in annual precipitation but further deepening of the water balance deficit from -338 mm to -439 mm leading to major decrease of effective global radiation which becomes even lower than those in zones Va and Vb; substantial increase in the heat and drought stress | Drought and heat-tolerant and less-dormant alfalfa cultivars; alfalfa-grass mixtures with drought-tolerant species such as Mediterranean germplasms of tall fescue, cocksfoot and potentially *Festulolium* (*Festuca*-types of LmFa) (northern part), tall oatgrass and *Bromus* (southern part) | LmFa (Festuca-types), LmFg, LpFm |
| 2a | Lowest increase of temperature from all regions (1.5 °C) with half of the region I TS10 increase and almost no increase in tropical days; no change in the precipitation is expected but water balance will decrease by 45 mm from current surplus of 370 mm on average; overall the effective global radiation will grow to the highest value among the subregions; risk of extremely wet conditions in the first half of growing season will increase and constitutes the dominant adverse weather risk for this region | Increasing usage of species tolerant to abiotic stresses, especially flooding (increased soil porosity due to the root systems rotting, better recovery after flooding events and reduced loss of nutrients (wash-out) prior to uptake) and drought-tolerant species such as tall fescue and fescue-types of LmFa (as alternative to perennial ryegrass), increasing usage of red clover. Priorities for *Festulolium* will be root systems for improved soil hydrology, reduced soil compaction, enhanced C sequestration and drought tolerance to ensure stable livestock feeding during the drought periods in growing season | Greater use of Lp based *Festulolium* especially LpFm and LpFg, in addition to LpFp and LmFp and additional use of fescue-type of LmFa for drought tolerance |
| 2b | Temperature increase is expected to be at 2 °C with marked increase in TS10 and more than doubling in number of tropical days; precipitation is expect to decrease substantially and will decrease from positive 70 mm to deficit of -90 mm per year this leads also to increase in number of days with soil moisture deficit from 107 to 125 d; decreasing water availability greatly reduces the effective global radiation so the originally most productive subregion rates 4$^{th}$ after IIa, IIc and IIIb regions. The reduction of EGR is the largest and greater than in case of Ia | alfalfa and alfalfa-grass mixtures; reduction of perennial ryegrass and increased usage of cocksfoot, tall fescues and *Festulolium* (*Festuca*-types of LmFa); increased usage of short-term ryegrasses and *Festulolium* (*Lolium*-types of LmFa) on arable land (sowing in autumn - cutting in spring) | LmFa (both *Festuca*- and *Lolium*-types), LmFg, LpFm |
| 2c | Temperature increase is with 2.2 greatest from region 2 with increase of TS10 and number of tropical days being moderate; Precipitation is expected to decrease slightly and water balance will worsen from slightly positive to values below 0; increase in days with soil moisture deficit is relatively pronounced by 21 d; due to longer growing season however the effective global radiation increases slightly making it the subregion with third highest EGR; the zone IIc has the lowest score in adverse weather event risk both under the present and expected climate | Continuity of established systems with dominant alfalfa and alfalfa-grass mixtures (south-west part) and red/white clover and clover-grass mixtures (northern and central part); increased usage of short-term ryegrasses and *Festulolium* on arable land (sowing in autumn - cutting in spring); reduction of perennial ryegrasses and increase usage of *Festulolium* (all types) for long-term grasslands | LmFp, LpFp, LmFa (both *Lolium*- and *Festuca*-types) |

| | | | |
|---|---|---|---|
| 3a | Larger temperature increase by 2.8 °C is expected together with major increase in tropical days from about 20 to 60. Precipitation decreases by 32 mm and water balance by 150 mm which leads to overall deficit of 440 mm shifting the IIIa water balance to relatively high deficit. This leads to relatively significant decrease of EGR; Major increase in probabilities of drought stress is accompanied by even larger increase of heat stress probabilities which would occur almost every second year | Alfalfa and alfalfa-grass mixtures (tall fescue, *Festulolium*); increased usage of short-term ryegrasses and *Festulolium* (*Lolium*-types of LmFa) on arable land (sowing in autumn - cutting in spring) | LmFp, LmFa (*Festuca*-types) |
| 3b | Temperature increase by 2.7 °C is expected as well as increase of TS10; currently rare tropical days (4) will increase to 20. Precipitation decreases but given the large altitudinal gradient local differences will be high. Despite major reduction in water balance (170 mm) the balance will remain positive but the number of days with water balance deficit will increase from 65 to 95 d; reduction in the frost and snow days is expected and overall increase of EGR is likely albeit small; prolonged snow cover will remain the major adverse weather event negatively affecting grasslands | Continuity of established systems; increased usage of tall fescues and *Festulolium* (*Festuca*-types of LmFa), red clovers and presumably alfalfa in lowlands | LmFa (*Festuca*-types) |
| 3c | Temperature increase is 2.8 °C leading to higher TS10 values and increase in the tropical days number similar to IIIb. Precipitation decreases by 45 mm and water balance by 130 mm leading to overall mean deficit of 170 mm per year and increase of days with soil moisture deficit to 140; major reduction of snow cover is expected together with small reduction of effective global radiation; but given the large altitudinal gradient local differences will be high. Despite major reduction in water balance (170 mm) the balance will remain positive but the number of days with water balance deficit will increase from 65 days to 95; reduction in the frost and snow days is expected and overall increase of EGR is likely albeit small; long snow cover will still be the main limiting factor negatively affecting grasslands but increase of drought probability is reason for concern even in this zone | Increased use of alfalfa and alfalfa-grass mixtures (tall fescues, *Festulolium* (*Festuca*-types of LmFa), tall oatgrass and *Bromus*) and reduction of red-clover and red clover-grass mixtures (southern and central part); continuity of established systems with red clover and red clover-grass mixtures with meadow fescue, increased mixture rate of *Festulolium* (LmFp and *Festuca*-types of LmFa) and perennial ryegrass and decreased mixture rate of timothy (northern part). For short-term and permanent grasslands: tall fescue, *Festulolium* (LmFp, *Festuca*-types of LmFa); increased use of short-term ryegrasses and *Festulolium* (*Lolium* types of LmFa) on arable land (sowing in autumn - cutting in spring; southern part) | LmFp, LmFa (both *Lolium*- and *Festuca*-types) |
| 4a | The sub region shows largest (+3.3 °C) temperature increase with the highest increase in TS10 but relatively low number of tropical days; precipitation is expected to be reduced by about 70 mm resulting in water balance deficit of 140 mm; largest increase of days with water deficit is expected together with major reduction in number of frost and snow days. Therefore, EGR will change only slightly and remain in the middle among the subregions; increase of risk without snow and heat stress occurrence is probable with excess of snow being major adverse type of adverse event | Continuity of established systems with red clover and red clover-grass mixtures with timothy, meadow fescue, cocksfoot; increased use of *Festulolium* (LmFp and *Festuca*-types of LmFa); increased use of short-term ryegrasses and *Festulolium* (*Lolium*-types of LmFa) on arable land (sowing in autumn - cutting in spring) | LmFp and LmFa (both types) |
| 4b | The expected temperature increase by 2.7 °C is markedly lower than in IVa but still will increase TS10 considerably as well as number of tropical days 55 from current man of 25; rainfall reduction with temperature increase will deeper the water balance deficit from 330 mm to 460 mm which is similar to the baseline deficit in the region I; number of days with soil moisture deficit will also reach similar levels as subregion Ib; while frost and snow days will be reduced also EGR will decrease making it subregion with the third lowest EGR value; while excess of snow will remain to be the major adverse event there are major increases in the frequency of heat and drought stress to be expected | Alfalfa and alfalfa-grass mixtures with *Bromus*, tall fescue, *Festulolium* (*Festuca*-types of LmFa), and cocksfoot | LmFa (*Festuca*-types) |

| | | | |
|---|---|---|---|
| 5a | Subregion temperature will increase by 2.6 °C with TS10 increasing but less than regions in the south. Number of tropical days will remain very low, precipitation will remain very similar as today and water balance will shift towards lower value but still stay highly positive; This will mean relatively small number of days with water deficit. Major decrease in snow and frost days is expected and that overall leads to slight increase in the EGR and the subregion will remain on the average of all subregions; excess of snow will remain the dominant adverse effect but occurrence of severe frost without snow cover will increase considerably | Minimal changes and continuity of established systems; usage of grass and red clover-grass mixtures with timothy, meadow fescue, perennial ryegrass; increased usage of tall fescue and *Festulolium* (*Festuca*-types of LmFa) to replace meadow fescue and LmFp and LpFp to replace perennial ryegrass. | LmFp, LpFp, LmFa (*Festuca*-types) |
| 5b | Temperature increase over 3 °C shifting the current temperature regime and TS10 towards baseline conditions in Va; precipitation is likely to increase and water balance will remain slightly positive; Frost and snow days will decrease while EGR will increase to levels currently find in Va; excess of snow and risk of major frost without snow cover will be of major concern with regards of the adverse weather conditions | Continuity of established systems without major changes with meadow fescue and timothy (cultivars bred for local conditions with strong reaction to short day-length) | LpFp, LmFa (fescue type) |
| 5c | Temperature increase over 3.1 °C but TS value will remain low despite the conditions coming close to current Vb subregion; precipitation will increase and water balance will stay positive with days with low soil moisture remaining low; while EGR is growing the most of the subregions it still remains on low levels similar to Ib subregion; the adverse event shifts are similar to Va and Vb | Continuity of established systems without major changes | no use |

Abbreviations: LmFa (*Festuca*-types) - *Lolium multiflorum* × *Festuca arundinacea* (backcrossed to *F. arundinacea*), such as cv. Hykor; LmFa (*Lolium*-types) - *L. multiflorum* × *F. arundinacea* (backcrossed to *L. multiflorum*), such as cv. Becva; LmFg - *L. multiflorum* × *F. glaucescens*, such as cv. Lueur; LmFp - *L. multiflorum* × *F. pratensis*, such as cv. Felopa; LpFm - *L. perenne* × *F. mairei*, such as cv. AberRoot; LpFp - *L. perenne* × *F. pratensis*, such as cv. Prior.

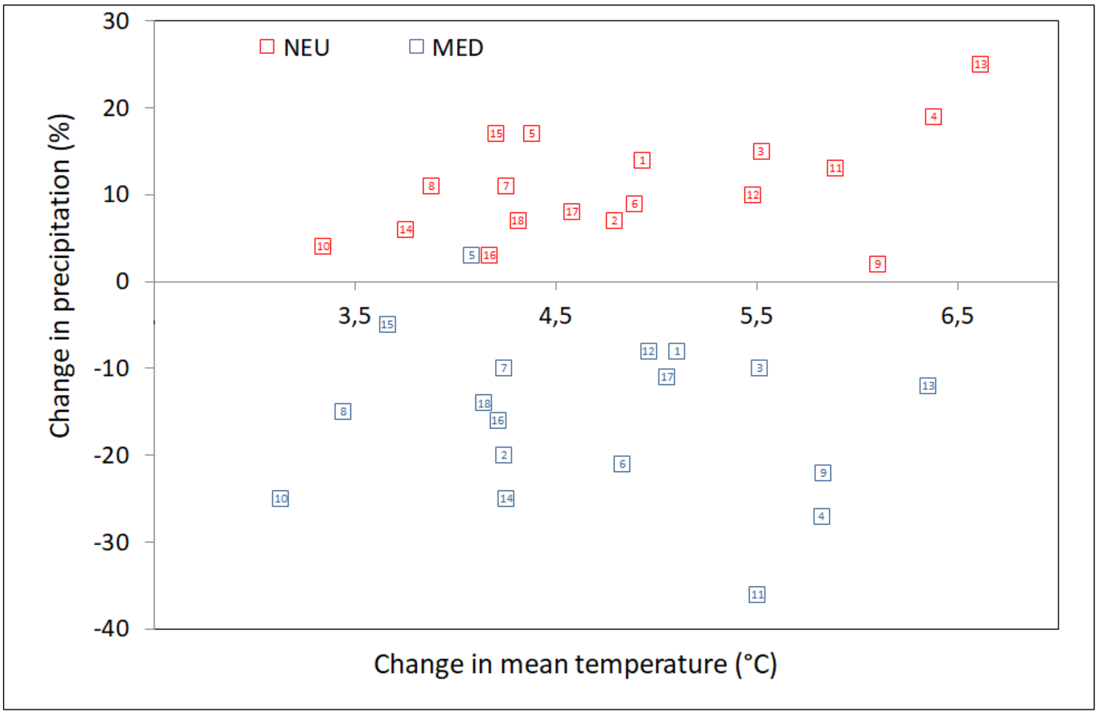


Fig. 1 Suppl. Absolute changes in mean annual temperature [ºC] and relative changes in annual mean precipitation calculated over Northern Europe (NEU, *red*) and Mediterranean Basin (MED, *blue*) regions between future 2080 - 2100 and GCM baseline 1995 - 2005 for 18 GCMs from the CMIP5 ensembles. GCMs descriptions are given in Table 1 Suppl. with [8] standing for the GISS model, [6] for CSIRO model and [9] for the HadGEM model. Values are calculated for land grid-cells from the 1-degree land mask. Note: the period 2080 - 2100 has been used to indicate better the differences between the GCMs.

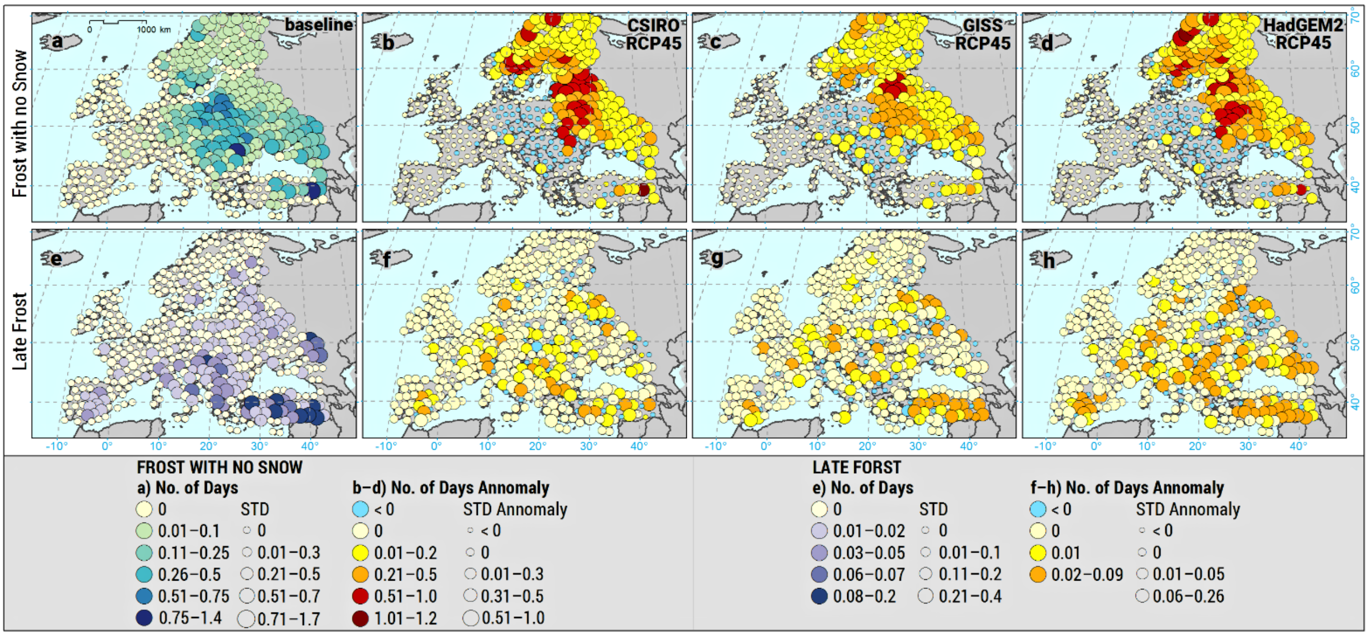


Fig. 2 Suppl. Probability of occurrence of severe frost without protective snow cover (*a*) during 1981 - 2010 baseline as well as probability of the late frost occurrence (*e*). The expected change compared to baseline is provided in the next three columns for CSIRO-RCP4.5 (*b,f*), GISS-RCP4.5 (*c,g*), and HadGEM-RCP4.5 (*d,h*) scenarios that represent period 2041 - 2060. The size of the *circle* in corresponding to the standard deviation (STD) of the given parameter over 300 individual yearly simulation. The STD of the anomaly represents increase (when STD > 1.0) or decrease (when STD < 1.0) of annual variability of the given indicator with respect to the baseline.

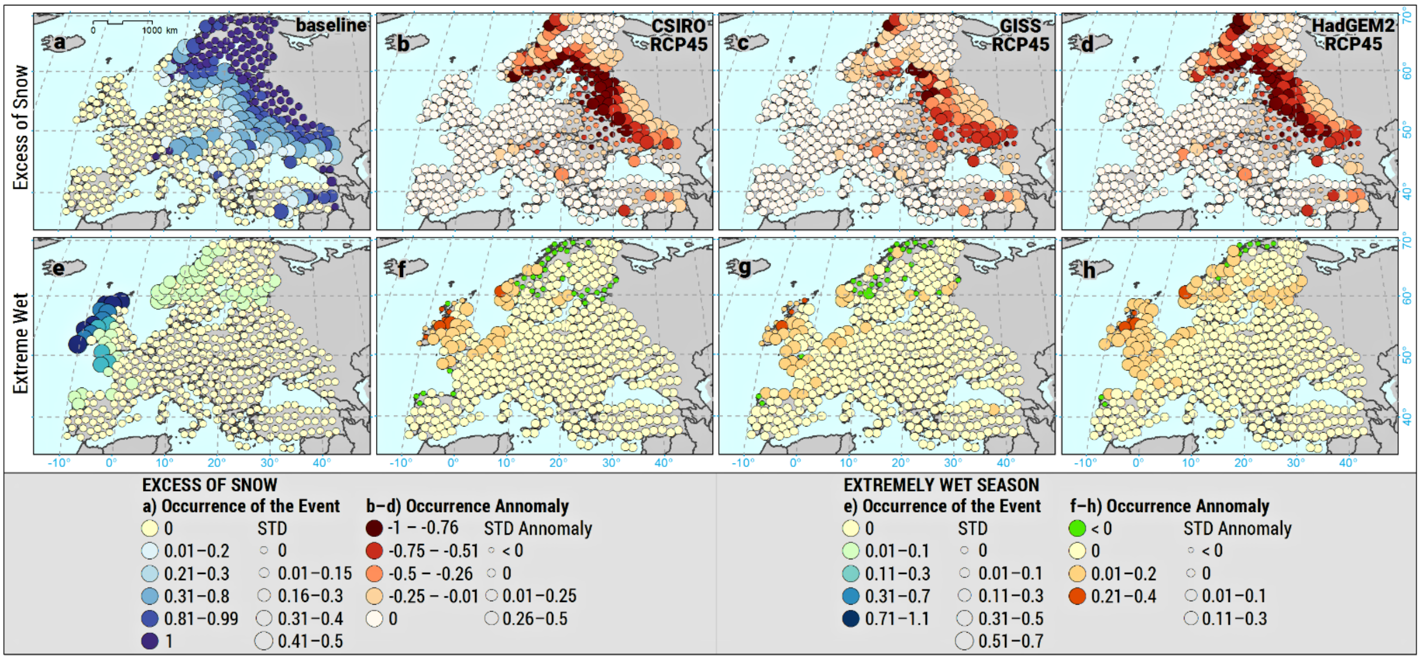


Fig. 3 Suppl. Probability of occurrence of excess of snow (*a*) during 1981-2010 baseline as well as probability of prolonged period with water saturated soils (*e*). The expected change compared to baseline is provided in the next three columns for CSIRO-RCP4.5 (*b,f*), GISS-RCP4.5 (*c,g*), and HadGEM-RCP4.5 (*d,h*) scenarios that represent period 2041 - 2060. The size of the *circle* is corresponding to the standard deviation (STD) of the given parameter over 300 individual yearly simulation. The STD of the anomaly represents increase (when STD > 1.0) or decrease (when STD < 1.0) of annual variability of the given indicator with respect to the baseline.

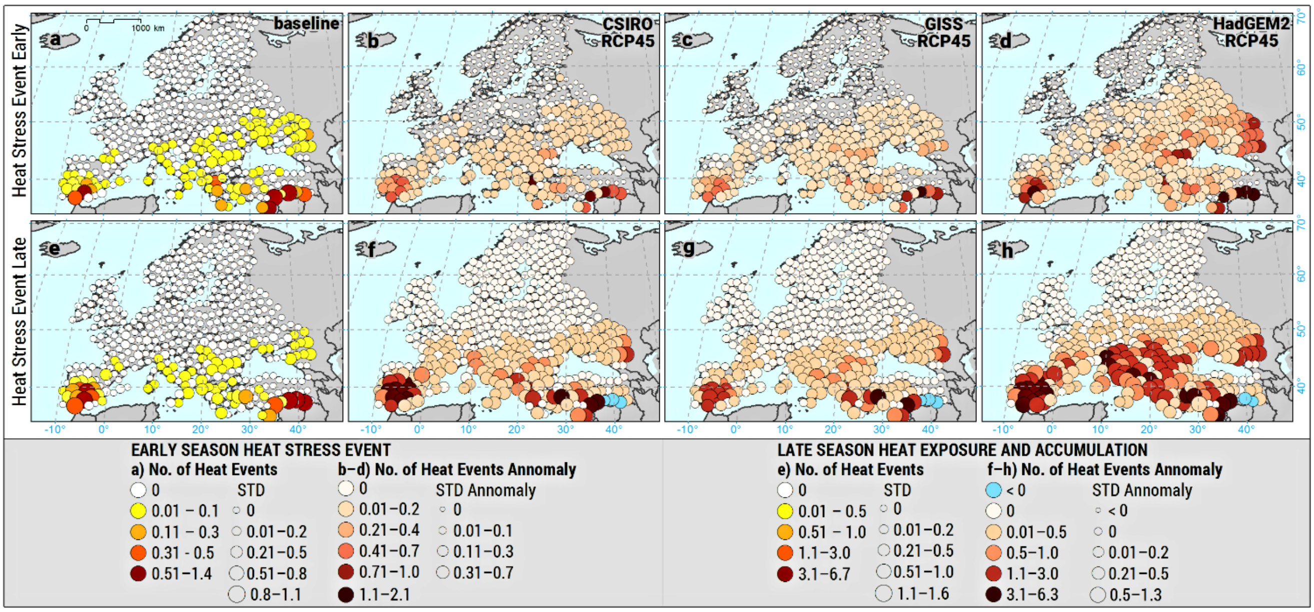


Fig. 4 Suppl. Probability of occurrence of at least 2 d with Tmax >+31 °C in the early season (January - May) (*a*) and Tmax > +35 °C for the period of late (June - October) season during 1981 - 2010 (*e*). The expected change compared to baseline is provided in the next three columns for CSIRO-RCP4.5 (*b,f*), GISS-RCP4.5 (*c,g*), and HadGEM-RCP4.5 (*d,h*) scenarios that represent period 2041 - 2060. The size of the *circle* is corresponding to the standard deviation (STD) of the given parameter over 300 individual yearly simulation. The STD of the anomaly represents increase (when STD > 1.0) or decrease (when STD < 1.0) of annual variability of the given indicator with respect to the baseline.

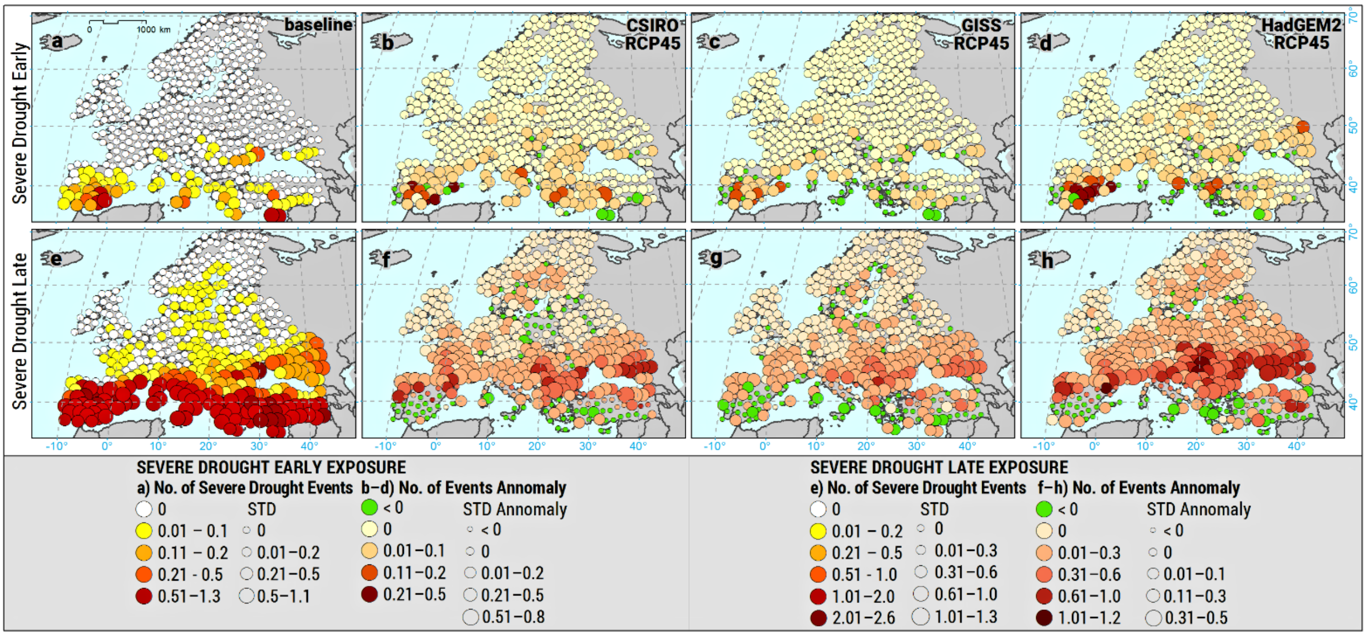


Fig. 5 Suppl. Probability of occurrence of severe drought, *i.e.* at least 10 consecutive days with severe water stress in the early season (January - May) (*a*) and late season (June - October) during 1981 - 2010 (*e*). The expected change compared to baseline is provided in the next three columns for CSIRO-RCP4.5 (*b,f*), GISS-RCP4.5 (*c,g*), and HadGEM-RCP4.5 (*d,h*) scenarios that represent period 2041 - 2060. The size of the circle in corresponding to the standard deviation (STD) of the given parameter over 300 individual yearly simulation. The STD of the anomaly represents increase (when STD > 1.0) or decrease (when STD < 1.0) of annual variability of the given indicator with respect to the baseline.