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Development and Climate Change

BACKGROUND NOTE

CLIMATE CHANGE IMPACTS ON AGRICULTURAL YIELDS

by

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Background note to the World Development Report 2010

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Methods

We employed the LPJmL model (Bondeau et al., 2007) to compute the effects of climate change and CO_2 fertilization on yields of major crops globally at a spatial resolution of 0.5°x0.5°. Yield simulations are based on process-based implementations of gross primary production, growth- and maintenance respiration, water-stress, and biomass allocation, dynamically computing the most suitable crop variety and growing period in each grid cell as described in more detail by Bondeau et al. (2007) and Fader et al. (under review).

We present percent changes in agricultural productivity between two 10-year periods: 1996-2005 and 2046-2055, representing the average productivity of the years 2000 and 2050. Management intensity has been calibrated to match national yield levels as reported by FAOSTAT[1] for the 1990s (Fader et al., under review). National and regional agricultural productivities are based on calorie- and area-weighted mean crop productivity of wheat, rice, maize, millet, field pea, sugar beet, sweet potato, soybean, groundnut, sunflower, and rapeseed. The spatial pattern of growing areas and the crop-specific share of irrigated area is based on Portmann et al. (submitted; 2008), Ramankutty et al. (2008) for the year 2000, see Fader et al. (under review).

Future development of crop yields are subject to several uncertainties: (a) changes in climate (Solomon et al., 2007), (b) changes in atmospheric CO_2 concentrations and the subsequent impact on crop water use efficiency and CO_2 fertilization (Long et al., 2006; Tubiello et al., 2007), (c) changes in management/breeding, and (d) changes in cropping area. Here, we account for the first two drivers only: climate change and CO_2 fertilization by employing different scenarios.

We computed 30 different scenarios from 1950 to 2055 for 3 different emission scenarios (SRES A1b, A2, B1) (Nakicenovic and Swart, 2000), each implemented by 5 different general circulation models (GCM): CCSM3 (Collins et al., 2006), ECHAM5 (Jungclaus et al., 2006), ECHO-G (Min et al., 2005), GFDL (Delworth et al., 2006), and HadCM3 (Cox et al., 1999). Climate data for these GCM-projections were generated by downscaling the change rates of monthly mean temperatures and monthly precipitation to 0.5° resolution by bi-linear interpolation and superimposing these monthly climate anomalies (absolute for temperature, relative for precipitation and cloudiness) on the 1961–1990 average of the observed climate (New et al., 2000; Österle et al., 2003). Since there was no information about the number of wet days in the future, these were kept constant after 2003 at the 30-year average of 1971–2000.

[1] http://faostat.fao.org/default.aspx

To assess the range of CO_2 fertilization uncertainty (e.g. Long et al., 2006; Tubiello et al., 2007), we computed each of the 15 scenarios twice: first, taking into account full CO_2 fertilization effects according to the prescribed SRES atmospheric CO_2 concentrations, and second, keeping atmospheric CO_2 concentrations constant at 370 ppm after 2000. Production area was static at the prescribed year-2000 pattern. Relative management levels were calibrated to match observed current production levels as described by Fader et al. (under review) but sowing dates were assumed to be adapted to climate change as described by Bondeau et al. (2007) and for wheat, maize, sunflower, and rapeseed we assume also adaption in selecting suitable varieties. Modelling constraints don't allow for adapting varieties for all other crops here. However, we do not account for the uncertainty in management changes as we here consider one setting only.

Population growth projections were taken from Nakicenovic and Swart (2000) to assess the impact of changes in crop yields and in population size on food self-sufficiency.

Results

Data on changes in crop yields are presented as country- and region-specific percent change rates. The overall changes in crop yields on current crop land (in percent relative to 1996-2005) are shown in Figure 2.2.1. Impacts on yields are shown in relation to projected changes in population (Nakicenovic and Swart, 2000) and the resulting impact on regional self-sufficiency rates. In 7 out of 10 world regions, the mean impact indicates rising crop yields in 2046-2055 compared to 1996-2005.

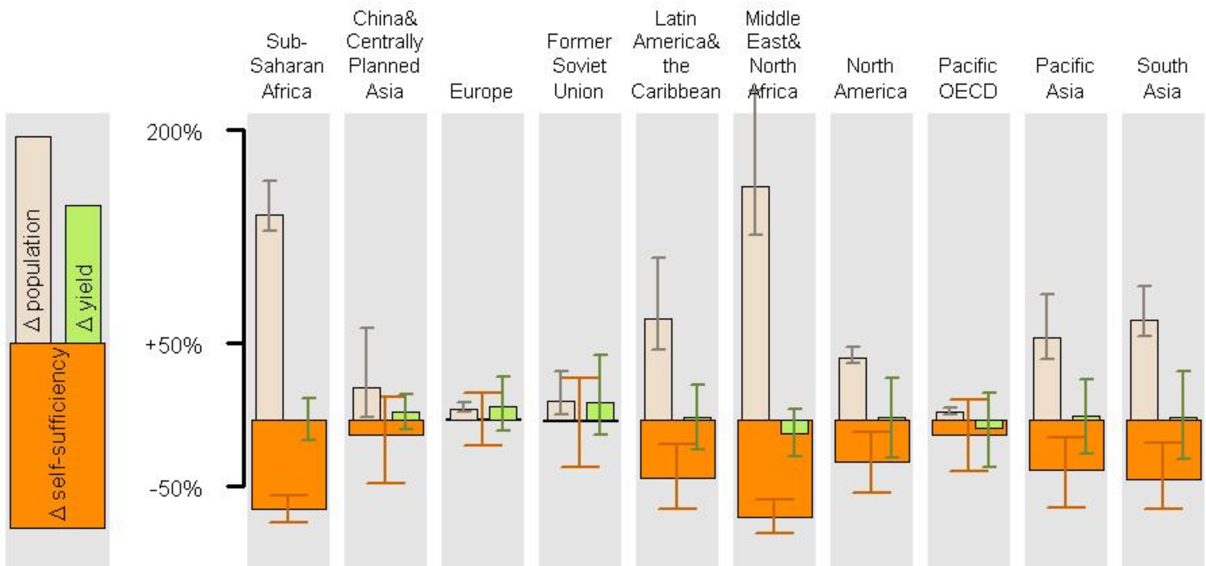

Figure 2.2.1: Mean change in crop yields (green bars) from 1996-2005 to 2046-2055 in all 30 scenarios considered here. Whiskers indicate the range of impacts, which is mainly determined by the effectiveness of CO_2 fertilization. Tan-coloured bars indicated projected changes in population (Nakicenovic and Swart, 2000). Most regions are likely to experience significant decreases in self-sufficiency, because population growth often offsets even increasing crop yields.

However, depending on climate scenario and the assumptions on effectiveness of CO_2 fertilization, all regions may experience significant decreases in crop yields as well as significant increases. The most important factor is the uncertainty in CO_2 fertilization, which outweighs the differences in climate scenarios. Figure 2.2.2 depicts the difference between changes in crop yields with (left hand panel) and without (right hand panel) CO_2 fertilization effects, aggregated at national level and sub-national level for larger countries (Australia, Brazil, Canada, China, India, Russia, USA). Whether or not farmers will be able to attain increased crop yields under elevated atmospheric CO_2 concentrations will much depend on the availability of additional inputs, especially nitrogen (Tubiello and Ewert, 2002). In regions where current inputs are already constraining crop yields considerably (Neumann et al., under review), major improvements are required to provide additional nitrogen inputs. Self-sufficiency in food production is likely to decrease in most regions as in many cases population growth outweighs even increasing crop yields. As a consequence, even the most optimistic scenarios with increasing crop yields on current crop land cannot mitigate the significant decrease in food self-sufficiency in 6 out of 10 regions (Figure 2.2.1).

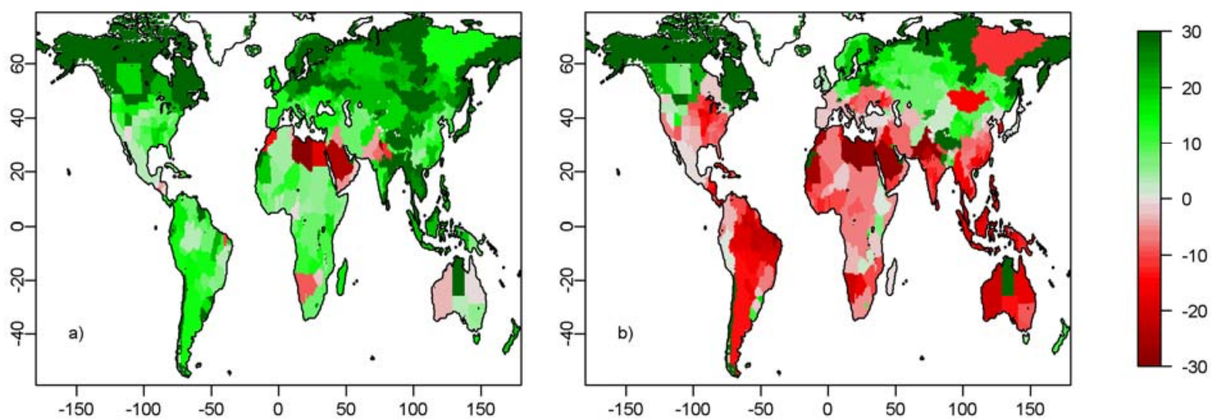

Figure 2.2.2: All climate scenario mean (3 emission scenarios in 5 GCMs) impact on (sub-) national crop yields in 2050 (2046-2055 average), expressed in percent change relative to 2000 (1996-2005 average). Panel a) with full CO_2 fertilization, panel b) without.

Increasing crop yields may be expected in regions currently constrained by too low temperatures as in the northern high latitudes and in mountainous regions (Figure 2.2.3, green areas in panel b). Here, all 30 model runs uniformly indicate increases in crop yields by 2050. On the contrary, there is hardly any location where all model runs uniformly indicate decreases in crop yields (Figure 2.2.3, red areas in panel a). If all effects of CO_2 fertilization are excluded, many regions and especially tropical croplands are uniformly projected in all 15 climate scenarios to experience decreases in crop yields (Figure 2.2.3, panel b).

Table 2.2.1 provides an overview of the regional climate change and CO_2 fertilization impacts on crop yields. It has to be noted that the beneficial effects of CO_2 fertilization are subject to heavy debate (Long et al., 2006; Tubiello et al., 2007) and that current management constraints cast considerable doubt on obtaining full CO_2 fertilization benefits in many regions.

The spatial patterns of climate change as well as the overall strength of climate change differ between GCM implementations of the three SRES emission scenarios. Figure 2.2.4 depicts the variation of changes in crop yields between the different climate scenarios, expressed as the standard deviation [%]. The patterns are very similar with and without CO_2 fertilization, because the differences in the spatial climate change patterns between GCMs are the main causes for differences in local/national crop yield impact projections. Some differences in precipitation patterns are less effective under increased atmospheric CO_2 concentrations, because crop water-use efficiency is increased under elevated atmospheric CO_2 concentrations.

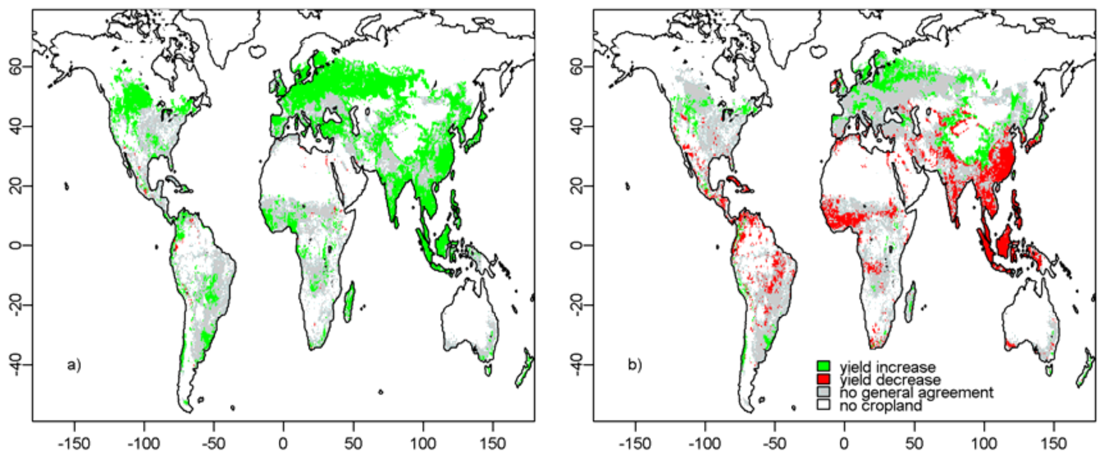

Figure 2.2.3: Multi-scenario agreement on the direction of changes in yields. Panel a) shows the overall agreement in all scenarios with CO_2 fertilization, while panel b) shows the overall agreement in all scenarios without CO_2 fertilization. The general agreement in all 30 scenarios can be deduced from these to figures: if there is agreement on yield increase without CO_2 fertilization, this is also true with CO_2 fertilization (green areas in panel b) and if there is agreement on yield decreases with CO_2 fertilization, this is also true without CO_2 fertilization (red areas in panel a).

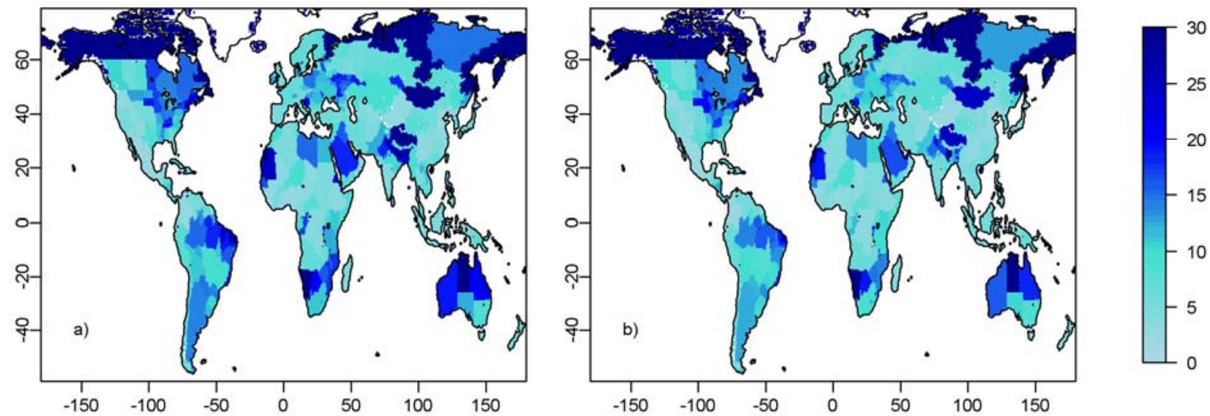

Figure 2.2.4: Standard deviation of changes in (sub-)national crop yields [%] in all 15 climate scenarios. The patterns are very similar with (panel a) and without (panel b) CO_2 fertilization, because the differences in the spatial climate change patterns between the different GCMs are the main causes for differences in local/national crop yield impact projections.

Table 2.2.2 at the end of this chapter shows that there are strong regional differences between the different GCMs. The region of MEA for example is projected to experience decreases in crop yields in 4 out of 5 GCMs under the A1b emission scenario, even with full CO_2 fertilization effects. The climate scenario of the GFDL model, however, causes a yield increase of 7.8%, which offsets the projected decreases in the other 4 cases, resulting in little change in the multi-GCM mean (-3.0%, Table 2.1.1). Differences in projected crop yields vary strongly between GCM climate projections, ranging on average between 3.2% in CPA and 24.2% in NAM. The largest range between different GCM projections is computed for the region of NAM, where crop yields are projected to increase by 26.7% (CCSM) or decrease by 3.4% (HADCM) under the A1b scenario with CO_2 fertilization effects.

While CO_2 fertilization effects dominate the impact on crop yields at regional and global scale, differences in climate projections often have larger influence on changes in crop yields at national and sub-national scales. This is especially true for countries in regions where climate projections between GCMs differ most strongly: AFR, LAM, MEA, and also in parts of PAO (Australia and New Zealand, but not Japan).

Table 2.2.1: Regional 5-GCM-mean climate change and CO_2 fertilization impacts on crop yields (percent change in 2046-2055 relative to 1996-2005) on current (2000) crop land.

	full CO_2 fertilization				no CO_2 fertilization			
	A1b	A2	B1	mean	A1b	A2	B1	mean
AFR	8.4	7.8	6.8	7.5	-8.2	-8.5	-5.9	-7.6
CPA	15.8	15.4	11.8	14.3	-3.6	-3.7	-2.9	-3.4
EUR	17.5	16.7	16.7	16.8	0.8	-0.3	3.7	1.2
FSU	21.4	22.3	21.4	21.4	-0.5	-0.2	4.3	0.9
LAM	9.5	12.2	13.3	11.8	-11.3	-9.4	-3.7	-8.2
MEA	-3.0	-0.7	-2.5	-2.1	-16.6	-14.5	-13.2	-14.8
NAM	10.6	11.6	14.7	12.2	-10.3	-9.3	-1.8	-7.1
PAO	3.3	3.6	4.6	3.5	-15.0	-14.7	-9.8	-13.5
PAS	22.8	23.0	19.9	21.9	-18.5	-18.0	-11.7	-16.0
SAS	21.3	24.6	14.6	19.8	-18.9	-15.3	-14.4	-16.4
World	12.4	13.1	12.5	12.6	-8.2	-7.6	-3.5	-6.5

Discussion

There is considerable uncertainty in the future development of crop yields on current cropland, ranging from a general decrease by 13% to a general increase by 22% in 2050 relative to 2000. The largest uncertainty is the effect of CO_2 fertilization, which principally can increase crop yields considerably due to enhanced carbon assimilation rates as well as improved water-use efficiency (Tubiello et al., 2007). However, to which extent this yield increase will be obtained by farmers is highly uncertain: First of all, increased carbon assimilation rates can only be converted into productive plant tissue or the only economically relevant part, the harvested storage organs, if sufficient nutrients are available to sustain the additional growth. Wherever growth is already constrained by nutrient limitations, additional growth will be very limited. On top of that, there is some likelihood that the quality of agricultural products decreases under increased CO_2 fertilization, as e.g. the protein content diminishes (e.g. Taub et al., 2008) and that crops grown under elevated CO_2 concentrations are more susceptible to insect pests (e.g. Dermody et al., 2008; Zavala et al., 2008).

At global or regional scale, the CO_2 fertilization effect determines the sign of yield changes. If CO_2 fertilization is fully accounted for, crop yields rise globally by 8-22% in 2050 relative to 2000, while all regions experience a decrease in crop yields (0-13%), if CO_2 fertilization is not taken into account. At national and sub-national scale, however, differences in climate projections often have larger influence on changes in crop yields than the CO_2 fertilization effect. This is especially true for countries in MEA and also in AFR, LAM, EUR and FSU. The selection of climate projections is therefore a major source of uncertainty for the assessment of national and sub-national climate change impacts on crop yields. However, it is not possible to identify a "most likely" climate change pattern. It is possible – to some extent – to identify hot spot regions of climate change impacts on yields, as e.g. in Figure 2.2.3.

Results presented here only indicate the scope of climate-related impacts on crop yields. Besides uncertainties in future development of drivers (climate change, CO_2 fertilization effect, management, technological change), modeling of crop yields at large scales adds to the overall uncertainty as many processes are necessarily implemented in a simplified manner only. If farmers have access to a broad selection of crop varieties, they are likely to select varieties most suited for the local growing conditions. That means that farmers will adapt to climate change and altered growing periods, if possible (e.g. Reidsma et al., 2009). The model LPJmL considers such adaptation processes in management only to a limited extent. While the sowing date is based on the last 20 years of experience and therefore adapts to changing climate conditions, crop varieties are only adapted for wheat, maize, sunflower, and rapeseed, for which the model internally computes the most suitable variety (Bondeau et al., 2007). For all other crops considered here, this is currently not possible as parameters are lacking.

The selection of different crop varieties yields the potential to greatly affect yields. Our simulations show that winter wheat varieties become suitable in more northern locations as temperatures rise. Winter varieties are typically higher-yielding varieties so that yield levels rise considerably with the switch from summer to winter varieties. This switch can be observed for wheat in north-east Europe, southern Canada, and mountainous regions, as shown in Figure 2.2.5.

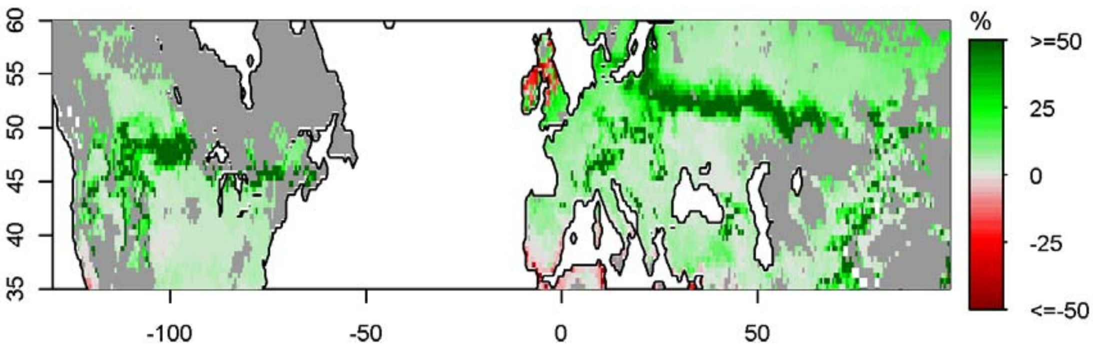

Figure 2.2.5: All scenario mean yield changes for wheat. Strongest yield increases occur in all scenarios where rising temperatures lead to a shift from summer to winter varieties.

Even the most optimistic scenarios lead to decreasing food self-sufficiency ratios in most regions (Figure 2.2.1) at current consumption patterns and technology levels. Improved management and technological change, as well as an expansion of agricultural land are thus inevitable to meet future food demand.

Conclusions

Projections of future crop yields are highly uncertain. At global to regional scale, CO_2 fertilization has the potential to generally increase crop yields on current crop land. However, it is highly unlikely that yield increases due to CO_2 fertilization will be fully achieved in most regions, as long term positive effects are subject to scientific debate and increased yield levels require also adaptations in management (Long et al., 2006; Tubiello and Ewert, 2002; Tubiello et al., 2007). Differences in climate patterns are a major source of uncertainty in local and national yield projections, as especially precipitation patterns differ considerably between GCMs. The range of modeled impacts on yields therefore is only an indication on the locations' susceptibility to climate change and for the necessity of adaptation measures. Future food demand will only be met if improved management and technological change will be able to increase crop yields considerably or if agricultural land is expanded. Even the most optimistic projections on future crop yields lead to decreasing food self-sufficiency ratios in most regions.

Table 2.2.2: Detailed regional percent crop yield changes in 2050 relative to 2000.

CO_2	SRES	MODEL	AFR	CPA	EUR	FSU	LAM	MEA	NAM	PAO	PAS	SAS
Full CO_2 fertilization	A1b	CCSM	14,8	28,1	25,3	27,0	10,5	-4,5	29,0	-11,6	14,5	13,9
		ECHAM	6,5	21,3	14,3	21,6	3,5	-1,0	12,1	34,7	13,8	30,6
		ECHO-G	6,9	24,7	20,2	34,6	10,3	-3,4	18,6	14,5	13,0	22,2
		GFDL	16,4	23,4	19,3	25,8	-6,4	10,4	3,6	9,1	14,9	9,3
		HADCM	4,7	20,5	10,4	15,1	-0,3	-4,4	-2,9	6,2	13,8	29,8
	A2	CCSM	14,5	28,7	28,3	50,0	7,7	-0,1	26,6	5,9	15,8	17,5
		ECHAM	3,6	15,9	10,4	20,6	2,7	1,5	20,6	-3,1	9,7	21,8
		ECHO-G	11,4	23,4	15,5	27,4	12,3	2,0	17,6	12,6	14,7	23,6
		GFDL	11,9	24,4	19,8	20,8	12,4	6,9	1,1	21,6	14,9	23,5
		HADCM	8,2	22,4	11,7	20,5	-1,5	-0,5	7,5	0,9	15,9	28,3
	B1	CCSM	12,6	16,7	16,7	28,3	10,1	7,5	27,7	2,2	14,4	5,7
		ECHAM	5,6	17,2	20,0	24,6	6,3	4,1	18,1	14,9	9,2	11,8
		ECHO-G	5,9	15,9	16,0	16,2	9,1	-10,7	10,1	5,7	13,3	17,5
		GFDL	15,3	15,9	20,6	29,7	18,5	1,6	15,9	23,8	10,9	18,1
		HADCM	3,2	13,8	12,6	21,3	-0,1	-4,7	10,0	7,3	12,0	18,2
No CO_2 fertilization	A1b	CCSM	-2,6	1,2	5,1	-3,9	-5,3	-21,1	3,0	-30,4	-10,7	-18,4
		ECHAM	-10,7	-4,8	-4,7	-7,0	-10,5	-17,1	-11,3	7,3	-10,6	-7,9
		ECHO-G	-10,3	-2,1	1,5	3,1	-3,8	-19,3	-6,5	-9,4	-11,5	-13,2
		GFDL	-4,8	-2,7	0,7	-2,9	-21,7	-7,7	-22,0	-12,2	-13,8	-21,9
		HADCM	-13,0	-6,5	-8,5	-13,6	-14,4	-20,2	-26,9	-16,8	-10,8	-7,9
	A2	CCSM	-3,1	1,0	7,2	13,9	-8,0	-17,1	0,2	-16,8	-9,6	-16,6
		ECHAM	-13,1	-8,0	-8,4	-7,3	-11,2	-15,0	-4,2	-23,1	-15,0	-13,7
		ECHO-G	-6,3	-3,3	-4,2	-4,4	-2,2	-14,9	-8,3	-10,4	-9,9	-11,3
		GFDL	-7,9	-1,5	1,0	-8,0	-4,7	-11,0	-23,3	-2,6	-12,5	-10,7
		HADCM	-9,5	-4,5	-6,9	-9,2	-16,6	-17,3	-18,2	-20,1	-9,1	-9,9
	B1	CCSM	-1,0	-2,8	1,3	3,8	-1,9	-6,6	7,5	-14,9	-4,5	-17,8
		ECHAM	-7,5	-1,9	5,2	2,8	-4,7	-9,5	-0,9	-3,7	-9,7	-14,3
		ECHO-G	-7,3	-3,8	1,2	-6,8	-1,9	-22,0	-9,7	-10,9	-5,9	-8,6
		GFDL	-0,2	-3,3	6,4	6,5	6,1	-12,0	-4,3	4,2	-10,0	-7,2
		HADCM	-10,3	-5,7	-2,1	-2,0	-11,2	-17,2	-9,9	-9,7	-7,2	-9,0

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Appendix

Country-to-region mapping for regional aggregation of results

AFR	CPA	EUR	FSU	LAM
Sub-Saharan Africa	**Centrally-Planned Asia**	**Europe**	**Former Soviet Union**	**Latin America**
Angola	Cambodia	Albania	Azerbaijan, Republic of	Argentina
Benin	China	Austria	Belarus	Belize
Botswana	Laos	Belgium-Luxembourg	Georgia	Bolivia
Burkina Faso	Mongolia	Bosnia and Herzegovina	Kazakhstan	Brazil
Burundi	Viet Nam	Bulgaria	Kyrgyzstan	Chile
Cameroon		Croatia	Moldova, Republic of	Colombia
Central African Republic		Czech Republic	Russian Federation	Costa Rica
Chad		Denmark	Tajikistan	Cuba
Congo, Dem Republic of		Estonia	Turkmenistan	Dominican Republic
Congo, Republic of		Finland	Ukraine	Ecuador
Côte d'Ivoire		France	Uzbekistan	El Salvador
Djibouti		Germany		French Guiana
Equatorial Guinea		Greece		Guatemala
Eritrea		Hungary		Guyana
Ethiopia		Iceland		Haiti
Gabon		Ireland		Honduras
Ghana		Italy		Mexico
Guinea		Latvia		Nicaragua
Guinea-Bissau		Lithuania		Panama
Kenya		Macedonia,The Fmr Yug Rp		Paraguay
Lesotho		Netherlands		Peru
Liberia		Norway		Suriname
Madagascar		Poland		Uruguay
Malawi		Portugal		Venezuela
Mali		Romania		
Mauritania		Slovakia		
Mozambique		Slovenia		
Namibia		Spain		
Niger		Sweden		
Nigeria		Switzerland		
Rwanda		Turkey		
Senegal		United Kingdom		
Sierra Leone		Yugoslavia, Fed Rep of		
Somalia				
South Africa				
Sudan				
Swaziland				
Tanzania, United Rep of				
Togo				
Uganda				
Western Sahara				
Zambia				
Zimbabwe				
MEA	**NAM**	**PAO**	**PAS**	**SAS**
Middle East/North Africa	**North America**	**Pacific OECD**	**Pacific Asia**	**South Asia**
Algeria	Canada	Australia	Indonesia	Afghanistan
Egypt	United States of America	Japan	Korea, Dem People's Rep	Bangladesh
Iran, Islamic Rep of		New Zealand	Korea, Republic of	Bhutan
Iraq			Malaysia	India
Israel			Papua New Guinea	Myanmar
Jordan			Philippines	Nepal
Kuwait			Solomon Islands	Pakistan
Libyan Arab Jamahiriya			Thailand	Sri Lanka
Morocco				
Oman				
Saudi Arabia				
Syrian Arab Republic				
Tunisia				
United Arab Emirates				
Yemen				