# 4

# Country-Level Climate Projections

The agricultural impact estimates of this study combine two sets of existing models to arrive at consistent geographically detailed estimates. The first set of models is from climate science; the second set is from agronomy and economics. This chapter sets forth what may be viewed as consensus general circulation model (GCM) climate projections for business as usual warming by the 2080s. These estimates are then used in the following chapter in applying the agronomic-economic impact models.

## The Climate Models

The new agricultural impact estimates of this study use the base climate and model scenario results available on the Intergovernmental Panel on Climate Change (IPCC) Data Distribution Centre Web site maintained for the IPCC by the Climate Research Unit, University of East Anglia, United Kingdom.[1] For the base climate of 1961–90, climate data are available at the $0.5° \times 0.5°$ grid resolution level ($360 \times 720 = 259{,}200$ cells). The analysis here selects two climate variables: temperature and daily precipitation. These data are available as monthly averages. The estimates here first obtain the annual average of these monthly averages, for each cell in the base grid. The base climate data are consolidated to averages for the stan-

---

[1] See http://ipcc-ddc.cru.uea.ac.uk. The other institutions participating in maintaining the Data Distribution Centre are the Deutsches Klimarechenzentrum (DKRZ/MPI) in Hamburg, Germany and the Center for International Earth Science Information Network (CIESIN) at Columbia University, New York.

**Table 4.1 General circulation models used for scenarios**

| Name | Organization/model | Author | Grid resolution | Climate sensitivity parameter (°C) |
|---|---|---|---|---|
| ECHAM4/ OPYC3 | German Climate Research Centre, European Centre/ Hamburg Model #4 | Roeckner et al. (1996); Zhang et al. (1998) | 2.8° × 2.8° | 2.6 |
| HadCM3 | UK Hadley Centre for Climate Prediction and Research Coupled Model #3 | Gordon et al. (2000) | 2.5° × 3.75° | 3.0 |
| CSIRO-Mk2 | Australian Commonwealth Scientific and Industrial Research Organisation Model #2b | Gordon and O'Farrell (1997) | 3.2° × 5.6° | 3.7 |
| CGCM2 | Canadian Centre for Climate Modeling and Analysis GCM #2 | Flato and Boer (2001) | 3.7° × 3.7° | 3.6 |
| GFDL-R30 | US Geophysical Fluid Dynamics Laboratory R-30 Resolution Model | Knutson et al. (1999) | 2.25° × 3.75° | 3.4 |
| CCSR/NIES | Japanese Centre for Climate System Research | Emori et al. (1999) | 5.6° × 5.6° | 3.5 |

*Source:* IPCC (1999; 2001a, 478, 538).

dard grid *G* used in this study, latitude height of 2°, and longitude width of 3° (90 × 120 = 10,800 cells) using the method set forth in appendix A.

The changes in climate variables from the present to a future target date as calculated by six GCMs are then similarly converted to standard grid *G* and added to the corresponding base period average climate variables to obtain temperature and precipitation at the future period, 2070–99. Table 4.1 reports the models, their grid resolution, and their climate sensitivity parameter *S*. This parameter indicates global mean surface warming to be expected from a doubling of carbon dioxide–equivalent atmospheric greenhouse gas concentration above preindustrial levels.

The scenario used for all six models is SRES A2 in the IPCC's Special Report on Emissions Scenarios (Nakićenović and Swart 2000). It is one of the six scenarios used in the IPCC's Third Assessment Report and the only scenario for which all six climate models providing data to the IPCC Data Distribution Center include projections.

Among the six scenarios considered by the Third and Fourth Assessment Reports of the IPCC, scenario A2 was the next to highest.[2] This scenario projects carbon emissions from all anthropogenic sources to rise from 7.3 gigatons of carbon (GtC) in 1990 to 17.4 GtC by 2050 and 29.1 GtC by 2100. As argued in Cline (2004, 14), two of the six scenarios (A1T and B1) have implausible declines in carbon intensity of energy and are inconsistent with a baseline with no policy incentive to reducing carbon dioxide emissions. In addition carbon intensity of energy could well rise later this century from the more rapid exhaustion of natural gas and oil supplies than of abundant coal supplies, in view of the higher carbon intensity of energy from coal. As a result, scenario A2 should be seen more as an intermediate path among those that are realistic than as a high emissions baseline.

It is also important to ask whether the climate models available for this study have any particular bias toward over- or understatement of future climate change. The climate sensitivity parameter ($S$) of the model is the best gauge for this question. The average sensitivity parameter in the six GCMs applied in this study is $S = 3.3°\text{C}$ (table 4.1). In comparison, the 2007 Fourth Assessment Report of the IPCC reported that the climate sensitivity parameter "is likely to be in the range 2 to 4.5°C with a best estimate of about 3°C" (IPCC 2007a, 12). So the GCMs used are close to the standard norm for the climate sensitivity parameter.

## Country-Level Climate Results: Present Day and for 2070–99

The present and future climate estimates are calculated at the level of each of the approximately 2,800 land-based cells in the standardized grid.[3] Table 4.2 reports the result of averaging these estimates at the level of 116 individual countries (68), regions (10), or subzones for the seven largest countries (38). Definitions of the multicountry regions and large-country subzones are in appendix D. Development of the estimates for agricultural land and output within each subzone of the large countries is discussed in appendix E.

Tables H.1 through H.4 in appendix H report the corresponding monthly average values for present and future temperatures and precipitation. Monthly detail is needed to implement several of the country- or region-specific Ricardian agricultural impact functions used in this study (see chapter 5).

---

[2] Cumulative anthropogenic carbon emissions from 2000 through 2100, including from deforestation, were as follows, by scenario: A1B, 1,430 GtC; A1T, 986 GtC; A1F1, 2,107 GtC; A2, 1,780 GtC; B1, 901 GtC; B2, 1,081 GtC (calculated from IPCC 2001a, 801).

[3] The standardized grid contains 10,800 cells (90 x 120). The mapping of base to future climate is first done at the $1° \times 1°$ grid level, which corresponds to $180 \times 360 = 64{,}800$ cells. There are 22,156 land-based cells at that resolution.

**Table 4.2 Present and future climate: Average temperature and precipitation** (°C and mm per day, annual averages)

| | Temperature | | Precipitation | |
|---|---|---|---|---|
| Country | Present, 1961–90 | Future, 2070–99 | Present, 1961–90 | Future, 2070–99 |
| Afghanistan | 13.10 | 18.75 | 0.86 | 0.86 |
| Algeria | 22.67 | 27.81 | 0.22 | 0.23 |
| Angola | 21.52 | 25.53 | 2.75 | 2.62 |
| Argentina | 14.65 | 17.89 | 1.63 | 1.66 |
| Australia | | | | |
| Southeast | 16.68 | 20.27 | 1.66 | 1.61 |
| Southwest | 18.35 | 21.75 | 0.79 | 0.65 |
| Central East | 22.02 | 26.10 | 1.59 | 1.61 |
| Central West | 23.49 | 27.63 | 0.81 | 0.75 |
| North | 26.38 | 30.04 | 2.55 | 2.55 |
| Bangladesh | 24.46 | 28.13 | 6.42 | 7.04 |
| Belgium | 9.62 | 13.72 | 2.23 | 2.27 |
| Brazil | | | | |
| Amazon | 26.04 | 30.38 | 5.97 | 5.84 |
| Northeast | 25.58 | 29.46 | 3.58 | 3.52 |
| South | 22.04 | 25.90 | 3.98 | 4.15 |
| Burkina Faso | 28.16 | 32.38 | 2.12 | 2.29 |
| Cambodia | 26.64 | 29.99 | 5.31 | 5.21 |
| Cameroon | 24.60 | 28.16 | 4.36 | 4.50 |
| Canada | | | | |
| Arctic | –15.09 | –7.28 | 0.46 | 0.78 |
| Central | –0.47 | 5.41 | 1.21 | 1.41 |
| Northwest Territories | –8.88 | –2.42 | 0.82 | 1.21 |
| Pacific Coast | 0.79 | 5.40 | 2.17 | 2.54 |
| Southeast | –0.93 | 5.42 | 2.26 | 2.56 |
| Central America | 24.23 | 27.76 | 6.51 | 6.18 |
| Central Europe | 7.67 | 12.54 | 2.39 | 2.35 |
| Chile | 9.01 | 11.91 | 1.52 | 1.43 |
| China | | | | |
| Beijing Northeast | 2.73 | 8.89 | 1.32 | 1.57 |
| Central | 9.49 | 14.48 | 2.03 | 2.43 |
| Hong Kong Southeast | 18.78 | 22.67 | 4.47 | 4.82 |
| Northwest | 6.06 | 12.08 | 0.37 | 0.44 |
| South Central | 17.50 | 21.27 | 3.59 | 3.95 |
| Tibetan Plateau | –1.45 | 4.15 | 1.13 | 1.53 |
| Yellow Sea | 14.59 | 19.25 | 2.77 | 3.12 |
| Colombia | 24.31 | 27.81 | 7.25 | 7.44 |
| Cuba | 25.25 | 28.19 | 3.57 | 3.50 |
| Democratic Republic of the Congo | 23.95 | 27.93 | 4.21 | 4.27 |
| Ecuador | 22.15 | 25.36 | 5.52 | 6.01 |

*(table continues next page)*

**Table 4.2 Present and future climate: Average temperature and precipitation** (°C and mm per day, annual averages) *(continued)*

| | Temperature | | Precipitation | |
|---|---|---|---|---|
| **Country** | **Present, 1961–90** | **Future, 2070–99** | **Present, 1961–90** | **Future, 2070–99** |
| Egypt | 22.16 | 26.79 | 0.12 | 0.12 |
| Ethiopia | 23.08 | 26.92 | 2.04 | 1.97 |
| France | 10.56 | 14.95 | 2.33 | 2.13 |
| Germany | 8.26 | 12.70 | 2.00 | 2.09 |
| Ghana | 27.15 | 30.87 | 3.23 | 3.27 |
| Greece | 13.86 | 17.96 | 1.78 | 1.47 |
| India | | | | |
| Northeast | 20.54 | 24.54 | 3.51 | 4.23 |
| Northwest | 23.55 | 27.52 | 1.58 | 1.97 |
| Southeast | 26.76 | 30.06 | 3.05 | 3.42 |
| Southwest | 26.23 | 29.32 | 3.04 | 3.47 |
| Indonesia | 25.76 | 28.58 | 7.74 | 8.02 |
| Iran | 17.26 | 22.63 | 0.62 | 0.62 |
| Iraq | 20.86 | 26.16 | 0.57 | 0.58 |
| Italy | 12.20 | 16.52 | 2.48 | 2.23 |
| Ivory Coast | 26.19 | 29.79 | 3.88 | 3.95 |
| Japan | 10.73 | 14.87 | 4.40 | 4.46 |
| Kazakhstan | 5.79 | 12.19 | 0.69 | 0.75 |
| Kenya | 24.33 | 27.83 | 2.02 | 2.19 |
| Madagascar | 22.28 | 25.53 | 4.12 | 3.91 |
| Malawi | 21.79 | 25.72 | 3.10 | 3.04 |
| Malaysia | 25.35 | 28.27 | 7.95 | 8.14 |
| Mali | 28.24 | 33.01 | 0.85 | 0.87 |
| Mexico | 20.66 | 24.71 | 2.09 | 1.84 |
| Morocco | 17.43 | 21.91 | 0.88 | 0.77 |
| Mozambique | 23.44 | 27.28 | 2.82 | 2.80 |
| Myanmar | 22.67 | 26.08 | 5.47 | 5.91 |
| Nepal | 12.90 | 17.13 | 3.64 | 4.57 |
| Netherlands | 9.26 | 13.21 | 2.16 | 2.31 |
| New Zealand | 10.22 | 12.71 | 4.79 | 5.03 |
| Niger | 27.13 | 31.53 | 0.46 | 0.68 |
| Nigeria | 26.73 | 30.46 | 3.09 | 3.29 |
| North Korea | 5.66 | 11.03 | 2.87 | 3.18 |
| Other Central Asia | 10.01 | 15.79 | 0.75 | 0.74 |
| Other Equatorial Africa | 24.81 | 28.46 | 4.23 | 4.30 |
| Other Horn of Africa | 26.79 | 30.35 | 0.81 | 0.96 |
| Other South America | 21.61 | 25.90 | 3.04 | 3.15 |
| Other Southern Africa | 20.57 | 24.91 | 0.93 | 0.80 |
| Other West Africa | 25.77 | 29.29 | 5.24 | 5.32 |
| Pakistan | 19.91 | 24.76 | 0.83 | 0.96 |
| Peru | 19.52 | 23.34 | 4.22 | 4.42 |

*(table continues next page)*

**Table 4.2 Present and future climate: Average temperature and precipitation** (°C and mm per day, annual averages) *(continued)*

| | Temperature | | Precipitation | |
|---|---|---|---|---|
| **Country** | **Present, 1961–90** | **Future, 2070–99** | **Present, 1961–90** | **Future, 2070–99** |
| Philippines | 25.51 | 28.24 | 6.52 | 6.68 |
| Poland | 7.80 | 12.81 | 1.66 | 1.82 |
| Portugal | 14.93 | 18.82 | 2.16 | 1.85 |
| Romania | 8.87 | 14.07 | 1.74 | 1.52 |
| Russia | | | | |
| Caspian Black Sea | 7.85 | 13.52 | 1.34 | 1.32 |
| Far Eastern | −10.56 | −2.69 | 1.05 | 1.52 |
| North European | 2.05 | 8.60 | 1.62 | 2.01 |
| North Urals Siberia | −7.02 | 1.00 | 1.30 | 1.70 |
| Northeast Siberia | −13.97 | −5.84 | 0.79 | 1.15 |
| South Urals Siberia | −0.25 | 6.79 | 1.33 | 1.62 |
| Southeast Siberia | −5.58 | 1.48 | 1.31 | 1.68 |
| Saudi Arabia | 24.57 | 29.30 | 0.22 | 0.34 |
| Scandinavia | 1.79 | 6.89 | 1.93 | 2.36 |
| Senegal | 27.80 | 31.51 | 1.95 | 1.80 |
| South Africa | 17.72 | 21.89 | 1.31 | 1.20 |
| South Korea | 11.03 | 15.33 | 3.72 | 3.96 |
| Southeast Europe | 10.32 | 15.08 | 2.27 | 1.99 |
| Spain | 13.24 | 17.90 | 1.76 | 1.43 |
| Sri Lanka | 26.80 | 29.64 | 4.67 | 4.96 |
| Sudan | 26.70 | 30.87 | 1.18 | 1.28 |
| Syria | 17.48 | 22.19 | 0.87 | 0.73 |
| Tanzania | 22.25 | 26.01 | 2.88 | 2.91 |
| Thailand | 26.20 | 29.39 | 4.38 | 4.69 |
| Turkey | 11.42 | 16.14 | 1.57 | 1.30 |
| Uganda | 22.36 | 26.04 | 3.24 | 3.30 |
| Ukraine | 8.16 | 13.67 | 1.55 | 1.47 |
| United Kingdom | 8.51 | 11.76 | 3.13 | 3.37 |
| United States | | | | |
| Alaska | −5.10 | 1.12 | 1.14 | 1.70 |
| Lakes and Northeast | 8.26 | 14.17 | 2.54 | 2.63 |
| Pacific Northwest | 7.57 | 12.11 | 1.98 | 2.09 |
| Rockies, Plains | 6.68 | 12.36 | 1.18 | 1.24 |
| Southeast | 16.69 | 21.44 | 3.52 | 3.44 |
| South Pacific Coast | 12.11 | 16.56 | 1.22 | 1.36 |
| Southwest and Plains | 15.05 | 20.20 | 1.35 | 1.20 |
| Uzbekistan | 12.36 | 18.14 | 0.52 | 0.48 |
| Venezuela | 25.44 | 29.17 | 5.33 | 5.31 |
| Vietnam | 24.09 | 27.44 | 4.87 | 4.94 |
| Yemen | 23.77 | 27.72 | 0.46 | 0.64 |
| Zambia | 21.57 | 25.86 | 2.75 | 2.61 |
| Zimbabwe | 21.03 | 25.39 | 1.85 | 1.81 |

As a first step in thinking about the agricultural implications of the climate projections, it is useful to keep in mind the turning point identified by Mendelsohn et al. (2000, 558) beyond which additional warming has negative effects. They place this optimal temperature at 11.7°C in their reduced form statistical equation for process-based crop model results, and at 14.2°C in their Ricardian model based on cross-section statistical estimates. Even if the more optimistic (higher) threshold is used, it turns out that already in the present climate 62 developing countries, developing regions, or developing-country subzones are above this level, and only 25 (of which 7 are in Russia) are below it. In India, for example, all four subzones are well above the optimal level (with the lowest average annual temperature being for the Northeast at 20.54°C). In China, 3 of the 7 subzones are above the 14.2°C optimum level.

In contrast, for industrial countries, regions, or subzones, only 7 are presently at temperatures above the optimum (5 in Australia and 2 in the United States) whereas 22 are below it. Broadly, then, data on the present climate indicate that the bulk of the developing world is already at temperatures that exceed optimal levels for agriculture. For these countries, further global warming would reduce agricultural production capacity. For many countries already well above the optimal temperature level, this deterioration could be severe, because the relationship is nonlinear with the negative impact rising with the square of temperature, as discussed later. These data similarly suggest that if an initial phase of warming would benefit rather than harm agriculture, it would primarily be to the advantage of industrial countries and disadvantage of developing countries.

It is useful to consider the global nonocean averages for present and future temperatures and precipitation based on the estimates of table 4.2. For this purpose, each entry in the table can be weighted by its share in global land area or global farm area, respectively, from appendix table E.1. The results of this weighting are shown in table 4.3.

Using broadly the same climate models and the same scenario (SRES A2), the IPCC (2001a, 527) places the change in global mean temperature from 1961–90 to 2070–99 at an average of 3.0°C and a range of 1.3°C to 4.5°C. The higher warming found here for land areas, 4.95°C weighting by land area and 4.43°C by farm area, reflects the fact that realized surface warming by a given future date is expected to be greater over land than for the oceans.[4] Actual warming to date from 1950 to 1993 for land surface air temperature has been about twice that for sea surface air temperature (IPCC 2001a, 26). This is an important distinction for exercises examining agricultural impact in response to temperature change, because it means that the relevant temperature change for agriculture will be higher than the change in global mean temperature including the oceans.

---

[4] "Generally, the land warms faster than the ocean, the land warms more than the ocean after forcing stabilizes, and there is greater relative warming at high latitudes" (IPCC 2001a, 528).

**Table 4.3 Global land-based climate averages and changes, 1961–90 to 2070–99**

| | Land area weighting | Farm area weighting |
|---|---|---|
| Temperature (°C), 1961–90 (base) | 13.15 | 16.20 |
| Precipitation (mm per day) | 2.20 | 2.44 |
| Change from base to 2070–99 average: | | |
| Temperature (°C) | 4.95 | 4.43 |
| Precipitation (mm per day) | 0.129 | 0.072 |
| Percent change (precipitation) | 5.9 | 2.9 |

Table 4.3 shows that when farm area rather than land area is used for weighting, the warming is somewhat smaller. This result reflects the fact that the share of land masses in the high latitudes (primarily in the Northern Hemisphere), for example, at latitudes above 50°, is much greater than the share of these regions in global farm area, reflecting the limited feasibility of farming in these areas. When this fact is combined with the expected greater warming at high latitudes, the result is (modestly) lesser warming weighting by farm area than weighting by land area.

The change in precipitation is found to be 5.9 percent weighting by land area and 2.9 percent weighting by farm area. This result is broadly consistent with the global mean change predicted for scenario SRES A2, which is 3.9 percent with a range of 1.3 to 6.8 percent (IPCC 2001a, 542). The difference between land and farm area–weighted averages is considerably greater for precipitation than for warming. Once again this result would appear to reflect a greater share of land not currently primarily in agriculture in the future increase in precipitation than of agricultural lands. Thus, the IPCC states of future precipitation change:

> Most tropical areas have increased mean precipitation, most of the sub-tropical areas have decreased mean precipitation, and in the high latitudes the mean precipitation increases (IPCC 2001a, 528).

Considering that prime agricultural land today is in neither tropical nor high-latitude areas, this prognosis implies lesser increase in precipitation for current agricultural areas than for the global land-based means.[5]

---

[5] In its color graphics of precipitation change by 2070–99, the IPCC (2001a, 550) shows increased precipitation on the order of 20 percent at latitudes higher than 60° and a patch of 20 percent or more increase across the Sahara Desert and into the Arabian Peninsula (but from minimal base precipitation). Precipitation declines on the order of 5 to 10 percent for Mexico, southern United States, the eastern half of Brazil and western half of Argentina, most of Australia, and the Mediterranean region. There is an increase of 0 to 5 percent for much of sub-Saharan Africa, most of China and Russia, and northern United States and most of Canada.