Changes in European drought characteristics projected by the PRUDENCE regional climate models

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Short title: Changes in European Drought projected by PRUDENCE RCMs

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ABSTRACT

One of the key features of global climate change will be perturbations to the hydrological regime across Europe. To date, assessments of the impacts of future change have generally used results from only one climate model, thus underestimating the range of possible change projected by different climate models. Here, the skill of six regional climate models (RCMs) in reproducing the mean precipitation for the 1961-90 period for six catchments across Europe are compared and their projections of changes in future precipitation are assessed. A simple drought index based on monthly precipitation anomalies is also described and used to assess the models. Considerable variation in model skill in reproducing monthly mean precipitation and drought statistics is observed, with model errors in the reproduction of drought events independent of those for the mean suggesting that the models have difficulties in reproducing the observed persistence of low monthly rainfall totals. In broad terms the models indicate decreases in summer and increases in winter precipitation across Europe. On the regional scales required for impacts analysis considerable model uncertainty is demonstrated for future projections, particularly for drought frequency. Although increases in the frequency of long-duration droughts are identified for catchments in southern Europe the magnitude of this change is not certain. In contrast, for a catchment in northern England, such events are likely to become less frequent. For shorter-duration droughts, future changes encompass the direction of change. For stakeholders in each of the regions these changes and uncertainties pose different challenges for the management of water resources. For the scientific community the challenge raised is how to incorporate this uncertainty in climate change projections in a way that allows those groups to make informed decisions based on model projections. It is suggested that probabilistic scenarios for specific hydrological impacts offers considerable potential to achieve this.

Keywords: drought; climate change; regional climate models; probabilistic scenarios; uncertainty; Europe

1 INTRODUCTION

Europe is likely to experience a diverse range of impacts in response to climate change, with temperature increases accompanied by a perturbed hydrological cycle. Changes in the distribution of daily precipitation totals and in the persistence of dry days may lead to an increased frequency of droughts in some areas and increased flooding in others (Watson *et al.*, 1997). Projections of human-induced climate changes driven by increases in atmospheric CO_2 have suggested increases in the frequency of low precipitation during summer and the occurrence of long dry spells for the Northern Hemisphere (Gregory *et al.*, 1997). In recent decades several extensive droughts have affected the European region, most notably 1976, 1988-1992, 1997 (Bradford, 2000) and 2003 (Fleig *et al.*, 2005). Drought conditions in Spain and Portugal in 2005 were the most severe since the late 1940s, with the south west of Spain receiving less than 50% of the annual average rainfall (Kennedy *et al.*, 2006) whilst the UK is currently facing drought conditions with restrictions in water use in parts of southern England due to anomalously low winter precipitation. The impact of such events may be felt in a wide range of sectors either directly e.g. food supply, energy use, natural fires, or indirectly e.g. recreation and insurance (Lehner *et al.*, 2006).

There have been several attempts to detect a climate change signal in the instrumental record using drought as an indicator. On a global scale a tendency towards fewer consecutive dry days has been noted during the second half of the twentieth century (Frich *et al.*, 2002) although regional increases in drought frequency were inferred in parts of South Africa, Canada and eastern Asia. On a European scale however, the ARIDE project (Assessment of the Regional Impact of Droughts in Europe) noted that trends were strongly influenced by the period of analysis and yielded distinct regional patterns. Increasing drought deficits were observed in Spain, eastern Europe and large parts of central Europe with changes in precipitation cited as a major explanatory factor (Demuth & Stahl, 2001). Lloyd-Hughes & Saunders (2002) have indicated that the proportion of Europe experiencing extreme and/or moderate drought conditions has changed significantly during the 20^{th} century with fewer droughts over Scandinavia, Netherlands and the Ukraine and more in areas of Eastern Europe and western Russia. Dai *et al.* (2004) identified strong increases in the area of combined severe dry and wet conditions in Europe over the last three decades and indicated that without global warming droughts would have been smaller and less pervasive. Van der Schrier *et al.* (2006) highlighted an absence of this recent drying, noting that an upward trend in area subject to extremes of the Palmer Drought Severity Index (PDSI) from the mid-1980s to the early 1990s identified by Briffa *et al.* (1994) has not continued and that possible summer drying over the last 50 years cannot be distinguished from multi-decadal variability. Additionally, Hisdal *et al.* (2001) did not detect significant trends, suggesting hydrological drought conditions in general have not become more severe or frequent. Many studies of drought across Europe have been more regional in nature. Much research has in particular been undertaken around the Mediterranean where there are concerns over desertification (Estrela *et al.*, 2000; Lana & Burgueño, 1998) and the assessment of drought risk (Vicente-Serrano & Beguería-Portugués, 2003). Considerable attention has also been paid to drought events affecting the UK due to the relatively large source of available data (e.g. (Bryant *et al.*, 1992, Bryant *et al.*, 1994; Jones *et al.*, 1997; Hannaford & Marsh, 2006).

Assessments of future droughts have traditionally used only one climate model to assess possible impacts. For example, HadCM2 has been used to project increases in drought-related sugar beet losses in parts of Europe (Jones *et al.*, 2003). Lehner & Döll (2001) did use two General Circulation Models (GCMs), HadCM3 and ECHAM4, to project decreases in hydrological drought for northern Europe and small areas in central Europe, with increases in southern Europe. However, GCMs project diverse patterns of change in climatic variables across Europe and these have been demonstrated to vary depending on which GCM is used, with some areas showing opposite developments or different magnitudes of change (Lehner *et al.*, 2006). Such uncertainty in the performance of climate models arises from the parameterization of small-scale physical processes as well as uncertainties in the structures used to represent large-scale climate processes. Consequently, any one model simulation of future climate may represent only one of many possible future climate states. One of the means by which such issues may be addressed is by undertaking a large number of model simulations to assess the uncertainty and estimate the most likely future climate. One solution is to use different models which may be compared in their ability to model historical climate and so their possible skill in predicting future climate. Methods using multi-model ensembles to provide probabilistic projections of future climate change have been developed recently (Allen *et al.*, 2000; Palmer *et al.*, 2005). However, this effort has been concentrated on assessing uncertainties in future temperature change at the global scale and there has been little analysis of other variables or attempts to develop probabilistic scenarios for impacts studies including drought. The EU FP6 project ENSEMBLES may advance this field by comparing different methods for representing climate model uncertainty, and linking these to downscaling methods to improve the robustness of climate change impact assessments. Other recent advances in applying probabilistic methods to hydrological impacts are reviewed by Fowler *et al.* (2007).

AquaTerra is an EU FP6 project which aims to address some of these deficiencies in impacts research by developing a framework for the construction of probabilistic climate change scenarios for the assessment of impacts on hydrological systems at regional to catchment scales. A key aim is to produce probability density functions (pdfs) of future change by weighting projections from each of a multi-model ensemble in a way that reflects their ability to reproduce observed climate statistics for the control integration (1961-1990), not only for the mean, but also for higher order statistics such as variability and extremes. Thus, weightings will be derived from the ability of models to produce a range of appropriate climate statistics that are relevant to the desired impact application. In this paper the skill of six regional climate models (RCMs) in reproducing the observed characteristics of mean precipitation and a drought index for six European catchments is assessed. The use of dynamically downscaled climate model data will enable these climatic characteristics to be examined on a spatial scale that is more appropriate than is the case for data obtained directly from GCMs. This will form the first stage towards the development of probabilistic climate change scenarios for future drought occurrence.

2 DATA AND METHOD

2.1 Data

An observed dataset has been used to examine the mean climate for the control period of 1961-1990. The CRU TS 2.0 data set (Mitchell *et al.*, 2004) is a gridded global series of monthly climate means for the land surface for the period 1901-2000. The data was constructed by the interpolation of station data onto a 0.5° grid and is an updated version of earlier datasets (New *et al.*, 1999a, New *et al.*, 1999b). This series will be referred to as CRU.

RCM data from the FP5 PRUDENCE project provides a series of high-resolution regional climate change scenarios for a large range of climatic variables for Europe for the period 2071-2100 using four high resolution GCMs and eight RCMs. As it is infeasible to evaluate climate change impacts arising from every simulation made available by PRUDENCE, it is important to examine a range of models to evaluate the uncertainty of future predictions. Déqué et al. (2006) indicated that for the European region although RCMs provide an adequate representation of temperature, simulations of precipitation are considered inadequate. PRUDENCE provides advice on the selection of RCM experiments for impacts analysis and here a selection has been made to examine the following uncertainty sources:

- Bounding GCM versus downscaled RCM
- Same bounding GCM in combination with different RCMs
- Same RCM in combination with different bounding GCMs

A list of the selected models and their acronyms used in this study is provided in Table 1. Model simulations are available for a control integration (1961-1990) and a future time-slice (2071-2100) using the SRES A2 emissions scenario. Each of these simulations were re-gridded onto a common 0.5° by 0.5° grid to allow direct comparison with the CRU series. A direct comparison of monthly precipitation totals is not possible as most of the RCMs are run for annual cycles consisting of twelve 30-day months. The use of monthly totals would include an inherent bias in some months and so, to enable a valid comparison between the observed and model data, the mean daily precipitation was calculated for each month.

2.2 Method

Droughts may be defined as climatological, agricultural, hydrological, and water resource types, with each exhibiting unique properties of frequency, severity and persistence (Bradford, 2000). Tate & Gustard (2000) identified 25 different measures used for climatological drought alone whilst Maracchi (2000) noted 17 based on just measures of rainfall. Two of the key factors in determining drought occurrence and severity are evapotranspiration and precipitation. However, difficulties in obtaining reliable series of evapotranspiration rates means that measures based on solely rainfall offer the most potential for an index which may be used on a European-wide scale. Such indices have been shown to perform well (Oladipo, 1985) compared with more complex indices and a good agreement between European precipitation changes and trends in droughts has been noted (Hisdal *et al.*, 2001).

This study uses a drought severity index (DSI) based on cumulative monthly precipitation anomalies; the concept originally defined by Bryant *et al.* (1992). The monthly precipitation anomaly is defined relative to the 1961-1990 mean, of which two indices, DSI3 and DSI6 have been used for the UK (Goldsmith *et al.*, 1997; Phillips and McGregor, 1998; Fowler and Kilsby, 2002) using different "termination rules". To illustrate this, the calculation of DSI3 is described here. If the precipitation anomaly in month t is denoted as X_t and is negative and the precipitation in the preceding three-month period (i.e. $t-1$, $t-2$, $t-3$) is also lower than its mean, then a drought sequence is initiated. The value of DSI3 is assigned as the positive value proportional to the deficit in month t. Considering month $t+1$, if the precipitation deficit is –Y mm, then DSI3 for month $t+1$ is X+Y provided the mean monthly precipitation total for the preceding three months has not been exceeded. If the precipitation anomaly is positive in month $t+1$ then the drought can continue provided the three-monthly mean total has not been exceeded. The termination of a drought occurs when the three-monthly mean total is exceeded, whereupon DSI3 is assigned a value of zero. In order to allow comparisons between sites and regions the DSI values are standardised by dividing the absolute deficit by the site/grid cell mean-annual precipitation, which is then multiplied by –100. Thus the final index value expresses the accumulated precipitation deficit as a percentage of the annual mean total precipitation. DSI6 is calculated in an identical way except that the six-month mean is used to determine drought termination.

Six regions are studied in detail here which encompass each of the catchments of interest and represent a selection of climatological and hydrological regimes (Figure 1). The Eden in north-west England is an upland catchment with a temperate maritime climate whereas the Meuse, which rises in France and flows through the Netherlands, and its tributary the Dommel are lowland catchments and less exposed to mid-latitude cyclones from the Atlantic. The Ebro and its tributary, the Gallego, in north-east Spain experience a Mediterranean climate and are highly regulated catchments with over 187 dams with a total capacity equivalent to 57% of total mean runoff (Batalla *et al.*, 2004). The final catchment, the Brenta, in northern Italy is in a topographically diverse region with the Alps to the north and the Po Valley to the south.

To better represent how changes in the DSI might affect specific types of drought the index may be calculated using different termination rules. For the UK, two types of drought event have been defined previously (Fowler & Kilsby, 2004). DRO3 is defined as a 3 to 6 month drought with an accumulated deficit exceeding 10% of mean annual rainfall, and is more likely to affect surface water resources. DRO6 is a longer drought, lasting at least 6 months, where the accumulated deficit exceeds 30% of annual mean precipitation and is likely to affect groundwater resources. However, the occurrence of surface water and groundwater droughts are dependent on the regional climate and catchment characteristics. To reflect this, the duration and threshold of precipitation deficits is modified for the other catchments where previous research indicates different relationships between precipitation and surface water or groundwater storage.

Vicente-Serrano & López-Moreno (2005) identified robust relationships in northern Spain between the Standardised Precipitation Index (SPI) and river discharges. The relationships between river discharges and SPI were robust on timescales of 1-3 months and for reservoir storage on scales of 7-10 months. Sumner *et al.* (2001) suggest that groundwater and reservoir reserves are recharged during the short period of cooler months when evapotranspiration is lower. Winter recharge is cited as the important aspect for groundwater droughts and so such a drought may be defined when precipitation deficits persist through winter (Hisdal & Tallaksen, 2001). Therefore for the Ebro/Gallego catchments alternative termination rules are suggested whereby DRO3e is defined by droughts of between 3 and 10 months duration and an accumulated deficit exceeding 10% of mean annual rainfall whilst DRO10 is used to define droughts lasting at least 10 months, where the accumulated deficit exceeds 30% of annual mean precipitation. Bordi *et al.* (2001) indicate that for Alpine areas of Italy wet periods may balance out deficits on timescales shorter than about 12 months and so prevent the formation of shorter events defined by precipitation. To reflect this, the same DRO3e index is used along with DRO10. Relationships between precipitation and water resources could not be found for the Meuse/Dommel catchments.Although Beersma & Buishand (2004) identified a relationship between Netherlands precipitation and the discharge of the Rhine River, they did not examine the relationship on different timescales. Therefore as the climatic regime of these catchments is temperate, similar to much of the UK, the same DRO3 and DRO6 indices were used as for the Eden. A summary of these definitions is given in Table 2.

3 Climate Models and Mean Precipitation

3.1 Reproducing observed means

Mean daily precipitation amounts were calculated on a seasonal basis across Europe for the CRU series for 1961-1990 and compared with each of the RCM control integrations. Although the magnitude and spatial extent of errors varies between the models some generalisations may be inferred from the spatial structure of model errors across Europe. During summer, precipitation amounts are under-estimated over southern, central and north-western Europe, particularly by HAD_P for which the area of under-estimation extends further north over Britain and Scandinavia. The largest negative errors generally occur over the central and eastern Mediterranean and the European continental interior. In contrast, larger, positive errors are confined to northern Scandinavia and the eastern Baltic states. Winter rainfall is over-estimated over most of the region with the largest errors over northern and western Europe, extending further east in the RCAO simulations. Under-estimation of winter rainfall is generally observed around the Mediterranean, particularly over the Iberian Peninsula.

Examining model errors on such a regional scale can highlight model deficiencies in reproducing large-scale processes but fails to address model skill in reproducing important features of climate on smaller scales. For each of the study regions, daily mean precipitation amount was calculated for each month to allow the examination of the models' skill in reproducing the annual precipitation cycle. By calculating the mean absolute monthly anomaly for each model a simple assessment of model skill may also be derived (Figure 2). Overall mean absolute errors are smallest for the Brenta and Ebro/Gallego. Of the six RCMs, HIRHAM_E performs best except for the Meuse/Dommel catchment. However, these errors are not distributed evenly throughout the year, indicating seasonal variability in the ability of individual models to represent physical processes responsible for precipitation. Particular problems of this nature are highlighted for the Brenta catchment where all the RCMs have poor skill in reproducing the annual distribution of mean precipitation. Northern Italy has a highly variable precipitation regime due to the complex topography provided by the Alps to the north, the Apennines to the south and the Po Valley in the centre of this region (Molteni *et al.*, 1983). Dividing the Brenta study region into northern and southern sub-regions indicates that the northern Alpine region has higher mean precipitation which is at a maximum during summer (not shown). Precipitation in the southern region peaks in autumn and is at a minimum during summer. Whilst the climate models reasonably reflect the relative magnitudes of precipitation in these two sub-regions they do not properly represent its annual distribution (not shown). A possible explanation may lie in the relative importance of summer extreme events in the northern Alpine region. These have a small spatial scale (Maugeri *et al.*, 1999) compared with winter events which are associated with large low-pressure systems (Brunetti *et al.*, 2000) and may not be adequately represented in the models. For some hydrological applications it may be more important that models are skillful in reproducing the spatial pattern of precipitation than the areal mean. For example, HIRHAM_H, HIRHAM_E and ARP_C all perform with similar skill in reproducing the mean July precipitation over the whole region but the errors for the two HIRHAM simulations have a strong spatial coherence, with under-estimates over the Alpine region and over-estimates to the south whereas ARP_C is characterised by moderate over-estimates over most of the region, suggesting it is better at reproducing the physical processes responsible for the observed precipitation patterns.

The analysis also indicates that the source of model error varies between catchments. For the Meuse/Dommel region all models over-estimate winter precipitation but the magnitude of the error is determined by the driving GCM, with similar errors for the two pairs of models driven by ECHAM4 and HadAM3H. In contrast, for the Eden, whilst model errors are of similar magnitude throughout the year, RCM choice is important during winter and spring but during summer and autumn GCM choice is also a source of error.

3.2 Future Changes in Mean Precipitation

Each of the models project widespread precipitation decreases across Europe during summer with increases only over northern Scandinavia and northern Russia (not shown). During winter the spatial distribution of model projections is more variable. Increases tend to be largest over northwest Europe and Scandinavia, extending as far south as northern Spain, Italy, northern Greece and southern France. RCAO_E provides the exception with projected decreases over the Mediterranean. Hadley-driven models also project decreased precipitation along the northern Scandinavian coast which is not apparent in the other RCMs. Projected changes during the transitional seasons (spring and autumn) indicate similar patterns of change, with increases in the north and decreases in the south, although changes are generally of smaller magnitude than summer and winter for Hadley-driven models. GCM choice is also an important factor in determining the spatial extent of change in autumn, with the ECHAM-driven models projecting precipitation decreases further to the north than other models.

Individual model projections for the six study regions reveal the range of uncertainty in future changes (Figure 3). For example, for the Ebro, during August the projected change ranges from -14% (HIRHAM_E) to -62% (RCAO_H). For the Eden, the largest range in future projections of monthly means occurs during summer months but for the other catchments, and in particular the Brenta, large ranges are projected throughout the year by the six models. As a simple way of combining multi-model ensembles of future projections of precipitation, the unweighted mean model change was calculated for each study region. This indicates that relatively large decreases in mean summer precipitation are projected for all of the AquaTerra catchments; up to

~50% for the Gallego/Ebro and Meuse/Dommel, and smaller decreases of around 30% for the Eden. However, large percentage decreases in summer precipitation may not provide much change in absolute values in Mediterranean catchments as summer totals are already low. The magnitude and timing of projected increases in precipitation is location dependent: the Ebro/Gallego shows the smallest winter increases (<10%) in December and January whereas increases over the Meuse/Dommel and Eden are >20% during these months with increases spanning October to March. The models suggest that water resources management will be most tested in the Spanish catchments where there will be little relative recharge of water during the winter to compensate for summer decreases. Using these unweighted means however does not take account of individual model skill during the control period and so the weighting of individual models will be a significant development in the construction of probabilistic scenarios.

The spatial distribution of projected change is also subject to uncertainty for all catchments. The source of this uncertainty is derived from both the choice of RCM and GCM driving data. For example, for the Eden RCAO_H projects a northeast-southwest gradient to decreases in mean July precipitation, RCAO_E indicates a clear north-south gradient whilst both HIRHAM simulations show little spatial variation in the distribution of future change. The spatial differences in projected change are greatest for the Brenta (Figure 4) for which most models indicate a north-south gradient of change with greater decreases in the lowland areas to the south of the region. The RCM choice seems to exert a stronger influence on the spatial distribution of change here with a much weaker gradient in the HIRHAM simulations.

4 Climate Models and Drought

4.1 European Drought

To examine drought on a broad scale, DSI3 and DSI6 are used to compare model performance and future projections of change across Europe. A comparison of DSI3 frequencies (not shown) indicates that it is difficult to characterise model performance on a regional scale as model errors show less spatial coherence than for mean precipitation statistics. The models consistently under-estimate short drought events

(DSI3) over the Iberian Peninsula and over-estimate them over parts of Scandinavia, most of France and northern Italy. However, the distribution of errors for longer drought events (DSI6) is different. Models over-estimate these events (DSI6) for the Iberian Peninsula but consistently under-estimate for most of the UK and for northern France. The lack of spatial consistency reflects the increased difficulty for models in reproducing the observed persistence of wet and dry months; as such errors are unrelated to errors for the mean. Such persistence is an important characteristic in being able to replicate the spatial characteristics of drought. Tables 3 and 4 show the mean DSI3 and DSI6 frequency for the CRU series and associated model errors averaged across each region. Not only do they demonstrate that the relative skill of the models over each region is different from that for mean precipitation. They also demonstrate that model skill varies with the temporal resolution of the indices being considered. For example, for DSI3, Hadley-driven RCMs produce the largest errors but for DSI6, ECHAM-driven models are less skilful in reproducing mean drought frequency. Spatially, models possess greatly different skill in reproducing different indices. HAD_P, for example, performs poorly in reproducing mean DSI3 for the Meuse/Dommel but is one of the most skilful for DSI6.

The SRES A2 scenario projections for the period 2071-2100 indicate much model uncertainty for DSI3 (Figure 5). The two ECHAM-driven models exhibit the strongest change signal with more frequent events affecting central and Eastern Europe, whilst for the other models increases are less spatially coherent but are most frequently projected for eastern Europe, parts of Scandinavia and the UK. DSI3 events in general are projected to become less frequent across Europe. This is surprising given that, for much of southern Europe in particular, mean precipitation is projected to decrease except during winter. This may suggest that overall there will be fewer short-duration droughts because decreases in monthly precipitation totals throughout most of the year will result in deficits being more likely to persist beyond the 6-month threshold to become DSI6 events. When European-wide changes in DRO3 are considered, that is, the accumulated precipitation deficit is more than 10% of the annual precipitation total, a higher proportion of grid cells are projected to experience more frequent droughts. These changes indicate that in the future, an increased proportion of shorter droughts are likely to be of the more severe DRO3 type.

Projections of future changes in DSI6 exhibit a greater degree of inter-model consistency than was apparent for DSI3 and are illustrated by examples from HAD_P (Figure 6a). The RCMs produce fewer DSI6 events over northern Europe, these decreases being largest for Scandinavia. Most models project an increase in these longer drought events further south, with increases over most of western and central Europe. This provides some evidence for the proposed transition from shorter to longer droughts for some regions in the future. There is not, however, a simple north-south pattern of decreased-increased drought, with models projecting fewer events for parts of the Iberian Peninsula and parts of the Mediterranean. Considerable uncertainty exists at the regional scale. For example, for Britain and northern Spain different models project both increases and decreases. Changes in the maximum duration (Figure 6b) and severity (Figure 6c) of DSI6 follow a similar spatial pattern with projected increases in southern Europe and increases in the north. All models project longer and more severe droughts in the Mediterranean and shorter, less severe, events for Scandinavia with greater uncertainty as to the direction of change for the rest of Europe.

4.2 Regional Changes in Drought

4.2.1 Brenta Region

For the Brenta, there is uncertainty in the direction of future change for DRO3e events dependent on choice of RCM (Figure 7). The two HIRHAM models project widespread increases in drought frequency whereas the RCAO models both indicate fewer events for most grid cells. More varied patterns of change are projected by both HAD_P and ARP_C. Future changes in longer drought events (DRO10) are less uncertain and these are likely to increase in frequency across the region by up to 2-3 additional events per decade, although HIRHAM_H indicates small decreases over the alpine part of the region. The maximum severity of these events is also likely to increase although there is more uncertainty for the maximum length of drought; models driven by HadAM3H project shorter droughts but other models indicate longer events.

4.2.2 Ebro/Gallego Region

As for the Brenta, there is considerable uncertainty in the spatial distribution of projections of DRO3e (Figure 8). However, for this region the source of the uncertainty seems to be linked to the choice of driving-GCM. Both ECHAM-driven models project overall decreases in future droughts, with some increases along the Mediterranean coast. In contrast, Hadley-driven RCMs project an overall increase in frequencies. Uncertainty in the future occurrence of DRO10 events is much smaller with all model projections indicating increases for almost all grid cells. The severity and duration of long droughts are projected to increase across the region; the maximum drought length increases by ~30 months for some grid cells. The region is therefore likely to experience increased pressure on water resources, particularly groundwater, due to decreases in recharge during the cooler, wetter part of the year.

4.3 Eden Region

Here, more uncertainty is again associated with projections of short-duration droughts, with the driving-GCM providing an important source of this uncertainty. Hadley-driven models project more frequent DRO3 droughts, with up to 3 additional events per decade driven by decreases in summer precipitation. However, ECHAM-driven models, particularly HIRHAM_E, project fewer events in the north of the region whilst ARP_C projects comparatively small changes. Longer events as measured by DRO6 show less inter-model variability but, in contrast to other regions, all models suggest a decrease in such events, typically by around one event per decade, due to increases in winter precipitation. A decrease in the maximum DRO6 drought severity and duration are also projected for the Eden. Blenkinsop & Fowler (2007) demonstrated that for the UK as a whole there is a tendency towards more frequent surface water droughts and fewer groundwater droughts due to increases in winter precipitation. However, uncertainty remains for future projections of the occurrence of groundwater droughts for the south east of England.

4.4 Meuse/Dommel Region

Projections of future change in both DRO3 and DRO6 exhibit a greater degree of spatial variability than for any of the other regions. For DRO3 (Figure 9a), most models project an increase in frequency for the Meuse and Dommel, although the spatial pattern of change is variable and due, at least partially, to the driving-GCM. ECHAM-driven models project larger increases in the northern part of the region (including the Dommel catchment), with decreases to the south. In contrast, the two models driven by HadAM3H suggest the opposite pattern of change. Unlike the Eden, there is some uncertainty as to the future direction of changes in DRO6 over this region (Figure 9b). Again, choices of both RCM and driving-GCM provide a source for this uncertainty. The two ECHAM-driven models, for example, project large increases across most of the catchment with over 3 additional droughts per decade for some grid cells. However, the two models driven by HadAM3H project only small increases of around one additional event per decade, mainly in the north of the region whereas decreases are projected by ARP_C. All models except ARP_C project an increase in drought duration with these most likely to be in the northern Dommel and the southernmost part of the Meuse. Increases in maximum drought severity are also projected for this region.

5 DISCUSSION AND CONCLUSIONS

The use of six RCMs has shown that there is no one “best model” for reproducing mean precipitation and drought statistics across Europe and that model skill varies temporally, even on the catchment scale. The models are particularly poor in reproducing mean precipitation for the Brenta catchment where, although they are able to reproduce spatial differences in the magnitude of precipitation produced by the complex regional topography, they are poor in reproducing spatial variations in the annual precipitation cycle, possibly indicating a poor realisation of summer extremes.

The use of six RCMs has demonstrated the range of uncertainty in future projections of even mean precipitation across Europe, but also enables some generalisations to be made. Increases in precipitation are likely during winter and these are likely to be largest and most persistent for northern Europe. In contrast, large decreases in precipitation are likely during summer; these being largest in southern Europe. These spatial differences are apparent in the projected changes produced for the six

AquaTerra catchments. Models errors in reproducing drought indices defined by mean monthly precipitation anomalies are independent of those for mean precipitation statistics and are less spatially coherent; the models do not necessarily over-estimate drought frequency in dry regions and under-estimate it in regions that are too wet. This suggests that the models experience additional difficulties in reproducing higher order statistics. An examination of model skill in reproducing the inter-annual variability of monthly precipitation totals indicates differences in the RCMs' abilities to reproduce observed variance (Blenkinsop & Fowler, 2005). The poor reproduction of drought frequency additionally indicates that they have difficulty in reproducing the persistence of anomalously dry periods on monthly timescales.

Projected changes in the frequency and character of droughts are dependent on the location and on the type of event considered, as is the source of this uncertainty; the choice of driving GCM, of RCM or both. Changes in short-term precipitation deficits are highly spatially variable and there is also considerable inter-model variability on regional and local scales. For longer-duration droughts there is a clearer spatial pattern which indicates fewer droughts in northern Europe due to larger increases in winter precipitation, and more droughts of increasing severity in the south. However, there are distinct regional differences in patterns of change. For the Eden in north-west England, fewer long groundwater droughts are projected but more short-term surface water droughts are likely. In contrast, for the Meuse/Dommel, there is more uncertainty in future projections of short-duration deficits but it is likely there will be more long droughts. These differences are related to the number of months over which winter precipitation is projected to increase. In locations where this recharge period is shorter, DRO3 events are more likely to become DRO6 events.

On the European scale, the changes highlighted in this study could present significant environmental and socio-economic problems. Issues of poor water quality during periods of low flows and the accumulation of pollutants in aquifers during groundwater droughts could affect many regions, whilst large-scale changes in agricultural production and potential population migration could represent significant challenges. The changes described in this paper also represent particular challenges for each of the catchments. For the Eden, the issues will be how to best manage water resources given changes in the seasonality of rainfall which will produce summer deficits. Several of the RCMs also project large increases in the variability of monthly mean precipitation during winter and so water suppliers need to plan for extreme events that may occur in the future. However, Blenkinsop & Fowler (2007) have shown that the hydrological response across Britain is likely to be varied with the possibility of more frequent groundwater droughts in the south-east and fewer in northern regions.

In contrast, catchments such as the Ebro/Gallego face different challenges. Ensuring sufficient flows for the generation of hydroelectricity (Batalla *et al.*, 2004) will remain a key strategic aim in this region whilst more frequent, longer lasting groundwater droughts will challenge other sectors, particularly agriculture. Considerable challenges already exist in this sector as groundwater extraction for irrigation across Spain tends to be developed and financed by private farmers and small- and medium-sized firms. The absence of an integrated approach may lead to problems of overexploitation of groundwater resources (Custodio *et al.*, 1998) in an area where the ratio of water withdrawals to water availability is projected to increase by the 2070s (Henrichs & Alcamo, 2001). Given that the Ebro and its tributaries are highly regulated, the authorities will need to carefully manage future flows.

Northern Italy, including the Brenta region currently experiences some of the highest rates of annual water availability in Europe (Henrichs & Alcamo, 2001). Approximately two-thirds of this, mainly surface water, is used for irrigation with stress from groundwater abstraction a problem in only a few areas (Massarutto, 1999). Changes in the quantity and timing of meltwater from the Alps due to future warming may result in water availability in the catchment becoming increasingly dominated by seasonal rainfall patterns. The uncertainty in future projections for short-duration droughts could thus become more important towards the end of the century and, as for the Ebro, may require a more integrated approach to the management of irrigation schemes than is observed at present.

The Meuse and Dommel regions perhaps face the most difficult strategic challenges in that there is uncertainty as to the future direction of change for both short- and long-duration events. Different projections of change for the north and south of the Meuse may also mean that different regional responses are required within the

Dommel. Managing abstractions from the system, given the possibility of more frequent long droughts, poses additional difficulties in this region, not only because of the uncertainty in model projections but because of a history of relatively low levels of international collaboration between France, Belgium and the Netherlands in managing this basin (Huisman *et al.*, 2000). The possibility of losses from the increased probability of flooding due to greater winter rainfall and land use change (De Roo *et al.*, 2001; Pfister *et al.*, 2004) are also additional concerns competing for the attention of policymakers.

The index used in this study is a measure of climatological drought and, despite the usefulness of such indices, several caveats should be discussed in relation to their application to future occurrence of hydrological or water resource droughts. Such events will also be affected by changes in land use such as agricultural intensification and afforestation as well as socio-economic factors which affect demand for water. Changes in drought severity for western Europe have been attributed to a changing climate but for eastern European countries the increased extraction of water for economic expansion is also a significant factor (Lehner *et al.*, 2006). It has been suggested that the influence of increases in water consumption on future droughts may even be of the same magnitude as the projected impact of climate change (Lehner & Döll, 2001).

Summer drying may also be attributed to a combination of both increased temperature and potential evaporation not balanced by changes in precipitation. The use of a precipitation-based index does not take account of changes in evapotranspiration which are likely given projected changes in temperature. However, as shown in Figure 10 for the Ebro, the largest temperature increases are likely to occur during summer months, whereas recharge tends to take place over winter months when temperature increases do not produce as significant an impact on potential evapotranspiration. Nonetheless, changes in temperature are likely to have important impacts on surface water flows produced by snowmelt in alpine regions. Therefore, to better understand likely changes in hydrological drought in the Brenta region, a more complex index may be more appropriate. Additionally, although the DSI is an extremely useful tool for highlighting changes in the occurrence of climatological drought, its use as a proxy for hydrological and groundwater droughts may also be less appropriate for larger catchments such as the Meuse, or highly heterogeneous catchments such as the Brenta. In such cases a more practical assessment may require drought definitions which vary across the catchment to reflect the diverse nature of such river basins. Notwithstanding this however, the methods used here provide a simple method for assessing droughts of different severity which will impact on different types of resources.

This study has highlighted the need for continued research in this area on a number of key issues. Firstly, it would be interesting to determine whether models reproduce the observed relationships between the atmospheric circulation and drought. This has been highlighted as the main factor in drought occurrence in the Mediterranean Basin (Maheras, 2000) and significant for low river flows on the Iberian Peninsula (Trigo *et al.*, 2004). This might offer insights as to whether projected changes in drought frequencies may be brought about by a change in the distribution of weather types or by more intense situations of the existing types and may also enable better future projections of drought characteristics through the use of modelled atmospheric fields. Also, large inter-model uncertainty in projections of future drought events is evident for some regions and, indeed, for some indices encompasses the direction of future change. This uncertainty may be reduced by a better understanding of how models reproduce the observed persistence in monthly precipitation totals and the incorporation of this understanding into future model development. In the meantime the uncertainty in future projections of precipitation and drought indices needs to be better incorporated into climate change scenarios and the development of probabilistic scenarios for specific impacts would seem to offer the most potential to achieve this aim. A considerable advance for research in this area would be to use the information generated from this type of research to inform how such probabilistic downscaled scenarios may be applied to specific impacts using hydrological models. Weighting climate models on their ability to reproduce extreme events, or persistence of low rainfall totals for use in flood or drought projections represents a much more robust and practical approach to scenario generation than has been achieved so far from single-model assessments.

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Figure Captions

Figure 1: The six regions studied: (1) Eden, (2) Ebro, (3) Gallego, (4) Meuse, (5) Dommel, and (6) Brenta.

Figure 2: Observed and modelled precipitation means for the 1961-1990 period. The left hand plots are the monthly mean precipitation statistics, the right hand column are the mean monthly errors for each RCM. Statistics are shown for: (a) the Brenta, (b) the Eden, and (c) the Meuse catchment. The shaded areas represent the 95% confidence intervals for the 30-year sample means.

Figure 2: Continued for (d) the Dommel, (e) the Ebro and (f) the Gallego.

Figure 3: Projected change in mean precipitation for the period 2071-2100 expressed as a percentage of the 1961-1990 means. Results are shown for: (a) the Brenta, (b) the Ebro, (c) the Eden, and (d) the Meuse catchments. Projected changes for the Gallego and Dommel are similar to panels (b) and (d) respectively. Panel (e) shows the unweighted 6-model mean change for each catchment.

Figure 4: Change in mean daily precipitation rate for the Brenta region for July. Changes are for the period 2071-2100 expressed as a percentage change from the 1961-1990 mean.

Figure 5: Projected change in the frequency of DSI3 events for the period 2071-2100 from 1960-1990 for the six RCMs.

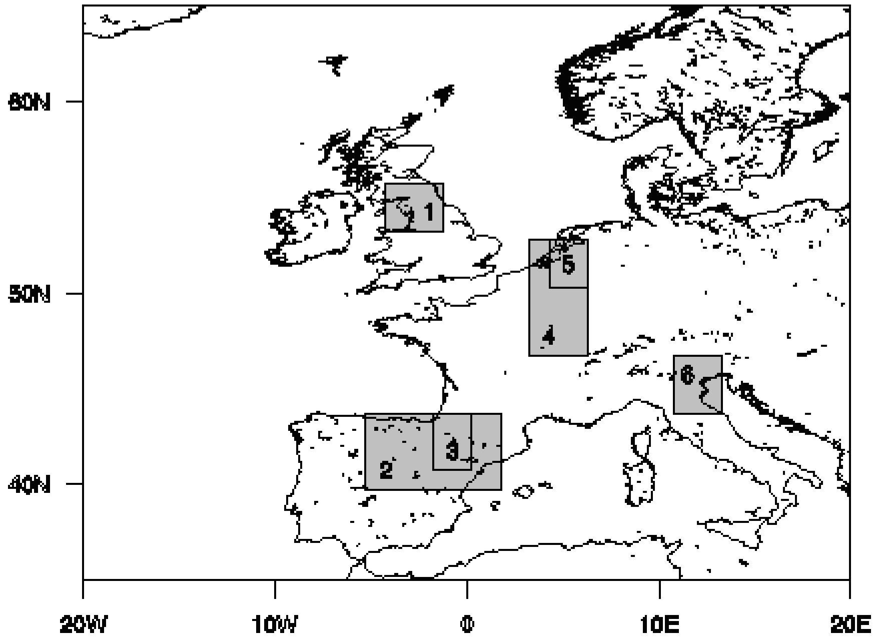
Figure 6: Projected change in: (a) the frequency of DSI6 events, (b) the maximum DSI6 duration in months, and (c) and the maximum DSI6 severity, for the HAD_P model. All changes are expressed for the period 2071-2100 as changes from 1960-1990.

Figure 7: Change in the frequency of DRO3e events for the Brenta region. Change is expressed for 2071-2100 from the period 1961-1990.

Figure 8: As for Figure 7 but for the Ebro/Gallego region.

Figure 9: Change in the frequency of: (a) DRO3, and (b) DRO6 events for the Meuse/Dommel region. Change is expressed as in Figure 7.

Figure 10: Projected mean monthly temperature change for the Ebro for the period 2071-2100 from 1961-1990.



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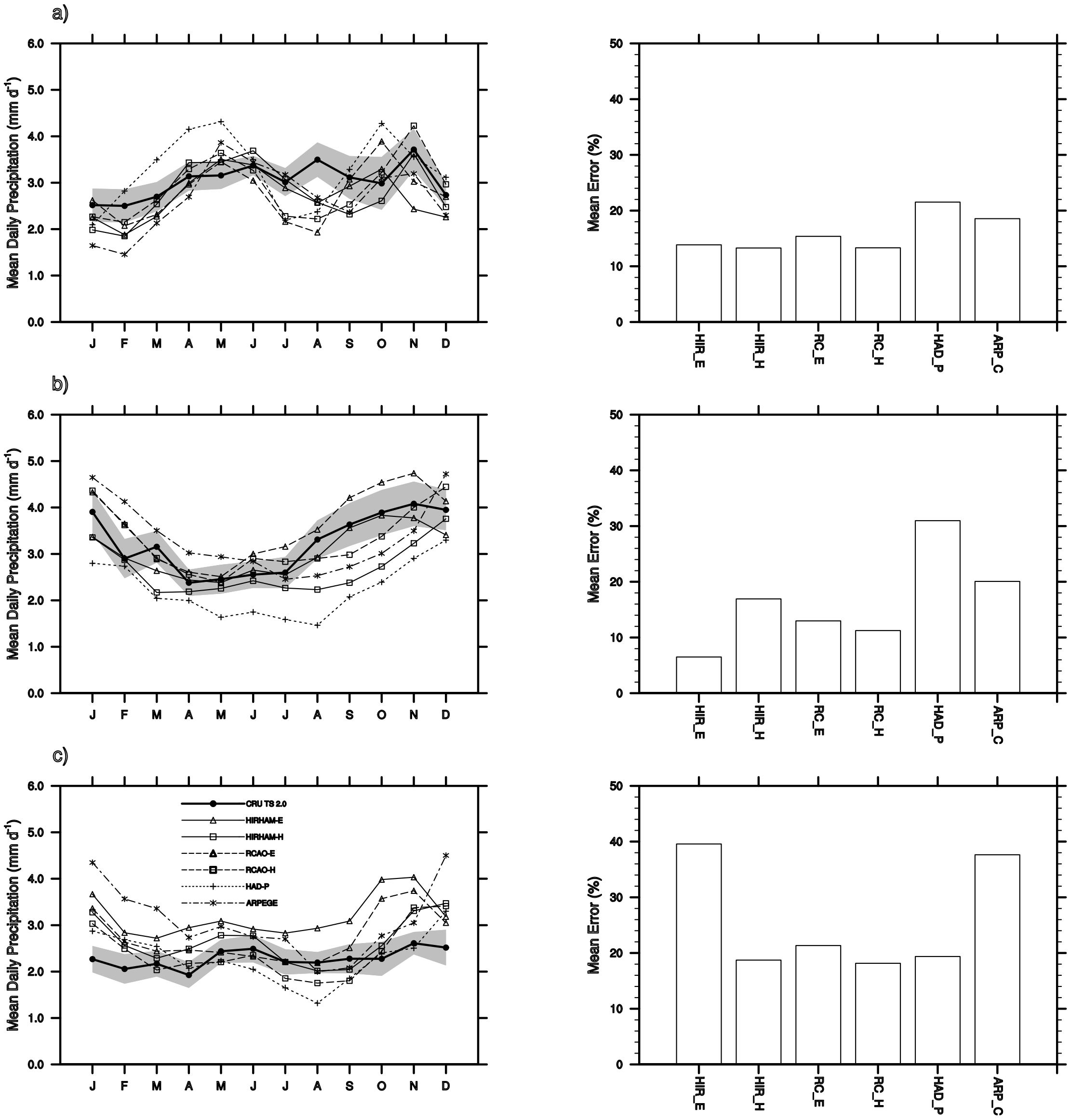

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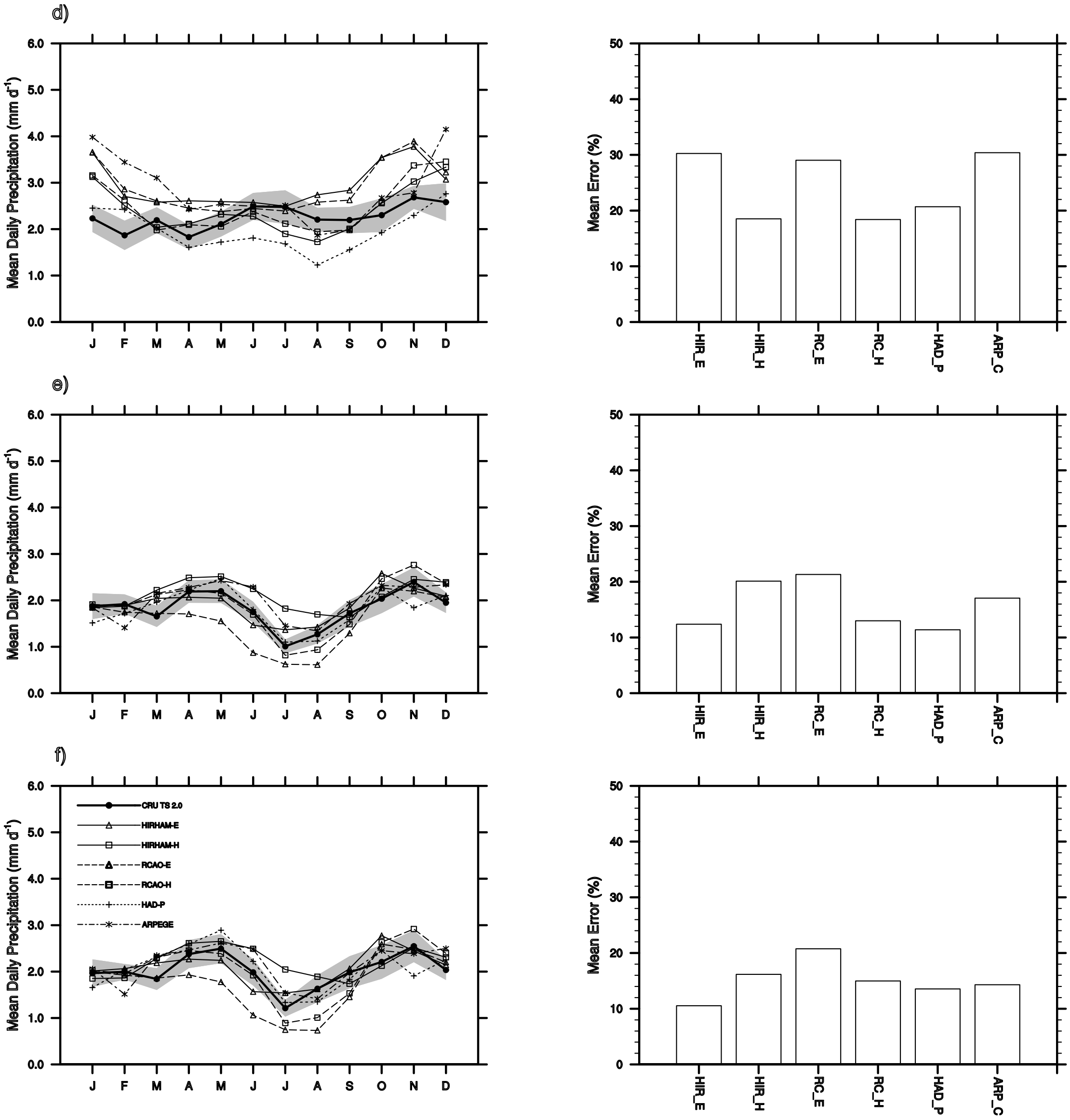


Figure 2: Continued for (d) the Dommel, (e) the Ebro and (f) the Gallego.

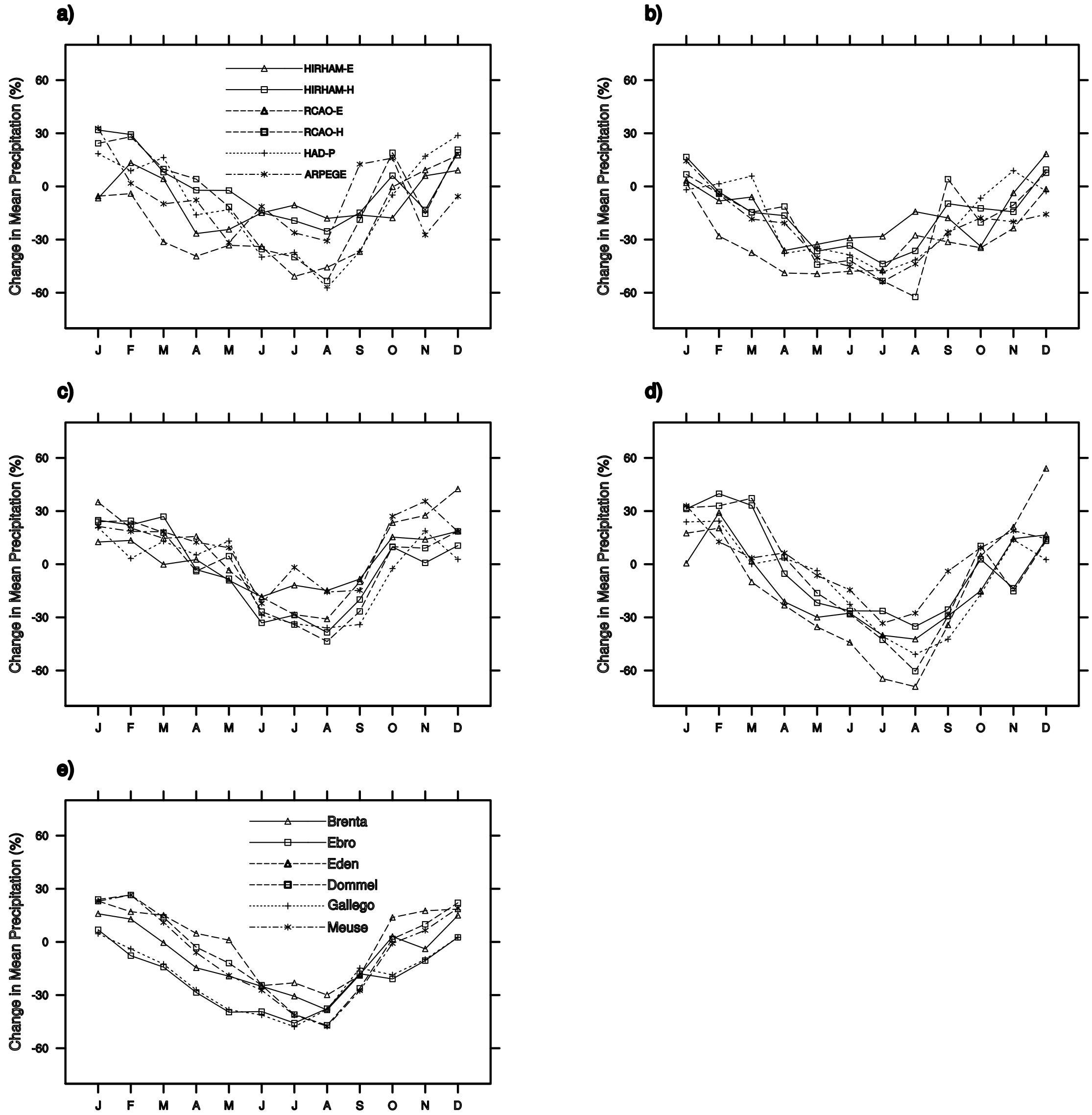
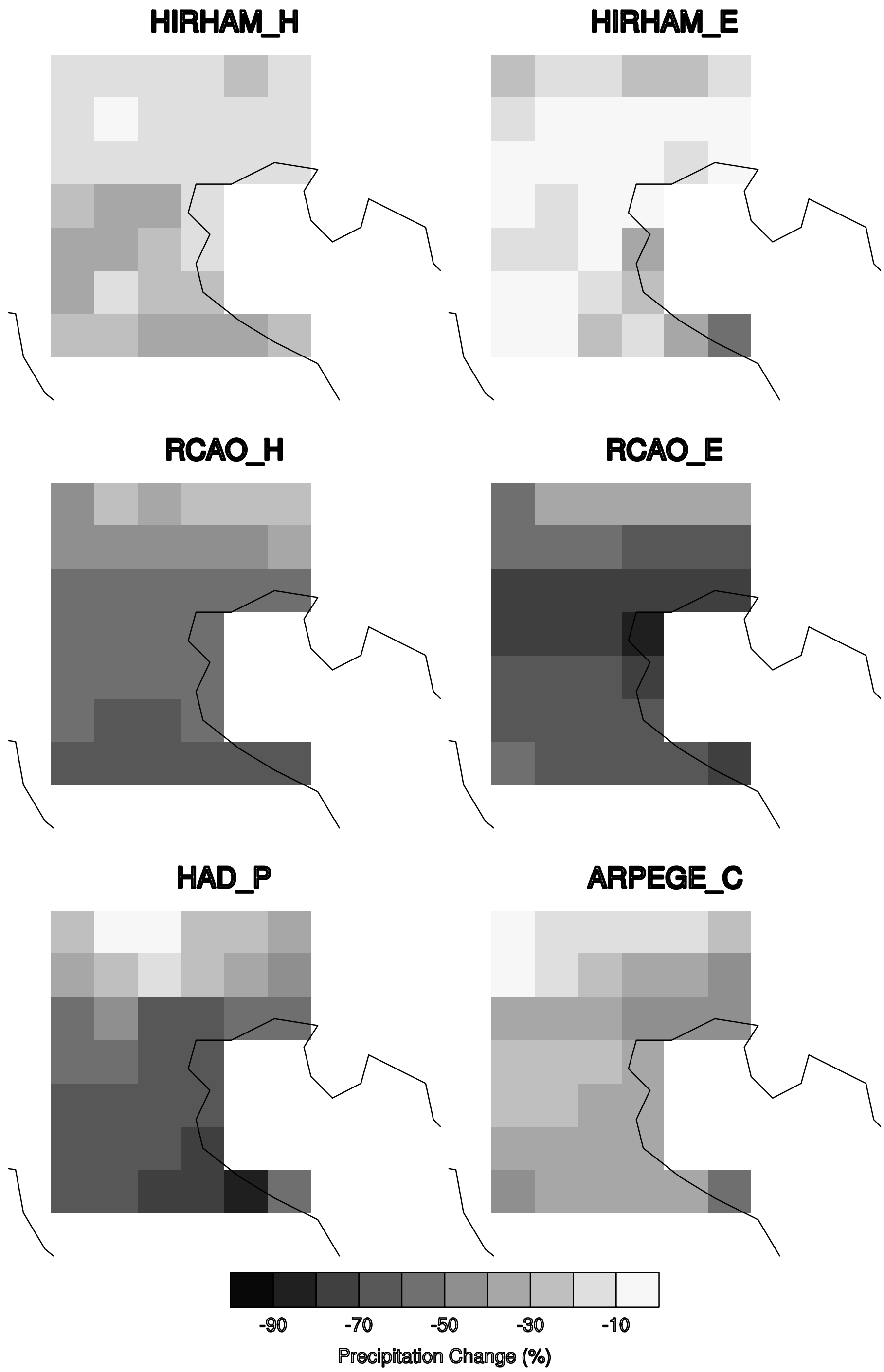


Figure 3: Projected change in mean precipitation for the period 2071-2100 expressed as a percentage of the 1961-1990 means. Results are shown for: (a) the Brenta, (b) the Ebro, (c) the Eden, and (d) the Meuse catchments. Projected changes for the Gallego and Dommel are similar to panels (b) and (d) respectively. Panel (e) shows the unweighted 6-model mean change for each catchment.



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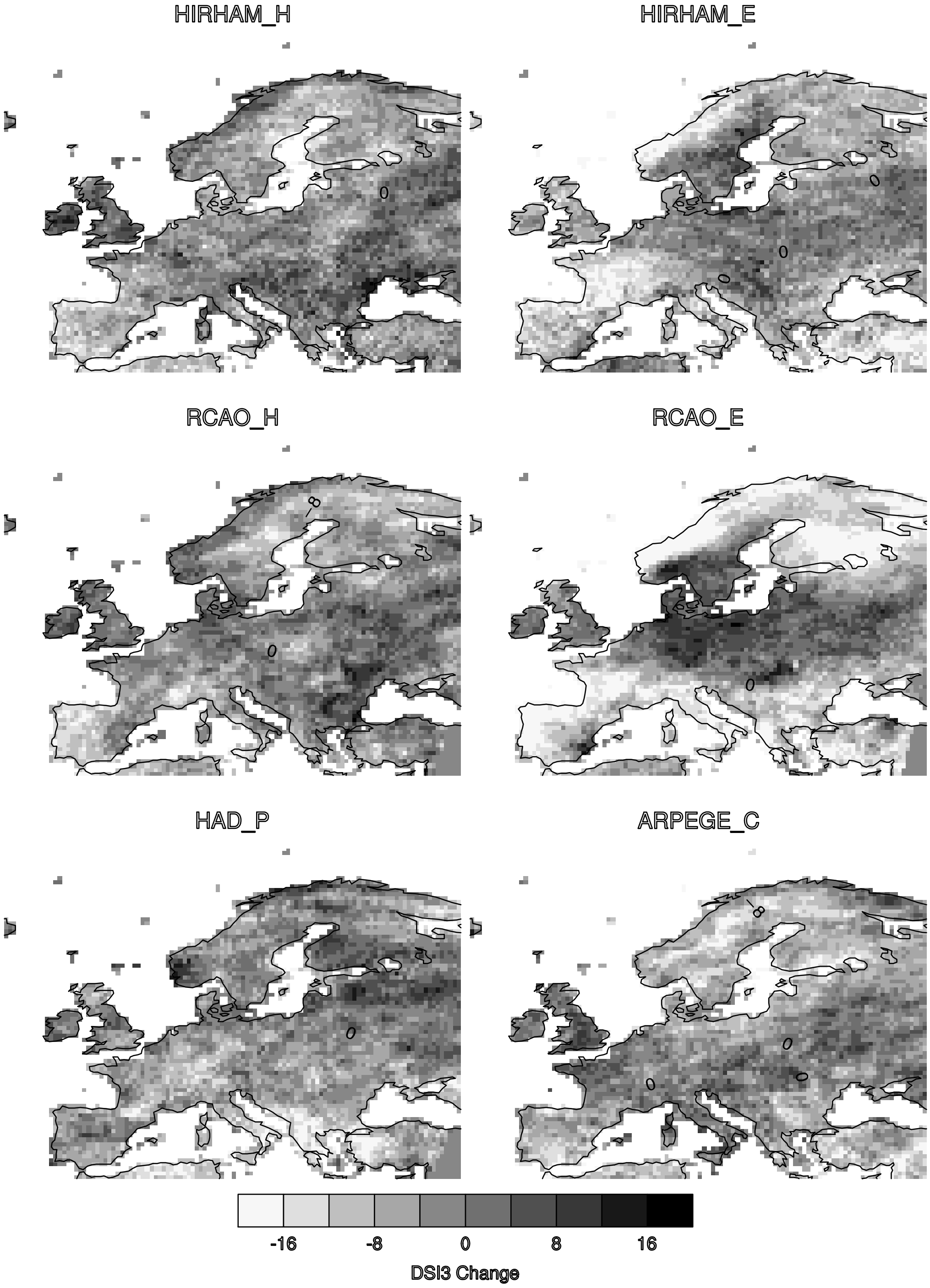

Figure 5: Projected change in the frequency of DSI3 events for the period 2071-2100 from 1960-1990 for the six RCMs.

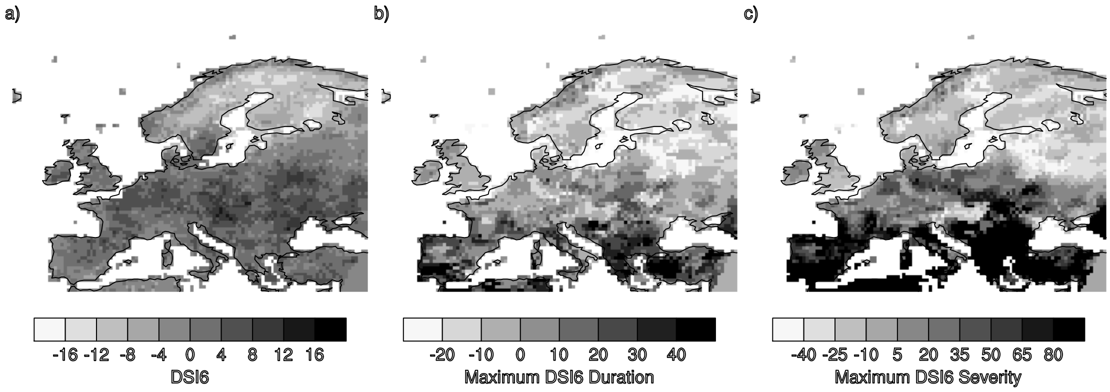

Figure 6: Projected change in: (a) the frequency of DSI6 events, (b) the maximum DSI6 duration in months, and (c) and the maximum DSI6 severity, for the HAD_P model. All changes are expressed for the period 2071-2100 as changes from 1960-1990.

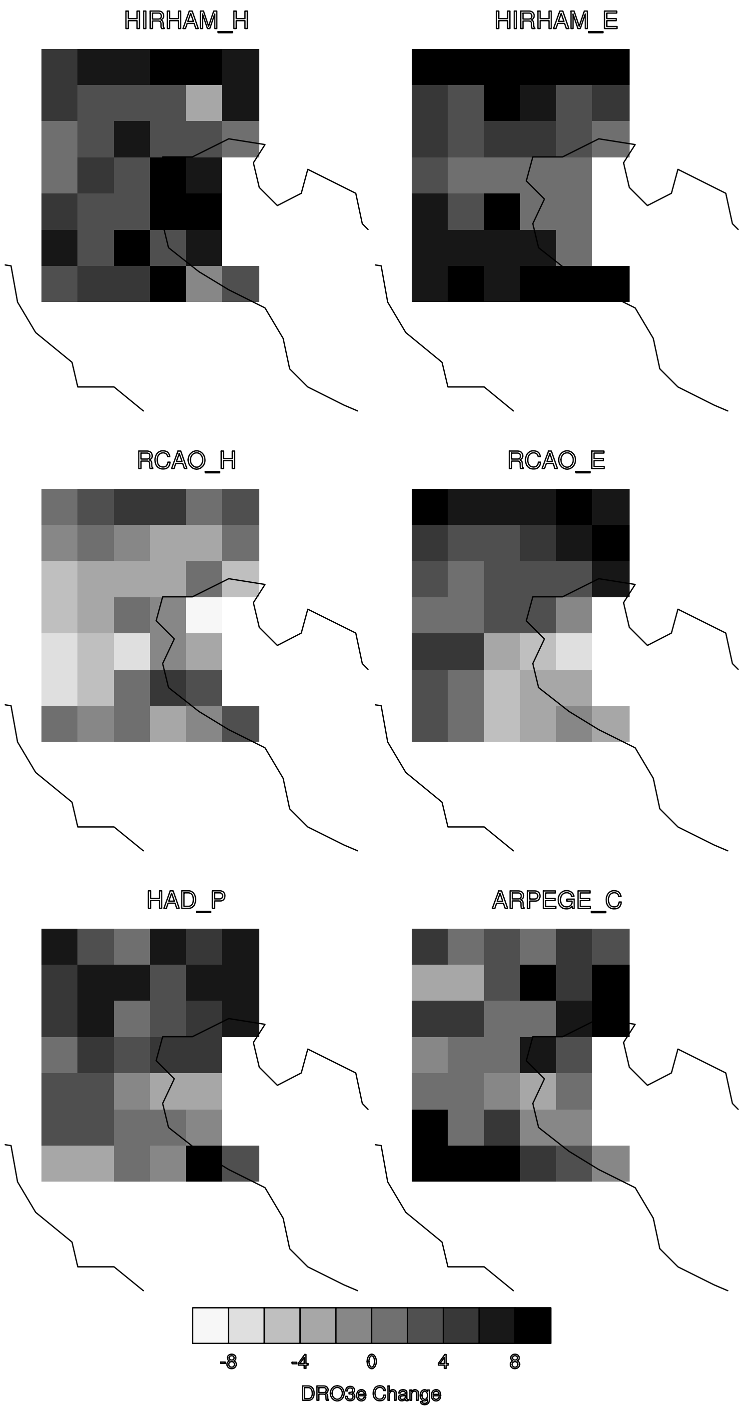

Figure 7: Change in the frequency of DRO3e events for the Brenta region. Change is expressed for 2071-2100 from the period 1961-1990.

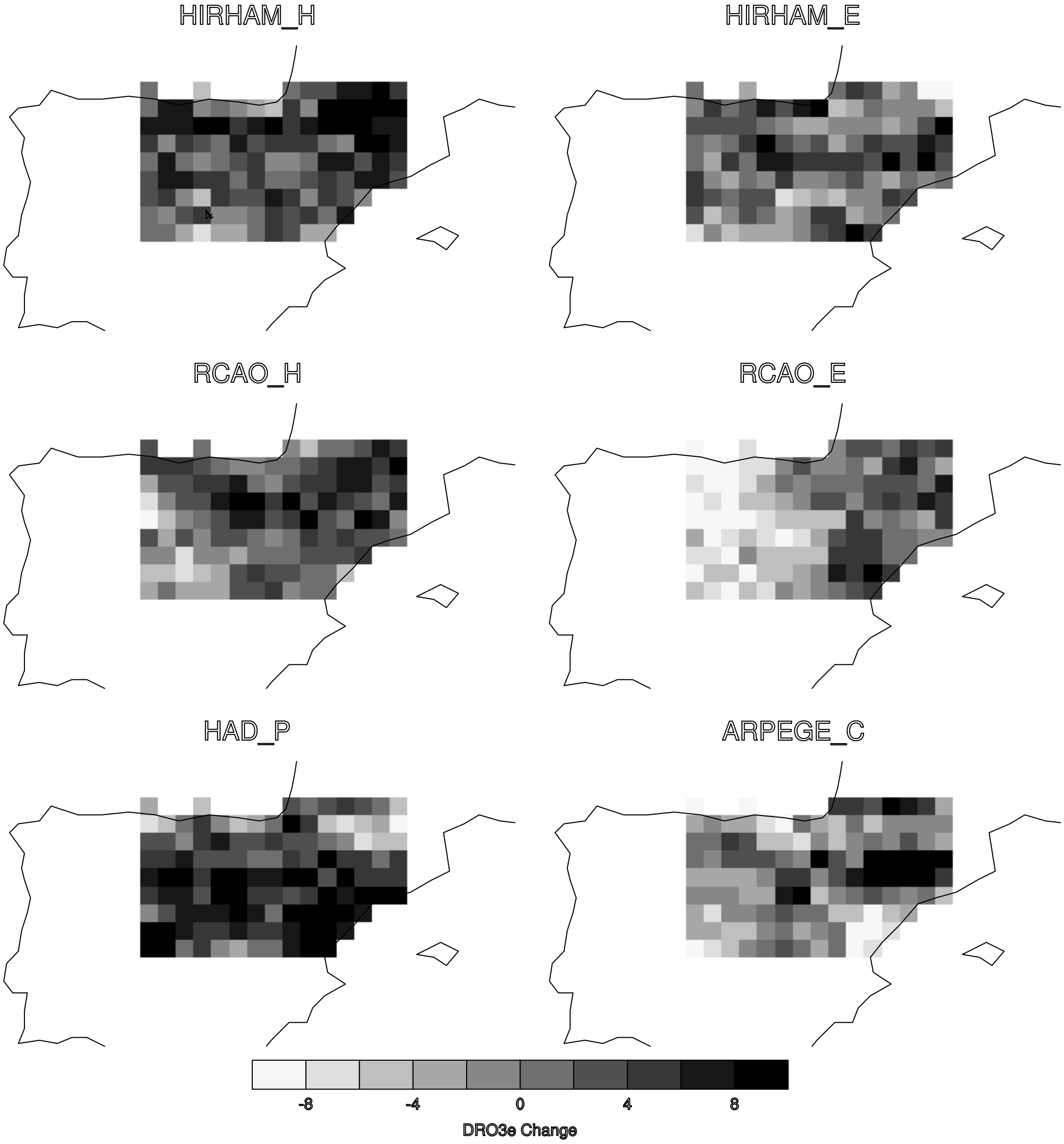

Figure 8: As for Figure 7 but for the Ebro/Gallego region.

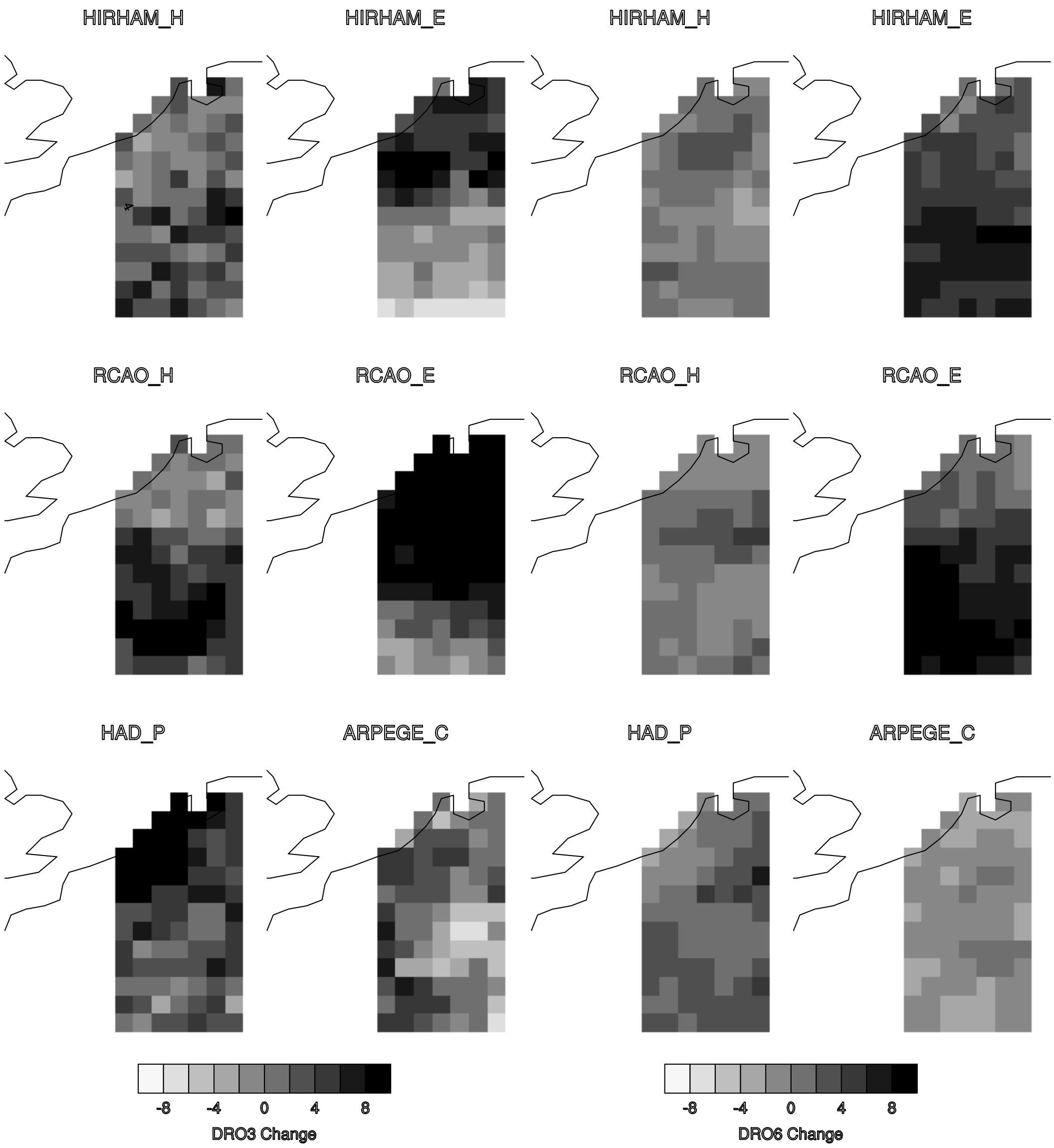

Figure 9: Change in the frequency of: (a) DRO3, and (b) DRO6 events for the Meuse/Dommel region. Change is expressed as in Figure 7.

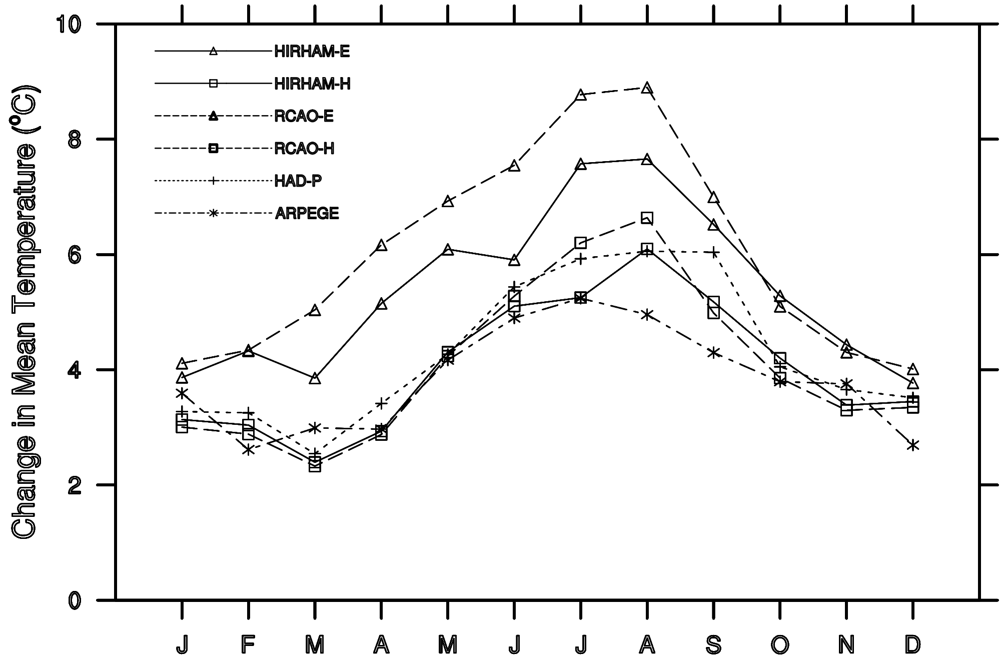

Figure 10: Projected mean monthly temperature change for the Ebro for the period 2071-2100 from 1961-1990.

	RCM	Driving Data	PRUDENCE Acronym	AquaTerra Acronym
Danish Meteorological Institute (DMI)	HIRHAM	HadAM3H A2	HC1 HS1	HIRHAM_H HIRHAM_H_A2
		ECHAM4/OPYC (OGCM SSTs)	ecctrl ecscA2	HIRHAM_E HIRHAM_E_A2
Swedish Meteorological and Hydrological Institute (SMHI)	RCAO	HadAM3H A2	HCCTL HCA2	RCAO_H RCAO_H_A2
		ECHAM4/OPYC A2	MPICTL MPIA2	RCAO_E RCAO_E_A2
Hadley Centre – UK Met Office	HadRM3P	HadAM3P	adeha adhfa	HAD_P HAD_P_A2
Météo-France, France	Arpège	HadCM3 A2/ Observed SST	DA9 DE6	ARPEGE_C ARPEGE_P_A2

Table 1: The selection of PRUDENCE Regional Climate Models used in this study. The AquaTerra acronyms are adopted here to provide an easier understanding of the format of each model run. The first part of each acronym refers to the RCM and the second to the GCM data used to provide the boundary conditions. Scenario simulations have the further suffix A2. The HadRM3P model is run for a total of 31 years (1960-1990 for control and 2070-2100 for the scenario).

Drought Index	**Definition**	**Applied Regions**
DSI3	Droughts lasting between 3 and 6 months.	Europe
DSI6	Droughts lasting at least 6 months.	Europe
DRO3	Droughts lasting between 3 and 6 months with an accumulated deficit exceeding 10% of mean annual rainfall.	Eden, Meuse, Dommel
DRO3e	Droughts lasting between 3 and 10 months duration with an accumulated deficit exceeding 10% of mean annual rainfall.	Ebro, Gallego, Brenta
DRO6	Droughts lasting at least 6 months, where the accumulated deficit exceeds 30% of annual mean precipitation.	Eden, Meuse, Dommel
DRO10	Droughts lasting at least 10 months, where the accumulated deficit exceeds 30% of annual mean precipitation.	Ebro, Gallego, Brenta

Table 2: Drought definitions used in this study and regions of application.

	CRU	**HIR_E**	**HIR_H**	**RCAO_E**	**RCAO_H**	**HAD_P**	**ARP_C**
Brenta	21.6	-0.7	-4.5	+1.5	-1.0	-3.1	-3.5
Eden	23.4	2.9	-3.1	+2.3	-0.3	+1.9	-4.7
Meuse	18.5	+1.8	+2.9	+1.0	+4.4	+8.0	+3.0
Dommel	20.2	-1.0	+1.9	0.0	+3.9	+7.0	+0.2
Ebro	22.4	-0.4	-3.7	-2.0	-2.3	-5.0	-5.9
Gallego	23.1	-0.2	-4.5	-3.3	-3.4	-4.7	-7.8

Table 3: Mean grid cell DSI3 frequency (as defined in Table 2) across each catchment for the period 1961-1990 (CRU). For each of the RCM simulations the mean frequencies are expressed as deviations from the observed CRU means.

	CRU	**HIR_E**	**HIR_H**	**RCAO_E**	**RCAO_H**	**HAD_P**	**ARP_C**
Brenta	11.6	-3.7	-2.4	-2.9	-0.9	-0.5	-1.6
Eden	7.9	+2.8	+2.0	+1.5	+2.3	+3.2	+1.0
Meuse	8.4	+3.5	+1.0	+3.3	+1.5	+0.8	+1.8
Dommel	8.4	+4.1	+1.4	+3.3	+1.7	+1.5	+0.7
Ebro	10.9	-1.5	+0.1	-2.5	+0.8	-0.8	+0.1
Gallego	10.7	-2.0	+0.1	-2.6	+0.7	+0.1	+0.5

Table 4: As for Table 3 but for DSI6 frequency.