FIRST-ORDER IMPACTS ON WINTER AND SUMMER CROPS ASSESSED WITH VARIOUS HIGH-RESOLUTION CLIMATE MODELS IN THE IBERIAN PENINSULA

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Abstract

The first-order or initial agricultural impacts of climate change in the Iberian Peninsula were evaluated by linking crop simulation models to several high-resolution climate models (RCMs). The RCMs provided the daily weather data for control, and the A2 and B2 IPCC scenarios. All RCMs used boundary conditions from the atmospheric general circulation model (AGCM) HadAM3 while two were also bounded to two other AGCMs. The analyses were standardised to control the sources of variation and uncertainties that were added in the process. Climatic impacts on wheat and maize of climate were derived from the A2 scenario generated by RCMs bounded to HadAM3. Some results derived from B2 scenarios are included for comparisons together with impacts derived from RCMs using different boundary conditions. Crop models were used as impact models and yield was used as an indicator that summarised the effects of climate to quantify initial impacts and differentiate among regions. Comparison among RCMs was made through the choice of different crop management options. All RCM-crop model combinations detected crop failures for winter wheat in the South under control and future scenarios, and projected yield increases for spring wheat in northern and high altitude areas. Although projected impacts differed among RCMs, similar trends emerged for relative yields for some regions. RCM-crop model outputs compared favourably to others using European Re-Analysis data (ERA-15), establishing the feasibility of using direct daily outputs from RCM for impact analysis. Uncertainties were quantified as the standard deviation of the mean obtained for all RCMs in each location and differed greatly between winter (wheat) and summer (maize) seasons, being smaller in the latter.

1. Introduction

The Iberian Peninsula, situated in south-west Europe, is in a transition zone between subtropical dry and mid-latitude temperate climates. Its small size, complex orography and the variety of vegetation types ranging from humid forest to deserts, requires high resolution models for studies on climate variability and change (Castro et al., 1995). The Peninsula supports diverse agricultural systems that extend over a wide thermal range from cool sites above 600 m altitude to warm sites on the Mediterranean coast. It can be expected that these systems will be affected differently by climate change. Changes in rainfall and temperature may either restrict or enhance productivity and crop options. Management practices, such as crop choice and irrigation, will have to be re-assessed on a regional basis for agricultural and hydrological planning.

The utility of crop simulation models linked to high resolution climate models for agricultural impact analysis has been evaluated in areas of complex physiography (Carbone et al., 2003, Mearns, 2003, Mearns et al., 2003), including Spain (Guereña et al., 2001). In the latter study, projections of yield, ET, and vernalisation fulfilment were shown to be scale dependant, revealing the benefit to be gained from the application of high resolution climate models in the Iberian Peninsula. The work presented here further explores the effect of spatial scale on impact analysis (Gates, 1985; Mearns 2003).

The objective of this work, within the PRUDENCE project (Christensen et al., 2002), is to evaluate and compare predictions on initial, i.e. first-order, agricultural impacts (Parson et al., 2003) generated by linking crop simulation models to several high-resolution regional climate models (RCMs). Inter-annual crop yield variability under control and future simulated climate scenarios, and their uncertainties, are evaluated for specific locations by considering all climate projections from RCMs.

2. Methodology

The initial impact of climate change on agriculture is assessed in this study through changes in crop yield resulting from exposure to projected changes in climate simulated by several RCMs. The analysis employed crop simulation models that use daily climate data from RCMs and were linked to a regional soil data base. The grids or cells vary among climate models and so individual maps were built for each climate model. Information was incorporated into a GIS (climate-soil-crop model) to produce maps for a preliminary evaluation.

2.1. CROP MODELS

The CERES wheat and maize models included in DSSAT versions 3.5 (Tsuji et al., 1994) were selected for the analysis. These models have been used previously for climate impact evaluation so their capabilities and limitations are well documented and have been reviewed recently (Tubiello and Ewert, 2002). These models can reflect, under specified assumptions, the effects of temperature change and CO_2 increase on crop photosynthesis and transpiration rates but not on assimilate partitioning.

Wheat and maize were chosen to provide a comparison of contrasting winter and summer cropping systems because the crops have distinct thermal responses and photosynthetic systems and are affected differently by increasing CO_2 (Amthor and Loomis, 1996). To standardise procedures, while maintaining balance between spatial scale and accuracy of the field data, crop model calibration and validation concentrated on the main processes involved at crop and cropping systems level, viz. yield, biomass, phenological development, crop evapotranspiration (ET), and net irrigation requirements. CERES has been calibrated and validated for various field sites across the Iberian Peninsula, (Iglesias and Mínguez, 1995, López-Cedrón et al., 2005, Mariscal, 1993, Quemada et al., 1997, Rebollo, 1993) .

2.2. CLIMATE INPUTS

Daily climate data from one high resolution AGCM (HadAM3H, Hadley Centre, United Kingdom) and various RCMs were used to provide inputs for the crop models (Table 1). Control simulations corresponded to the period 1961-1990 while two future scenarios for 2071-2100 corresponded to the A2 and B2 IPCC CO_2 emission scenarios (SRES A2 and B2) (IPCC, 2001). A2 and B2 scenarios correspond respectively to high (635 to 856 ppm CO_2 from 2070 to 2100) and relatively low (531 to 621 ppm) future greenhouse gas emissions (Nakicenovic et al., 2000). RCMs were run using boundary conditions mainly from HadAM3H and were: HIRHAM, PROMES, RegCM, ARPEGE, CHRM, CLM, RCAO, REMO, RACMO, KNMI, and HadRM3H. In addition, ARPÈGE was alternatively driven by ARPÈGE/OPA (SRES B2) and RCAO by ECHAM/OPYC4 (SRES A2 and B2). ACGMs and RCMs are described extensively in this issue of Climatic Change. The RCMs have a 50 km x 50 km resolution and can differentiate among altitude areas in the Peninsula (*Figure 1*).

The performance of the RCM-crop model was also recorded using the European Re-Analysis data for years 1979-1993 (ERA-15, Gibson et al., 1999), corrected for the elevation of each site. The outputs (yields) are shown to provide a reference for control climate RCM-crop model outputs.

2.3. SOIL DATA BASE AND LINKAGE TO REGIONAL CLIMATE OUTPUTS

A soil data base was constructed from the literature and CIEMAT (Trueba et al., 2000) to contain the means and standard deviations of soil properties by profile layers for 34 different soil groups. Soil organic matter was set to 1.2 % for soils under Xeric and Aridic moisture regimes and to 1.5% for the remainder.

Weather files from each RCM cell were reorganized to provide individual files of all weather variables for each combination of year and soil type. The data were extended from 360 days to actual years (365 or 366 days) by adding an extra day to various months. The climate variables for the additional days were estimated as means of the previous and following days while precipitation was set to 0 mm.

3. Patterns from direct outputs

Grain yield or biomass generated by the crop models condense the responses of crops to climate change into one numerical value (kg/ha). Crop biomass accumulates from daily intercepted solar radiation that determines potential growth that is then modulated for the effects of CO_2 concentration, temperature, and water availability. It is a broad indicator for canopy photosynthesis, closely related to water use or water availability of the crop under rain-fed conditions, and along with crop evapotranspiration (ET), can be used to determine water requirements for irrigation. Yield, in contrast, is a further consequence of biomass partitioning and is the key agronomic indicator for economic analysis and land use planning.

By choosing crops with growing periods that cover different seasons, i.e. maize centred in summer, and wheat in winter, it is possible to provide an overview of the trends of climate change impacts and help focus on a range of short-term adaptation strategies for the study of second-order impacts (Parson et al., 2003). Furthermore, by selecting species, cultivars, and management we could test climate models and modify uncertainties. In Table 1 we summarise the experiments and identify the main objectives of the simulations that are presented below.

3.1. HadAM3H BOUNDARY CONDITIONS

3.1.1. *Testing RCMs with management: winter vs spring wheat*

Winter and spring wheats have similar growth and development characteristics except for their response to low temperature. Whereas winter wheats require exposure to low but above freezing temperatures to proceed to flowering, spring wheats do not. Winter wheats are thus suited to autumn sowing in environments where the winter is not too cold for survival. Spring wheats, by contrast, are suited to spring sowing in sites with extremely cold winters but also to autumn sowing in locations with moderately cold winters. This contrast in temperature response provides an agriculturally significant option for analysis of climatic impact on crop production. The cold requirement is included in the CERES model through a scalar coefficient (PV1 = 6; for PV1, see definition in Ritchie and Otter, (1985)) . RCMs using boundary data conditions from HadAM3H were linked to CERES-winter wheat model to confirm, as currently occurs, that crop failure could be detected in southern regions under control climate. The responses (Figure 2 a,b,c,d,) show the relative changes in yield for A2/control scenarios of a mid-autumn sown winter wheat, cv. (cultivated variety) Marius, grown under rainfed conditions. The CERES combinations with REMO and RegCM represent two examples from within the range for which PROMES-CERES and HIRHAM-CERES present the extreme relative variations.

The analysis reveals yield failure of winter wheat in southern regions that is more frequent under future predicted climates than under control climate (*Figure 2,* below the lower line). In central and northern regions results differed among models but major trends could be found. Yield decreases in the central Plateau (circled) reflect inadequate cold requirement and consequently smaller yields in a greater number of years under future climate, an effect that is more pronounced in some RCMs.

In northern regions (*Figure 2*, above the upper line) results differ most among the RCM-crop model combinations. In this orographically complex area, where cropping extends along river valleys that reach 800 m elevation, and plateau areas around 600 m, yield decreases can be linked to low elevation areas and increases to higher elevation. Impact patterns arise as shown in *Figure 2*, with overall yield decreasing most with HIRHAM and least with PROMES.

All RCMs with HadAM3H boundary conditions correctly describe the failure to flower and yield for control climate in the south, and present a gradient in response for the Central Plateau and the North. Also, different results are found within land grids, as a function of soil type. Note that in constructing the map legend, zero change encompasses the range 90-110% of relative yield and that nearby regions with sequential colours may have close relative yields. Other intervals produced results that matched those presented here.

In the Iberian Peninsula, spring wheats are usually sown in autumn to benefit from autumn and winter rainfall, while relying on variable spring rainfall and stored soil water for grain filling. Spring wheat cultivars can thus be cultivated in all regions. The response of the spring cv. Anza shows that current winter temperatures limit crop growth, mainly in northern regions, and that yields could increase in future climate as shown for the relative yield maps, for A2/control and rainfed conditions (*Figure 3*). Similar positive signals are found for all RCMS nested in HadAM3H. The same four RCM-crop combinations as in *Figure 2* show the impact gradient found, PROMES (*Figure 3c*) presenting the largest relative yields and HIRHAM (*Figure 3d*) the smallest (central and south-eastern regions of the Peninsula). Large increases should be taken as a clear signal of improved conditions for the growth of spring wheat that can be linked to milder winter temperatures, and also to the direct effect of CO_2. The former implies a more efficient water use by crops able to grow more during winter when vapour pressure deficit is smaller. The latter effect of CO_2 increase is common to all RCMs-crop model combinations and will not be discussed here.

3.1.2. *Testing RCMs with management: wheat irrigation*

Crop failure persists with irrigated winter wheat supporting the proposition that these RCMs capture the current winter temperature regime in these regions (*Figure 2 e*) and thereby improve simulations previously made with AOGMS (Guereña et al., 2001). Crop failures were not detected in recent work with GCMs from the Hadley Centre (Flato et al., 1997, Johns et al., 1997) or from the Canadian Centre (Flato et al., 1997), when linked to CERES-winter wheat for the southern Iberian Peninsula (Iglesias et al., 2000).

Winter wheat yields are maintained around 90-130 % in most regions in contrast with rainfed conditions and point to the importance of the changes in rainfall and the complexity of the combined effects of temperature and CO_2 increases. Other RCMs also presented these trends with little variation among the regions.

Irrigated spring wheat (*Figure 3 e*) also presents for RegCM a stabilisation of relative yields around 90-130 %. These results show the need to analyse the possibility that strategic (few) irrigations would be economically viable, were water available.

3.2. DIFFERENT BOUNDARY CONDITIONS OF RCMs

Two RCM models that used boundary conditions from a different AGCM to HadAM3 provided daily data for direct input to the crop models. Maps for the relative yield of winter wheat for A2/control scenarios for RCAO nested in HadAM3H and ECHAM/OPYC4 are presented (*Figure 4 a,b*). Both detect crop failures in the South and the regional distribution of results is similar to those shown for HadAM3H-RCMs. ECHAM/OPYC4-RCAO projects a greater negative impact in the southern and central areas, and relative yields are systematically smaller. *Figure 4 c,d* compares projections from HadAM3H-ARPEGE vs ARPEGE/OPYC4-ARPEGE for absolute yield of spring wheat under a B2 scenario and under rainfed conditions. The regional distribution is similar and the same pattern of impact arises although smaller yields are projected by ARPÈGE/OPA-ARPÈGE (b). In the North, both simulations point to similar yields.

4. Climate variability and uncertainties through crop outputs

Climate variability can be expressed through the coefficient of variation or the standard deviation (SD) of mean yield, obtained from each 30-year period. Variability and uncertainties were studied both for winter and for summer crops and some examples are presented here.

4.1 WINTER CROPS

Yield of spring wheat for Albacete (Castilla La Mancha) (location 4 in *Figure 1*) is shown in *Figure 5* for ten RCMs (1 to 3 and 5 to 11 in the figure) and HadAM3H (4), for control, A2 and B2 SRES, and ERA-15. Smaller values correspond to rainfed and larger to irrigated crops. Yield obtained with ERA-15 weather on the same average soil type is represented by a line to allow comparison with each RCM-crop model yield. Inter-annual variability of the RCM-crop model combinations shadows the statistically significant increase in mean yield found in most RCM, for A2-yield and B2-yield. In this location, yields were not significantly different for HIRHAM (6) with rainfed wheat, and for HadRM3H (5), RACMO (9) and PROMES (10) with irrigated wheat. These responses would not necessarily be maintained in other locations.

Uncertainty is quantified for control, A2 and B2 scenarios by the standard deviation of mean yield obtained from all RCMs for each location and scenario (*Figure 6a, b*). The 12 individual locations correspond to agricultural areas differing in elevation, temperature regime, annual precipitation and its distribution, and are shown in *Figure 1*. In most locations there is an increase in yield of rainfed spring wheat (*Figure 6b*), either under B2 or A2 SRES, but overall uncertainties are large for winter-grown crops. Yield is greater in northern areas with greater altitude (locations 7, 10 and 11) but decreases, or is unchanged, in warm locations in the South (1), South East (3), or coastal areas in the North (12) for A2 SRES. In this case, B2 SRES presents better growing conditions.

Irrigation of spring wheat (*Figure 6*) was simulated in order to check for decrease in uncertainties linked to the direct use of daily rainfall outputs from the RCMs. This was not the case and, as in the rainfed simulations, the smallest SD were found in locations that correspond to the Central Plateaux, and the largest to North (10), Northwest (11, 12) and Southern areas (1, 2), all in complex orographical areas or near the coast.

4.2 SUMMER CROP

Decreases in yield of irrigated maize are significant and inter-annual variability is smaller (results not shown) across most locations and RCMs. The ERA-15-crop model simulations are consistent with control yields. Uncertainties are also substantially smaller than for winter-grown crops *(Figure 7)*. Yield decreases from control, to B2 and is smallest in A2 SRES, except for the colder areas (10, 11 and 12) where B2-yields are greater. Supra-optimal temperatures affect crop duration and growth in all locations. The analysis reveals that the predictions of most RCMs coincide in summer when temperatures are currently high and effective precipitation, i.e. that leads to water accumulation in the soil, is smallest or zero.

5. Discussion and conclusions

A methodology that combines crop simulation models with RCMs has enabled us to systematically analyse the impacts of climate change on aspects of agricultural production across the Iberian Peninsula. The typification of soils and crops, and selection of indicators, was the preliminary steps. The inclusion of observed soil profiles remains an aim, but soil variability (depth and texture) within agricultural areas, and certainly in individual paddocks, cannot be dealt at the present scale of resolution. The use of standardised crop cultivars that evaluate seasonal impacts has proven useful. In the Iberian Peninsula, as well as in other Mediterranean countries, there are large differences in rainfall and temperature between summer and winter that require different cropping management, especially where water is available for irrigation. Farmers and agricultural agencies base their planning on these two contrasting seasons. Finally, the use here of yield as an indicator, that integrates the seasonal effects of climate variables, can be complemented by others, such as biomass, evapotranspiration, and irrigation requirements.

The objective here was to connect RCMs directly to crop models. The use of eleven RCMs has clearly shown the limitations of single RCM (and GCM) impact analyses. The results obtained for fifteen years of ERA-15 climate scenarios that are not significantly different to yields in most areas and for most RCM-crop model combinations (e.g. *Figure 5, 6 and 7*) support this methodology. Specific comparisons within regions and between model combinations to establish the reasons for differences with ERA-15 derived outputs should be the aim of further research.

This study has enabled us to discriminate among closely situated regions and between soils in the same land grid. We have identified regions where projections differed among RCM-crop model combinations, although they are nested in the same AGCM. Nevertheless, in other regions, impacts could be established through either coincident projections among the majority of RCM-crop models, or similarity of the trends in changes in relative yield. In the latter case, yield increases, e.g. over 150 % for A2/control, can be taken as a signal of a positive effect of climate change. The quantification of uncertainties has allowed us to further check these results. This modelling exercise with more than ten RCMs suggests that in Southern Europe, there are areas above 600 m asl where a positive effect is likely for autumn-sown crops.

In the process of impact assessment, new uncertainties have been added, both derived from the simulation models *per se*, and from their extrapolation to a domain wider than where they were calibrated and validated (Gabrielle et al., 2002, Passioura, 1996). Uncertainties relate to soil information, water balance and water stress impact. The direct effect of CO_2 on plants is incorporated in the crop models through an increase on the photosynthetic rate and a decrease in transpiration that increases water use efficiency. Although the nature of the CO_2 effect on plants is still being discussed and magnitudes questioned (Gonzalez-Maler et al., 2004), evidence of increased water use efficiency continues to accumulate, e.g. (Tubiello et al., 1999) (Triggs et al., 2004).

We propose that crop management can change the level of uncertainty, enhancing the differences among the RCMs in temperature projections. Irrigation of winter crops was used to change the level uncertainty linked to rainfall simulation by RCMs (we do not imply that crop should be irrigated) and soil information. It is important to highlight the different level of uncertainties that exist between the winter (representing autumn, winter and spring environments) and the summer crops.

Finally, the use of various RCMs linked to more than one AGCM has raised questions about the validity of single AGCM-RCM-crop assessments. Here, different boundary conditions for the RCMs have produced different results, shown especially by ARPÈGE and RCAO. Further exploration with other AGCM boundary conditions is also required for impact assessment.

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Table 1. Regional climate models (RCM) driven by global circulation models (GCM) and various emissions scenarios used with the crop model CERES for impact analysis on wheat and maize yield together with details and objectives of the experiments.

<table>
<tr><th>GCM</th><th>IPCC
SRES</th><th>RCM *</th><th>Crop/management</th><th>Objectives or tests</th></tr>
<tr><td rowspan="2">HadAM3H</td><td>A2</td><td>HIRHAM
PROMES
RegCM
ARPEGE
CHRM
CLM
RCAO
REMO
RACMO
HadRM3H</td><td rowspan="2"><u>Winter crops</u>

Winter wheat
Rainfed
Irrigated
Spring wheat
Rainfed
Irrigated

<u>Summer crop</u>

Maize Irrigated</td><td rowspan="2">- Cold requirements
- Cold requirements without rainfall-linked uncertainties
- Impact on high elevation areas
- Impact without rainfall-linked uncertainties
- Effect on summer crop and uncertainties in comparison with autumn sown crops</td></tr>
<tr><td>B2</td><td>PROMES
RegCM</td></tr>
<tr><td>ECHAM/
OPYC4</td><td>A2</td><td>RCAO</td><td>Winter wheat
Spring wheat
Maize</td><td>Comparison with HadAM3H-RCAO</td></tr>
<tr><td>ECHAM/
OPYC4</td><td>B2</td><td>RCAO</td><td>Winter wheat
Spring wheat
Maize</td><td>Comparison with HadAM3H-RCAO</td></tr>
<tr><td>ARPÈGE/
OPA</td><td>B2</td><td>ARPÈGE</td><td>Winter wheat
Spring wheat
Maize</td><td>Comparison with HadAM3H-ARPEGE</td></tr>
</table>

(*) see Christensen, J.H., Christensen, O.B., and al. 2006

FIGURE CAPTIONS

Figure 1. (a) Elevation map of the Iberian Peninsula with the PROMES grid. The agricultural regions considered are under 800 m asl. Specified locations correspond to the provinces: 1, 2 Córdoba; 3, Murcia; 4, Albacete; 5, Badajoz; 6, Madrid; 7, 8: León; 9, Zaragoza; 10; Navarra; 11; Lugo; 12, La Coruña. (b) 50 km x 50 km land grid for impact studies derived from HIRHAM and PROMES (vertical grids) over a soil map in Central Spain.

Figure 2. Relative yield of rainfed winter wheat obtained from A2/control scenarios with HadAM3H boundary conditions from (a) REMO, (b) RegCM, (c) PROMES, (d) HIRHAM, and (e) for irrigated winter wheat RegCM.

Figure 3. Relative yield of rainfed spring wheat from A2/control scenarios with HadAM3H boundary conditions from (a) REMO, (b) RegCM, (c) PROMES, (d) HIRHAM and (e) for irrigated spring wheat RegCM.

Figure 4. Relative yield of rainfed winter wheat from RCAO using boundary conditions from HadAM3H (a) and ECHAM/OPYC4 (b). Absolute yield of rainfed spring wheat obtained in B2 SRES with ARPÈGE driven by HadAM3H (c) and by ARPÈGE/OPA (d).

Figure 5. Mean yield of spring wheat in Albacete, simulated under control, A2 and B2 (only RegCM and PROMES) scenarios from 1, ARPEGE; 2, ETH; 3, GKSS; 4, HadAM3H; 5, HadRM3H; 6, HIRHAM; 7, RegCM; 8, RACMO; 9, REMO; 10, PROMES and 11, RCAO (only A2). Standard deviation is shown by one-sided bars. Smaller yields correspond to rainfed (RSW) and larger to irrigated (ISW) wheat. Significant differences were found for all

RCMs except for HIRHAM and HadAM3H between control and A2 SRES. Average yields derived from ERA-15 data are presented with a solid line and SD with a dotted line.

Figure 6. Uncertainties expressed as standard deviation of the mean yield of rainfed (RSW) and irrigated spring wheat (ISW) for control (a) and future climate scenarios A2 and B2 (b), obtained in each location (see *Figure 1*) by all RCMs driven by HadAM3H boundary conditions. ERA-15 driven yields are also included in (a). Locations: 1 and 2, Córdoba (two soil types); 3, Murcia; 4, Albacete; 5, Badajoz; 6, Madrid; 7 and 8 León (two soil types); 9; Zaragoza; 10, Navarra; 11, Lugo and 12, Coruña.

Figure 7. Uncertainties expressed as standard deviation of the mean yield of irrigated maize obtained in each location (see *Figure 1*) by all RCMs driven by HadAM3H boundary conditions. ERA-15 driven yields are also included. Locations: 1 and 2, Córdoba (two soil types); 3, Murcia; 4, Albacete; 5, Badajoz; 6, Madrid; 7 and 8 Valladolid (two soil types); 9, Zaragoza; 10, Navarra; 11, Lugo and 12, Coruña.