Danish Ministry of the Environment
Environmental Protection Agency

Prediction of climatic impacts on pesticide leaching to the aquatic environments.

Evaluation of direct and indirect (crop rotations, crop management, and pesticide use) climate change effects of pesticide leaching in a regulatory perspective for two Danish cases.

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Prediction of climatic impacts on pesticide leaching to the aquatic environments.

Authors & contributors:

Henriksen, H.J.[1], Rosenbom, A. [1], Keur, P. van der[1], Olesen, J.E. [2], Jørgensen, L.J. [2], Kjær, J. [1], Sonnenborg, T[1] og Christensen, O.B. [3]

[1] Geological Survey of Denmark and Greenland (GEUS)
[2] Department of Agroecology at Aarhus University (AU)
[3] Danish Meteorological Institute (DMI)

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Preface

PRECIOUS (Prediction of climatic impacts on pesticide leaching to the aquatic environments) is funded by the Danish Environment Agency under the pesticide research programme. The project is carried out in collaboration between the Danish Meteorological Institute (DMI), Department of Agroecology at Aarhus University (AU) and the Geological Survey of Denmark and Greenland (GEUS). The project was initiated in January 2008 and is expected to conclude in January 2012.

The leader of the project is Hans Jørgen Henriksen (GEUS). The following researchers have contributed to the project: Ole B. Christensen (DMI), Jørgen E. Olesen and Lise Nistrup Jørgensen (AU), Annette Rosenbom, Peter van der Keur, Jeanne Kjær, Torben O. Sonnenborg, Karen Villholth, Lieke Roosmalen and Eline Haarder (GEUS).

The project has during its course been supported by a reference group with the following composition: Jørn Kirkegaard (Danish EPA, chairman), Anne Louise Gimsing (Danish EPA), Claus Hansen (Danish EPA), Henrik Brødsgaard (Danish EPA), Rasmus Søgaard (Danish EPA), Hans Jørgen Albrechtsen (Technical University of Denmark), Walter Brüsch (GEUS), Dean Jacobsen (University of Copenhagen), Bjarne W. Strobel (University of Copenhagen), Peter R. Jørgensen (PJ-Bluetech), Niels Lindemark (Dansk Planteværn), Hans Roust Thysen (Knowledge Centre for Agriculture) and Jørgen Jakobsen (former head of research DJF). Among these Peter R. Jørgensen, Bjarne W. Strobel, Anne Louise Gimsing, Niels Lindemark and Jørgen Jakobsen has reviewed and commented the draft report.

Sammenfatning

Nærværende rapport beskriver det arbejde, som er udført i PRECIOUS projektet.

Pesticidanvendelse under fremtidige klimaændringer afhænger af afgrødevalg, afgrøderotationer, timingen i produktionen, og forekomsten af ukrudt, skadedyr og sygdomme. Der er defineret afgrødevalg og – rotationer for nutidigt og fremtidigt (2050) klima for to forskellige bedriftstyper: Kvægbedrifter og plantebedrifter/svinebedrifter. Sædskifterne er blevet defineret for sandjord og lerjord baseret på nuværende afgrødestatistikker for to oplande i Danmark. Ændringerne i afgrødevalg, afgrøderotationer og pesticidanvendelse i et fremtidigt klima (2050) blev baseret på ekspertvurderinger opnået via en studietur til Tyskland og Frankrig og på litteratur om klimaændringernes effekt på landbruget. Teknologiske ændringer i afgrøder og landbrugspraksis er ikke inkluderet i scenarierne.

Scenarierne for afgrøderotationer, landbrugspraksis og pesticidanvendelse for udvalgte landbrugstyper viser ingen ændringer i afgrøderotationer for kvægbedrifter og kun små ændringer for svineproduktion (inklusiv majs til foder). Et varmere klima og ændringer i jordens vandindhold vil ændre så- og tilplantningstidspunkter, ligesom afgrødeudvikling påvirkes, så der generelt opnås en hurtigere udvikling inklusiv tidligere blomstring, tidligere såning af vårafgrøder og senere såning af vinterafgrøder. Dette vil have konsekvenser for timingen af pesticidanvendelsen. Scenarierne viser kun små ændringer i pesticidanvendelse for de fleste afgrøder. Der er imidlertid en generel tendens til øget brug af pesticider.

For at kunne vurdere de direkte (nedbør, fordampning og temperatur) og indirekte (sædskifte, landbrugspraksis og pesticidanvendelse) konsekvenser af klimaforandringerne på pesticidudvaskningen igennem en variabelt mættede sandjord og lerjord fra arealer, der henholdsvis er underlagt bedrift typerne kvægbedrift og plantebedrift/svinebedrift, er MACRO-modellen version 5.1 anvendt. Simuleringsresultaterne af fem modelpesticider i det følgende benævnt P1-P5 (se Appendiks F) viser, at:

- trods et generelt øget forbrug af pesticider i fremtiden vil udvaskningen af pesticidtyperne stærkt adsorberende ukrudtsmidler (herbicider - P3), svampemidler (fungicider - P4) og midler mod insekter (insekticider - P5) ikke øges. Derimod kan der forventes en øget udvaskning af lav-dosis ukrudtsmidler (herbicider - P1) og i et mindre omfang ordinære ukrudtsmidler (herbicider - P2).
- de direkte klimafaktorer (ændret nedbør, temperatur og fordampning) vil have en relativ stor indflydelse på pesticid-udvaskningen igennem lerjord (øget makropore strømning), men kun minimal betydning på sandjord.
- de indirekte klimafaktorer (ændrede afgrøde- og pesticidbehandlings-forhold) vil have en minimal eller reducerende indflydelse på pesticid-udvaskningen på lerjord og er negligerbar på sandjord.

- Som følge af de fremtidige klimaforandringer vil pesticidudvaskningen på sandede jorder mindskes på arealer underlagt plante- og svineavl, hvorimod der vil være øget pesticidudvaskning på kvægavls bedrifter.
- Som følge af de fremtidige klimaforandringer vil pesticidudvaskningen på lerede jorder øges på arealer underlagt både kvæg-, plante og svinebedrift.
- Dog vil introduktionen af majs på lerjord til foder i fremtidens svinebedrifter kunne resultere i en højere udvaskning af lav-dosis ukrudtsmidler (herbicider - P1) via øget makroporestrømning og drænafstrømning.
- For kvægbedrifter ses en øget udvaskning af lav-dosis ukrudtsmidler (herbicider – P1) via makroporer og via peak koncentrationer for samlet nedsivning (mikro- og makroporer), makroporer og dræn
- Kun peak koncentrationer af lav-dosis ukrudtsmidler (herbicider - P1) og midler mod insekter (insekticider - P5) udvasket fra 1,2 meters dybde på sandede jorde vil overskride den maximalt tilladte koncentration på 0,1 µg L^{-1}.

Der er opstillet en MACRO-MIKE SHE oplandsmodel med henblik på simulering af udvaskning af pesticider fra rodzonen til grundvand og vandløb. Den, af MACRO, simulerede perkolation og stoftransport fra den umættede zone videreføres til oplandsmodellen MIKE SHE, og MACRO input kan således betragtes som en øvre randbetingelse til MIKE SHE, dog uden dynamisk feedback til MACRO (fx ved ændret grundvandstand i et fremtidigt klima). Der er valgt en histogram-korrektions metode (intensitets baseret) til at korrigere klimadata til brug i den hydrologiske model. Valget af bias-korrektionsmetoden er yderligere testet for ændringer i klimaet svarende til slutningen af det 21. århundrede for 2 lokaliteter, Faardrup og Jyndevad, der hhv. repræsenterer en leret og sandet jord. Ved denne test viste det sig, at pesticider udvaskede mest med den valgte intensitets baserede bias korrektions metode for den lerede lokalitet (Faardrup), hvorimod forskellen i udvaskning ved brug af korrektions metode for den sandede lokalitet var begrænset. Opland skala simuleringen er foretaget for det sandede opland (Odderbæk) og den lerede opland (Lillebæk) for de 5 udvalgte modelpesticider (P1-P5) for nutid (1960-1990) samt fremtid (2031-2060) scenarier og har ført til følgende resultater:

- Øget perkolation til mættet zone som følge af øget nedbørsmængde til MACRO i fremtidsscenarier fører til øget drænafstrømning til overflade vand af samme størrelsesorden, hvor ændring i baseflow (grundvands-afstrømning til vandløb) og ændret grundvandsafstrømning til overfladen er mere begrænset.
- Pesticid udvasket til grundvandszonen forlader denne igen som grundvandsafstrømning til dræn (85-94 %), grundvands-afstrømning til overfladevand (4-11 %) og som overfladisk afstrømning (0-3 %).
- For lav-dosis ukrudtsmidler (herbicider - P1) i Odderbæk oplandet øges pesticid udvaskning til overflade og grundvand. For ordinære ukrudtsmidler (herbicider - P2) er situationen modsat, her aftager pesticid udvaskning med ca. 90 % for fremtidsscenariet sammenlignet med nutids klima. For Lillebæk er de tilsvarende tal adskillige størrelsesordner lavere.
- Simulerede gennemsnits grundvands koncentrationer for Odderbæk oplandet for 6 grundvands-modellag varierende fra det terrænnære til det dybe grundvand og var mellem 30 og 99 % højere under fremtidsscenariet for lav-dosis ukrudtsmidler

(herbicider - P1) sammenlignet med nutid. Udvaskning af ordinære ukrudtsmidler (herbicider - P2) og svampemidler (fungicider - P4) blev derimod reduceret med henholdsvis 93 % og 91 %. På dette sandjordsopland, fører klimaændringer til øgede koncentrationer i overfladevand af lav-dosis ukrudtsmidler (herbicider - P1), som illustreret for tre vandløb, men i reducerede koncentrationer for ordinære ukrudtsmidler (herbicider - P2) og svampemidler (fungicider – P4).

Summary

The present report describes the work carried out in the PRECIOUS project.

Pesticide use under future climate depends on crop choice, crop rotations, timing of crop production, and occurrence of problematic weeds, pests and diseases. Here, crop choice and rotations are defined for current and future (until 2050) climate conditions for two different farm types: dairy farms and for arable/pig production farms. The crop rotations were defined for sandy and loamy soils respectively based on current crop statistics for two catchments in Denmark. The changes in crop choice, crop management and pesticide use under climate change for 2050 were based on expert judgement from experience from a study tour to Germany and France and from literature on climate change impacts on agriculture. Technological changes in crop and crop management are not included in the scenarios.

The scenarios of crop rotations, crop management and pesticide use for the selected farm types show no changes in rotations of the dairy farming systems, and only small changes for the pig farms (introduction of grain maize). A warmer climate and changes in soil water content will also shift sowing and planting dates and change crop development times, generally leading to faster development, including earlier flowering, earlier sowing of spring crops and later sowing of autumn crops. This will have consequences for the timing of pesticide applications. The scenarios show only small changes in pesticide use for most crops. However, there is an overall tendency towards increased use of pesticides.

To evaluate on the implication of direct (precipitation, actual evapotranspiration, and temperature) and indirect (crop rotations, crop management, and pesticide use) climatic factors on pesticide-leaching through variable saturated sandy and loamy soil the MACRO-model version 5.1 was applied. For the two soil types, model-scenarios with dairy, arable and pig farming systems is included. The following conclusions can be derived from this analysis of five model pesticides P1-P5 (see Appendix F):

- Despite general increase in use of pesticides, no drastic increase in pesticide-leaching of strongly sorbing herbicides (P3), fungicides (P4), and insecticides (P5) is to be expected. An increased leaching of the low-dose herbicides (P1) is through to be expected together with a minor increase in the leaching of ordinary herbicides (P2).
- Direct climatic factors will have implications for pesticide-leaching especially loamy soils (increased macropore flow) and only minimal for sandy soils.
- Indirect climatic factors will have a minimal or reducing influence on pesticide-leaching at loamy soils and negligible at sandy soils.
- The overall leaching risk on sandy soils posed by future climatic factors seems to be decreasing under arable agricultural management and increasing under dairy agricultural management.
- The overall leaching risk on loamy soils posed by future climatic factors seems to be increasing under both arable and dairy agricultural management.

- Introduction grain maize on loamy soils under arable agricultural management (pig farms) will result in higher leaching of low-dose herbicides (P1) to the aquatic environment via bulk matrix and drains,
- Dairy agricultural management will result in increased leaching of low-dose herbicides via macropores and peak concentrations via bulk-matrix (micropores and macropores), macropores, and drains.
- Only peak concentrations of the low-dose herbicide and fungicide leaching from 1.2 meter depth on sandy soil exceed the maximum allowed concentration of 0.1 μg L^{-1}.

A catchment scale model MACRO-MIKE SHE was applied for simulating changes in pesticide concentrations in the aquatic environment, i.e. groundwater and surface water. The MACRO model was used to model the effect of changes in climate and pesticide management on pesticide leaching from the unsaturated zone to recipients, i.e. groundwater and surface water. Simulated percolation as well as solute flow from the MACRO model was propagated to the MIKE SHE model. The output of the MACRO model is therefore an upper boundary condition for the MIKE SHE model. The intensity based bias correction method for converting from Regional Climate Modelling data to hydrological input data is the most appropriate method as it best reflects changes in rainfall intensity. It is shown that leaching of a selected pesticide using the intensity based bias correction method is largest as compared to the other correction methods for the clayey soil at Faardrup whereas differences for the sandy soil (Jyndevad) are insignificant. Catchment scale simulations for the sandy catchment (Odderbæk) and the clayey catchment (Lillebæk) for 5 selected model pesticides (P1 – P5) is leading to the following observations:

- Increased percolation simulated by the MACRO model and propagated to the MIKE SHE model nearly all ends up in increased drainage to the river. Other recipients, baseflow (groundwater to surface water) and surface water thus receive much less.
- Pesticide solute entering the groundwater zone (SZ) is mainly leaving SZ via drainage (85-94 %), base flow to the river (4-11 %) and overland flow to river (0-3 %)
- For low dose herbicides (P1) in the sandy catchment future climate simulations render a larger amount available for an increase in pesticide leaching to surface water and ground water recipients. For ordinary herbicides (P2) the situation appears to be vice versa, i.e. decrease in pesticide leaching to recipients. In the case of the clayey Lillebæk catchment simulated absolute values of pesticide concentrations in surface and groundwater are several orders of magnitude smaller
- Mean concentrations in groundwater increase by 30-99 % for low dose pesticides (P1) under future climatic conditions, whereas mean concentrations decrease for ordinary herbicides (P2) and fungicides (P4) by app. 93 and 91 % respectively. In the sandy catchment, future climatic conditions lead to higher concentrations in surface water for low dose herbicides (P1), illustrated for three streams, but to decreased concentrations for ordinary herbicides (P2) and fungicides (P4).

1 Background

1.1 Motivation

The rationale behind the PRECIOUS research project is grounded on:

- Implications of future climate changes needs to be accounted for within the regulatory framework
- Knowledge on how future climate changes will influence leaching of pesticides is currently not available

Future climate change will affect:

- The pesticide leaching source term due to:
  - Changing rainfall patterns (changes in seasonality and intensity)
  - Changing crop and cropping system
  - Changing pesticide application frequency and pesticide types
- Leaching pattern of pesticides as:
  - Rainfall intensity will increase in winter months (more by-pass flow)
  - Transport of pesticides through preferential flow paths will gain increasing importance
- The aquatic environment due to:
  - Increasing likelihood of rapid pesticide movements to drains, surface waters and groundwater
  - Decreasing summer river flow resulting in higher pesticide concentrations

1.2 Objectives

The objective of PRECIOUS is to evaluate implications of future climate changes for the risk assessment of pesticides leaching to the aquatic environment.

1.3 Background for climate change and pesticide leaching risk modelling to groundwater and the environment

Pesticide leaching from agricultural fields to the aquatic environment is a problem in many countries and in Europe especially with respect to comply with the requirements of the various EU directives, such as the Water Framework Directive (EC, 2000) and the Habitat Directive (EC, 1992). During the last decade significant research effort has been dedicated to understand the effects of increasing greenhouse gas emissions on primarily the climate (e.g. Christensen and Christensen, 2004), but recently also hydrological impact studies have emerged (e.g. Graham, 2004; Andersen et al., 2006). Using advanced numerical climate model codes like HIRHAM (Christensen and Christensen, 2004) and hydrological model codes like MIKE SHE (Graham and Butts, 2006) the effect on the water fluxes and pathways has recently been carried out in Denmark (Sonnenborg et al., 2006; Roosmalen et al., 2008). The impacts of future climate changes in Denmark have generally been predicted as higher temperatures, higher winter stream discharges caused by increasing winter rainfall, and higher rainfall intensities. However, this information have to date not been used for quantifying the effects on pesticide transport. Therefore, the impact of climate change is not accounted for in pesticide regulatory assessments by the Danish Environmental Agency. Until now no studies have been published in the peer-reviewed literature that have specifically considered the impacts of climate change on pesticide fate and transport in the context of environmental protection.

Climate changes will affect pesticide use in various ways. A warmer climate will enable new crops to be cultivated at the expense of existing crops (Olesen and Bindi, 2002). The largest changes in Denmark are projected to occur within crop rotations for arable farms and pig production with grain maize and some new protein and oil seed crops being cultivated (Olesen et al., 2007a,b). A warmer climate and changes in soil water content will also shift sowing and planting dates and change crop development times, generally leading to faster development, including earlier flowering (Cmielewski et al., 2004), earlier sowing of spring crops and later sowing of autumn crops (Olesen, 2005). This will have consequences for the timing of pesticide applications. A warmer climate is likely to lead to increased problems with pests and diseases, and probably to changes in efficacy of some of the herbicides (Olesen et al., 2007b). However, the relationships are complex and a good data basis for evaluating many of the relationships is still lacking (Chakraborty et al., 2000; Boland et al., 2004).

The overall effect of climate change on pesticide fate and transport to groundwater aquifers is very difficult to assess and associated with considerable uncertainty because of the complexity of the environmental system. Bloomfield et al. (2006) carries out a qualitative analysis of the impacts of climate change on the fate and behaviour of pesticides in surface and groundwater, and concludes that catchment-based modelling studies of pesticide behaviour under a range of climate change scenarios may provide further insight into the fate and transport of pesticides. Increased and higher intensity winter rainfall will lead to higher moisture content in the top soils and this will trigger both increased pesticide transport through both the soil matrix as well as through preferential flow paths (DEFRA, 2004). Kordel and Klein (2006) demonstrate that preferential flow is more the rule than the exception in well-structured fine-textured soils, and pesticide losses to groundwater via macropore flow may exceed losses via matrix transport considerably.

In Denmark, Christiansen et al. (2004) used the MIKE-SHE/DAISY code (Styczen and Storm, 1993) to simulate macropore flow to groundwater and transport processes at catchment scale. They concluded that macropore flow has a very significant effect on the leaching of pesticides to the groundwater aquifer and that macropore flow generation depends in a very complex way on both soil characteristics and the hydrological regime. Pesticide transport through preferential flow paths is therefore expected to gain increasing importance under climate change conditions. Moreover, higher groundwater levels as a consequence of increased winter rainfall may increase interception of pesticides in the unsaturated zone, leaving less time for degradation (DEFRA, 2004).

It is well known that both diffusive loads and point sources play an important role in polluting surface streams. Diffusive loads enter surface water through spray drift, surface runoff and leaching to field drains (see Brown and van Beinum, 2009 for a recent review). For non-drained soils an increase in groundwater pollution is expected, as future climate with increased rainfall amounts during fall and winter will result in additional infiltration to groundwater aquifers. There is a need to quantify the consequences of changed climate to surface and groundwater quality as this must be accounted for in local and regional water plans in most countries, and thus decision making is heavily dependent on reliable estimates.

Estimations of consequences of climate change for pollution to the aquatic environment must necessarily involve simulation models and assumptions on how the boundary conditions of models change over time. Future climate conditions are usually predicted by various scenarios based on assumptions, e.g. to which degree environmental variables change and economic development (IPCC, 2007).

Agriculture in Denmark is intensive and therefore knowledge on to, which degree surface- and groundwater is affected by use of pesticides, and how this may change in the future is of major importance to assess measures to control and decrease pollution and obtain a sustainable management, in the present situation and for the future. Pesticide leaching via pipe drainage is probably a major source of contamination of surface water and is subject of recent research (Styczen et al., 2004; Rosenbom et al., 2010). In this paper an integrated model approach is applied to assess consequences of climate change for pesticide leaching to the aquatic environment in two small well described catchments with contrasting soil properties.

2 Materials and methods

The impacts of climate change on pesticide contamination risk will be assessed using numerical models. Present and future scenarios for climate, land use and pesticide application provide a realistic parameterization of the numerical models MACRO and MIKE SHE (Refsgaard and Storm, 1995) representing the unsaturated zone, saturated zone to the groundwater zone and surface waters will be linked enabling a risk assessment of pesticides in the environment.

2.1 Downscaling climate change impacts to pesticide leaching risk dynamics

The regional climate model RACMO will be used for the generation of meteorological variables for the future climate. RACMO (Meijgaard et al., 2008) is a state-of-the-art climate model and has been used for a wide range of climate change applications (e.g. in the PRUDENCE and ENSEMBLES projects). The model provides a relatively fine resolution both spatially (down to 25 km) and temporarily (down to hourly values) and produces the output required by the present project.

2.1.1 Climate model simulations

In the European project ENSEMBLES, which was completed in 2009, a dozen European climate research institutions have performed climate change simulations with regional models in 25 km resolution. These simulations are performed with lateral and sea-surface boundary conditions from various coupled global models in lower resolution. The simulations are transient, covering the period 1951-2050 or 1951-2100 according to the SRES scenario A1B, see Figure 1 (van der Linden and Mitchell, 2009). The A1B emission scenario represents a mid-range scenario for greenhouse gas emissions in the IPCC Special Report on Emission scenarios (SRES) (Nakicenovic et al. 2000).

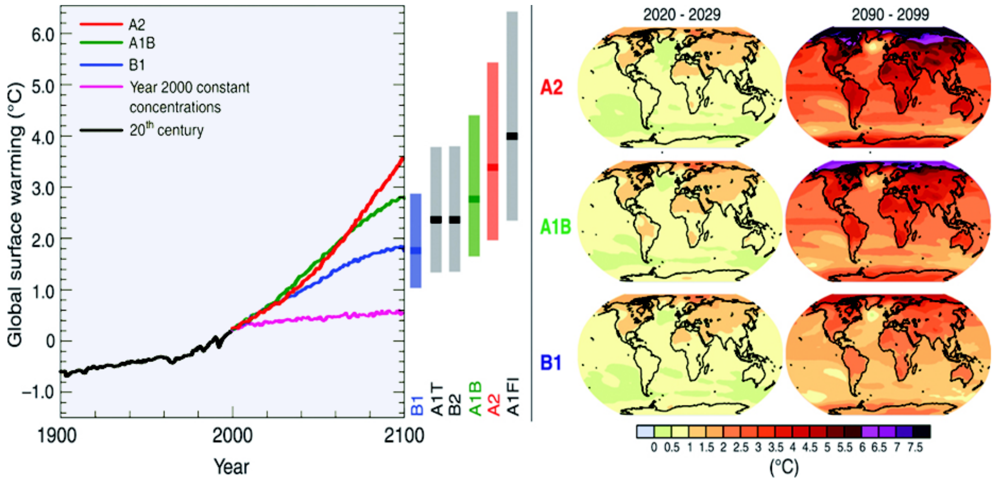


Figure 1. Predictions of global surface warming (°C) based on different climate scenarios. A1B has "a medium high" CO_2 increase, compared to the stronger A2 and A1FI scenarios and more moderate B1, A1T and B2-scenarios (van der Linden and Mitchell, 2009).

Two models from the ENSEMBLES project have been selected for the project. The first model is the RACMO model of the Royal Dutch Meteorological Institute, KNMI, which has been driven by the German global model ECHAM5 for 1951-2100. The second model is the $HadRM_3$ model of the British Hadley Centre driven by the British global model HadCM3 for the period 1951-2098.

The argument for selecting the first climate model RACMO (KNMI/ECHAM from the Royal Netherlands Meteorological Institute) is that this model has a moderate climate signal and a good performance to predict the present-day climate, and that RACMO represents a 'middle range' in the ENSEMBLES datasets. The $HadRM_3$ (HC HADRM3Q0 model from the UK Hadley Center Met Office) was selected because it has a stronger climate change signal (both in temperature and precipitation) thereby exploring the range of possible climate change scenarios (Christensen et al. 2010). In Appendix B a comparison of RACMO and $HadRM_3$ with observed climate is provided, leading to the selection of RACMO for the projections.

Output data from the ENSEMBLES regional climate models are stored in a central database at the DMI (http://ensemblesrt3.dmi). These output data contain around 130 different meteorological fields in daily or sub-daily temporal resolution. For the present project, the following fields have been extracted: surface evaporation, surface specific as well as relative air humidity, surface average, maximum, minimum and dew-point air temperature, precipitation, 10-meter wind speed, net long- and short-wave surface radiation; all fields on a daily scale. The area covered contains Denmark (see Figure 2).

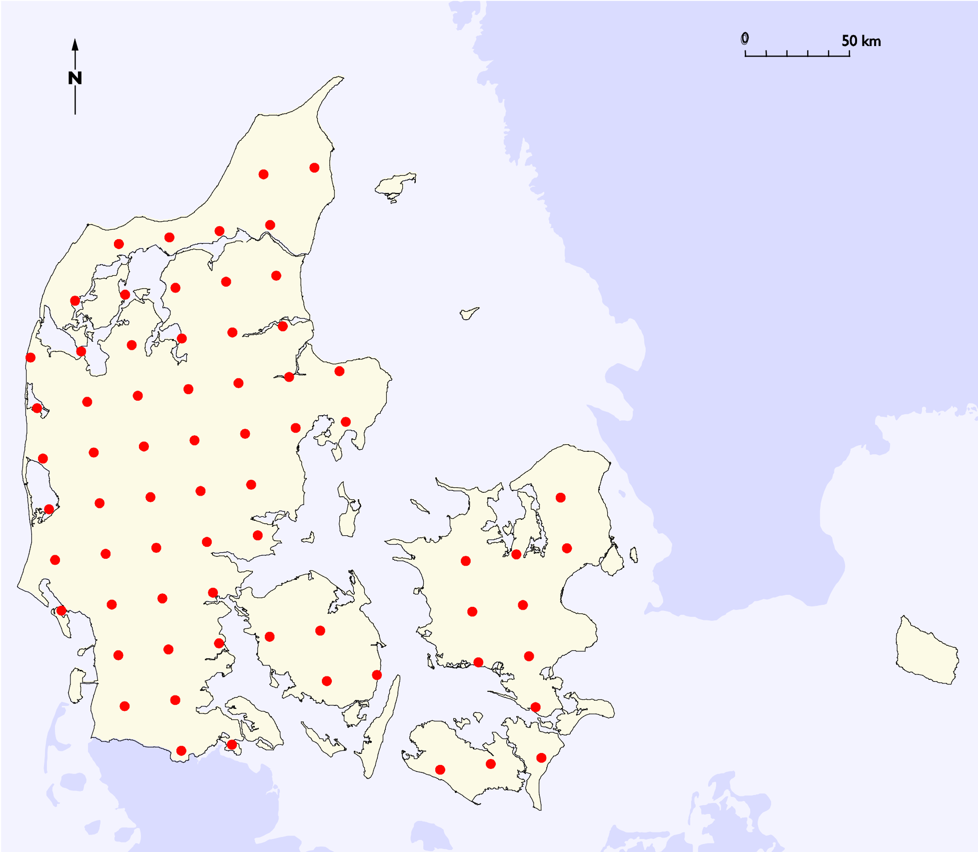


Figure 2. Map showing the location of climate model points where daily results are extracted for surface evaporation, air humidity, air temperature, precipitation, wind speed and radiation (ENSEMBLES, http://ensemblesrt3.dmi).

2.1.2 Bias correction of climate model results

Because of the scale at which the climate model simulates and other uncertainties in the model, the climate model results are not expected to be accurate enough to be used as direct input to a calibrated hydrological model. The result is e.g. that the total annual precipitation is inaccurate or that too many days with very low precipitation intensity are generated. Inaccuracies in both the total precipitation and precipitation intensity can greatly affect the water balance of the catchment, and it is therefore necessary to correct the data before used in hydrological modeling.

A number of different methods for conversion of climate model results to hydrological input data have been tested. In the first two methods the observed climate is used as the baseline for prediction of the future climate. This means that daily values of observed climate are modified to represent the future climate. The remaining three methods use the climate model results as the baseline. The purpose of the test has been to identify the most suitable bias correction method for describing changes in pesticide leaching to groundwater due to climate change effects.

The more detailed information on the five methods and comparison of bias correction methods are included in Appendix C.

2.1.3 Summary of bias correction methods

Table 1 presents an overview of the five proposed bias correction methods.

Table 1. List of methods that show if observed or simulated climate controls the future precipitation distribution.

	Adjusted			
Method	No of wet days	Mean	Variance	Dynamics
B. RCM data	Sim	Sim	Sim	Sim
1. Delta Obs	Obs	Obs/Sim	Obs	Obs
2. Stat. Trans.	Obs	Obs/Sim	Sim	Obs
3. Delta RCM	Obs/Sim	Obs/Sim	Sim	Sim
4. Intensity-bas.	Obs/Sim	Obs/Sim	Sim	Sim

The five methods are tested against observed meteorological data from the period 1991-2006 from Jyndevad and Tystofte. It has also been evaluated how the five methods affect the hydrological response in the scenario period by specifying the resulting time series for precipitation, evapotranspiration and temperature as input to the MACRO model setup for Jyndevad and Faardrup. Finally, the effects on pesticide leaching from the vadose zone will be assessed for each of the five methods for Jyndevad and Faardrup.

2.1.4 Observed climate data

Observations of precipitation, temperature and global radiation (incoming short wave radiation) are available from station 26400 Jyndevad and station 29440 Tystofte. Station 26400 is located approximately 2 km north of the VAP area St. Jyndevad while station 29440 is located approximately 7 km south of the VAP area Faardrup. For both stations data from 1961-2006 are available.

At station 26400 no data was missing. At station 29440 no data was missing in the period 1961-1990 but 37 data were missing in the period 1991-2006. The missing precipitation data was estimated based on measurement from the nearby station 29450 Flakkebjerg. Precipitation was corrected for measurement errors (Allerup et al., 1998) based on shelter conditions provided by Flemming Vejen, DMI.

Reference evapotranspiration was calculated using the Makkink equation

$$ET_{ref} = 0.7 \frac{\Delta_e}{\Delta_e + \gamma} \frac{R_g}{\lambda} \qquad (15)$$

where Δ_e is the curvature of the saturated vapour pressure curve, γ is the psychrometer constant (0.66 hPa/K), R_g is the global radiation and λ is the latent heat of evaporation for water.

For each location (Jyndevad and Tystofte) relevant climate statistics (precipitation and evapotranspiration) are calculated in Appendix A for 1961-90 and 1991-2006. Furthermore, results of the selected regional climate model RACMO (from the Dutch meteorological institute KNMI), using boundary conditions from the global climate model ECHAM5 (the German Max Planck Institute) are presented in Appendix B for different 30-year periods: 1961-90, 1991-2020, 2031-2060 and 2071-2100 which documents that the projected geographical distribution in precipitation is similar to the control period, however the precipitation is seen to increase with time, resulting in significant increases in mean annual precipitation in the latest period. Results from the British $HadRM_3$ simulation are used for comparison, but this model showed a relatively poor match of the spatial precipitation distribution for Denmark for the control period (1961-1990).

In Appendix C different bias correction methods are described and analysed and results of an analysis of the five downscaling methods for 2071-2100 based on MACRO is provided. Based on this analysis, the intensity based downscaling method was selected for PRECIOUS.

In Figure 3 the downscaling methodology used in PRECIOUS is summarized.

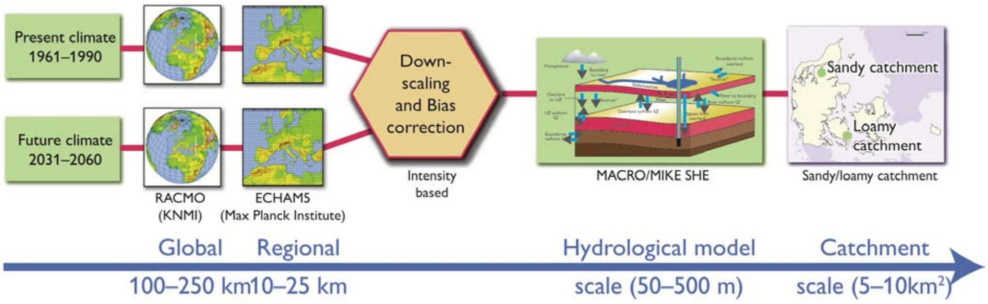


Figure 3. Downscaling of results for IPCC scenario A1B for 2031-2060 from global and regional models (RACMO/ECHAM5) using intensity based bias correction as input for the integrated modelling concept based on MACRO and MIKE SHE models, to analyse leaching from root zone using PLAP-model-scenarios (Barlebo et al., 2007), and hypothetically illustrating the impacts on groundwater concentrations and surface water concentrations in runoff for two LOOP areas: Lillebæk and Odderbæk.

The effect of future climate will be investigated for the period up to 2050, with special focus on 2031-2060. The period 2031-2060 represents the near future and at the same time the change in climate is predicted to be strong enough to differentiate it from model uncertainties (see Figure 1). The impact of future climate changes on the leaching and transport of pesticides will be quantified based on the IPCC scenario A1B (IPCC, 2000; Figure 1 and 3). This climate scenario represents a moderately strong greenhouse gas emission scenario. According to IPCC (2000), the atmospheric concentration of greenhouse gases is relatively insensitive towards the specific choice of the climate scenarios. Only one climate scenario will therefore be considered in this report, since the uncertainty on the impact studies of individual climate scenarios will be higher than the difference between the climate scenarios for this period.

To summarize, the climate model results from the selected RACMO model (KNMI-ECHAM) has been converted to the hydrological models (Figure 3) using the selected intensity based (histogram equalization) correction method (Method no. five according to Appendix C). This correction method incorporates the changes in the dynamics of the future climate. Of the other methods, the first two have been tested previously (e.g. Roosmalen et al., 2007) and are robust, but as also shown in Appendix C tend to underestimate the intensity of especially extreme rainfall events that are expected to be important to be tested, evaluated and compared. It is expected that the leaching of pesticides is strongly correlated to rainfall intensity on a relatively fine temporal scale. In addition, a sensitivity analysis has been included (Appendix C) with respect to pesticide leaching from the root zone using climate data corrected by the mentioned alternative four bias correction methods. In this sensitivity analysis the leaching of three selected pesticides at two locations (from Barlebo et al., 2007), Jyndevad (sandy soil) and Faardrup (loamy/clayey soil), has been simulated by the MACRO model for the periods

1961-90 (control period) and 2071-2100 (future scenario) and compared and with the implications for pesticide leaching assessed.

2.2 Present and future land use and pesticide management scenarios

Pesticide use under future climate change depends on crop choice, crop rotation, timing of crop production, and occurrence of problematic weeds, pests and diseases. Crop choice and rotations will be defined for current and future (2050) climate conditions for three different farm types: dairy farms, pig production farms and crop production farms. Technological changes in crops, crop management (incl. crop protection) will not be included in the future scenarios. The crop rotations may also differ depending on soil type (sand and loam), in particular for the pig and crop production farms. However, the need to differentiate these has been evaluated during the initial survey of current crop of current crop rotations.

2.2.1 CO_2 effect on transpiration

CO_2 affects the transpiration from plants through its control on stomatal conductance. The degrees to which the plants open their stomatals diminish as the CO_2 concentration increases and the amount of moisture that is lost to the surroundings is therefore reduced. As shown by Gedney et al. (2006), Betts et al. (2007), Boucher et al. (2009), and Cao et al. (2009) increasing CO_2 concentrations results in decreasing transpiration and hence counteracts the effect of increasing temperature on evapotranspiration. Witte et al. (2006) and Kruijt et al. (2008) describe an approach to quantify the effect of CO_2 on potential evapotranspiration.

They formulate a relatively simple model for potential evapotranspiration, PET

$$PET = c\ f\ ET_{ref} \tag{16}$$

where f is the crop factor, ET_{ref} is the reference evapotranspiration and c is a CO_2-dependent, vegetations specific multiplier that are derived from three factors relating to stomatal conductance, boundary-layer properties, and transpiration share of total evapotranspiration, together with the change in atmospheric CO_2 concentration. Based on the methodology described in Kruijt et al. (2008) values for c may be calculated, see Table 2.

The effect on c increases over time in connection with the increasing atmospheric CO_2 concentration. Except for grass the largest effect is observed during summer. Since the dominant part of total evapotranspiration takes place during the summer period, these values control the effect on total evapotranspiration. The impact on evapotranspiration from grass is relatively low, whereas the impact on maize (C_4 plant) is relatively high with absolute values of c down to 0.87.

Table 2. Values for the CO_2-dependent, vegetations specific multiplier (c-factor) defined by equation 16 as a function of time and land use for SRES scenario A1B. Summer refers to the period April-September and winter to the period October-March.

Year	CO_2 conc. (ppm)	Grass	Corn Summer	Corn Winter	Maize Summer	Maize Winter
2030	454	0.98	0.97	1.00	0.96	1.00
2040	491	0.98	0.96	1.00	0.94	1.00
2050	532	0.97	0.95	1.00	0.93	1.00
2060	572	0.97	0.95	1.00	0.92	0.99
2070	611	0.96	0.94	1.00	0.91	0.99
2080	649	0.96	0.93	1.00	0.89	0.99
2090	685	0.95	0.92	1.00	0.88	0.99
2100	717	0.95	0.91	1.00	0.87	0.99

2.2.2 Direct climate model results effect on pesticide leaching.

A limited assessment of the sensitivity of the four different bias correction methods (described in paragraph 2.1) for climate models results on pesticide leaching from the vadose zone excluding indirect climate factors (changed land use and pesticide application pattern), has been conducted for the PLAP locations Jyndevad (sandy soil) and Faardrup (loamy soil), and for the periods 1961-90 (control period) and 2071-2100 (for results see Appendix 3). To facilitate this assessment, MACRO-model (Figure 4) setups as reported in Barlebo et al. (2007) have been applied directly. Hence, three model-pesticides are used (Table 3), applied in doses of 1 kg/ha (100 mg/m^2), and used in line with conventional practice for spring and winter cereals.

Table 3. Pesticide sorption (K_{oc}) and degradation properties (DT_{50}) for solute A, B and C (Barlebo et al. 2007).

Pesticide	DT_{50} [d]	K_{oc} [ml/g]
A	49	99.5
B	6.1	30
C	80	400

The leaching of the future climate scenario of 2071-2100 is compared to that of the control period 1961-1990. The period 2071-2100 is selected for the future scenario, as opposed to 2031-2060, in order to show as contrasting leaching simulation results as possible for this limited assessment.

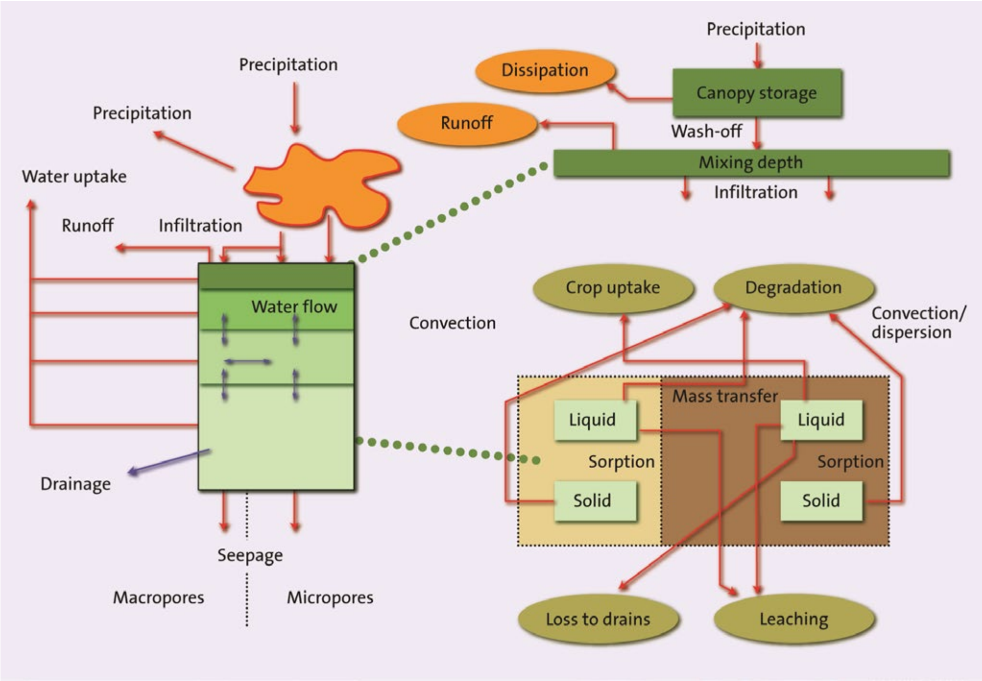


Figure 4. MACRO model (Larsbo and Jarvis, 2005).

2.2.3 Present and future scenarios for land and pesticide use

Pesticide use under future climate change depends on crop choice, crop rotations, timing of crop production, and occurrence of problematic weeds, pests and diseases. Crop choice and rotations are defined for current and future (2050) climate conditions for three different farm types: dairy farms, pig production farms and crop production farms. For simplicity both pig farms and arable farms have been defined as grain based cropping systems with identical crop rotations and crop management. Technological changes in crops, crop management (incl. crop protection) are not included in the future scenarios. The crop rotations also differ depending on soil type (sand and loam).

The case study in the project was based on data defining present and future crop rotations in the two catchments, Odderbæk and Lillebæk. Lillebæk (4.4 km^2) is located on Funen, and Odderbæk (11.4 km^2) is located in Northern Jutland. Both catchments are included in the Nation-wide monitoring programme under the Action Plan on the Aquatic Environment. Statistics on area of different crops in these catchments and the pesticide use were used for defining current conditions. Odderbæk is located in an area with predominantly sandy soils, whereas the Lillebæk area mainly has loamy soils (Styczen et al., 2004). This is also reflected in the main farming types of the regions, with cattle farms dominating in the Odderbæk area and arable/pig farms dominating in the Lillebæk catchment. Only main agricultural crops are considered in this study excluding crops like orchards and Christmas trees.

The future total nitrogen fertiliser use for a given crop was assumed to be the same as under current conditions, even though crop model results have shown that crop nitrogen demand may change with changes in both changes in atmospheric CO_2 and temperature (Olesen et al., 2004; Børgesen and Olesen, 2011). The assumption here is that the restrictions related to protection of the aquatic environment will maintain nitrogen fertiliser use at current levels. The current recommended crop fertiliser rates for sandy loam soils were therefore used for both current and future climate conditions (Plantedirektoratet, 2007).

Timing of crop production (e.g., sowing and harvesting) and crop development (e.g. flowering in cereals) under current climatic conditions was taken from the current crop cultivation guidelines published by the Knowledge Centre for Agriculture and from data on growth stages in crops observed from the Danish network for crop disease monitoring also run by the Knowledge Centre for Agriculture. Timing of crop management under climate change (2050) were estimated based on current practice in Northern France and Central Germany (Olesen and Jørgensen, 2008) in combination with results from modelled changes in crop phenology (Olesen et al., 2000; Olesen, 2005; Patil et al., 2012; Olesen et al., 2012). Analyses of projections of climate change have shown that temperature conditions for Denmark in 2050 may resemble current climatic conditions in Central Germany or Northern France (Trnka et al., 2011). Since temperature conditions to a large extent determine cropping patterns and timing of soil and crop management (Elsgaard et al., 2012; Olesen et al., 2012), comparison of current crop rotations and crop management between these regions and Denmark may provide information on likely changes in agricultural land use and management under projected climate change.

The official pesticide statistics (Anonym, 2007) was used for defining the current pesticide practice and specific recommendations provided by the advisory service, and this was combined with data from current practices in Northern France and Central Germany to estimate pesticide usage under future climate in Denmark (Olesen and Jørgensen, 2008; Jørgensen and Kudsk, 2006). The pesticide products used also for the future scenarios were taken as products that are currently approved in Denmark. There may in 40 years time have been major changes in the spectrum of pesticides, which will be approved, but these changes cannot be predicted and taken into account. Seed treatments of the crops were not considered.

2.3 Conceptualisation of pesticide leaching at field scale

The dual permeability model MACRO 5.1 (Larsbo and Jarvis, 2005) has been used in the present study to quantify the leaching of pesticides through the root zone. MACRO is a well documented numerical model, which have been used for many years in a regulatory context in accordance with the European Union (EU) directives to predict the leaching of both pesticides and metabolites (Rosenbom et al., 2009).

The MACRO model differs from most other models by its ability to deal with preferential flow, which is a widespread important process documented to take place in a large variety of soils (e.g. Fredericia, 1990; Jørgensen and Fredericia, 1992; Villholth et al., 1998; Sidle et al., 1998; Larsson and Jarvis, 1999a,b; Mortensen et al., 2004; Larsbo and Jarvis, 2005; Rosenbom et al., 2008). This ability is important as the occurrence of preferential flow is expected to increase under future climate conditions. These conditions is expected to bring a warmer climate and hereby a higher biodegradation – an effect, which also is well described in MACRO. Hence, MACRO is considered the most suitable model for the study.

The impact of climate changes on pesticide leaching seen in a regulatory context will first be evaluated using two of the well founded PLAP-model-setups Jyndevad (sandy soil) and Faardrup (loamy soil), already calibrated (for the period May 1999-June 2004) and validated (for the period July 2004-July 2011) towards water balance and bromide transport (Barlebo et al., 2007; Rosenbom et al., 2010).

These two one-dimensional model-setups have hence demonstrated that they captured the flow-dynamic of the soil-systems during a 10 years period. As these scenarios are intended to be used within the Danish regulation process, they do provide a unique opportunity to address factors being especially important for the regulatory framework. MACRO´s shortcomings with regard to simulating leaching of strongly sorbing pesticides such as glyphosate (Aagaard et al., 2011) and leaching in connection with snowmelt, though, need to be taken into account.

To be able to understand and describe leaching of strongly sorbing herbicides more research is imperative. With the existing knowledge incorporated in numerical models like MACRO, leaching of strongly sorbing pesticides can be underestimated. An attempt to incorporate a colloid module in MACRO failed because it gave unrealistic results, why it is excluded from the present version of MACRO.

The present and future climatic conditions were defined with respect to the direct (rainfall, evaporation and temperature) and indirect (changed land use and pesticide application pattern) factors.

2.3.1 Direct Factor Input - MACRO Scenarios

As direct factors, the present climatic time-series (1961-1990) from the climate-station 26400 at Jyndevad and climate-station 29440 at Faardrup were applied, whereas the future climatic time-series (2031-2060) were derived from the climate model scenario IPCC A1B using an intensity based correction for the precipitation (as described in paragraph 2.2). The climatic daily time-series are composed of the potential evapotranspiration (mm), air temperature (^{o}C), and precipitation (mm). Before application of the potential evapotranspiration of the future climate in the MACRO-setups, it has been adjusted/reduced with the CO_2-factors given in Table 1A In accordance with Kruijt et al. (2008), this factor is multiplied with the potential evapotranspiration to account for the implication of increased CO_2-concentration in air.

Artificial irrigation is incorporated in the simulation with MACRO using an irrigation concept suggested by Centofanti et al. (2008). Here an irrigation amount is added to the daily precipitation input to MACRO, when water deficit exceed a given threshold (Figure 5 and Eq. 17). Water deficit is calculated from daily precipitation and evapotranspiration (Eq. 17), whereas thresholds (50 mm at Jyndevad and 70 mm for Faardrup) were defined manually so that the estimated days of artificial irrigation under the present climate scenario reflect the artificial irrigation presently at the five PLAP-sites. The irrigation amount is set to 30 mm as normally applied on the two sandy PLAP-sites Jyndevad and Tylstrup.

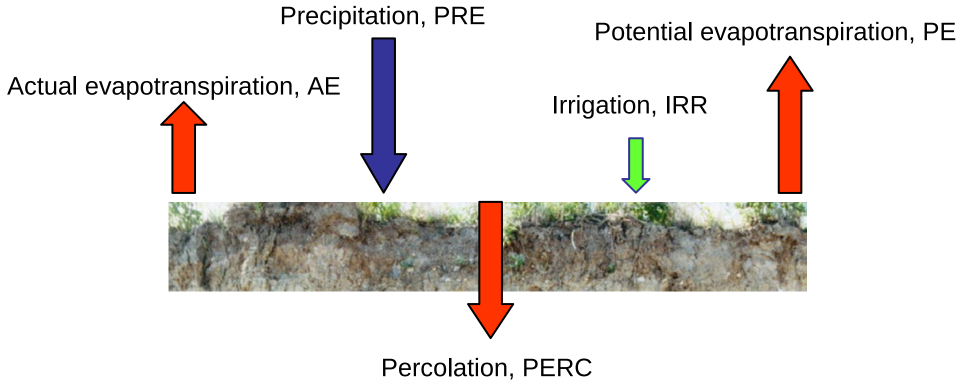


Figure. 5. Principle behind the artificial irrigation scheme.

$$IRR_i = \begin{cases} 0\,mm\,if\;Deficit_{i-1} < 50mm\;for\;Jyndevad\;and\;70\,mm\;for\;Faardrup \\ 30\,mm\,if\;Deficit_{i-1} \geq 50mm\;for\;Jyndevad\;and\;70\,mm\;for\;Faardrup \end{cases} \qquad Eq.17$$

where:

$i \in [1; simuleringsperiode\;in\;number\;of\;days]$

$Deficit_{i-1} = Deficit_i - AE_i + PRE_i - PERC_i + IRR_i$

$$AE_i = \begin{cases} PE_i & if\;Deficit_{i-1} < CRIT_i \\ \min(PRE_i, PE_i) & if\;Deficit_{i-1} \geq CRIT_i \end{cases}$$

$$PERC_i = \begin{cases} PRE_i - Deficit_{i-1} & if\;Deficit_{i-1} < PRE_i \\ 0 & if\;Deficit_{i-1} \geq PRE_i \end{cases}$$

$CRIT_i$ = 50 mm in the period of May - September, else $CRIT_i$ = 15 mm (the critical deficit for reduction of ET below the potential rate; values for winter and summer, reflecting relative importance of soil evaporation vs. transpiration).

2.3.2 Indirect Factor input - MACRO Scenarios

2.3.2.1 Land use

The crop rotations in present and future scenario on loamy soils (Faardrup, Lillebæk; Table 4) and sandy soils (Jyndevad, Odder Bæk; Table 5), respectively, are defined in paragraph 3.2. It is assumed that the crop-parameters for each crop, defined as those used in the FOCUS-Hamburg-scenario (see Appendix E), are representative for the present and future MACRO-model-scenarios for both sites. Different values for the “maximum root depth-crop-parameter are though included for loamy and sandy soils.

Table 4. Proposed crop rotations in present and future (2050) scenario on *loamy soils* equivalent to the Lillebæk catchment area.

Area coverage	Present crop rotation	Future crop rotation
80% (arable/pig farms)	Winter barley	Winter barley
	Winter rape	Winter rape
	Winter wheat	Winter wheat
	Winter wheat	Grain maize
	Spring barley	Spring barley
20% (dairy farms)	Spring barley (undersown)	Spring barley (undersown)
	Grass seed	Grass seed
	Grass seed	Grass seed
	Silage maize	Silage maize
	Silage maize	Silage maize

Table 5. Proposed crop rotations in present and future (2050) scenario on *sandy soils* equivalent to the Odder Bæk catchment area.

Area Coverage	Present Crop Rotation	Future Crop Rotation
80% (dairy farms)	Spring barley (undersown) Grass-clover Grass-clover Grass-clover Silage maize Silage maize	Spring barley (undersown) Grass-clover Grass-clover Grass-clover Silage maize Silage maize
20% (arable/pig farms)	Winter rape Winter wheat Spring barley Spring barley	Winter rape Winter wheat Grain maize Spring barley

2.3.2.2 Pesticide Application Pattern

Present and future scenarios involved 21 different pesticides. Including each of these pesticides in the simulation runs would be too time-consuming and not possible within this project. Instead pesticide usage within each of the selected crop rotation will be simulated using five model-pesticides representing different categories of pesticides normally used in Denmark (Table 6).

Table 6. Categories and concept for selection of model pesticides.

Category of Pesticide		Leach Ability	Dose	Application Time
P1. Herbicide	Low dose Compound	High	Low	Autumn
			High	Spring
P2. Herbicide	Ordinary Compound	Medium	Low	Autumn
			High	Spring
P3. Herbicide	Strongly sorbing compound	Low	Low	Autumn
			High	Spring
P4. Fungicide		Low	Same	Summer
P5. Insecticide		Low	Same	Summer

Based on dosage, sorption and degradation properties, each of the 21 pesticides were classified according the above 5 categories P1, P2, P3, P4, and P5 (see Appendix F). Within each of these categories a model-pesticide, defined by given sorption and degradation characteristics, were subsequently selected and used in all simulations (Table 7). For example, the model pesticide P1 resembling thifensulfuron-methyl representing the category "Herbicide – Low dose compound" characterised by a K_{oc} = 22 ml g^{-1} and a DT_{50} = 9 days will then be applied in all the crop-rotations where herbicides of low dose are used. The five model-pesticides were selected among the 21 pesticides based on their representatively in the present and future crop-rotations. Doses were subsequently adjusted in manner, which meant that the actual product doses proposed were translated to TFI (Treatment Frequency Index), which then again was translated to the a similar TFI in the model-product.

Fungicides: Epoxiconazole was chosen as the model-fungicide in all crops. It is currently widely used in particular in cereals. Sister products (e.g. tebuconazole) are used in other crops like oil seed rape.

Insecticides: Lamda-cyhalothrin was chosen as the model-insecticide in all crops. It is a pyrethroid, which is the most widely used group in all crops. It is believed to be a fair representative for the insecticides used in arable crops.

Herbicides: Three substances were used as model herbicides representing different types of treatments being either application of a low dose compound, ordinary compound or strongly sorbing compound. For the latter prosulfocarp was chosen as a model-pesticide. It works both through leaf and root uptake. It is widely used in cereals in current time. It has been used instead of products like glyphosate, diflufenican and propaquinzafop. Thifensulfuron-methyl, representing the low dose compound, was chosen as model pesticide for the sulfonylureas (e.g. florasulam). The products are widely used in many crops. Fluazypoor was chosen as the product representing other treatments (ordinary compounds) including later post emergence treatments - covering products like MCPA, clopyralid and others.

Table 7. Properties of selected model pesticides. Values in brackets indicate the range found within each category of model-pesticides (Appendix E).

Model-Pesticide	No. of pesticides represented	Type of Pesticide	GUS[1)] [-]		K_{oc}[1)] [ml g^{-1}]		DT_{50}[1)] [days]	
P1	4	Low dose herbicide	1.54	[1.54;2.74]	22	[22;78]	9	[4;9]
P2	7	Ordinary herbicide	1.04	[0.50;5.06]	66	[5;287]	3	[1;83]
P3	4	Strongly sorbing herbicide	1.15	[-0.36;1.36]	1693	[1693;21699]	31	[2;542]
P4	4	Fungicide	2.47	[-0.06;2.51]	1073	[769;11000]	354[2]	[32;354]
P5	2	Insecticide	-1.67	[-1.67;1.44]	157000	[615;157000]	25	[16;25]

[1)] Obtained from the FOOTPRINT database (http://sitem.herts.ac.uk/aeru/footprint/)

[2)] For active substances that are subject to a national reassessment, the Danish Environmental Protection Agency find that it is not at present possible to appraise the long-term consequences of the use of highly persistent substance (i.e. with half-lives of more than six months). This is not included yet in the European environmental risk assessment why the FOOTPRINT-value of 354 days was chosen for P4 resembling a worst case scenario.

2.4 Catchment scale pesticide transport in groundwater

2.4.1 Background and modelling framework

The impact of climate changes on pesticide loading to surface waters and groundwater require a large scale assessment, which in this project will be carried out using a combination of the MACRO and MIKE SHE modeling systems. MIKE SHE is a state-of-the-art model for integrated modeling of the freshwater cycle including groundwater and stream water flow and transport. MIKE SHE has consistently received top rank in recent reviews as a professional tool for integrated groundwater/surface water studies (DHI, 2007). Styczen et al. (2004a) set up a modeling system, PestSurf, for simulating transport of pesticides from agricultural fields to surface water, including sorption and degradation processes and also drift of pesticides as a result from spraying. This model was based on the MIKE SHE model and applied to the Odderbæk and Lillebæk catchments.

Preferential flow processes through macropores in the unsaturated zone in MIKE SHE are simulated by the dual-porosity model MACRO, as explained further below. Overland flow is not explicitly taken account of although the

MACRO model allows excess water to be removed from the soil surface and this process can thus be considered as a proxy for overland flow. The MACRO model generates water and solute flow in the two domains, micropore (soil matrix) and macropore and lateral losses to drains.

The latter MACRO simulated drain flow cannot directly be routed to MIKE SHE drainage system and this constitutes a conceptual error in the connection interface between the two models, that only can be solved by a true integration of the two models at the code level or by means of a e.g. OpenMI coupling (www.openmi.org). Hence, the MIKE SHE model, in combination with MACRO, is found highly suitable for the present study of pesticide transport through groundwater to surface water bodies. The latest available version of the MIKE SHE modelling system has been used in the present study.2.4.2 Study areas.

The Odderbæk and Lillebæk catchments (Figure 6) are included in the National Monitoring Programme (LOOP) established in 1989/1990 as part of the Action Plan on the Aquatic Environment, with the aim to monitor the effect of nitrogen reduction to the environment. The catchment scale model MIKE SHE (Refsgaard and Storm, 1995) and the root zone model Daisy (Hansen et al., 1991) were combined to quantify nitrogen leaching to the aquatic environment (Styczen and Storm, 1993).

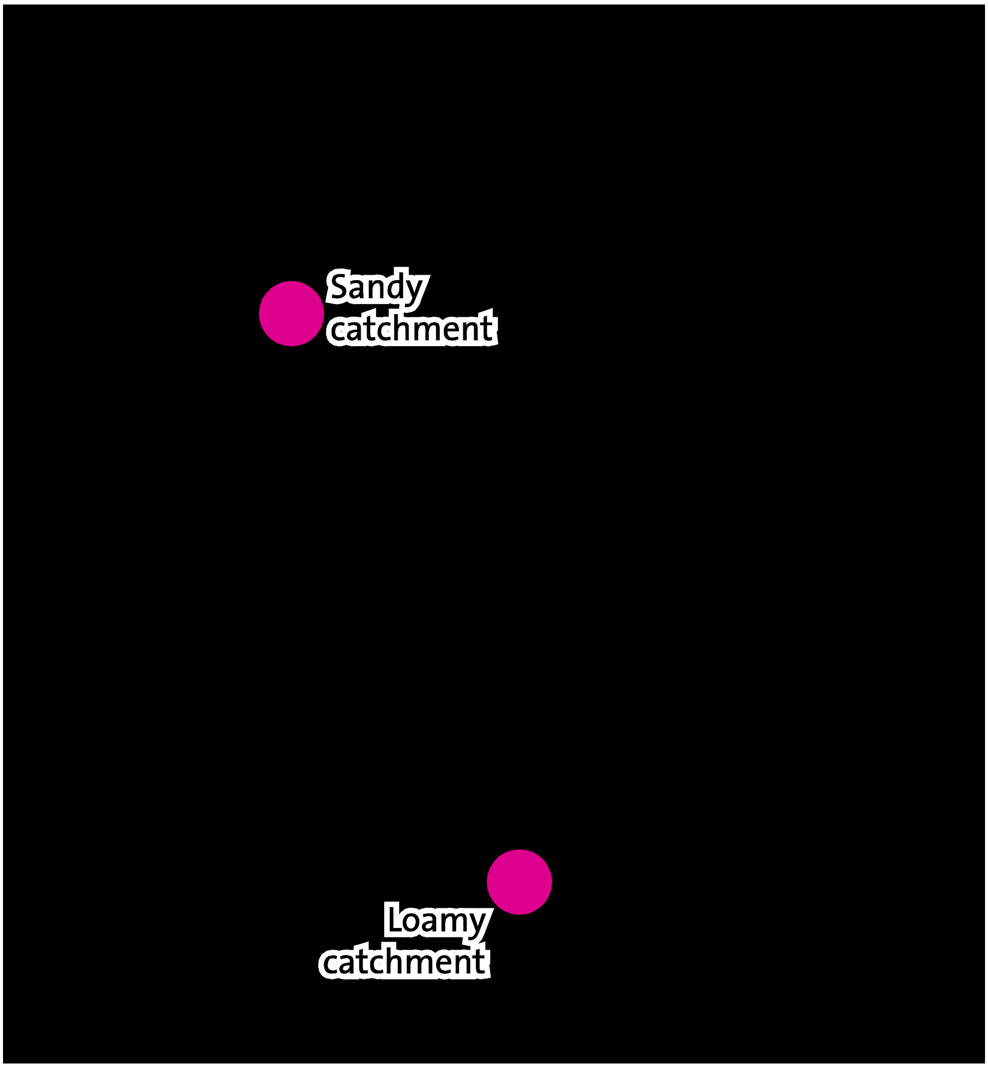


Figure 6. Location of Odderbæk and Lillebæk catchments (Styczen et al., 2004).

The Odderbæk (11.4 km^2) in the northern part of the Danish peninsula and Lillebæk (4.4 km^2) on the island of Funen catchments represent sandy loam and clayey soils respectively, constituting the majority of soils in Denmark. For both catchments, the groundwater catchment is different from the topographic catchment. In the sandy loam catchment model, the borders are open towards east and west, so water runs to the area from upstream and to the Great Belt via the groundwater.

For the sandy catchment, the borders closed except towards the south where potential maps and simulations indicate that water drains to a stream to the south rather than towards the model stream (Styczen et al., 2004). Both catchments are heavily monitored including soil moisture stations, groundwater level and content logging, stream flow stations and weather stations and described elsewhere (Pedersen et al., 2010; Blicher-Mathiesen et al., 2010; Styczen et al., 2004).

Agricultural management including use of pesticides is yearly surveyed at the field level by means of questionnaires issued at farmers.

The catchment simulations provide information on the fate and transport of pesticides in groundwater and surface water. Based on the results, a transparent effect-matrix on changes in pesticide fate and transport as a function of direct climate changes (rainfall, evaporation and temperature), indirect climate changes (land-use, pesticide application) are produced.

As indicated in previous section, an integrated hydrologic model approach is opted for by using a combination of two state-of-the-art hydrologic models to describe essential processes in the unsaturated zone, the saturated groundwater zone and surface water. The dual porosity model MACRO (Larsbo & Jarvis, 2005) is selected to simulate water flow and pesticide transport through the unsaturated zone, here defined as a 95 cm long column where MACRO simulated water and solute flow as input to MIKE SHE just above drain level at -1.0 m.

The model is able to explicitly account for preferential flow in the root zone, which is known to be a dominant mechanism for transport of pesticides towards important underlying drinking water aquifers (Jørgensen et al., 2008; Stenemo et al., 2005; Roulier et al., 2006). Preferential flow is only simulated in the rootzone and not continued below this level. This implies that travel time of water and solute in the unsaturated zone between -1.0 m and the upper groundwater level is ignored. The MACRO model is one of the endorsed models for pesticide testing and registration within the EU. The MIKE SHE model (Refsgaard and Storm, 1995) is a fully distributed and physically based model that can handle 1-D unsaturated zone, 2-D overland and 3-D groundwater flow and solute transport. In the context of this study, it is used for simulating pesticide transport in the groundwater domain and simulation of flow to streams from groundwater and drainage channels.

Stream flow simulation is handled by MIKE11, part of the MIKE SHE model package. In this study the UZ part of MIKE SHE is replaced by MACRO, sequentially coupled to MIKE SHE and providing an upper boundary to the groundwater-surface water model. Thus water and pesticide transport are propagated from UZ (MACRO) to SZ (MIKE SHE) without feedback from SZ to UZ. Solute transport in the saturated zone is described by the advection-dispersion equation and no account is taken of preferential pathways in the zone below drain level, as mentioned previously. This is schematically illustrated in Figure 7.

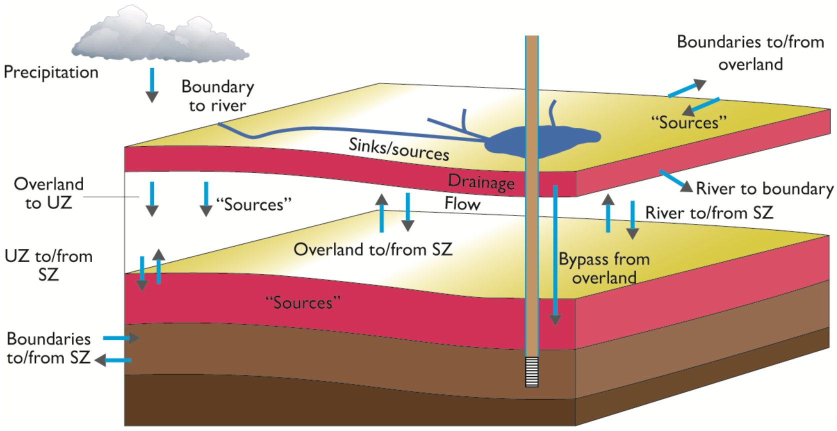


Figure 7. Schematic presentation of MACRO-MIKE SHE model setup. The most upper layer, unsaturated zone (UZ), and the lower layers, saturated zone (SZ), are represented by the MACRO and MIKE SHE model respectively.

The model setups for the sandy (Odderbæk) and clayey (Lillebæk) catchment build on existing setups developed for the Danish Watershed Monitoring Programme (in Danish LOOP) established for monitoring effects of the Aquatic Environment Plans I, II and III (Grant et al., 2007).

2.4.2 Odderbæk model setup

The Odderbæk (LOOP2) setup used in this study builds on and is described in detail in Hansen et al. (2006) and is derived from the model described in Styczen et al. (2004). The catchment is modeled using an integrated MIKE SHE MIKE11 model with a numerical grid size of 50 m x 50 m. In vertical direction the model layers follow the geological layers: upper sand, aquitard and lower sand, of which the upper sand layer is shown in Figure 8.

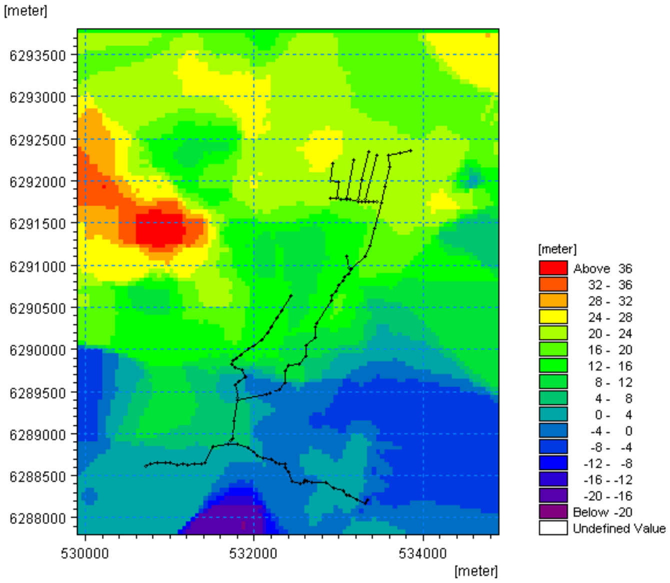


Figure 8. Upper sand geological layer in the Odderbæk / LOOP2 MIKE SHE setup.

The geological layers are subdivided into 6 computational layers, i.e. each geological layer is divided into 2 computational layers. The topographic map has a 25 m x 25 m resolution (Figure 9).

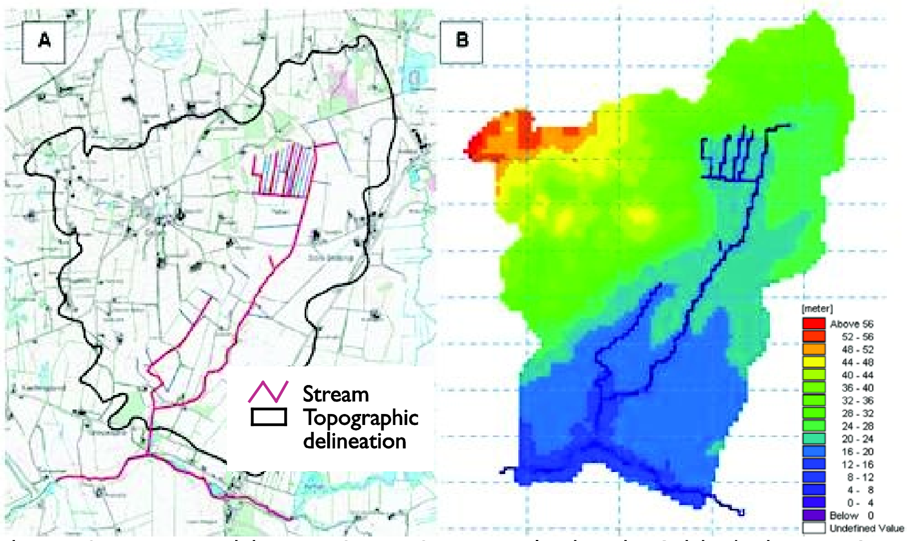


Figure 9. Topographic map, 25 m x 25 m resolution in Odderbæk MIKE SHE model representation.

The MACRO model as an upper boundary for water percolation and solute transport to the MIKE SHE model operates with two management types, dairy and arable farming (refer to chapter 3). The dairy farming type and the arable farming areas are associated to sandy and clay-loamy soil types respectively and therefore for pragmatic reasons agricultural management in sandy and clayey areas are distributed to areas that do not and do drain to the nearest stream respectively. In the Odderbæk catchment, arable farming and dairy farming represent 20 and 80 percent of the area respectively (Table 21). MACRO output for the arable farming management types is assigned to catchment areas with draincode 1 (Figure 10), that drain to the nearest stream in the catchment

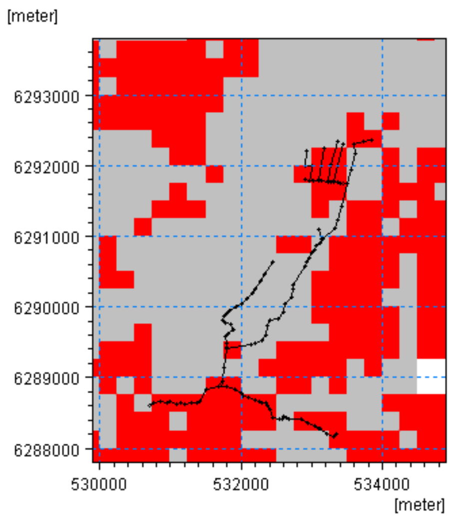


Figure 10. Draincode 1 (red pixels) for arable farming management type.

Areas with the dairy farming type is assigned to pixels with drain code value 2 in the MIKE SHE drain code map, meaning areas that do not drain to the nearest stream in the catchment (Figure 11). Drain pipes are situated at -1 m below surface and MACRO output, percolation and solute transport, enter the MIKE SHE model at -0.95 m, just above drain pipe depth.

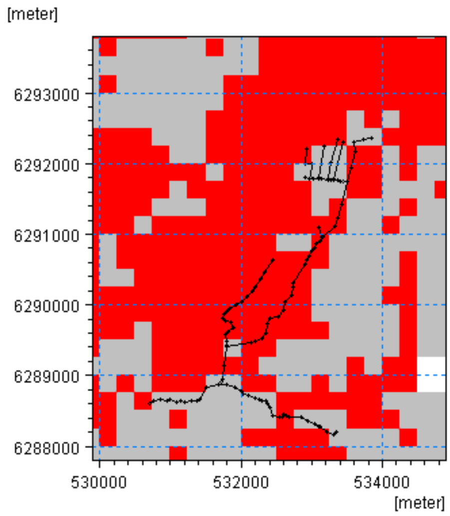


Figure 11. Draincode 2 (red pixels) for the dairy farming management type.

2.4.3 Lillebæk setup

The Lillebæk (LOOP4) setup used in this study builds on and is described in detail in Hansen et al. (2011) and is partly derived from the model described in Styczen et al. (2004). The catchment is modeled using an integrated MIKE SHE - MIKE11 model with a numerical grid size of 50 m x 50 m. In vertical direction the model layers follow the geological layers: Weichsel Moraine Clay and Saale Moraine Clay, of which the upper Weichsel layer is shown in Figure 12.

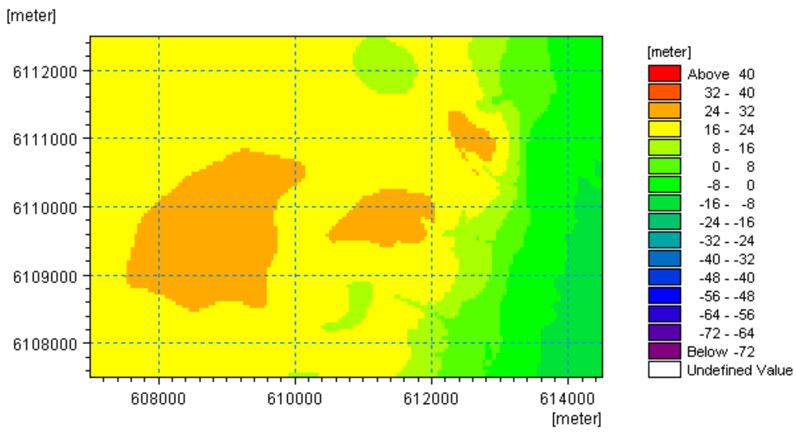


Figure 12. Upper geological layer in Lillebæk / LOOP4 MIKE SHE setup.

The geological layers are subdivided into 7 computational layers. The topographic map has a 25 m x 25 m resolution (Figure 13).

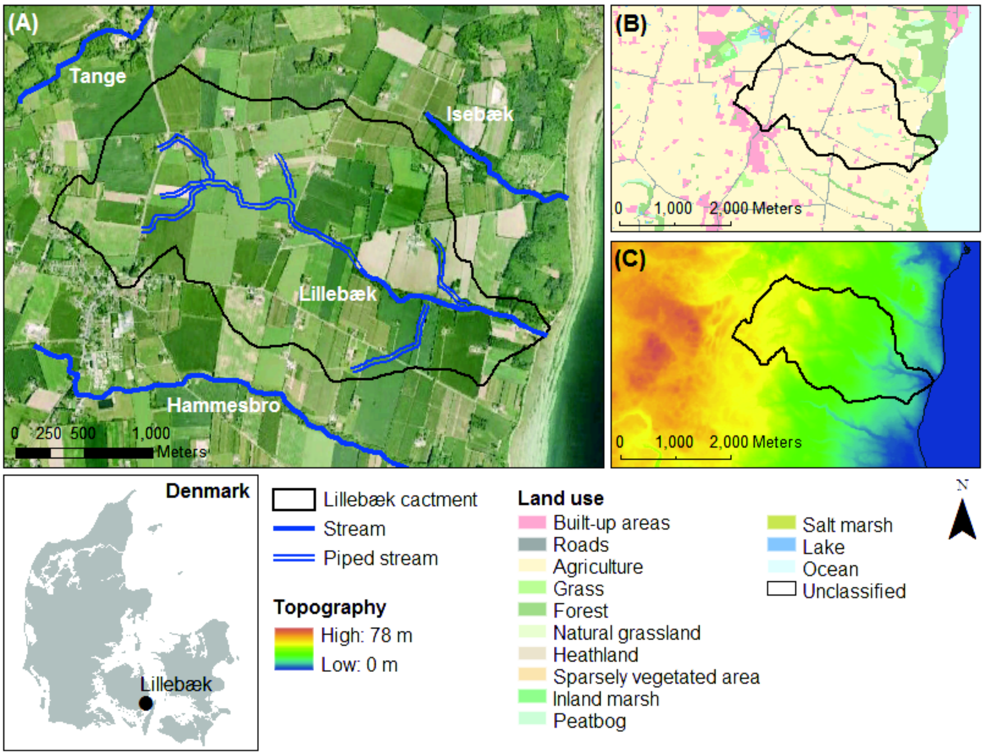


Figure 13. Topographic map for Lillebæk catchment in MIKE SHE model.

The MACRO model as an upper boundary for water percolation and solute transport to the MIKE SHE model operates with two management types, dairy and arable farming (refer to chapter 3). The dairy farming type and the arable farming areas are associated to sandy and clay-loamy soil types respectively. In the Lillebæk catchment, arable farming and dairy farming represent 80 and 20 percent of the area respectively (Table 22).

MACRO output for the arable farming management types is assigned to catchment areas with draincode 1 (Figure 14), that drain to the nearest stream in the catchment, and remaining codes that do not. As for Odderbæk, drain pipes are situated at -1 m below surface and MACRO output, percolation and solute transport, enter the model at -0.95 m, just above drain pipe depth. However, in saturated zone no preferential flow processes are accounted for below drain level, and this implies limitations in the description of the transport processes by use of MIKE SHE for Lillebæk (e.g. Chambon et al., 2011; Jørgensen et al., 2004; Miljøstyrelsen, 2005 and Miljøstyrelsen, 2002). However, point of departure is the regulatory tool MACRO under the assumption that most adsorption and degradation occurs in the upper 1 m biologically active rootzone and remaining preferential pathways below this depth are not mapped and therefore ignored.

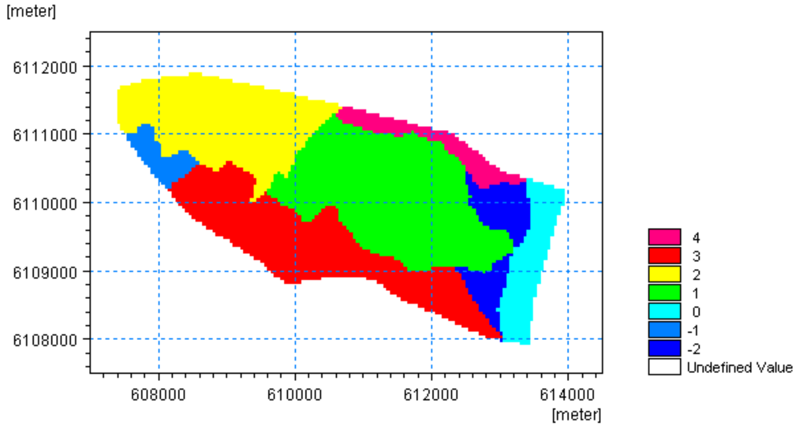


Figure 14. Map with draincodes for Lillebæk catchment. Draincode 1 (drain) is assigned to arable farming whereas the remaining codes apply to dairy farming (no drain to nearest river).

3 Results

3.1 Climate model results

Observed climate data from Jyndevand and Tystofte for the reference period: 1961-90 and for the present period (hydrological model period): 1991-2006 are described in Appendix A.

In the following, the results from the regional climate model RACMO (the Dutch meteorological institute KNMI) are presented. Boundary conditions for the regional model are defined by the global climate model ECHAM5 (the German Max Planck Institute). The results are generated using the SRES scenario A1B from the RACMO model. More information can be found in Appendix B including a comparison with an alternative climate model HadRM, which was less credible, compared to RACMO especially regarding the description of precipitation distribution for Denmark.

3.1.1 Results for Denmark with RACMO model

30-years averages for temperature, precipitation, and reference evapotranspiration are listed in Table 8 for the period 1961-2100. The temperature increases for each period. In Figure 14 the increase in temperature is seen to be moderate up to 2030. However, after 2030 a steeper increase in temperature is observed. Compared to the control period average increases in temperature of 1.4 and 2.6 °C are found for 2031-2060 and 2071-2100, respectively (Table 8).

Table 8. Development in mean climate for Denmark (excl. Bornholm) according to the RACMO simulation. Changes are calculated using the period 1961-1990 as reference.

Variable	1961-1990	1991-2020	2031-2060	2071-2100
Temperature (°C)	8.1	8.5	9.5	10.6
- change (°C)	-	0.5	1.4	2.6
Precipitation (mm)	1007	994	1031	1086
- change (%)	-	-1.3	2.4	7.8
Ref. Evapo. (mm)	452	467	481	500
- change (%)	-	3.3	6.5	10.7

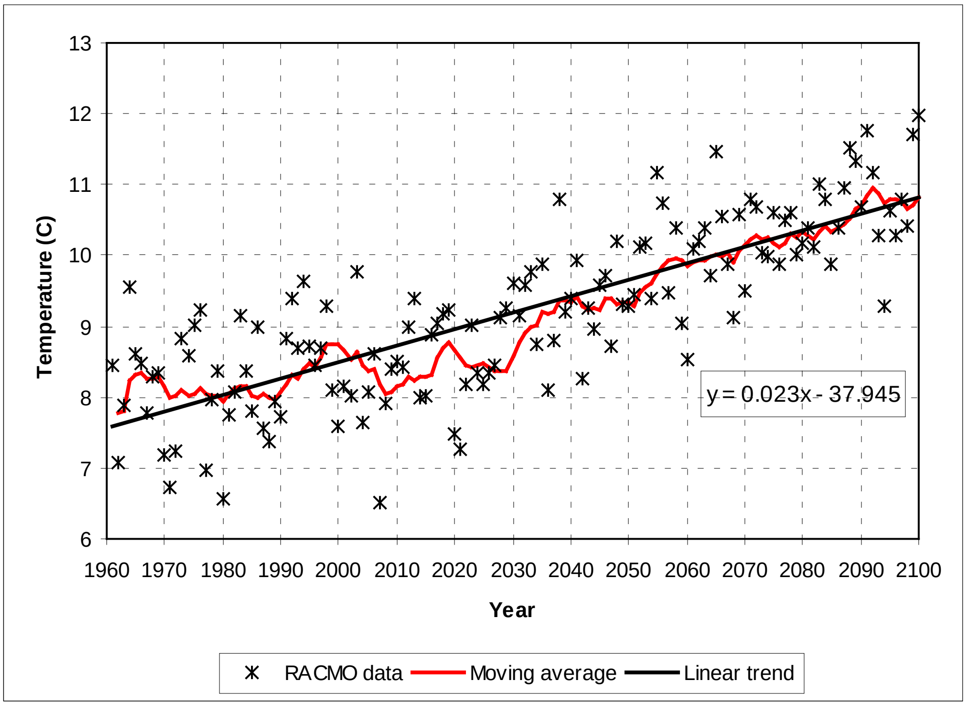


Figure 14. Development in annual mean temperature 1961-2100 according to the RACMO simulation, with a moderate increase up to 2030 and a steeper increase after 2030 (five years "moving averages" shown with red line and linear trend shown with black line).

Precipitation increases over time except for the period 1991-2020, where a small decrease compared to the control period is observed. The development in precipitation is also seen on Figure 15. Here, annual mean precipitation for Denmark is plotted for the period 1961-2100. Large fluctuations in annual mean precipitation is seen, however, an average trend of 0.68 mm/year is found.

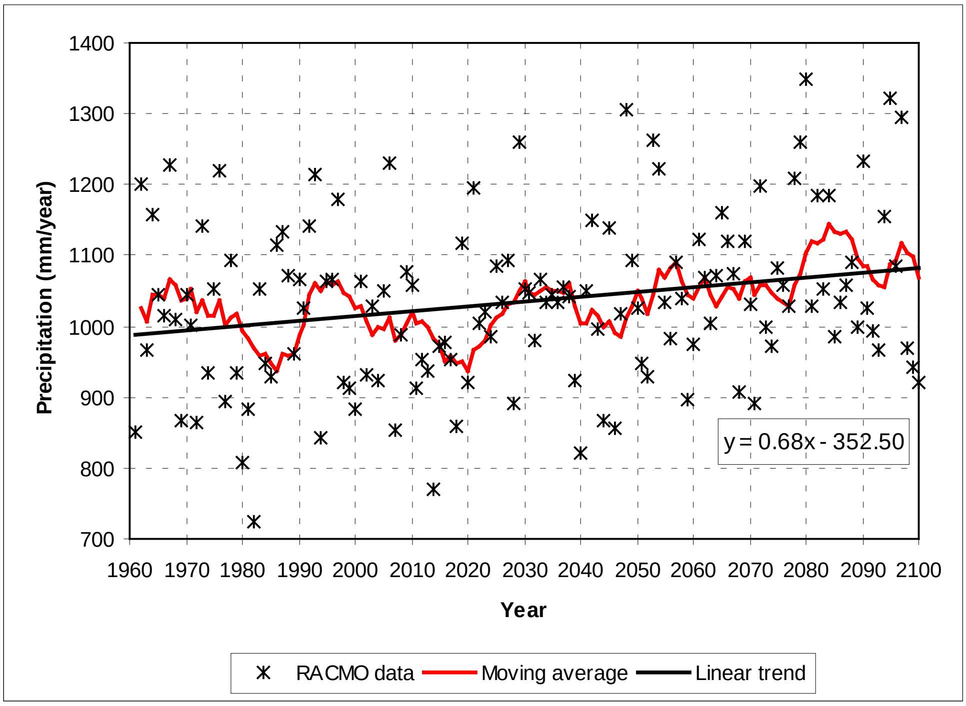


Figure 15. Development in annual mean precipitation 1961-2100 according to the RACMO simulation (five years "moving averages" shown with red line and linear trend shown with black line).

In Figure 16 the development in reference evapotranspiration is shown. An almost linear trend is found with an average increase of 0.4 mm/year. Compared to the control period the reference evapotranspiration increases by 29 mm (6.5%) and 48 mm (10.7%) in 2031-2060 and 2071-2100, respectively (Table 8).

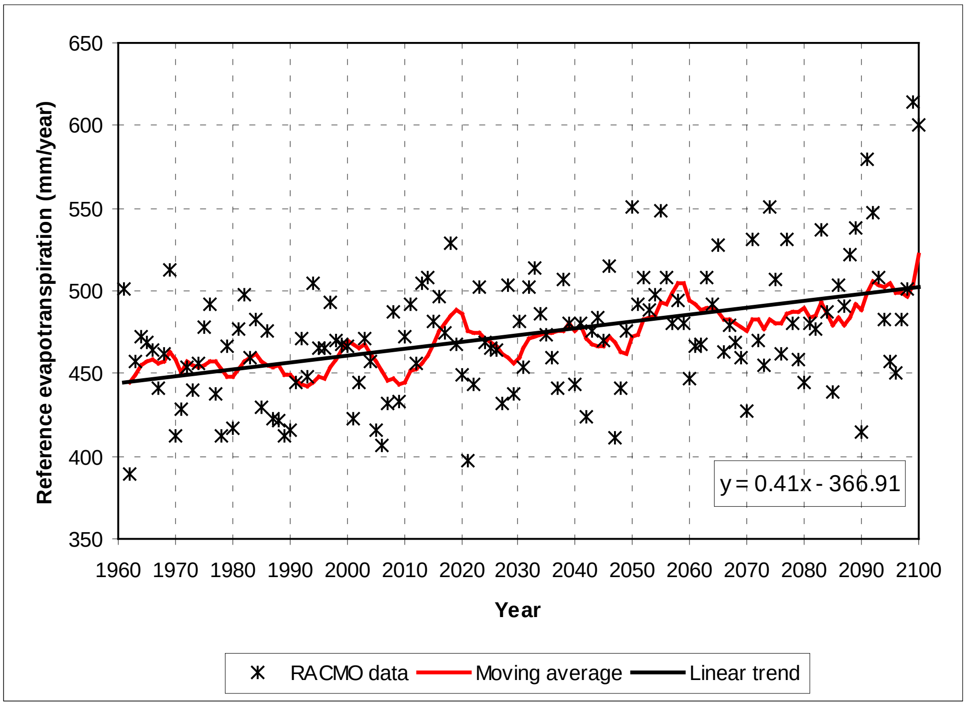


Figure 16. Development in annual mean reference evapotranspiration 1961-2100 according to the RACMO simulation (five years "moving averages" shown with red line and linear trend shown with black line).

In Figure 17 the RACMO results for the precipitation distribution for Denmark 1961-1990 is shown. The distribution of precipitation resembles the observed distribution (Figure 18) satisfactorily, with maximum precipitation in the south-western part of Jutland, and decreasing precipitation towards east with minimum values in the Great Belt and the islands of Lolland and Falster. The magnitude of precipitation is captured reasonable in western Jutland (the values shown in Figure 18 are uncorrected and should be multiplied by 1.21 to obtain estimates of true precipitation). However, the simulated decrease towards the east is underestimated resulting in too high precipitation results for eastern Denmark.

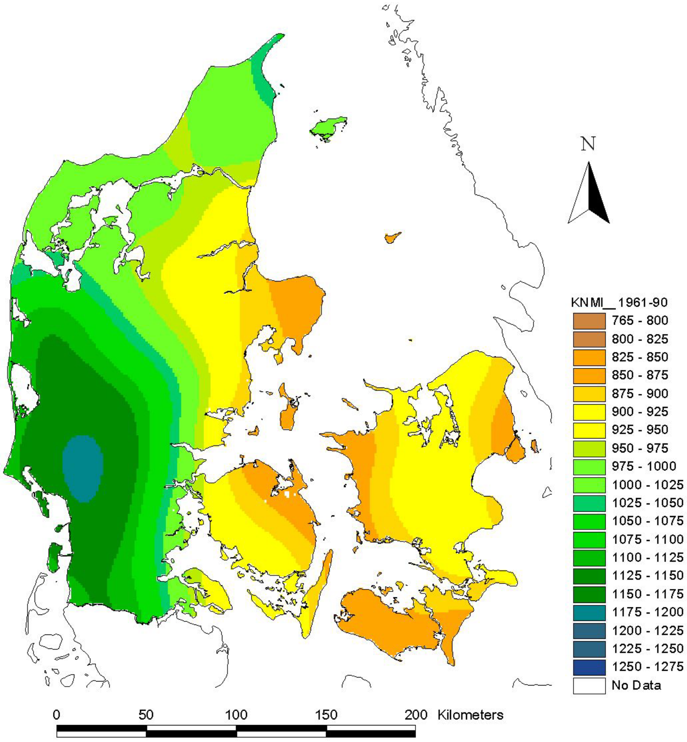


Figure 17. Average precipitation 1961-1990 from the RACMO model (mm/year) with maximum precipitation in the south-western part of Jutland, and decreasing precipitation towards the east resembling satisfactory with observed overall distribution for Denmark (shown below in Figure 18).

Figure 18. Spatial distribution of uncorrected observed precipitation 1961-1990 (from Frich et al., 1997) (must be multiplied by 1.21 for "standard corr.").

Figure 19 and 20 show the projected geographical distribution of precipitation for 2031-2060 and 2071-2100, respectively. In both cases the spatial distribution is similar to the control period. However, the precipitation is seen to increase with time, resulting in significant increases in mean annual precipitation in the latest period.

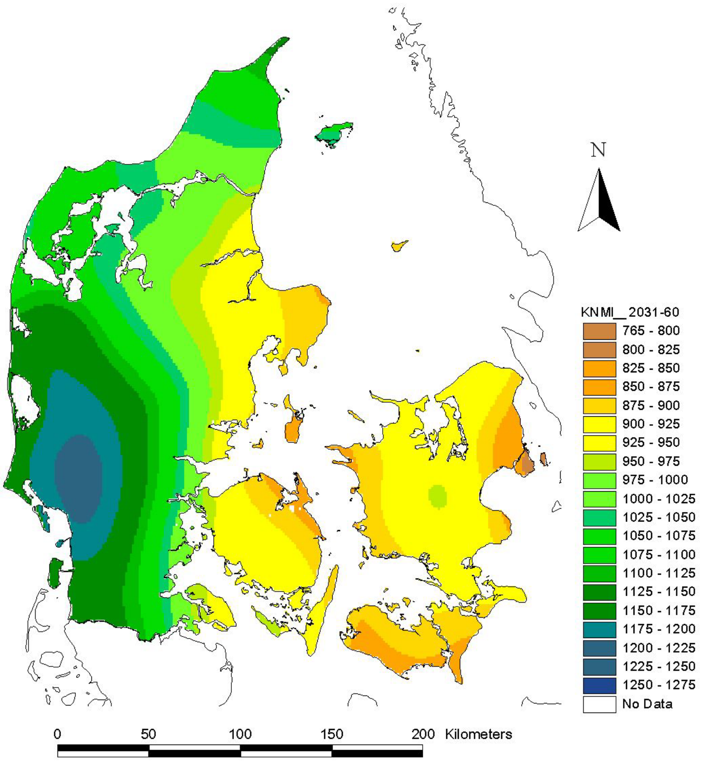


Figure 19. Average precipitation 2031-2060 from the RACMO model (mm/year) having fairly similar distribution as control period (Figure 17).

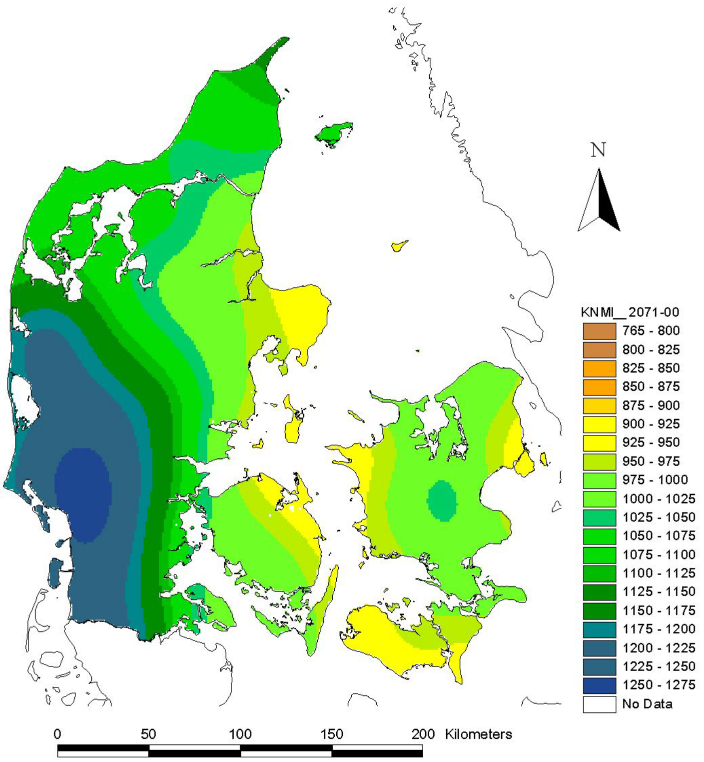


Figure 20. Average precipitation 2071-2100 from the RACMO model (mm/year) with fairly similar distribution as control period (Figure 17).

3.1.2 Comparison of observed and simulated climate at climate stations

The downscaled climate simulation cannot be expected to follow reality completely. The difference between one year and another is decided not by observation, but rather by a series of model simulations. Therefore the only validation that can be done is of a statistical nature.

The temperature, Figure 21, is generally captured satisfactorily at both stations by the RACMO model. However, the model overestimates the winter temperature with up to 2 °C at Jyndevad. At the same time the summer temperatures are generally underestimated, at Tystofte by up to 1 °C. The error in annual average temperature is 0.4 and 0.1 °C at Jyndevad and Tystofte, respectively.

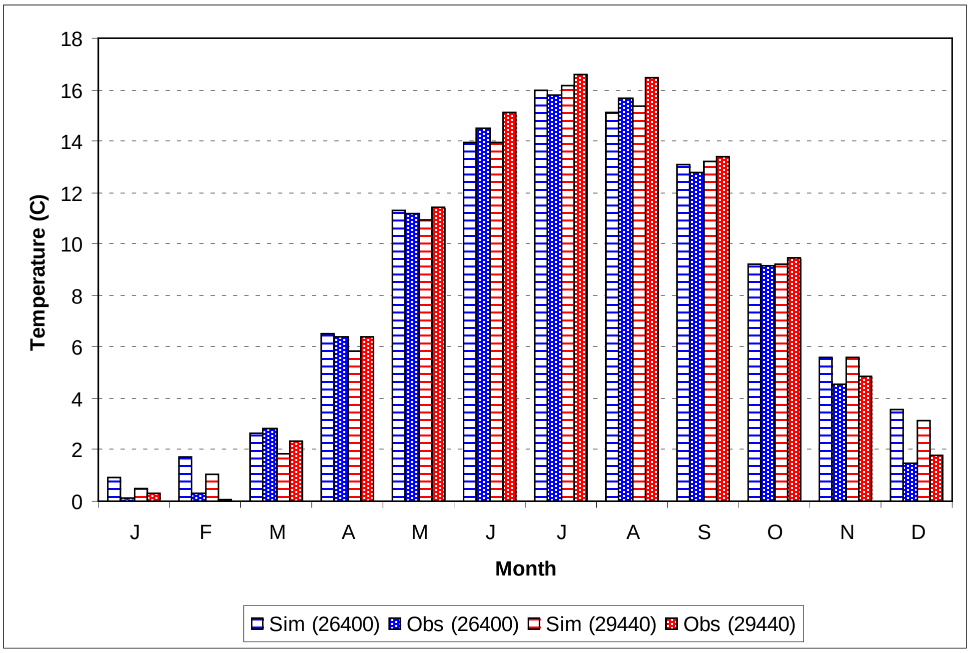


Figure 21. Monthly mean temperature simulated by RACMO model and compared with observed temperature for Jyndevad (station 26400) and Tystofte (station 29440).

In Figure 22 the simulated and observed average monthly precipitation for Jyndevad and Tystofte are illustrated. Generally, the temporal precipitation distribution is captured well at Jyndevad, where only the results for July and August are overestimated. At Tystofte the precipitation is overestimated in all 12 months. Average annual precipitation is overestimated by 78 mm at Jyndevad and 238 mm at Tystofte.

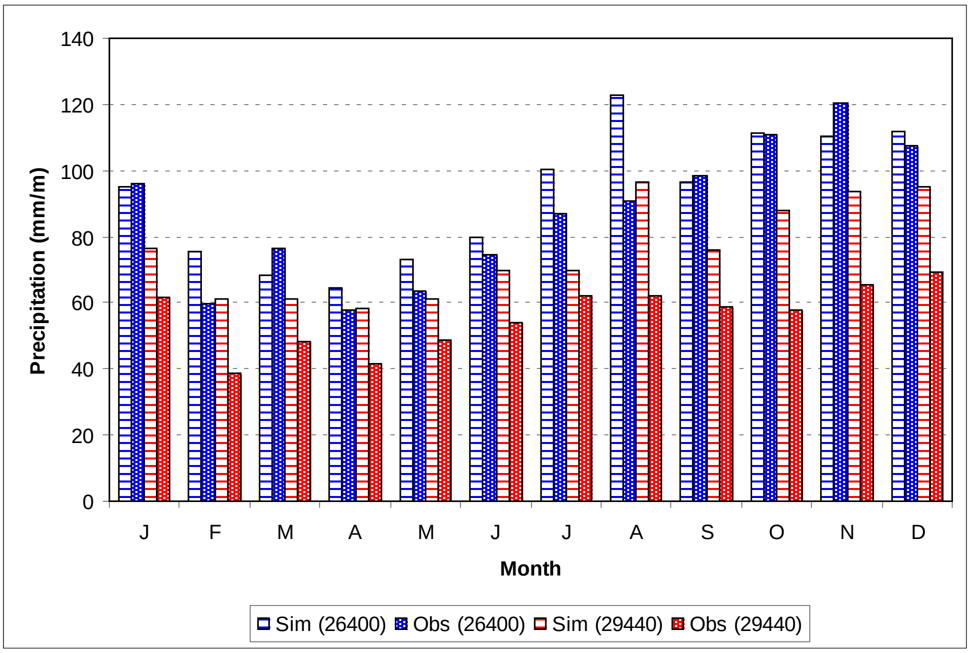


Figure 22. Monthly mean precipitation simulated by RACMO and compared with observed precipitation for Jyndevad (station 26400) and Tystofte (station 29440).

The seasonal distribution of reference evapotranspiration is shown in Figure 23. On average the evapotranspiration is underestimated at both stations, with values of 106 mm at Jyndevad and 110 mm at Tystofte. The error is especially high during the summer months, which is the period with highest evapotranspiration. The difference between observed and simulated evapotranspiration may be a result of the different methods used to estimate reference evapotranspiration, where the Makkink and the Penman methods have been used for observed and simulated evapotranspiration, respectively.

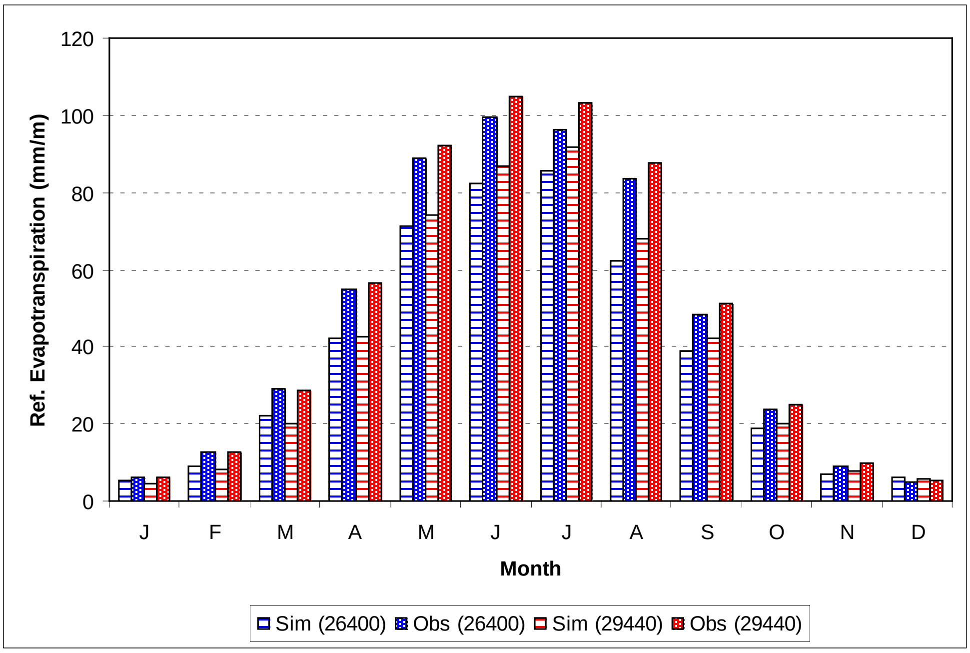


Figure 23. Monthly mean reference evapotranspiration simulated by RACMO and compared with observed data for Jyndevad (station 26400) and Tystofte (station 29440).

3.1.3 Extreme values

In Table 9 statistics on maximum precipitation for each month at the two stations are listed for the control period. The highest observed values for Jyndevad are found in late summer and autumn (August to November), see also Figure 24. The simulated maximum precipitation underestimates the observed values for all months except February. The variability in maximum precipitation is significant for all months with coefficients of variation up to more than 1.

At Tystofte, Table 9 and Figure 25, the highest observed values are found in late summer (July to September). During this period the simulated maximum precipitation is underestimated. However, in the rest of the year the maximum precipitation is captured well by the model.

Table 9. Monthly mean maximum precipitation (mm/day) at Jyndevad and Tystofte for 1961-1990. Standard deviations are listed in parenthesis.

	Month											
	J	F	M	A	M	J	J	A	S	O	N	D
Jyndevad												
Observed	19.4 (13.2)	14.2 (15.3)	17.5 (13.7)	15.0 (15.0)	16.3 (14.5)	20.4 (13.4)	21.0 (13.3)	23.3 (13.2)	21.9 (13.0)	23.0 (12.2)	23.8 (11.9)	20.0 (12.8)
RACMO	16.8 (10.1)	14.3 (10.9)	13.3 (10.9)	12.6 (11.1)	14.1 (10.5)	17.4 (11.4)	20.3 (11.4)	19.0 (9.6)	17.9 (9.2)	18.5 (9.5)	17.1 (9.7)	17.4 (9.6)
Tystofte												
Observed	15.1 (14.4)	10.2 (15.8)	12.8 (15.1)	12.0 (15.6)	16.7 (15.8)	16.7 (14.7)	18.5 (14.4)	20.0 (17.0)	18.5 (15.1)	16.2 (14.8)	15.3 (14.2)	16.5 (14.8)
RACMO	14.4 (11.8)	11.7 (12.7)	13.5 (12.5)	14.0 (12.4)	14.5 (12.2)	18.4 (13.0)	16.9 (13.9)	19.0 (11.4)	14.7 (11.9)	15.8 (11.5)	16.0 (11.4)	15.8 (11.4)

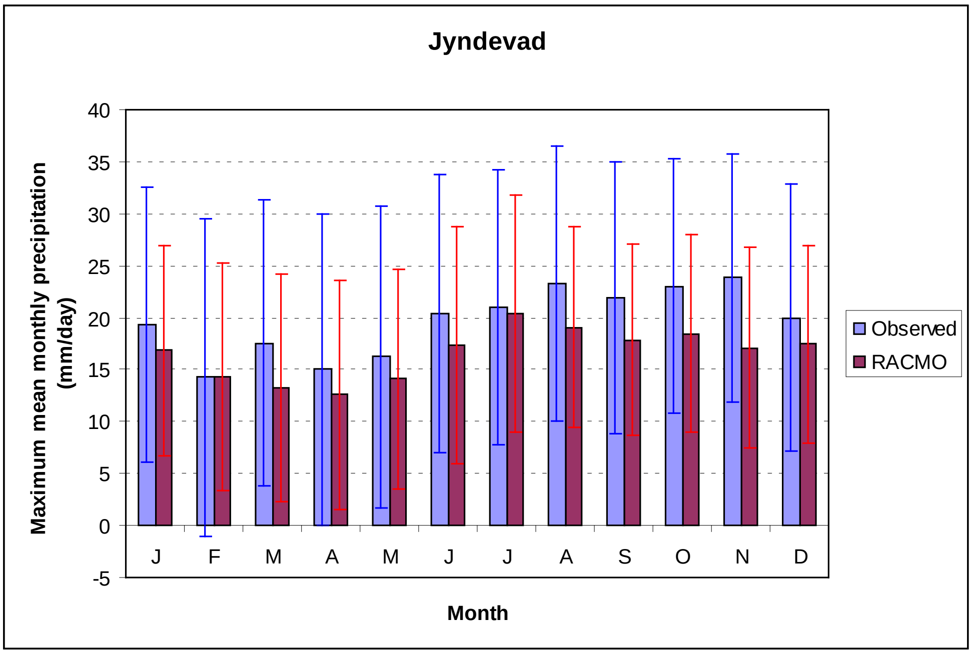


Figure 24. Mean monthly maximum precipitation (mm/day) indicated by bars for Jyndevad (1961-90) based on observed and RACMO daily results. Standard deviations are shown as lines.

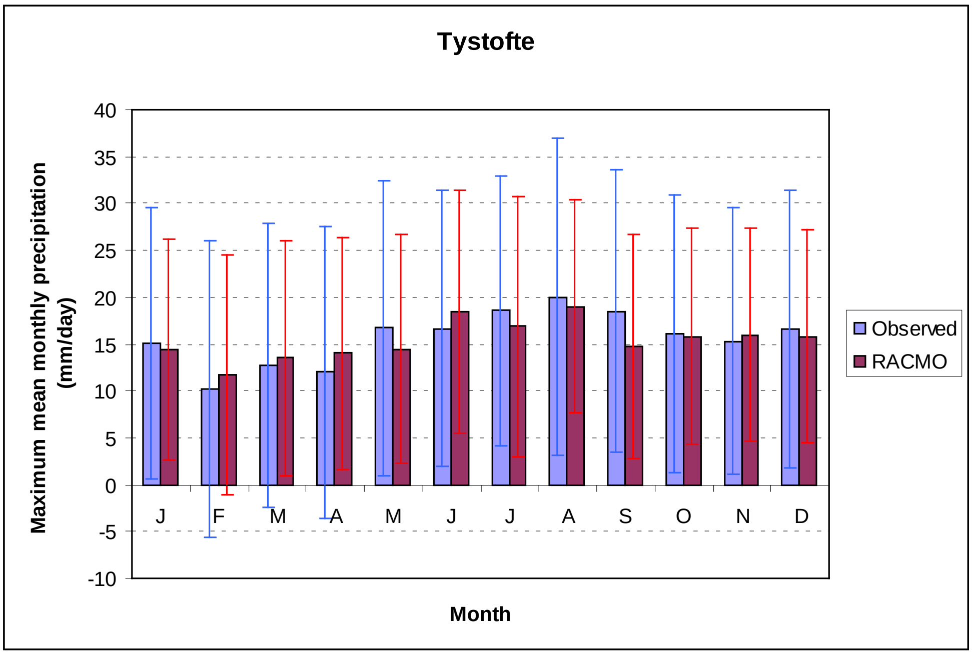


Figure 25. Mean monthly maximum precipitation (mm/day) indicated by bars for Tystofte (1961-1990) based on observed and RACMO daily results. Standard deviations are shown as lines.

The simulated variability in maximum precipitation is underestimated at both stations, Table 10. Hence, as seen from Table 10, where the absolute maximum precipitation event found for each month in the period 1961-1990 is illustrated, the model predicts in general lower maximum precipitation events. Especially in August and September large discrepancies are found where the simulated maximum events are approximately half that of the observed values.

Table 10. Observed and simulated monthly maximum precipitation events (mm/day) at Jyndevad and Tystofte in the period 1961-1990.

	Month											
	J	F	M	A	M	J	J	A	S	O	N	D
Jyndevad												
Observed	40.3	35.9	43.1	44.5	35.1	38.9	41.4	49.5	54.3	54.8	40.2	33.2
RACMO	32.5	29.3	26.9	21.3	23.2	57.4	40.1	33.6	27.4	38.0	29.4	26.9
Tystofte												
Observed	32.7	22.0	32.7	29.8	45.4	40.6	40.8	72.6	58.1	38.4	28.7	36.0
RACMO	27.8	28.4	31.6	25.4	28.2	58.6	52.7	34.7	32.8	34.8	37.9	27.4

3.1.4 Downscaling climate change impacts to pesticide leaching risk dynamics

3.1.4.1 Annual values

In Figure 26 annual mean precipitation in four 30-year periods are shown for the Jyndevad location based on RACMO model results. The four grid cells surrounding the Jyndevad location have been used to derive the results. Figure 27 show the similar derived results for Tystofte.

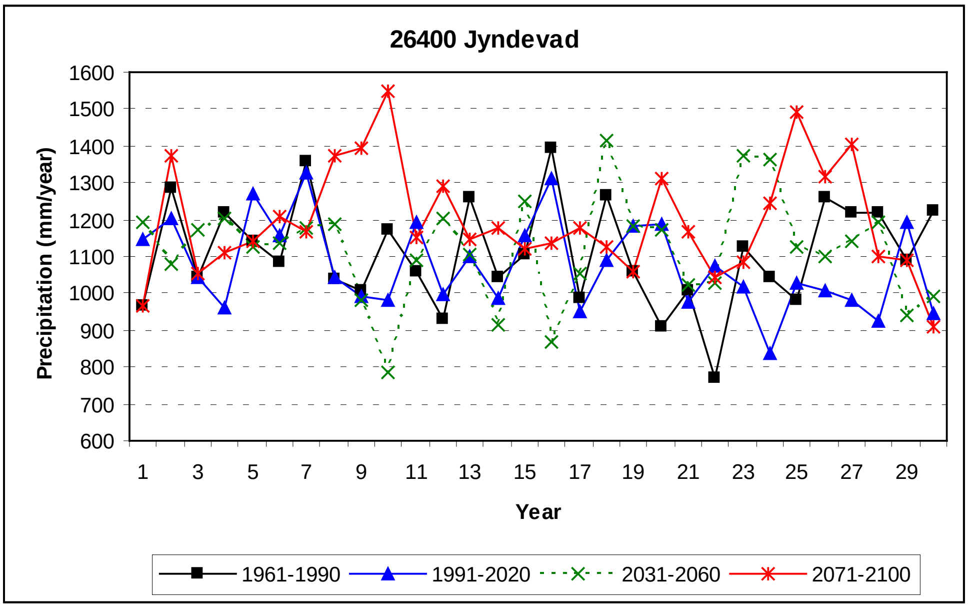


Figure 26. Projected annual mean precipitation development for four 30-year periods for Jyndevad.

The results for the first three periods are comparable and only in the last period (2071-2100) significant higher annual precipitation amounts are found. Also minimum and maximum annual mean precipitation increases in 2071-2100, Table 11.

Table 11. Development in annual mean precipitation (mm) at station 26400 Jyndevad based on RACMO.

Variable	1961-1990	1991-2020	2031-2060	2071-2100
Annual mean (mm)	1109	1075	1119	1196
- change (%)	-	-3.0	0.9	7.8
Stand. Dev. (mm)	142	133	143	152
Annual max (mm)	1392	1325	1415	1548
- change (%)	-	-4.8	1.6	11.2
Annual min (mm)	772	837	784	912
- change (%)	-	8.4	1.5	18.1

The same trend is seen for Tystofte, Figure 21 and Table 12.

Table 12. Development in annual mean precipitation at station 29440 Tystofte based on RACMO.

Variable	1961-1990	1991-2020	2031-2060	2071-2100
Annual mean (mm)	907	887	917	996
- change (%)	-	-2.2	1.2	9.9
Stand. Dev. (mm)	130	113	105	129
Annual max (mm)	1117	1129	1178	1261
- change (%)	-	1.1	5.4	12.9
Annual min (mm)	550	701	765	781
- change (%)	-	27.5	39.2	42.0

Both for temperature and actual evapotranspiration a linear development in the two variables are found over the period from 1961-2100 (Table 13 and 14). It is noticed that higher values of reference evapotranspiration are found for the scenario periods compared to the control and the validation periods.

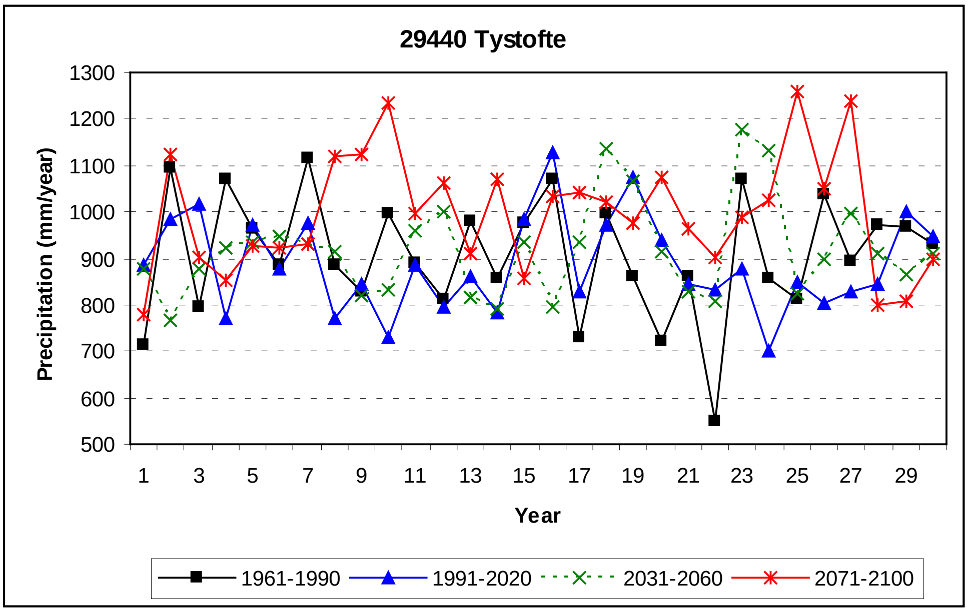


Figure 27. Projected annual mean precipitation development for four 30-year periods for Tystofte based on RACMO.

In table 13 and 14 the development in annual mean temperature and ref. evapotranspiration for Jyndevand and Tystofte is shown.

Table 13. Development in annual mean temperature and ref. evapotranspiration for 1961-1990, 1991-2020, 2031-2060 and 2071-2100 at station 26400 Jyndevad based on RACMO.

Variable	1961-1990	1991-2020	2031-2060	2071-2100
Temperature (°C)	8.3	8.7	9.7	10.9
- change (°C)	-	0.4	1.4	2.5
Stand. Dev. (°C)	0.8	0.6	0.7	0.6
Ref. evap. (mm)	451	465	479	498
- change (%)	-	3.0	6.1	10.3
Stand. Dev. (mm)	32	24	34	49

Table 14. Development in annual mean temperature and ref. evapotranspiration for 1961-1990, 1991-2020, 2031-2060 and 2071-2100 at station 29440 Tystofte based on RACMO.

Variable	1961-1990	1991-2020	2031-2060	2071-2100
Temperature (°C)	8.1	8.6	9.6	10.8
- change (°C)	-	0.5	1.5	2.7
Stand. Dev. (°C)	0.8	0.7	0.7	0.7
Ref. evap. (mm)	472	490	505	527
- change (%)	-	3.9	6.9	11.6
Stand. Dev. (mm)	34	29	34	53

3.1.4.2 Monthly values

In Figure 28 and 29 the development in monthly mean temperature is shown. The temperature increases for all months with more or less the same value. In Table 15 the absolute increase in temperature is listed. Except for May and December that for some reason have a tendency for relatively small temperature increase the change in temperature is relatively constant throughout the year.

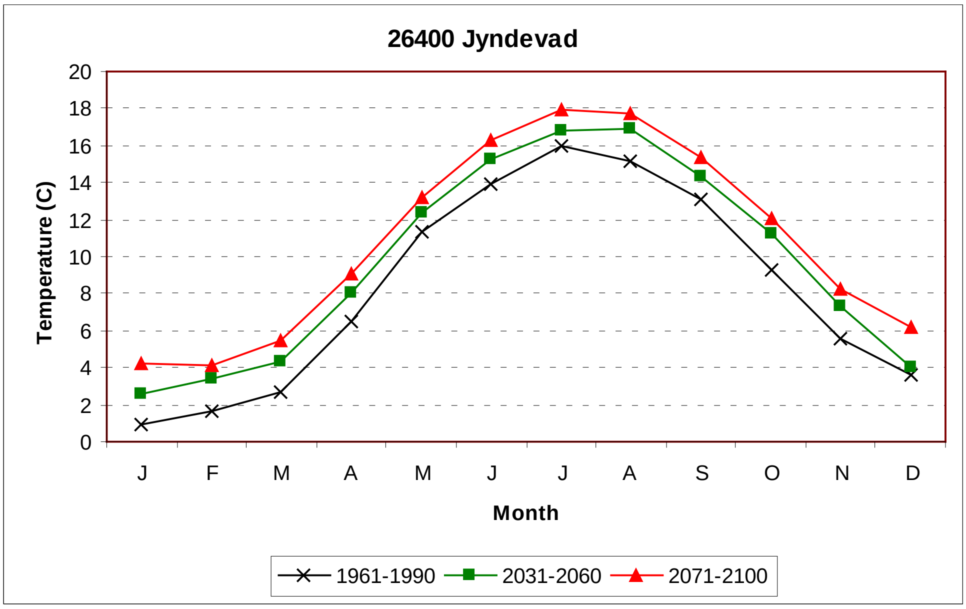


Figure 28. Mean monthly temperature distribution for three periods from Jyndevad based on RACMO. An almost identical increase in temperature is projected for all seasons

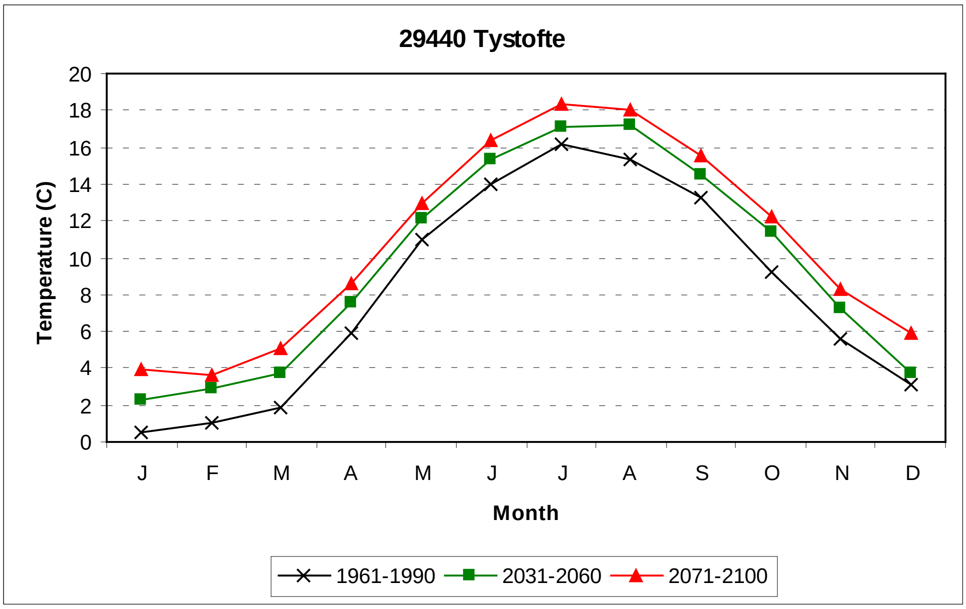


Figure 29. Mean monthly temperature distribution for four periods from Tystofte based on RACMO. As for Jyndevand (Figure 28) an almost identical increase in temperature is projected for all seasons.

Table 15. Increase in temperature (°C) for Jyndevad and Tystofte for 1991-2020, 2031-2060 and 2071-2100 compared to 1961-1990 based on RACMO.

	Month											
	J	F	M	A	M	J	J	A	S	O	N	D
Jyndevad												
1991-2020	1.10	0.47	1.36	0.73	-0.19	0.36	0.30	0.56	0.48	0.57	0.43	-0.22
2031-2060	1.66	1.72	1.65	1.49	1.02	1.33	0.86	1.80	1.26	1.96	1.68	0.40
2071-2100	3.28	2.41	2.84	2.54	1.87	2.34	1.95	2.59	2.22	2.86	2.69	2.58
Tystofte												
1991-2020	1.32	0.65	1.47	0.93	-0.02	0.37	0.34	0.57	0.56	0.60	0.22	0.03
2031-2060	1.83	1.91	1.93	1.66	1.17	1.40	0.97	1.81	1.31	2.11	1.72	0.62
2071-2100	3.45	2.61	3.20	2.74	2.03	2.45	2.16	2.64	2.31	2.97	2.69	2.80

In Figure 30 and 31 the seasonal distribution of precipitation at the two climate stations are illustrated. For the period 2031-2060 higher winter (DJF) precipitation are generated and lower summer precipitation (JJA) are predicted. No systematic changes are found for autumn and spring. In 2071-2100 higher precipitation are generated in the period from September to March, and the increase is most significant in November to January. In the summer period (JJA) lower precipitation are found.

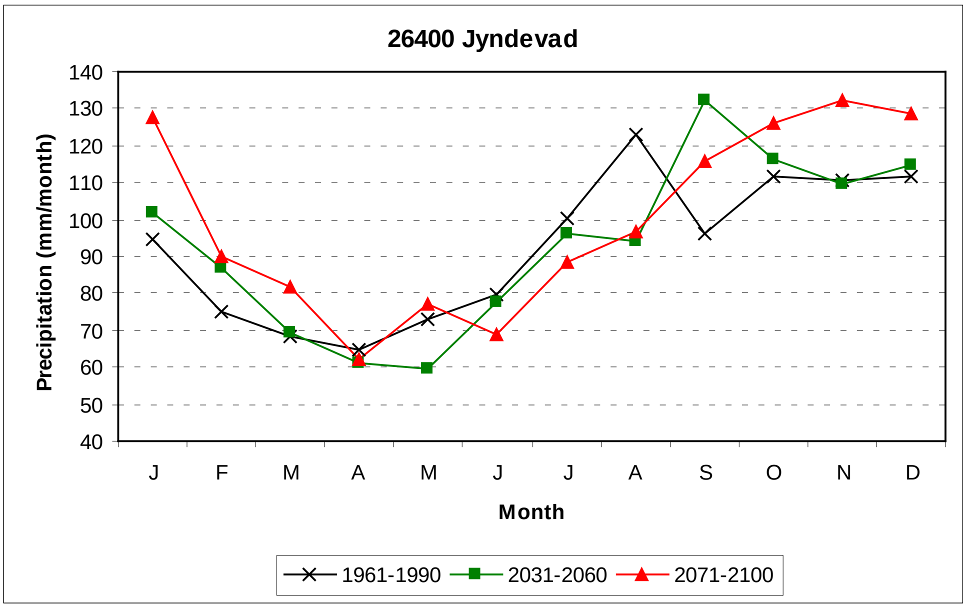


Figure 30. Mean monthly precipitation distribution for three 30 year periods from Jyndevad based on RACMO (1961-1990, 2031-3060 and 2071-2100).

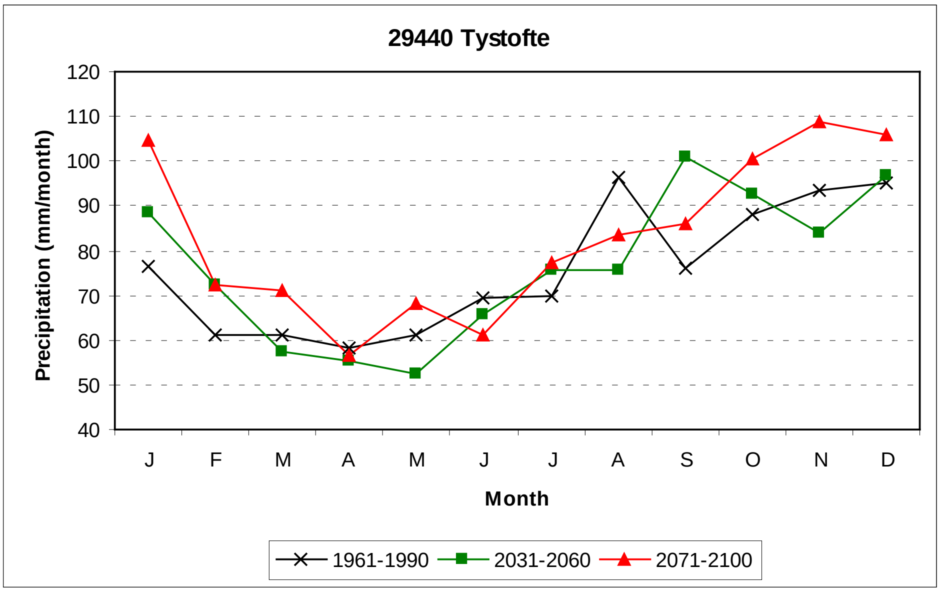


Figure 31. Mean monthly precipitation distribution for three 30 years periods from Tystofte based on RACMO (1961-1990, 2031-2060 and 2071-2100).

In Appendix B the change in the mean and standard deviation of monthly precipitation are shown addition. It is noticed that for 2031-2060 the precipitation during most of the growing season (April-August) is reduced compared to the control period, especially for Jyndevad. At the same time the standard deviations are reduced corresponding to less variability in mean monthly precipitation. In the late period (2071-2100) the same tendency is found. At Jyndevad precipitation is reduced with 10-20% during the months June to August. At Tystofte the pattern is not so consistent. However, at both stations the variability in monthly mean precipitation is decreasing during the summer months.

The development in monthly mean reference evapotranspiration is illustrated in Figure 32 and 33. The evapotranspiration increases for all months, however, the increase is highest during the growing season (MJJA), with the most significant development in June.

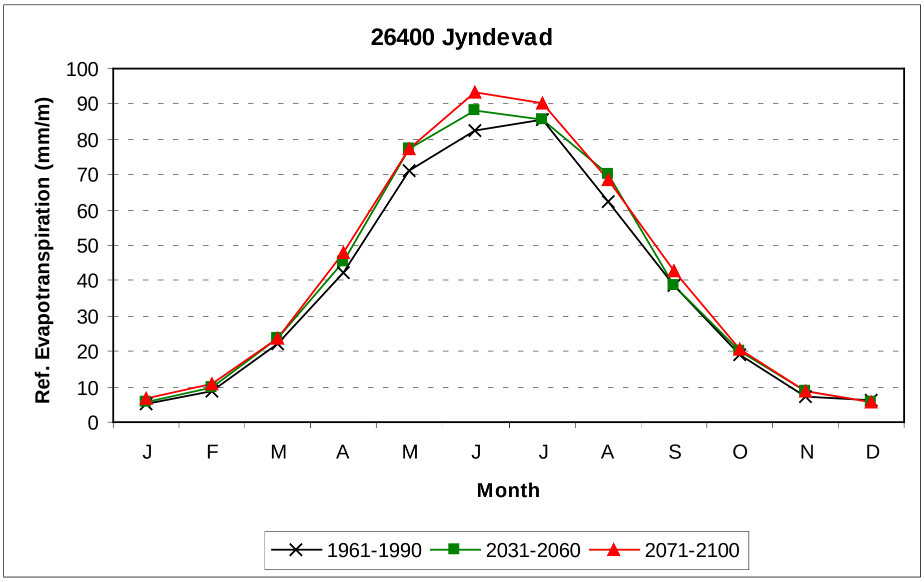


Figure 32. Mean monthly reference evapotranspiration distribution for Jyndevad based on RACMO for three periods (1961-1990, 2031-2060 and 2071-2100).

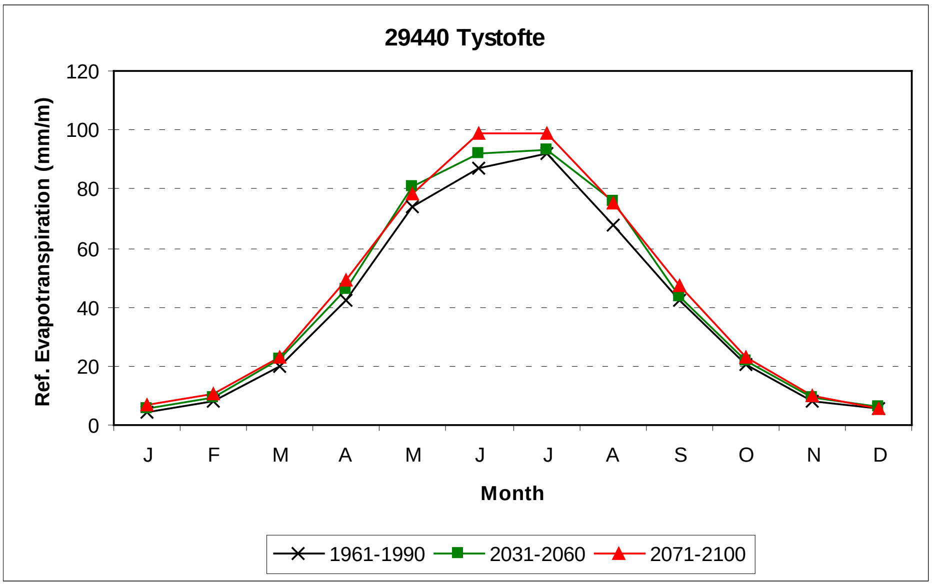


Figure 33. Mean monthly reference evapotranspiration distribution for Tystofte based on RACMO for three periods (1961-1990, 2031-2060 and 2071-2100).

In Table 16 the relative change in reference evapotranspiration is shown. Again, a general increase in reference evapotranspiration is observed with time.

Table 16. Relative change (%) in mean monthly RACMO simulated reference evapotranspiration for Jyndevad and Tystofte for three periods (1991-2020, 2031-2060 and 2071-2100) compared to 1961-1990.

	Month											
	J	F	M	A	M	J	J	A	S	O	N	D
Jyndevad												
1991-2020	1.2	6.6	7.2	0.2	-2.4	0.6	0.1	0.1	2.0	4.4	4.7	-6.3
2031-2060	6.6	9.9	5.4	7.5	8.6	6.6	0.0	12.4	-0.4	6.4	23.0	-2.9
2071-2100	33.0	21.0	7.5	13.6	8.3	13.1	5.6	9.9	10.0	10.3	25.9	-1.4
Tystofte												
1991-2020	3.7	7.4	10.3	3.4	-2.0	1.2	1.1	4.8	2.9	8.8	-1.6	3.8
2031-2060	15.2	14.2	11.7	8.7	8.6	5.9	1.4	11.4	2.2	6.5	22.2	5.9
2071-2100	49.0	24.3	15.4	16.0	5.8	14.1	7.6	11.1	11.7	12.7	24.9	2.9

3.1.4.3 Extreme precipitation

In Table 17 the mean and standard deviation of annual maximum precipitation at the two climate stations are listed. At Jyndevad the mean annual maximum value increases steadily with time and there is a tendency for higher variation in the annual maximum in the future. At Tystofte the development in mean annual maximum is not significant before the end of the century where an increase of approximately 5 mm/day is found. The standard deviation follows the development in the mean.

Table 17. Mean and standard deviation of annual maximum precipitation base on RACMO at Jyndevad and Tystofte for four 30-year periods (1961-1990, 1991-2020, 2031-2060 and 2071-2100).

	Jyndevad		Tystofte	
	Mean (mm/day)	Standard deviation (mm/day)	Mean (mm/day)	Standard deviation (mm/day)
1961-1990	30.1	8.1	30.5	9.4
1991-2020	30.3	10.5	29.2	8.0
2031-2060	33.4	11.2	30.9	9.5
2071-2100	35.5	9.9	35.7	10.1

In Table 18 statistics on monthly maximum precipitation at the two stations are listed. There seems to be no changes in mean monthly maximum precipitation going from 1961-1990 to 1991-2020. In the period 2031-2060 a tendency for higher mean maximum precipitation in early autumn (SO) is observed, but for the remaining months no development is observed. However, the standard deviation of mean monthly maximum precipitation increases significantly for all months, especially in August and September where an increase of up to 50% is found. Hence, the extreme precipitation events are expected to increase significantly especially in late summer.

In the last period (2071-2100) the most significant increases in mean monthly maximum precipitation are found in the period September to December for Jyndevad and July to December for Tystofte. At the same time the standard deviations of the maximum monthly precipitation increases for the entire year with changes of up to 50% in late summer. Hence, the extreme precipitation events can be expected to increase significantly for especially late summer and autumn.

Table 18. Change (in %) of the mean and the standard deviation (in parenthesis) of RACMO projected monthly maximum precipitation for Jyndevad and Tystofte compared to the period 1961-90.

	Month											
	J	F	M	A	M	J	J	A	S	O	N	D
Jyndevad												
1991-2020	-4.3 (15.1)	-8.5 (13.8)	4.2 (11.1)	3.5 (16.2)	11.5 (16.2)	-6.8 (7.4)	-10.4 (29.3)	-4.9 (18.1)	7.3 (22.4)	3.5 (19.1)	-7.1 (26.0)	-9.3 (34.4)
2031-2060	-3.9 (30.1)	5.3 (23.1)	-1.3 (32.3)	13.3 (26.7)	0.6 (32.4)	2.5 (30.2)	-14.5 (24.2)	-7.5 (45.2)	17.5 (49.9)	11.1 (26.0)	-3.7 (34.7)	4.5 (32.3)
2071-2100	9.3 (21.1)	19.0 (18.4)	22.0 (20.1)	3.6 (28.5)	12.8 (27.9)	3.9 (35.4)	-6.9 (19.8)	6.8 (38.0)	28.9 (53.5)	16.7 (29.3)	23.8 (19.1)	25.7 (20.7)
Tystofte												
1991-2020	-0.6 (6.5)	2.4 (5.3)	-11.5 (7.9)	-3.6 (14.1)	-19.6 (15.9)	-4.1 (1.4)	-11.0 (-3.2)	-20.0 (13.8)	30.2 (21.3)	5.9 (11.1)	2.3 (17.8)	-7.6 (16.4)
2031-2060	8.1 (19.7)	10.9 (18.4)	-21.1 (27.9)	-4.1 (25.6)	-0.3 (26.9)	-1.0 (17.8)	-2.1 (18.5)	-9.5 (29.1)	28.0 (36.9)	25.5 (16.1)	-14.2 (30.8)	6.3 (21.6)
2071-2100	6.5 (30.0)	20.9 (26.2)	8.8 (22.9)	-4.8 (35.1)	6.0 (30.9)	2.0 (27.0)	30.4 (30.9)	18.2 (47.9)	27.8 (38.2)	26.1 (35.1)	18.7 (27.8)	26.1 (30.4)

3.2 Present and future land use and pesticide management scenarios

3.2.1 Introduction

In order to obtain information about possible chances in future cropping pattern as well as future pesticide consumptions and use pattern, it was decided to create possible future cropping and crop protection scenarios based on experiences from climatically comparable zones, as they are expected for Denmark by 2050. The wish was to compare such future scenarios with current cropping and crop protection practises.

A specific study tour with visits and interviews to crop protection specialist in Northern France and Southern Germany (Appendix F), created the bases for the needed knowledge about likely future changes in crop development, timing of treatments and problems in the area of crop protection. The wish was to investigate possible changes both in a typical pig/arable farm setup as well as in a dairy farm set up.

3.2.2 Cropping pattern

It was decided to focus on two well described catchments area, Lillebæk and Odderbæk. The current cropping patterns in the Lillebæk and Odderbæk catchments are shown in Table 19. Lillebæk (4.4 km^2) is located on Funen and Odderbæk (11.4 km^2) is located in Northern Jutland. Odderbæk is located in an area with predominantly coarse sandy soils, whereas the Lillebæk area mainly has sandy loamy soils (Styczen et al., 2004). Only main agricultural crops are considered in this study. The approximate area of each crop when adjusting the removal of these minor area usages (e.g. orchards, Christmas trees) are shown in Table 19.

The area of winter cereals is considerably larger in Lillebæk compared with Odderbæk catchment. On the other hand the area of fodder crops (grass, silage maize and green cereals) is considerably larger for Odderbæk catchment. This reflects in the main farming types of the regions, with cattle farms dominating in the Odderbæk area and arable/pig farms dominating in the Lillebæk catchment (Table 20).

Table 19. Present information about cropping in the Lillebæk and Odderbæk catchments. The approximate percentage area of each crop is shown as well as an adjusted area deleting those crops, which are not taken into account in the present study.

Lillebæk			Odderbæk		
	% area Present	% area Adjusted		% area Present	% area Adjusted
Winter wheat	25	30	Winter wheat	8	10
Winter barley	12	15	Triticale/rye	5	5
spring barley/oat	12	15	Spring barley/oat	25	25
Winter rape	15	15	Winter rape	3	5
Grass seed	15	15	Maize	16	20
Maize	5	8	Grass-clover	20	25
Permanent grass/set aside.	5	2	Green cereal	5	-
			Permanent grass/set aside	15	10
Other (fruit, plantation etc)	11	-	Other	3	-

Table 20. Proposed division of farming types in the two catchments areas based on the present cropping.

Lillebæk	Odderbæk
80% Arable farming/pig	20% Arable farming/pig
20% Dairy farming	80% Dairy farming

Two sets of crop rotations were defined for each of the two catchments, representing dairy farms and arable/pig farms. In the Lillebæk catchment winter cereals dominate the current crop rotation (Table 21), and it is assumed that one of the winter cereals will be replaced by grain maize in the scenario for the 2050-climate, corresponding to projected changes in the growing of maize under climate change (Olesen et al., 2007; Elsgaard et al., 2012). No change is assumed in crop choice for the rotation on dairy farms, where dairy farming is combined with grass seed production, since these farms have already introduced maize. For the Odderbæk catchment the dairy farm crop rotation is dominated by grass-clover and silage maize (Table 22). It is assumed that this will not change with climate change until 2050. In the arable crop rotation, it is assumed that one of the spring barley crops will be replace by grain maize, since grain maize will yield better under climate change.

Table 21. Proposed crop rotations in present and future (2050) scenario on loamy soils equivalent to the Lillebæk catchment area.

Area coverage	Present crop rotation	Future crop rotation
80% (arable/pig farms)	Winter barley Winter rape Winter wheat Winter wheat Spring barley	Winter barley Winter rape Winter wheat Grain maize Spring barley
20% (dairy farms)	Spring barley (undersown) Grass seed Grass seed Silage maize Silage maize	Spring barley (undersown) Grass seed Grass seed Silage maize Silage maize

Table 22. Proposed crop rotations in present and future (2050) scenario on sandy soils equivalent to the Odderbæk catchment area.

Area coverage	Present crop rotation	Future crop rotation
80% (dairy farms)	Spring barley (undersown) Grass-clover Grass-clover Grass-clover Silage maize Silage maize	Spring barley (undersown) Grass-clover Grass-clover Grass-clover Silage maize Silage maize
20% (arable/pig farms)	Winter rape Winter wheat Spring barley Spring barley	Winter rape Winter wheat Grain maize Spring barley

3.2.3 Scenarios of changes in crop management under climate change

Based on interviews with cropping specialists in Germany and France, new crop management schemes were set up, including both new crops as well as new specific pest issues. In several cases specific new pest or diseases problems were expected to enter the Danish cropping systems and control measures were proposed in order to manage the new problems.

Specific changes in the timing of crop management and the application of nitrogen fertilisers and pesticides are shown for individual crops in Tables 23 to 31. For each activity a specific products, doses and date of application is stated, current practise mainly being based on the recommendations provided by Knowledge Centre for Agriculture.

Crop development is hastened in a warmer climate. This leads to later sowing of winter cereals and earlier sowing of spring cereals (Olesen et al., 2012). It also generally advances harvest time. In autumn this means that application of autumn applied herbicides will be delayed relative to current practices, whereas pesticide application in spring and summer is generally advanced because of faster crop development. The major part of the pesticide usages are expected to be similar to the current practises as it can be seen in the tables.

Table 23. Crop management of winter wheat under present and future (2050) climate for both loamy and sandy soils.

Operations	GS	Date present	Input present per ha	Date future 2050	Input future per ha
Ploughing		12 Sep.		28 Sep.	
Sowing		15 Sep.		1 Oct.	
Application of insecticides	21			20 Oct.	0.15 l Karate
Application of herbicides	13-21	20 Oct.	1 l Boxer EC + 0.04 l DFF + 0.12 l Oxitril	20 Oct.	1.15 l Boxer EC + 0.05 DFF + 0.12 Oxitril
Application of nitrogen	25	15. Mar.	80 kg N	10 Mar.	80 kg N
Application of herbicides	30	1 Apr.	0.4 l Starane XL	20 Mar.	0.4 l Starane XL
Application of PGR	31	5 May	None	25 Apr.	None
Application of fungicides 1	32	10 May	0.25 l Folicur	1 May	0.25 l Folicur
Application of nitrogen	32	10 May	85 kg N	1 May	85 kg N
Application of fungicides 2	55	5 June	0.75 l Bell	28 May	0.75 l Bell
Application of insecticides	71	30 June	0.15 l Karate	20 June	0.15 l Karate
Application of glyphosate	89	1 Aug.	2 l glyphosate	20 July	2 l glyphosate
Harvest		15 Aug.		1 Aug.	

Table 24. Crop management of winter barley under present and future (2050) climate for both loamy and sandy soils.

Operations	GS	Date present	Input present per ha	Date future 2050	Input future per ha
Ploughing		2 Sep.		23 Sep.	
Sowing		5 Sep.		25 Sep.	
Application of insecticides	21			20 Oct.	0.15 l Karate
Application of herbicides	13-21	10 Oct.	1 l Boxer EC + 0.04 l DFF + 0.12 l Oxitril	20 Oct.	1.15 l Boxer EC + 0.05 l DFF + 0.12 l Oxitril
Application of nitrogen	25	5 Apr.	151 kg N	25 Mar.	151 kg N
Application of herbicides	30	1 Apr.	0.4 l Starane XL	25 Mar.	0.4 l Starane XL
Application of PGR			None		None
Application of fungicides	39	12 May	0.25 l Comet + 0.25 l Opus	2 May	0.25 l Comet + 0.25 l Opus
Harvest		1 Aug.		10 July	

An increase in the herbicide dosages is generally projected as the weed problems are seen to increase and higher temperatures will shorten the persistence of the product in the soil. The dosages are proposed to increase in winter cereals, ryegrass and maize. In winter barley an insecticide application is added in autumn under climate change to prevent transmission of BYDV by aphids. In winter oilseed rape additional applications of fungicides and insecticides are added based on current experience in Germany and France. The problems with Phoma is expected to increase in the autumn and the need for growth regulations is also expected to increase as milder autumn and winters will prolong the growing period. The current use of insecticides on loamy soils in Denmark is omitted in spring barley under climate change, again based on experience from Germany and France. This is slightly contradicting effects of a warmer climate on aphids, which predict an increase (Hansen, pers. com.). However, this may be related to changes in the timing of the barley growth as well as effects on predators of aphids. In maize an additional insecticide application is added to control the European corn borer.

Table 25. Crop management of winter oilseed rape under present and future (2050) climate for both loamy and sandy soils.

Operations	GS	Date present	Input present per ha	Date future 2050	Input future per ha
Ploughing		18 Aug.		28 Aug.	
Sowing		20 Aug.		1 Sep.	
Application of N		20 Aug.	30 kg N	1 Sep.	30 kg N
Application of insecticides Rapsjordlopper	10-11	5 Sep.	0.3 l Karate	15 Sep.	0.3 l Karate
Application of fungicides Phoma + growth regulation	15		None	1 Oct.	0.5 l Folicur
Weed control	13-21	10 Oct.	0.25 l Command	20 Oct.	0.25 l Command
Weed control	21	10 Nov.	0.4 l/ha Agil	10 Nov.	0.4 l Agil
Application insecticides Ceuthorhynchus napi (snudebille)	30		None	15 Feb.	0.3 l Karate
Application of N1	30	20 Mar.	149 kg N	5 Mar.	149 kg N
Weed control	30	1 Apr.	0.8 l Matrigon	5 Mar.	0.8 l Matrigon
Application of insecticides Melingetes	50	15 Apr.	0.3 l Biscay	5 Apr.	0.3 l Biscay
Application of fungicides	65	1 May	0.5 l Folicur	20 Apr	0.5 l Folicur
Harvest		25 July		15 July	

Table 26. Crop management of spring barley under present and future (2050) climate for both loamy and sandy soils.

Operations	GS	Date present	Input present per ha	Date future 2050	Input future per ha
Ploughing, loamy soil		15 Jan.		15 Jan.	
Ploughing, sandy soil		15 Mar.		5 Mar.	
Application of N		15 Mar.	121 kg N	15 Mar.	121 kg N
Sowing		1 Apr.		15 Mar.	
Weed control	13-21	1 May	1 tab Express + 0.25 l Oxitril	20 Apr.	1 tab Express + 0.25 Oxitril
Application of fungicides	37-39	10 May	0.25 l Comet 0.25 l Opus	5 May	0.25 l Comet 0.25 l Opus
Application of insecticide, loamy soil	71	1 June	0.15 l Karate		None
Harvest		15 Aug.		25 July	

Table 27. Crop management of spring barley (undersown with grass) under present and future (2050) climate for both loamy and sandy soils.

Operations	GS	Date present	Input present per ha	Date future 2050	Input future per ha
Ploughing, loamy soil		15 Jan.		15 Jan.	
Ploughing, sandy soil		15 Mar.		5 Mar.	
Application of N		15 Mar.	121 kg N	15 Mar.	121 kg N
Sowing		1 Apr.		15 Mar.	
Weed control	13-21	1 May	8 g Harmony	20 Apr.	8 g Harmony
Application of fungicides	37-39	10 May	0.25 l Comet + 0.25 l Opus	5 May	0.25 l Comet + 0.25 l Opus
Application of insecticide, loamy soil	71	1 June	0.15 l Karate		None
Harvest		15 Aug.		25 July	

Table 28. Crop management of silage maize under present and future (2050) climate for both loamy and sandy soils.

Operations	GS	Date present	Input present per ha	Date future	Input future per ha
Ploughing, sand		22 Apr.			
Ploughing, clay		15 Jan.			
Sowing		25 Apr.		15 Apr.	
Application of N		25 Apr.	30 kg N	15 Apr	30 kg N
Weed control	13-21	5 May	0,4 l Callisto + 5,6 g Harmony	25 Apr.	0.5 l Callisto + 7.5 g Harmony
Weed control		15 May	0.75 l Maizter + 1.0 l Maisoil + 0.2 l Starane 180S	5 May	0.9 l Maizter + 1.2 Maisoil + 0.25 l Starane 180S
Application of N	15	1 June	127 kg N	20 May	127 kg N
Application of insecticides European corn borer	51	None		15 July	0.3 l Karate
Harvest		20 Oct.		1 Oct.	

Table 29. Crop management of grain maize under present and future (2050) climate for both loamy and sandy soils.

Operations	GS	Date present	Input present per ha	Date future	Input future per ha
Ploughing, sand		22 Apr.			
Ploughing, clay		15 Jan.			
Sowing		25 Apr.		15 Apr.	
Application of N		25 Apr.	30 kg N	15 Apr.	30 kg N
Weed control	13-21	5 May	0,4 l Callisto + 5,6 g Harmony	25 Apr.	0.5 l Callisto + 7,5 g Harmony
Weed control		15 May	0.75 l Maizter + 1.0 l Maisoil + 0.2 l Starane 180S	5 May	0.9 l Maizter + 1.2 l Maisoil + 0.25 l Starane 180S
Application of N	15	1 June	127 kg N	20 May	127 kg N
Application of insecticides European corn borer	51	None		15 July	0.3 l Karate
Harvest		20 Oct.		20 Oct.	

Table 30. Crop management of ryegrass for seed production under present and future (2050) climate for both loamy and sandy soils. The crop is undersown in barley in the previous year.

Operations	GS	Date present	Input present per ha	Date future	Input future per ha
Weed control	Gs 26	10 Oct.	1.0 Boxer EC + 0.08 l DFF	10 Oct	1.25 Boxer EC + 0.1 l DFF
Application of N		20 Mar.	40 kg N	5 Mar.	40 kg N
Weed control	30	5 Apr.	2.0 kg Ariane FG	20 Mar.	2.0 kg Ariane FG
Application of N		25 Apr.	96 kg N	15 Apr.	96 kg N
Application of fungicides	45	20 May	0.5 l Folicur	10 May	0.75 l Folicur
Harvest		1 Aug.		20 July	

Table 31. Crop management of grass-clover under present and future (2050) climate for both loamy and sandy soils. The crop is undersown in barley in the previous year.

Operations	GS	Date present	Input present per ha	Date future	Input future per ha
Application of N		20 Mar.	100 kg N	5 Mar.	40 kg N
First cut		15 May		10 May	
Application of N		20 May	80 kg N	15 Apr.	80 kg N
Second cut		15 July		15 July	
Application of N		15 July	65 kg N	15 July	65 kg N
Third cut		10 Sep.		20 Sep.	

3.2.4 Effekt on TFI

Pesticide consumption is traditionally measured as treatment frequency index (TFI). A calculation of TFI in the different crops and the proposed crop rotations is provided in Tables 32 and 33. Generally speaking the differences in TFI are minor, but with overall small increases in TFI under projected climate change. The changes in pesticide use are mainly related to changes in timing of application, but also in some cases the input and need for insecticides has increased the TFI. A description of the individual reasons changes in TFI is given in Table 34.

Table 32. Proposed crop rotations in present and future (2050) scenario on loamy soils equivalent to the Lillebæk catchment area including TFI.

Area coverage	Present crop rotation	TFI	Future crop rotation	TFI
80% (arable/pig farms)	Winter barley	1,6	Winter barley	2,2
	Winter rape	4,3	Winter rape	5,6
	Winter wheat	3,3	Winter wheat	3,9
	Winter wheat	2,7*	Grain maize	2,5
	Spring barley	1,7	Spring barley	1,3
	Gns BI per year	2,7		3,1
20% (dairy farms)	Spring barley (undersown)	1,8	Spring barley (undersown)	1,3
	Grass seed	2,3	Grass seed	2,7
	Grass seed	2,3	Grass seed	2,7
	Silage maize	1,6	Silage maize	2,5
	Silage maize	1,6	Silage maize	2,5
		1,9		2,3

* glyphosate not included

Table 33. Proposed crop rotations in present and future (2050) scenario on sandy soils equivalent to the Odder Bæk catchment area including TFI.

Area coverage	Present crop rotation	TFI	Future crop rotation	TFI
80% (dairy farms)	Spring barley (undersown)	1,8	Spring barley (undersown)	1,3
	Grass-clover	0	Grass-clover	0
	Grass-clover	0	Grass-clover	0
	Grass-clover	0	Grass-clover	0
	Silage maize	1,6	Silage maize	2,5
	Silage maize	1,6	Silage maize	2,5
		0,8		1,1
20% (arable/pig farms)	Winter rape	4,3	Winter rape	5,6
	Winter wheat	3,3	Winter wheat	3,9
	Spring barley	1,7	Grain maize	2,5
	Spring barley	1,7	Spring barley	1,3
		2,8		3,3

Table 34. Main changes in crop protection problems given specifically in individual crops.

Crop	Problem	Impact on TFI
Wheat	Increase in problems with aphids in the autumn will add to the need for insecticides. Increase in doses of herbicides as it is expected that weeds will grow more during autumn and winter	0,15 Karate Autumn
Winter barley	Increase in problems with aphids in the autumn will add to the need for insecticides Increase in doses of herbicides as it is expected that weeds will grow more during autumn and winter	0,15 Karate Autumn
Spring barley	Less problems seen with summer aphids in mid Europe.	Insecticide treatment removed
Oil seed rape	Increases in problems with weevil (snudebille) (Ceuthirhynchus napi) in spring More problems with phoma in autumn and vigorous growth	0,3 Karate 0,5 Folicur
Grass seed	Milder winters are expected to increase problems with stemrust in ryegrass Increase in doses of herbicides as it is expected that weeds will grow more during autumn and winter	Added and extra 0,25 Folicur
Sillage Maize	Higher temperatures will increase the risk for attack of European Corn borer. Increase in doses of herbicides as it is expected that weeds will grow more in the extended growing season	0,3 l Karate
Grain maize	Higher temperatures will increase the risk for attack of European Corn borer and need for control of aphids. Increase in doses of herbicides as it is expected that weeds will grow more in the extended growing season	0,3 l Karate

Most of the problems found in the present cropping systems are expected to stay more or less at the same level in the future. This statement is supported by the experience which was obtained from the visits to Germany and France. However, at present the two countries have considerable higher TFIs than Denmark (Jørgensen, 2011), which most likely reflects the lack of focus on reducing input as well as less tradition in using reduced and appropriate rates (ENDURE). Even so there is still a tendency to higher TFI in the climate change scenarios compared with the present, mainly due to increased problems with insects and need for slightly higher herbicide inputs as the growing seasons are extended. The increase is most pronounced in winter oil seed rape.

3.3 Pesticide leaching at field scale

Both direct (precipitation, actual evapotranspiration, and temperature) and indirect (changed land use and pesticide application pattern) climatic factors have in different degrees implications for the overall pesticide leaching through the unsaturated zone at Jyndevad (sandy soil) and Faardrup (loamy soil). This is illustrated via MACRO-simulated leaching of five different types of pesticides:

P1: Low-dose herbicide
P2: Ordinary herbicide
P3: Strongly sorbing herbicide
P4: Fungicide
P5: Insecticide

through both the sandy soil and the loamy soil. For each site, two types of agricultural management (farm types) scenarios are set up: arable and dairy. These leaching scenarios are simulated without and with the influence of direct and indirect climatic factors (Table 35).

Table 35. Present (PP) and future (PF/FF) climatic scenario included in the analysis. The analysis comprises both direct (precipitation, actual evapotranspiration, and temperature) and indirect (changed land use and pesticide application pattern) climatic factors.

INFLUENCED BY	Scenario	Agricultural management	Climate
Present climatic factors	PP	Present	Present
Direct climatic factors	PF	Present	Future
Direct and indirect climatic factors	FF	Future	Future

The PF-scenario is included to illustrate to which degree direct climatic factors play a role in comparison with the indirect climatic factors on the overall pesticide leaching.

With regard to the indirect climatic factors, the total dose of the five model-pesticides applied over the 30 years period will increase (Table 36).

Table 36. Present and future total dose of P1 (low-dose herbicides), P2 (ordinary herbicides), P3 (strongly sorbing herbicides), P4 (fungicides), and P5 (insecticides) under arable and dairy agricultural management at the sandy and loamy site.

Model pesticide	Site – agricultural management scenario	Total dose after 30 years		
		PP or PF [kg ha-1]	FF [kg ha-1]	DIFF [%]
P1 low-dose herbicides	Sandy – Arable	0.07	0.13	78
	Sandy – Dairy	1.14	1.47	29
	Loamy – Dairy	1.37	1.76	29
	Loamy – Arable	0.06	0.12	95
P2 ordinary herbicides	Sandy – Arable	2.97	3.47	17
	Sandy – Dairy	9.42	11.68	24
	Loamy – Dairy	13.06	15.78	21
	Loamy – Arable	2.63	3.1	18
P3 strongly sorbing herbicides	Sandy – Arable	35.62	37.70	6
	Sandy – Dairy	-	-	-
	Loamy – Dairy	23.04	28.80	25
	Loamy – Arable	52.64	38.00	-28
P4 fungicides	Sandy – Arable	1.65	1.90	15
	Sandy – Dairy	0.31	0.31	0
	Loamy – Dairy	0.75	1.13	50
	Loamy – Arable	2.48	1.80	-27
P5 insecticides	Sandy – Arable	0.20	0.29	44
	Sandy – Dairy	0.02	0.08	295
	Loamy – Dairy	0.02	0.09	295
	Loamy – Arable	0.16	0.25	56

3.3.1. Mass balance at field scale

By only assuming vertical flow and transport, the sandy and loamy site differ as expected remarkably in the degree of total mass leaching through the upper 5 meter of soil, which off course is due to both leaching concentration (Figure 34) as well as percolation (Figure 36). The percolation on the loamy site is approximately 17 % of the total percolation at the sandy site.

At the sandy site (Jyndevad), the total mass of pesticide, which on a long-term basis (30 years), entered the ground water 5 meters below soil surface was much higher with dairy agricultural management than arable, which is caused by the higher total dose being applied of pesticides (especially P1 Low-dose herbicides) on the soil surface (Figure 35 and 37). Both of the farm-type scenarios were only slightly affected by the direct and indirect climatic factors (Figure 37a and 37b). In figure 37, the difference between PP and the PF scenarios indicates impact posed by the direct climatic factors, while the difference between PF and FF indicates additional impact posed when indirect climatic factors (changes crop rotation and pesticide application) are introduced. The difference between PP and FF indicates the total impact posed by both direct and indirect climatic factors. Under arable agricultural management the direct climatic factors result in a decrease of mass leaching, whereas the indirect climatic factors - given an increased in use of the low-dose herbicide P1 - will minimize this decrease. Under dairy agricultural management the direct climatic factors will during the 30 years period both increase and decrease the mass reaching the groundwater at 5 meters depth, though with a total decrease in mass leached to the groundwater after 30 years. Adding the indirect climatic factors with an increase in the applied dose of the low-dose and ordinary herbicides in connection with silage maize (Figure 35, Table 36) more mass leaching below 5 meters depth is to be expected in the future. For both farm-types the percolation will increase with approximately 8 % given an increase in precipitation including artificial irrigation (Figure 36). This will, however, not have a mention ally impact on the mass transported to 5 meters depth given the decreasing influence of the direct climatic factors on the total mass leaching to the groundwater after 30 years.

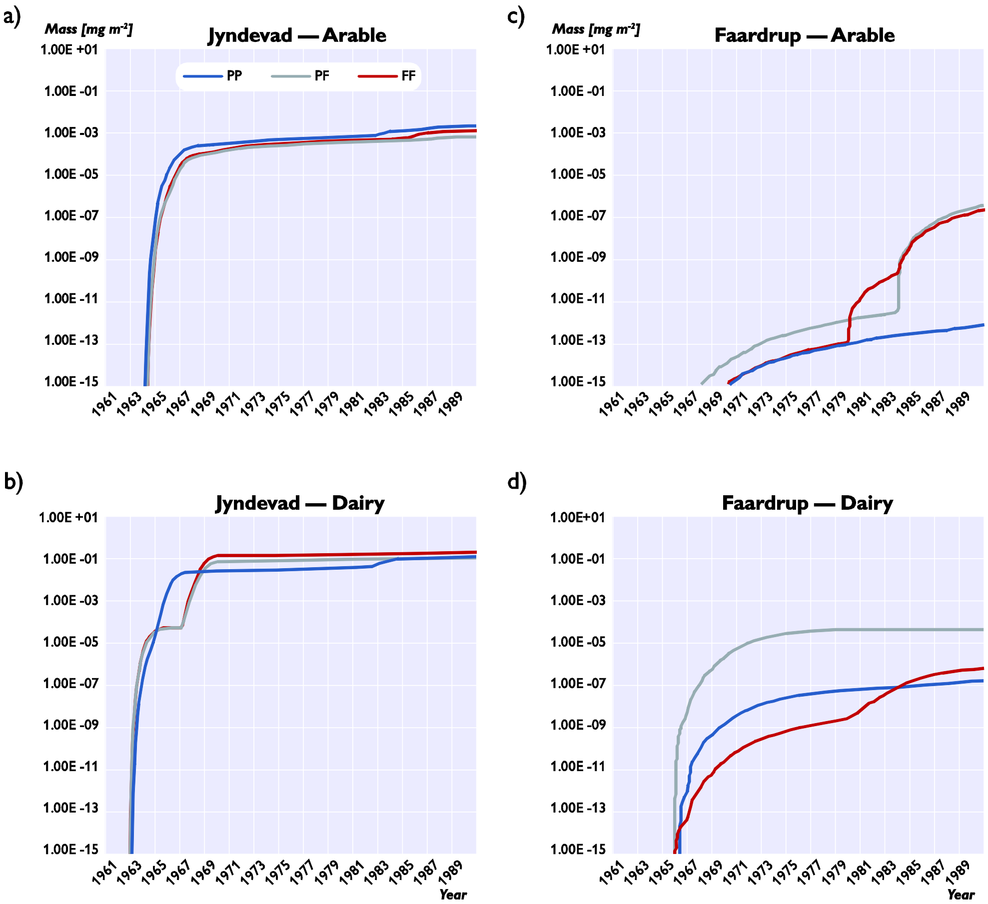


Figure 34. Total mass of pesticides leached out from the five meter soil column for the four different agricultural managements influenced by present (PP), direct (PF) and both direct and indirect (FF) climatic factors. Data represents the daily total mass of all five pesticides, which is accumulated for the entire simulation period for the sandy soil Jyndevad (left figures) and the loamy soil Faardrup (right figures). Difference between PP and PF scenarios indicates impact solely posed by the direct climatic factors, while the difference between PF and PP indicates additional impact posed when the indirect climatic factors (changed agricultural management) are introduced. The difference between PP and FF indicates the impact posed by both direct and indirect factors.

At the loamy site (Faardrup), the total mass of pesticide, which on a long-term basis (30 years), entered the ground water 5 meters below soil surface was much higher with dairy agricultural management than arable, which is caused by the higher total applied dose of pesticides (especially P1 Low-dose herbicides) on the soil surface (Figure 37 and 38). The relative impact of future climatic factors were much higher with regard to leaching of mass 5 meters below soil surface than that simulated for the sandy soil at Jyndevad, with a more pronounced relative change caused by direct climatic factors (Figure 34). Under both farm-types, the total mass leached after 30 years was higher under future climatic conditions than present (comparing FF-scenario with PP-scenario) and being relatively highest with arable agricultural management – a difference which cannot be seen in the percolation (Figure 36). Under arable agricultural management the increased usage of the low-dose herbicide P1 applied on silage maize in the future (Figure 35) is not evident and can only be accountable for the rapid increase in mass leaching during 1980-1984 (Figure 34c). Under dairy agricultural management it is clear that the direct climate factors (comparing PP-scenario with PF-scenario) will increase the overall mass leaching through the 5 meters loamy soil if the agricultural management is not changed accordingly (FF-scenario). By introducing the indirect climatic factors, the impact of the direct climatic factors on mass leaching to 5 meters below soil surface will decrease (difference between PF and FF scenario), however, still resulting in an increase in total mass after 30 years (Figure 34d). Leaching in the scenarios of Faardrup, both present and future, was mainly caused by the low-dose herbicide P1, accounting for approximately all mass being leached through the upper 5 meter during 30 years.

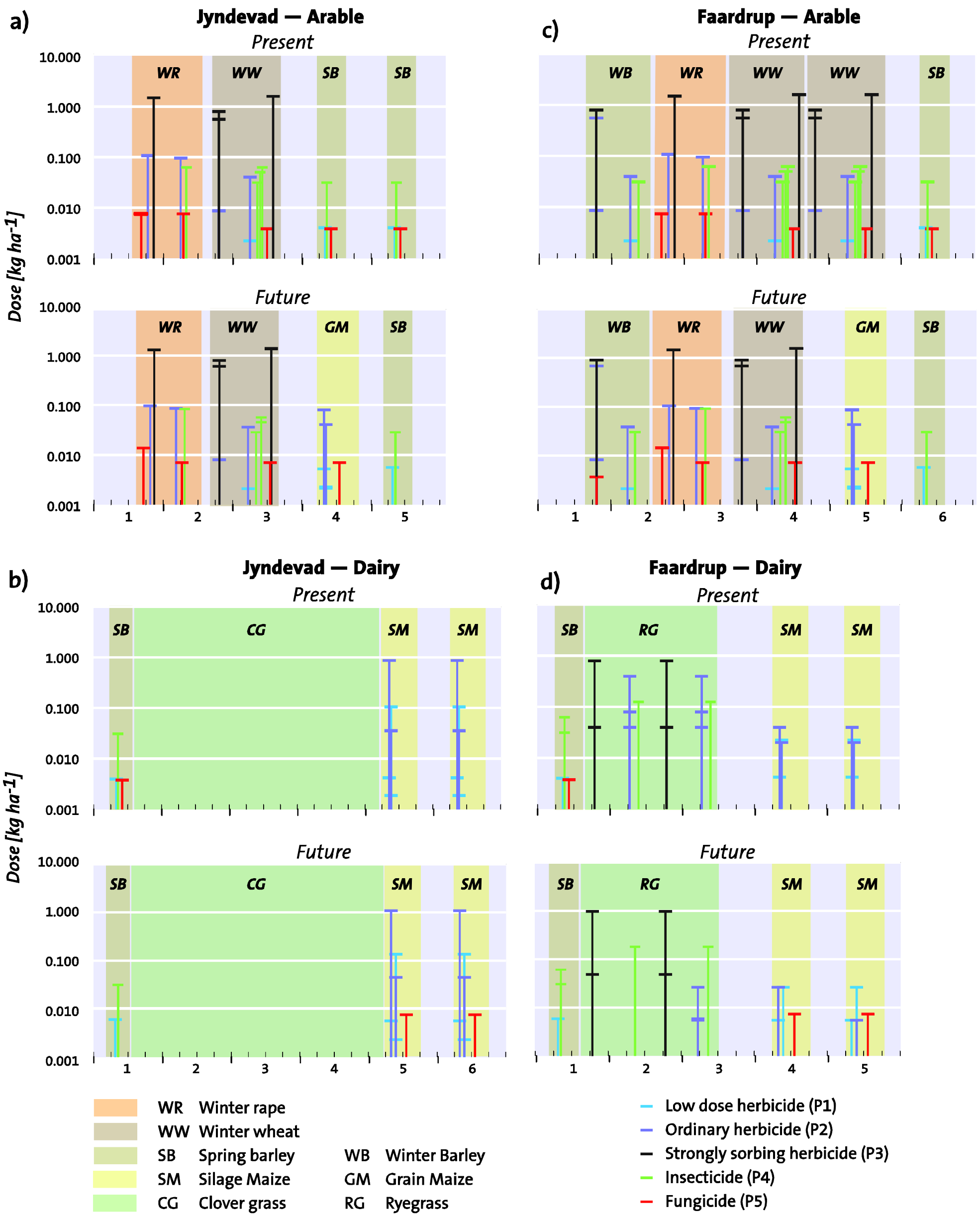


Figure 35. Dose and application pattern for the five model pesticides (P1: Low-dose herbicide; P2: ordinary herbicide; P3: Strongly sorbing herbicide; P4: Fungicide; P5: Insecticide) for Jyndevad (sandy site, left figures - a and b) and Faardrup (loamy site, right figures – c and d)) with arable/dairy agricultural management.

The usage of the low-dose herbicide P1 increases much more in the future scenario of Faardrup-Arable than in Faardrup-Dairy (Figure 35 and 38), however it seems to be the direct climate factors (PF mass leaching -grey line – will during the 30 year be higher than both the PP and FF mass leaching) causing the difference between present and future mass leached to be highest in Faardrup-Arable.

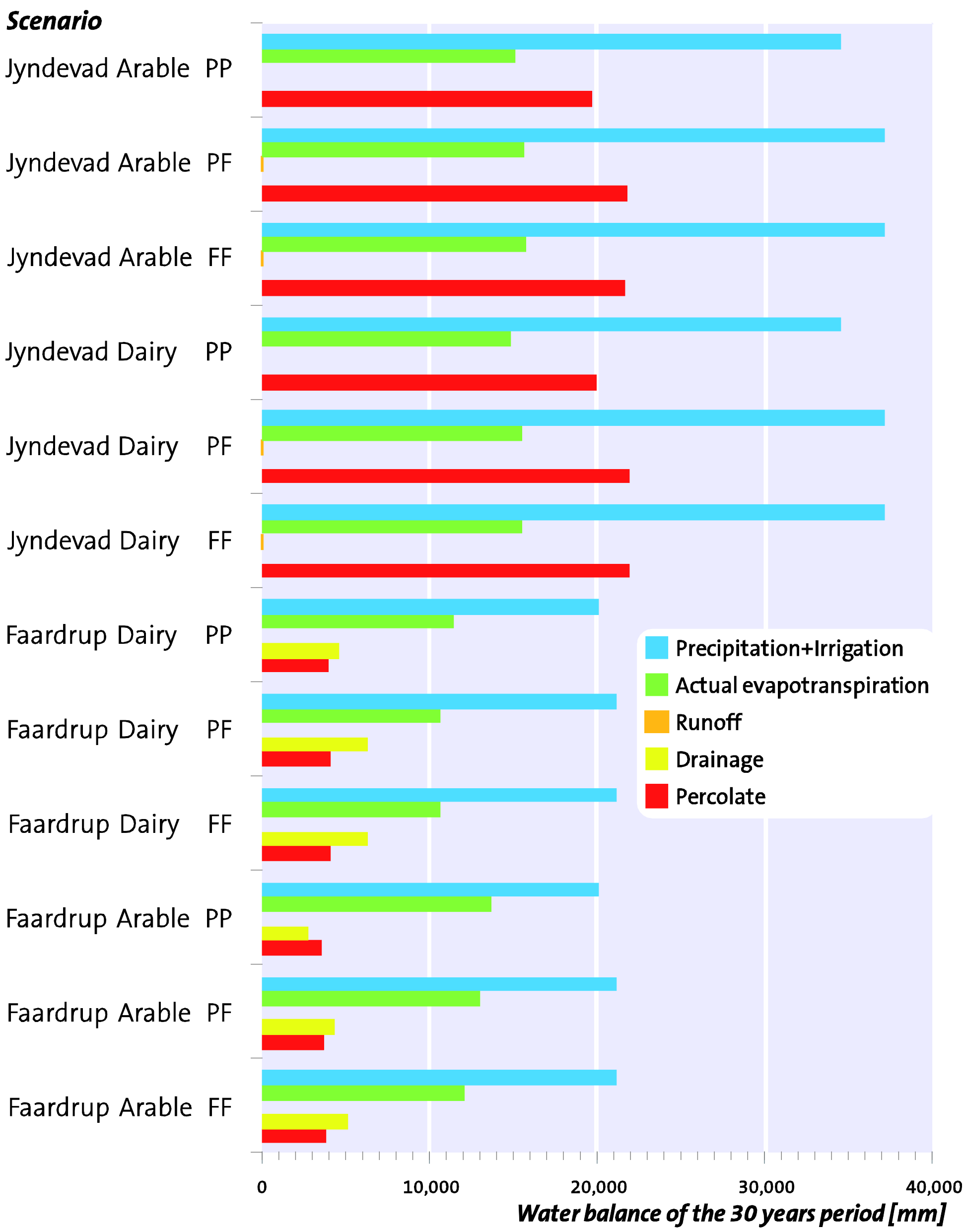


Figure 36. Water balance of the 30 years period for the whole 5 m profile of Jyndevad and Faardrup. The balance includes precipitation + irrigation, actual evapotranspiration, runoff, drainage, and percolate. Example of scenario "Jyndevad – Arable - PP": Jyndevad is the sandy site (Faardrup is the loamy site), Arable represents arable farming (Dairy represents dairy farming), and PP represents present agricultural management and climate (PF = present agricultural management and future climate; FF = future agricultural management and future climate).

3.3.2. Pesticide leaching at field scale

The impact that the future agricultural management and climate poses on leaching at 1.2 meters below soil surface of each of the five pesticides is illustrated in Figure 37 and 38. The first figure shows the implication of the future climatic factors (both direct and indirect) on the leaching via bulk matrix (GW), macropores, and drains (if present) at 1.2 meters depth. The latter figure gives a more detailed picture of whether it is the direct or indirect climatic factors causing a change in 80-percentil-concentrations and peak-concentrations of P1-P5 through the bulk matrix and drainage system.

The introduction of future climatic factors with a general increase in applied doses will on the sandy site and only under diary agricultural management caused an increase in 80-percentile-concentration of ordinary herbicide P2 and fungicide P4 with an increase in peak-concentration of low-dose herbicide P1, ordinary herbicide P2, and fungicide P4 (Figure 37). For these three pesticides a decrease both in 80-percentil-concentration and peak-concentration under arable agricultural management is simulated together with a decrease in 80-percentil-concentration of P1 under dairy agricultural management. A similar decrease under arable agricultural management is also the outcome for the strongly sorbing herbicide P3 - a result with high uncertainty given evidence of MACRO's shortcoming in capturing such leaching scenarios. This uncertainty is not present under the dairy agricultural management, since P3 is not applied (Figure 35 and 43). No changes in 80-percentil-concentrations and peak-concentrations for the insecticide P5 are simulated even though an increased dose is applied - a 4 times higher dose is applied under dairy agricultural management (Figure 38 – small tables with doses; Table 36).

At the loamy site, the future climatic factors will result in a decrease of the applied dose of the strongly sorbing herbicide P3 and fungicide P4 under arable agricultural management, whereas the future doses in the rest of the scenarios will increase (Table 36). This pesticide application picture, however, only results in an increase in the peak-concentrations of low-dose herbicide P1 and to a minor degree the ordinary herbicide P2 in the bulk matrix and drainage system at 1.2 meters depth under dairy agricultural management (Figure 37). The 80-percentile concentration of P1 in both bulk matrix and drainage system is decreased under dairy agricultural management, whereas both the 80-percentile concentration and the peak concentration of P1 in the macropore domain are increased. Nearly the opposite picture is simulated under arable agricultural management, where the leaching in the macropore domain at 1.2 meters depth either is unchanged or decreased. The 80-percentile and peak concentration of the strongly sorbing herbicide P3, fungicide P4, and insecticide P5 will not be affected by the future climatic conditions, even though the applied dose of P5 (strongly sorbing with a K_{oc} = 157000 mL g^{-1}) is four time higher in the future scenarios (Table 36). Again, MACRO-simulation-results regarding P3 is affected with high uncertainty especially at loamy site with preferential macropore-transport.

The future climatic factors (direct and indirect) do not result in pesticide concentrations generally exceeding the maximum allowed concentration of 0.1 $\mu g\ L^{-1}$ (Figure 38). Peak-concentrations of the low-dose herbicide P1 and fungicide P4 exceeding this level are though simulated under arable and dairy agricultural management at the sandy site.

At the sandy site, both direct and indirect climatic factors will in a varying degree decrease the average (GW-FOCUS), 80-percentil (GW-80), and peak (GW-MAX) bulk concentration of P1-P4 at 1.2 meters depth under arable agricultural management, whereas they will increase the leaching of P1, P2, and P4 under diary agricultural management (P3 is not applied). In the future, the overall leaching risk on sandy soils is expected to decrease under arable agricultural management and decrease in diary agricultural management.

At the loamy site, direct climatic factors (Figure 38; comparing PP with PF dots) will increase the average (GW-FOCUS), 80-percentil (GW-80), and peak (GW-MAX) bulk concentrations and the 80-percentil (DRAIN-80), and peak (DRAIN-MAX) drainage water concentrations of especially the low-dose herbicide P1 and the ordinary herbicide P2 leaching from 1.2 meters depth, whereas the indirect factors generally will minimize this effect on leaching (Figure 38; comparing FF with PF dots). This minimizing effect is highest under dairy agricultural management, which does not have a doubling in the applied dose of P1 as under arable agricultural management, where P1 is accounting for the overall leaching from 1.2 meters depth. The overall leaching risk on loamy soils posed by future climatic factors thus seems to be increasing under both arable and diary agricultural management.

Figure 37. Impact of future climate and agricultural management on pesticide leaching of the five pesticides (P1, P2, P3, P4, and P5). The colour of the squares indicate that when going from present (PP) to future (FF) leaching will either increase (red), increase from zero to 10-8 □g-1L (yellow) or decrease (green). Grey indicates that no leaching occurs, why a given impact cannot be evaluated. The difference reflect the 80-percentiel and maximum concentration between daily future and present simulated total pesticide flux at 1.2 m depth in the bulk soil (DIFF GW), the macropore domain (DIFF MACROPORE), and drain (DIFF DRAIN) for Jyndevad (sandy) and Faardrup (loamy). Leaching to GW is calculated as the daily pesticide leaching loss in the bulk soil divided by the daily flow in the bulk soil during the 30-years period. MACROPORE is calculated as the daily pesticide leaching loss in the macropore domain divided by the daily flow in the macropore domain during the 30-years period. DRAIN is daily pesticide concentration in the drain.

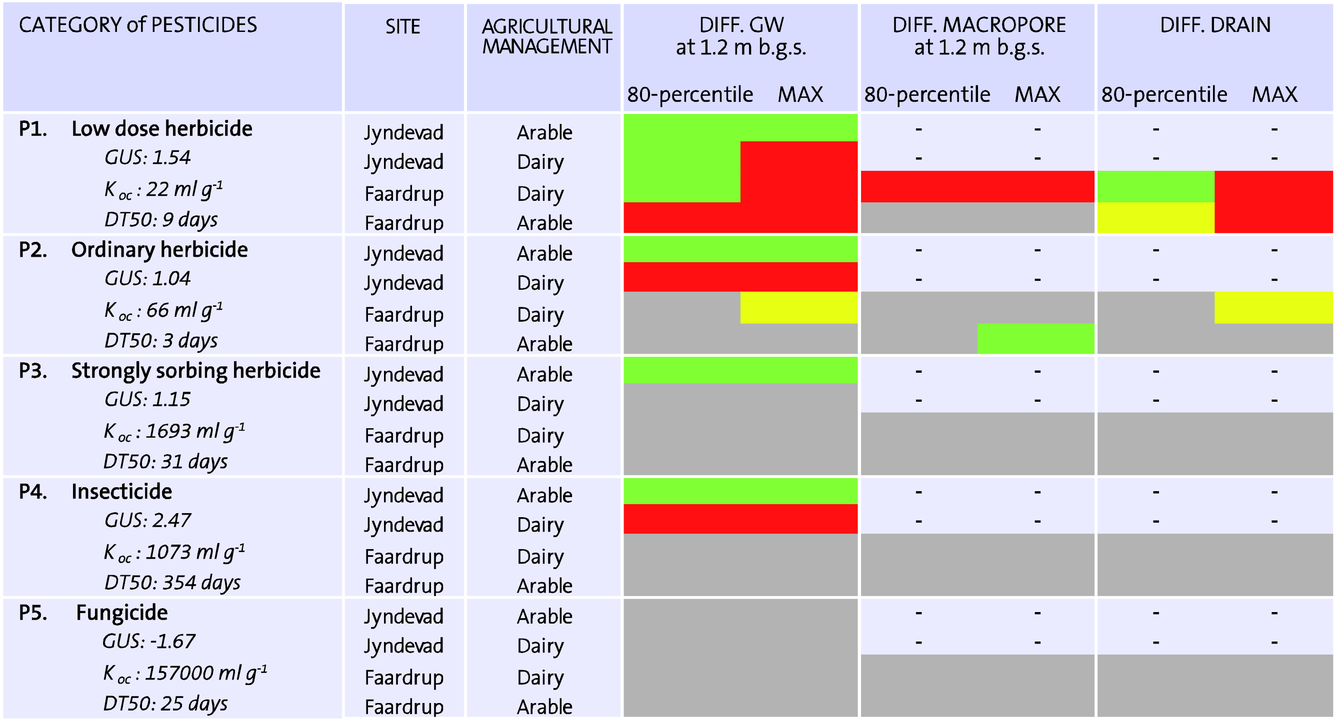


Figure 38. The average bulk matrix (GW-FOCUS), 80-percentil bulk matrix (GW-80), peak bulk matrix (GW-MAX), 80-percentil drainage water (DRAIN-80), and peak drainage water (DRAIN-MAX) MACRO-simulated daily concentrations of pesticide flux (P1, P2, P3, P4, and P5) at 1.2 meters depth at sandy (Jyndevad) and loamy (Faardrup) soils. GW is calculated as the daily pesticide flow rate (macropore+micropore domain) in the bulk soil divided by the daily water flow rate (macropore+micropore domain) in the bulk soil during the 30-years period. DRAIN is daily pesticide concentration in the drain.

Jyndevad - Arable

Dose - 30 years period [kg ha^{-1}]:

P	PP/PF	FF	DIFF
1	0.07	0.13	78%
2	2.97	3.47	17%
3	35.62	37.70	6%
4	1.65	1.90	15%
5	0.20	0.29	44%

Jyndevad - Dairy

Dose - 30 years period [kg ha^{-1}]:

P	PP/PF	FF	DIFF
1	1.14	1.47	29%
2	9.42	11.68	24%
3	-	-	-
4	0.31	0.31	0%
5	0.02	0.08	295%

Faardrup - Dairy

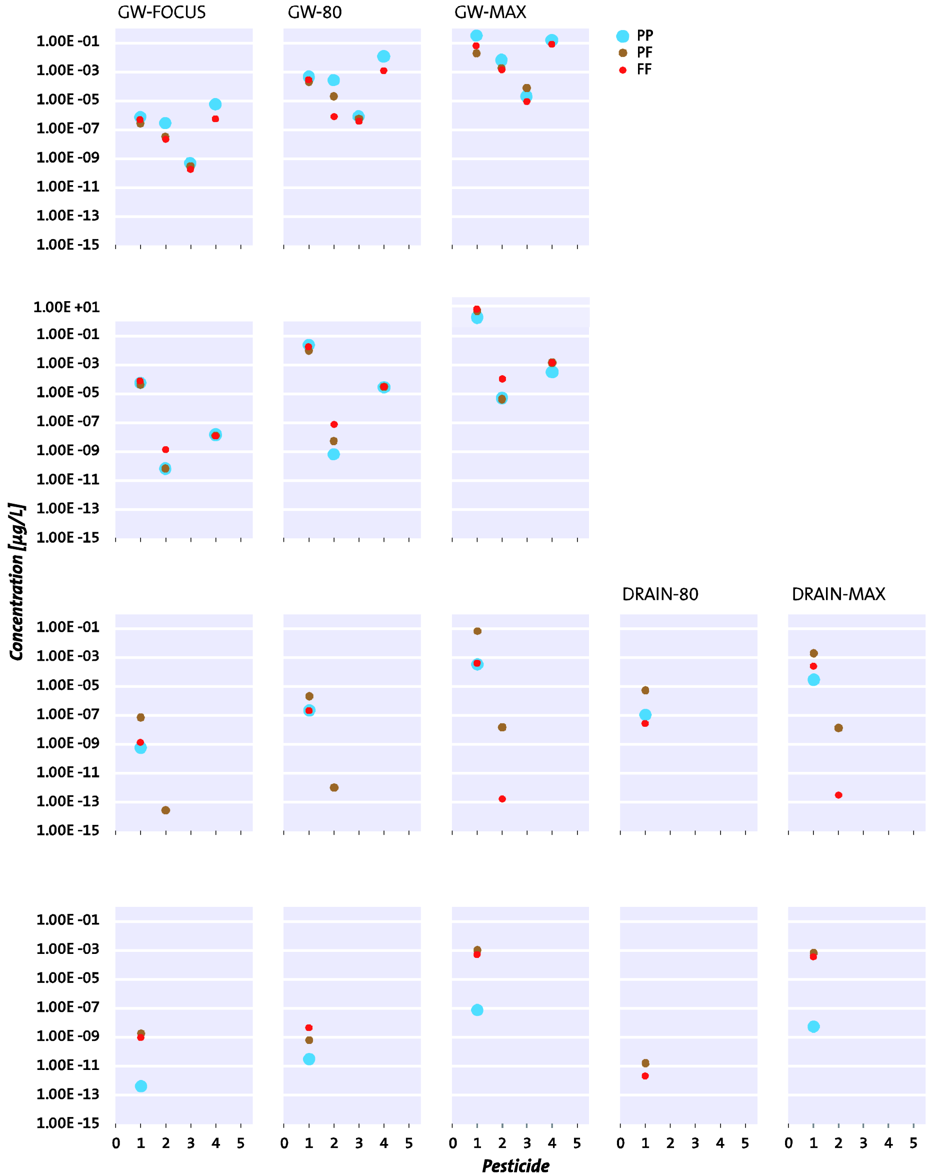
Dose - 30 years period [kg ha^{-1}]:

P	PP/PF	FF	DIFF
1	1.37	1.76	29%
2	13.06	15.78	21%
3	23.04	28.80	25%
4	0.75	1.13	50%
5	0.02	0.09	295%

Faardrup - Arable

Dose - 30 years period [kg ha^{-1}]:

P	PP/PF	FF	DIFF
1	0.06	0.12	95%
2	2.63	3.10	18%
3	52.64	38.00	-28%
4	2.48	1.80	-27%
5	0.16	0.25	56%



3.4 Catchment scale pesticide transport modelling in groundwater

This section describes the results at catchment scale of the MIKE SHE simulated solute mass balances for Odderbæk and Lillebæk for present and future scenarios. Simulated groundwater pesticide concentrations with spatially averaged and spatially distributed values will be presented. Furthermore, an analysis of simulated pesticide concentrations for selected surface water locations, are given.

3.4.1 Selection of bias correction method

The simulated leaching of pesticide A by MACRO at 1 m and 3 m for the Faardrup and Jyndevad site, representing the clayey and sandy catchment respectively, using RCM downscaled time series of climatic data are shown in Figure 39. The compared bias correction methods are listed in Table 37 (see section 2.1 and Appendix C).

Table 37. Considered bias-correction methods for climate input to MACRO model. BC1: Delta Change (obs), BC2: Distribution transformation, BC3: Delta change (RCM) and BC4: Intensity based. Description and reference.

Bias correction method	Description	Reference
BC1, Delta Change (Obs)	Future climate data by scaling observed data. Dynamics of observed data preserved	Hay et al., 2000; Xu et al., 2005
BC2, Distribution transformation	Future changes in the statistical distribution of precipitation is transferred to the historical data	Mileham et al., 2009
BC3, Delta Change (RCM)	Future climate data by scaling simulated scenario data. Dynamics of simulated future data preserved	Xu et al., 2005
BC4, Intensity based statistical bias correction	Future climate data by using intensity dependent scaling og RCM scenario data set	Piani et al., 2008

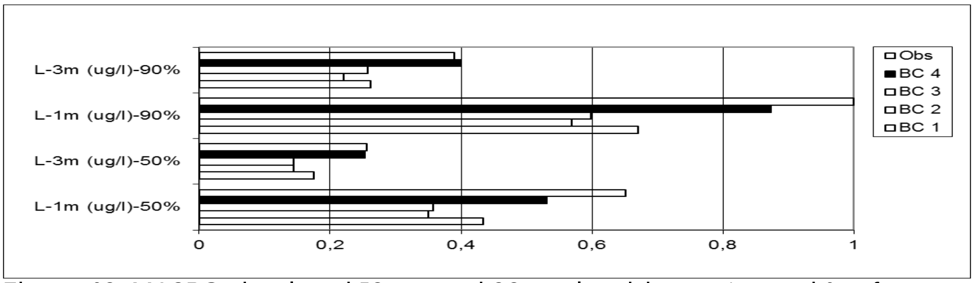


Figure 39. MACRO simulated 50 pct and 90 pct leaching at 1 m and 3 m for pesticide P1 Low-dose herbicides at the clayey PLAP (Faardrup) site normalized for the period 2071-2100. Obs: BC4-1 (intensity based) indicate observed data and bias correction (BC) method 4 to 1 (Table 37), for which BC4 (intensity based) is associated with highest leaching.

The bars in the diagram (Figure 39) follow the sequence in the legend. From Figure 39 it is clear that using climate time series corrected by the intensity based statistical bias correction (Intensity based) leads to highest leaching of pesticide A (DT_{50} = 49 d, K_{oc} = 99.5 mL g^{-1}) for the clayey site and future scenario period 2071-2100. Precipitation for this period has an average of 996 mm yr^{-1} and a minimum and maximum of 781 mm and 1261 mm respectively. The average temperature is 10.8 °C. Results of simulations for the sandy PLAP site (Jyndevad) and pesticide P1 Low-dose herbicides for the four different bias correction methods were less clear, and showed little difference between BC4 and BC1, P2 Ordinary herbicides and P3 Strongly sorbing herbicides (not shown). Leaching has also been simulated for two other pesticides P2 Ordinary herbicides (DT_{50} = 6.1 d, K_{oc} = 30 mL g^{-1}) and P3 Strongly sorbing herbicides (DT_{50} = 80 d, K_{oc} = 400 mL g^{-1}). Simulated leaching results for pesticide P2 and P3 with different bias correction methods showed highest concentrations at 1 m and 3 m for intensity based bias correction for both summer and winter crop rotation and the clayey site. Again, for the sandy site little differences in leaching resulted from applying different bias correction methods. Intensity based bias correction is adopted for the main study as a results of the higher simulated leaching for pesticide P1 Low-dose herbicides, P2 Ordinary herbicides and P3 Strongly sorbing herbicides for the clayey site. The adopted method accounts best for especially extreme precipitation events, deemed important for the effect of preferential flow in clayey soils for pesticide leaching. For the reason of comparing results of the clayey catchment (Lillebæk) and the sandy catchment (Odderbæk), for which bias correction method seems not to be as important as for the clayey soil, the intensity based bias corrected climate data is applied in both catchments.

3.4.2 Simulation results for sandy and clayey catchments

The MACRO model is used to provide an upper boundary for the catchment scale MIKE SHE model. Five model pesticides (P1 to P5) are simulated for present and future climate conditions, crop rotations and pesticide management. Simulations are carried out for the sandy and the clayey catchment (Rosenbom et al., in prep). In table 38 and 39 accumulated pesticide leaching for P1 to P5 is listed for present and future climate for both catchments and 100 % is taken as reference for simulations under present conditions, so changes under future scenarios can be readily seen.

Table 38. Change in accumulated pesticide leaching (P1, P2, P4 & P5) in sandy catchment (Odderbæk) and clayey catchment (Lillebæk) between present and future climate (%). P3 Strongly sorbing herbicides is not used in this catchment (Chapter 3.3). N/A means that accumulated leaching is zero. The first and second percentage separated by ‘;’ is for dairy and arable farming respectively.

	Change in accumulated leaching: Dairy ; Arable farming type, (%).	
Compound	Sandy catchment (Odderbæk)	Change in Clayey catchment (Lillebæk)
P1 Low-dose herbicides	+43 % ; -28.5 %	+283 % ; ; +3094 %
P2 Ordinary herbicides	+2097 % ; -92%	/ N/A
P3 Strongly sorbing herbicides	N/A	-100 %; -100 % *
P4 Fungicides	-9 %; -89 %	N/A / N/A
P5 Insecticides	N/A; N/A	N/A; N/A

* Approximately as absolute numbers very small.

From Table 38 it is clear that the highest changes in accumulated leaching are for the ordinary herbicides (P2) in the sandy catchment, and Low-dose herbicides (P1) in the clayey catchment with properties and present / future doses previously described in section 3.2.2. Note that high percentage change, e.g. for P2 Ordinary herbicides in sandy catchments is due to change in orders of magnitude small absolute values, e.g. between 10^{-2} and 10^{-5} (1000 %).

3.4.3 Changes in water balance

Water balances for both catchments are extracted for the present and future climate conditions. Both present (1961-1990) and future climate (2031-2060) periods are recycled to extend the 30 years simulation to 140 years, in order to obtain a warming up for stabilizing hydraulic heads and to allow the leached solutes to reach deeper groundwater domains. Results for both water and solute balance are extracted for the last 25 years of simulation, and error in water balance never exceeds 1 %. No calibration of the models has been performed and focus is solely on the simulated differences in water (and solute) balances due to changed climatic conditions. MACRO simulated water flow, extracted at 1.2 m, enters the sandy catchment model as percolation 5 cm above drain level and reaches the water stream through drainage pipes, overland flow or base flow from the saturated zone (SZ). For the sandy catchment MACRO does not simulate solute flow through drains in the unsaturated zone, whereas it does for the clayey catchment. For both the sandy and clayey catchment water and solute flow is simulated in the micro pore (soil matrix flow) and macro pore (preferential flow) domain, as described previously. Percolation to SZ is not equal for all solutes (pesticides), as pesticides are associated with different crop rotations and irrigation demands for both present and future climate conditions.

Table 39. MACRO simulated percolation input (column 4) to MIKE SHE at catchment scale and distribution to major water balance components (columns 5-7) for P1 (Low-dose herbicides), P2 (Ordinary herbicides) and P4 (Insecticides). OL indicates overland flow. P3 (strongly sorbing herbicides) is not used; P5 Fungicides do not leach.

Catchment	Solute	Climate	Percolation to catchment	Baseflow to River	Drain to River	OL to River
			[mm.yr-1]	[mm.yr-1]	[mm.yr-1]	[mm.yr-1]
Odderbæk	P1	Present	640	41	593	6.7
Odderbæk	P1	Future	706	43	656	7.2
Odderbæk	P2	Present	673	43	622	7.0
Odderbæk	P2	Future	706	43	657	7.2
Odderbæk	P4	Present	676	43	625	7.0
Odderbæk	P4	Future	737	45	685	7.5
Lillebæk	P1	Present	219	0.1	175	5.4
Lillebæk	P1	Future	280	0.1	226	6.4

From Table 39 it is seen that the main part of the MACRO imposed percolation from the root zone is routed through the draining system to the river recipient, whereas a lesser part is infiltrating to groundwater and contributing to the river flow as base flow, or overland flow. For the sandy catchment, changed accumulated percolation as a result of changed climatic forcing imposed to the MACRO model is leading to an increase in drain to river, base flow and overland flow of 9.6 %, 4.4 % and 6.1 % respectively for P1 Low-dose herbicides. For P2 Ordinary herbicides the increases are 5.3 %, 0.4 % and 1.7 %, and P4 Insecticides 8.9 %, 3.9 % and 5.9 %. For the clayey catchment (Lillebæk) increase in the drain and overland flow to the river is 23 % and 21 % for future climate conditions as compared to present. The base flow component for the clayey catchment is low, MACRO simulated percolation is routed to drain, and unchanged for changed climatic conditions. Note that for the clayey catchment, in addition to the drain and overland flow components in Table 39, the remaining part of incoming percolation leaves as drainage and flow across the catchment boundary.

3.4.4 Changes in solute balance

Pesticides solutes that are not degraded or sorbed in the unsaturated zone, simulated by MACRO, are propagated to the MIKE SHE catchment model, as described in a previous section. Solutes that enter the groundwater zone (SZ) of the catchment model as an upper boundary either stay in SZ as a storage component or leave the saturated zone as overland flow, baseflow to the river, drainage to the river, unsaturated zone or remaining sinks (e.g. well extractions). This is illustrated in Table 40 and 41 in which SZ input is taken as 100 % and SZ output and storage a fraction of this. The remaining, i.e. SZ-input minus SZ-output and SZ storage, is the deviation and represents a model error.

Table 40. Changes in solute balance components between 140 years MIKE SHE – MACRO simulations, 1961-1990 (present) and 2031-2170 (future). SZ denotes groundwater zone – balances for entire 140 year simulations.

Catchment	Solute	SZ input change	SZ output change	SZ storage change
		[%]	[%]	[%]
Odderbæk	P1 Low-dose herbicides	+53	+58	+7
Odderbæk	P2 Ordinary herbicides	-90	-91	-95
Odderbæk	P4 Fungicides	-88	-88	-89
Lillebæk	P1 Low-dose herbicides	>>+100	>>+100	>> +100

From Table 40 it is seen that for pesticide P1 Low-dose herbicides in the sandy catchment SZ input and output averaged for the whole catchment increases with 58 %, whereas storage increases with 7 % under future climate conditions as compared to present climate which renders a larger amount available for an increase in pesticide output from the saturated zone to surface water and ground water recipients. For pesticide P2 Ordinary herbicides the situation appears to be vice versa, i.e. decrease in SZ input and output under future conditions to 90 % and 91 % respectively as compared to the present climate scenario. Also a decrease in SZ storage of the same order of magnitude is simulated. For pesticide P4 Fungicides a similar decrease is simulated. In the case of the clayey Lillebæk catchment solute input, output and storage are all much larger for the future climate scenario. However, simulated absolute values are several orders of magnitude smaller and must therefore be treated with caution.

Table 41. Change in solute balance for last 25 years of 140 years MIKE SHE simulations, 1961-2100 (Present) and 2031-2170 (Future). SZ denotes groundwater zone – balances for last 25 years of 140 years simulations.

Catchment	Solute	SZ input change	SZ output change	SZ storage change
		[%]	[%]	[%]
Odderbæk	P1 Low-dose herbicides	+71	+80	-7
Odderbæk	P2 Ordinary herbicides	-89	-91	-81
Odderbæk	P4 Fungicides	-89	-89	-91
Lillebæk	P1 Low-dose herbicides	>>+100	>>+100	>>+100

Table 41 indicates for the last 25 years of 140 years model simulation changes in solute balance components is in the same order of magnitude as for the entire 140 years as shown in Table 40.

Most of the pesticide solute leaving the groundwater zone is through drainage to the river and in the order of magnitude 85-95 %. Here pesticide P1 Low-dose herbicides lie in the high end (app. 94 % for both present and future climate). Next most important recipient is from the groundwater zone to the river via base flow, varying from 4 to 11 % of with lowest values for pesticide P1 Low-dose herbicides. It must be noted that MACRO simulated input to the MIKE SHE model of the clayey catchment as compared to the sandy is several orders of magnitude lower and absolute values of contributions to overland flow, base flow and drain to river are very low and data must be considered with caution.

3.4.5 Changes in groundwater concentrations

Concentrations of pesticides in the various geological layers of the saturated zone (groundwater) are computed for the last 25 years of the 140 years simulation. The spatial distribution and thickness of the geological layers is specified as GIS layers in the model as explained in the methodology section.

Table 42. Change for present vs. future climate scenarios in MIKE SHE-MACRO simulated pesticide mean concentrations for the last 25 years of 140 years simulations in Layer-1 (closest to surface) to Layer-6 (deepest groundwater) in sandy catchment.

Catchment	Solute	Climate	Layer-1	Layer-2	Layer-3	Layer-4	Layer-5	Layer-6
			[%]	[%]	[%]	[%]	[%]	[%]
Odderbæk	P1 Low-dose Herbicides	Future	+56	+99	+49	+41	+33	+31
Odderbæk	P2 Ordinary herbicides	Future	-93	-93	-93	-93	-92	-92
Odderbæk	P4 Fungicides	Future	-91	-91	-91	-91	-91	-91

From Table 42 it appears that for the sandy catchment between 31 % and 99 % higher mean concentrations are simulated for pesticide 1 under future climate scenario conditions. Quite opposite are the lower simulated mean concentrations for both pesticide P2 Ordinary herbicides and pesticide P4

Fungicides with around 7 % and 11 % respectively for future climate conditions as compared to present climate conditions. This tendency is also clear from simulated maximum concentrations for, which the same order of magnitude change is observed, although even higher increases for future scenarios are indicated for pesticide P1 Low-dose herbicides, but lesser so for pesticide P2 Ordinary herbicides. No meaningful comparison between present and future scenario conditions is possible for simulated mean concentrations in the clayey catchment as mean concentrations are zero under present conditions and still very low under future conditions, and thus omitted in Table 42. This is, however, possible for the simulated maximum concentrations (Table 43), although (absolute) data is still in the same low order of magnitude and should be treated with caution. Table 43 expectedly shows a larger difference, as compared to mean values in Table 42, between present and future values for pesticide P1 Low-dose herbicides. For pesticide P2 Ordinary herbicides differences are somewhat smaller and remain about the same for pesticide P4 Fungicides.

Table 43. Change in MIKE SHE-MACRO for present vs. future scenarios for simulated pesticide maximum concentrations for the last 25 years of 140 years simulation in Layer-1 (closest to surface) to Layer-6 (deepest groundwater) in sandy catchment.

Catchment	Solute	Layer-1	Layer-2	Layer-3	Layer-4	Layer-5	Layer-6
		[%]	[%]	[%]	[%]	[%]	[%]
Odderbæk	P1 Low-dose herbic.	+50	+29	+102	+104	+102.7	+91
Odderbæk	P2 Ordinary herbic.	-100	-73	-72	-79	-85	-93
Odderbæk	P4 Fungicides	-86	-90	-90	-90	-89	-89
Lillebæk	P1 Low-dose herbic.	+408	+606	+433	+500	+600	+400

3.4.6 Changes in concentrations in surface water

MACRO simulated pesticide enters the MIKE SHE model as an upper boundary condition and can reach surface water, i.e. streams in the catchment, either directly via overland flow or drainage, or indirectly through base flow from the saturated zone (groundwater aquifer). Solute concentrations are calculated for each computational node in the river streams and extracted at the most downstream point of the stream. In the sandy catchment there are eight streams included in the simulations, whereas in the clayey catchment there are 12. From Table 38 it is clear that by far the largest contribution to surface water is from drainage, and from the water balance changes between present and future climate scenarios it is also clear that an increased amount of MACRO simulated percolation and increased intensity of percolation, as a result of corresponding rainfall conditions as input to the MACRO model, is directly reflected in an increased drainage, both amount and dynamics. Figure 40-42 show results for pesticide P1 Low-dose herbicides, pesticide P2 Ordinary herbicides and pesticide P4 Fungicides concentrations, aggregated as an accumulated measure, in the sandy catchment and 3 streams, i.e. Odderbæk stream, Riskjær stream and Lerkenfeldt stream. Simulated concentrations at the most downward node for each stream are accumulated for the final 25 years of the 140 years simulations and then normalized relative to the highest accumulated value for that period. In that way both temporal dynamics and overall highest accumulated concentrations in the streams can be readily identified and compared for pesticide P1 Low-dose herbicides, P2 Ordinary herbicides and P4 Fungicides as well as for different streams. The results show that for pesticide P1 Low-dose herbicides, Figure 40, the normalized accumulated concentration is highest for leaching under future climatic conditions and temporal dynamics dominated by a large MACRO simulated peak input, for all three streams. Thus the sudden increase in the curve for the future climatic scenario is caused by a large pulse in MACRO simulated pesticide leaching from preferential flow in the root zone to the river system via MIKE SHE simulated drainage. In contrast, for pesticide P2 Ordinary herbicides Figure 41 the normalized accumulated concentration is highest under present climatic conditions, and temporal dynamics for Riskjær stream appears to be different from the other two pesticides. Note that the slope of the curve representing present accumulated concentrations is steeper for the future scenario, indicating larger temporal gradients as a result of increased precipitation input to the MACRO model. Also for pesticide P2 Ordinary herbicides inclination points, most clearly for the Riskjær stream, can be observed caused by increased preferential flow in the root zone to the river system through drainage. Finally for pesticide P4 Fungicides (Figure 42) temporal dynamics, resembling pesticide P2 Ordinary herbicides also shows steeper curves for the future scenario, and also a higher normalized accumulated concentration. The results are not easily interpreted from the MACRO propagated data from UZ to SZ. Table 38 shows that for pesticide P1 Low-dose herbicides there is an 43 % increase in accumulated leaching from present to future for dairy farming, assigned to areas that do not drain to the river, but either do not drain or to the catchment boundary. The arable farming type is assigned to areas draining to the river system, and here accumulated leached pesticide P1 Low-dose herbicides concentration is less for future scenarios. The combined effect results in higher concentrations for pesticide P1 Low-dose herbicides in the three selected streams. For pesticide P2 Ordinary herbicides (Table 38) there is an increase in accumulated leaching for the dairy farming, assigned to non-draining areas whereas there is a large decrease in leaching for arable farming type, which is controlling the lesser concentrations for P2 Ordinary herbicides in Figure 41. The same, as for pesticide P2 Ordinary herbicides, applies to pesticide P4 Fungicides. This requires a more in-depth analysis and an identification of sensitive, controlling, factors.

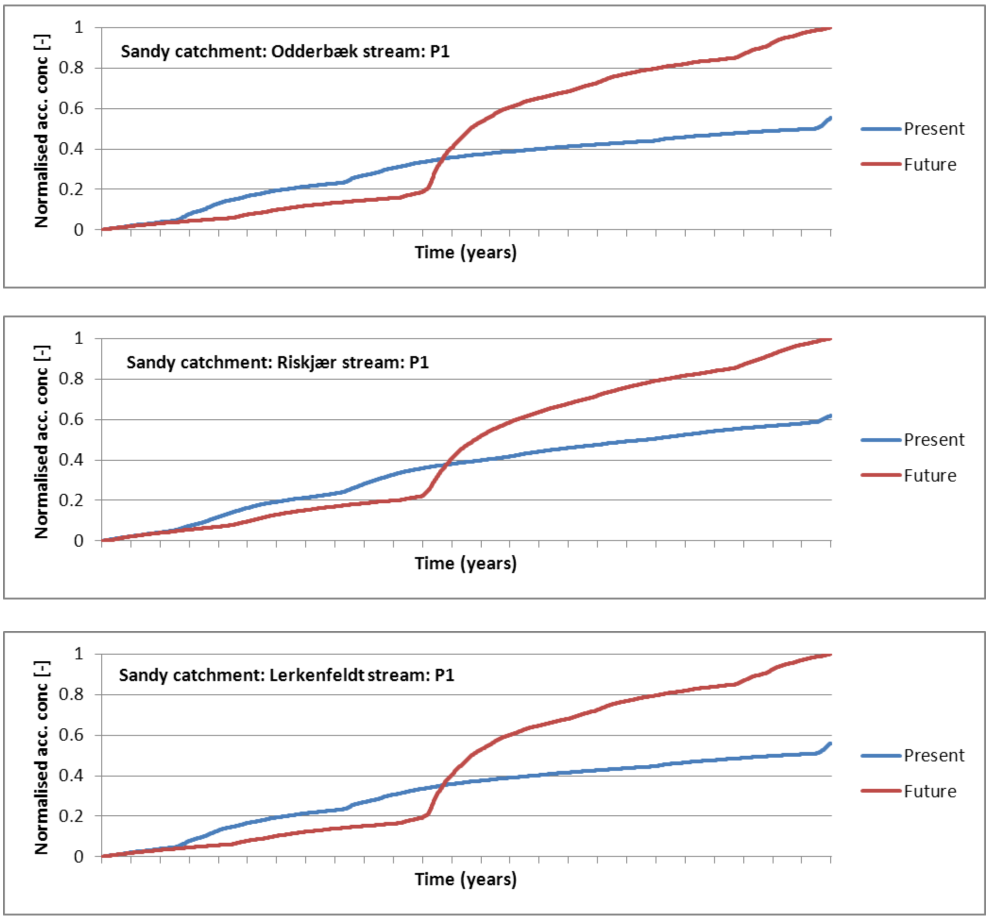


Figure 40. Normalised accumulated MACRO-MIKE SHE simulated pesticide P1 Low-dose herbicides concentrations for the last 25 years of 140 years simulation at the most downstream point of the Odderbæk, Riskjær and Lerkenfeldt stream. Time axis represents 2075-2100 and 2145-2170 for present and future scenario respectively.

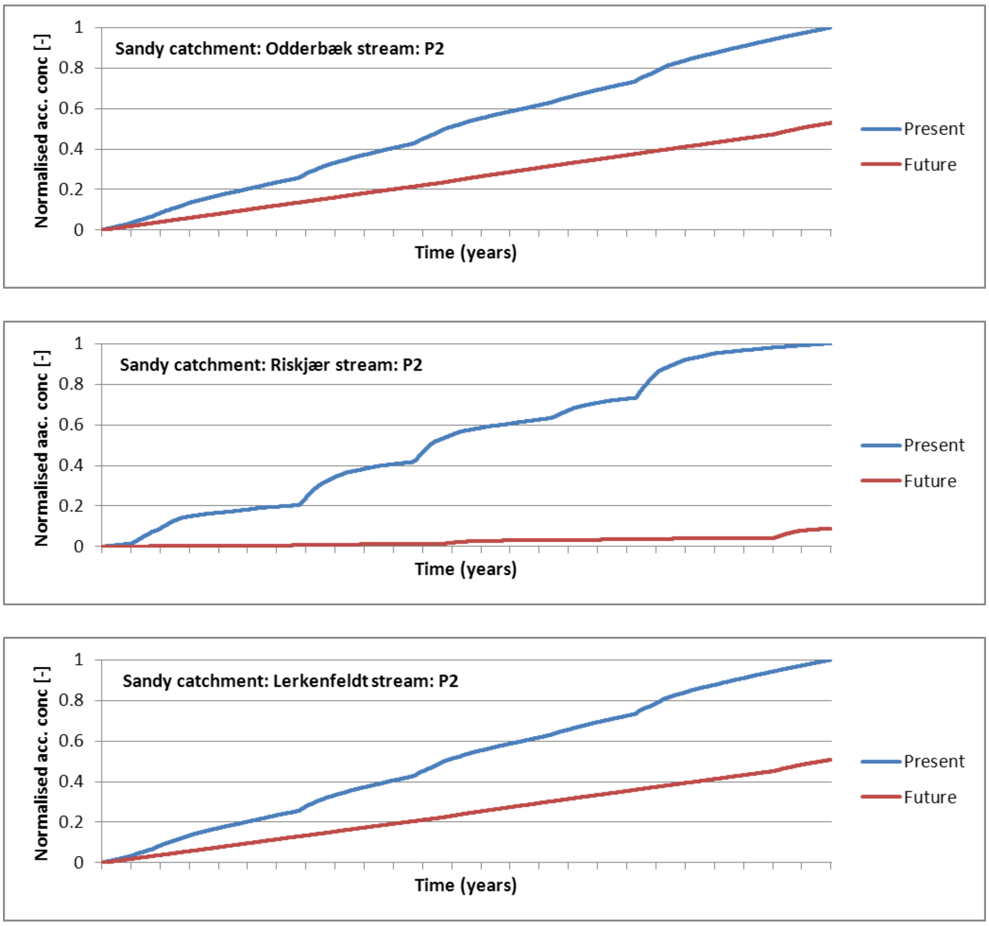


Figure 41. Normalised accumulated MACRO-MIKE SHE simulated pesticide P2 Ordinary herbicides concentrations for the last 25 years of 140 years simulation at the most downstream point of the Odderbæk, Riskjær and Lerkenfeldt stream. Time axis represents 2075-2100 and 2145-2170 for present and future scenario respectively.

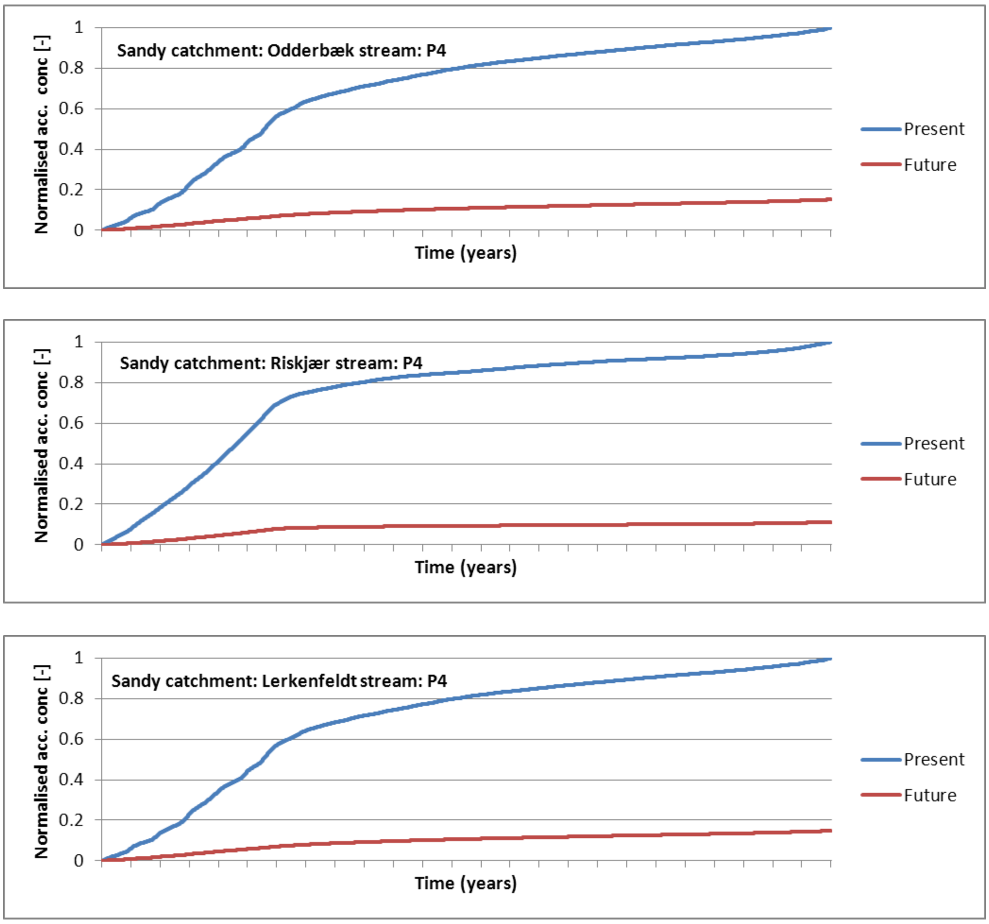


Figure 42. Normalised accumulated MACRO-MIKE SHE simulated pesticide P4 Fungicides concentrations for the last 25 years of 140 years simulation at the most downstream point of the Odderbæk, Riskjær and Lerkenfeldt stream. Time axis represents 2075-2100 and 2145-2170 for present and future scenario respectively.

4 Discussion

4.1 Downscaling climate change impacts to pesticide leaching dynamics

Observations of temperature, precipitation and reference evapotranspiration from the period 1961-2006 are available from the two climate stations, Jyndevad in Southern Jutland and Tystofte on the south-eastern corner of Zealand. The data was divided into two periods, where the first covers the period 1961-1990 and the second 1991-2006. The first period represents the control period of the climate model. The control period data was tested statistically for trends and these were in no case found to be significant on a 5 % significance level. Hence, the data represents a stationary climatic period that is well suited as a reference period for climate change studies.

At both stations the temperature were found to increase from the control period to the validation period 1991-2006, at Jyndevad with 0.8 ºC and at Tystofte with 0.7 ºC. In both cases this is in the same order of magnitude as the standard deviation on the annual values. The same tendency was found for reference evapotranspiration, where changes of 30 mm/y and 54 mm/y were found for Jyndevad and Tystofte, respectively, which is similar to or larger than the standard deviations. Precipitation did, however, not show significant changes. The small increases in precipitation at the two stations were much lower than the respective standard deviations.

Based on a screening of results from several climate models available from the ENSEMBLES project two models were selected for further analysis. Results from the two climate models were examined with respect to spatial distribution of precipitation in Denmark. This showed that the Dutch climate model RACMO was able to reproduce the variation of annual mean precipitation over Denmark significantly better than the British climate model $HadRM_3$. The RACMO model was able to reproduce the precipitation maximum in western Jutland and the gradient of decreasing precipitation from west to east in Denmark. Hence, the RACMO model was selected as the basis for the remaining project. It should be emphasized that the choice of regional climate model is very important for the results of the current project. The result produced with the different climate models in the ENSEMBLES project show a pronounced variability and especially with respect to precipitation, large differences between the models are found. This is expected to be important for the analysis of the impact on pesticide leaching. Hence, it should be emphasized that there is a significant uncertainty on the climate model results used here. This uncertainty is not taken into account in the current study.

Comparison of climate model results to observations for the control period (1961-1990) from the two climate stations Jyndevad and Tystofte showed that temperature is reproduced relatively well by the model with a maximum bias of 0.4 ºC on mean annual temperature for Jyndevad. However, with respect to precipitation and reference evapotranspiration relatively large biases were found. Precipitation is overestimated at both stations, with 78 mm/y and

238 mm/y at Jyndevad and Tystofte, respectively. The bias on reference evapotranspiration was in the same magnitude at both stations with an underestimation of approximately 90 mm/y. additionally, the extreme precipitation events were found to be underestimated by the climate model, despite the overestimation in mean annual precipitation. Especially for Tystofte the biases are of a magnitude that is not acceptable for hydrological modelling. Therefore, the climate model results cannot be used directly as input to a pesticide simulation model but need to be corrected for biases beforehand.

Four different methods for bias correction of the climate model results were tested. Two of the methods use observed data as baseline for the future climate where correction factors are derived from the difference between climate model results representing the control and the scenario period. The fundamental assumption to this approach is that the model biases remain constant through time, which means that the change in meteorological variables as simulated by the climate model is assumed to be more accurate than the absolute values. The method does not take changes in number of wet days or variability into account because it only scales the mean, maximum, and minimum values of the observed baseline data set. Nevertheless, the method has been applied in many hydrological impact studies (e.g., Andréasson et al., 2004; Arnell, 1998; Bergström et al., 2001; Graham, 2004; Graham et al., 2007a,b; Lettenmaier et al., 1999; Middelkoop et al., 2001; Reynard et al., 2001), because its simplicity makes it possible to rapidly apply the method to a large set of scenarios or climate models. Additionally, the method implies that the derived time series for the future period have the same temporal trends as the observed time series. In the present case where the observations were shown to be stationary the predictions of future climate will also be stationary within the period upon which the method is derived (typically a 30-year period). This is an approximation to the real developments in future climate which was shown to develop continuously in chapter 3.3.3.

The two other methods use model data as baseline. In this case corrections are based on observed data and climate model data from the control period. The correction can subsequently be applied to a continuous time series of climate model data expanding, e.g., from 2000 to 2100. Hence, the numbers of assumptions are less than for the former method and are therefore appealing to use.

The four methods were tested on the validation period 1991-2006 and the scenario periods 2031-61 and 2071-2100. The results from the four methods show that with respect to the validation period method no. 4, referred to as the Intensity-based method, results in the lowest annual mean bias between observations and bias corrected precipitation for one climate station and the method produces the second best result for the other station. With respect to annual mean maximum precipitation (mean of the maximum precipitation of each year), intensity based method is the most precise. When monthly mean values are examined all four methods produces results that are very similar whereas the intensity based method is superior when monthly mean maximum precipitation (mean of maximum precipitation of each month) is considered. This shows that when extreme events are considered the intensity based method is considerable better than the other three methods. This is expected to be important for the subsequent simulation of pesticide leaching which is sensitive to extreme precipitation events.

When the scenario periods are considered the basic assumption is that the bias-correction methods should be able to reproduce the trends projected by the climate model. Even though the climate model produce results with bias on the absolute magnitude of the climate variables it is expected that the model is able to capture the development with acceptable precision.

For mean annual precipitation, the intensity based method has a tendency to produce higher values than the other methods for the period 2071-2100. However, the method is able to capture the reduction found for Jyndevad in 2031-2060 compared to the validation period which is in favour of this method. If monthly mean values are considered the two methods based on climate model data (method no. 3 and 4) yields a much better representation of the changes predicted by the climate model than the two methods based on observed data (method no. 1 and 2). With respect to maximum precipitation, the method based on climate model data (no. 3 and 4) are significantly better to capture both the mean maximum as well as the relative increase in annual mean maximum values than those based on observed data.

Based on the analysis of the validation period and the two scenario periods (2031-61 and 2071-2100) the intensity based method is found to be the best bias correction method. Especially the extreme precipitation events are captured well by this method, both with respect to the absolute values in the validation period and with respect to the development found in the scenario periods. At the same time the method is producing satisfactorily results for annual mean and monthly mean precipitation. It was therefore suggested that this method should be used for bias correction of the climate model results from the regional climate model RACMO.

The sensitivity analysis in which leaching from the root zone was simulated for 3 selected pesticides supports the view that the intensity based method (4) was likely to be the most appropriate for further use in PRECIOUS. This was motivated by the observation that the method preserves RCM simulated future dynamics and corrects precipitation values depending on its intensity, which is a well-known controlling factor on leaching of pesticides, especially in structured soils. The intensity based method thus in most cases represents a situation with highest simulated pesticide concentrations, especially for the Faardrup location with loamy/clayey soil, as this bias correction accounts for changed future extremes in precipitation and therefore increased risk for preferential flow. Simulated concentrations at 1 m and 3 m b.g.s. (below ground surface) for the future period 2071-2100 are usually lower for the sandy location (Jyndevad) as compared to the period 1961-1990. This is caused by a predicted future increase in temperatures (causing higher degradation) and precipitation (mean and extremes) leading to higher percolation and increased dilution (lower simulated concentrations). For the clayey location (Faardrup) this is often reverse. Here, changed future intensity in precipitation causes increased preferential flow and higher simulated concentrations at 1m and 3m.

4.2 Present and future scenarios for land use and pesticide management

Pesticide use under future climate change depends on crop choice, crop rotations, timing of crop production, and occurrence of problematic weeds, pests and diseases. Here, crop choice and rotations are defined for current and future (2050) climate conditions for two different farm types: dairy farms and for arable- and pig production farms. The crop rotations were defined for sandy and loamy soils respectively based on current crop statistics for two catchments in Denmark. The changes in crop choice, crop management and pesticide use under climate change for 2050 were based on expert judgement from experience from a study tour to Germany and France and from literature on climate change impacts on agriculture. Technological changes in crop and crop management were not included in the scenarios.

The scenarios of crop rotations, crop management and pesticide use for the selected farm types show no changes in rotations of the dairy farming systems, and small changes for the pig farms. In fact it can be argued that the changes for the dairy farms due to climate change have already occurred through the introduction of forage maize into the crop rotations over the past 20 years (Odgaard et al., 2011). For the arable and pig farms the major change will be introduction of some grain maize in the system to replace existing cereals for production of feed for pigs. It is estimated here that this will amount to about of 25% of the rotations being replaced with grain maize, corresponding to projections of climate change effects on crop choice in Denmark (Elsgaard et al., 2012).

This is in accordance with previous research, which shows that a climatic warming will expand the area of cereals cultivation (e.g. wheat and maize) northwards (Kenny et al., 1993; Carter et al., 1996; Fronzek and Carter, 2007; Elsgaard et al., 2012). For wheat, a rise in temperatures will lead to a small yield reduction, which often will be more than counterbalanced by the effect of increased CO_2 on crop photosynthesis (Olesen et al., 2007). On the other hand warm season crops like grain maize will greatly benefit from warmer conditions. Therefore some of the current small-grain cereals will be replaced by grain maize.

The major changes in crop management will occur in timing of farming operations. For winter crops this generally means later sowings, whereas for spring sown crops it means earlier sowings (Ghaffari et al., 2002; Alexandrov et al., 2002; Tubiello et al., 2000; Chen and McCarl, 2001; Olesen et al., 2012). As a consequence of changes in sowing dates and timing of crop development there will also be minor changes in timing of other crop management, including fertilisation and pesticide application.

The scenarios show only small changes in pesticide use for most crops. This is a consequence of the expected changes in weeds, pests and diseases. Most of these estimates were based on interviews with agricultural advisors and crop protection specialists in Germany and France under climatic conditions similar to those resembling the climate change scenarios applied here. The major reason for the small changes in crop protection is that the majority of the pest and disease problems are closely linked with their host crops. This makes major changes in plant protection problems less likely (Coakley et al., 1999). Even so for the crop rotations studies, there is a tendency to higher TFI (increases in TFI of 0.3 to 0.5) in the future scenarios compared with the present, mainly due to increased problems with insects and need for slightly higher herbicide inputs as the growing seasons are extended. The increase is most pronounced in winter oil seed rape.

Conditions are more favourable for the proliferation of insect pests in warmer climates, because many insects can then complete a greater number of reproductive cycles (Bale et al., 2002). Warmer winter temperatures may also allow pests to overwinter in areas where they are now limited by cold, thus causing greater and earlier infestation during the following crop season. Insect pests are also affected directly by the CO_2 effect through the amount and quality of the host biomass (Cannon, 1998). Climate warming will lead to earlier insect spring activity and proliferation of some pest species (Cocu et al., 2005). A similar situation may be seen for plant diseases leading to an increased demand for fungicides (Salinari et al., 2006), although the changes proposed based on the experiences from France/Germany is not of major size. Impact from changes in temperatures has been investigated for major diseases in arable crops, and for a significant number of diseases more favourable conditions can be expected (Jørgensen, 2011). Most of these changes will however still be covered by the current fungicide practise.

Changes in climatic suitability may lead to invasion of weed, pest and diseases adapted to warmer climatic conditions (Baker et al., 2000). The speed at, which such invasive species will occur, depends on the change of climatic change, the dispersal rate of the species and on measures taken to combat non-indigenous species (Anderson et al., 2004). The dispersal rate of pests and diseases are most often so high that their geographical extent is determined by the range of climatic suitability (Baker et al., 2000). The Colorado beetle, the European cornborer and karnal bunt are examples of pests and diseases, which are expected to have a considerable northward expansion in Europe under climatic warming. It is particularly for winter rape and grain maize that this is expected to give rise to increased pesticide input in the present crop rotations.

Pesticide use under future climate change depends today also in the future on crop choice, crop rotations, timing of crop production, and occurrence of problematic weeds, pests and diseases. Today the common European agricultural policy questions the increasing dependency of pesticides and supports the concept of integrated pest management (IPM) by establishing a framework for community action to achieve the sustainable use of pesticides (Directive 2009/128/EC). The new framework directive states that by 2014 all EU members must have implemented IPM, with the aim to reduce the impact and use of pesticides. This includes more widespread use of alternative methods/cultural methods and pesticides, which can help to minimize pest, disease and weed problems. How and when implementation of this framework will influence the proposed scenarios is unclear, but as Denmark already has a relatively low use of pesticides in comparison with other countries the impact might be relatively low (Jørgensen & Jensen, 2011).

Other political elements might also have a major impact on the actual use pattern and choices of pesticides in the future. A new tax system is expected to be introduced in Denmark ranking taxes depending on expected impact on human health and environmental. As the pricing of products could be significantly influenced by this system, the farmers preferences and chooses could be influenced to a great extent compared with the solutions used today.

4.3 Modelling pesticide at field scale

Based on the present and future scenarios of crop rotations, crop management, and pesticide use for the two selected farm types (arable and dairy), MACRO-model-scenarios have been setup with the purpose of evaluating the implication of future climatic factors both direct (precipitation, actual evaporation, and temperature) and indirect (changed land use and pesticide application pattern) on leaching to the aquatic environment from the variable saturated sandy soil (Jyndevad) and loamy soil (Faardrup).

This evaluation has aim at describing the implications of future climatic factors on pesticide leaching to the aquatic environment as realistic as possible. Whether the choice of grouping the pesticides in five categories was correct can always be discussed. Especially by including strongly sorbing herbicide like glyphosate in the evaluation can be discussed, since the processes controlling the leaching of these compounds are not fully understood and therefore not included in MACRO (Aagaard et al., 2011). Hence the modelling-procedure applied in this evaluation is in line with the regulatory risk assessment procedure.

4.4 Catchment scale pesticide transport in groundwater

A catchment scale model MACRO-MIKE SHE is applied for simulating changes in pesticide concentrations to the aquatic environment. The MACRO model is used to model the effect of changes in climate and pesticide management on pesticide leaching from the unsaturated zone to recipients, i.e. groundwater and surface water. Simulated percolation as well as solute flow from the MACRO model is propagated to the MIKE SHE model. The output of the MACRO model is therefore an upper boundary condition for the MIKE SHE model Catchment scale simulations for the sandy catchment (Odderbæk) and the clayey catchment (Lillebæk) for 5 selected pesticides is leading to the following observations:

- Increased percolation simulated by the MACRO model and propagated to the MIKE SHE model nearly all ends up in increased drainage to the river. Other recipients, base flow (groundwater to surface water) and surface water thus receive much less.
- Pesticide solute entering the groundwater zone (SZ) is mainly leaving SZ via drainage (85-94%), base flow to the river (4-11%) and overland flow to river (0-3 %)
- For pesticide P1 Low dose herbicides in the sandy catchment future climate simulations render a larger amount available for an increase in pesticide leaching to surface water and ground water recipients. For P2 Ordinary herbicides the situation appears to be vice versa, i.e. decrease in pesticide leaching to recipients in the case of the clayey Lillebæk catchment simulated absolute values of pesticide concentrations in surface and groundwater are several orders of magnitude smaller and must therefore be treated with caution.

4.5 Conceptual challenges and the way forward

The modeling approach chosen is subject to conceptual challenges when pesticide transport is modeled at the spatial scale of a catchment. There are several steps in the modeling process that introduce conceptual difficulties and in which there may be substantial uncertainty. It is important that such difficulties and uncertainties are made explicit and transparent when the results are interpreted. It is important to keep in mind that the purpose of the modeling study has been to explore the effect of future climate on pesticide leaching to the aquatic environment as compared to the present situation. Therefore, the same uncertainties in the modeling concept apply to both the present and future climate scenarios and differences in model result rather than absolute values are the main outcome. This is elaborated on in the section below.

The modeling concept departs from combining a one dimensional root zone leaching model and a catchment scale integrated groundwater – surface water model, i.e. one dimensional soil columns are represented by a model (here MACRO) and, so to speak, put on top of a catchment scale model (here MIKE SHE). This concept can be considered when it is important to combine the most up-to-date process understanding related to: 1.) pesticide compound degradation and sorption as well as the partitioning between water and solute flow in the matrix and in fractures in the unsaturated zone, root zone; and 2.) process understanding of pesticide transport in ground and surface water at a larger scale (e.g. Jarvis, 2007). This has previously been reported by Stenemo et al. (2005) for a similar combination of the three dimensional integrated FRAC3DVS model and MACRO for a 40 m by 40 m site near Havdrup in Denmark. When distributing soil profiles (columns) that represent a grid in a catchment scale model, no account is taken of heterogeneity in the unsaturated zone (root zone) within a grid, whereas the heterogeneity in the saturated zone is represented in the specified geological layers. In this study, the root zone simulations are based on Jyndevad and Faardrup soil profiles that are assumed to represent the soils in the sandy Odderbæk catchment and the clayey/loamy Lillebæk catchment, so soil properties used in the root zone simulations do only approach mean properties of the catchments and no account is taken of heterogeneity in soil properties at catchment scale. However, as the root zone simulations based on the same soil properties provide water and solute flow to the MIKE SHE model for both the present and future scenarios, this still provides useful changes in water percolation and leached pesticide. To account for soil heterogeneity, varying soil properties in the catchment scale model could be applied, i.e. Monte Carlo type simulations, although this is computationally demanding at this scale. Stenemo et al. (2005) used Monte Carlo simulations for the Havdrup site and aggregated output from these was propagated to the FRAC3DVS mode. However, this was at a much finer spatial discretization and for a much less area as compared to this study. Only diffusive leaching as a result of normal agricultural practice is simulated and no account is taken of conceivable point source leaching. This would be an issue when trying to compare model results to actual measured concentrations in surface and groundwater, but as changes in simulations are in focus this is not a major factor. The vertical and horizontal discretization of the MIKE SHE model is probably too coarse for accurate solute transport simulations. The coarse vertical solution following the geological layers results in too high dilution of MACRO simulated pesticide, also reported by Styczen et al. (2004), and renders it intractable in all cases except for pesticide P1 Low dose herbicides.

A conceptually not yet resolved issue is that the root zone model MACRO and MIKE SHE are sequentially (‘loosely’) coupled, as in similar studies by Stenemo et al. (2005) for a location near Havdrup and earlier on by Loage et al. (1998). This means that no feedback from MIKE SHE to MACRO, i.e. the ground water flow to the unsaturated zone is simulated. This is potentially problematic when the groundwater level is so close to the surface that upward flow can be expected, and therefore a ‘loose’ coupling should be applied in areas where downward flow is dominant, i.e. in groundwater recharge areas. The groundwater level controls drainage flow, both through drainage pipes and as subsurface and overland flow to surface water recipients. This could partly be accommodated by retrieving simulated ground water level by MIKE SHE for present and future climatic conditions and use this information as a lower boundary of the MACRO model. A weakness of this approach is that different models for simulating processes in the unsaturated zone would be needed, i.e. first one of the modules builds in the MIKE SHE model and then the MACRO model. Simulated water and solute received from MACRO enters the MIKE SHE and from there a major part is leaving the saturated (groundwater) zone through MIKE SHE simulated drain flow. A conceptual problem rises as MACRO simulates except water and solute flow also drain flow (the latter for Lillebæk only), but MACRO simulated drain flow cannot conceptually be connected directly to MIKE SHE simulated drain flow. A coupled, either fully or by OpenMI (www.openmi.org) is not envisaged. Styczen et al. (2004) applied an integrated coupled MIKE SHE – SD (Sorption-degradation module) for simulating pesticide fate and transport in the Odderbæk and Lillebæk catchments. Although reasonable results were reported in this study (Styczen et al., 2004) the availability of calibrated MACRO models based on PLAP scenarios and the generally recognized and well documented ability of the in Danish regulation used MACRO model lead to the modeling approach applied here. For future research, developments in coupling MIKE SHE and the Daisy model (Abrahamsen & Hansen, 2000) with improved pesticide leaching simulation capabilities.

For pragmatic reasons the two agricultural management types, i.e. arable and dairy farming, are indirectly connected to the dominant soil types in the two catchments. The Odderbæk and Lillebæk catchments are predominantly sandy and clayey respectively. Instead of distributing farming types according to their respective soil types this was pragmatically done by assigning them to areas in the catchment that were drained to nearest river and to not-drained to nearest river under the assumption that clayey soils usually are drained whereas sandy soils are not. A better solution for this would be to perform a GIS analysis to locate the actual land management (arable and dairy) and distribute MACRO simulations accordingly. Again, the same procedure is followed for both present and future scenarios and for comparative results this probably has no major consequences.

The MACRO model is calibrated for the Jyndevad and Faardrup PLAP scenarios, but not for the sandy Odderbæk and clayey Lillebæk catchments. A root zone model like MACRO cannot feasibly be calibrated, and seldom done, as water percolation from the bottom of the profile is seldom measured. Here we rely on MACRO as ‘state-of-the-art’ and well documented elsewhere. Furthermore, processes controlling the leaching of strongly adsorbed compounds are not well understood (section 4.3) and this places restrictions on the simulation results by MACRO. The catchment scale MIKE SHE model has been calibrated for water balance in the two LOOP catchments, LOOP2 (Odderbæk) and LOOP4 (Lillebæk). MIKE SHE has been calibrated for water balance for LOOP simulations, but the models water balance should be recalibrated when receiving water from MACRO as upper boundary condition.

5 Conclusion

A warmer climate with more precipitation and changes in soil water content will shift sowing and planting dates and change crop development times, generally leading to faster development, including earlier flowering, earlier sowing of spring crops and later sowing of autumn crops. This will have consequences for the timing of pesticide applications. The scenarios based on A1B 2031-2061 (with reference period 1961-1990) show only small changes in pesticide use for most crops. However, there is an overall tendency towards increased use of pesticides. At the same time, an increased intensity and amount of precipitation is projected by the selected climate model (RACMO). For the crops rotations studied, there is a tendency to higher TFI (increases in TFI of 0.3 to 0.5) in the future scenarios compared with the present, mainly due to increased problems with insects and need for slightly higher herbicide uses as the growing season are extended. The increase is most pronounced in winter oil seed rape. The RACMO climate model inputs indicate that precipitation for Denmark will increase from about 1005 mm/year to 1030 mm/year for 2041-60, whereas temperature is expected to increase from around 8 to 9.5 ^{o}C.

The following conclusions have been derived based on MACRO model scenarios for the two selected farm types (arable and dairy) for the variable saturated sandy soil (Jyndevad) and loamy soil (Faardrup) and for five selected model pesticides (P1 Low-dose herbicides, P2 Ordinary herbicides, P3 Strongly sorbing herbicides, P4 Fungicides and P5 Insecticides):

- Despite general increase in use of pesticides, no drastic increase in pesticide-leaching of strongly sorbing herbicides, fungicides, and insecticides is to be expected. This outcome is primarily given by the sorption properties and processes included in MACRO and therefore affected with high uncertainty for the strongly sorbing herbicides where colloid-facilitated transport is not included. An increased leaching of the low-dose herbicides is though to be expected together with a minor increase in the leaching of ordinary herbicides.
- Direct climatic factors (changes in precipitation, temperature and Evapotranspiration) will have implications for pesticide-leaching through especially loamy soils (increased macropore flow) and only minimal effects for sandy soils.
- Indirect climatic factors (changed crop and pesticide management practice) will have a minimal or reducing influence on pesticide-leaching at loamy soils and negligible at sandy soils.
- The overall leaching risk on sandy soils posed by future climatic factors seems to be decreasing under arable agricultural management and increasing under diary agricultural management.
- The overall leaching risk on loamy soils posed by future climatic factors seems to be increasing under both arable and diary agricultural management.
- Introduction of grain maize on loamy soils under arable agricultural management (pig farms) will result in higher leaching of low-dose herbicides to the aquatic environment via bulk matrix (both micropores and macropores) and drains,

- Dairy agricultural management will result in increased leaching of low-dose herbicides via macropores and peak concentrations via bulk-matrix, macropores and drains.
- Only peak concentrations of the low-dose herbicide and fungicide leaching from 1.2 meter depth on sandy soil exceed the maximum allowed concentration of 0.1 μg L^{-1}.

A MACRO-MIKE SHE catchment scale model has been applied for simulation of changes in pesticide concentrations in groundwater and to the aquatic environment for two hypothetical catchments (configured over Odderbæk and Lillebæk LOOP hydrogeological settings, combined with Jyndevad/Faardrup climate data inputs). The results of the hypothetical MACRO-MIKE SHE catchment model simulations indicated for the sandy catchment an increase in mean concentrations in groundwater by 30-99 % for low dose herbicides under future climatic conditions, whereas mean concentrations decreased for ordinary herbicides and fungicides by app. 93 and 91 % respectively. In the sandy catchment, future climatic conditions lead to higher concentrations in surface water for low dose herbicides, but to decreased concentrations for pesticide ordinary herbicides and fungicides.

6 Perspectives

In this section the political-administrative and regulatory implications of the results of the PRECIOUS project will be briefly discussed. After that, we will discuss the future scientific research needs from downscaling of climate impacts on pesticide leaching risks to modeling of pesticide leaching and transport to groundwater and aquatic environment at catchment scale.

According to EUs framework directive on sustainable use of pesticides, the protection of the aquatic environment is expected to be enhanced. The member States will have to create the necessary conditions for implementing Integrated Pest Management (IPM), which would become mandatory as of 2014. In the context of IPM, the EU would draw up crop-specific standards, the implementation of which would be voluntary and a set of harmonized indicators is expected to be developed to measure progress in implementing the strategy. Furthermore, existing legislation on pesticides will be amended to integrate other measures such as improving the way compliance with the legal requirements is monitored, promoting low pesticide-input farming, reinforcing annual monitoring programs on residues of pesticides in food and feed, determining pesticide concentration in water and intensifying research on pesticides.

These changes in regulation practices within EU as well as introduction of new cut-off criteria, which might limit the number of available activities significantly that, could have major impact on the validity and credibility of the developed agricultural land use scenarios developed and used in PRECIOUS. Furthermore, foreseen governmental adjustments of taxes on pesticides in Denmark, could impact the price setting in agriculture, and thus farmers decisions regarding pesticide management and use in agriculture.

It is most likely that the use of low-dose herbicides (P1) could be increased compared to use of ordinary and strongly absorbing herbicides, which is problematic due to the increased leaching risk of low dose herbicides in a future warmer climate. Increasing use of low dose herbicides could also lead to a higher risk of herbicide resistance weed species, which again will require other activities or means of managing weeds in the fields.

The regulatory practice for approval of new pesticides in Denmark is based on climate data for 1961-90 from a selected Hamburg dataset. These data therefore do not incorporate climate change effects on precipitation and temperature, which has already resulted in increased observed precipitation and temperature for 1991-2010 compared to 1961-90. It is therefore recommended, that the used “normal climate periods” (1961-90), which has been used assuming stationarity in climate, should be updated at a 10-year basis, in order to adapt data to non-stationarity, which is already seen due to climate change. Since, farmers and agriculture adapt rapidly to changing climate and economic conditions (within very few years), and since approval of pesticides are updated every 10 years, the regulatory approval of pesticides do not necessarily need to include projections of climate change with downscaling to pesticide leaching from root zone or to catchment scale, groundwater and aquatic environment.

Since the EU framework on sustainable pesticide management call for a generally enhanced protection of vulnerable areas (through buffer strips, low spray drift equipment and designation of areas of reduced or zero pesticide use) it is important that guidelines for evaluation of protection zones in terms of groundwater and surface water pollution risks follow use appropriate time downscaling approaches, time perspective and scenario development and follow the learning from PRECIOUS, e.g. by using the histogram bias correction method (intensity based correction), which provide a worst case scenario for such assessments. Since both direct and indirect climate effects by PRECIOUS have proven to be significant for the evaluation, it is recommended to include such scenario development of changes in land use and pesticide use and management as established in the reported scenario development in PRECIOUS, where five model pesticides was selected for covering the entire spectrum of pesticides (from low dose, ordinary, strongly sorbing herbicides to fungicides and insecticides).

Finally, the best available tools for integrated modeling of pesticide leaching from the root zone and catchment modeling should be selected and used in order to analyze areas designated for reduced or zero pesticide use. At the moment there are no available real operational tools for practitioners for integrated modeling of pesticide leaching to groundwater and the aquatic environment, more research therefore is needed within this field in order to develop better tools and guidelines for authorities and their consultants at different scales, for especially development of conceptual models and numerical integrated catchment scale models. Furthermore, guidelines for uncertainty assessments as part of non regulatory pesticide modeling projects (e.g. Water Framework Directive) should be established covering uncertainties in data, integrated numerical modeling and scenario development especially as part of pesticide transport modeling at different scales.

The scenarios used in PRECIOUS has quite a small difference in farming and quantities used as input for the modeling of leaching with MACRO, causing the difference in simulated pesticide concentrations also to have been small (MIKE SHE). Simultaneously, the absolute values also have been small especially when compared to dilution effects in groundwater. In retrospect it might have been more appropriate to take 2071-2100 as a future scenario with regard to climate input in order to run the modeling with a “stronger signal”. However, it most likely would have been difficult to define pesticide use for such a distant future. Instead, the PRECIOUS project therefore has included a first example of modeling of pesticide leaching and transport based on recycling of 30 year time series of 6 year crop rotations, for a near future, and for regulatory assumption.

Some processes has not be covered by the modeling, and thus the description of processes important for modeling pesticide leaching and transport of strongly sorbing herbicides lacks credibility and results therefore should be evaluated carefully, due to these limitations. Therefore, even though the results of PRECIOUS indicate, that despite general increase in use of pesticides, no drastic increase in pesticide-leaching of strongly sorbing herbicides, fungicides, and insecticides is to be expected to groundwater and subsequently the aquatic environment, this finding therefore should not be overemphasized, due to the limited (or poor) process description of strongly sorbing pesticides that has been used, and the lack of integration regarding especially the description of drain flow mechanisms, which the loose coupled MACRO/MIKE SHE is not able to handle properly.

The coupling of 1D root zone model (MACRO) with 3D basin model (MIKE SHE), and grid size / the relatively coarse description in the form of 6 model layers in the saturated zone causes that the simulated concentrations are very low. The significance of the heterogeneity within a calculation grid is also not described.

A further development and testing of integrated and more operational modeling tools that can describe the site specific flow and transport of pesticides with all relevant flow and transport processes is needed. Especially, feedback processes due to highly fluctuating groundwater levels, and in some places increased groundwater levels in a warmer climate (instantaneous overland flow) is a challenge, because in order to include prediction uncertainty of climate model inputs, model parameters, and alternative conceptual understandings of processes and geology (heterogeneity) an operational tool is needed. In addition, such development and testing will require a more detailed mapping of the shallow hydrogeology and modeling, including validation/history matching of the transport model with realistic development of scenarios (in addition to intended agricultural usage other usage such as spills, point sources etc. would need to be included when evaluating models predictions towards monitoring data) for present and future climate and land use/pesticide management.

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Appendix A Climate data

A1 Observed climate data

The observed precipitation, temperature and reference evapotranspiration at the two measurement stations were analysed. In Table A1 statistics on annual mean values for precipitation, temperature and reference evapotranspiration are listed for the periods 1961-1990 and 1991-2006.

The most significant difference between the two stations is seen for precipitation. At station 26400 Jyndevad the precipitation exceeds 1000 mm/year and is approximately 50% higher than the value observed at station 29440 Tystofte. Compared to the reference evapotranspiration the mean precipitation is almost twice as high at 26400 Jyndevad and monthly precipitation exceeds monthly reference evapotranspiration in all month except May, June and July. At 29440 Tystofte the precipitation and reference evapotranspiration have comparable magnitudes.

The climate is observed to change slightly from 1961-1990 to 1991-2006. Temperature shows the most significant change with increase of 0.8 and 0.7 ºC at Jyndevad and Tystofte, respectively. Reference evapotranspiration increase by 30 and 54 mm/year at Jyndevad and Tystofte, respectively, while the increase in precipitation is more moderate (17 mm/year at Jyndevad and 35 mm/year at Tystofte). Hence, the data shows a tendency for a warmer climate and, comparing the changes in precipitation and evapotranspiration, also a drier climate (on annual basis).

Table A1. Annual mean precipitation, temperature and reference. evapotranspiration for station 26400 Jyndevad and station 29440 Tystofte in the period 1961-1990 and 1991-2006. The standard deviation of annual mean values is listed in parenthesis.

	26400 Jyndevad		29440 Tystofte	
	1961-1990	1991-2006	1961-1990	1991-2006
Temperature (°C)	7.9 (0.68)	8.7 (0.71)	8.2 (0.68)	8.9 (0.64)
Precipitation (mm/y)	1043 (165)	1060 (177)	669 (112)	704 (142)
Ref. Evap. (mm/y)	557 (34)	587 (32)	582 (36)	636 (32)

The development in annual mean temperature at the two stations is shown in Figure A1 and A2. At both stations the temperature increases slightly. At Jyndevad the mean increases by approximately 0.5 ºC and at Tystofte the increase amounts to approximately 0.65 ºC. However, compared to the annual variations, characterized by a standard deviation of 0.7 ºC (Table 8) at both stations, the trend is not significant.

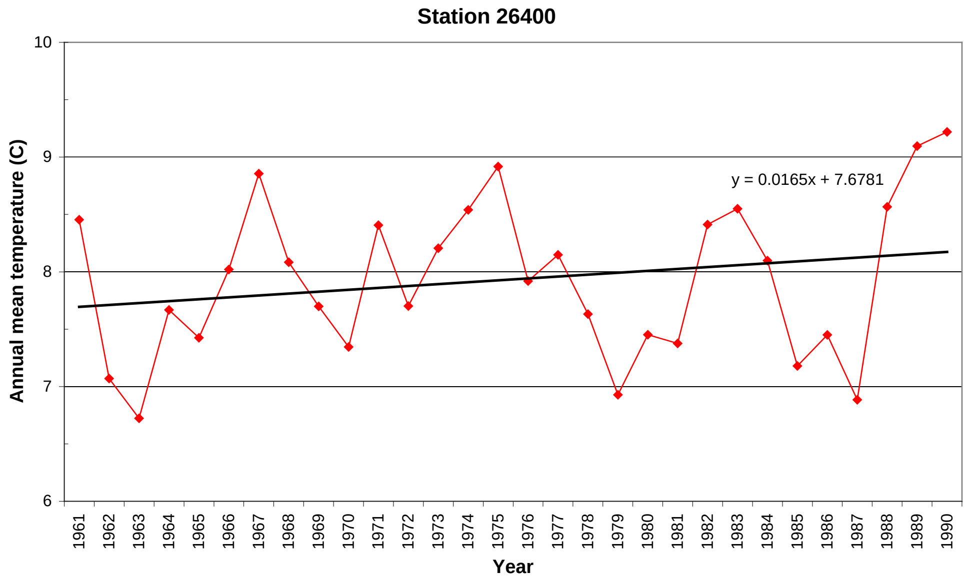

Figure A1. Annual mean temperature at station 26400 Jyndevad in the period 1961-90.

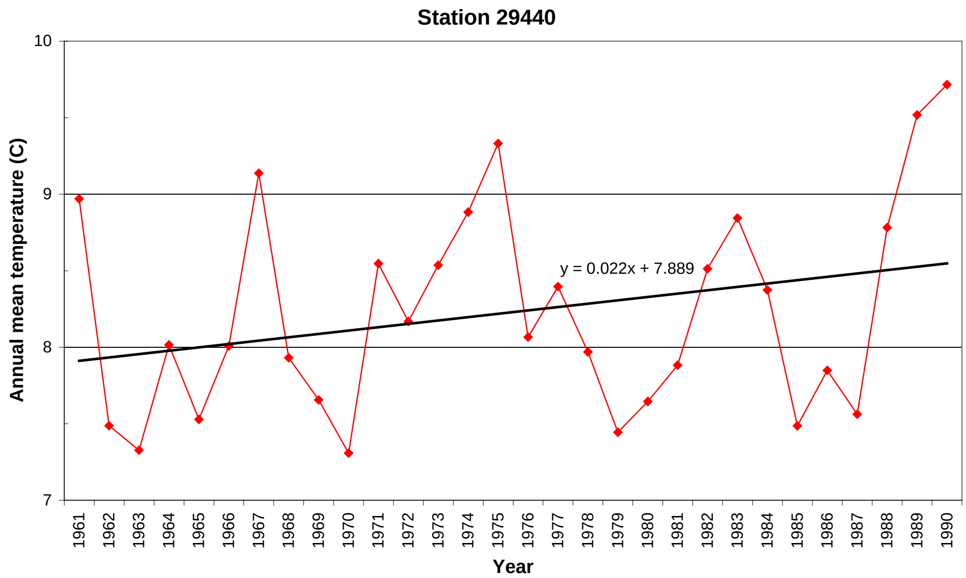

Figure A2. Annual mean temperature at station 29440 Tystofte in the period 1961-90.

In Figure A3 the development in annual precipitation at station 26400 Jyndevad is shown. The precipitation increases slightly during the 30-year period. Annual precipitation varies between 700 and 1350 mm/year and the variability are characterized by a standard deviation of 165 mm/year.

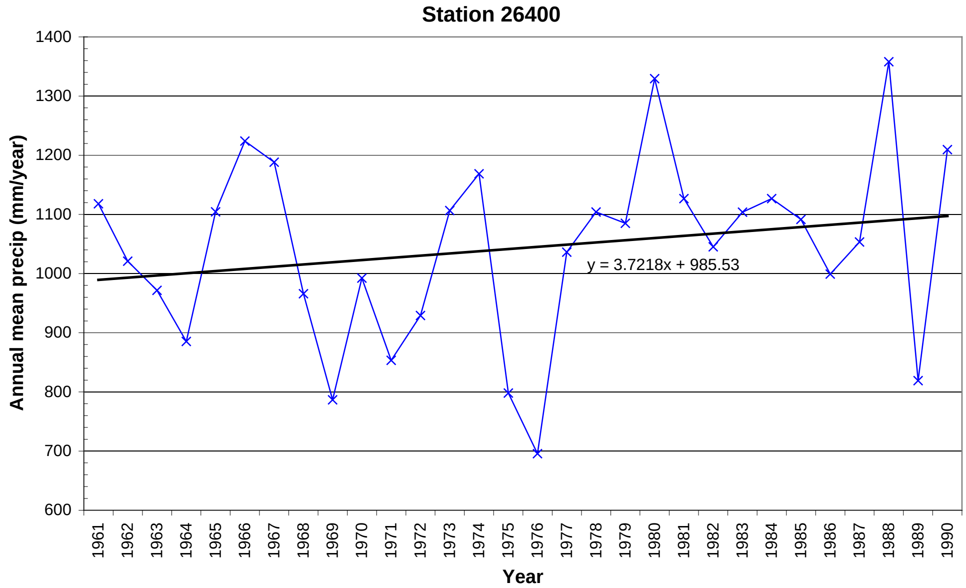

Figure A3. Annual mean precipitation at station 26400 Jyndevad in the period 1961-90.

In Figure A4 the annual mean precipitation at station 29440 Tystofte is illustrated. Here almost no trend is observed. A variation in annual precipitation from 460 to 880 mm/year is found with a standard deviation of 112 mm/year.

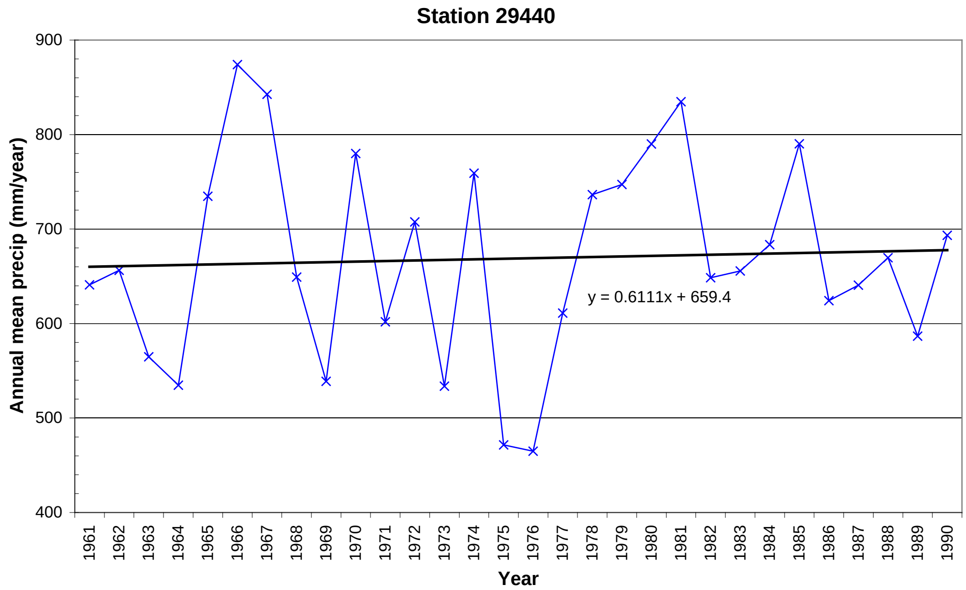

Figure A4. Annual mean precipitation at station 29440 Tystofte in the period 1961-90.

In Figure A5 and A6 the reference evapotranspiration at the two stations are shown. At station 26400 Jyndevad a small decrease of 29 mm is found over the 30-year period. The temperature at the same station showed a small increase which has in increasing effect on evapotranspiration. However, the global radiation, which is slightly decreasing during the period, controls the estimate of the evapotranspiration. Compared to the standard deviation of the annual mean evapotranspiration of 34 mm the trend is however small.

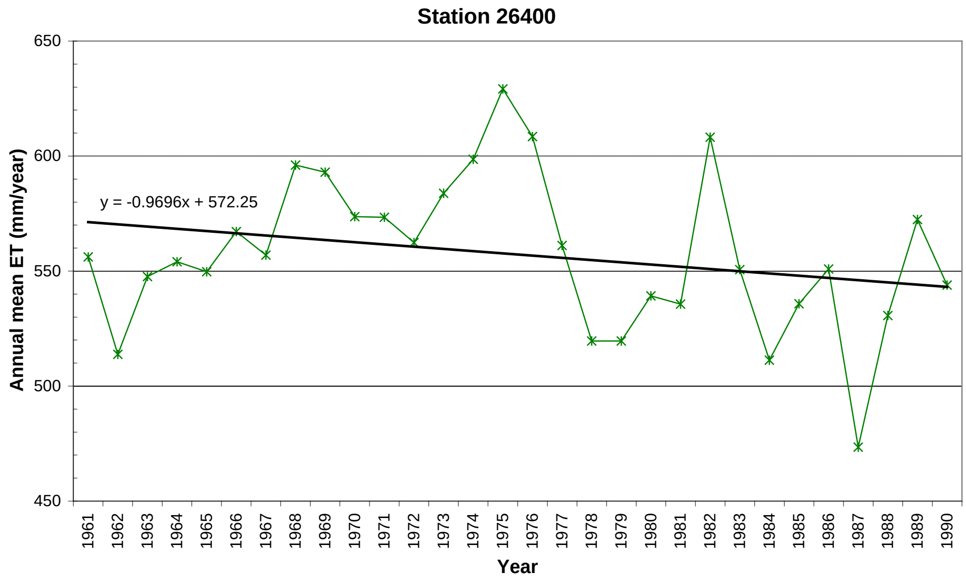

Figure A5. Annual mean reference evapotranspiration at station 26400 Jyndevad in the period 1961-90.

The reference evapotranspiration for Tystofte, Figure A6, increases slightly with 20 mm over the 30 years, which is well below the standard deviation of 31 mm. In this case the development in evapotranspiration corresponds well to the temperature at the same station.

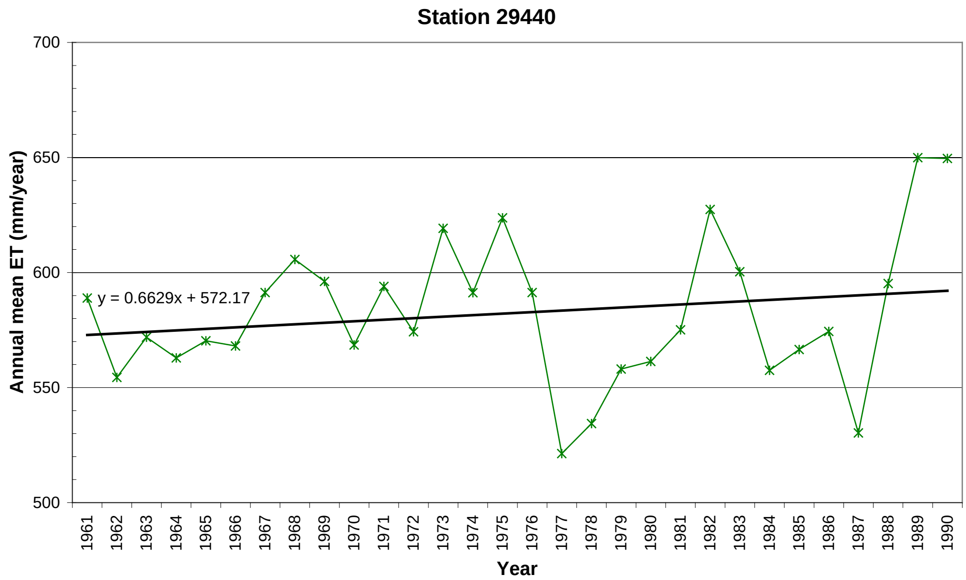

Figure A6. Annual mean reference evapotranspiration at station 29440 Tystofte in the period 1961-90.

The trends shown in Figures A1-A6 representing 1961-1990 were tested statistically and the slopes were in no case found to be statistically significant different from zero at a 5% significance level. For the period 1991-2006 only the increase in temperature at Jyndevad was significant with a P-value of 4.1%.

A2 Seasonal variability

In Figure A7 and A8 the monthly mean temperature at station 26400 Jyndevad and 29440 Tystofte are shown. At both stations the temperature is observed to increase for all months except June. The increase is highest in January, February, April, July and August where the temperature increases by more than 1 °C.

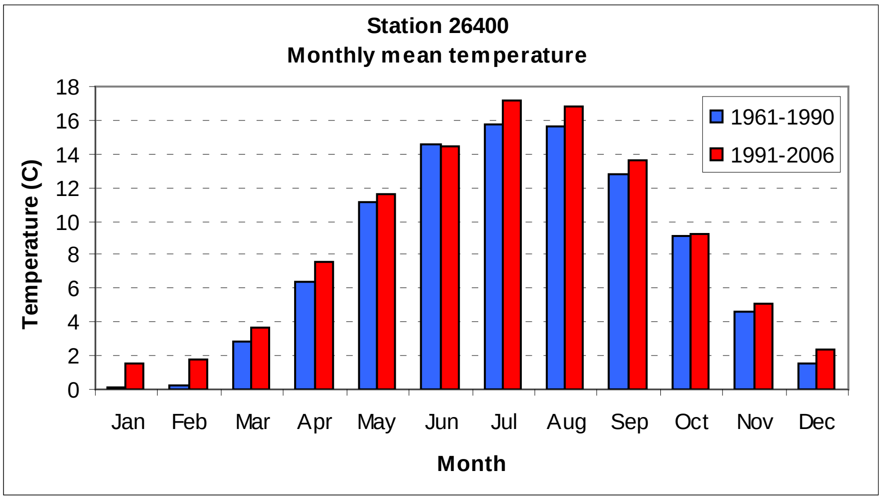

Figure A7. Monthly mean temperatures at station 26400 Jyndevad for the periods 1961-1990 and 1991-2006.

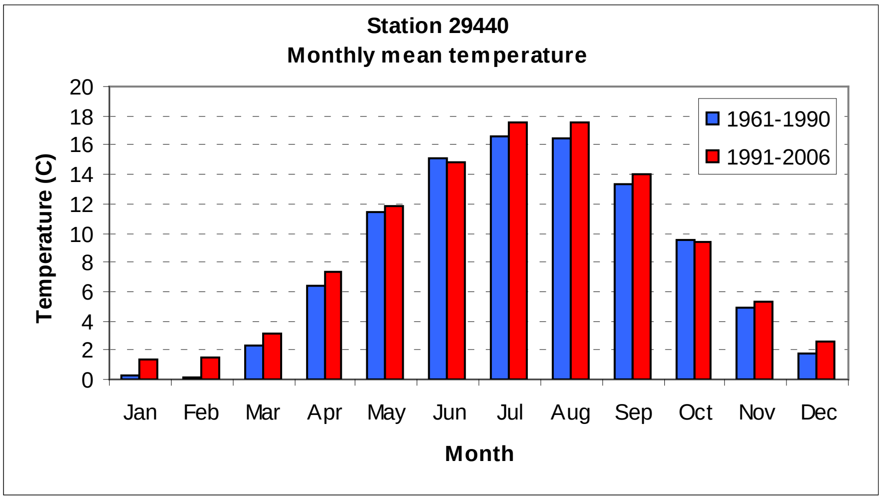

Figure A8. Monthly mean temperatures at station 29440 Tystofte for the periods 1961-1990 and 1991-2006.

In Figure A9 the mean monthly precipitation at Jyndevad for the two periods 1961-1990 and 1991-2006 is shown. On a seasonal basis there is a tendency for higher precipitation in winter (DJF) and lower precipitation in autumn (SON) in 1991-2006 compared to 1961-1990.

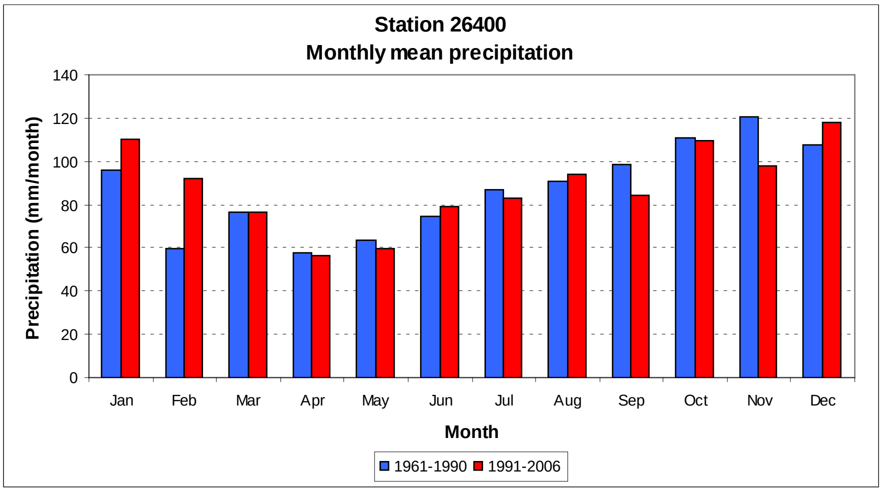

Figure A9. Monthly distribution of precipitation at station 26400 Jyndevad for the periods 1961-1990 and 1991-2006.

In Figure A10 the monthly mean precipitation for Tystofte is shown. For 9 out of 12 months the precipitation is higher in 1991-2006 than 1961-1990. The periods with the most consistent changes are winter and autumn.

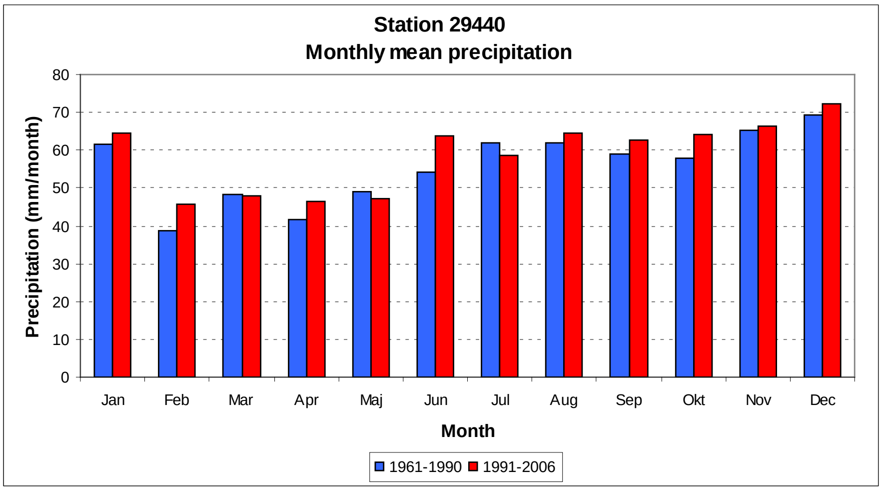

Figure A10. Monthly distribution of precipitation at station 29440 Tystofte for the periods 1961-1990 and 1991-2006.

The monthly distribution of reference evapotranspiration ET_{ref} at the two stations is shown in Figure A11 and A12. For all month the ET_{ref} is at the same level or higher for 1991-2006 compared to 1961-1990. The largest absolute increases are found in March, April, May and July, where especially July shows large increases of 9.5 and 14.2 mm for Jyndevad and Tystofte, respectively. As a result, the month with maximum ET_{ref} has shifted from June to July for both stations.

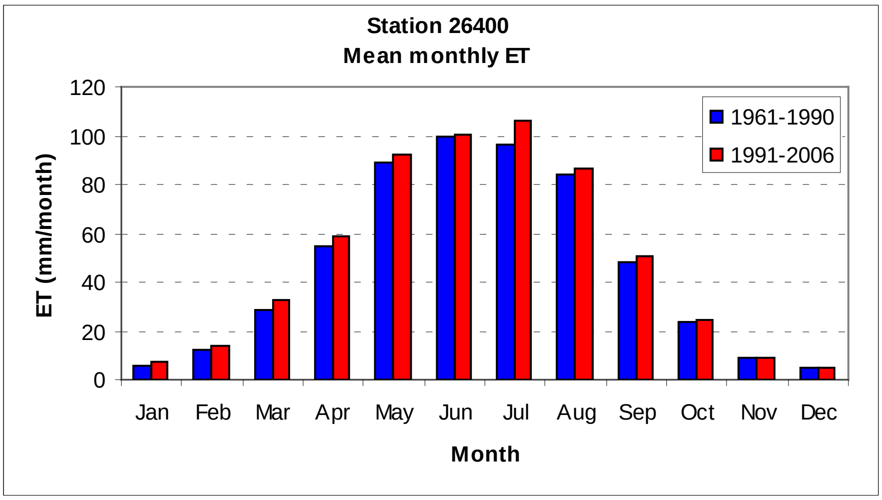

Figure A11. Reference evapotranspiration at station 26400 Jyndevad for the periods 1961-1990 and 1991-2006.

At Jyndevad monthly reference evapotranspiration only exceeds monthly precipitation in the period from May to July. At Tystofte the period with negative net precipitation (here defined as precipitation minus reference evapotranspiration) extends from April to August.

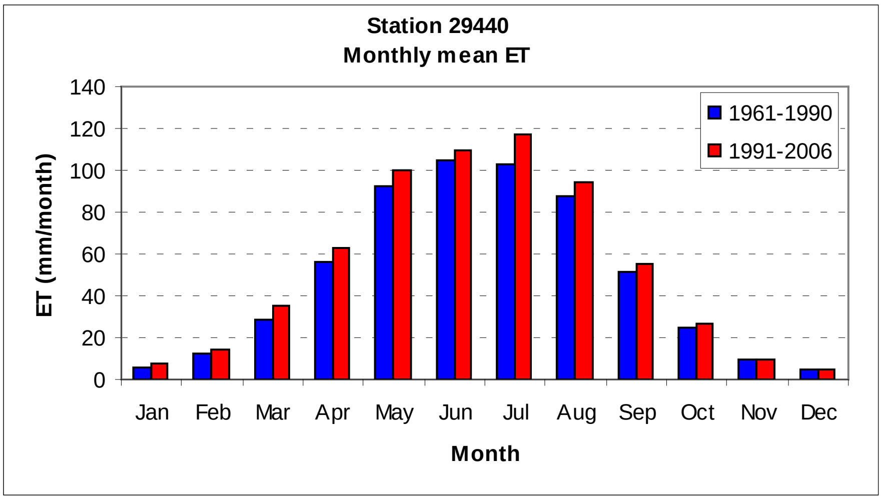

Figure A12. Reference evapotranspiration at station 29440 Tystofte for the periods 1961-1990 and 1991-2006.

In summary, the largest increase in temperature is found in January and February and this results in a reduction of days with mean temperature below 0 °C from 41.5% and 43.2% to 32.4% and 33.4% for Jyndevad and Tystofte, respectively. Hence, a larger part of the precipitation will fall as wet precipitation rather than solid precipitation. The most significant changes in precipitation amounts are observed in winter (DJF), where an increase of 56.5 and 12.8 mm is found at Jyndevad and Tystofte, respectively. The largest increases in reference evapotranspiration are found in spring and July.

Appendix B Climate model results

B1 Downscaling climate change impacts to pesticide leaching risk dynamics

B1.1 Results at the climate stations for the future climate

B1.1.1Annual values

In Figure B1 annual mean precipitation in four 30-year periods are shown for the Jyndevad location based on RACMO model results. The four grid cells surrounding the Jyndevad location have been used to derive the results.

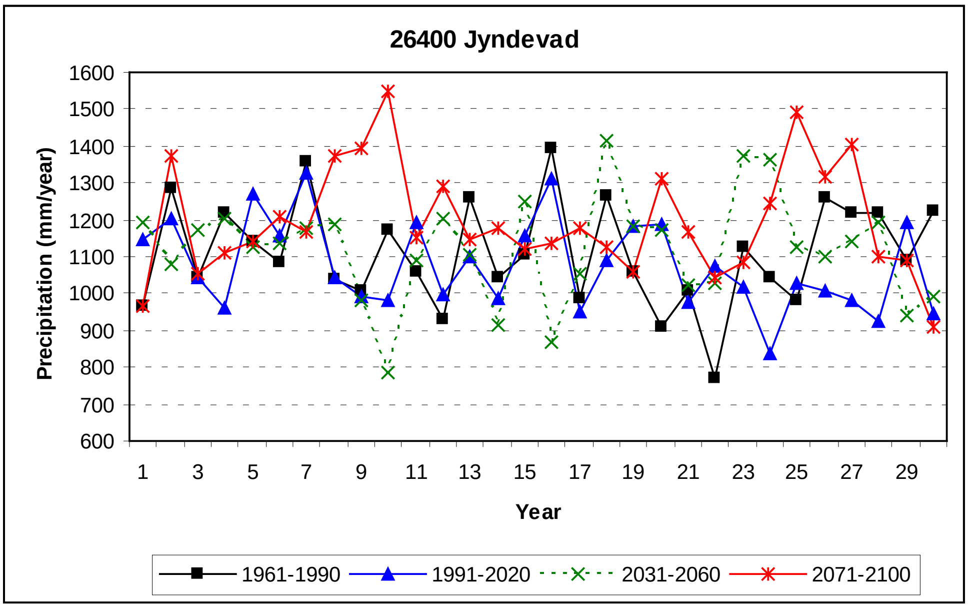

Figure B1. Projected annual mean precipitation development for four 30-year periodes for Jyndevad.

The results for the first three periods are comparable and only in the last period (2071-2100) significant higher annual precipitation amounts are found. Also minimum and maximum annual mean precipitation increases in 2071-2100, Table B1.

Table B1. Development in annual mean precipitation at station 26400 Jyndevad.

Variable	1961-1990	1991-2020	2031-2060	2071-2100
Annual mean (mm)	1109	1075	1119	1196
- change (%)	-	-3.0	0.9	7.8
Stand. Dev. (mm)	142	133	143	152
Annual max (mm)	1392	1325	1415	1548
- change (%)	-	-4.8	1.6	11.2
Annual min (mm)	772	837	784	912
- change (%)	-	8.4	1.5	18.1

The same trend is seen for Tystofte, Figure B2 and Table B2.

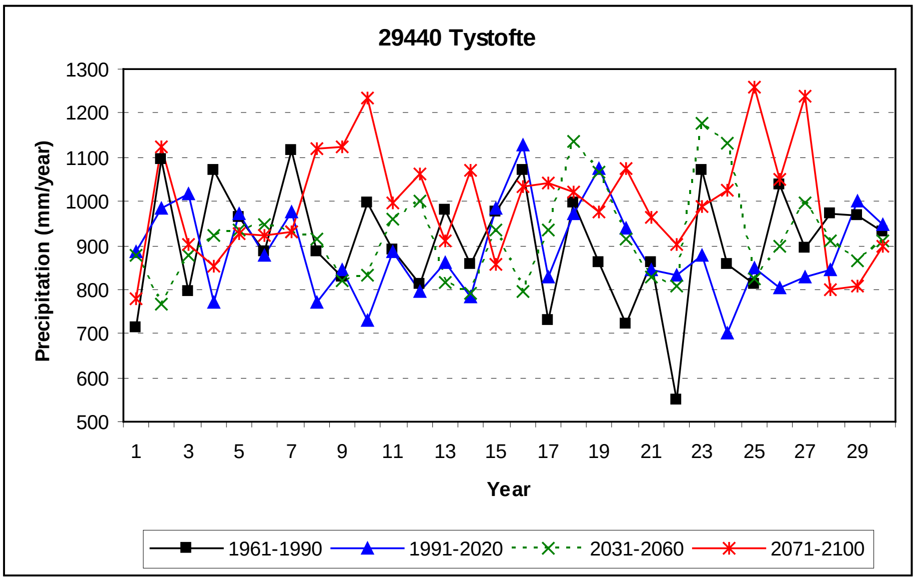

Figure B2. Projected annual mean precipitation development for four 30-year periods for Tystofte.

Table B2. Development in annual mean precipitation at station 29440 Tystofte.

Variable	1961-1990	1991-2020	2031-2060	2071-2100
Annual mean (mm)	907	887	917	996
- change (%)	-	-2.2	1.2	9.9
Stand. Dev. (mm)	130	113	105	129
Annual max (mm)	1117	1129	1178	1261
- change (%)	-	1.1	5.4	12.9
Annual min (mm)	550	701	765	781
- change (%)	-	27.5	39.2	42.0

In Table B3 and B4 the projected development in temperature and reference evapotranspiration is listed. In both cases a linear development in the two variables are found over the period from 1961-2100 (Figure B3-B6). It is noticed that higher values of reference evapotranspiration are found for the scenario periods compared to the control and the validation periods.

Table B3. Development in annual mean temperature and ref. evapotranspiration at station 26400 Jyndevad.

Variable	1961-1990	1991-2020	2031-2060	2071-2100
Temperature (°C)	8.3	8.7	9.7	10.9
- change (°C)	-	0.4	1.4	2.5
Stand. Dev. (°C)	0.8	0.6	0.7	0.6
Ref. evap. (mm)	451	465	479	498
- change (%)	-	3.0	6.1	10.3
Stand. Dev. (mm)	32	24	34	49

Table B4. Development in annual mean temperature and ref. evapotranspiration at station 29440 Tystofte.

Variable	1961-1990	1991-2020	2031-2060	2071-2100
Temperature (°C)	8.1	8.6	9.6	10.8
- change (°C)	-	0.5	1.5	2.7
Stand. Dev. (°C)	0.8	0.7	0.7	0.7
Ref. evap. (mm)	472	490	505	527
- change (%)	-	3.9	6.9	11.6
Stand. Dev. (mm)	34	29	34	53

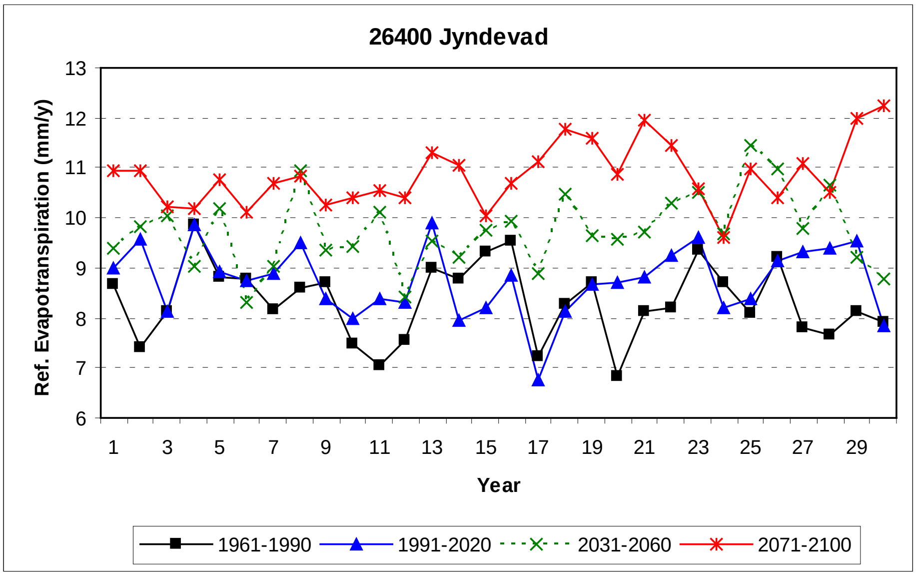

Figure B3. Projected annual mean temperature development for four 30-year periodes for Jyndevad.

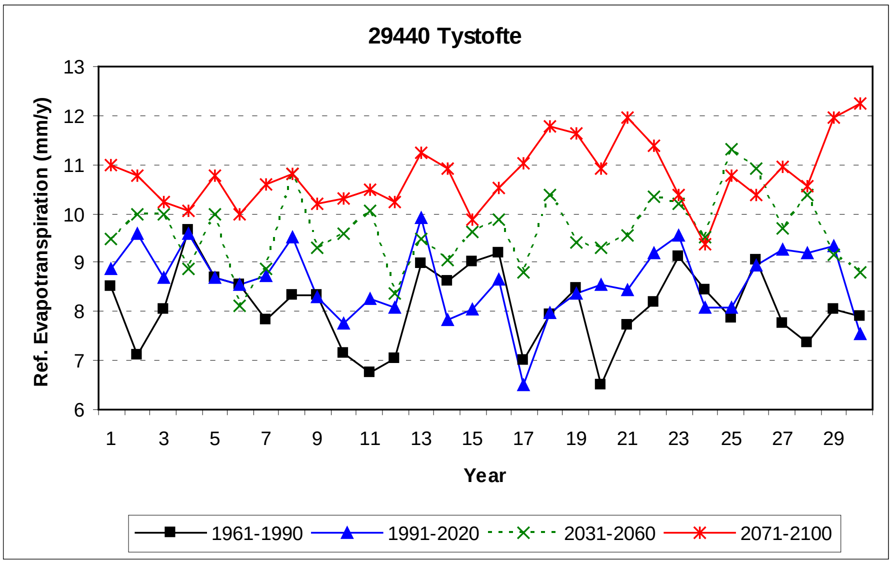

Figure B4. Projected annual mean temperature development for four 30-year periodes for Tystofte.

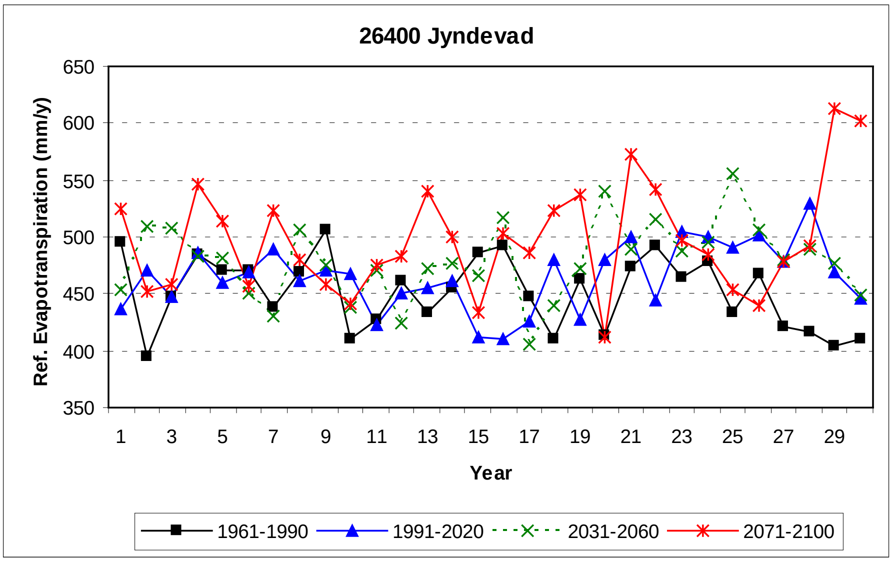

Figure B5. Projected annual mean ref. evapotranspiration development for four 30-year periodes for Jyndevad.

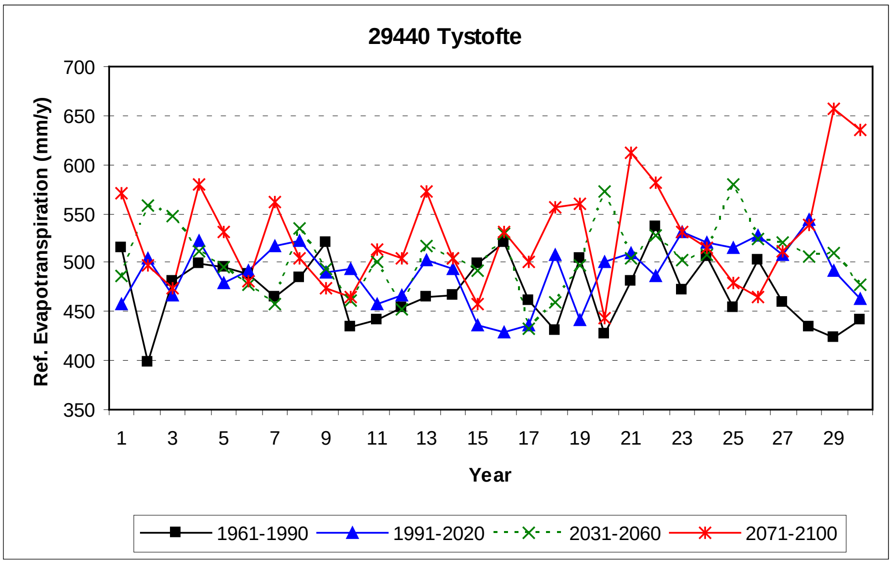

Figure B6. Projected annual mean ref. evapotranspiration development for four 30-year periodes for Tystofte.

B1.1.2 Monthly values

In Figure B7 and B8 the development in monthly mean temperature is shown. The temperature increases for all months with more or less the same value. In Table B5 the absolute increase in temperature is listed. Except for May and December that for some reason have a tendency for relatively small temperature increase the change in temperature is relatively constant throughout the year.

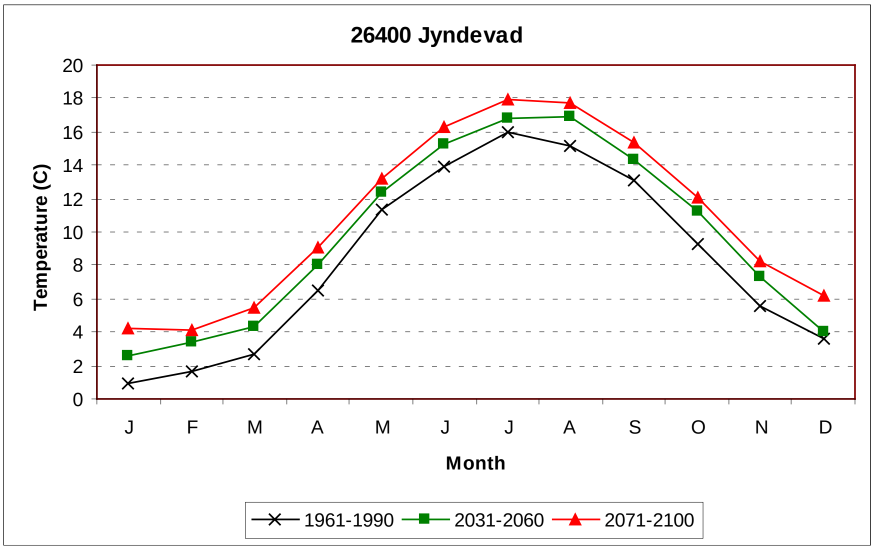

Figure B7. Mean monthly temperature distribution for four periods from Jyndevad.

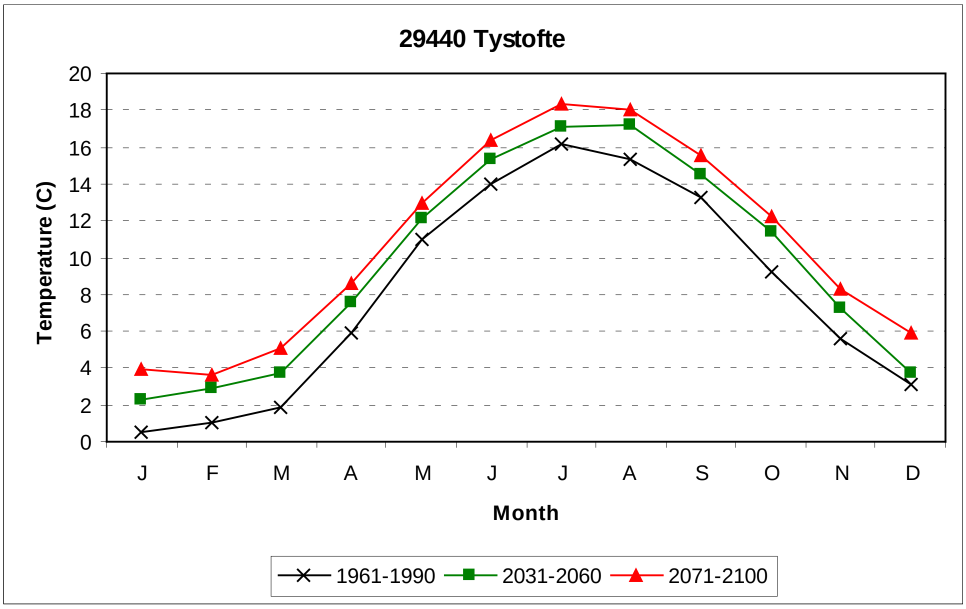

Figure B8. Mean monthly temperature distribution for four periods from Tystofte.

Table B6. Absolute change in temperature (°C) for Jyndevad and Tystofte compared to 1961-1990.

	Month											
	J	F	M	A	M	J	J	A	S	O	N	D
Jyndevad												
1991-2020	1.10	0.47	1.36	0.73	-0.19	0.36	0.30	0.56	0.48	0.57	0.43	-0.22
2031-2060	1.66	1.72	1.65	1.49	1.02	1.33	0.86	1.80	1.26	1.96	1.68	0.40
2071-2100	3.28	2.41	2.84	2.54	1.87	2.34	1.95	2.59	2.22	2.86	2.69	2.58
Tystofte												
1991-2020	1.32	0.65	1.47	0.93	-0.02	0.37	0.34	0.57	0.56	0.60	0.22	0.03
2031-2060	1.83	1.91	1.93	1.66	1.17	1.40	0.97	1.81	1.31	2.11	1.72	0.62
2071-2100	3.45	2.61	3.20	2.74	2.03	2.45	2.16	2.64	2.31	2.97	2.69	2.80

In Figure B9 and B10 the seasonal distribution of precipitation at the two climate stations are illustrated. For the period 2031-2060 higher winter (DJF) precipitation are generated and lower summer precipitation (JJA) are predicted. No systematic changes are found for autumn and spring. In 2071-2100 higher precipitation are generated in the period from September to March, and the increase is most significant in November to January. In the summer period (JJA) lower precipitation are found.

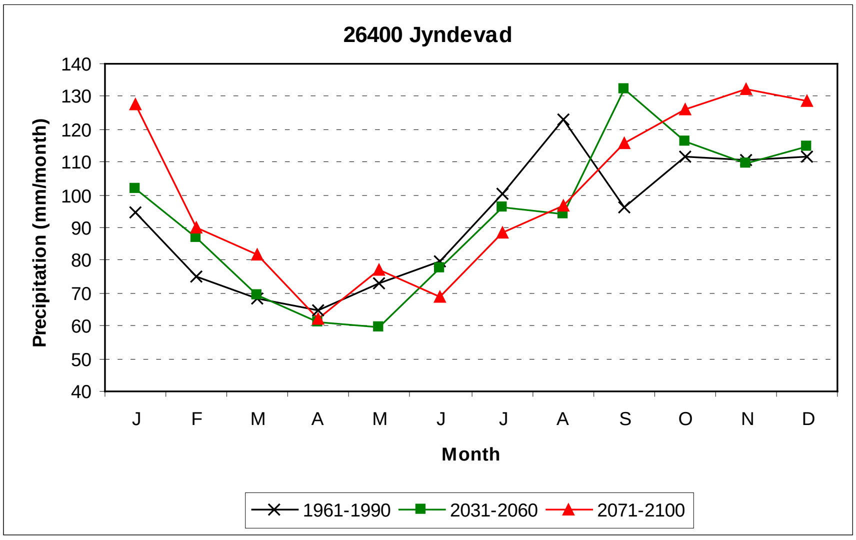

Figure B9. Mean monthly precipitation distribution for four periods from Jyndevad.

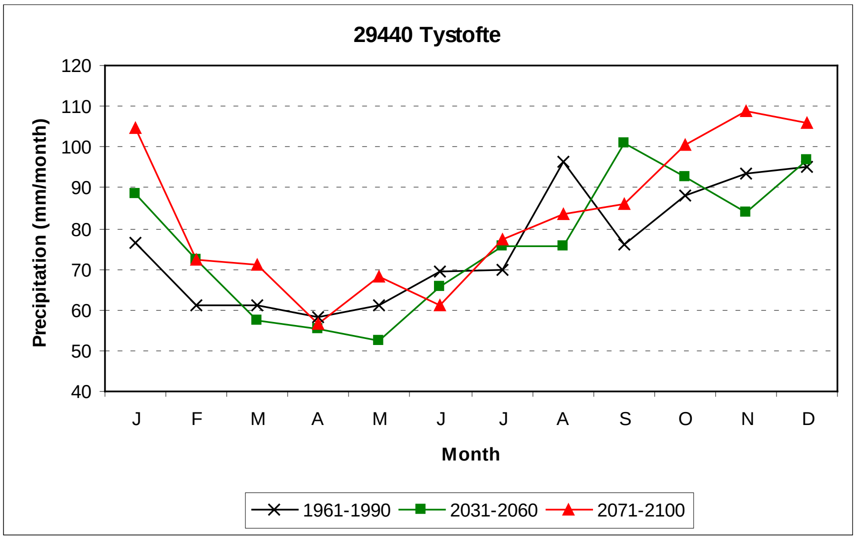

Figure B10. Mean monthly precipitation distribution for four periods from Tystofte.

These results can also be read from Table B7, where the relative change in the mean and standard deviation of monthly precipitation is shown. It is noticed that for 2031-2060 the precipitation during most of the growing season (April-August) is reduced compared to the control period, especially for Jyndevad. At the same time the standard deviations are reduced corresponding to less variability in mean monthly precipitation. In the late period (2071-2100) the same tendency is found. At Jyndevad precipitation is reduced with 10-20% during the months June to August. At Tystofte the pattern is not so consistent. However, at both stations the variability in monthly mean precipitation is decreasing during the summer months.

Table B7. Relative change (%) in the mean and the standard deviation of monthly precipitation and for Jyndevad and Tystofte compared to 1961-1990.

	Month											
	J	F	M	A	M	J	J	A	S	O	N	D
Jyndevad												
1991-2020	2.1 (-5.3)	-5.3 (-10.5)	-11.5 (-2.0)	-2.3 (-4.6)	-2.5 (-23.6)	-7.0 (3.5)	2.9 (0.4)	4.8 (-8.6)	17.0 (35.1)	18.9 (12.6)	-3.9 (0.5)	-4.0 -1.8)
2031-2060	7.6 (8.9)	15.5 (3.7)	1.5 (-2.6)	-5.1 (-9.4)	-18.7 (-30.8)	-2.8 (-5.4)	-4.0 (-1.3)	-23.7 (-21.6)	37.2 (59.1)	4.4 (-11.0)	-0.9 (15.0)	2.6 (16.5)
2071-2100	34.5 (26.7)	19.5 (-9.5)	19.8 (-3.9)	-3.5 (13.4)	5.6 (2.2)	-13.9 (-2.9)	-11.4 (-14.5)	-21.2 (-26.2)	20.3 (69.2)	13.2 (17.1)	19.5 (19.8)	15.1 (12.7)
Tystofte												
1991-2020	4.3 (-24.0	-0.9 (-32.7)	-15.2 (-21.0)	-7.0 (-16.3)	-6.6 (-38.8)	5.5 (0.9)	4.2 (-34.9)	-8.4 (-24.5)	0.8 (11.5)	16.5 (-14.8)	-4.4 (-22.4)	-11.0 (-31.2)
2031-2060	15.6 (-10.4	18.0 (-11.4)	-6.3 (-20.9)	-5.0 (-6.2)	-13.9 (-38.8)	-5.6 (-19.5)	8.4 (-25.0)	-21.4 (-37.6)	32.8 (24.3)	5.3 (-37.5)	-10.2 (-15.5)	2.1 (-9.7)
2071-2100	36.8 (-3.5)	18.4 (-27.5)	16.0 (-21.3)	-2.9 (20.0)	11.6 (-7.2)	-12.1 (-14.2)	10.8 (-21.7)	-13.6 (-27.5)	13.3 (-4.2)	14.4 (-13.6)	16.6 (-5.2)	11.4 (-12.2)

The development in monthly mean reference evapotranspiration is illustrated in Figure B11 and B12. The evapotranspiration increases for all months, however, the increase is highest during the growing season (MJJA), with the most significant development in June.

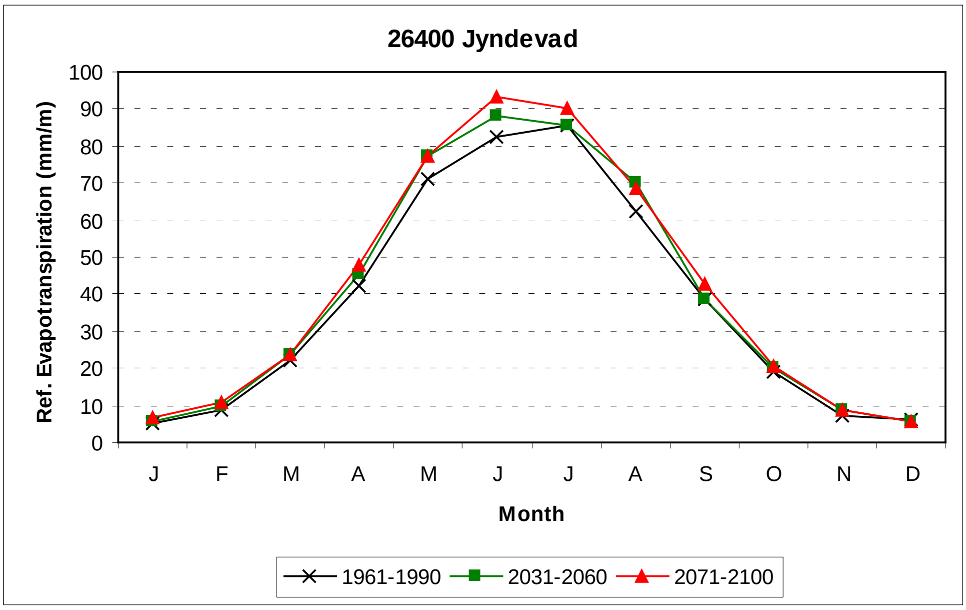

Figure B11. Mean monthly reference evapotranspiration distribution for Jyndevad.

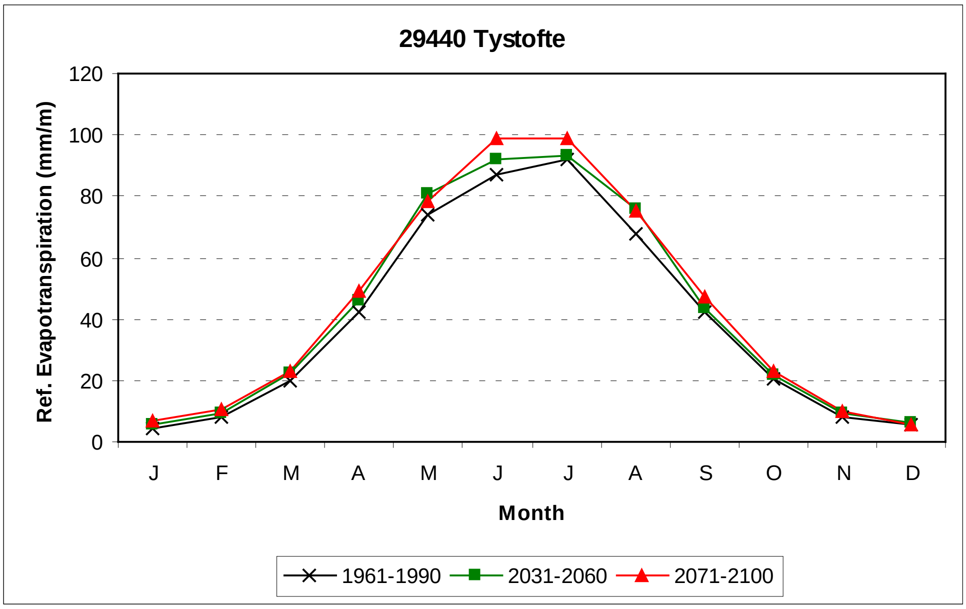

Figure B12. Mean monthly reference evapotranspiration distribution for Tystofte.

In Table B8 the relative change in reference evapotranspiration is shown. Again, a general increase in reference evapotranspiration is observed with time.

Table B8. Relative change (%) in mean monthly reference evapotranspiration for Jyndevad and Tystofte compared to 1961-1990.

	Month											
	J	F	M	A	M	J	J	A	S	O	N	D
Jyndevad												
1991-2020	1.2	6.6	7.2	0.2	-2.4	0.6	0.1	0.1	2.0	4.4	4.7	-6.3
2031-2060	6.6	9.9	5.4	7.5	8.6	6.6	0.0	12.4	-0.4	6.4	23.0	-2.9
2071-2100	33.0	21.0	7.5	13.6	8.3	13.1	5.6	9.9	10.0	10.3	25.9	-1.4
Tystofte												
1991-2020	3.7	7.4	10.3	3.4	-2.0	1.2	1.1	4.8	2.9	8.8	-1.6	3.8
2031-2060	15.2	14.2	11.7	8.7	8.6	5.9	1.4	11.4	2.2	6.5	22.2	5.9
2071-2100	49.0	24.3	15.4	16.0	5.8	14.1	7.6	11.1	11.7	12.7	24.9	2.9

B1.1.3 Extreme precipitation

In Table B9 the mean and standard deviation of annual maximum precipitation at the two climate stations are listed. At Jyndevad the mean annual maximum value increases steadily with time and there is a tendency for higher variation in the annual maximum in the future. At Tystofte the development in mean annual maximum is not significant before the end of the century where an increase of approximately 5 mm/day is found. The standard deviation follows the development in the mean.

Table B9. Mean and standard deviation of annual maximum precipitation at Jyndevad and Tystofte for four 30-year periods.

	Jyndevad		Tystofte	
	Mean (mm/day)	Standard deviation (mm/day)	Mean (mm/day)	Standard deviation (mm/day)
1961-1990	30.1	8.1	30.5	9.4
1991-2020	30.3	10.5	29.2	8.0
2031-2060	33.4	11.2	30.9	9.5
2071-2100	35.5	9.9	35.7	10.1

In Table B10 statistics on monthly maximum precipitation at the two stations are listed. There seems to be no changes in mean monthly maximum precipitation going from 1961-1990 to 1991-2020. In the period 2031-2060 a tendency for higher mean maximum precipitation in early Autumn (SO) is observed, but for the remaining months no development is observed. However, the standard deviation of mean monthly maximum precipitation increases significantly for all months, especially in August and September where an increase of up to 50% is found. Hence, the extreme precipitation events are expected to increase significantly especially in late summer.

In the last period (2071-2100) the most significant increases in mean monthly maximum precipitation are found in the period September to December for Jyndevad and July to December for Tystofte. At the same time the standard deviations of the maximum monthly precipitation increases for the entire year with changes of up to 50% in late summer. Hence, the extreme precipitation events can be expected to increase significantly for especially late summer and autumn.

Table B10. Change (in %) of the mean and the standard deviation (in parenthesis) of monthly maximum precipitation for Jyndevad and Tystofte compared to the period 1961-90.

	Month											
	J	F	M	A	M	J	J	A	S	O	N	D
Jyndevad												
1991-2020	-4.3 (15)	-8.5 (14)	4.2 (11)	3.5 (16)	11.5 (16)	-6.8 (7.4)	-10.4 (29)	-4.9 (18)	7.3 (22)	3.5 (19)	-7.1 (26)	-9.3 (34)
2031-2060	-3.9 (30)	5.3 (23)	-1.3 (32)	13.3 (27)	0.6 (32)	2.5 (30)	-14.5 (24)	-7.5 (45)	17.5 (50)	11.1 (26)	-3.7 (35)	4.5 (32)
2071-2100	9.3 (21)	19.0 (18)	22.0 (20)	3.6 (29)	12.8 (28)	3.9 (35)	-6.9 (20)	6.8 (38)	28.9 (54)	16.7 (29)	23.8 (19)	25.7 (21)
Tystofte												
1991-2020	-0.6 (6.5)	2.4 (5.3)	-11.5 (7.9)	-3.6 (14)	-19.6 (16)	-4.1 (1.4)	-11.0 (-3.2)	-20.0 (14)	30.2 (21)	5.9 (11)	2.3 (18)	-7.6 (16)
2031-2060	8.1 (20)	10.9 (18)	-21.1 (28)	-4.1 (26)	-0.3 (27)	-1.0 (18)	-2.1 (19)	-9.5 (29)	28.0 (37)	25.5 (16)	-14.2 (31)	6.3 (22)
2071-2100	6.5 (30)	20.9 (26)	8.8 (23)	-4.8 (35)	6.0 (31)	2.0 (27)	30.4 (31)	18.2 (48)	27.8 (38)	26.1 (35)	18.7 (28)	26.1 (30)

B1.2 Scenario periods

B1.2.1Precipitation

In Table B11 the annual mean precipitation predicted by the different bias-correction methods is listed. The uncorrected RCM results show a small decrease at Jyndevad for 2031-2060 and a subsequent increase of 5.5% in 2071-2100. None of the methods that use the observed precipitation as baseline (no. 1 and 2) are able to capture this development. Both methods predict a significant increase in the first scenario period and a relative large increase in the last period. The methods using the RCM data as baseline (no. 3 and 4) fits on the other hand the development in the simulated results satisfactorily, with a small decrease in the first period followed by an increase in the last period.

Table B11. Annual mean precipitation (mm) of the bias correction methods for the periods 1991-2006, 2031-2060, and 2071-2100. Relative change compared to the period 1991-2006 is listed in parenthesis.

No	Method	1991-2006	2031-2060	2071-2100
Jyndevad				
A	Observations	1060	-	-
B	RCM data	1133	1119 (-1.2)	1196 (5.5)
1	Delta obs	1008	1062 (5.4)	1139 (13.0)
2	Stat. Trans	1013	1079 (6.4)	1125 (11.1)
3	Delta RCM	1066	1063 (-0.3)	1143 (7.2)
4	Intensity-based	1085	1084 (-0.1)	1188 (9.4)
Tystofte				
A	Observations	704	-	-
B	RCM data	891	918 (3.0)	996 (11.8)
1	Delta obs	635	680 (7.0)	737 (16.1)
2	Stat. Trans	645	689 (6.9)	749 (16.1)
3	Delta RCM	659	683 (3.6)	746 (13.3)
4	Intensity-based	663	705 (6.3)	802 (20.9)

In Figure B13 and B14 the relative change at Jyndevad in monthly mean precipitation is illustrated for the periods 2031-2060 and 2071-2100 using 1991-2006 as reference. The uncorrected RCM results generally show increasing precipitation during January to March while decrease is observed in the growing season from May to August. This development is only captured by the methods using RCM data as baseline. The delta change method (no. 1) overestimates the increase during winter and do not capture the decrease in May and June. The same tendency is seen for method no. 2 although not so significant. When the period 2071-2100 is examined this tendency is even stronger. The two methods using observed data as baseline are not able to reproduce the development in monthly precipitation projected by the climate model. The methods using RCM results as baseline are on the other hand capable of reproducing the changes in precipitation dynamics.

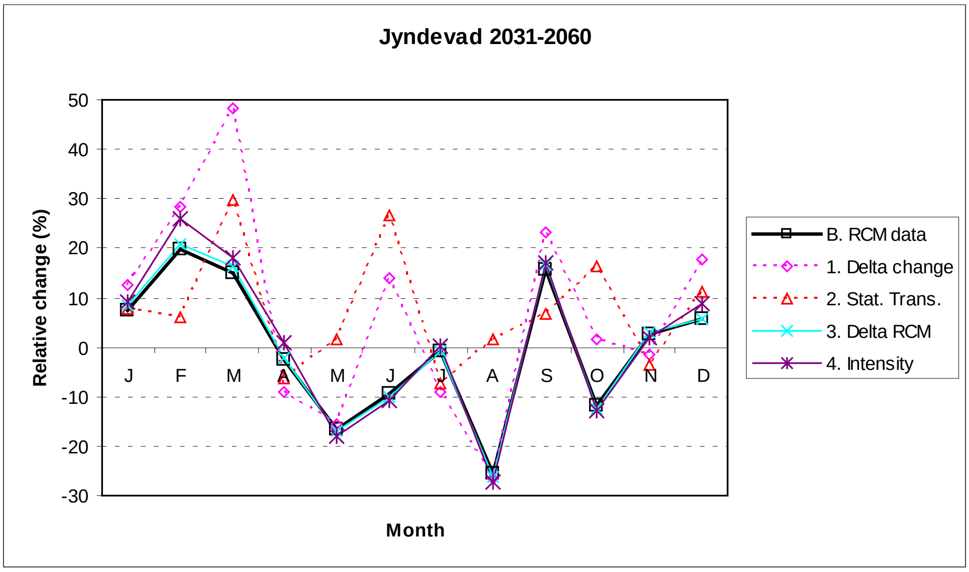

Figure B13. Relative change in mean monthly precipitation 2031-2060 for each of the bias-correction methods compared to the period 1991-2006 for Jyndevad.

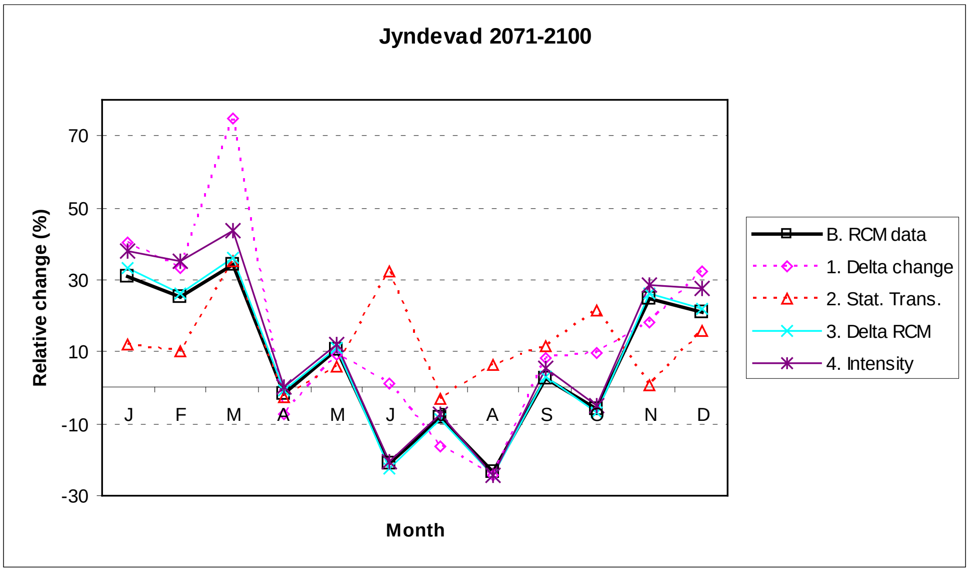

Figure B14. Relative change in mean monthly precipitation 2071-2100 for each of the bias-correction methods compared to the period 1991-2006 Jyndevad.

Similar results from Tystofte, Figure B15 and B16, support the observations from Jyndevad. The Tystofte results yields larger difference between the RCM data and method no. 3 and especially method no. 4. However, at Tystofte the bias of the RCM data was significantly larger than at Jyndevad and it is therefore expected that the difference between uncorrected and corrected data will be higher.

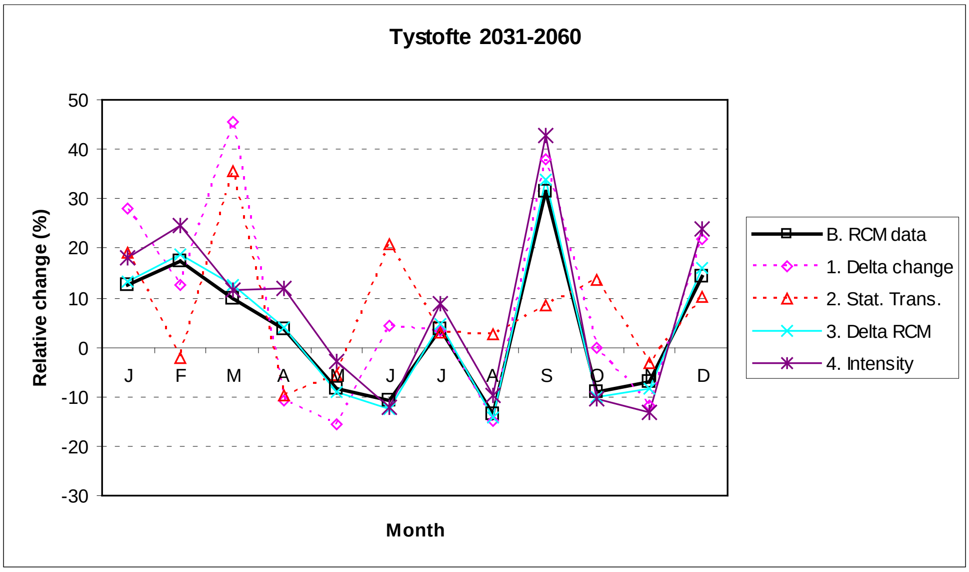

Figure B15. Relative change in mean monthly precipitation 2031-2060 for each of the bias-correction methods compared to the period 1991-2006 for Tystofte.

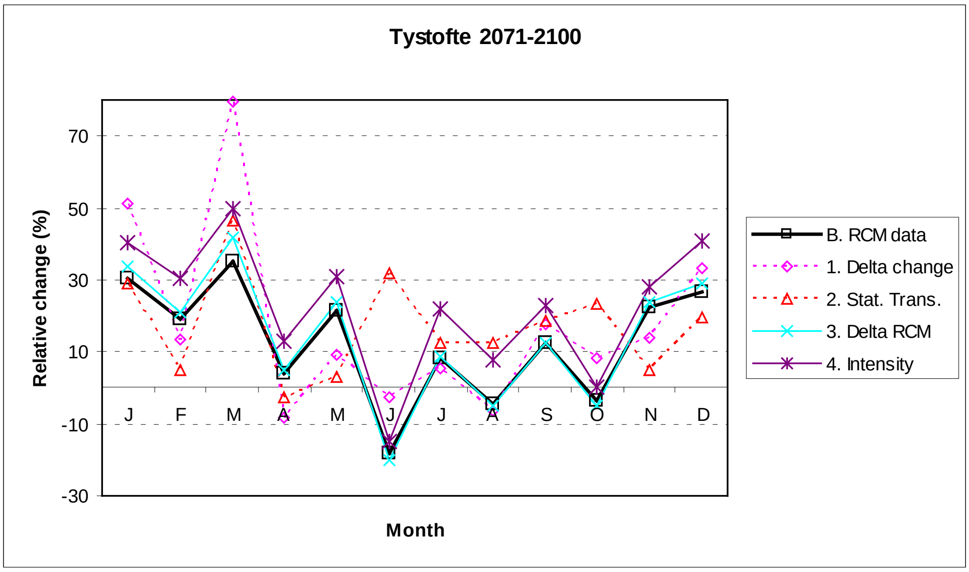

Figure B16. Relative change in mean monthly precipitation 2071-2100 for each of the bias-correction methods compared to the period 1991-2006 Tystofte.

The development in annual mean maximum precipitation is presented in Table B12. At both stations the two methods based on observed data (no. 1 and 2) have difficulties predicting the increase in maximum precipitation. The two methods based on RCM results (no. 3 and 4) do a much better job in describing the relative increase in mean maximum precipitation projected by the climate model. Method no. 4 is especially accurate when the increase in maximum values is considered.

Table B12. Annual mean maximum precipitation (mm/day) of the bias correction methods for the periods 1991-2006, 2031-2060, and 2071-2100. Relative change (%) compared to 1991-2006 is listed in parenthesis.

No	Method	1991-2006	2031-2060	2071-2100
Jyndevad				
A	Observations	37.6	-	-
B	RCM data	29.2	33.4 (14.4)	35.5 (21.6)
1	Delta obs	39.7	38.7 (-2.5)	41.5 (4.5)
2	Stat. Trans	38.9	39.1 (0.5)	41.3 (6.2)
3	Delta RCM	28.6	32.0 (11.9)	35.5 (24.1)
4	Intensity-based	38.9	44.8 (15.2)	48.2 (23.9)
Tystofte				
A	Observations	33.8	-	-
B	RCM data	28.1	30.9 (10.0)	35.7 (27.0)
1	Delta obs	35.3	34.6 (-2.0)	37.2 (5.4)
2	Stat. Trans	35.3	35.4 (0.2)	40.4 (14.4)
3	Delta RCM	23.1	25.5 (10.4)	28.4 (22.9)
4	Intensity-based	35.0	38.6 (10.3)	45.8 (30.9)

In Figure B17 the relative change in mean monthly maximum precipitation for 2031-2060 is illustrated. The RCM results project significant increases in January – Aril and a large decrease in May and to a lesser extent June. The changes in the rest of the year are relatively small. The changes in seasonal dynamics are again only captured by the two methods using RCM results as baseline (no. 3 and 4) whereas large discrepancies are found between the RCM results and method no. 1 and 2. Especially the delta change method has difficulties to reproduce the simulated development and the disagreement increases when the period 2071-2100, Figure B18, is considered.

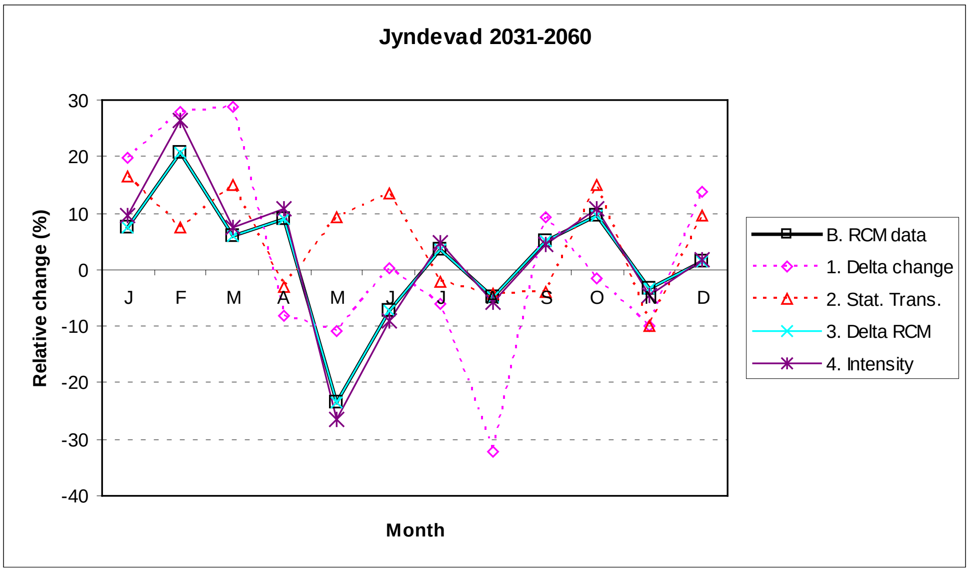

Figure B17. Relative change in mean monthly maximum precipitation 2031-2060 for each of the bias-correction methods compared to the period 1991-2006 for Jyndevad.

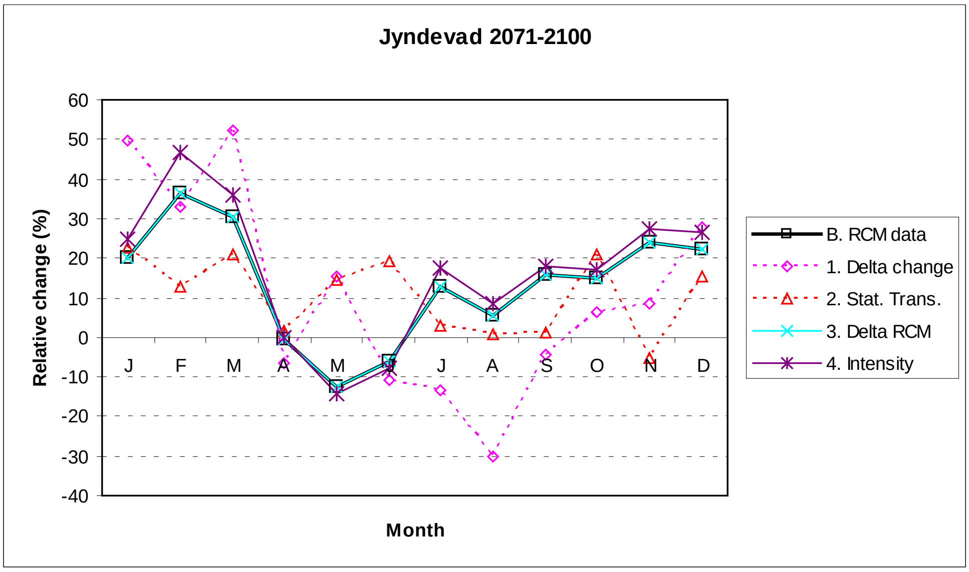

Figure B18. Relative change in mean monthly maximum precipitation 2071-2100 for each of the bias-correction methods compared to the period 1991-2006 for Jyndevad.

At Tystofte the RCM results from 2031-2060 show an increase in maximum precipitation for most of the months of up to 20%, Figure B19. However, during 2071-2100 the increase in maximum precipitation is much more pronounced (Figure B20), especially in July and August. As for Jyndevad only methods no. 3 and 4 are able to reproduce this development. The intensity-based statistical method (no. 4) predicts an increase of up to 70% in maximum precipitation for August. The delta change method (no. 1) projects a decrease in the same month of -5% which illustrates the importance of the choice of bias-correction method.

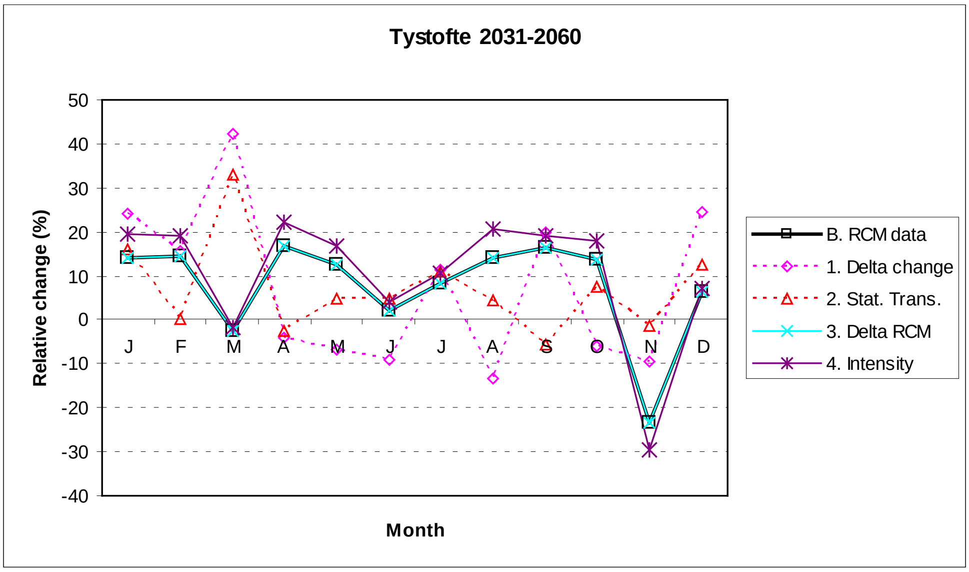

Figure B19. Relative change in mean monthly maximum precipitation 2031-2060 for each of the bias-correction methods compared to the period 1991-2006 for Tystofte.

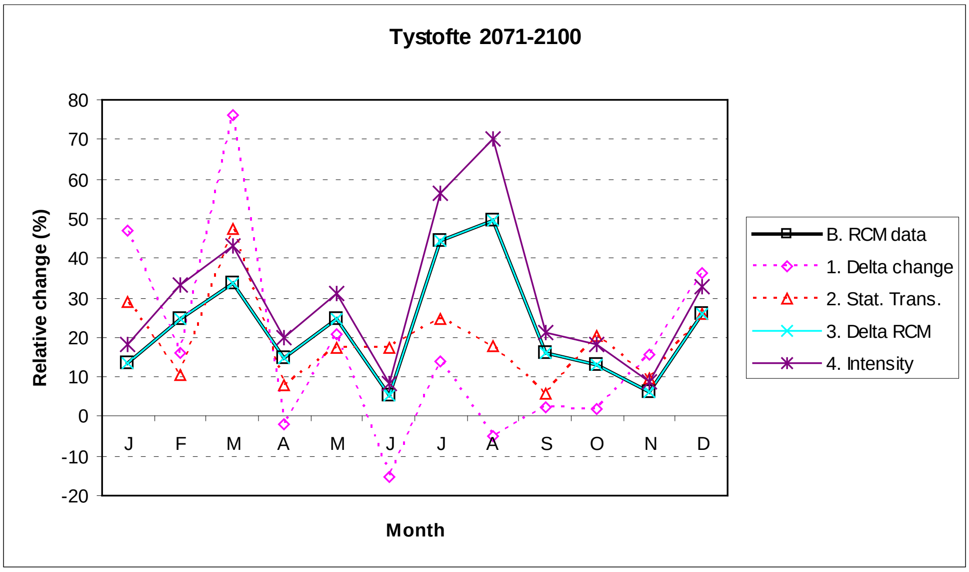

Figure B20. Relative change in mean monthly maximum precipitation 2071-2100 for each of the bias-correction methods compared to the period 1991-2006 for Tystofte.

B1.2.2 Reference evapotranspiration

In Table B13 the development in annual mean reference evapotranspiration is presented. The uncorrected RCM data (B) yields a relatively small increase of 0.7% and 2.0% at Jyndevad and Tystofte, respectively, for the period 2031-2060. In the late scenario period larger increases of 4.3% and 5.8% are found. The increase of all the bias-correction methods is larger than for the RCM data, in some cases up to nearly 10% in 2071-2100. However, the bias of the RCM data in the control period is relatively high (in the order of 20%) and it is therefore expected that the correction of the RCM data will results in changes in the increase. If the period 2071-2100 is considered the difference between the three bias-correction methods is low – at Jyndevad the methods deviates by 9 mm/year while at Tystofte discrepancies of 16 mm/year are found.

Table B13. Annual mean reference evapotranspiration (mm) of the bias correction methods for the periods 1991-2006, 2031-2060, and 2071-2100. Relative change compared to the period 1991-2006 is listed in parenthesis.

No	Method	1991-2006	2031-2060	2071-2100
Jyndevad				
A	Observations	587	-	-
B	RCM data	459	462 (0.7)	478 (4.3)
1	Delta obs	577	593 (2.7)	615 (6.6)
3	Delta RCM	561	593 (5.6)	615 (9.6)
4	Intensity-based	553	582 (5.4)	604 (9.2)
Tystofte				
A	Observations	636	-	-
B	RCM data	477	486 (2.0)	504 (5.8)
1	Delta obs	601	624 (3.9)	651 (8.5)
3	Delta RCM	600	627 (4.5)	653 (9.0)
4	Intensity-based	587	612 (4.3)	637 (8.6)

In Figure B21 the relative change in mean monthly reference evapotranspiration for the period 2031-2060 is illustrated. The uncorrected RCM data shows relatively small changes in the period from May to November (less than 5%). A larger increase is seen in January to April, however, the absolute evapotranspiration in this period is so low that this increase is insignificant with respect to the annual evapotranspiration. A strange behaviour is seen for December which must be assumed to be caused by modelling errors. The three bias-correction methods show generally the same picture with increases between zero and 15%. Relatively large increases are observed in the growing season from April to August. It is interesting to notice that all three methods are able to estimate a more reasonable change for December that was otherwise unrealistic low according to the climate model.

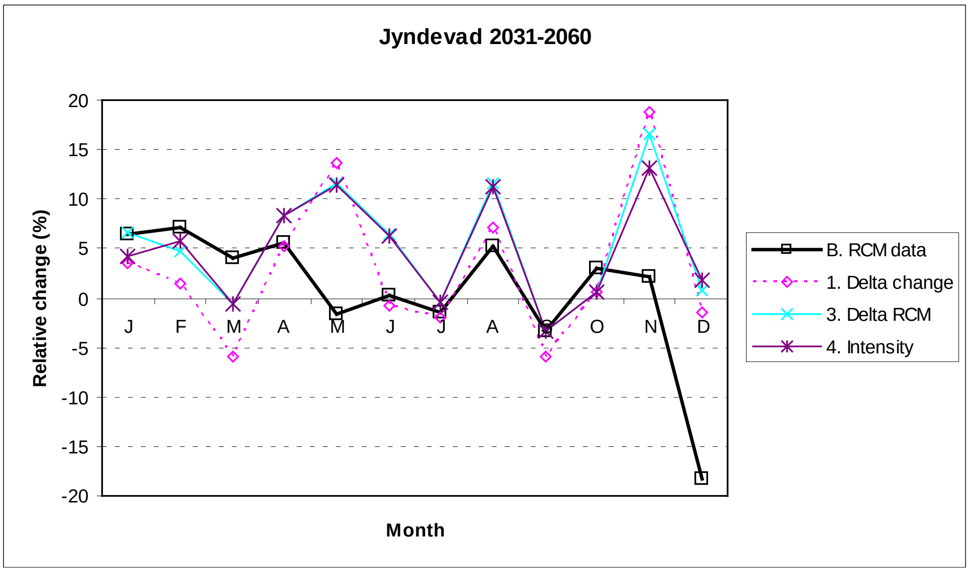

Figure B21. Relative change in mean monthly reference evapotranspiration 2031-2060 for each of the bias-correction methods compared to the period 1991-2006 for Jyndevad.

The relative changes in ET_{ref} for the period 2071-2100 are generally more pronounced (Figure B22). The uncorrected RCM data generates a fluctuating picture of the monthly increase. The seasonal variation of the bias-corrected results is more continuous over season, but it is difficult to conclude if they are closer to the true values. The two methods using the RCM data as baseline for the correction (no. 3 and 4) yield an increase in monthly ET_{ref} in the order 10% during the growing season from April to September. A significant increase is observed for January but in absolute values this only corresponds to a couple of mm and is hence relatively unimportant for the hydrological system.

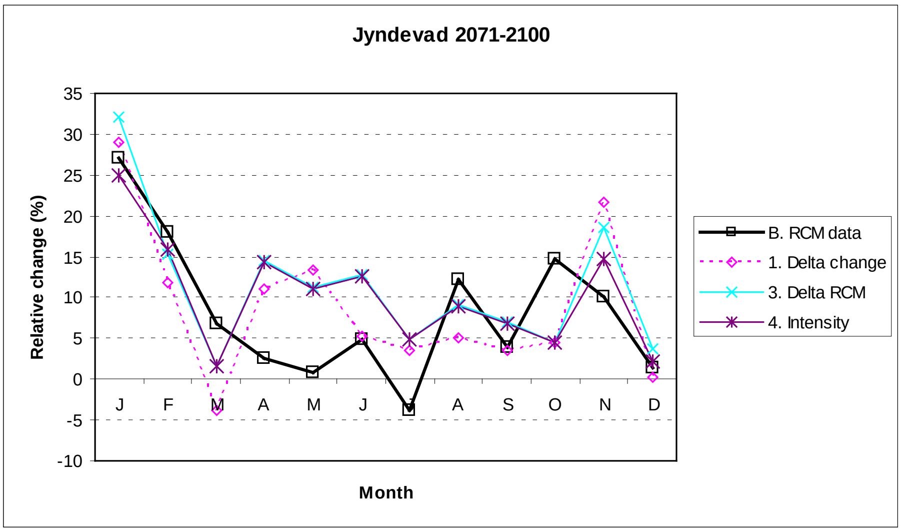

Figure B22. Relative change in mean monthly reference evapotranspiration 2071-2100 for each of the bias-correction methods compared to the period 1991-2006 for Jyndevad.

In Figure B23 and B24 the results for Tystofte (2031-2060) are shown. In both cases results similar to those found for Jyndevad are found.

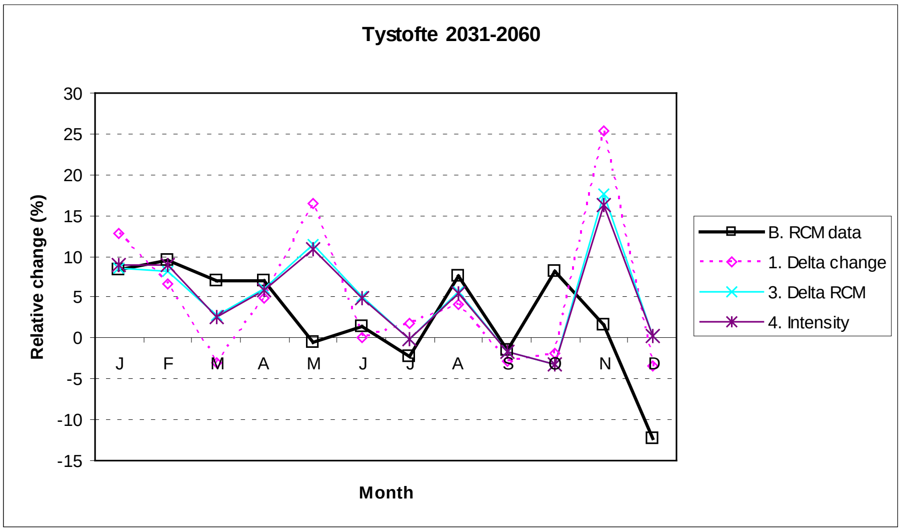

Figure B23. Relative change in mean monthly reference evapotranspiration 2031-2060 for each of the bias-correction methods compared to the period 1991-2006 for Tystofte.

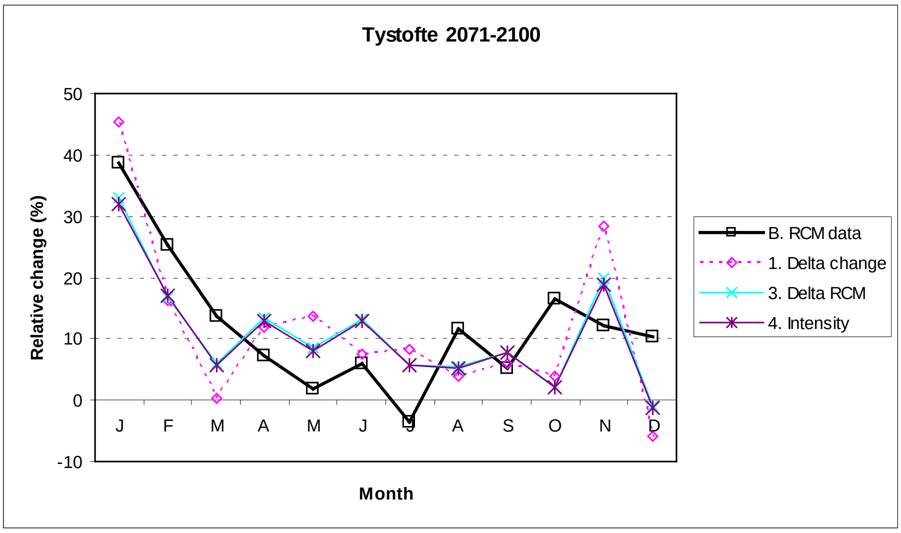

Figure B24. Relative change in mean monthly reference evapotranspiration 2071-2100 for each of the bias-correction methods compared to the period 1991-2006 for Tystofte.

In Figure B25 the precipitation distribution for 1961-1990 from the British HadRM$_3$ model is shown. The HadRM$_3$ model captures the peaks in precipitation in the southern and northern part of Jutland. However, in general the precipitation distribution is not described as well as by the RACMO model.

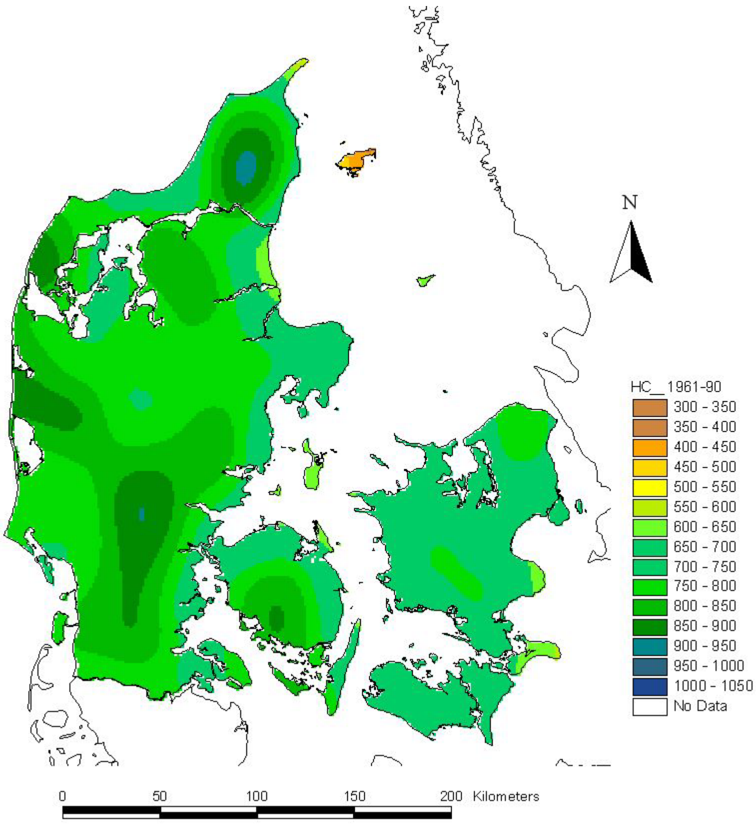

Figure B25. Average precipitation 1961-90 from HadRM.

In Figure B26 and B27 HadRM$_3$ results for 2031-2060 and 2071-2098 are shown. Precipitation increases in the first period but a small decrease is observed in the last period. The majority of the ENSEMBLES model simulations show a continuous increase in precipitation over time. Based on this fact together with the relatively poor match of the spatial precipitation distribution for the control period (1961-1990), it was decided to use the results from the RACMO model in the remaining of the project.

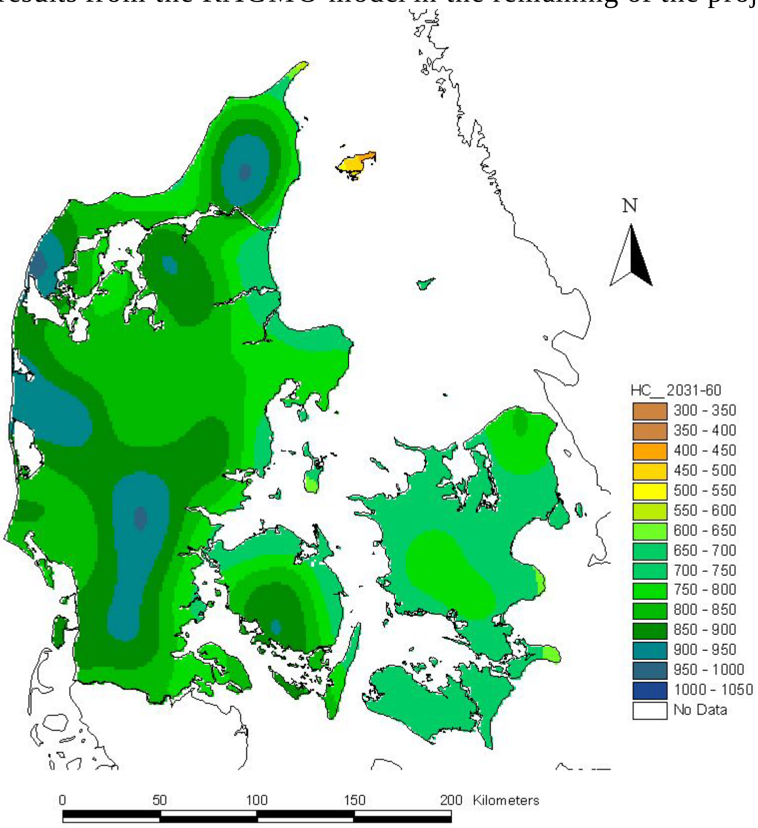

Figure B26. Average precipiation 2031-60 from $HadRM_3$.

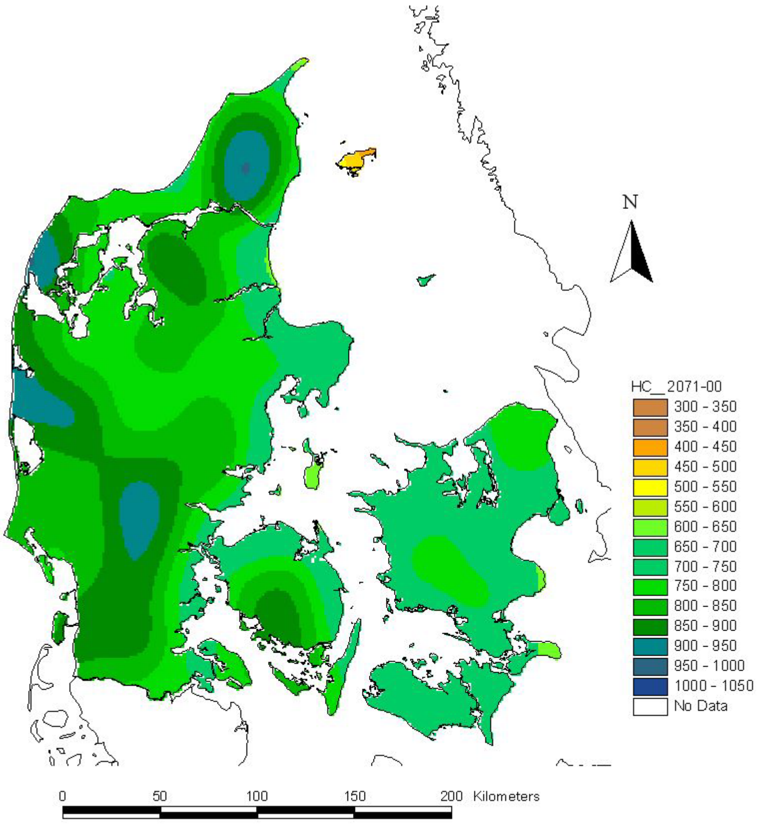

Figure B27. Average precipitation 2071-2098 from $HadRM_3$.

Appendix C Bias correction

In this section the five methods will first briefly be described before turning to a comparison of results of the five bias correction methods.

C1 Description of the five bias correction methods

C1.1 Delta change method

This method uses the observed climate as baseline and is described by the following equation (Roosmalen et al., 2007):

$$P_{cor}(i,j) = \Delta_{PC}(j) \times P_{obs}(i,j) \quad ; \quad i = 1,2,.....,31;\ j = 1,2,....,12 \tag{1}$$

where P_{cor} is the precipitation input to the hydrological model for the scenario run. P_{obs} is the observed precipitation representing the current climate. The suffixes i and j stand for the ith day of the jth month. Δ_{PC} is the delta change factor, which is calculated using the expression

$$\Delta_{PC}(j) = \frac{\overline{P}^{sce}_{sim}(j)}{\overline{P}^{cont}_{sim}(j)} \quad ; \quad j = 1,2,....,12 \tag{2}$$

where $\overline{P}$ (j) is the precipitation in month j averaged for the control or scenario period as simulated by the RCM. The index sce stands for the scenario period, while the index cont indicates the control period. A similar procedure as described by eq. (1) and (2) is used to correct reference evapotranspiration.

For temperature the absolute change is used for the delta factor, as follows:

$$T_{cor}(i,j) = T^{cont}_{obs}(i,j) + \Delta_{TC}(j) \tag{3}$$

where Δ_{TC} is given by

$$\Delta_{TC}(j) = \overline{T}^{scen}_{sim}(j) - \overline{T}^{cont}_{sim}(j) \quad ; \quad j = 1,2,....,12 \tag{4}$$

This method can only be applied for pre-specified time intervals for which the delta factors are calculated.

C1.2 Transformation of distribution

This method also use observed climate as baseline. Using this method the future changes in the statistical distribution of precipitation is transferred to the historical data. It is assumed that precipitation is log-normally distributed with mean μ and standard deviation σ. Changes in rainfall intensity of the scenario RCM precipitation are transferred to the observed data, P_{obs}, using the following procedure (Mileham et al., 2009)

$$Y_t = \mu_{sce} + \left[\sigma_{sce} \frac{\log(P_{obs}) - \mu_{obs}}{\sigma_{obs}} \right] \tag{5}$$

where μ_{obs} and σ_{obs} are the mean and standard deviation of the log-transformed observed precipitation, respectively, and μ_{sce} and σ_{sce} are the mean and standard deviation of the log-transformed RCM results for the scenario period, respectively. Y_t represents the transformation of the observed precipitation to the future distribution. Since the RCM precipitation for both the control period, P_{cont}, and the scenario period, P_{sce}, are assumed to be biased, it is necessary to convert the precipitation using the following equation

$$\log(P_{cor}) = \mu_{obs} + \left[\sigma_{obs} \frac{\log(Y_t) - \mu_{cont}}{\sigma_{cont}} \right] \quad (6)$$

where P_{cor} is the corrected precipitation for the future while μ_{cont} and σ_{cont} are the mean and standard deviation of the log-transformed RCM results for the control period, respectively.

Using equation (5) and (6) a transformation of the historical precipitation that matches the future statistical distribution (mean and standard deviation) is carried out. However, rainfall occurrence is still controlled by the observation data and therefore possible changes in dynamics are not captured.

With respect to reference evapotranspiration and temperature the delta change method (paragraph 2.2.1.1) is used.

C1.3 RCM data

This and the following two methods use the future climate as baseline. I the RCM data method, the climate model results are used directly as input to the hydrological model.

$$P_{cor} = P_{sim}^{sce} \quad (7)$$

Also reference evapotranspiration and temperature are used without any corrections. Hence, it is assumed that the results from the regional climate model are accurate enough to be used as input to the hydrological model.

C1.4 Delta RCM

The first step of the approach in the Delta RCM method is to define a threshold below which all RCM precipitation is set to zero. This threshold is determined by calculating the percentage of dry days in the observational data set, f_{dry}, which are days with precipitation less than P_{dry} = 0.1 mm. The control period RCM data values are then ranked and the precipitation value corresponding to the percentage of dry days in the observational data set, f_{dry}, is then selected as the threshold value, P_{cutoff}. For both the control and scenario data set, all RCM simulated precipitation values below this threshold are set to zero.

The second step of this method is described by the following equation (Lenderink et al., 2007):

$$P_{cor}(i,j) = \Delta_{PS}(j) \times P_{sim}^{scen}(i,j) \quad ; \quad i = 1,2,.....,31 \,;\; j = 1,2,....,12 \qquad (8)$$

where P_{cor} is the precipitation input to the hydrological model for the scenario run. P_{sim}^{scen} is the threshold corrected scenario precipitation simulated by the climate model. The suffixes i and j stand for the ith day of the jth month. Δ_{PS} is the delta change factor, which is calculated using the expression

$$\Delta_{PS}(j) = \frac{\overline{P}_{obs}^{cont}(j)}{\overline{P}_{sim}^{cont}(j)} \quad ; \quad j = 1,2,....,12 \qquad (9)$$

where $\overline{P}$ (j) is the precipitation in month j averaged for the observed data or the control period as simulated by the RCM. The index obs stands for the observation data, sim symbolize the climate model results, while the index cont indicates the control period.

Using this method the RCM precipitation is adjusted such that the total precipitation matches the observed total precipitation. However, the distribution of precipitation is not accounted for. A similar approach is used to obtain the future reference evapotranspiration.

Temperature is adjusted as

$$T_{cor}(i,j) = T_{sim}^{scen}(i,j) + \Delta_{TS}(j) \qquad (10)$$

where Δ_{TS} is the delta change factor defined by

$$\Delta_{TS}(j) = \overline{T}_{obs}^{cont}(j) - \overline{T}_{sim}^{cont}(j) \quad ; \quad j = 1,2,....,12 \qquad (11)$$

This method applies for any period after the control period on which the delta factors are based.

C1.5 Intensity-based correction

This method is referred to as an intensity-based statistical bias correction method (Piani et al., 2008) sometimes also termed “histogram-correction”. The first step of the approach is to correct for the superfluous drizzle of the RCM. A threshold is determined below which all RCM precipitation is set to zero. This threshold is determined by calculating the percentage of dry days in the observational data set, f_{dry}, which are days with precipitation less than P_{dry} = 0.1 mm. The control period RCM data values are then ranked and the precipitation value corresponding to the percentage of dry days in the observational data set, f_{dry}, is then selected as the threshold value, P_{cutoff}. For both the control and scenario data set, all RCM simulated precipitation values below this threshold are set to zero.

The bias correction approach not only corrects the mean precipitation amount, but also scales the precipitation values depending on its intensity. The second step of the approach, after threshold correction of the RCM data set, is to fit a statistical distribution to the probability density function (PDF) of the daily values of the observed data set and the threshold corrected RCM control period. Here, the gamma distribution is used because it approaches the asymmetrical and positively skewed properties of the precipitation data set well (Wilks, 1995). The fit is only performed for wet days, because the bias correction is not applied to dry days. The PDF of the gamma distribution is defined as follows:

$$f(P) = \frac{(P/\beta)^{\alpha-1}\exp(-P/\beta)}{\beta\Gamma(\alpha)} \quad ; \quad P,\alpha,\beta > 0 \qquad (12)$$

where P is precipitation (mm/day), α and β are the shape and scale parameter of the gamma distribution, and $\Gamma(\alpha)$ is the gamma function:

$$\Gamma(\alpha) = \int_0^\infty t^{\alpha-1}e^{-t}dt \qquad (13)$$

which in general must be evaluated numerically (Wilks, 1995). Two sets of parameters are determined using the method of maximum likelihood: one set for the observations (α_{obs} and β_{obs}) and another set for the RCM control simulation (α_{cont} and β_{cont}). Through an iterative procedure the parameters that maximizes the log-likelihood function is found using the multidimensional generalization of the Newton-Raphson method (e.g., Press et al., 1986).

In the present version of the method the gamma distribution is fitted to each season (winter, spring, summer, autumn) in order to obtain a better description of especially extreme events.

The estimated PDF for the RCM control period precipitation is subsequently used to find the probability of a certain precipitation value. Feeding this probability into the PDF for the observations yields the corresponding precipitation value. This can be described by the following equation:

$$P_{cor} = f^{-1}(\alpha_{obs}, \beta_{obs}, f(\alpha_{cont}, \beta_{cont}, P_{RCM}) \qquad (14)$$

where P_{cor} is the bias corrected RCM daily precipitation value to be used in the hydrological simulation, f indicates the PDF of the gamma distribution and $f(\alpha_{cont}, \beta_{cont}, P_{RCM})$ is the probability of the precipitation value P_{RCM} using the PDF fitted to the gamma distribution of the control period RCM values. The P_{RCM} value can either be RCM precipitation for the control or scenario period implying that the same bias correction is applied to both the control and scenario period. This is a valid approach if it is assumed that the model biases are the same for the control and scenario period (as for the delta change method). Thus, the RCM control and scenario precipitation values are corrected similarly, but because of the changes in the precipitation distribution as simulated by the RCM the PDFs of the corrected values are expected to differ for the two periods.

The described two step correction method is applied to all simulated precipitation values of both the control and the scenario periods.

Reference evapotranspiration is corrected using an approach similar to that used for precipitation. With respect to temperature the results from the delta RCM method is used.

C2 Results of the five bias correction methods

C2.1 Delta change method

In Table C1 the delta change factors for precipitation are listed for Jyndevad and Tystofte. At both locations factors above 1.0 are generally found for the period September to March whereas delta factors close to or below 1.0 are generally found in the summer period from April to August. The effect on winter precipitation is more significant for the latest period. Especially the January precipitation shows a large increase.

Table C1. Delta change factors for precipitation for Jyndevad and Tystofte.

	Month											
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Jyndevad												
1991-2006	1.02	0.95	0.88	0.98	0.97	1.07	0.97	1.05	1.17	1.19	0.96	0.96
2031-2060	1.08	1.16	1.02	0.95	0.81	0.97	0.96	0.76	1.37	1.04	0.99	1.02
2071-2100	1.34	1.19	1.20	0.97	1.06	0.86	0.89	0.79	1.20	1.13	1.19	1.15
ystofte												
1991-2006	1.04	0.99	0.85	0.93	0.93	1.05	1.04	0.92	1.01	1.17	0.96	0.89
2031-2060	1.16	1.18	0.94	0.95	0.86	0.94	1.08	0.79	1.33	1.05	0.90	1.02
2071-2100	1.37	1.18	1.16	0.97	1.12	0.88	1.11	0.86	1.13	1.14	1.17	1.11

In Table C2 the delta factors for temperature are found. For the two latest scenario periods all numbers are higher than zero. A relatively uniform increase through the months of the year is found.

Table C2. Delta change factors for temperature for Jyndevad and Tystofte (units in K).

	Month											
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Jyndevad												
1991-2006	1.10	0.47	1.36	0.73	-0.19	0.36	0.30	0.56	0.48	0.57	0.43	-0.22
2031-2060	1.66	1.72	1.65	1.49	1.02	1.33	0.86	1.80	1.26	1.96	1.68	0.40
2071-2100	3.28	2.41	2.84	2.54	1.87	2.34	1.95	2.59	2.22	2.86	2.69	2.58
Tystofte												
1991-2006	1.32	0.65	1.47	0.93	-0.02	0.37	0.34	0.57	0.56	0.60	0.22	0.03
2031-2060	1.83	1.91	1.93	1.66	1.17	1.40	0.97	1.81	1.31	2.11	1.72	0.62
2071-2100	3.45	2.61	3.20	2.74	2.03	2.45	2.16	2.64	2.31	2.97	2.69	2.80

The delta change factors for reference evapotranspiration are found in Table C3. For the scenario periods 2031-2060 and 2071-2100 all factors except for December at Jyndevad are above one, corresponding to an increase in reference evapotranspiration.

Table C3. Delta change factors for reference evapotranspiration for Jyndevad and Tystofte.

	Month											
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Jyndevad												
1991-2006	1.01	1.07	1.07	1.00	0.98	1.01	1.00	1.00	1.02	1.04	1.05	0.94
2031-2060	1.07	1.10	1.05	1.08	1.09	1.07	1.00	1.12	1.00	1.06	1.23	0.97
2071-2100	1.33	1.21	1.07	1.14	1.08	1.13	1.06	1.10	1.10	1.10	1.26	0.99
Tystofte												
1991-2006	1.04	1.07	1.10	1.03	0.98	1.01	1.01	1.05	1.03	1.09	0.98	1.04
2031-2060	1.15	1.14	1.12	1.09	1.09	1.06	1.01	1.11	1.02	1.06	1.22	1.06
2071-2100	1.49	1.24	1.15	1.16	1.06	1.14	1.08	1.11	1.12	1.13	1.25	1.03

C2.2 Transformation of distribution method

In Table C4 the statistics on which the transformation method is based are presented, see also eq. (5) and (6).

Table C4. Statistics on log-transformed precipitation at Jyndevad and Tystofte.

Location	Para-meter	Observations	RCM data			
		1961-1990	1961-1990	1991-2006	2031-2060	2071-2100
Jyndevad	μ	0.379	0.238	0.252	0.242	0.255
	σ	0.610	0.607	0.604	0.617	0.622
Tystofte	μ	0.310	0.159	0.161	0.174	0.192
	σ	0.593	0.602	0.598	0.599	0.619

C2.3 Delta RCM method

In Table C5 the delta factors for temperature, precipitation, and reference evapotranspiration are listed. The delta values for temperature are generally small implying that the match of the RCM simulation is close to the observed data in the control period. With respect to precipitation, values close to one are found for most months at Jyndevad, however, for July and August relatively small values are found. At Tystofte the general overestimation of the precipitation is recognised on the delta factors, where values much smaller than one are found for all months. As a result all precipitation data at Tystofte are reduced.

Relatively large delta values are found for reference evapotranspiration for both stations for all months except December. This implies that the simulated reference evapotranspiration should be increased in order to represent the observed values.

Table C5. Delta values for Jyndevad and Tystofte.

	Month											
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Temperature (K)												
Jyndevad	-0.78	-1.41	0.17	-0.14	-0.16	0.57	-0.19	0.54	-0.31	-0.10	-1.02	-2.07
Tystofte	-0.16	-0.96	0.50	0.50	0.50	1.19	0.45	1.07	0.16	0.23	-0.70	-1.34
Precipitation												
Jyndevad	1.01	0.80	1.12	0.90	0.87	0.93	0.87	0.74	1.02	0.99	1.09	0.96
Tystofte	0.88	0.69	0.86	0.78	0.86	0.82	0.94	0.67	0.82	0.70	0.74	0.78
Ref. Evapotranspiration												
Jyndevad	1.17	1.40	1.30	1.30	1.25	1.21	1.12	1.34	1.24	1.26	1.29	0.82
Tystofte	1.28	1.51	1.45	1.33	1.24	1.21	1.12	1.29	1.21	1.23	1.24	0.92

C2.4 Intensity-based statistical method

In Table C6 the estimated parameters for the gamma distributions (see eq. (12)) at the two locations are listed. At Jyndevad α_{obs} varies from 0.829 to 0.885 over the season whereas at Tystofte α_{obs} varies in the interval from 0.842 to 0.907. The α-values are larger for the RCM data; however, the variation over the season is larger than for the observed data with variations of 1.260 to 1.797 at Jyndevad and 1.604 to 1.964 at Tystofte.

The β-values for the observations show more significant variation over season. β_{obs} varies from 5.007 to 6.954 at Jyndevad and from 4.302 to 5.969 at Tystofte. The RCM parameters vary from 3.210 to 4.345 and 2.672 to 3.353 at Jyndevad and Tystofte, respectively. Especially the differences between the β-values justifies that the parameterization is carried out on a seasonal level.

Table C6. Estimated alpha and beta values for observations and RCM data for the period 1961-1990.

Data type	Location	Winter	Spring	Summer	Autumn
α values					
Observations	Jyndevad, α_{obs}	0.885	0.868	0.862	0.829
	Tystofte, α_{obs}	0.877	0.907	0.852	0.843
RCM data	Jyndevad, α_{cont}	1.613	1.319	1.797	1.260
	Tystofte, α_{cont}	1.933	1.604	1.884	1.964
β values					
Observations	Jyndevad, β_{obs}	5.689	5.007	6.467	6.954
	Tystofte, β_{obs}	4.647	4.302	5.969	5.290
RCM data	Jyndevad, β_{cont}	3.210	3.312	3.603	4.345
	Tystofte, β_{cont}	2.672	2.977	3.353	3.001

C2.5 Precipitation

In Table C7 mean annual precipitation for the alternative bias-correction methods in the validation period 1991-2006 are listed together with the observed values at the two stations. At Jyndevad the uncorrected RCM data overestimates the mean annual precipitation with 77 mm corresponding to a relatively error of 6.9% which may be considered satisfactorily. However, at Tystofte the error amount to 187 mm or 26.6%. This error is clearly so large that bias-correction is required.

Comparing the alternative bias-correction methods to the observed precipitation for the period 1991-2006 shows that all methods results in a reduced error compared to the RCM data. The delta change method (no. 1) yields the maximum error both at Jyndevad (52 mm) and at Tystofte (69 mm). The minimum error is provided by the delta RCM method (no. 3) at Jyndevad (6 mm) and by the intensity-based method (no. 4) at Tystofte (41 mm). With respect to the annual variation expressed through the listed standard deviations, all methods underestimate the observed variability. However, especially the delta RCM method produces low variability at both stations.

Table C7. Annual mean precipitation (mm) of the bias correction methods for the period 1991-2006. Standard deviations are listed in parenthesis.

No	Method	1991-2006	Error – mean
Jyndevad			
A	Observations	1060 (177)	-
B	RCM data	1133 (133)	77
1	Delta obs	1008 (159)	-52
2	Stat. Trans	1013 (160)	-47
3	Delta RCM	1066 (129)	6
4	Intensity-based	1085 (150)	25
Tystofte			
A	Observations	704 (142)	-
B	RCM data	891 (113)	187
1	Delta obs	635 (125)	-69
2	Stat. Trans	645 (126)	-59
3	Delta RCM	659 (90)	-45
4	Intensity-based	663 (110)	-41

In Table C8 and in Figure C1 and C2 the monthly mean precipitation is presented for the period 1991-2006. The match of the uncorrected RCM results to the observations is generally unsatisfactory due to the bias on total annual precipitation. All the bias-correction methods are able to capture the seasonal variation at Jyndevad and reproduce the low values in spring and summer and high values in autumn and winter. The largest discrepancies between the four methods are found in the period from August to October, where method no. 2 yields relatively small values and method no. 4 produces relatively large values. At Tystofte the different bias-correction methods are generally very similar, except for October, where the same trend as for Jyndevad is observed again, with relatively small values for method no. 2 and relatively large values for methods no. 4.

Table C8. Monthly mean precipitation (mm) of the bias correction methods for the period 1991-2006.

	Month											
Method	J	F	M	A	M	J	J	A	S	O	N	D
Jyndevad												
A Obs	109.9	91.8	76.3	56.5	59.4	79.1	83.0	93.8	84.3	109.8	97.9	118.3
B RCM	96.8	71.3	60.3	63.1	71.3	85.5	97.2	128.9	112.7	132.5	106.3	107.4
1 Delta	91.9	53.8	52.5	60.3	61.5	63.6	91.7	94.5	108.8	114.3	121.4	93.4
2 Stat.	92.4	58.3	60.9	63.5	64.8	61.0	96.8	92.5	95.4	98.5	129.2	99.8
3D. RCM	98.2	56.6	67.1	56.3	61.9	80.6	83.6	95.3	115.4	132.9	115.1	103.1
4 Intensity	91.9	64.0	56.1	59.9	71.4	70.6	81.3	113.0	120.7	141.8	110.3	104.2
Tystofte												
A Obs	64.4	45.7	47.8	46.6	47.0	63.7	58.5	64.4	62.5	64.3	66.4	72.4
B RCM	79.9	60.6	52.0	54.3	56.9	73.4	72.7	88.4	76.5	102.4	89.3	84.5
1 Delta	55.6	40.5	31.2	44.3	50.0	48.9	64.9	57.5	56.6	61.2	66.7	58.0
2 Stat.	53.3	40.8	36.7	47.6	53.3	46.2	62.0	62.4	56.0	52.5	69.5	64.9
3 D. RCM	65.5	38.5	39.6	38.5	45.2	58.0	64.5	56.8	59.5	68.7	62.8	61.4
4 Intensity	58.3	42.0	37.3	40.0	43.9	58.0	53.9	66.2	55.4	79.0	66.1	62.6

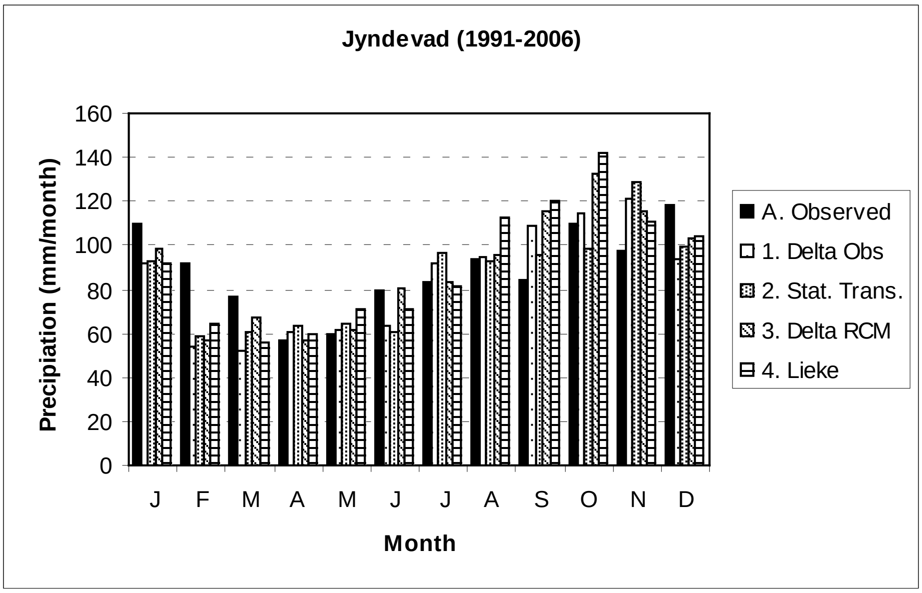

Figure C1. Monthly mean precipitation of the bias correction methods for the period 1991-2006 for Jyndevad.

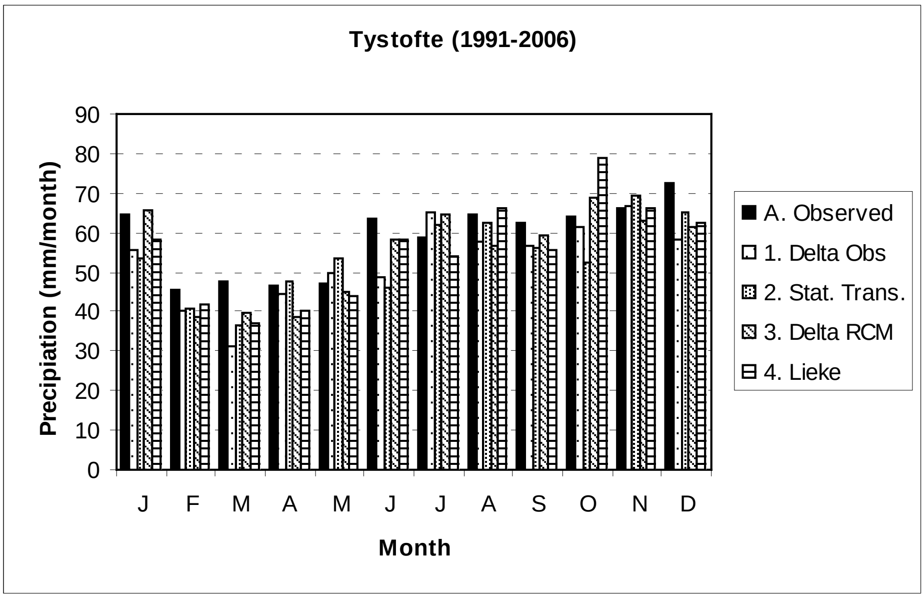

Figure C2. Monthly mean precipitation of the bias correction methods for the period 1991-2006 for Tystofte.

In Table C9 the annual mean maximum precipitation, found as the mean of the annual maximum precipitation for each of the years in the period considered, is listed. For the period 1991-2006 the RCM results are seen to severely underestimate the observed maximum precipitation at both stations (by 8.4 and 5.7 mm/day for Jyndevad and Tystofte, respectively). When bias-correction is carried out the match to the maximum precipitation is generally improved, except for method no. 3 (delta RCM), where it is actually worse. The results of other three methods are all very close to the observed values. Method no. 4 is however superior when comparing the variability expressed through the standard deviation.

Table C9. Annual mean maximum precipitation (mm/day) of the bias correction methods for the period 1991-2006. Standard deviations on annual maximum values are listed in parenthesis.

No	Method	1991-2006	Error - Mean
Jyndevad			
A	Observations	37.6 (9.1)	-
B	RCM data	29.2 (4.9)	-8.4
1	Delta obs	39.7 (7.6)	2.1
2	Stat. Trans	38.9 (6.4)	1.3
3	Delta RCM	28.6 (5.4)	-9.0
4	Intensity-based	38.9 (7.9)	1.3
Tystofte			
A	Observations	33.8 (8.6)	-
B	RCM data	28.1 (7.8)	-5.7
1	Delta obs	35.3 (13.3)	1.5
2	Stat. Trans	35.3 (13.4)	1.5
3	Delta RCM	23.1 (5.8)	-10.7
4	Intensity-based	35.0 (10.8)	1.2

Results on the seasonal distribution of maximum precipitation are found in Table C10 and Figure C3 and C4. Method no. 3 underestimates the maximum precipitation severely at both stations. Methods no. 1 and 2 yields comparable results that generally fits the observations acceptable. However, for some months, e.g. November and December for Jyndevad together with December for Tystofte, the bias is substantial. Method no. 4 provides the best overall match to the maximum precipitation at both stations. This is also seen from Table 26 where the mean error (ME) and the root mean squared error (RMS) is presented for both monthly mean and monthly maximum precipitation. Method no. 4 provides the lowest ME (1.1 and -4 mm/day) and RMS (3.0 and 2.2 mm/day) values with respect to maximum precipitation for the two stations. The errors of the other methods are significantly higher.

Table C10. Monthly mean maximum precipitation (mm/day) of the bias correction methods for the period 1991-2006.

	Month											
Method	J	F	M	A	M	J	J	A	S	O	N	D
Jyndevad												
A Observations	18.6	19.1	18.8	14.1	17.6	19.6	22.2	25.4	22.6	21.5	19.5	25.6
B RCM data	15.1	12.5	12.4	13.1	18.4	19.2	16.8	19.7	19.4	18.7	17.0	18.0
1 Delta obs	17.4	12.8	13.8	15.5	14.9	19.7	21.5	26.3	27.5	24.5	26.2	18.0
2 Stat. Trans	17.4	13.9	15.9	16.2	15.6	18.8	22.6	25.5	24.0	21.1	27.8	19.1
3 Delta RCM	15.9	10.4	14.6	12.3	16.6	18.6	14.9	14.8	20.3	19.1	19.0	17.7
4 Intensity-bas.	18.8	14.9	14.5	15.4	22.8	22.9	19.4	23.6	24.7	23.8	21.5	23.3
Tystofte												
A Observations	14.6	13.2	13.8	13.0	13.3	17.4	20.9	17.4	16.8	17.1	16.5	18.6
B RCM data	13.6	11.3	10.9	11.5	12.5	17.8	15.3	15.1	16.1	17.4	17.9	15.8
1 Delta obs	14.1	10.5	8.4	11.9	15.4	17.3	18.0	18.2	20.5	18.1	15.4	13.5
2 Stat. Trans	13.4	10.5	9.9	12.7	16.4	16.3	17.1	19.7	20.1	15.4	16.0	15.1
3 Delta RCM	12.0	7.9	9.4	8.9	10.8	14.6	14.4	10.1	13.2	12.2	13.3	12.3
4 Intensity-bas.	14.7	11.7	10.7	11.5	12.7	20.2	16.5	16.1	17.5	19.3	19.8	18.1

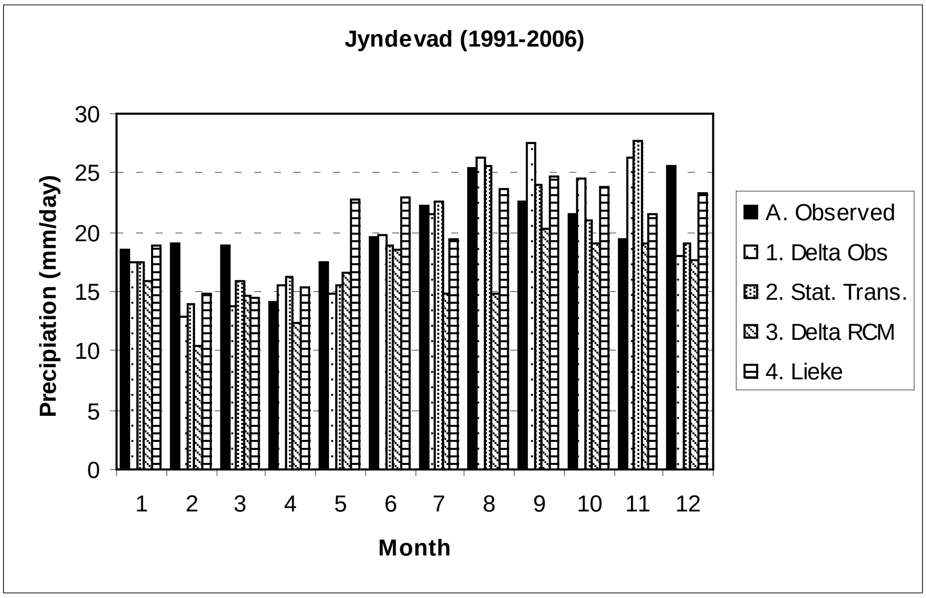

Figure C3. Monthly mean maximum precipitation for Jyndevad in the period 1991-2006.

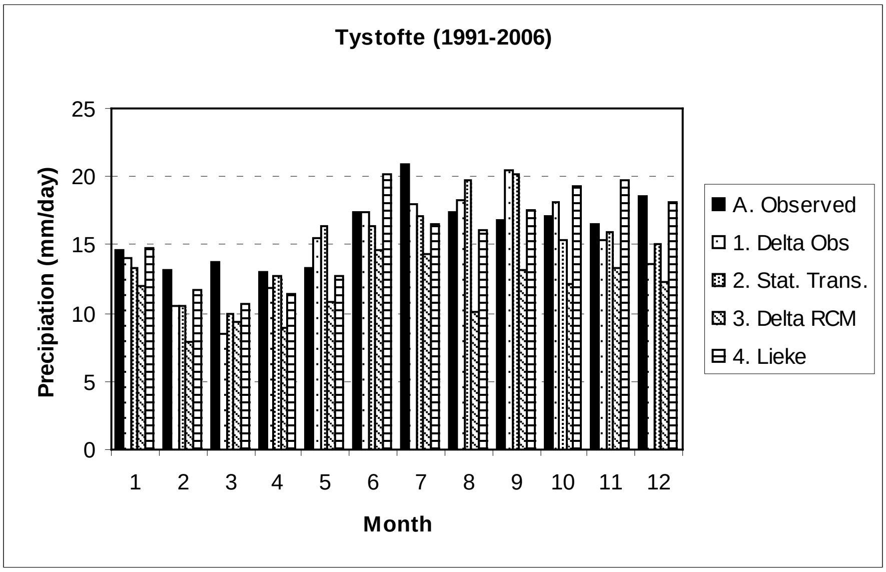

Figure C4. Monthly mean maximum precipitation for Tystofte in the period 1991-2006.

When the statistical match to the mean monthly precipitation is examined (Table 31) we find that with respect to the ME method no. 3 is best, closely followed by method no. 4 for Jyndevad. At Tystofte the ranking between these two methods is switched. The best RMS values for Jyndevad are found for method no. 3, which is also the case for Tystofte. However, the relative difference between the RMS values is small at both stations.

Table C5. Quantification of the match between observed and bias corrected mean monthly and monthly maximum precipitation assessed by the mean error (ME) an the root mean squared (RMS) values.

		Monthly Mean		Monthly Max	
No	Method	ME (mm/m)	RMS (mm/m)	ME (mm/day)	RMS (mm/day)
Jyndevad					
B	RCM data	73.0	18.3	-44.2	4.5
1	Delta obs	-52.3	19.3	-6.4	4.2
2	Stat. Trans	-47.0	17.9	-6.6	3.7
3	Delta RCM	6.0	17.1	-50.5	5.4
4	Intensity	24.9	20.0	1.1	3.0
Tystofte					
B	RCM data	187.5	17.9	-17.3	2.3
1	Delta obs	-68.2	8.9	-11.4	2.8
2	Stat. Trans	-58.5	8.6	-10.2	2.6
3	Delta RCM	-44.6	6.3	-53.6	4.7
4	Intensity	-40.8	7.3	-4.0	2.2

C2.6 Evapotranspiration

In Table C6 the annual mean reference evapotranspiration (ET_{ref}) for the validation period (1991-2006) is listed. The uncorrected ET_{ref} is clearly underestimated at both sites with a maximum error of 159 mm/year at Tystofte. Correction of the RCM data generally generates data with much smaller errors. At Jyndevad the error is reduced to an interval from 10 to 34 mm/year whereas at Tystofte the evapotranspiration is underestimated by 35 to 49 mm/year. With the exception of the delta change method (no. 1) at Tystofte the variability in annual ET_{ref} is well captured by the correction methods.

Table C6. Annual mean reference evapotranspiration (mm) of the bias correction methods for the periods 1991-2006. Standard deviations (SD) on annual values are listed in parenthesis.

No	Method	1991-2006	Error – mean
Jyndevad			
A	Observations	587 (32)	-
B	RCM data	459 (32)	-128
1	Delta obs	577 (28)	-10
3	Delta RCM	561 (28)	-26
4	Intensity-based	553 (28)	-34
Tystofte			
A	Observations	636 (32)	-
B	RCM data	477 (33)	-159
1	Delta obs	601(21)	-35
3	Delta RCM	600 (34)	-36
4	Intensity-based	587 (34)	-49

In Figure C5 and C6 the match between the measured bias-corrected estimates of ET_{ref} at the two field sites are shown. All three methods generally reproduce the observed variation over the year satisfactorily.

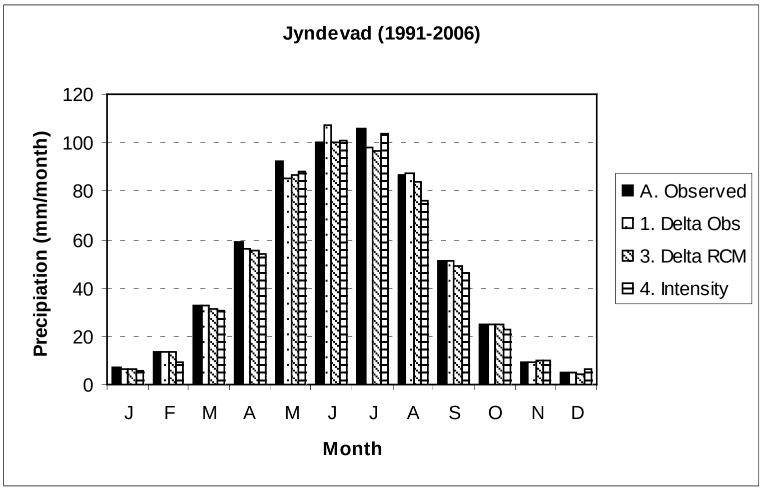

Figure C5. Monthly mean reference evaotranspiration of the bias correction methods for the period 1991-2006 for Jyndevad.

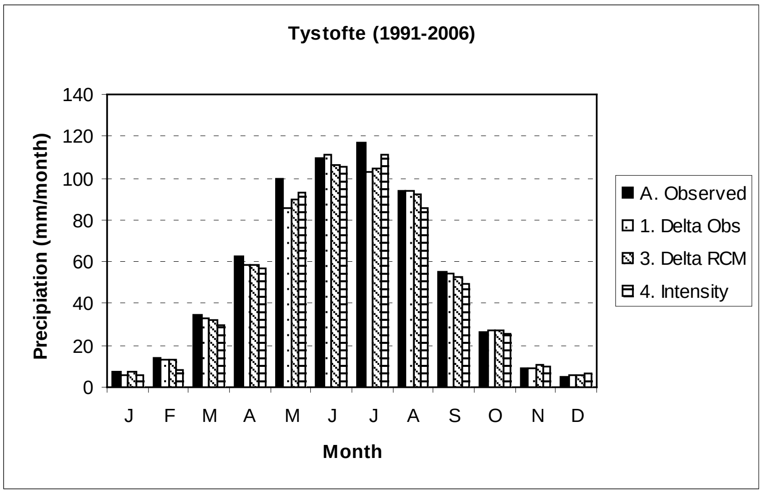

Figure C6. Monthly mean reference evaotranspiration of the bias correction methods for the period 1991-2006 for Tystofte.

Appendix D Test of correction methods for pesticide leaching

D1 Corrected climate time series and impact on pesticide leaching.

The effect of climate time series correction on simulated leaching for two PLAP locations, Faardrup and Jyndevad, and three different pesticide compounds with varying sorption and degradation properties is presented here. In the graphs below, the simulated pesticide concentration at 1 m below surface is presented for the following correction methods, as earlier explained in this document.

Table D1. Summary of correction methods used for test of pesticide leaching.

Correction method	Description
0 (correspond to B)	Direct, i.e. no correction applied. Climate data directly from Regional Climate Model
1	Delta Change (obs). Scaling observed data from climate model predictions
2	Transformation of Distribution. Transferring future changes in statistical distribution to observed data
3	Delta Change (RCM). Scaling simulated data to observed data.
4	Intensity based. Future climate found by scaling the scenario results with the fraction between observed and simulated data for control period
Obs	Observed data for 1961-1990

Below, selected results are shown (Figure D1-D2) for the Jyndevad and Faardrup locations (2071-2100) while it is anticipated that the loamy/clayey soil (Faardrup) is most susceptible for changes in amount, timing and intensity of future rainfall data. This is so, because higher intensity and amount can initiate preferential water- and solute flow, bypassing the biologically active upper part of the vadose zone. The results for spring are included in the appendix.

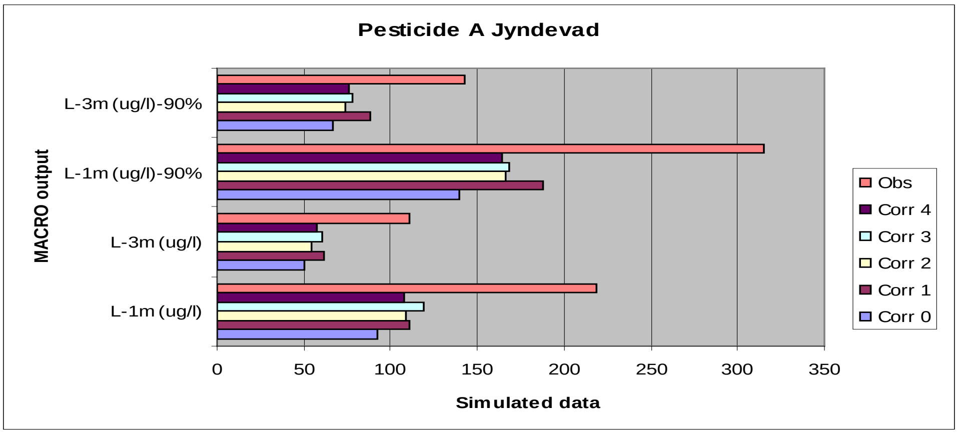

Figure D1. Simulated pesticide A concentration at 1 m and 3 m depth at Jyndevad. The upper bars represent 90% percentile values, whereas the two lower bars the median values.

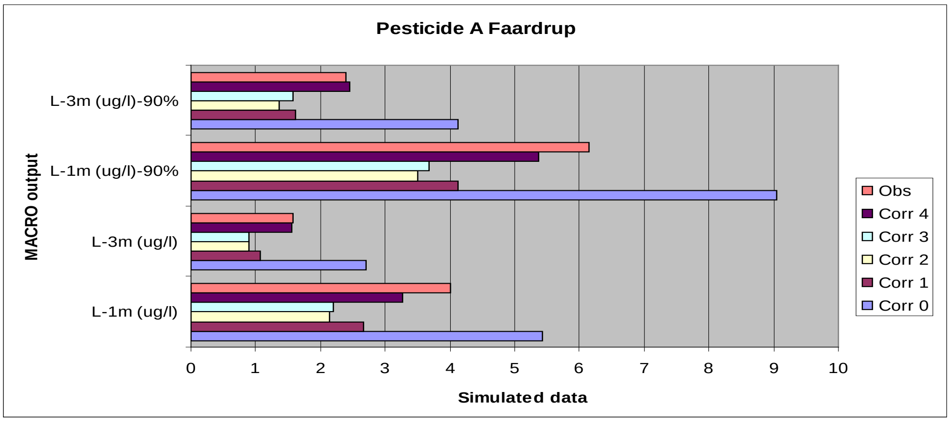

Figure D2. Simulated pesticide A concentration at 1 m and 3 m depth at Faardrup. The upper bars represent 90% percentile values, whereas the two lower bars the median values.

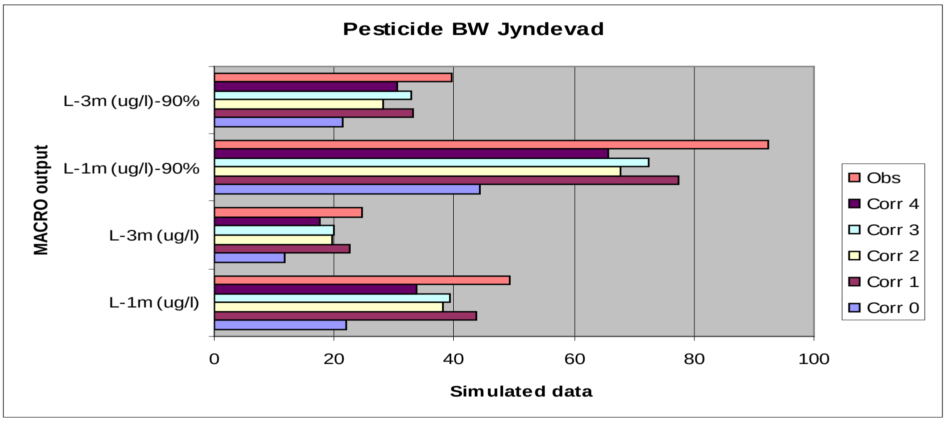

Figure D3. Simulated pesticide B concentration at 1 m and 3 m depth at Jyndevad. The upper bars represent 90% percentile values, whereas the two lower bars the median values.

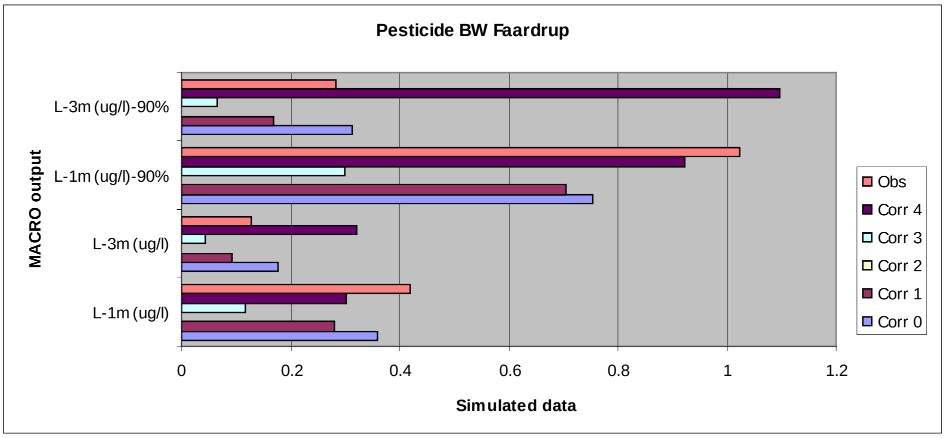

Figure D4. Simulated pesticide B concentration at 1 m and 3 m depth at Faardrup. The upper bars represent 90% percentile values, whereas the two lower bars the median values.

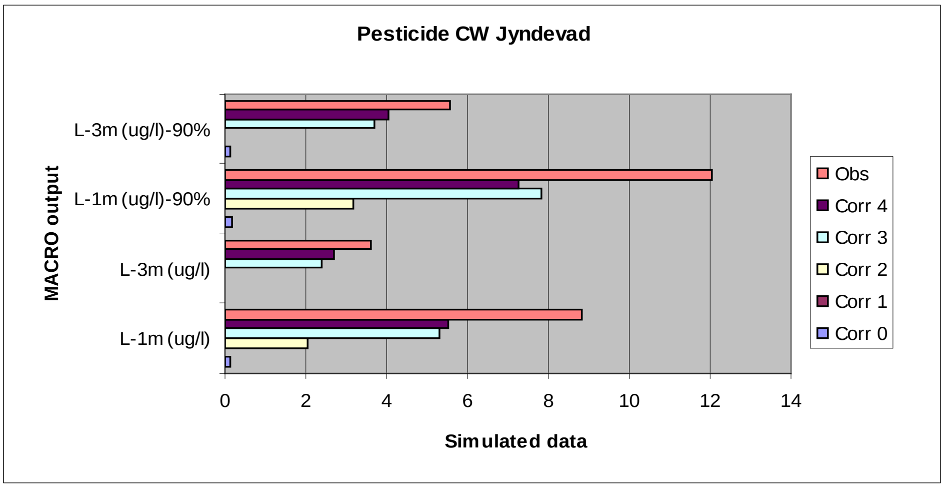

Figure D5. Simulated pesticide C concentration at 1 m and 3 m depth at Jyndevad. The upper bars represent 90% percentile values, whereas the two lower bars the median values.

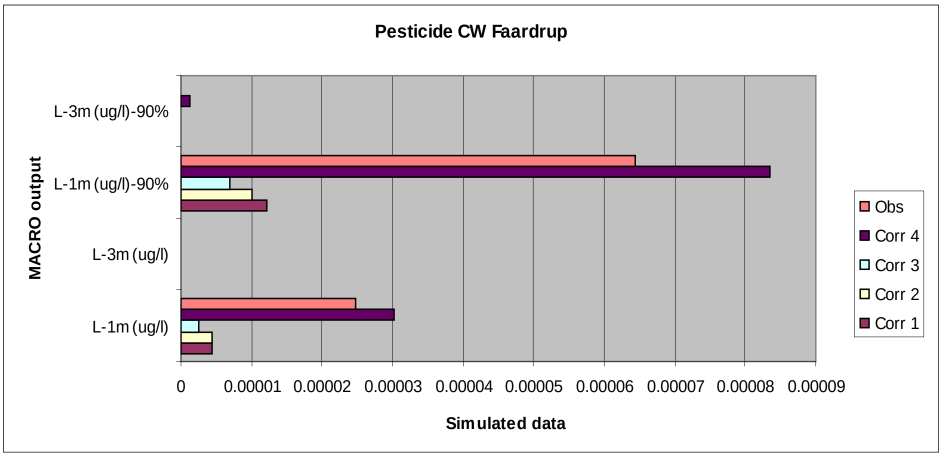

Figure D6. Simulated pesticide C concentration at 1 m and 3 m depth at Faardrup. The upper bars represent 90% percentile values, whereas the two lower bars the median values. Simulated concentration for correction method 0 are not shown as it is 2 orders of magnitude larger.

The intensity based bias correction method (Corr 4) is deemed to be the most appropriate for simulating effects of pesticide leaching as affected by the selected future climate scenarios.

This is motivated by: the method corrects precipitation values depending on its intensity, which is a well-known controlling factor on leaching of pesticides, especially in structured soils. In many cases no substantial difference are found in simulated pesticide concentration in 1 m and 3 m depth between the intensity based method (4) and the delta change methods (1 and 3). In case there is a substantial difference, the intensity based method in most cases represents simulations with highest simulated pesticide concentration at 1 m as this as correction accounts for changed future extremes in precipitation.

Simulated concentrations at 1 m and 3 m b.g.s. for the future period 2071-2100 are usually lower for the sandy location (Jyndevad) as compared to the period 1961-1990. This is caused by a predicted future increase in temperatures (higher degradation) and precipitation (mean and extremes) leading to higher percolation and increased dilution (lower simulated concentrations). For the clayey location (Faardrup) this is less pronounced or reverse. Here, changed future intensity in precipitation causes increased preferential flow and higher simulated concentrations at 1m and 3

Appendix E Overview of MACRO crop input parameters for present and future climate scenarios

Table E1. Overview of the MACRO crop input parameters for the present and future climate scenarios. JDN: Julian Day Number, where the days are counted starting from January (i.e. 1 January equals JDN =1 and 2 January equals JDN=2).

Crop Input Parameter	Grain maize	Grass seed	Grass-clover	Silage maize	Spring Barley	Spring barley *(under sown)*	Winter barley	Winter rape	Winter wheat
Day of crop emergence (JDN)	145	240	240	135	93.8	89	265	238	272.2
Day of intermediate crop development stage (JDN)	134.5	92	92	134.5	109.6	108	90	82	94
Day of maximum leaf area/root depth (JDN)	226.5	170	160	226.5	169.6	168	176	154.5	180
Day of harvest (JDN)	293	207	300	283.5	217.2	213	202	201	221.4
Form factors – the rate of increase of leaf area between emergence and maximum leaf area (-)	1.7	2	2	1.7	2	2	2	2	2
Root distribution (%)	67	67	67	67	60	60	60	60	60
Fraction of available water exhausted before reduction in transpiration occurs (-)	0.35	0.35	0.35	0.35	0.35	0.35	0.2	0.2	0.2
Critical soil air content for root water uptake (%)	5	5	5	5	5	5	5	5	5
Root adaptability factor (-)	0.2	0.2	0.2	0.2	0.2	0.2	0.1	0.1	0.1
Canopy interception capacity (mm)	3	3	3	3	2	2	3	3	3
Correction factor for wet canopy evaporation (-)	1.5	0.5	0.5	1.5	1	1	1	1	1
Initial root depth (m)	0.01	0.2	0.2	0.01	0.01	0.01	0.2	0.2	0.2
Max root depth (m), sand	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6
Max root depth (m), loam	1.2	0.8	0.8	1.2	0.8	0.8	1.2	1.4	1.2
Initial Leaf Area Index (-)	0.01	1	1	0.01	0.01	0.01	1	1	1
Maximum Leaf Area Index (-)	5	5	3	5	4	4	6	6	6
Leaf area at harvest (-)	2	0.01	3	2	2	2	2	2	2
CO_2 effect on E_p	0.96	0.98	0.98	0.96	0.97	0.97	0.97	0.97	0.97

Appendix F Overview of the 21 pesticides and five model pestides used in present and future scenarios

Table F1. Overview of the **21** pesticide and five model-pesticides used in the present and future scenarios. Applied dose and application date is shown together with pesticide characteristics. Colour indicate the selected pesticide category (**P1**=Low dose herbicide; **P2**=Ordinary herbicide; **P3**=Strongly sorbing herbicide; **P4**=Insecticide; **P5**=fungicide). Julian Day Number is day-counted starting from January (i.e. 1 January equals JDN =1 and 2 January equals JDN=2).

CROP	PESTICIDE	MODEL - PESTICIDE		TYPE	GUS [1]	K_{OC} [1] [mL g^{1}]	DT50 [1]	APPLIED DOSE [kg ha^{-1} * y]		MODEL - APPLIED DOSE [kg aktiv ha^{-1} * y]		APPLICATION DATE [Julian Day Number]	
								Present	Future	Present	Future	Present	Future
Grain Maize	Fluroxypyr	P2	Fluroxypyr	Herbicide	1.04	66	3	0.0360	0.0450	0.0360	0.0450	135	125
	Foramsulturon	P1	Thifensulfuron-methyl	Herbicide	1.56	78	5.5	0.0225	0.0270	0.0019	0.0023	135	125
	Lamda-cyhalothrin	P5	Lamda-cyhalothrin	Insecticide	-1.67	157000	25	0.0000	0.0075	0.0000	0.0075		196
	Mesotrion	P2	Fluroxypyr	Herbicide	1.47	80	5	0.0400	0.0500	0.0720	0.0900	125	115
	Thifensulfuron-methyl	P1	Thifensulfuron-methyl	Herbicide	1.54	31	4	0.0042	0.0056	0.0042	0.0056	125	115
	Idosulfuron	P1	Thifensulfuron-methyl	Herbicide	2.12	45	8	0.0008	0.0009	0.0020	0.0024	135	125
Silage Maize	Fluroxypyr	P2	Fluroxypyr	Herbicide	1.04	66	3	0.0200	0.0250	0.0360	0.0450	135	140
	Foramsulturon	P1	Thifensulfuron-methyl	Herbicide	1.56	78	5.5	0.0225	0.0270	0.0019	0.0023	135	140
	Lamda-cyhalothrin	P5	Lamda-cyhalothrin	Insecticide	-1.67	157000	25	0.0000	0.0075	0.0000	0.0075		196
	Mesotrion	P2	Fluroxypyr	Herbicide	1.47	80	5	0.0400	0.0500	0.8750	1.0920	125	115
	Thifensulfuron-methyl	P1	Thifensulfuron-methyl	Herbicide	1.54	31	4	0.0042	0.0056	0.0042	0.0056	125	115
	Idosulfuron	P1	Thifensulfuron-methyl	Herbicide	2.12	45	8	0.0008	0.0009	0.1062	0.1360	135	140
Ryegrass	Diflufenican	P3	Prosulfocarb	Herbicide	1.36	3186	542	0.0400	0.0500	1.1200	1.4000	283	283
	Clopyralid	P2	Fluroxypyr	Herbicide	5.06	5	34	0.0400	0.0400	0.0384	0.0384	95	79
	Fluroxypyr	P2	Fluroxypyr	Herbicide	1.04	66	3	0.0800	0.0800	0.0800	0.0800	95	79
	Prosulfocarb	P3	Prosulfocarb	Herbicide	1.15	1693	31	0.8000	1.0000	0.8000	1.0000	283	283
	MCPA	P2	Fluroxypyr	Herbicide	2.51	74	15	0.4000	0.4000	0.0280	0.0280	95	79
	Tebuconazole	P4	Epoxiconazole	Fungicide	2	769	62	0.1250	0.1875	0.0625	0.0938	140	130
Spring Barley	Lamda-cyhalothrin	P5	Lamda-cyhalothrin	Insecticide	-1.67	157000	25	0.0038	0.0000	0.0038		152	
	Pyreclostrobin	P4	Epoxiconazole	Fungicide	-0.06	11000	32	0.0625	0.0625	0.0313	0.0313	130	125
	Thifensulfuron-methyl	P1	Thifensulfuron-methyl	Herbicide	1.54	31	4	0.0040	0.0060	0.0040	0.0060	121	110
	Epoxiconazole	P4	Epoxiconazole	Fungicide	2.47	1073	354	0.0313	0.0313	0.0313	0.0313	130	125
Winter Barley	Diflufenican	P3	Prosulfocarb	Herbicide	1.36	3186	542	0.0200	0.0250	0.5600	0.7000	283	293
	Bromoxynil	P2	Fluroxypyr	Herbicide	0.5	174	1	0.0240	0.0240	0.0086	0.0086	283	293
	Fluroxypyr	P2	Fluroxypyr	Herbicide	1.04	66	3	0.0400	0.0400	0.0400	0.0400	91	84
	Ioxynil	P2	Fluroxypyr	Herbicide	1.21	276	6	0.0240	0.0240	0.0086	0.0086	283	293
	Lamda-cyhalothrin	P5	Lamda-cyhalothrin	Insecticide	-1.67	157000	25	0.0000	0.0038	0.0000	0.0038		293
	Prosulfocarb	P3	Prosulfocarb	Herbicide	1.15	1693	31	0.8000	0.9200	0.8000	0.9200	283	293
	Pyreclostrobin	P4	Epoxiconazole	Fungicide	-0.06	11000	32	0.0625	0.0625	0.0313	0.0313	132	122
	Florasulam	P1	Thifensulfuron-methyl	Herbicide	2.47	22	8.5	0.0010	0.0010	0.0022	0.0022	91	84
	Epoxiconazole	P4	Epoxiconazole	Fungicide	2.47	1073	354	0.0313	0.0313	0.0313	0.0313	132	122
Winter Wheat	Diflufenican	P3	Prosulfocarb	Herbicide	1.36	3186	542	0.0200	0.0250	0.5600	0.7000	293	293
	Bromoxynil	P2	Fluroxypyr	Herbicide	0.5	174	1	0.0240	0.0240	0.0086	0.0086	293	293
	Fluroxypyr	P2	Fluroxypyr	Herbicide	1.04	66	3	0.0400	0.0400	0.0400	0.0400	91	79
	Glyphosate	P3	Prosulfocarb	Herbicide	-0.36	21699	12	0.7200	0.7200	1.5999	1.5999	213	201
	Ioxynil	P2	Fluroxypyr	Herbicide	1.21	276	6	0.0240	0.0240	0.0086	0.0086	293	293
	Lamda-cyhalothrin	P5	Lamda-cyhalothrin	Insecticide	-1.67	157000	25	0.0038	0.0075	0.0038	0.0075	181	195
	Prosulfocarb	P3	Prosulfocarb	Herbicide	1.15	1693	31	0.8000	0.9200	0.8000	0.9200	293	293
	Boscalid	P4	Epoxiconazole	Fungicide	2.51	809	200	0.1748	0.1748	0.0625	0.0625	156	148
	Florasulam	P1	Thifensulfuron-methyl	Herbicide	2.47	22	8.5	0.0010	0.0010	0.0022	0.0022	91	79
	Tebuconazole	P4	Epoxiconazole	Fungicide	2	769	62	0.0625	0.0625	0.0313	0.0313	130	0
	Epoxiconazole	P4	Epoxiconazole	Fungicide	2.47	1073	354	0.0503	0.0503	0.0503	0.0503	144	148
Winter Oilseed Rape	Clopyralid	P2	Fluroxypyr	Herbicide	5.06	5	34	0.0800	0.0800	0.0959	0.0959	91	64
	Lamda-cyhalothrin	P5	Lamda-cyhalothrin	Insecticide	-1.67	157000	25	0.0075	0.0150	0.0075	0.0150	248	152
	Thiacloprid	P5	Lamda-cyhalothrin	Insecticide	1.44	615	15.5	0.0720	0.0720	0.0075	0.0075	105	95
	Propaquizafop	P3	Prosulfocarb	Herbicide	0.21	2200	2.1	0.0400	0.0400	1.4930	1.4930	314	314
	Clomazon	P2	Fluroxypyr	Herbicide	2.96	287	83	0.0900	0.0900	0.1080	0.1080	283	293
	Tebuconazole	P4	Epoxiconazole	Fungicide	2	769	62	0.1250	0.1875	0.0625	0.0938	121	110

[1] Obtained from the FOOTPRINT database (http://sitem.herts.ac.uk/aeru/footprint/)

CODE	PESTICIDE TYPE	PESTICIDE	GUS	Koc	DT50
P1	**Herbicide - Low dose compound**	Thifensulfuron-methyl	1.54	22	9
P2	**Herbicide - Ordinary compound**	Fluroxypyr	1.04	66	3
P3	**Herbicide - Strongly sorbing compound**	Prosulfocarb	1.15	1693	31
P4	**Fungicide**	Epoxiconazole	2.47	1073	354
P5	**Insecticide**	Lamda-cyhalothrin	-1.67	157000	25

[1] Obtained from the FOOTPRINT database (http://sitem.herts.ac.uk/aeru/footprint/).

Appendix G Report from a study tour to Germany and France, 9-10 April 2008

Jørgen E. Olesen and Lise Nistrup Jørgensen
University of Aarhus, Faculty of Agricultural Sciences

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G1. Background

Climate changes will affect pesticide use in various ways. A warmer climate will enable new crops to be cultivated at the expense of existing crops. The largest changes in Denmark are projected to occur within crop rotations for arable farms and pig production with grain maize and some new protein and oil seed crops being cultivated. A warmer climate and changes in soil water content will also shift sowing and planting dates and change crop development times, generally leading to faster development, including earlier flowering, earlier sowing of spring crops and later sowing of autumn crops. This will have consequences for the timing of pesticide applications. A warmer climate is likely to lead to increased problems with pests and diseases, and probably to changes in efficacy of some of the herbicides. However, the relationships are complex and a good data basis for evaluating many of the relationships is still lacking.

G2. Objective

The objective of the study tour to Germany and France was to collect background information on crop management practises as basis for describing future cropping scenarios in 2050. Information was achieved by interviewing agronomist in Germany (Rheinland Pfalz) and north of France (south of Paris). Focus was given to obtain information about a) present crop rotations, b) problems with pest, diseases and weeds, c) pesticide use strategies.

G3. Visit to Germany

The place visited in Germany was in Rheinland-Pfalz at Dienstleistungszentrum Ländlicher Raum; Bad Kreuznach, and we were hosted by Dr. Erich Jörg, Abteilungsleiter Landwirtschaft. The institute is a national institute run by the regional government. Their activities include: Support on arable cropping, extension services, training of farmers, environmental advisors and ecologists, development of DSS and web-sites for the whole of Germany through ZEPP (DSS for many diseases and pests) and ISIP (internet platform) – The activity with DSS employs 13 persons.

The region is divided in to two major regions with different climate: a dry warm region in the south (550 mm rain) and a wetter region in the northwest (700-800 mm rain). The cropping in the two regions is quite different. Livestock production is mainly concentrated in the northwest. The cropping patterns are outlined in Table 1.

Table 1. Cropping area in Rheinland-Pflaz.

Crop	Area (ha)
Winter wheat	120.000
Spring barley	55.000
Winter barley	30.000
Winter rye	6.000
Triticale	10.000
Winter oilseed rape	40.000
Sugar beet	25.000
Grain maize (in the south)	5.000

Generally the pesticide input in the region is seen as quite moderate compared to other regions of Germany. They have in their region still poor results with warm season crops like sunflower and soybeans. They expect in future to grow sugar beet as winter crops (winter sugar beet). Sorghum is seen as a new crop in the drier regions, e.g. in the Rhine valley.

G3.1 Crop rotations

The agronomists identified a number of typical crop rotations for the region.

G3.1.1 Arable farms

Sugar beet – wheat - wheat
Sugar beet – wheat – s. barley (malting)

W. oilseed rape – wheat – wheat
W. oilseed rape – wheat – s. barley

Increased growing of second year wheat (now about 25 % of the area)

Maize – maize – maize.
Grain maize is grown in monoculture due to risk of fusarium if grown in rotation with wheat.

G3.1.2 Pig farms

W. barley – oilseed rape – wheat - wheat
A few farms use triticale
Some pig farms grow silage maize for additional feed stock to their biogas plants.

G3.1.3 Dairy farms

Permanent grassland on dairy farms
Wheat – triticale - Silage maize

G3.1.4 Other crop rotation characteristics

Catch crops are common in regions with sugar beet. Oil radish and mustard are being grown before sugar beet. They are grown to reduce infestation with root nematodes. The two crops are seen as possibly increasing problems with clubroot in oilseed rape.

G3.2 Crop management

G3.2.1 Sugar beet

Sowing in mid March to early April. Only one out of 20 years with frost damage.
Harvest in November to January. Top is left in the field.

G3.2.2 Winter wheat

Yield (6.5 to 7.5 t/ha), few areas with 10 ton/ha.
Sown from mid September to end October (normally first half of October). There is a recent tendency to earlier sowing due to increased area.
The crop is fertilised with 160-200 kg N/ha.
Harvest in late July – early August (in warm regions) and mid August in cooler regions (higher altitudes).

G3.3.3 Spring barley (malting)

This is an extensive culture (4.5 t/ha) to maintain malting quality.
Sowing normally in March (but can be from February to April)
Fertilised with 30-60 kg N/ha.
Harvest in late July.

G3.3.4 Winter barley

Yield (6-7 t/ha)
Sowing in second half of September or early October.
Harvest in end of June or early July.

G3.3.5 Winter oilseed rape

Sown in the two last decades of August and early September.
Harvested early July. Harvested directly.

G3.3.6 Grain maize

Half of the area sown without ploughing. Sowing in late April. At higher altitudes in early May.
Fertilised with 160-200 kg N/ha.
Harvest in October. Straw is left in the field.

G3.3.7 Silage maize

Cultivated as grain maize.
Harvest in September.

G3.3 Crop protection measures

G3.3.1 Sugar beet

<u>Disease</u>
Cercospora (main disease, in particular irrigated), powdery mildew (in particular in unirrigated), sugar beet rust (with late harvest). No problem with ramularia.

Cercospora is the major problem due to intensive cropping of sugar beet, every 3rd year. Two disease treatments (triazols like difenoconazol and epoxiconazole) in irrigated, one treatment is standard in better rotations. Fenpropidin is used against mildew.
No reduced dosages for fungicides.
Rhizoctonia solani can be a problem due to the crop rotation where maize has been included in the rotation. It is a late problem causing rot around gs 30-40. Not sure whether this is a climate or crop rotation problem.
No virus problems anymore due to resistant varieties (Rhizomania) and seed treatments with nicotinoides (imidacloprid etc). Seed treatment with both fungicides and insecticides is standard

Pest
Atomaria linearis – (Runkelroebiller) (common, but not a problem due to seed treatments).
In most seasons no additional treatments need in addition to the seed treatment.
Scrobipalpa ocellatella. A pest that shows up in very warm years. With 3 generations they can be a problem, but with low damage, but can cause rot in wet seasons. Irrigation destroys the population.
Gamma ugler can kill plants in early season.
Aphids can become a problem in warm years. This is very seldom treated.

Weeds
As in maize. Chenopodium, mercuriano alis (?), galinsoga, hirse arter, amarant.
New weed: hundepersille; Avena fatua main grass problem but generally few grass problems.
3-split strategy with reduced dosages (cotyledon stage of weeds, +8-10 days, +8-10 days). A typical strategy would be 3 x (1 Betanal + 1 Goltix).

G3.3.2 Winter wheat

Diseases
Early sowing and mild winters gives eyespot.
Septoria (most fungicide demanding), brown rust (most damaging), yellow rust (controlled by cultivar, rarely big outbreaks). Stagonospora nodorum is not seen as a problem any longer.
High yielding crops have two fungicide treatments, but the average is only one treatment in this area.
Treatments are done at gs 37-51 using typically 75% of normal rate. The main fungicides are triazoles + strobes and chlorothalonil.
Crops are rarely controlled for fusarium in the growing season.
General seed treatment to control fusarium and bunt is used.

Pests
Recently early attack of aphids and transmission of BYDV has been seen (1989, 1990), in particular with early sowing. Also serious problems in 2007 were found. 10% have seed treatment against aphids. If not seed treated then they in some cases have to spray.
There is rarely a need to treat for aphids in summer (only in one out of 10 years).
Rarely have leaf beetles (kornbladbillens larve) been a problem.
Some problems with yellow or orange mitches have been found (Hvedegalmyg) in certain years, however not seen as a problem every year. New virus Wheat Dwarf Virus transmitted by leaf hopper is expected to be an increasing problem.

Weeds:
With early sowing herbicides are applied in autumn (e.g. against blackgrass). They are getting increasing resistance problems with blackgrass. Bromus seen as an increasing problem with reduced tillage.
¾ of the herbicide treatments are done in spring (against e.g. Gallium) (early April)
Sulfounylurea + Starane; MCPA against C. arvensis.

Growth regulators in reduced dosages. 80% uses this as an insurance against lodging. Only 20% gives yield increase. In particular animal producers with slurry emphasise the need for use of growth regulators.

G3.3.3 Spring barley

Disease:
Mildew is not a problem. Rhyncosporium and net blotch can cause problems. Rarely brown rust (P. hordei) as a problem due to late appearance and early ripening.
70% is untreated with fungicides. 30% is treated with reduced dosages (appr. 50%) using a mix of strobes and triazoles.

Pests:
No need is seen for use of insecticides

Weeds:
Polygonum, Chenopodium, Senecio gaia, Stellaria, Chrysantemum segetum, Gallium (only in small extent), early sugar beet weeds. 100% controlled with reduced dosages (50%) using products like Starane XL, Pointer etc. Wild oat is the most serious grass weed.

No use of growth regulators.

G3.3.4 Winter barley

Diseases:
Rhyncosporium is the major disease in the wetter regions. Net blotch might also give problems.
New problems with Ramularia. Rust is not a problem in winter barley.
Maximum one fungicide treatment (stobilurine with azole), ¾ to full dose.

Pests:
Transmission of BYDV by aphids is a problem. In 1996 all of the winter barley had to be resown.
50% of the crop area was seed treated against aphids. If not seed treated then they have to spray.
No pests control during the growing season.

Weeds
Herbicide as in early sown w. wheat; 80% treatment in autumn.

30% is growth regulated at reduced rates.

G3.3.5 Winter oilseed rape

Seed treated commonly using the product Cruiser.

Pest
In total one to two insecticide treatments are carried out in rape.
Ceuthorhynchus napi (snudebille). Invades the stem. Not known as a problem in DK. One early treatment in February and March is normal using a standard treatment with pyretroid. Thresholds for spraying when temperature >5-6 °C.
Melingethes aeneus (glimmerbøsser) has only become a problem within the last 5-10 years. They are generally resistant to pyrethroids.
Psylliodes (flea beetles) are present all of the time but in little abundance. Not a major problem.
Slugs are a problem in the wetter areas and with several wet years in succession and with reduced tillage. Metaldehyd and methiocarb are used.

Diseases
Diseases were not previously a problem. With a narrow crop rotation more attack of phoma is now seen, but still not reason enough to treat. Sclerotinia is only a local/regional problem. The fungicide is used to restrict growth in autumn (Folicur). Normally one treatment is carried out in autumn. This is only done in years with unusually warm years and vigorous growth in autumn.
In narrow crop rotations, two fungicide treatments are used, one in autumn and one in spring to control Sclerotinia. The warning system developed by Tiedemanns group seems to be promising, but the period in which it should be active needs to be extended. 2 triazoles are used either tebuconazole or metconazole.

Weeds
One application in autumn only. Butisan-S. Chlomazon (Command).
Possibly a second treatment for grass in autumn (e.g. fusillade).
New weed species (Besenrauke (Descurainia Sophia), Lösels-Rauke (Sisymbrium loeselii) has caused change to pre-emergence treatments.

G3.4.6 Grain maize

Pests
Western corn root borer (Diobrotica). They have made an alarm plan for this pest. There are EU regulations on treating this. Seen as a new an invasive species, which will find its way round the whole of Europe. Could increase the need for insecticide treatments.
Seed treatment with insecticide (Thiametoxam)
Granulate (Thiametoxam) combined with pyrethroid is an option along with the possibility of 1-2 pyrethroids later in season.

Ostrinia nubilalis (European corn borer).
One insecticide treatment late in season (GS 51). Problem to get good coverage due to the tall crop. Larvae live on the leaves before the hide in the stem. Attacks are surveyed by trapping. Treatments has to carry out 1-2 weeks after flying has been found to take place.

Diseases
Normally no disease control is regarded necessary, but in recent years Helmintosporium turcicum a disease in dry and warm seasons has been seen as a new problem. Currently not controlled by fungicides (recommendation goes in the direction of switching away from susceptible cultivars). No currently tested fungicides is available for this disease.
Maize bunt (Ustilago maidis) is not a problem in grain production, but is sometimes gives concerns in silage maize. The corn borer can increase the risk of Fusarium.
Aphids is late autumn is not controlled, but can transfer BYDV to cereals. In case of severe numbers this may lead to yield reductions.

Weeds

Common weeds seen in the crop include several new species. Solanum nigrumm, Chenopodium E. crus-galli, Amarant, hirse.

Herbicide between 2-6 leaf (Mid May). Typical products are MaisTer, which is a broad spectrum product.

G3.4.7 Silage maize

Same as for grain maize.

Minor risks of corn root borer and corn borer, because of better rotations.

G4. Visit to France

The place visited in France was Arvalis Institut de Végétal, Boigneville, just south of Paris. We were hosted by Valérie Leveau, Patrick Retaureau and Philippe Viaux. The institute is a national institute, which does research and development work in the area of crop management and crop protection. The institute is supported by a levy from the trade of grain. They have close contact with the “Agriculture Chambers”, who are responsible for doing extension work with direct contact to the farmers.

The institute is heavily involved in discussing the pesticide policy in France. They are at present having a committee work (like the Bichel committee) discussing future pesticide policy. They have a master student studying the situation in Denmark, as the Danish pesticide action plan has been looked at, as a possible model for future development.

The results reported here are based on interview with Patrick and Philippe.

G4.1 Crop rotations

G4.1.1 Arable farms

Sugar beet – spring barley – winter barley
Sugar beet – w. wheat – s. barley + possibly lucerne
Winter oilseed rape – w. wheat – w. barley
Oilseed rape/pea – w. wheat – maize - w. barley / w. wheat

More spring barley in the north and winter barley in the south due to differences in temperature and summer droughts.

Much of the maize is irrigated. Maize is not grown continuously, because of the corn borer.

Some farmers participate in agro-environmental programmes with restrictions on rotations. In a part of the region there is a requirement to cultivate >50% of the area with winter crops (oilseed rape, winter wheat, winter barley).

G4.1.2 Pig farms

Same crop rotations as for arable farms, but a lot of cereals and with maize for feeding.

The maize production will depend on soil type and availability of irrigation. There are currently water scarcity and restrictions on irrigation. Maize is a more expensive crop to grow and with similar yields this will favour wheat at the expense of maize.

G4.1.3 Dairy farms

Both permanent and rotational grasslands.
Silage maize is used.

G4.2 Crop management

There is an increased use of minimum tillage.
With oilseed rape – wheat – barley. Before oilseed rape, plough is not used. The plough is used between wheat and barley.

G4.2.1 Sugar beet

Sowing at end March or beginning of April.
Harvested at end September to beginning of November.
Nitrogen is applied at 1 time, in total 120 kg N/ha.

G4.2.2 Winter oilseed rape

Sowing in end August to early September.
Harvest in mid July
Nitrogen applied at 2 times, in total 160-200 kg N/ha. First 50-80 kg N/ha in early February, and the second in mid March.

G4.2.3 Winter wheat

Sowing in early - mid October (late September in northern France).
Harvest in late July
Nitrogen is applied at 3 times in total 160-220 kg N/ha. Mid February (50-80 kg N/ha), 20 March, 1 May (<50 kg N/ha).

G4.2.4 Grain maize

Sowing in mid April.
Harvest in mid to late October
Nitrogen in total 150 kg N/ha. 1-2 times application (perhaps mostly applied only once)

G4.2.5 Spring barley

Sowing from January to April (normal 15 February)
Harvest in late July
Nitrogen applied at 1-2 times, in total 100-120 kg N/ha.

G4.2.6 Winter barley

Sowing in mid October.
Harvest at end June or early July.
Nitrogen in total <150 kg N/ha. Same timing as for winter wheat

G4.3 Crop protection measures

G4.3.1 Sugar beet

<u>Diseases</u>
Cercospora is the main disease. One fungicide treatment (end July or start of August) using epoxicoanzole + fenrpopomorph. 75% rate.

Pests
Seeds are treated with Gaucho, which mean that no other insecticide is needed.

Weeds
3 to 4 treatments with different herbicides: 3 x (1 l Betanal + 1 kg Goltix)

G4.3.2 Winter oilseed rape

Diseases
Tebuconazole is sometimes in autumn as growth regulator (in mild winter) (full rate)
One fungicide treatment for sclerotinia (full rate): Cantus (boscalid are used).

Pests
Melingethes (glimmerbøsser) is a serious pest and pyrethroids resistance is widespread
One to three insecticide treatments, due to resistance.
First treatment in autumn in Sep-Oct (jordlopper), second in Nov-Feb (snudebille, a problem every year now with warmer years like in Germany). In April Melingethes is controlled.

Weeds
Two treatments are most common: Trifluralin is used before emergence (will be banned after 1 more season). Colzore is used (Command) and Kerb after emergence. The last product if volunteer grass is a problem.

G4.3.3 Winter wheat

Diseases
Main disease problems are Septoria and brown rust. In some regions eyespot is a problem. In north 3 fungicide applications are applied; in Central region 2 fungicides application are carried out. Reduced dosages (30-80% of max dose). First in April, second in May. If 3 fungicides applications are carried out the first one is in early April (Eyespot), mid April and mid May. In some year spraying against fusarium may be necessary. Triazols are used increasingly but also strobulurins are still used.

Pests
In some years aphids in autumn may need to be controlled. For early sowing an insecticide may be applied. No insect problems in summer. Only insecticide use in one out of 5-10 years.

Weeds
Herbicides applied in spring (March), sulfonylurea (70-80% of max dose). In some areas the herbicide is applied in autumn + herbicide in spring.
There are some farms with minimum tillage (30% of area). On these farms there are problems with grass weeds: Bromus, ryegrass. On these farms winter cereals are treated in autumn.

Growth regulator is systematically being used (CCC). One treatment (2 treatments in north).

G4.3.4 Grain maize

Diseases
No fungicide treatment

Pests
No treatment

Weeds

Two treatments (sulfonylurea) typically MaisTer

G4.3.5 Spring barley

Diseases

Rhyncosporium and mildew are the main problems.
One or two fungicide treatments are used. Two in the East and only one in Central. Using one application: Mid May; Two application: Early and end May. For two sprayings it is a systematic treatment. A mix of triazols and strobilurins are used. Half dose rates.

Pests

Moth larvae (caterpillar) cuts stems, in particular near forests (måske stængelmøl?). Vary with temperature in spring. Insecticides are used depending on the problem. Aphids are rarely a problem.

Weeds

Aleopecurus, ryegrass, wild oat.
One spraying with Avadex (preemergence), if problem with grass weeds. In general only one herbicide treatment in April (Baccara, few herbicides with effect on grass weeds available, sulfonylurea is used, but not effective for the grass weeds)

Growth regulator is systematically being used (CCC), in particular for early sowing and on deep soils.

G4.3.6 Winter barley

Diseases

Rhyncosporium and rust are major problems.
Two fungicide treatments, both triazoles and strobilurins (50-80% of normal dose). First on 10 April, second in end April.

Pests

Seed treatment against aphids with insecticide (Gaucho).
No insecticide in spring/summer.

Weeds

Generally the same as for winter wheat.
Herbicides generally applied in both autumn and spring, because the weeds continue to emerge during mild winters. Autumn (IPU, full rate) and spring (sulfonylurea, slightly reduced dose).

Growth regulator is systematically being used (CCC). One treatment (2 treatments in north).

G5. Proposed crop rotations

Proposal for crop rotation in the region of Germany/ France

Crop	Sowing date	harvest date	Nitrogen Kg/ha	Timing Gs /date	herbicides	Timing Gs /date	fungicides	Timing Gs /date	insekticides
W. oilseed Rape	1 sept	5 july	?	1. Oct	0,33 Command	October. 25April	1,0 Folicur 1,0 Folicur	1 march 1. april	Fastac Biscay
Wheat	1. oct	1. august	180	10 March	1 t Express 0,75 Starane	10.May	0,5 Opus+ 0,25 Comet		0
Wheat	1. oct	1. august	180	10 Oct 10 March	150 g Atlantis 0,75 starane	10.May	0,5 Opus+ 0,25 Comet	1 oct	pyrethroid
W barley	20 sept	1 July		October	150 g Atlantis 0,75 starane	1. April	0,25 Opus + 0,25 Comet	1. oct	Pyretroides

:* seed treatments with insecticides and fungicides in winter barley and winter oil seed rape.

Crop rotations which include grain maize, wheat,
Germany

Crop	Sowing date	harvest date	Nitrogen Kg/ha	Timing Gs /date	herbicides	Timing Gs /date	fungicides	Timing Gs /date	insekticides
Grain maize	25 april	15 oct.	?	15 may	100 g MaisTer	0	0	1 june	Fastac
Grain maize	25 april	15 oct.	?	15 may	100 g MaisTer	0	0	1 june	Fastac
Grain maize	25 april	15 oct.	?	15 may	100 g MaisTer	0	0	1 june	Fastac
Grain maize	25 april	15 oct.	?	15 may	100 g MaisTer	0	0	1 june	Fastac

Summary
The report evaluates direct (precipitation, actual evapotranspiration and temperature) and indirect (crop rotations, crop management, and pesticide use) climatic change effects on pesticide-leaching to groundwater and the aquatic environment by use of MACRO and MIKE SHE model. The analysis is based on five model pesticides: low-dose herbicides, ordinary herbicides, strongly sorbing herbicides, fungicides and insecticides, and selected farm types (arable and dairy) for the variable saturated sandy soil (Jyndevad) and loamy soil (Faardrup). The evaluation has the aim at describing the implications of future climatic factors on pesticide leaching to groundwater as realistic as possible, based on realistic doses and parameters from MACRO setups from the Danish Pesticide Leaching Assessment Programme.

Rapporten evaluerer klimaændringers betydning for ændret pesticidudvaskning til grundvand og vandmiljø som følge af direkte effekter (ændret nedbør, fordampning og temperatur) og indirekte effekter på landbrugspraksis (ændret sædskifte, afgrøde rotation og pesticidanvendelse). Analysen er udført for fem model pesticider (p1-p5): lav-dosis ukrudtsmidler (herbicid – p1), ordinære ukrudtsmidler (herbicid – p2), og ukrudtsmidler som bindes stærkt i jorden (herbicid – p3), svampemidler (fungicid – p4) og midler mod insekter (insekticid – p5) baseret på modelberegninger af nutidig og fremtidigt klima ved hjælp af MACRO og MIKE SHE. Analysen er udført for udvalgte bedriftstyper (planteavl/svinebedrifter og kvægbedrifter) på sandjord (Jyndevad) og lerjord (Faardrup). Undersøgelsen har til formål at beskrive konsekvenserne af fremtidige klimaændringer for pesticidudvaskning, med udgangspunkt i realistiske doser og MACRO modelopsætninger opstillet i forbindelse med Varslingssystemet (VAP).

Danish Ministry of the Environment
Environmental Protection Agency

Strandgade 29
DK - 1401 København K
Tlf.: (+45) 72 54 40 00

www. mst.dk