CLM-AG: An Agriculture Module for the Community Land Model version 3.5

Arthur Gueneau, C. Adam Schlosser, Kenneth M. Strzepek, Xiang Gao and Erwan Monier

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Arthur Gueneau*†, C. Adam Schlosser*, Kenneth M. Strzepek*, Xiang Gao* and Erwan Monier*

Abstract

It is estimated that 40% of all crops grown in the world today are grown using irrigation. As a consequence, shifting precipitation patterns due to climate change are viewed as a major threat to food security. This report presents the Community Land Model-Agriculture module (CLM-AG), which models crop growth and water stress. The CLM-AG model is a global generic crop model built in the framework of the Community Land Model version 3.5. This report describes the structure and main routines of the model. Two different evaluations of the model are then considered. First, at a global level, CLM-AG is run under a historic climatology and compared to the Global Agro-Ecological Zones, an existing model of irrigation need. Second, the irrigation need computed for the United States is compared to survey data from the United States Department of Agriculture. For both evaluations, CLM-AG results are comparable to either the model results or the surveyed data.

Contents

1. INTRODUCTION 2
2. A GLOBAL PROCESS-BASED MODEL FOR GLOBAL CHANGE 3
   2.1 The IGSM Framework 3
   2.2 Philosophy of the Model and Inspiration 5
3. DESCRIPTION OF THE MODEL 5
   3.1 Structure in CLM 5
   3.2 Crop Physiology 6
      3.2.1 Growing Degree Days 6
      3.2.2 Crop Cover 7
      3.2.3 Crop Coefficient, Crop Height and Root Growth 9
      3.2.4 Leaf Area Index 10
   3.3 Biogeophysics and Hydrology 10
   3.4 Irrigation Need and Yield Reduction 11
      3.4.1 Potential Evapotranspiration 12
      3.4.2 Actual Evapotranspiration and Evapotranspiration Demand 12
      3.4.3 Irrigation Demand 13
      3.4.4 Yield Factor 13
4. MODEL EVALUATION: HISTORIC RUNS 13
   4.1 Input Data and Method for the Evaluation 13
      4.1.1 Crop Data 13
      4.1.2 Weather Data 14
      4.1.3 Evaluation Model Runs 14
   4.2 Results and Comparison with GAEZ 14
      4.2.1 The GAEZ Dataset 14
      4.2.2 Results for Maize 14
      4.2.3 Analysis 16
   4.3 Evaluation for the United States with FRIS 17
      4.3.1 Results 17
      4.3.2 Analysis 18
5. CONCLUSION 18
6. REFERENCES 19
APPENDIX A: Crop Parameters 22
APPENDIX B: Evaluation of CLM-AG versus GAEZ for Cotton 23
APPENDIX C: Evaluation of CLM-AG versus GAEZ for Spring Wheat 25
APPENDIX D: Implementing Yield Calculation in CLM-AG 27

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1. INTRODUCTION

With the global population projected to reach nine billion by 2050 (UN, 2004) and economic growth transforming the lives of millions in developing countries, world food demand is expected to roughly double by 2050 (FAO, 2009). This includes a westernization of diets in lower-income countries, where energy-, land- and water-intensive meat demand is expected to increase significantly. Agriculture already uses 34% of ice-free land worldwide (Ramankutty *et al.*, 2008) and is responsible for 10 to 12% of direct global greenhouse gases emissions[1] (Smith *et al.*, 2007), including most of the global emissions of methane. Humans used about 54% of all attainable runoff in 1996 (Postel *et al.*, 1996). Of this amount, 87% was used for agriculture, mostly for irrigation purposes (Shiklomanov, 2000).

In the broader context of food security, irrigation is an often overlooked but nevertheless important issue. Indeed, even if irrigated land composes only 20% of the cultivated area globally, it accounts for around 40% of the global food production (Döll, 2002). As is shown on the map of irrigated areas worldwide presented in Siebert *et al.* (2005) irrigation is crucial for food production in certain countries like Egypt, Pakistan and India. Any drop in irrigation capacity, whether from increased water demand from crops or decreased runoff in the streams would have dire consequences for these countries, especially at a time when they need to ramp up their production capacity to meet the demands of a growing population. At the same time, the development of irrigation in some areas (mostly in Africa) could spur an agricultural revolution in these countries and increase crop yields, thus improving food security and being part of the answer to meeting food demand growth.

Irrigation is crucial to the agricultural policies of many countries, but evaluating the relevance of irrigation projects becomes increasingly difficult as climate changes. Indeed, one of the major factors relevant to assessing the potential success of such a project is the amount of water required by crops to grow healthily. However this irrigation need is highly dependent on temperature and on precipitation, and is likely to vary significantly under a changed climate.

We thus need tools to assess the potential impact of climate change and its surrounding uncertainty. These tools can help policy makers make informed decisions on irrigation projects and, more broadly, to assess the risks future climate change could pose for human food supplies. As it is impossible to rely on past observations to predict future irrigation need—given climate change and its impact on the planet—we must rely on models to answer these questions. This paper describes the crop and irrigation model Community Land Model-Agriculture module (CLM-AG). This model was designed to be a part of the MIT Integrated Global System Model (IGSM) framework (Prinn *et al.*, 1999; Sokolov *et al.*, 2005). This integrated approach ensures that all models, parameters and results (from greenhouse gases emissions to irrigation need) are consistent with one another and do not result in physical impossibilities.

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[1] This number would be higher if we were to take into account indirect emissions due to deforestation to claim new crop land or pastureland, which is much harder to quantify.

2. A GLOBAL PROCESS-BASED MODEL FOR GLOBAL CHANGE

2.1 The IGSM Framework

The CLM-AG model has been developed with the potential to become a component of the MIT IGSM (Prinn *et al.*, 1999) that would be used for water and food studies under global change. In the context of an integrated global assessment, a crop water stress and irrigation demand model must meet certain specifications that differ from other crop models (yield prediction or irrigation planning at the field scale require different specifications for example). First the model needs to output a monthly irrigation demand (later used in the Water Basin Model in the IGSM framework) and a rainfed yield factor (that quantifies the effects of water stress on crop yields, and that is used in calculating the agricultural output). Second, as the model has to be global, it must be able to run on large grid cells and to be as computationally efficient as possible. Finally, as it is difficult to predict how crop characteristics will change in the future, this model needs to be a generic crop model with a minimal set of inputs.

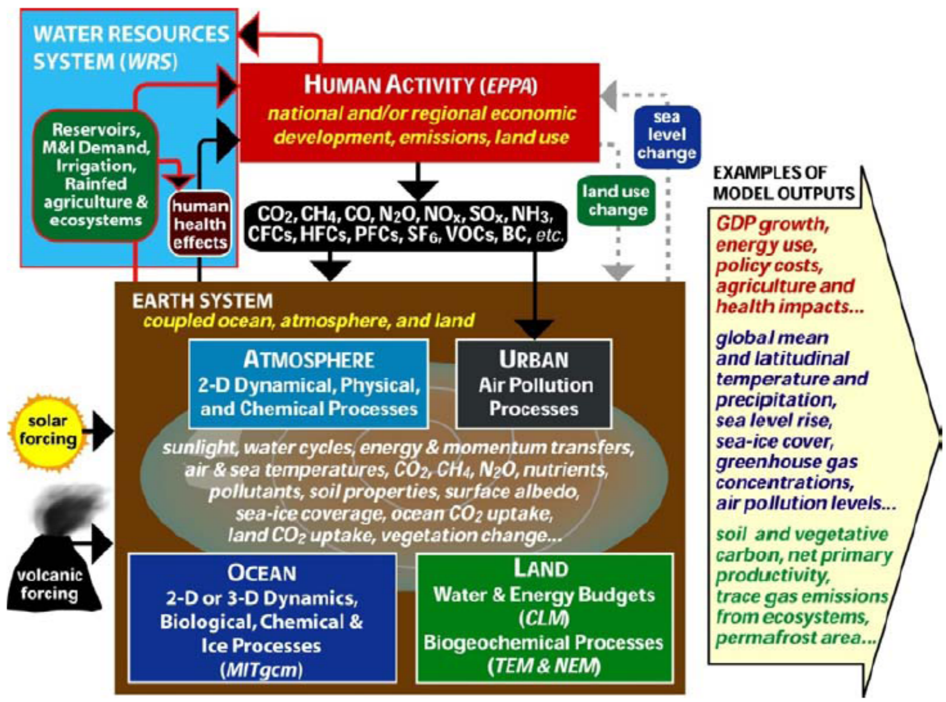

Figure 1. The IGSM Framework.

Figure 1 describes the MIT IGSM framework, with a particular highlight on the Water Resource System (WRS)(Strzepek *et al.*, 2010). Using emission predictions and economic outputs from the MIT Emission Prediction and Policy Analysis (EPPA) model (Paltsev *et al.*, 2005) and earth system modeling predictions from the IGSM (Sokolov *et al.*, 2005), the Water Basin Module (WBM) describes climate impacts on water demand as described in **Figure 2**. Previously, the hydrology part (runoff) would come from the Community Land Model (CLM)(Bonan *et al.*, 2002) and the agriculture part from CliCrop (Fant *et al.*, 2012). These two distinct parts may create an inconsistency in the framework. Indeed, CLM and CliCrop did not have the same soil water calculation algorithms, leading to inconsistencies in their respective water balance when putting the results together in WBM. CLM-AG solves this issue by integrating the two models with a single soil water module. It also integrates advances in crop modeling that were not simulated or simulated differently in CliCrop.

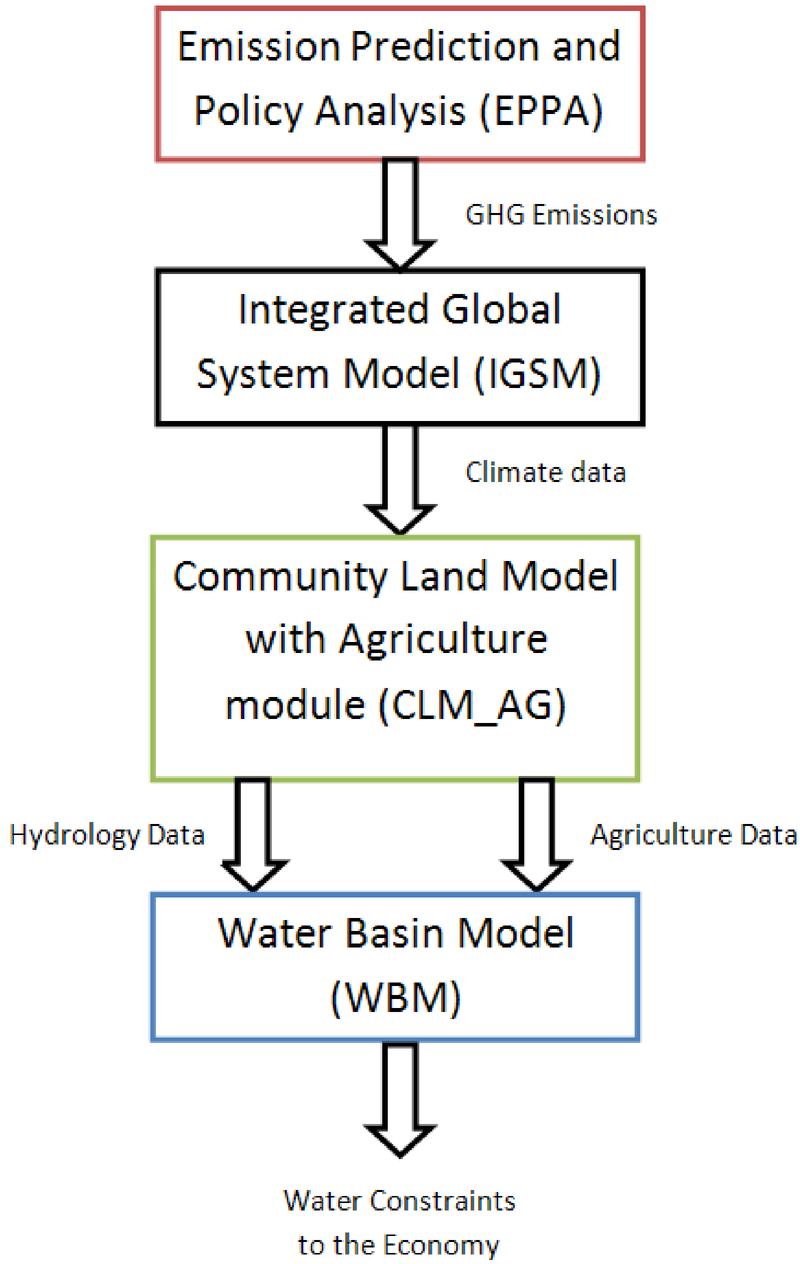

Figure 2. The WRS framework.

2.2 Philosophy of the Model and Inspiration

CLM-AG was originally intended to be a simple implementation of CliCrop in the very flexible Community Land Model (CLM v3.5) (Oleson *et al.*, 2004, 2008)[2]. However, it evolved to include advances in modeling and a better understanding of management options for agriculture.

As an evolution of CliCrop, CLM-AG relies on the same principles; the irrigation and yield reduction routines are taken from CROPWAT (Smith, 1992). However, the physiology of the crop needed to be more precise than the one in CROPWAT as CLM runs on an hourly time-scale (CROPWAT is monthly). CLM-AG thus relies primarily on AquaCrop physiology routines to drive plant growth (Raes *et al.*, 2009). Meanwhile the soil hydrology remains unchanged from the original CLM model.

3. DESCRIPTION OF THE MODEL

We describe here only the agriculture and irrigation routines created during the course of this work. The interested reader will find a precise description of the other CLM routines in the CLM 3.0 technical description (Oleson *et al.*, 2004) and the subsequent improvements of CLM 3.5 in the CLM 3.5 description (Oleson *et al.*, 2008).

3.1 Structure in CLM

The CLM structure is a nested subgrid hierarchy under the unit of the gridcell. Climate inputs are given at the gridcell unit. Each gridcell is composed of multiple landunits, soil columns and Plant Functional Types (PFTs). Soil properties are defined at the landunit level. The energy and water balances are made at the column level. Of primary concern for agriculture, soil hydrology routines operate at this level. Finally, plant dynamics are simulated at the PFT level with both biophysical and biochemical routines.

Figure 3 shows the changes from the usual CLM structure made in CLM-AG. Cropland is now a separate landunit with each crop being a distinct column. Separating crops in different columns (and not only PFTs) prevents them from competing for the same water resources present in the ground: the two distinct fields are completely independent when it comes to the water content in the soil.

The scheme is entirely flexible and one can add new crops as needed. Currently, only maize, spring wheat and cotton are implemented in the framework as they are among the two most important food crops and cash crop, respectively. It is also important to note that besides the plant physiology, all other CLM routines (hydrology, energy and water balance, snow cover, etc.) apply to crop landunits as they apply to natural PFTs. This ensures consistency between the different landunits.

[2] The MIT Joint Program on the Science and Policy of Global Change currently uses the version 3.5 of CLM for all its land studies.

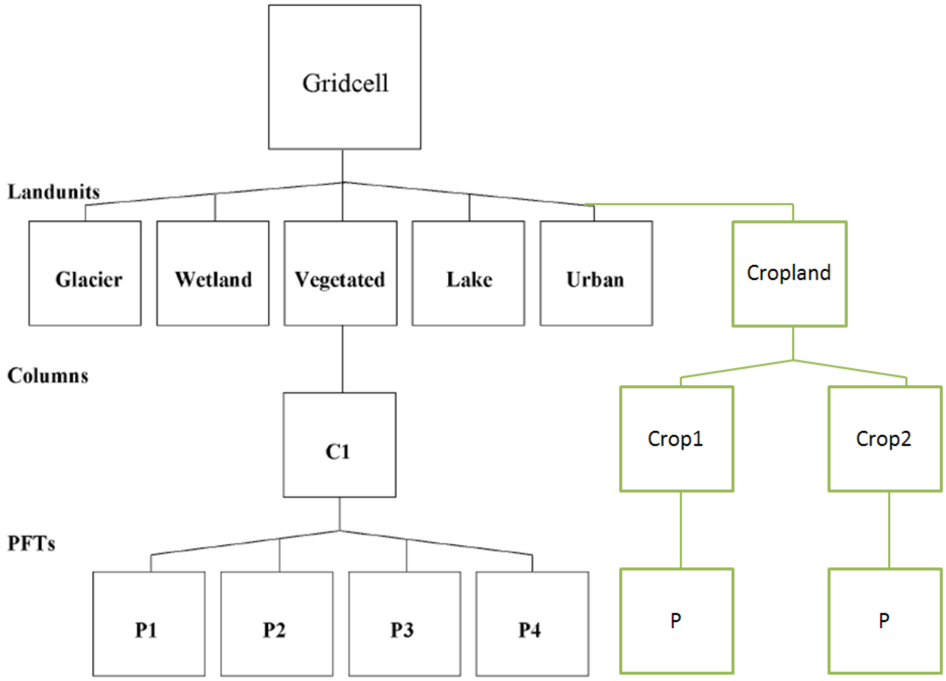

Figure 3. The CLM-AG structure. Changes to the usual CLM structure are represented in green. (Adapted from Oleson *et al.* (2004).)

3.2 Crop Physiology

CLM-AG adds new plant types to CLM. The physiology of these news plants (the crops) differs from the other plants physiology as simulated in CLM. In the standard CLM, root extension is fixed and plant height and Leaf Area Index (LAI) are interpolated from monthly input data. This is a good approximation for natural plants but is too imprecise to calculate crop water stresses. To generate an accurate representation of the irrigation demand, we indeed need a better representation of the crop itself. The representation implemented in CLM-AG is largely based on the physiology routines of AquaCrop (Raes *et al.*, 2009).

CLM-AG being a generic crop model, all crop parameters appearing below, except mentioned otherwise, are crop dependent and do not vary geographically. The values of these parameters for maize, spring wheat and cotton are detailed in Appendix A.

3.2.1 Growing Degree Days

The planting date and the length of the growing season are prescribed by an input data file and held constant for this study. In CLM-AG the growth of a crop is not measured in days but in growing degree days (GDD) that are defined for each day as follows:

$$GDD = \frac{T_{min}+T_{max}}{2} - T_{base} \tag{1}$$

where GDD is the accumulated growing degree days for the day, T_{min} and T_{max} are respectively the minimum and maximum temperatures (with minimum and maximum threshold values being the crop parameters T_{base} and T_{upper}) for the day and the crop parameter T_{base} is the base temperature for the crop (all temperatures are in Kelvin).

We also define for each crop and each gridcell a GDD ratio that is the ratio between the length of the growing season in a particular gridcell and a standard length of the growing season to account for the fact that farmers in colder climates will plant faster-growing crops than in warm climates[3] . This standard length is defined arbitrarily as it is but a reference point and has no impact on the final result. The GDD ratio is calculated as follow:

$$gddratio = \frac{gr\_length(lat,lon)}{gr\_length\_std} \tag{2}$$

where $gddratio$ is the unitless growing length ratio, $gr\_length(lat, lon)$ is the growing length of the gridcell (in GDD) and gr_length_std is the arbitrary standard value of the length of the growing season for this crop (in GDD).

3.2.2 Crop Cover

Figure 4 presents the AquaCrop physiology implemented into CLM-AG. The crop cover is the basis for calculating the physiology of the plant and varies with the number of growing degree days elapsed since the planting date. The crop cover is defined as the proportion of the ground covered by the crop canopy at a given time. There are four distinct stages in the growing season:

- Initial stage: the seed is in the ground and the roots grow until the emergence of the plant.
- Vegetative stage: the plant grows and develop its leaves until it reaches full canopy cover.
- Yield formation: the plant is at full canopy cover. This is when flowering happens and fruits begin to appear.
- Senescence: the canopy cover diminishes as the plant ages and the fruits finish growing until they are harvested.

We describe below how CLM-AG simulates these different stages in chronological order.

After planting the seed stays in the ground until emergence time that is prescribed by:

$$gdd > t\_em \cdot gddratio \tag{3}$$

where gdd is the accumulated[4] growing degree days since planting and the time to emergence t_em is a crop parameter (in GDD).

Upon emergence, the initial crop cover of the crop is defined by the crop parameter CC_0 and the crop enters the vegetative state.

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[3] A longer growing season usually improves the yield but can create a weather risk (freezing, drought, etc.) in some areas.

[4] Growing degree days are accumulated by adding every day to the previous day total which is equal to the corresponding number of growing degree days.

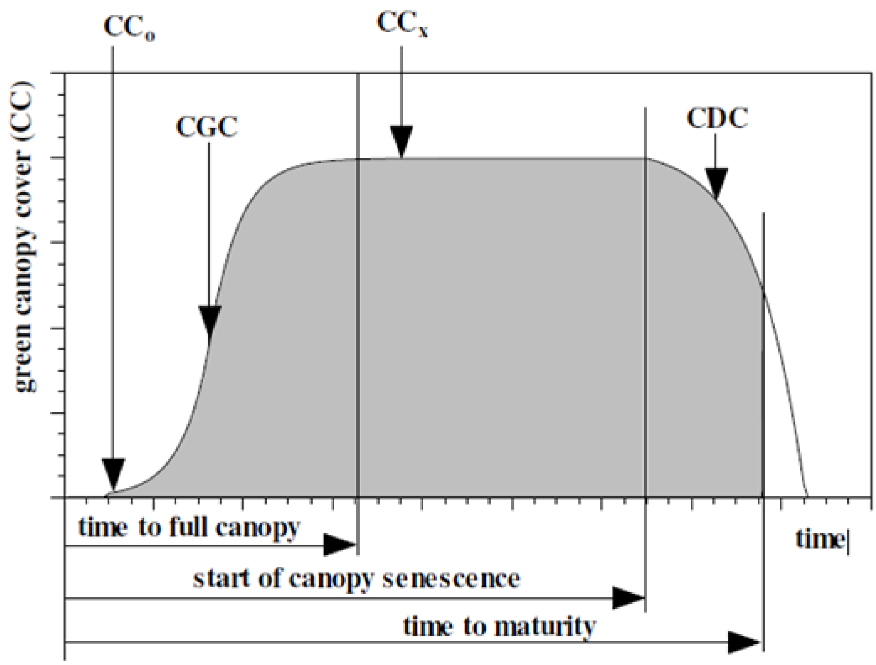

Figure 4. CLM-AG crop physiology is a transcription of the AquaCrop model (Raes *et al.*, 2010).

Then, until it reaches a crop cover of 0.5 (or 50%), the crop grows exponentially at the end of every day:

$$CC = CC_0 \cdot \exp\left(\frac{gdd}{gddratio} \cdot CGC\right) \tag{4}$$

where CC is the crop cover, CC_0 is the initial crop cover, gdd is the accumulated growing degree days since emergence (in GDD) and CGC is a crop parameter.

After reaching this threshold of $CC = 0.5$, the growth rate of the crop decreases until it reaches 98% of the maximal crop cover value CC_x (which is a crop parameter):

$$CC = CC_x - 0.25 \cdot \frac{CC_x^2}{CC_0} \cdot \exp\left(-\frac{gdd}{gddratio} \cdot CGC\right) \tag{5}$$

where CC is the crop cover, CC_0 is the initial crop cover, CC_x is the maximum crop cover, gdd is the accumulated growing degree days since emergence (in GDD) and CGC is a crop parameter.

At this point the crop has reached the yield formation stage and the crop cover stays at CC_x until senescence, which is triggered by:

$$gdd > t\_sen \cdot gddratio \tag{6}$$

where gdd is the accumulated growing degree-days since emergence and the time to senescence t_sen is a standard crop parameter (in GDD).

The crop then starts to decay during the senescence stage according to the equation:

$$CC = CC_x \left(1 - 0.05 \cdot \exp\left(\frac{CDC}{CC_x} \frac{gdd}{gddratio} - 1\right)\right) \tag{7}$$

where CC is the crop cover, CC_x is the maximum crop cover, gdd is the accumulated growing degree days since the beginning of senescence (in GDD) and CDC is a crop parameter.

Finally the crop is harvested when the crop reaches maturity as follows:

$$gdd > t\_mat \cdot gddratio \quad (8)$$

where gdd is the accumulated growing degree days since the beginning of senescence and the time to maturity t_mat is a standard crop parameter (in GDD).

CC is subsequently held at zero until the beginning of the next growing season the following year.

3.2.3 Crop Coefficient, Crop Height and Root Growth

The basal crop coefficient Kcb expresses how much evapotranspiration comes from the crop as compared with a well-watered reference grass (a precise definition of which can be found in Allen *et al.* (1998)).

As in AquaCrop, before the canopy reaches the maximum canopy cover Kcb can be calculated as:

$$Kcb = (1.72 \cdot CC - CC^2 + 0.3 \cdot CC^3) \cdot Kcb_x \quad (9)$$

where Kcb is the basal crop coefficient, CC is the crop cover and Kcb_x is a crop parameter representing the maximum basal crop coefficient.

Once the crop has reached maximal canopy cover, and after a five day time lag, Kcb is expressed as:

$$Kcb = Kcb_x - (t - 5) \cdot f_{age} \cdot CC_x \quad (10)$$

where t is the number of days since maximum canopy cover, the crop parameter CC_x is the maximal canopy cover and f_{age} is a crop parameter.

Finally when senescence starts and the canopy starts to decay the previous expression of Kcb is corrected by the ratio $\frac{CC}{CC_x}$ as follows:

$$Kcb = \frac{CC}{CC_x} \cdot (Kcb_x - (t - 5) \cdot f_{age} \cdot CC_x) \quad (11)$$

The height of the canopy is calculated following AquaCrop by:

$$h = h_x \cdot \frac{CC}{CC_x} \quad (12)$$

where h is the height of the canopy, h_x is a crop parameter representing the maximum height of the canopy, CC is the crop cover and CC_x is the maximum crop cover. The crop height does not decrease after senescence starts but stays at maximum height until harvesting, even after the crop cover declines.

Roots grow by a fixed amount on a daily basis as soon as the crop is planted and until maximum depth is reached. Initial root depth (rt_{ini}), daily root growth (rt_{gr}) and maximum root depth (rt_{max}) are crop parameters. The root fraction in a given layer of soil (per unit of volume) is then calculated at the end of every day using the same routine CLM uses for other plants (see Oleson *et al.* (2004)).

3.2.4 Leaf Area Index

The Leaf Area Index (LAI) is defined as the area of leaf per area of ground and represents the density of the canopy. It differs from crop cover in the sense that it takes into account multiple layers of leaves. CLM needs the LAI as a crucial parameter to calculate the energy and water balances in the crop. We follow here the observations and parametrization of LAI by Vina (2004) that shows that the crop cover is an exponential function of the LAI.

We thus estimate the LAI based on the crop cover as:

$$LAI = LAI_x \cdot \frac{log(1-CC)}{log(1-CC_x)} \quad (13)$$

where LAI and LAI_x are respectively the current and maximum LAI of the plant (LAI_x is a crop parameter) and CC and CC_x are respectively the current and maximal crop cover.

3.3 Biogeophysics and Hydrology

Figure 5 presents the biogeophysical and hydrological processes simulated in CLM 3.5. CLM-AG uses these same routines for crop columns to preserve consistency.

It is interesting to note that CLM has ten different soil layers among which water flows. This implies for crops that even if it does not rain they may still absorb required moisture from deeper soil layers. Accurate simulation of the snow pack is also crucial in some areas. On the American Great Plains for example most of the water crops need come from snow melt on the field at the beginning of the season. The interested reader will find a more extensive description of the biogeophysical and hydrological routines in the CLM technical description (Oleson *et al.*, 2004).

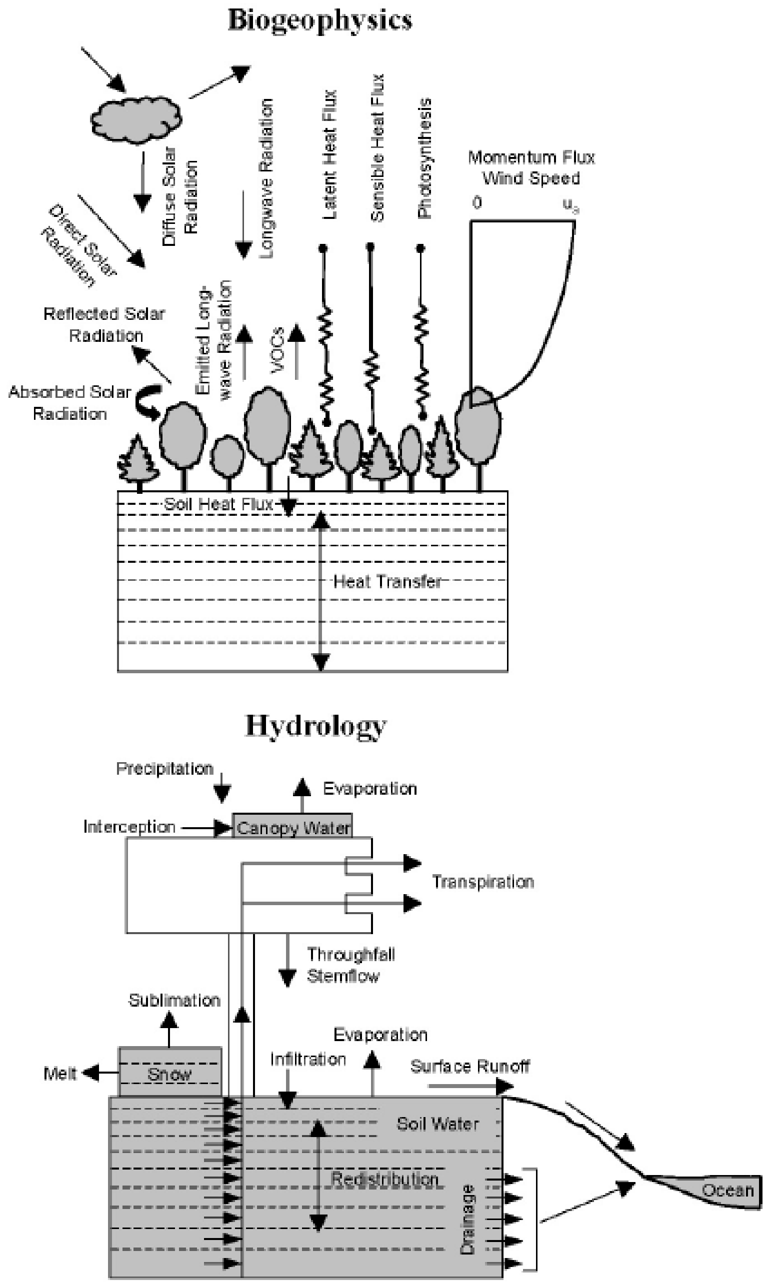

Figure 5. The biophysical and hydrological processes simulated in CLM (Oleson *et al.*, 2004).

3.4 Irrigation Need and Yield Reduction

Following CROPWAT (Smith, 1992), the water deficit is calculated in CLM-AG as the difference between potential and actual evapotranspiration of the crop. Actual evapotranspiration is easily drawn from existing CLM variables, however we need to define a measure of the potential evapotranspiration.

3.4.1 Potential Evapotranspiration

There are several methods to calculate evapotranspiration in the literature; they differ in precision and complexity. The historic and most trusted method is the Penman-Monteith equation (Monteith, 1965; Allen *et al.*, 1998). However, this formula is data-intensive as it requires precise measures of humidity and wind. To address this issue, many methods have been developed to estimate potential evapotranspiration (PET) with less data requirements. One such method is the Modified Daily Hargreaves method (Farmer *et al.*, 2011) developed at the MIT Joint Program. It requires only daily average, maximum and minimum temperatures as well as daily precipitation.

CLM-AG follows this approach and expresses PET as:

$$PET = 0.0019 \cdot 0.035 \cdot Ra \cdot (T_m + 21.0584) \cdot ((T_x - T_n) - 0.0874 * P)^{0.6278} \quad (14)$$

where PET is the daily PET (in mm/day), Ra is the incoming solar radiation (in W/m2), T_m, T_x, T_n are respectively the average, maximum and minimum temperature (in °C) and P is the precipitations (in mm/day).

3.4.2 Actual Evapotranspiration and Evapotranspiration Demand

The Actual Evaporation is calculated from the CLM routines of canopy fluxes and plant biochemistry using Monin-Obukov similarity theory and a Newton-Raphson iteration to solve for energy and water vapor fluxes (Oleson *et al.*, 2004). We define the actual evapotranspiration of the crop as:

$$ETA = Qevap_{veg} + Qevap_{soil} \quad (15)$$

where ETA is the actual evapotranspiration (in mm/day), $Qevap_{veg}$ and $Qevap_{soil}$ are the evaporation (and transpiration) of the plant and the soil, respectively.

The evapotranspiration demand is then calculated following AquaCrop methodology (Raes *et al.*, 2010) as:

$$ETD = (Kcb + Ke) \cdot PET \quad (16)$$

where ETD is the evapotranspiration demand (in mm/day), Kcb is the basal crop coefficient calculated as described in the previous section and Ke is the soil evaporation coefficient.

The soil evaporation coefficient Ke depends on the crop cover CC and is calculated as in AquaCrop by:

$$Ke = (1 - (1.72 \cdot CC - CC^2 + 0.3 \cdot CC^3)) \cdot Ke_x \quad (17)$$

where the maximum evaporation coefficient Ke_x is a model parameter (constant for all crops and locations) taken equal to 1.1 as in AquaCrop.

To account for reduced evaporation due to dead canopy cover during senescence, the previous Ke is multiplied during the senescence stage by $(1 - f_{CC} \cdot CC_x)$ where f_{CC} is a crop parameter.

3.4.3 Irrigation Demand

The irrigation demand is the difference between potential and actual evapotranspiration. For a given month, the irrigation demand is expressed as:

$$IRR = \Sigma_{days}\left(ETD - ETA\right) \tag{18}$$

3.4.4 Yield Factor

The yield factor expresses the percentage of the yield of a crop lost due to water stress as compared with that of an irrigated crop with the same inputs (fertilizer, soil, etc.) The yield factor is defined in CROPWAT (Smith, 1992) and we employ this same method in CLM-AG.

The yield factor is defined as:

$$YF = 1 - \prod_s \left(Ky_s\left(1 - \frac{ETA_s}{ETD_s}\right)\right) \tag{19}$$

where the yield coefficient Ky_s is a crop parameter dependent on the growing stage s, ETD_s and ETA_s are the total demanded and total actual evapotranspiration for the growing stage s (in mm) respectively.

The four growing stages are the same as those defined in Section 3.2:

- Initial Stage: from planting to 10% of the crop cover.
- Vegetative Stage: from 10% of the crop cover to full crop cover.
- Yield Formation: from full crop cover until senescence. It is the stage where crops are the most sensitive to water stress with Ky_3 often greater than one.
- Senescence: from the start of senescence to harvesting.

4. MODEL EVALUATION: HISTORIC RUNS

To evaluate the model, we run it with observed weather from the late twentieth century and current crop datasets. As observations of irrigation demand at the aggregate scale are unavailable, we evaluate the model by comparing it to an existing modeled dataset: the IIASA-FAO Global Agro-Ecological Zones (GAEZ) dataset (Fischer *et al.*, 2012). CLM-AG is run for corn, spring wheat and cotton for this comparison.

For a second evaluation, we concentrate on the United States and use the 2008 USDA Farm and Ranch Irrigation Survey (FRIS)(USDA, 2008) for corn crops. After computing a measure of the irrigation efficiency, we compare it to usually accepted values for this parameter.

4.1 Input Data and Method for the Evaluation

4.1.1 Crop Data

The crop parameters used in this study are drawn from multiple sources that include CROPWAT, AquaCrop and several other publications. These values and their sources for maize, spring wheat and cotton can be found in Appendix A.

The crop calendar (planting date and length of the growing season) is drawn from the GAEZ dataset. It is important to note that the planting date identified in GAEZ is modeled as the one that results in the highest yield for the year and is not based on observation or survey. However, as in the real world, rainfed crop planting dates can differ significantly from irrigated planting dates. We use crop calendars that are reflective of irrigated maize and cotton and rainfed wheat for this study.

4.1.2 Weather Data

We use the National Centers for Environmental Prediction/National Center for Atmospheric Research Corrected by Climate Research Unit (NCC)(Ngo-Duc *et al.*, 2005) as a weather forcing data for CLM-AG. NCC is a six-hourly weather dataset with temperature, rainfall, snowfall, wind, pressure, specific humidity, longwave and shortwave incident radiation at a resolution of 1x1 degrees. It is built by taking the six-hourly NCEP/NCAR reanalysis runs and correcting the monthly means with East Anglia Climate Research Unit (CRU) observations. To reduce the processing time of CLM, we run it at a 2x2.5 degrees resolution instead of 1x1[5].

4.1.3 Evaluation Model Runs

We run the model from 1975 to 2000 and calculate the average irrigation need on the 1980–1999 period (the first five years being considered as a spin-up time for the soil hydrology in CLM before it reaches an equilibrium state).

4.2 Results and Comparison with GAEZ

4.2.1 The GAEZ Dataset

The IIASA-FAO GAEZ dataset (Fischer *et al.*, 2012) is a dataset constituted as the output of a global agriculture and soil model. It has a resolution of five by five minutes of arc. GAEZ includes numerous data for a wide variety of crops. It distinguishes irrigated and rainfed crops, the input level (low, intermediate or high)[6], and the year (the model uses the CRU global historic weather dataset).

For this particular study, we look at the water deficit (in mm) for the three selected crops (irrigated maize, irrigated cotton and rainfed spring wheat) under an intermediate input scenario averaged over the years 1961–1990.

4.2.2 Results for Maize

This section only shows the results for maize as the results for spring wheat and cotton are highly similar. These other results can be found in Appendix B and C.

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[5] Another reason for running at 2x2.5 degrees is that it is the standard IGSM resolution used in most other MIT Joint Program studies.

[6] A low input level is associated with a traditional subsistence agriculture. An intermediate input level is associated with a subsistence and partially market-oriented agriculture with some mechanization. High input level relates to industrial agriculture. It is useful to note that the input level does not change the planting date or the length of the growing season in GAEZ, but only the yield.

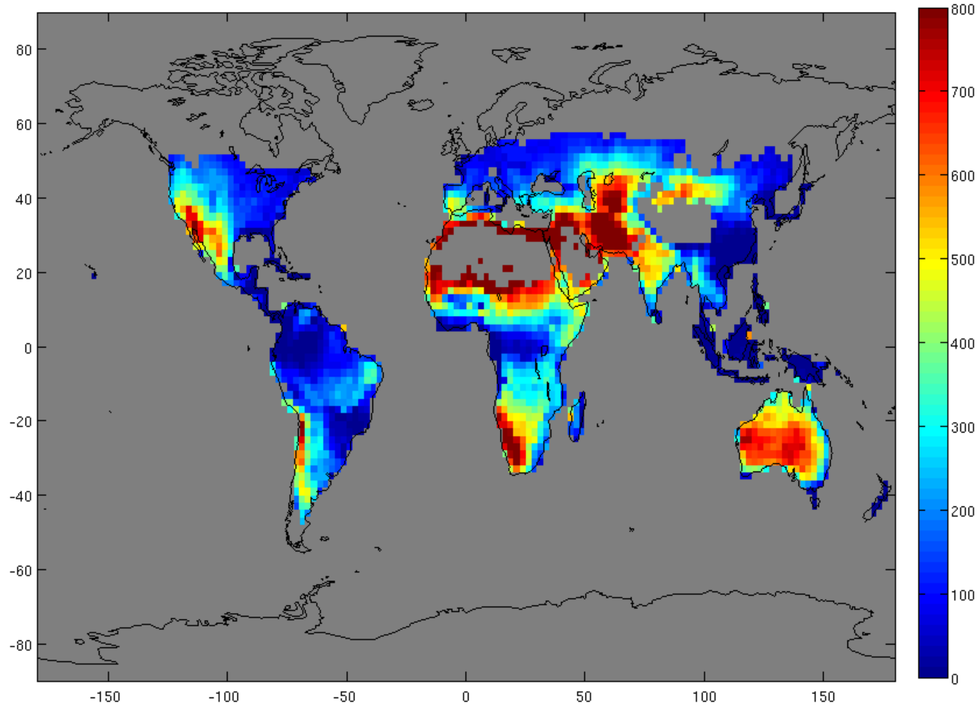

Figure 6. CLM-AG water deficit (in mm) for irrigated maize—NCC dataset, 1980–1999 average.

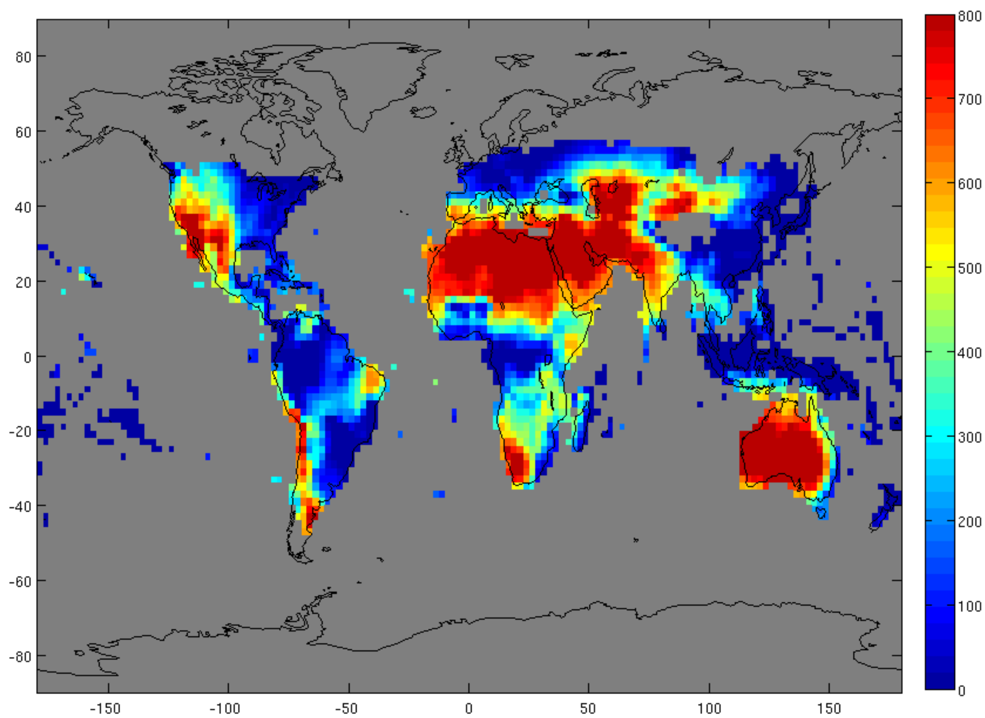

Figure 7. GAEZ water deficit (in mm) for irrigated maize—CRU dataset, 1961–1990 average.

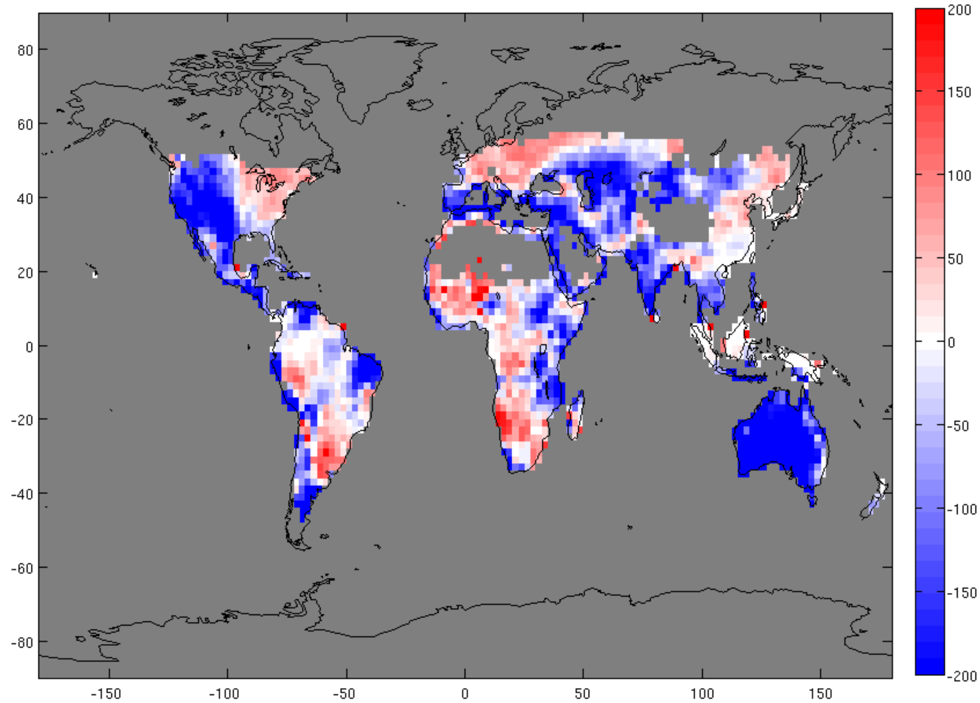

Figure 8. Difference in water deficit estimates between CLM-AG and GAEZ (in mm) for irrigated maize—same specifications as the previous figures.

4.2.3 Analysis

CLM-AG and GAEZ define the same patterns in terms of irrigation need for maize in the world (**Figures 6 through 8**). Wet zones more suitable for agriculture appear at the same place in CLM-AG and GAEZ, while drier zones (with a higher irrigation need) also match between the two models. As Figure 8 shows, the only difference resides in the magnitude. CLM-AG is wetter than GAEZ in dry areas (western United States, Australia, Mediterranean Basin, etc.) and slightly drier in wet areas (eastern USA, central Europe, northern Argentina, etc.). This difference may be explained by a difference in the treatment of the soil in the models. CLM-AG benefits from the full ten-layer CLM model, while GAEZ relies only on a ”bucket layer” soil that evaporates more quickly under a dry climate; the deep layers of soil in CLM do not evaporate so as rain percolates down, water remains available in the ground longer for the crop to use. Appendix B and C presents similar results for rainfed spring wheat and irrigated cotton. It is worth noting that CLM-AG is globally slightly drier than GAEZ for rainfed spring wheat, which may be explained by differences in crop parametrization between the models.

Despite these few differences and considering the uncertainty in both models, CLM-AG represents the irrigation need accurately enough for studies in the global framework we have developed.

4.3 Evaluation for the United States with FRIS

Every five years the United States Department of Agriculture's National Agricultural Statistics Service (USDA-NASS) conducts the Agriculture Census as mandated by law. For a few selected farms in the country (around 10 percent of the total number of farms) the census includes an extra survey on irrigation. The Farm and Ranch Irrigation Survey (FRIS) is usually released a year after the census. The latest available version is the 2008 FRIS with 2007 data (USDA, 2008). From the results of the survey, FRIS reports the amount of water withdrawn by farmers per acre of land irrigated and per crop aggregated at the state level.

4.3.1 Results

To carry out this analysis, we aggregate CLM-AG results at the State level and calculate the implied irrigation efficiency (defined as the irrigation demand from CLM-AG divided by the amount of water withdrawn by the farmers as reported in FRIS). **Table 1** presents the results for the states where irrigated maize covers more than fifty thousand acres of land.

Table 1. Irrigation efficiency for maize in the United States drawn from CLM-AG results and FRIS data.

State (sorted by acreage)	Irrigation efficiency modeled
Nebraska	50.3 %
Kansas	44.1 %
Texas	62.2 %
Colorado	46.9 %
Missouri	45.0 %
Illinois	67.5 %
California	67.4 %
Arkansas	65.4 %
Michigan	69.0 %
Minnesota	54.9 %
Indiana	74.6 %
South Dakota	59.9 %
Mississippi	36.9 %
Louisiana	21.9 %
Georgia	48.8 %
Oklahoma	42.5 %
Wisconsin	42.3 %
Iowa	72.1 %
Washington	36.4 %
North Dakota	59.9 %
Idaho	32.9 %

4.3.2 Analysis

The average efficiency (weighted by the cultivated surface) is 51.4% according to this study[7]. Pimentel *et al.* (1997) reports an average irrigation efficiency of 50% for the United States so CLM-AG is an accurate measure of irrigation need on this measure.

Individual numbers vary significantly from a state to another. There are several explanations for this fact, some explaining why different states have different efficiencies, some being modeling shortfalls.

First, states where water is scarce (Texas, California) tend to have a higher irrigation efficiency thanks to highly efficient irrigation systems while wetter states (like Missouri or Washington) are not as efficient.

Second, we do not take into account in CLM-AG water needs for uses other than irrigation, like freezing prevention or salt leaching[8]. These can make a significant difference in the total irrigation need in certain states.

Third, FRIS data is likely to contain systematic biases and/or errors as it is a survey of farmers and not field observations. FRIS itself warns that farmers in drier areas keep better accounting of the water they use as the price they pay for it is higher.

However, the biggest discrepancies may come from the spatial aggregation of the data. Irrigation varies tremendously from location to location within a state (or even within a 2 x 2.5 degree grid cell) and any one farm will likely have a different approach to irrigation from the next one. This study also aggregates water demand at a state level. This raises two issues. First, precipitation, and hence water deficit, can vary significantly inside the state borders (this is particularly a concern in places like California). Second, farms may not be homogeneously spread in the state and concentrate on a specific area where there is a specific climate (for example in Colorado, farms are situated on the eastern part of the state that faces a drier climate than the western mountainous areas).

Going forward, we contend that CLM-AG is far too imprecise to be used in a current situation setting at a regional scale to do any kind of planning[9]. Nevertheless, it still adds value by correctly approximating the irrigation need and determining the large-scale patterns. Moreover, despite being imperfect at the local level, it will be able to measure the relative impacts of climate variations on irrigation needs. After this evaluation, CLM-AG can be confidently used to provide insights on the impact of future climate on water stress for agriculture.

5. CONCLUSION

This study shows that at a global level CLM-AG reveals the expected patterns of wet and dry zones for irrigation need. The comparison to the GAEZ (Fischer *et al.*, 2012) shows that CLM-AG, forced with a historic dataset, represents accurately enough the water stress at a global level for the type of studies it was designed for.

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[7] Nebraska and Kansas alone make up more than three quarter of the surface irrigated.

[8] Use of irrigation for salt leaching probably explains the very low number obtained for Louisiana.

[9] We would recommend using a model like DSSAT instead.

Results are further validated at the national level. Using the irrigation observations contained in FRIS (USDA, 2008) and the crop irrigation needs as calculated by CLM-AG, a theoretical irrigation efficiency table was constructed. This irrigation efficiency is aggregated by state and the results are presented in Table 1. These results are extremely close to what would be expected given the different efficiencies of irrigation systems over the United States. Overall, the average irrigation efficiency for maize in the United States is estimated at 51.4% using CLM-AG. This is consistent with the approximate value of 50% reported by Pimentel *et al.* (1997).

In the future, CLM-AG is set to replace CliCrop as the principal model for irrigation studies at the MIT Joint Program on the Science and Policy of Global Change. It will be used in studies on the impacts of climate change on the food and water systems. Future work will develop a parametrization for more crops and a measure of the yield, dependent on carbon dioxide concentration and temperature stress.

Acknowledgements

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APPENDIX A: Crop Parameters

Table A1. Crop Parameters.

Parameter	Maize	Spring Wheat	Cotton	Source
T_{base} (in °C)	8.0	0.0	12.0	AquaCrop
T_{upper} (in °C)	30.0	26.0	35.0	AquaCrop
CC_0 (unitless)	0.004	0.075	0.007	AquaCrop
CC_x (unitless)	0.90	0.95	0.90	AquaCrop
CGC (in GDD^{-1})	0.012	0.006	0.0065	AquaCrop
CDC (in GDD^{-1})	0.010	0.004	0.0025	AquaCrop
t_em (in GDD)	75.0	150.0	50.0	AquaCrop
t_sen (in GDD)	1400.0	1650.0	1400.0	AquaCrop
t_mat (in GDD)	250.0	500.0	200.0	AquaCrop
Kcb_x (unitless)	1.05	1.10	1.10	AquaCrop
f_{age} (in day^{-1})	0.003	0.0015	0.003	AquaCrop
h_x (in m)	2.0	1.0	1.3	TexasET (2012)
rt_{ini} (in mm)	30.0	30.0	30.0	AquaCrop
rt_{gr} (in mm/day)	20.0	15.0	20.0	AquaCrop
rt_{max} (in mm)	2500.0	2000.0	2500.0	AquaCrop
LAI_x (unitless)	6.0	3.0	5.0	See below
f_{CC} (unitless)	0.5	0.5	0.6	AquaCrop
Ky_1 (unitless)	0.4	0.2	0.2	FAO Water
Ky_2 (unitless)	0.4	0.6	0.5	FAO Water
Ky_3 (unitless)	1.3	0.8	0.5	FAO Water
Ky_4 (unitless)	0.5	0.4	0.25	FAO Water

Maximum LAI values come from Vina (2004), Li *et al.* (2004) and Heitholt (1994).

APPENDIX B: Evaluation of CLM-AG versus GAEZ for Cotton

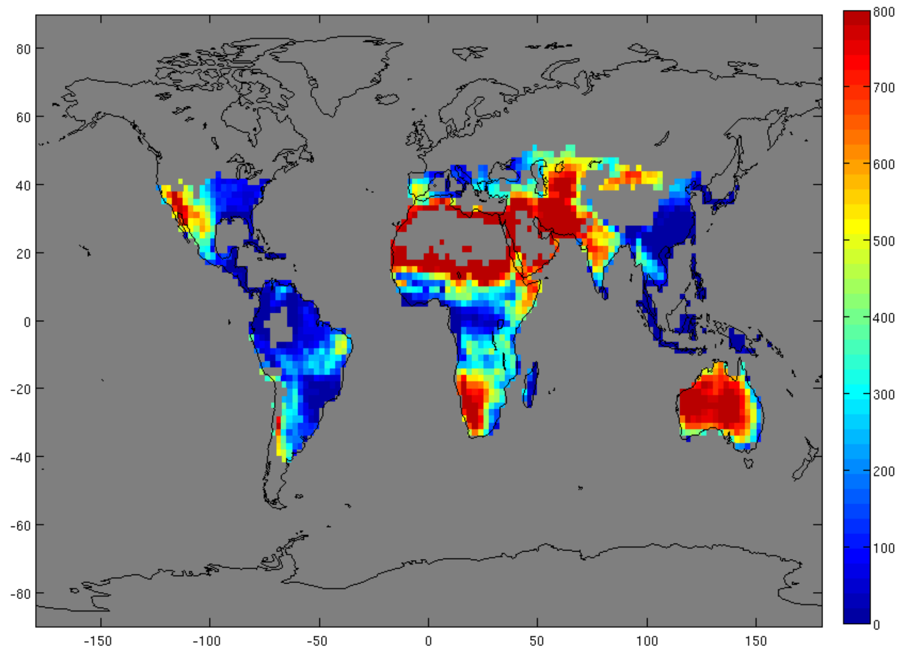

Figure B1. CLM-AG water deficit (in mm) for irrigated cotton—NCC dataset, 1980–1999 average.

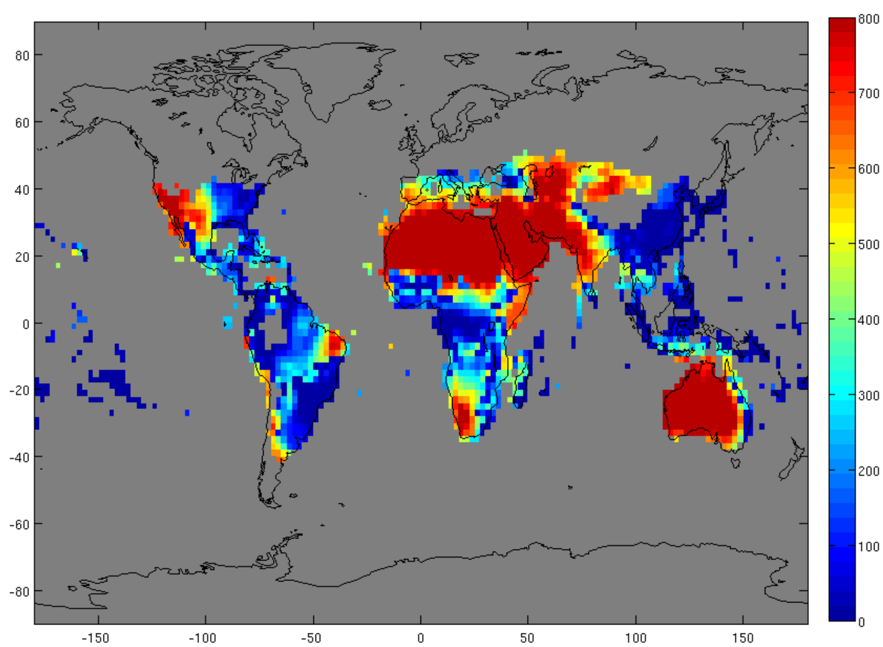

Figure B2. GAEZ water deficit (in mm) for irrigated cotton—CRU dataset, 1961–1990 average.

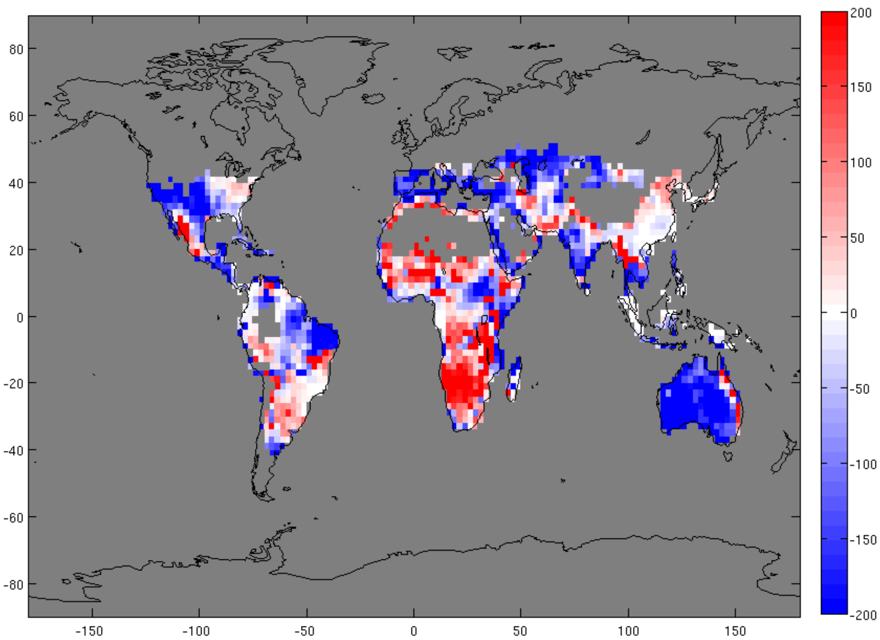

Figure B3. Difference in water deficit estimates (in mm) for irrigated cotton between CLM-AG and GAEZ—CRU dataset, 1961–1990 average.

APPENDIX C: Evaluation of CLM-AG versus GAEZ for Spring Wheat

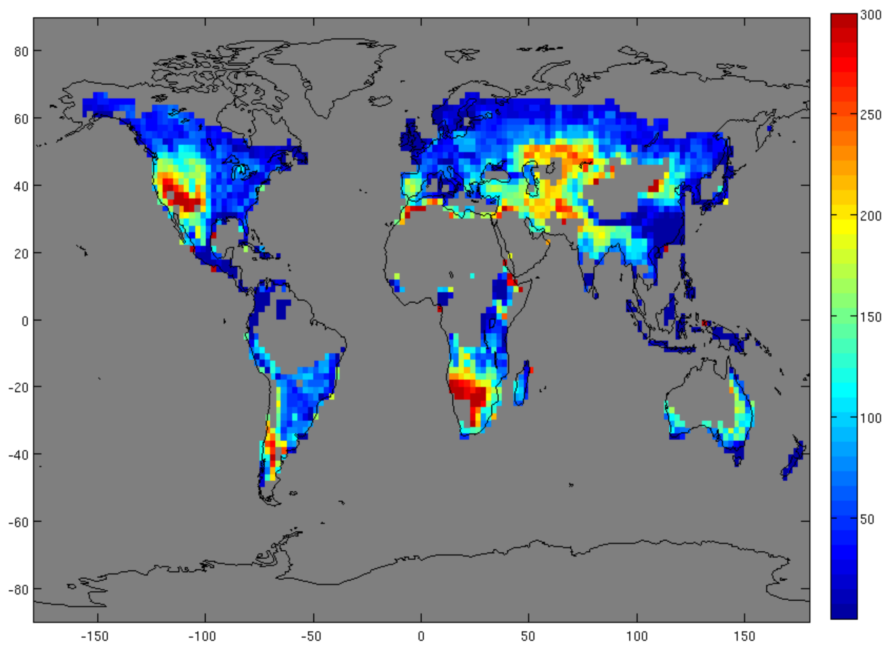

Figure C1. CLM-AG water deficit (in mm) for rainfed spring wheat—NCC dataset, 1980–1999 average.

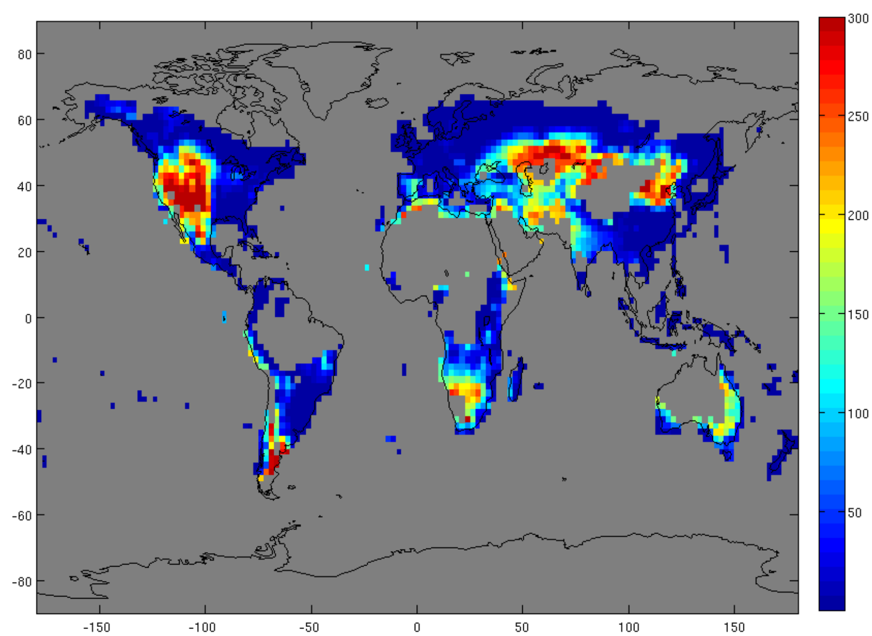

Figure C2. GAEZ water deficit (in mm) for rainfed spring wheat—CRU dataset, 1961–1990 average.

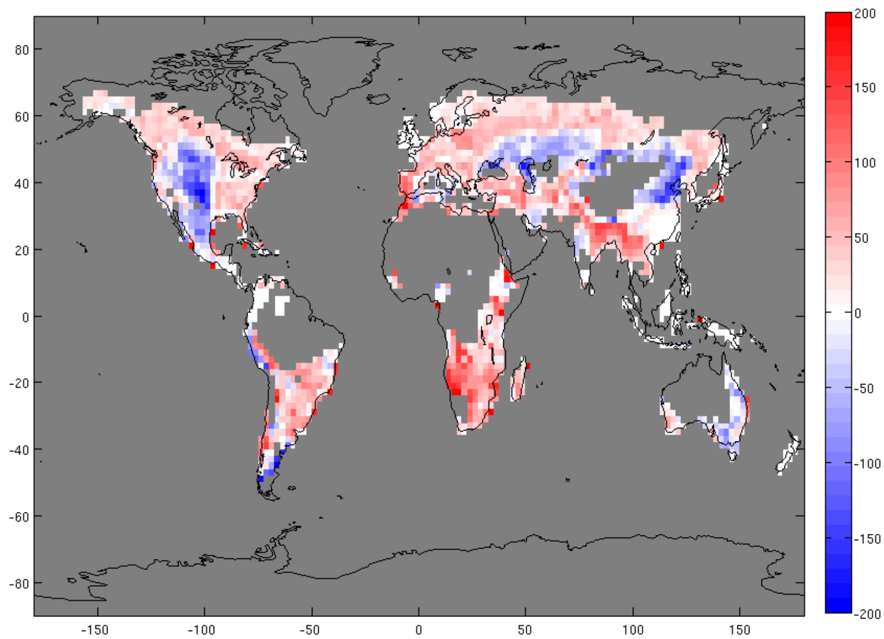

Figure C3. Difference in water deficit estimates (in mm) for rainfed spring wheat between CLM-AG and GAEZ—CRU dataset, 1961–1990 average.

APPENDIX D: Implementing Yield Calculation in CLM-AG

To directly calculate crop yields in CLM-AG, we follow once again AquaCrop (Raes *et al.*, 2010). CLM-AG distinguishes rainfed and irrigated yield for the same crop. Conceptually, the yield is constructed by a daily accumulation of above ground biomass in the crop, a portion of which is the yield. For irrigated crops, the yield can be expressed as:

$$Y_{irr} = biomass \cdot HI \tag{20}$$

where $biomass$ is the total biomass weight accumulated per area of crop planted (in tons/hectare) and HI is the Harvest Index, representing the proportion of this biomass that is yield (in percent).

For rainfed crops, the yield factor (YF) defined above is used as a measure of water stress and the rainfed yield is defined as:

$$Y_{rf} = biomass \cdot HI \cdot YF \tag{21}$$

The above ground biomass production every day is:

$$biomass_{t+1} = biomass_t + f_y \cdot f_{CO_2} \cdot Ksb(GDD) \cdot WP \cdot Kcb \tag{22}$$

where f_y is a unitless crop parameter to account for reduction in biomass production during the yield formation period, f_{CO_2} is a unitless factor that takes into account carbon dioxide fertilization, Ksb is a temperature-stress factor dependent on the amount of degree-days accumulated during the day, WP is the standard water productivity of the crop (in tons/hectare) and Kcb is the basal coefficient as defined above[10].

Following Aquacrop, the CO_2 fertilization factor is calculated as[11]:

$$f_{CO_2} = \frac{([CO_2]/[CO_2]_0)}{1+0.000138([CO_2]-[CO_2]_0)} \tag{23}$$

where $[CO_2]$ is the mean atmospheric concentration of CO_2 for the year considered (in ppm) and $[CO_2]_0$ is a reference value taken as $369.41ppm$.

The reference harvest index HI_0 (a crop parameter) is modified to take into account pollination failure due to heat or cold stress. The calculation procedure is the same as described in Section 3.10.2 of the AquaCrop manual (Raes *et al.*, 2010).

CLM-AG thus produces two measures of yield. The first one is of the perfectly irrigated crop, with no fertilization, soil salinity or disease stresses. It encompasses only temperature stresses and potential carbon fertilization. The second one is a measure of the rainfed crop. It measures both temperature and water stresses, under carbon fertilization. Other stresses or potentially negative interactions between stresses are ignored. Thus these measures of yield should be seen as a maximum attainable yield, given the climate conditions.

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[10] Kcb is the rapport transpiration over potential evapo-transpiration in non water-stress conditions. Potential water stress is directly accounted for in the calculation of the rainfed yield.

[11] As CLM does not track greenhouse gases concentrations, this calculation is currently performed offline using the output of the climate model used to force CLM-AG.

Figure D1 presents the maximum attainable yield for irrigated maize over 1980–1999 and **Figure D2** the maximum attainable yield for rainfed spring wheat over the same period calculated using CLM-AG.

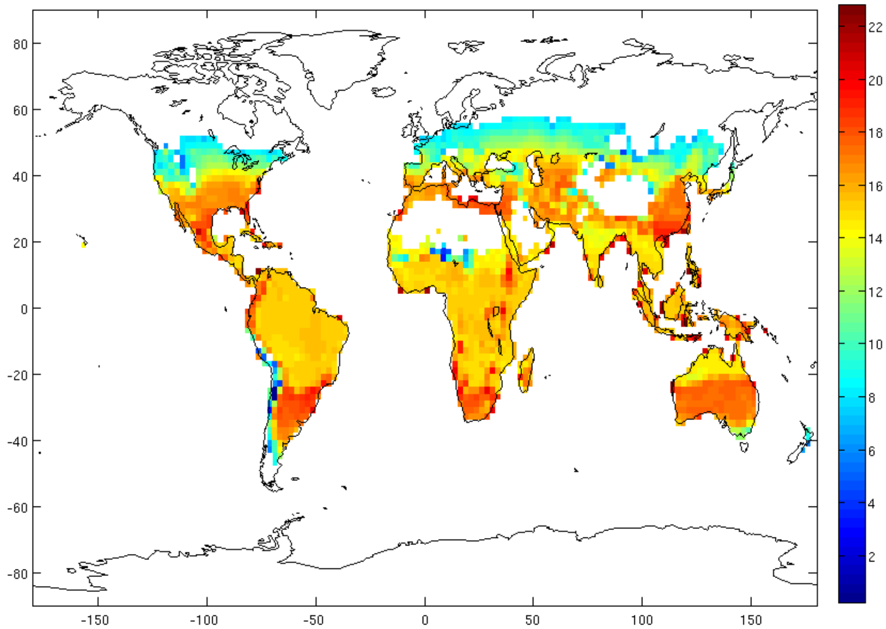

Figure D1. Maximum attainable yield of irrigated maize (in tons/hectare)—NCC weather data, 1980–1999 average.

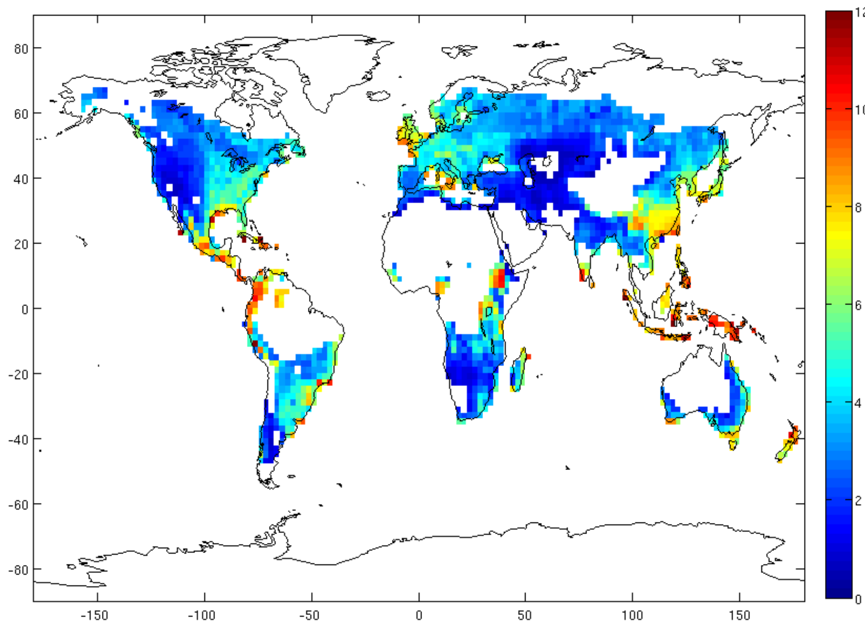

Figure D2. Maximum attainable yield of rainfed spring wheat (in tons/hectare)—NCC weather data, 1980–1999 average.

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