A Closer Look at the IMPACT of Climate Change on Country-Level Food Security and Nutrition

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Paper presented at the Annual GTAP Conference

Purdue University, West Lafayette, Indiana, June 7th –9th, 2007

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Summary:

In light of increasing variability of climatic conditions and its effect on global food systems and the ecosystems that support them, increasing attention is being paid by policymakers and researchers to the policies that can best address the likely impacts on food supply and security in those countries that are particularly vulnerable – namely, developing countries. The global food and water policy modeling framework of IMPACT-WATER was used to look at possible adaptation strategies that food producers and resource managers might undertake to cope with changing environmental conditions, as part of the ADAPT project. For this project, IFPRI's IMPACT-WATER model was linked to other streamflow and runoff models that could downscale the climate scenarios from General Circulation Models down to the relevant river basin scales, in order to examine their impact on food production and markets. The discussion of the model linkage process and some highlighted results will illustrate the importance of incorporating environmentally-focused research questions into trade policy modeling framework in order to address important issues surrounding global environmental change and its effect on global food systems and economies.

1. Introduction

Global projections for increasing food demand combined with increasing variability of climatic conditions point towards increasing stress on food systems and their supporting ecosystems. In many parts of the world, trend of increasing variability of climatic conditions and rainfall are being observed, leading to longer and more severe weather events, or periods of drought. Accompanying the world's steady population growth is an increasing demand for food and the necessary feedstuffs to fuel the requisite increases in livestock production. The combination of these two trends will inevitably lead to greater stresses and demands on the natural resource base and eco-systems that underlie the world's food production systems.

Those countries which rely primarily on rainfed agricultural production will face increasing challenges to maintain crop productivity in the face of shifts and variability in environmental conditions. The proportion of rainfed agriculture has risen over time, in response to the limited opportunities for expanding the area under irrigation, and the steady increase of demand for food and feed products. Those countries that have limited opportunities to bring land under irrigation, due to lack of water resource endowments or the necessary infrastructure to convey water on a large scale will have to rely on rainfed agriculture to a greater degree and, as a result, will have to face increasing variability of rainfed yields as environmental conditions continue to change.

Policymakers are becoming increasingly aware of the future challenges posed by global environmental change and are looking for more innovative strategies to allow crop production and food systems to adapt to these changing conditions. Developing countries, in particular, must find appropriate strategies to reinforce the resilience of their food systems, in order to protect vulnerable populations and to maintain their access to necessary nutrients as well as their livelihoods, which are heavily reliant upon agriculture. The ability of rural farm households to adapt to changing environmental and economic conditions will be a key determinant of their success in meeting the challenges of global change.

In order to better inform policymakers of the best strategies available to them, policy researchers need to adapt their policy models to address important environmental issues within modeling frameworks that have traditionally been driven purely by price. The 'dual' approach of most food policy models has relied heavily on the interaction between prices and levels of output, but have overlooked the importance of key 'primal' variables that relate environmental conditions to food production, such as temperature, soil conditions, and water availability. In order to address the challenges facing food systems in the face of environmental change and variability, researchers have to find creative ways to interface their policy models with other environmentally-focused models or analytical tools that can directly address the impact of important physical variables to crop production, food supply and trade.

As part of the ADAPT project, the global food and water policy modeling framework of IMPACT-WATER was used to analyze scenarios for climate change and variability by linking it with other environmentally-driven models. In order to link the IMPACT-WATER modeling framework with the necessary inputs from General Circulation Model (GCM) climate scenarios, a combination of streamflow and runoff models were used. These physically-based flow models created the necessary linkages between the climate change and variability scenarios generated by the GCM's and the spatial units used by the environmentally-driven module of the IMPACT-WATER model, in order to examine the impacts of food production and markets.

The lessons that we draw from this experience should prove both instructive and useful to those policy modelers wishing to incorporate the impacts of environmental change into food production and trade models in order to address pressing issues facing vulnerable food economies. As policy questions focused on the adaptability of food systems and economies to the pressures of global environmental change continue to surface, policy researchers will be called upon to address these issues more explicitly in their modeling frameworks. By so doing, researchers will be able to provide needed insights to policy makers and environmental managers about the best and most viable options available to enhance the productivity and adaptability of food systems in the face of an increasingly challenging physical and economic environment.

The rest of this paper is designed as follows. Following a brief description of the IMPACT-WATER modeling framework, we discuss the linkages between it and the other necessary streamflow and runoff models needed to downscale the climate change and variability scenarios to the appropriate spatial units. This is then followed by a discussion of some of the key model results generated under these scenarios, and some immediate policy implications that follow from them. A final section highlighting the key features of our study and possible avenues for further research conclude the paper.

2. The IMPACT-WATER Model

2.1 Model Overview

A lack of a long-term vision and consensus about the actions that are necessary to feed the world in the future, reduce poverty, and protect the natural resource base spurred IFPRI to develop a global food projection model in the beginning of the nineties: the **I**nternational **M**odel for **P**olicy analysis of **A**gricultural **C**ommodities and **T**rade or IMPACT. In 1993, these same long-term global concerns launched the 2020 Vision for Food, Agriculture and the Environment Initiative. This initiative created the opportunity for further development of the IMPACT model, and in 1995 the first results from the IMPACT model were published as a 2020 Vision discussion paper: *Global Food Projections to 2020: Implications for Investment* (Rosegrant, Agcaoili-Sombilla and Perez, 1995). This publication studies how the effect of population, investment, and trade scenarios affects food security and nutrition status, especially in developing countries.

Since then, the IMPACT model has been used for a variety of research analyses which link the production and demand of key food commodities to national-level food security. For example, the paper *Alternative Futures for World Cereal and Meat Consumption* (Rosegrant, Leach and Gerpacio, 1999), examines whether high-meat diets in developed countries limit improvement in food security in developing countries, while the article *Global Projections for Root and Tuber Crops to the Year 2020* (Scott, Rosegrant and Ringler, 2000) gives a detailed analysis of roots and tuber crops. *Livestock to 2020: The next food revolution* (Delgado *et al.*, 1999) assesses the influence of the livestock revolution, which was triggered by increasing demand through rising incomes in developing countries the last decade. IMPACT also provided the first comprehensive policy evaluation of global fishery production and projections for demand of fish products in the book *Fish to 2020: Supply and Demand in Changing Global Markets* (Delgado, Wada, Rosegrant, Meijer and Ahmed, 2003). Besides these global projections, regional studies have also been completed such as *Asian Economic Crisis and the Long-Term Global Food Situation* (Rosegrant and Ringler, 2000) and *Transforming the Rural Asian Economy: the Unfinished Revolution* (Rosegrant and Hazell, 2000). These studies were a response to the Asian financial crisis of 1997 and analyzed the impact of this crisis on future developments of the food situation in that region.

More recently, the IMPACT model has been applied to looking at scenario-based assessments of future food production and consumption trends, under both economic and environmentally-based drivers of change. The most comprehensive set of results from the IMPACT model were published in the book *Global Food Projections to 2020* (Rosegrant *et al.,* 2001), which gives a baseline scenario under which the best future assessment of production and consumption trends are given, for all IMPACT commodities. In addition to the baseline, alternative scenarios are also offered, based on differing levels of productivity-focused investments, lifestyle changes and other policy interventions. These scenarios describe changes that are both global as well as regional in nature – such as those which are specific to meeting the MDG goals in Sub-Saharan Africa (Rosegrant *et al.*, 2005). Policy analyses based on alternative scenarios that are more environmentally-focused were published in an IFPRI book titled *World Water and Food to 2025: Dealing with Scarcity* (Rosegrant, Cai and Cline, 2002). The version of IMPACT that was used to generate the results for this study (IMPACT-WATER) will be used to discuss the climate change scenarios examined in this paper.

2.2 The Modeling Methodology of IMPACT

IFPRI's IMPACT model offers a methodology for analyzing baseline and alternative scenarios for global food demand, supply, trade, income and population. IMPACT coverage of the world's food production and consumption is disaggregated into 36 countries and regional groupings, and covers 16 commodities, including all cereals, soybeans, roots and tubers, meats, milk, eggs, oils, oilcakes and meals. IMPACT models the behavior of a competitive world agricultural market for crops and livestock, and is specified as a set of country or regional sub-models, within each of which supply, demand and prices for agricultural commodities are determined. The country and regional agricultural sub-models are linked through trade in a non-spatial way, such that the effect on country-level production, consumption and commodity prices is captured, through the net trade flows in global agricultural markets. The model uses a system of linear and nonlinear equations to approximate the underlying production and demand relationships, and is parameterized with country-level elasticities of supply and demand (Rosegrant *et al.*, 2001). World agricultural commodity prices are determined annually at levels that clear international markets. Demand is a function of prices, income and population growth. Growth in crop production in each country is determined by crop prices and the rate of productivity growth. Future productivity growth is estimated by its component sources, including crop management research, conventional plant breeding, wide-crossing and hybridization breeding, and biotechnology and transgenic breeding. Other sources of growth considered include private sector agricultural research and development, agricultural extension and education, markets, infrastructure and irrigation.

A wide range of factors with potentially significant impacts on long-term, future developments in the world food situation can be used as exogenous drivers within IMPACT. Among these drivers are: population and income growth, the rate of growth in crop and livestock yield and production, feed ratios for livestock, agricultural research, irrigation and other investment, price policies for commodities, and elasticities of supply and demand. For any specification of these underlying parameters, IMPACT generates long-term projections for crop area, yield, production, demand for food, feed and other uses, prices, and trade; and livestock numbers, yield, production, demand, prices, and trade. The version of the model used for this paper has a base year of 1995 (a three-year average of 1994-96 FAOSTAT data) and makes projections out to the year 2025.

2.3 Incorporating Water Availability into IMPACT

The primary IMPACT model simulates annual food production, demand, and trade over a 30-year period based on a calibrated base year. In calculating crop production, however, IMPACT assumes a "normal" climate condition for the base year as well as for all subsequent years. Impacts of annual climate variability on food production, demand, and trade are therefore not captured in the primary IMPACT model.

In reality, however, climate is a key variable affecting food production, demand, and trade. Consecutive droughts are a significant example, especially in areas where food production is important to local demand and interregional or international trade. More importantly, water demand is potentially increasing but supply may decline or may not fully satisfy demand because of water quality degradation, source limits (deep groundwater), global climate change, and financial and physical limits to infrastructure development. Therefore future water availability—particularly for irrigation—may differ from water availability today. Both the long-term change in water demand and availability and the year-to-year variability in rainfall and runoff will affect food production, demand, and trade in the future. To explore the impacts of water availability on food production, water demand and availability must first be projected over the period before being incorporated into food production simulation. This motivates an extension of IMPACT using a simulation model for inter-sectoral water allocation that operates at the global scale.

The Water Simulation Module (WSM) simulates water availability for crops accounting for total renewable water, nonagricultural water demand, water supply infrastructure, and economic and environmental policies related to water development and management at the river basin, country, and regional levels. Crop-specific water demand and supply are calculated for the eight of the key crops modeled in IMPACT—rice, wheat, maize, other coarse grains, soybeans, potatoes, sweet potatoes and yams, and cassava and other roots and tubers—as well as for crops not considered (which are aggregated into a single crop for water demand assessment). Water supply in irrigated agriculture is linked with irrigation infrastructure, permitting estimation of the impact of investment on expansion of potential crop area and improvement of irrigation systems.

IMPACT-WATER—the integration of IMPACT and WSM—incorporates water availability as a stochastic variable with observable probability distributions to examine the impact of water availability on food supply, demand, and prices. This framework allows exploration of water availability's relationship to food production, demand, and trade at various spatial scales—from river basins, countries, or regions, to the global level—over a 30-year time horizon.

Although IMPACT-WATER divides the world into 36 spatial units (Figure 1), significant climate and hydrologic variations within large countries or regions make large spatial units inappropriate for water resources assessment and modeling. IMPACT-WATER, therefore, conducts analyses using 69 basins, with many regions of more intensive water use broken down into several basins. China, India, and the United States (which together produce about 60 percent of the world's cereal) are disaggregated into 9, 13, and 14 major river basins, respectively (see Figure 2). Water supply and demand and crop production are first assessed at the river-basin scale, and crop production is then summed to the national level, where food demand and trade are modeled. Other countries or regions considered in IMPACT are combined into 33 aggregated "basins."

3. Model Linkages to IMPACT-WATER

In this study, IMPACT has been supported by two additional models that provided forcing data to drive it. The first model is a global hydrology model that uses first-order data (climate, land cover, soil type, etc.) specified at a 0.5°x0.5° spatial grid for all global land points (excluding Artic and Antarctica) to produce estimates of river basin runoff over a 30-year time horizon and on a monthly time step. The river basin runoff data are used by IMPACT to define the water supply to each of the hydro-economic zones. A second external model, the Global Agro-Ecological Zones (GAEZ) model is used to determine crop potential yield. The GAEZ provides a standardized framework for the characterization of climate, soil and terrain conditions relevant to agricultural production, most notably the estimate of maximum potential crop yield in a gridded format that can be used by IMPACT. In GAEZ, crop modeling and environmental matching procedures are used to identify crop-specific limitations due to climate, soil, and terrain, under assumed levels of inputs and management conditions.

Since a keen interest of this study is adaptation, the lower right corner of Figure 3 expresses the implicit adaptation that can be accounted for in the IMPACT model. IMPACT is a representation of a competitive world agricultural market for tradable crops and livestock, which determines supply, demand, and prices for these commodities and determines their price such that international markets clear. Thus, under different climate or socio-economic scenarios we observe autonomous adaptation behavior that is implicit in the IMPACT model results because of the operation of market mechanisms. Autonomous adaptation implies either gradual or abrupt changes in food production such as increases in acreage, changes in water use, changes in cropping patterns over time, that result from the dynamics of a competitive food market, constrained by production factors such as a limited water supply or limited agricultural capital (labor, land, mechanization, etc.).

Although the IMPACT model will account for autonomous adaptation, IMPACT is also capable of describing the response of global water use and food production to exogenous adaptation strategies such as improved irrigation efficiency, changes in farm subsidies, capital investments, etc, via policy options or parametric analysis. These external or exogenous variables would be prescribed, and would comprise individual scenarios whose results would be examined relative to baseline, non-exogenously driven scenarios. For this study, we have only focused upon autonomous adaptations, with the hopes of extending the work to include scenarios of explicit, exogenous adaptation strategies in the future.

3.1 Including Necessary Climatic Drivers

Climate Data

The historical climate data was the CRU 1901-1995 Monthly Climate Time-Series dataset (New *et al.*, 2000). This dataset provides global gridded precipitation and temperature data at 0.5º x 0.5º of monthly surface climate extending from 1901 to 1995 over global land areas, excluding Antarctica. Primary variables in the CRU dataset are interpolated directly from station time-series and for the purposes of this study included precipitation and mean temperature. Secondary variables in the CRU dataset are interpolated from station series where data are available and estimated using relationships with primary variables in regions with no data. The secondary variable used in this study was vapour pressure, which is used in the estimate of potential evapotranspiration.

GCM-based Scenarios

The Inter-governmental Panel on Climate Change (IPCC) published a Special Report on Emissions Scenarios (SRES) in 2000. This report describes the new set of emissions scenarios used in the Third Assessment Report (IPCC, 2001). The SRES scenarios have been constructed to explore future developments in the global environment with special reference to the production of greenhouse gases and aerosol precursor emissions. The SRES were used as atmospheric 'forcing' functions for a suite of Global Circulation Models (GCM) that provide simulations of future climatic variables.

The GCM results used comprise 30-year mean monthly changes (for periods centered on the 2020s, 2050s, and 2080s) with respect to model-simulated mean 1961-90 climate. No information is therefore presented about changes in inter-annual variability or inter-monthly variability. Many climate change impacts may be sensitive to changes in these aspects of climate variability.

The GCM's (Global Circulation Models) used in this analysis to provide precipitation and temperature for climate change scenarios include Max Plank Institute Model (**ECHAM4)** for B2 2020 and B2 2080 and the Hadley Center Model (**HadCM3)** for A1 2020, A1 2080, B2 2020, and B2 2080. These scenarios are explained in more detail, below.

The A1 Scenario: A future world of very rapid economic growth, low population growth and rapid introduction of new and more efficient technology. Major underlying themes are economic and cultural convergence and capacity building, with a substantial reduction in regional differences in per capita income. In this world, people pursue personal wealth rather than environmental quality. Table 1 shows the global mean temperatures relative to 1990, for this scenario.

The B2 Scenario: The SRES B2 scenario a world in which the emphasis is on local solutions to economic, social, and environmental sustainability. It is again a heterogeneous world with less rapid, and more diverse technological change but a strong emphasis on community initiative and social innovation to find local, rather than global solutions. Table 2 shows the global mean temperatures relative to 1990, for this scenario.

ENSO Variability Scenarios

In addition to mean based GCM based climate scenarios, we developed a statistical technique to derive new scenarios based on changes in the occurrence of the El-Niño, Southern Oscillation phenomenon (ENSO) because the ENSO phenomenon explicitly modeled in GCM. The ENSO are sea-surface temperature anomalies that occur periodically off the western coast of South America, with a seasonal timescale. When sea-surface temperatures are above normal, the condition is referred to as El Niño, while if the sea-surface temperatures are below normal, the condition is called La Niña. Table 3 shows the years of El Niño and La Niña over the period 1901 to 1996. In all, 28 years were considered to be either El Niño or La Niña, while the remainder were considered 'neutral' years.

Alternative climate scenarios allow us to systematically investigate the impacts of different global climate regimes (such as increased occurrence of ENSO years), on food production. To develop these scenarios, we employed a modified version of the *K-nearest neighbor* (*K-nn*) algorithm of Lall and Sharma [1996], Rajagopalan and Lall [1999], and Buishand and Brandsma [2001] to generate monthly time series of global and regional (basin) climate data, conditioned on the ENSO index. Essentially, the *K-nn* method is a strategic re-sampling of historical precipitation and temperature data to derive new climate series.

The *K-nn* algorithm employed here uses the Mahalanobis distance metric [Davis 1986], which has an operational advantage over a Euclidean distance approach by not requiring the explicit weighting of variables and does not require the variables to be standardized. A strategy is introduced that gives priority to certain years from which to resample, which can be used to derive alternative scenarios with differing statistical attributes.

3.2 Streamflow and Agronomic Modeling

The two supporting models include a global river basin runoff model, that estimates streamflow for each hydro-economic river basin and the GAEZ model that estimates maximum attainable yield across the globe based on environmental and physical constraints to agricultural capacity. The output from these two models is used by the IMPACT model, and is briefly described below.

River Basin runoff and PET

The river basin runoff model applies a gridded approach to computing the water balance that matches each of the 0.5°x0.5° land surface grids based on the CRU climate dataset (the land surface mask). In addition to the land surface mask, a 0.5°x 0.5° mask that corresponds to the major hydro-economic river basins was also defined, and is used to accumulate the runoff from each 0.5°x 0.5° grid cell to represent total basin stream flow. Figure 2 (a-c) presents maps of the major hydro-economic river basins used in the modeling exercise, including 9 basins in China, 13 basins in India, 14 basins in the United States, and 33 "aggregated basins" in other countries or regions. A GIS program is used to extract the runoff and precipitation values and aggregate the grids into IMPACT spatial units.

The hydrologic model consists of a conceptually simple, one-dimensional water balance model that incorporates a soil moisture accounting scheme based on empirical functions that describe evapotranspiration and surface runoff and sub-surface runoff or interflow as a function of relative storage (Yates, 1996). A temperature-index, snowmelt model is used to track snow accumulation and melt, over those cells with temperatures that fall below a threshold corresponding to rain changing to snow. Evapotranspiration is a function of the relative soil moisture of the one-dimensional 'bucket' and the total potential evapotranspiration (PET) that is computed based on the classical Penman-Montieth model. Figure 4 shows the components of the conceptual water balance model that allows for the characterization of land use specific impacts on runoff. Since this is a monthly runoff model, river routing is not considered, but for larger basins, there can be a one-month lag associated with the sub-surface runoff, or baseflow component.

The uniqueness of this gridded water balance model is in its use of continuous functions of relative storage to represent surface outflow, sub-surface outflow, and evapotranspiration in the form of a differential equation (Yates 1996).

The monthly soil moisture balance is written as:

$$S_{\max} \frac{dz}{dt} = PT - R_s(P, z, t) - R_{ss}(z, t) - Ev(Pet, z, t)$$

where

PT = total effective precipitation (length/time)
R_s = surface runoff (length/time)
R_{ss} = sub-surface runoff (length/time)
E_v = evaporation (length/time)
S_{max} = maximum storage capacity (length)
z = relative storage ($0 \leq z \leq 1$)

The monthly water balance contains two parameters related to: 1) surface runoff (λ, unitless); and 2) subsurface runoff (α, units of mm/month). A third model parameter, maximum catchment water-holding capacity (S_{max}), was obtained from a global dataset based on the work of Dunne and Willmott (1996). The total effective precipitation (PT) is the amount of water entering the storage zone, after snowmelt accumulation and melt are considered where applicable. Note that total effective precipitation along with the estimate of potential evapotranspiration (PET) is passed to the IMPACT model for those agro-economic basins with agriculture.

Analysis of Monthly Mean Runoff for Select Basins

Calibration of the regions and basins that comprise the 69 hydro-economic zones was done by enumerating on the λ_j values that would minimize the RMSE error between the 'observed' mean monthly discharge, and the estimated discharge from the model for each of the 69 basins. Thus calibrations for each basin results in a unique λ_j for each land cover within that basin.

The WATERGAP model [Alcamo *et al.*, 2000] produces an estimate of mean monthly discharge which is assumed to be the natural flow of the basin, without the impact of water storage and water diversions. We present a series of monthly mean plots for a select number of the 69 basins and hydro-economic regions. The final calibration shows some estimates of basin runoff were subjectively better than others, although only a few showed poor performance. Most of this difference can be contributed to both model and data errors, remembering that we are assuming naturalized flows which in many cases is difficult to surmise and is subject to a great deal of uncertainty. The model was calibrated to the 12 mean monthly flows because the time-series dataset of precipitation and temperature used by WATERGAP was not available. Thus the goal was to calibrate to the central tendencies of the CRU climate dataset and the "natural" flows. Once the model is calibrated against the mean monthly flows, it can be run for any time series length. In our case, the model was run for sequences of 30-years.

Agronomic GAEZ model

The agronomic Global Agro-Ecological Zones (GAEZ) model was developed jointly by FAO and the Institute for Applied Systems Analysis in Vienna, Austria. The AEZ methodology follows an environmental approach; it provides a standardized framework for the characterization of climate, soil and terrain conditions relevant to agricultural production. Crop modeling and environmental matching procedures are used to identify crop-specific limitations of prevailing climate, soil and terrain resources, under assumed levels of inputs and management conditions. This part of the AEZ methodology provides maximum potential and agronomically attainable crop yields for basic land resources units (usually grid-cells in the recent digital databases). (Fischer *et al.*, 2002).

The AEZ computations were completed for a range of climatic conditions, including a reference climate (average of period 1961-1990), individual historical years of 1960 to 1996, and scenarios of future climate based on the published outputs of various global climate models. Hence, the AEZ results consistently quantify impacts on land productivity of historical climate variability as well as of potential future climate change.

The FAO/UNESCO Digital Soil Map of the World (DSMW) has been made the reference for constructing a land surface database comprising of more than 2.2 million grid-cells at 5' latitude/longitude within a raster of 2160 rows and 4320 columns. On the input side, the key components of the database applied in AEZ include the FAO DSMW and linked soil association and attribute tables, a slope distribution database, and a layer providing distributions in terms of eleven aggregate land-cover classes derived from a global 30 arc-seconds latitude/longitude seasonal land cover data set. On the output side, many new data sets have been compiled at grid-cell level and have been tabulated at country and regional level, including general agro-climatic characterizations of temperature and moisture profiles, and time-series of attainable crop yields for major food and fiber crops.

The information contained in these data sets forms the basis for several further AEZ applications. Examples are: the quantification of land productivity, the estimation of extents of land with rain-fed or irrigated cultivation potential, the occurrences of environmental constraints to agricultural production, the identification of potential 'hot spots' of agricultural conversion, and the possible geographical shifts of agricultural land potentials as result of changing climate. Finally, the results of AEZ land productivity assessments provide a spatially explicit and agronomically sound basis for applications of multi-criteria optimization of land resources use and development. The yield results from the AEZ model are then fed into the IMPACT model, and are used as the maximum potential yields for the crops within a given spatial unit**.**

The GAEZ assumes unlimited amounts of water to calculate potential yields but changing climate impacts yields via planting date, degree-growing days, and temperature during the key phonological periods of the plant. The GAEZ estimates water demand using the Penmen-Monteith equation, the same as the Runoff model and IMPACT-WATER uses.

3.3 Creating the Modeling Linkages

Using the various models, just described, we created linkages between the inputs and outputs of the various modeling components, in order to create an integrated, global-level assessment, and so as to capture the essential inter-connections between the economic, hydrologic, agronomic and environmental phenomena being modeled.

To summarize, again, the models called upon are:

1. The *K-nn* model – which generates conditionally-linked, statistical ensembles from historical climate data in order to model the variability of monthly surface climate conditions. This model was developed at National Center for Atmospheric Research and University of Colorado.
2. The Global Agro-Ecological Zones model (GAEZ) – which provides a standardized framework for the characterization of climate, soil, and terrain conditions relevant to agricultural production. This was developed at the International Institute for Applied System Analysis, with cooperation of FAO.

3. The IMPACT-WATER model – which was developed by IFPRI, and combines a price-driven economic model of commodity supply, demand and trade with a simulation model that models the production effects of water availability.
4. The WATBAL model – which takes global streamflow data from the WATERGAP model of the University of Kassel and translates it to basin-specific runoff, evapotranspiration, storage as well as both surface and sub-surface streamflow. This model is calibrated to the land cover types for each basin of IMPACT-WATER, so as to translate the results of global GCM downscaling to the conditions observed in each water basin.

The linkages between the various models (in terms of their inputs and outputs) is shown in Figure 3, which summarizes the conceptual modeling framework within which our analysis was done. Based on this framework, the analysis of the climate change and variability scenarios was carried out in order to produce the results that will be discussed in the next section

4. Climate Scenario Results and Policy Implications

In this section the key results from the analysis of the climate change and variability scenarios are examined, with a view to evaluating the performance of the combined modeling framework, and to illustrate the kinds of policy conclusions that can be drawn from them. .

4.1 Mean-Value Climate Change Results

The results of a changed climate on the water related inputs to food production were presented in the last section. These changes are presented as scenarios developed by taking the historical climate time series from 1961 to 1995 and adding the GCM produced 30 year decadal averages of monthly climate change. The IMPACT-WATER model simulated the time period from 1996 to 2025 with climate change acting as shock to the prevailing environmental conditions. We are reporting the results from 2000 onward to allow for model adjustments to the "mathematical shock".

The model is driven not only by climate by also by socio-economic change and the associated technological changes. Thus, as seen in Figure 5, the prices of wheat decline from 2000 to 2025 as the economic impacts of yield increase is felt by the system. Note, however, that the climate change scenarios preserve this trend but impact the level of final prices. Globally, the climate factors of production of wheat are enhanced by climate change and this leads to lower world market prices. However, regions can experience the opposite effect at a more local level. This same phenomenon is illustrated in Figure 6 showing an increase in global food demand as the result of increase population and lower prices. Climate change again impacts the rate and level of this increased demand by reduced global prices.

When looking at food production and demand in developed and developing countries, one can see that climate change will affect the countries differently (Figure 7) Irrigated and rain fed production will increase more in developed versus developing countries. Rain fed production is actually decreasing slightly in developing countries under some of the climate change scenarios. This may lead to more poverty relative to the developed nations as the poorer farmers rely on rain fed agriculture to grow their crops. If rain fed production decreases, these farmers that cannot afford irrigation will be hurt the most. When it comes to food demand, both developed and developing countries show the same trend of slightly increasing demand. IMPACT–WATER assumes that consumers will have the income to purchase low-priced imported food. For the low income consumers, especially the urban poor (taking into account underemployment and economy-wide factors,) this assumption may not hold and reduced productions will not be made up for by purchases of imports and hunger will increase. One should investigate trade to further dissect what is happening in the different regions.

Given the enormous amount of data that was generated from the global analysis we did, in this paper we will highlight some of the key findings, by only presenting the results that show the impact of climate change on food price, demand and production. These results will be reported as changes in the average of the variable over the period

2001 to 2025. Please note that what is being presented is the relative change from the base conditions, in the absence of climate change. So while demand might be increasing in an absolute sense, under climate change, it could actually be shown as a decreasing trend with respect to the baseline conditions.

Figure 8 shows total production increasing slightly for rice, and increasing more for maize, while either slightly increasing or decreasing for wheat, depending on the climate scenario. These same trends can be seen in the results for both irrigated and rain fed production with the exception that irrigated wheat production decreases and rain fed wheat production increases.

The increase in global production results in a decrease in world market prices (Figure 9) Rice shows about a 20% decrease, wheat between 10-20% while maize experiences price drops of 40-50%. These price changes correlate somewhat directly to the production changes but changes in the other crops and consumer preference can impact prices and market conditions.

Figure 10 shows the results of decreased prices, increased food demand and decreased hunger. Even in primarily subsistence agricultural economies, world and local prices impact subsistence household food consumption. Thus decrease in prices will lead to increased demand in all income sectors and should be reflected in a reduced proportion of the population that is at risk of hunger.

4.2 Climate Variability Results

GCM based climate scenarios provide only a single ‘point’ estimate of future climatic conditions. Whether that realization is used directly or as a relative change to a historic climate period, the output reflects only the mean monthly changes. To test how sensitive our agricultural system is to variability we used a Monte Carlo approach and simulated many realizations of future climates known as a statistical ensemble of climates. With these climate ensembles, we are able to examine how changes in climate variability impact food production, demand and prices, as opposed to just looking at impacts from greenhouse gas-induced changes in the mean. Two climate variability scenarios each with an ensemble of 30 future climate outcomes were developed and run through the IMPACT-WATER model, and the results are presented below.

Figure 11 shows the impact of increased and decreased ENSO events on global food demand. While halving the number of ENSO has little effect, doubling the frequency of ENSO events shows an appreciable effect on world food production and demand. Food demand decreases because yield and production decrease and prices increase on average because of the impacts of more frequent extreme events both flood and droughts. Lack of water from droughts decreases production, while increased water from flooding cannot be fully utilized. So even though the mean water availability remains the same, the mean food production goes down.

Figures 12 and 13 show the impact of the variability scenarios on a range of model variables disaggregated by developing and developed regions. The results show that developing regions are impacted more than developed because developing countries are located in more highly variable climate regions and generally have lower firm yield from storage to absorb the extreme events.

4.3 Climate Change versus Climate Variability

A question often posed is what is the relative importance to food systems of changes in mean climatic conditions versus changes in their variability? Since this assessment examined both type of scenarios we are able to present some comparative results.

Figure 14 shows the relative impact on global food demand and Figure 15 on food prices for climate change versus climate variability. The results show that for food demand the climate change scenarios have a positive affect while the variability scenarios have a negative or zero effect. This is due to the fact that under increases in greenhouse gases there will be a CO_2 fertilization impact on certain crops. Globally, this effect dominates any negative impact of temperature increases or precipitation decrease. While under the variability scenarios, lack of water from droughts decreases production, while increased water from flooding cannot be fully utilized. So even though the mean water availability remains the same, the mean food production goes down with no fertilization effects. This leads to higher prices and lower demand and increased risk of hunger.

4.4 Observations and Insights from Analysis

From this multi-component analysis, we were able to construe some important messages and conclusions from the extensive body of model output. Among the many insights that were generated from this work, the following points are particularly notable.

With respect to the spatial scale of analysis, we noted that there was a large difference between the magnitudes (and directions) of impacts at more aggregate spatial scales. Particularly with respect to those countries for which we had more detailed sub-regional spatial definitions (China, India and the United States), a notable difference could be seen when comparing the aggregate, country-level impacts to those seen at the basin level. It became clear from our analysis that a combination of both global and local-scale analysis is needed. While many of the trade and price effects are only measurable at the country-level (due to the way national accounts are created and reported), the interactions between water availability and food production (and the yield reductions due to deficit) occur at the basin-level – which necessitates a more local-level scale of analysis, from which one can aggregate upwards.

There also exists a combination of both mitigating as well as accentuating effects that can be observed from an integrated analysis such as ours. When analyzed together, the climate impacts that occur through certain agronomic pathways can be seen to either mitigate or accentuate the effects that are observed from other causes. For example, results from the GAEZ model show that non-water stress-related yield decreases can also be realized from adverse changes in temperature; but after evaluating the results from IMPACT-WATER, increased irrigation or effective precipitation was seen to lead, in some cases, to increased production in these same river basins – effectively offsetting the negative temperature impacts.

This analysis also pointed out the important difference between simply looking at changes in mean climatic conditions as opposed to looking at the impacts arising from changes in variability of climate. The former has been the focus of much of the work that has been done on climate change impacts, within the economic literature, whereas the latter has clear implications for vulnerability and risk, which is of particular importance when looking at impacts on countries with low infrastructural and institutional resilience, as well as on the poor. In all the scenarios, developing country regions were seen to be impacted more severely than the more developed regions, which suggests that particularly close attention should be paid to those regions when considering policies regarding national-level agricultural extension, grain stocking and productivity-enhancing research (such as for drought-tolerance).

From our results, the distinction between irrigated and rainfed production was also seen to be very important, when looking at crop-specific impacts on production due to either changes in mean climatic conditions or in climate variability. Rainfed production was seen to be impacted much more heavily than that of irrigated crops, due to the absence of means with which to supplement deficits in water requirements with irrigation. Under some wetter GCM scenarios, however, rainfed yield could increase dramatically due to increases in effective precipitation – so there are no hard-and-fast generalizations that can be made across all scenarios. Nonetheless, these results suggest that those regions which depend heavily on rainfed agriculture for production should look closely at ways of utilizing supplementary irrigation techniques, such as rainwater harvesting, and moisture-preserving cultivation practices in order to increase the effective infiltration of whatever water is available, and to reduce soil moisture losses under adverse climatic conditions. Agricultural research activities that lead towards improvements in crop traits that enhance resilience under environmental changes could also be of particular importance to these countries, and could yield high returns to investment.

Related to this, is the importance of technological change, which is shown by the results of our analysis. Our study shows that dynamic assessments of climate change should take socio-economic changes into account, such as population and income growth – but, particularly, those related to crop yield and productivity growth. It can be seen that for all scenarios modeled, the yield potentials are continuing to increase, along with per-capita demand for food from 1995 to 2025, even though actual production might be negatively impacted over the 30-year simulation period. The rate of change of yield and productivity potential is an important factor in determining how severe the impact of environmental shocks might be in the future, and should be assessed carefully under alternative scenarios, for the sake of maintaining the robustness of the analysis and determining the sensitivity of the results.

5. Conclusions

In this paper, we have described the methodology by which we were able to link several physically-driven models together with the IMPACT-WATER model in order to analyze the impacts of climate change and variability on global food production, demand and trade. The model linkage that we described was necessary to downscale the results from the global GCM climate models down to the spatial units that IMPACT-WATER uses to link food production to water availability, at the basin-level.

The results from this analysis show the differences in climate-driven impacts that are realized by irrigated and rainfed cropping systems under the various scenarios, and underscore the importance of this distinction when doing analyses of agriculture that are driven by effects closely tied to the environment. In the same way, making a distinction between C-3 and C-4 plant types is also important when trying to agronomically model the fertilization effects from atmospheric $C0_2$ content, that are also embedded in these climate scenarios. Therefore, researchers looking to generate environmental scenario-based results for crop production need to construct models with a greater degree of disaggregation in crop types than that which is usually given by standard economic models of agricultural production and trade. This, in turn, places greater data demands on the researcher, and may require the use of more detailed data than the highly aggregated statistics that are usually collected by national statistical bureaus or found in publicly-available databases.

When considering these types of environmentally-focused studies of agriculture, the need for linking traditional price-driven economic policy models with other models that look at specific physical phenomenon and their effects on productivity becomes clear. While this paper has shown one application of such an approach, other kinds of model linkage and integration could be possible, and should be pursued by policy researchers, with the help of hydrologists, agronomists or other type of physical modelers, in order to address the stresses of global environmental and economic change facing the future of the world agricultural economy and its underlying food systems.

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Figure 1. 36-Region Spatial Definition of IMPACT-WATER

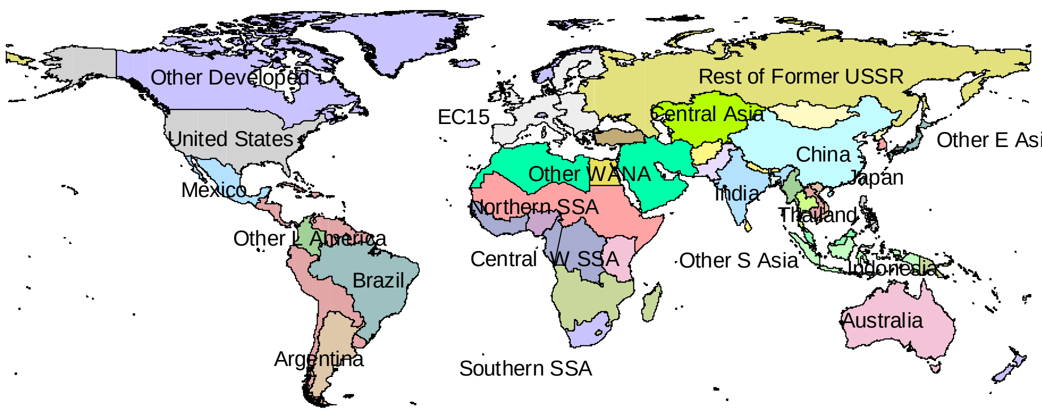
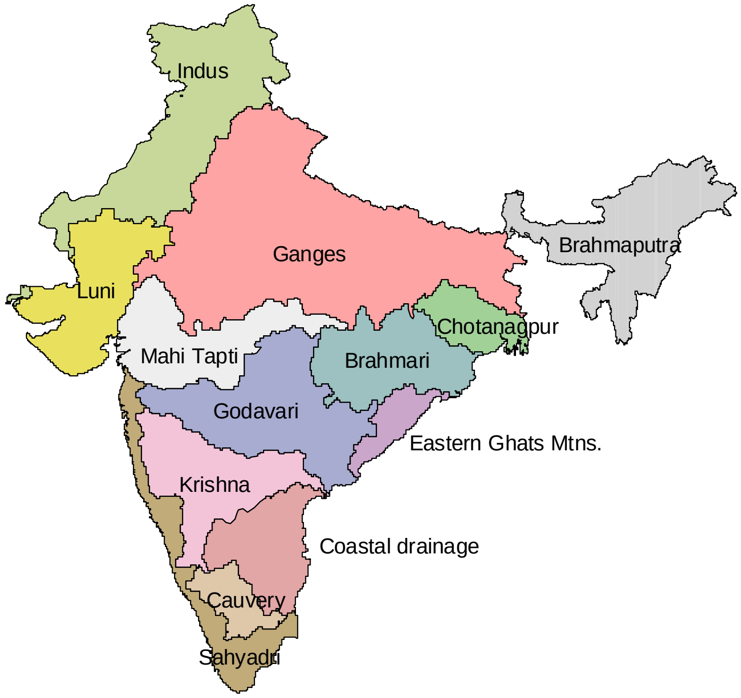


Figure 2. Spatial definitions for major sub-regional basins in IMPACT-WATER.

(a) Major basins in China

(b) Major basins in India



(c) Major basin in the United States

Figure 3. Schematic overview of model components and linkage.

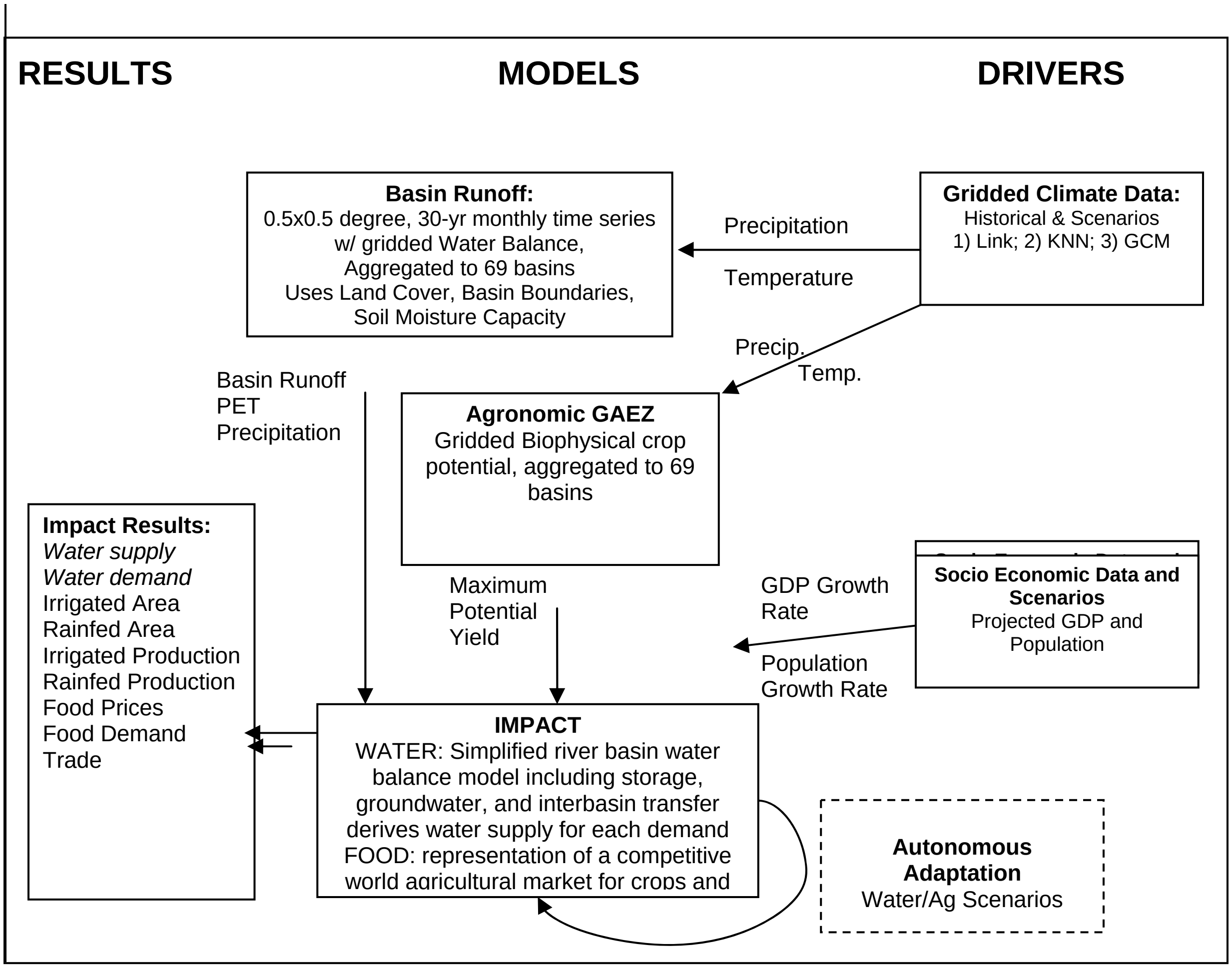


Figure 4. Schematic of the soil moisture scheme used to generate basin runoff and potential evapotranspiration.

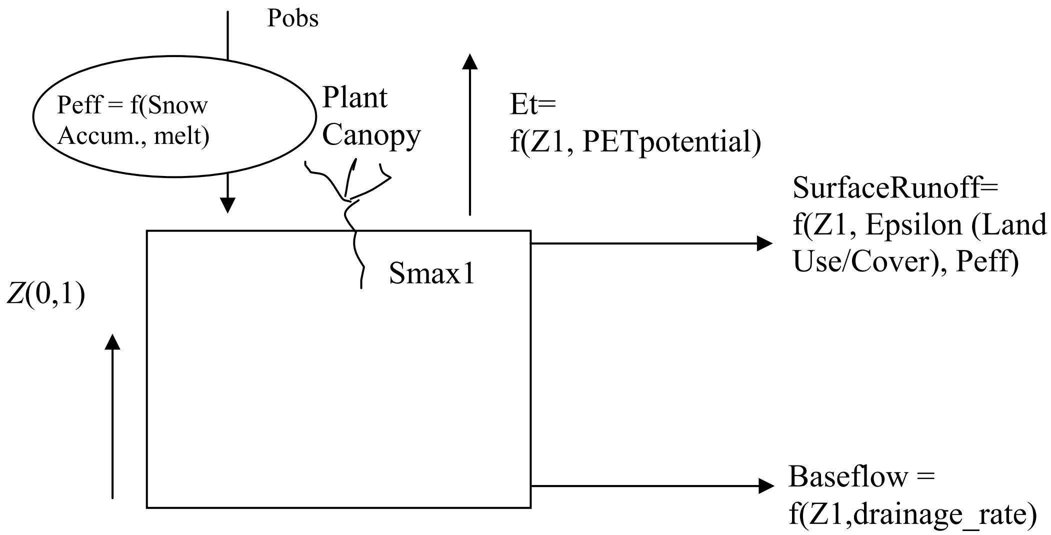


Figure 5. World Market Prices for Wheat

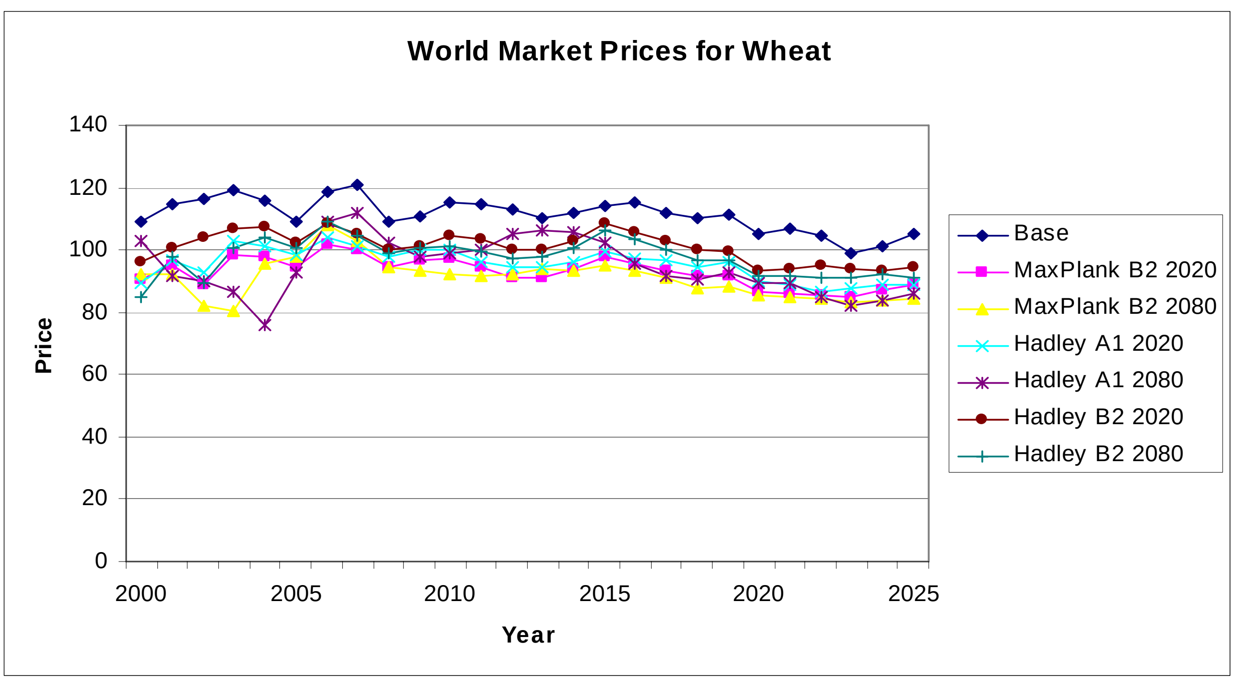


Figure 6. World Food Demand for Wheat

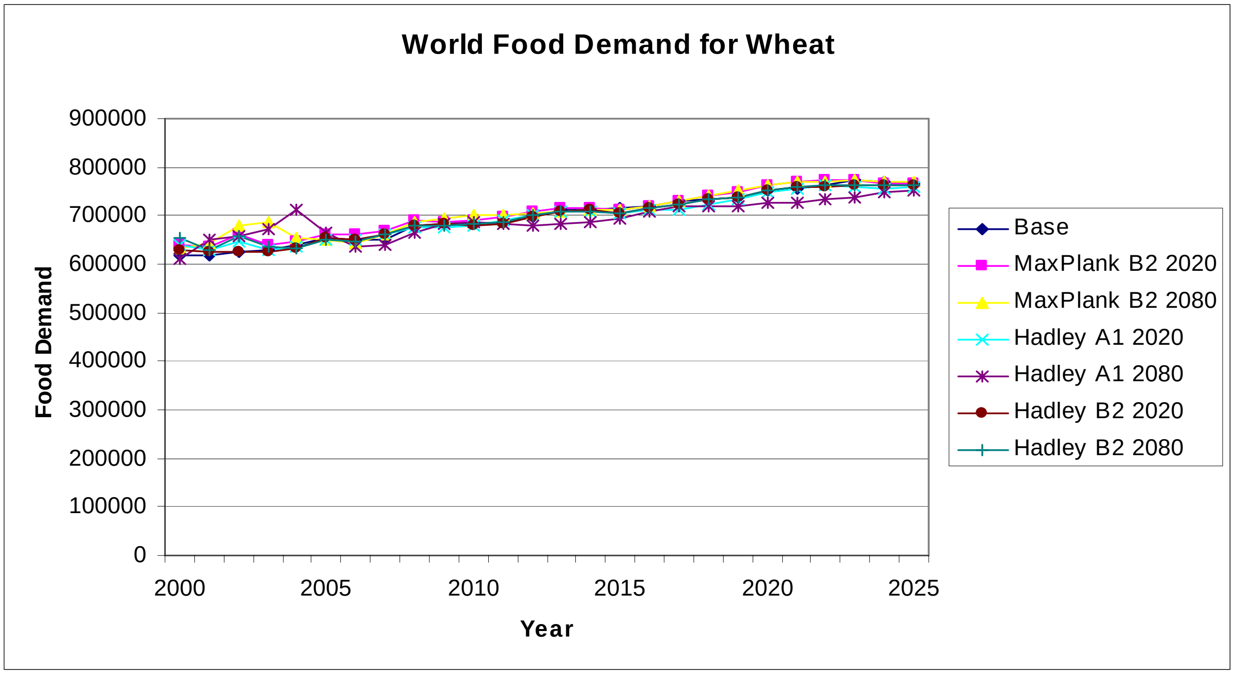


Figure 7. Global Food Analysis for Developed and Developing Countries with Climate Change

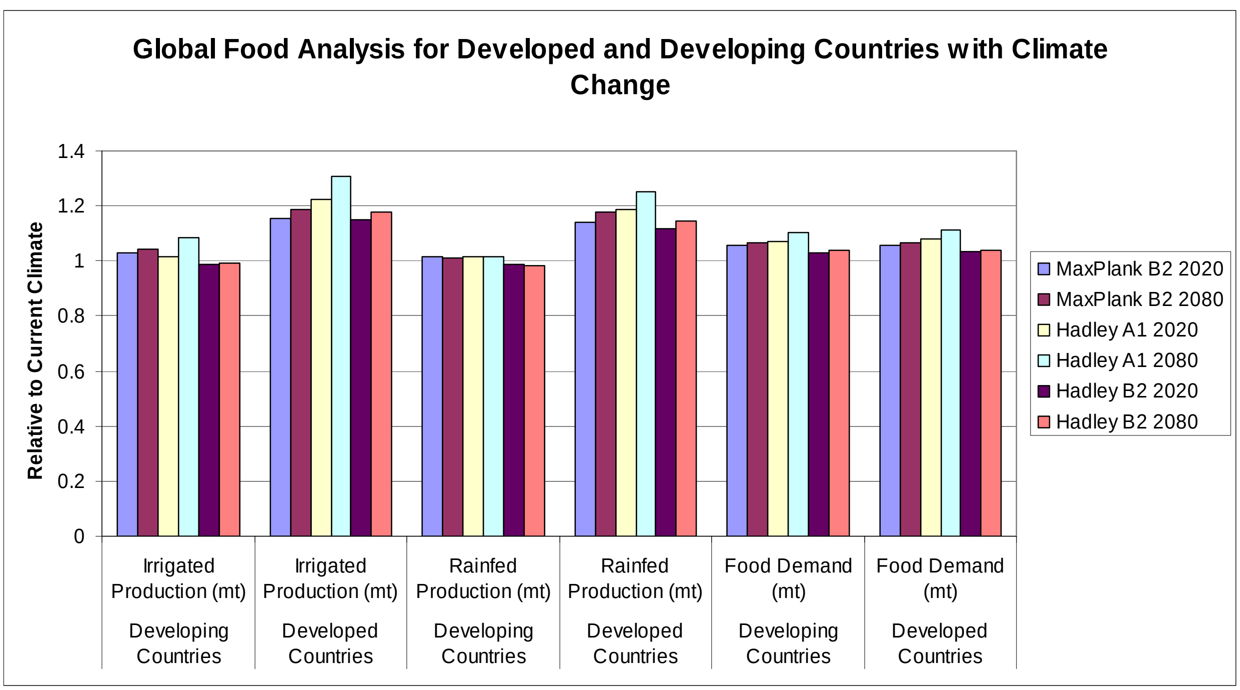


Figure 8. World Total (Irrigated and Rainfed) Production for Rice, Wheat and Maize

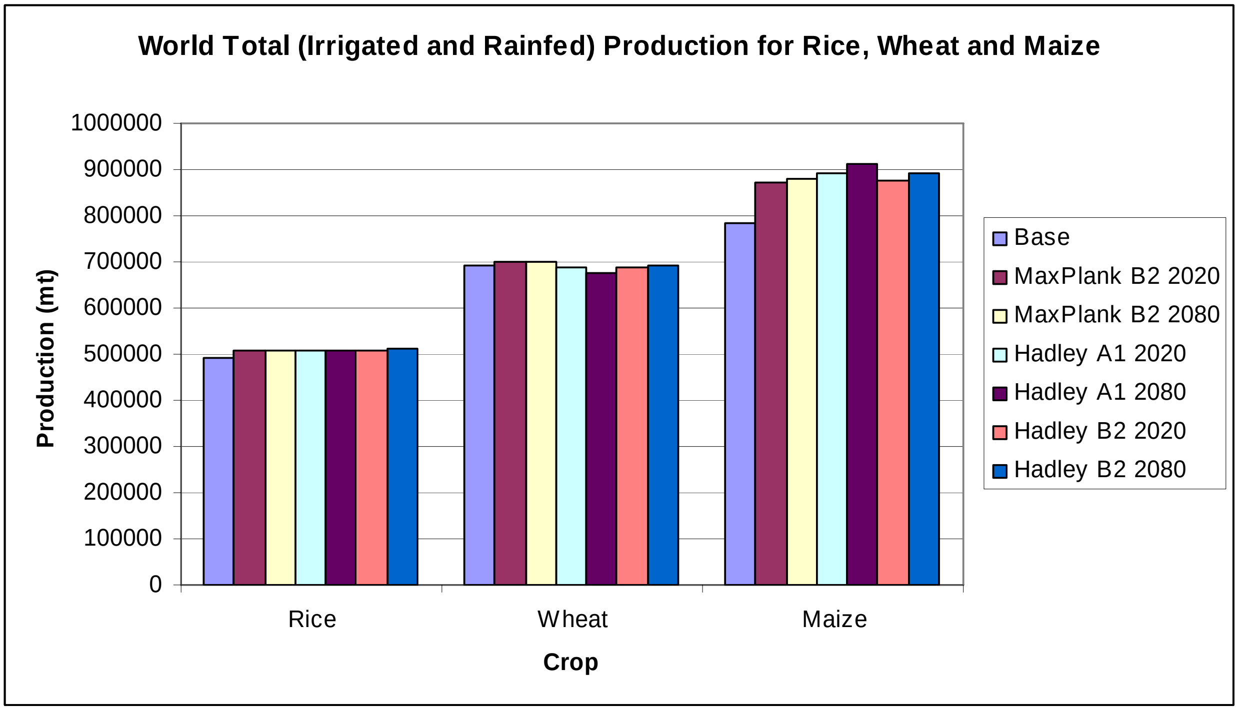


Figure 9. World Market Prices for Rice, Wheat and Maize

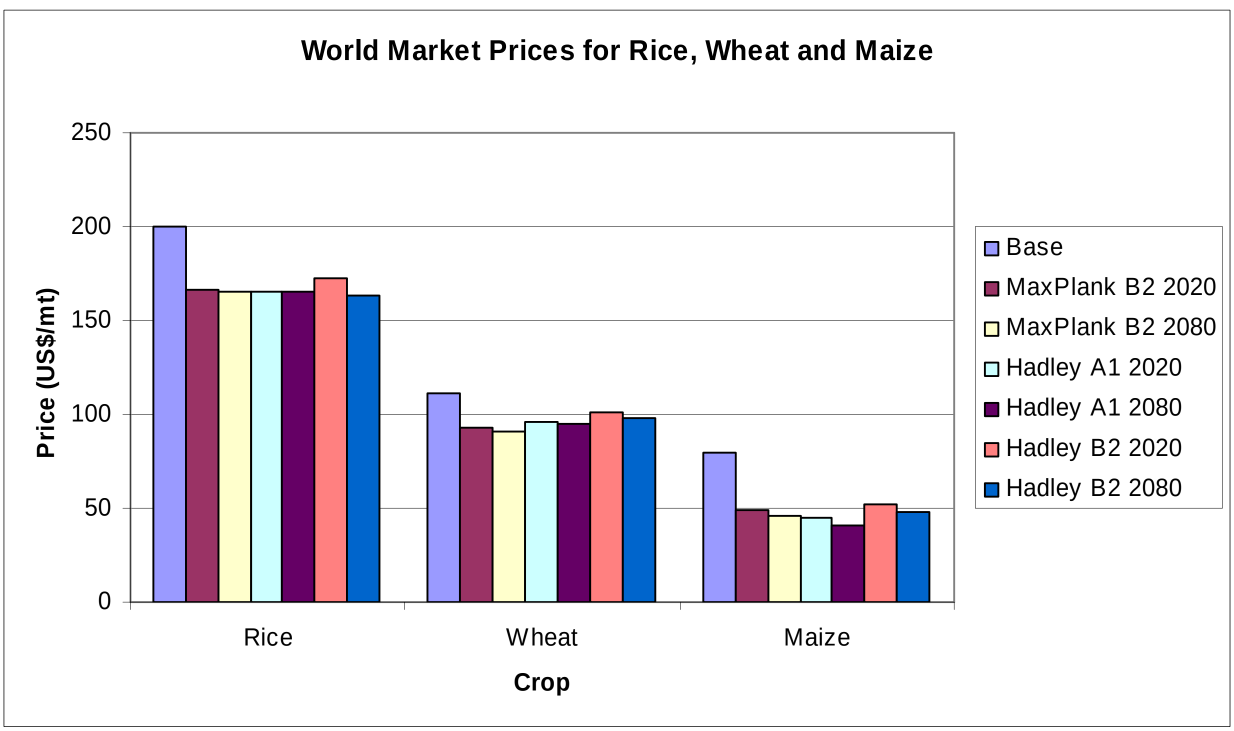


Figure 10. World Food Demand for Rice, Wheat and Maize

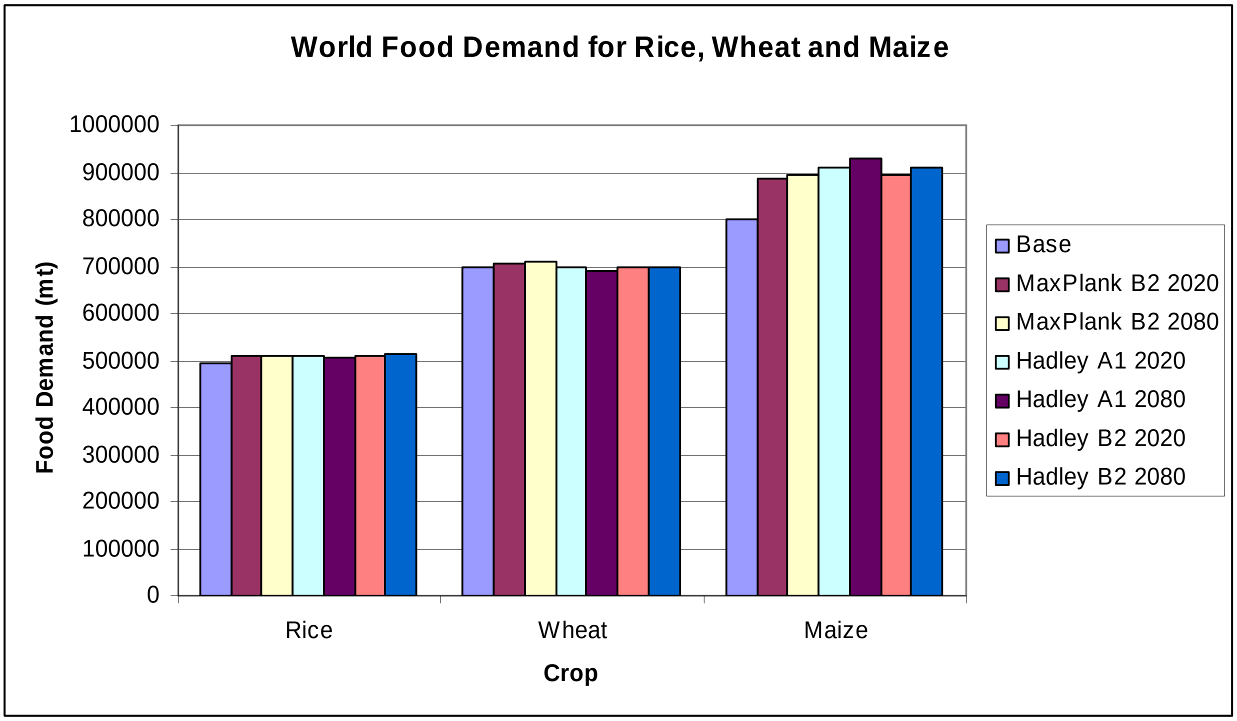


Figure 11. Average Effect of ENSO Years on Global Food Demand for Major Crops

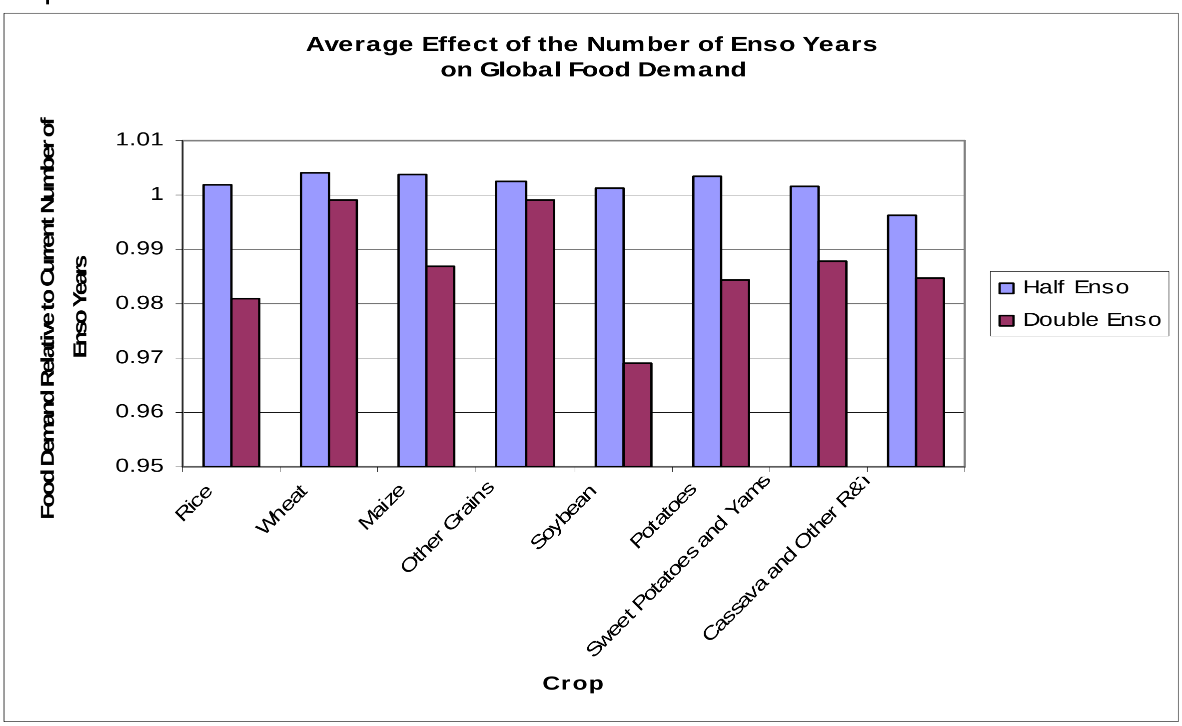


Figure 12. Global Effects of Halving ENSOs

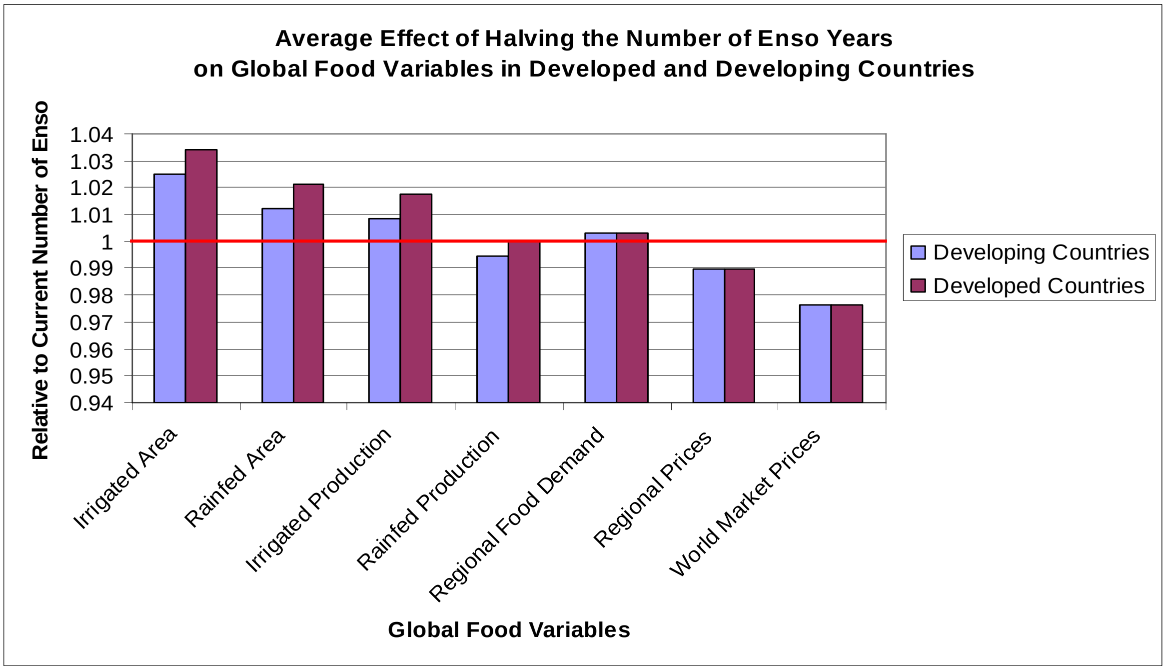


Figure 13. Global Effects of Doubling ENSOs

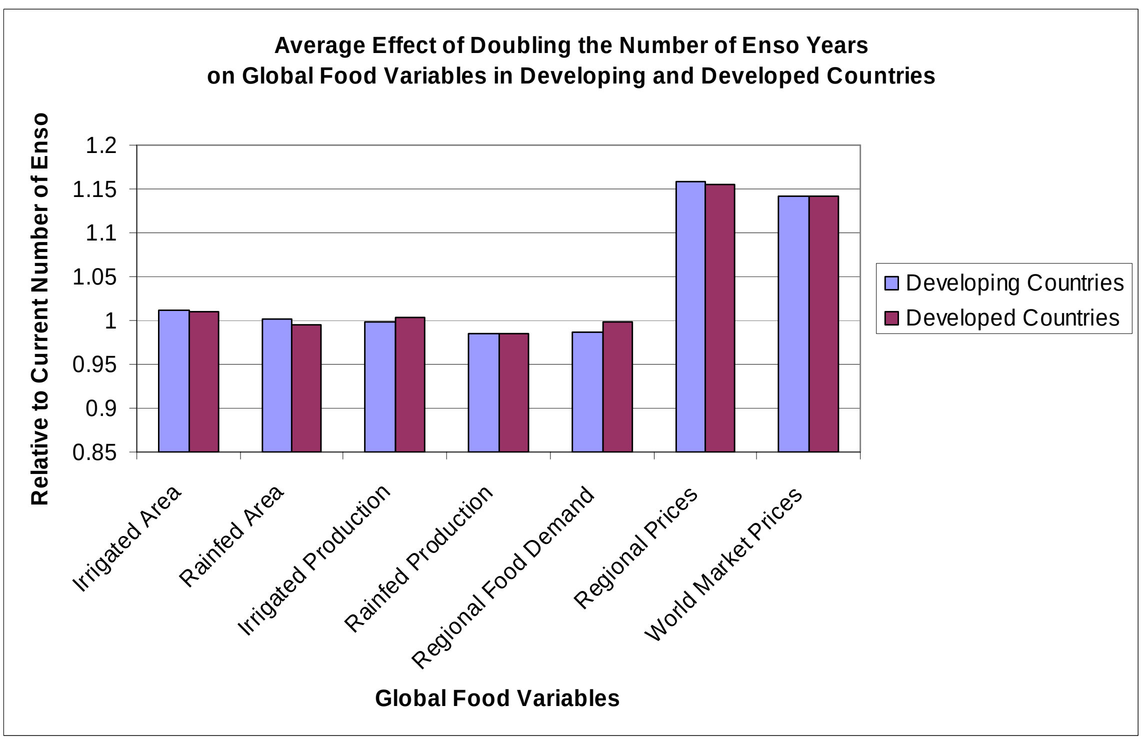


Figure 14. Effects of Climate Change and Variability on Global Food Demand

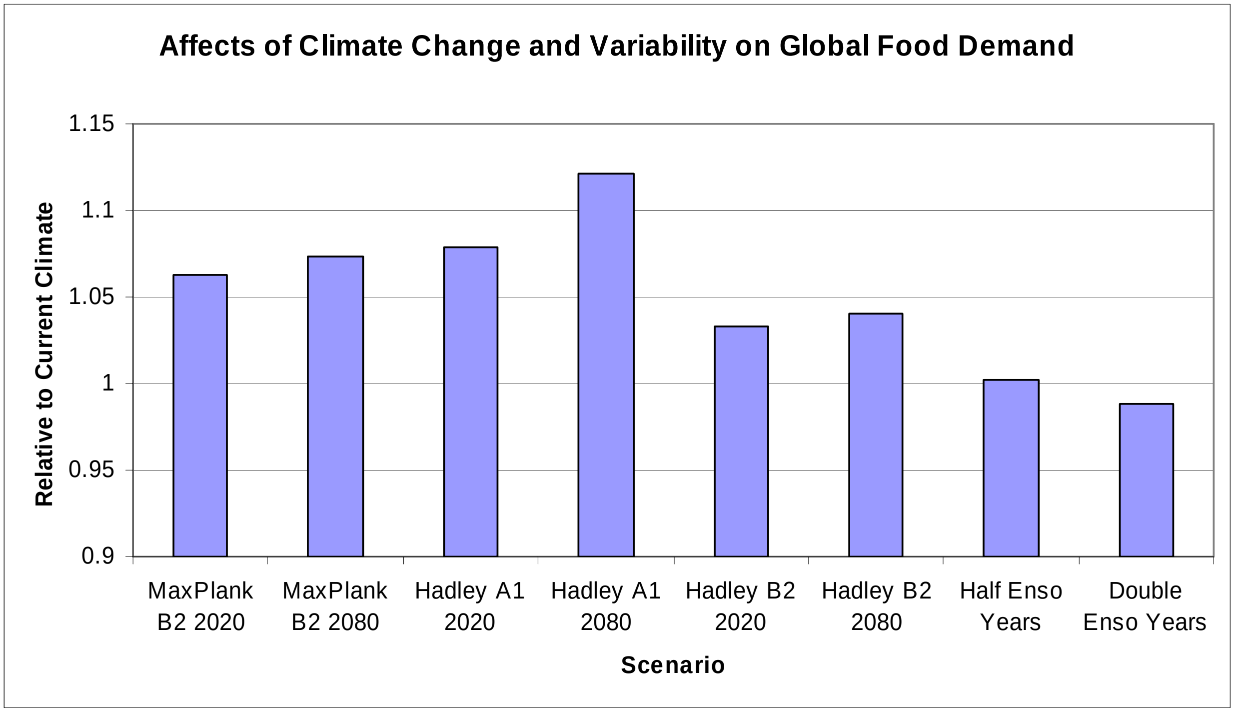


Figure 15. Effects of Climate Change and Variability on World Market Prices

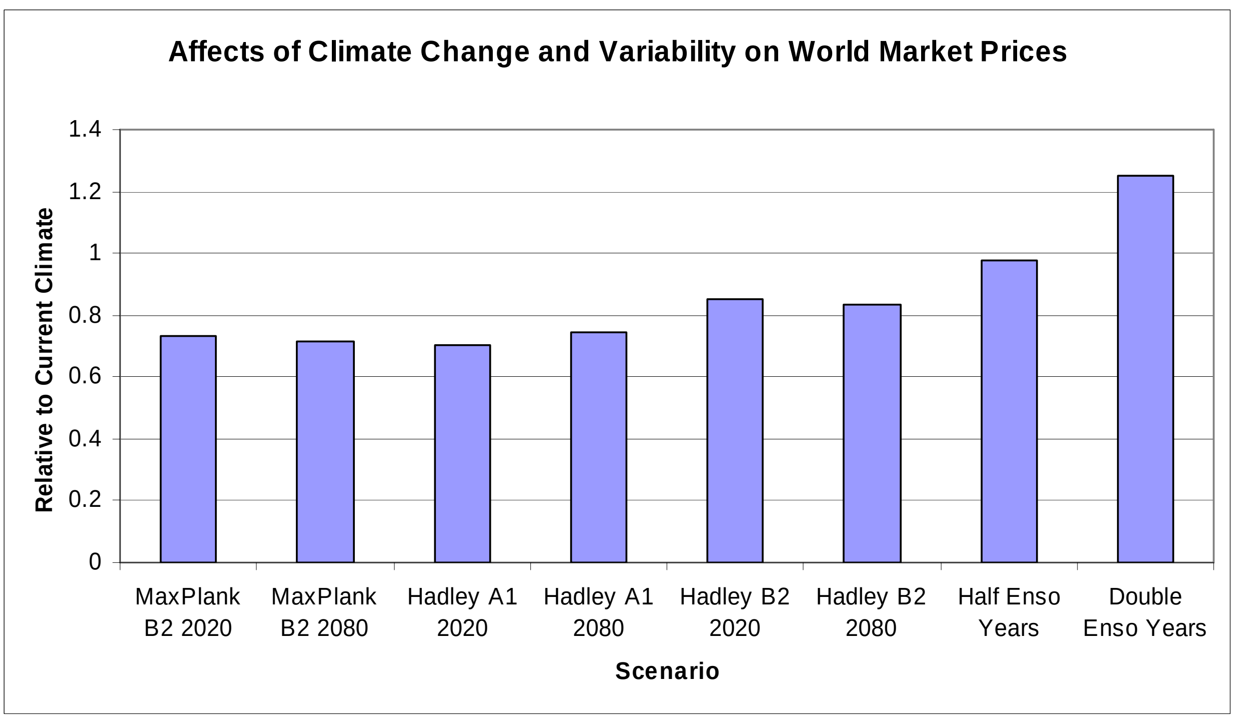


Table 1. GCM results from Hadley and Max Planck Models for Scenario A1.

Global Mean Temperatures Relative to 1990											
°C Celsius	**2000**	**2010**	**2020**	**2030**	**2040**	**2050**	**2060**	**2070**	**2080**	**2090**	**2100**
HadCM3	0.570	0.730	0.989	1.385	1.863	2.253	2.695	3.081	3.383	3.621	3.823
ECHAM4	0.379	0.488	0.671	0.962	1.315	1.595	1.923	2.209	2.434	2.614	2.770

Table 2. GCM results from Hadley and Max Planck Models for Scenario B2.

B2 Global Mean Temperatures Relative to 1990											
Celsius °C	**2000**	**2010**	**2020**	**2030**	**2040**	**2050**	**2060**	**2070**	**2080**	**2090**	**2100**
HadCM3	0.570	0.839	1.163	1.468	1.768	2.070	2.362	2.653	2.943	3.229	3.510
ECHAM4	0.379	0.577	0.813	1.033	1.251	1.472	1.686	1.900	2.115	2.328	2.538

Table 3. The ENSO years, characterized by either a La Niña or El Niño conditions.

La Niña	**El Niño**
1909	1903
1910	1906
1917	1912
1918	1915
1925	1919
1943	1926
1950	1931
1956	1941
1971	1942
1974	1958
1976	1966
1989	1973
	1983
	1987
	1992
	1995

Note: All other years (68 in total) were considered 'neutral' years.