

June 2011

Technical descriptions of the interactive crop management (CLM4CNcrop) and interactive irrigation models in version 4 of the Community Land Model

Samuel Levis and William Sacks

Preface

The reader should consider this document an addendum to other CLM4 and Community Earth System Model (CESM1) documentation posted on respective web sites or published in journals. In Part A of this document we describe the interactive crop management model coupled to the carbon-nitrogen parameterizations of the Community Land Model (CLM4CNcrop). In Part B we describe the interactive irrigation model in the CLM4. Although these two new capabilities are related to each other in theory, one cannot use them together in the CLM4. To use them together, one would need to introduce the fractions of irrigated and rain-fed corn, soybean, and temperate cereals to the CLM.

A. Technical description of the interactive crop management model in the Community Land Model (CLM4CNcrop)

Samuel Levis

1. Introduction

Groups developing Earth System Models generally account for the human footprint on the landscape in simulations of historical and future climates. Traditionally we have represented this footprint with natural vegetation types that resemble many crops, e.g., grasses. Most efforts have not incorporated more explicit representations of land management such as crop type, planting, harvesting, tillage, fertilization, and irrigation, because global scale datasets of these factors have lagged behind vegetation mapping. As this begins to change, we increasingly find models that will simulate the biogeophysical and biogeochemical effects not only of natural but also human-managed land cover.

AgroIBIS is a state-of-the-art land surface model with options to simulate dynamic vegetation (Kucharik *et al.* 2000) and interactive crop management (Kucharik & Brye 2003). The interactive crop management parameterizations from AgroIBIS (March 2003 version) were coupled as a proof-of-concept (not published) to the Community Land Model version 3 (CLM3, Oleson *et al.* (2004)) and CLM3.5 (Levis *et al.* 2009). Now we have coupled these parameterizations directly to the CLM4's carbon (C) and nitrogen (N) cycle algorithms (CLM4CN, Thornton (in prep.)). We refer to this coupling as CLM4CNcrop.

With interactive crop management and, therefore, a more accurate representation of agricultural landscapes, we hope to improve the CLM's simulated biogeophysics and biogeochemistry. These advances may improve fully coupled simulations with the Community Earth System Model (CESM), while helping human societies answer questions about changing food, energy, and water resources in response to climate, environmental, land use, and land management change (e.g., Kucharik & Brye 2003; Lobell *et al.* 2006). Choice of land management available in updated versions of CLM4CNcrop may include crop rotation, irrigation, fertilization, and tillage.

The present document focuses on the scientific description of CLM4CNcrop. This includes the addition of new plant functional types (section 2) and of crop-specific phenology (section 3) and allocation (section 4) parameterizations. A peer reviewed article that documents this model and presents coupled simulations to the Community Atmosphere Model should appear in 2012 in the Journal of Climate's CESM1 Special Collection (Levis *et al.* in prep.).

2. Crop plant functional types

CLM's default list of plant functional types (pfts) includes an unmanaged crop (Table 2.1, Oleson *et al.* 2010) treated as a second C3 grass. The unmanaged crop has grid cell coverage assigned from satellite data, as do all natural pfts when CLM4CNDV (dynamic vegetation) (Castillo and Levis in prep.) is not active.

The new crop pfts used in CLM4CNcrop get grid cell coverage from the present-day crop dataset of Ramankutty and Foley (1998). We assign these managed crops in the proportions given by Ramankutty and Foley without exceeding the area previously assigned to the unmanaged crop. The unmanaged crop continues to occupy any of its original area that remains and continues to be handled just by the CN part of CLM4CNcrop. The managed crop types (corn, soybean, and temperate cereals) were chosen based on the availability of corresponding algorithms in AgrolBIS. Temperate cereals include wheat, barley, and rye here. We treat all temperate cereals as summer crops (like spring wheat, for example) at this time. We may introduce winter cereals (such as winter wheat) in a future version of the model.

To allow crops to coexist with natural vegetation in a grid cell and be treated by separate models (i.e., CNcrop versus CNDV), we separate the vegetated landunit into a naturally vegetated landunit and a human managed landunit. Pfts in the naturally vegetated landunit share one soil column and compete for water (default CLM4 setting). Pfts in the human managed landunit do not share soil columns and thus permit for differences in land management between crops.

3. Phenology

CLM4CN includes evergreen, seasonally deciduous (responding to changes in day length), and stress deciduous (responding to changes in temperature and/or soil moisture) phenology algorithms. In CLM4CNcrop we have added the AgrolBIS crop phenology algorithm, consisting of three distinct phases.

Phase 1 starts at planting and ends with leaf emergence, phase 2 continues from leaf emergence to the beginning of grain fill, and phase 3 starts from the beginning of grain fill and ends with physiological maturity and harvest.

Planting

Corn and temperate cereals must meet the following requirements between April 1st and June 14th for planting in the northern hemisphere (NH):

$$\begin{aligned}
T_{10d} &> T_p \\
T_{10d}^{\min} &> T_p^{\min} \\
GDD_8 &\geq GDD_{\min}
\end{aligned}
\tag{Eq. A1}$$

where T_{10d} is the 10-day running mean of T_{2m} , (the simulated 2-m air temperature at every model time step) and T_{10d}^{\min} is the 10-day running mean of T_{2m}^{\min} (the daily minimum of T_{2m}). T_p and T_p^{\min} are crop-specific coldest planting temperatures (Table 1), GDD_8 is the 20-year running mean growing degree days (units are degree days or °days) tracked from April through September (NH) base 8°C with maximum daily increments of 30°days (see Eq. A3), and GDD_{\min} is the minimum growing degree day requirement (Table 1). Soy must meet the same requirements but between May 1st and June 14th for planting. If the requirements in Eq. A1 are not met by June 14th, then corn, soybean, and temperate cereals are still planted on June 15th as long as $GDD_8 > 0$. In the southern hemisphere (SH) the NH requirements apply 6 months later.

GDD_8 does not change as quickly as T_{10d} and T_{10d}^{\min} , so it determines whether the crop can be planted in a grid cell, while the two faster-changing variables determine when the crop may be planted.

At planting, each crop is assigned 1 g leaf C m⁻² pft column area to be transferred to the leaves upon leaf emergence. An equivalent amount of seed leaf N is assigned given the pft's C to N ratio for leaves (CN_{leaf}). (This differs from AgrolBIS, which uses a seed leaf area index instead of seed C.)

At planting, the model updates the average growing degree days necessary for the crop to reach vegetative and physiological maturity, GDD_{mat} , according to the following AgrolBIS rules:

$$\begin{aligned}
GDD_{mat}^{\text{corn}} &= 0.85GDD_8 \quad \text{and} \quad 950 < GDD_{mat}^{\text{corn}} < 1850^\circ\text{days} \\
GDD_{mat}^{\text{temp. cereals}} &= GDD_0 \quad \text{and} \quad GDD_{mat}^{\text{temp. cereals}} < 1700^\circ\text{days} \\
GDD_{mat}^{\text{soy}} &= GDD_{10} \quad \text{and} \quad GDD_{mat}^{\text{soy}} < 1700^\circ\text{days}
\end{aligned}
\tag{Eq. A2}$$

where GDD_{10} is the 20-year running mean growing degree days tracked from April through September (NH) base 10°C with maximum daily increments of 30°days. Eq. A3 shows how we calculate GDD_0 , GDD_8 , and GDD_{10} :

$$\begin{aligned}
GDD_0 &= GDD_0 + T_{2m} - T_f \quad \text{where} \quad 0 \leq T_{2m} - T_f \leq 26^\circ\text{days} \\
GDD_8 &= GDD_8 + T_{2m} - T_f - 8 \quad \text{where} \quad 0 \leq T_{2m} - T_f - 8 \leq 30^\circ\text{days} \\
GDD_{10} &= GDD_{10} + T_{2m} - T_f - 10 \quad \text{where} \quad 0 \leq T_{2m} - T_f - 10 \leq 30^\circ\text{days}
\end{aligned}
\tag{Eq. A3}$$

where, if $T_{2m} - T_f$ takes on values outside the above ranges, then it equals the minimum or maximum value in the range. Also T_f equals 273.15 K, T_{2m} has units of K, and GDD has units of °days.

Leaf emergence

According to AgrolBIS, leaves may emerge when the growing degree days of soil temperature to 0.05 m depth tracked since planting ($GDD_{T_{soi}}$) reaches 3 to 5% of GDD_{mat} (Table 1). $GDD_{T_{soi}}$ is base 8, 0, and 10°C for corn, soybean, and temperate cereals. Leaf onset as defined in the CN part of the model (Thornton, in prep.) occurs in the first time step of phase 2, at which moment all seed C is transferred to leaf C. Subsequently, the leaf area index generally increases and reaches a maximum value during phase 2.

Grain fill

Phase 3 begins in a similar way to phase 2. A variable tracked since planting like $GDD_{T_{soi}}$ but for 2-m air temperature, $GDD_{T_{2m}}$, must reach a heat unit threshold, h , of 40 to 70% of GDD_{mat} (Table 1). For corn the percentage itself is an empirical function of GDD_{mat} (not shown). In phase 3, the leaf area index begins to decline in response to a background litterfall rate calculated as the inverse of leaf longevity for the pft (Thornton, in prep.).

Harvest

Harvest is assumed to occur as soon as the crop reaches maturity. When $GDD_{T_{2m}}$ reaches 100% of GDD_{mat} or the number of days past planting reaches a crop-specific maximum (Table 1), then the crop is harvested. Harvest occurs in one time step using CN's leaf offset algorithm (Thornton, in prep.). New variables track the flow of grain C and N to food and of live stem C and N to litter. Currently, food C and N are routed directly to litter using CN's distinction of labile, cellulose, and lignin fractions for leaves. The same fractions for leaves are used for the flow of live stem C and N to litter for corn, soybean, and temperate cereals. This is in contrast to the CLM4CN approach which puts live stem C and N to dead stems first, rather than to litter.

4. Allocation

Allocation responds to the same phases as phenology (section 4). Simulated C assimilation begins every year upon leaf emergence in phase 2 and ends with harvest at the end of phase 3; therefore, so does the allocation of such C to the crop's leaf, live stem, fine root, and reproductive pools.

Leaf emergence to grain fill

During phase 2, the allocation coefficients (fraction of available C) to each C pool are defined as:

$$\begin{aligned}
 a_{repr} &= 0 \\
 a_{froot} &= a_{froot}^i - (a_{froot}^i - a_{froot}^f) \frac{GDD_{T_{2m}}}{GDD_{mat}} \quad \text{where} \quad \frac{GDD_{T_{2m}}}{GDD_{mat}} \leq 1 \\
 a_{leaf} &= (1 - a_{froot}) \cdot \frac{a_{leaf}^i (e^{-b} - e^{-b \frac{GDD_{T_{2m}}}{h}})}{e^{-b} - 1} \quad \text{where} \quad b = 0.1 \\
 a_{livestem} &= 1 - a_{repr} - a_{froot} - a_{leaf}
 \end{aligned} \tag{Eq. A4}$$

where a_{leaf}^i , a_{froot}^i , and a_{froot}^f are initial and final values of these coefficients (Table 2), and h is a heat unit threshold defined in section 3. At a crop-specific maximum leaf area index, L_{max} (Table 2), carbon allocation is directed exclusively to the fine roots.

Grain fill to harvest

The calculation of a_{froot} remains the same from phase 2 to phase 3. Other allocation coefficients change to:

$$\begin{aligned}
 a_{leaf} &= a_{leaf}^{i,3} \quad \text{when} \quad a_{leaf}^{i,3} \leq a_{leaf}^f \quad \text{else...} \\
 a_{leaf} &= a_{leaf} \left(1 - \frac{GDD_{T_{2m}} - h}{GDD_{mat} d_L - h} \right)^{d_{alloc}^{leaf}} \geq a_{leaf}^f \quad \text{where} \quad \frac{GDD_{T_{2m}} - h}{GDD_{mat} d_L - h} \leq 1 \\
 a_{livestem} &= a_{livestem}^{i,3} \quad \text{when} \quad a_{livestem}^{i,3} \leq a_{livestem}^f \quad \text{else...} \\
 a_{livestem} &= a_{livestem} \left(1 - \frac{GDD_{T_{2m}} - h}{GDD_{mat} d_L - h} \right)^{d_{alloc}^{stem}} \geq a_{livestem}^f \quad \text{where} \quad \frac{GDD_{T_{2m}} - h}{GDD_{mat} d_L - h} \leq 1 \\
 a_{repr} &= 1 - a_{froot} - a_{livestem} - a_{leaf}
 \end{aligned} \tag{Eq. A5}$$

where $a_{leaf}^{i,3}$ and $a_{livestem}^{i,3}$ (initial values) equal the last a_{leaf} and $a_{livestem}$ calculated in phase 2, d_L , d_{alloc}^{leaf} and d_{alloc}^{stem} are leaf area index and leaf and stem allocation decline factors, and a_{leaf}^f and $a_{livestem}^f$ are final values of these allocation coefficients (Table 2).

5. General comments

C and N accounting now includes new pools and fluxes pertaining to live stems and reproductive tissues. E.g., the calculations of growth respiration, above ground net primary production, litter fall, and displayed vegetation all now account for reproductive C.

We track allocation to reproductive C separately from CN's allocation to other C pools but within the CN framework. CN uses $\frac{a_{root}}{a_{leaf}}$ and $\frac{a_{livestem}}{a_{leaf}}$ to calculate C and N allometry and plant N demand. We also calculate $\frac{a_{repr}}{a_{leaf}}$ but merge the reproductive and live stem pools at this time instead of tracking them separately.

Stem area index (S) is equal to $0.1L$ for corn and $0.2L$ for other crops, as in AgrolBIS, where L is the leaf area index. All live C and N pools go to 0 after crop harvest, but the S is kept at 0.25 to simulate a post-harvest "stubble" on the ground.

Crop heights at the top and bottom of the canopy, z_{top} and z_{bot} (m), come from the AgrolBIS formulation:

$$z_{top} = z_{top}^{\max} \left(\frac{L}{L_{\max} - 1} \right)^2 \geq 0.05 \text{ where } \frac{L}{L_{\max} - 1} \leq 1 \quad (\text{Eq. A6})$$

$$z_{bot} = 0.02\text{m}$$

The CN part of the model keeps track of a term representing excess maintenance respiration that for perennial pfts or pfts with C storage may be extracted from later gross primary production. Later extraction cannot continue to happen after harvest for annual crops, so at harvest we turn the excess respiration pool into a flux that extracts CO₂ directly from the atmosphere. This way we eliminate any excess maintenance respiration remaining at harvest as if such respiration had not taken place.

An implementation of interactive fertilization is forthcoming (Beth Drewniak, pers. comm.) and interactive irrigation does not work for corn, soybean, and temperate cereals, yet (Part B, this document). Therefore, we consider all pfts rain fed, and we disable CLM4CN's interactive nitrogen limitation for corn, soybean, and temperate cereals. Instead, we prescribe the $V_{c\max25}$ value (101) proposed for crops by Kattge *et al.* (2009) as used in carbon-only simulations with the CLM4 by Bonan *et al.* (in press).

In the list of plant physiological and other parameters used by CLM4CN, we started the managed crops with the existing values assigned to the unmanaged C3 crop. Then we changed the following parameters to distinguish corn, soybean, and temperate cereals from the unmanaged C3 crop and from each other:

- Growth respiration coefficient from 0.30 to the AgrolBIS value of 0.25.

- Fraction of leaf N in the Rubisco enzyme from 0.1 to 0.2 g N Rubisco g⁻¹ N leaf for temperate cereals to increase productivity (not chosen based on AgroIBIS).
- Fraction of current photosynthesis displayed as growth changed from 0.5 to 1 (not chosen based on AgroIBIS).
- CLM4CN values of the C to N ratio, CN , rather than values from AgroIBIS. For reproductive C we used the value for live wood, CN_{lw} , equal to 50. Changed CN_{leaf_litter} to equal CN_{leaf} , in order to suppress retranslocation
- CLM4CN curve for the effect of temperature on photosynthesis instead of crop-specific curves from AgroIBIS.
- Quantum efficiency at 25°C, α , from 0.06 to 0.04 $\mu\text{mol CO}_2 \mu\text{mol}^{-1}$ photon for C4 crops (corn and unmanaged C4 crop), using CLM4CN's C4 grass value.
- Slope, m , of conductance-to-photosynthesis relationship from 9 to 4 for C4 crops as in AgroIBIS.
- Specific leaf areas, SLA , to the AgroIBIS values (Table 1).
- Leaf orientation, χ_L , to the AgroIBIS values (Table 1).
- Soil moisture photosynthesis limitation factor, β_t , for soybeans multiplied as in AgroIBIS by 1.25 for increased drought tolerance.

Table 1. Crop plant functional types (pfts) in CLM4CNcrop and their parameters relating to phenology and morphology. Numbers in the first column correspond to the list of pfts in Table 2.1 of Oleson *et al.* (2010).

Number and pft corresponding or added to CLM's list of pfts	Phenological Type	T_p K	T_p^{\min} K	GDD_{\min} °days	GDD_{mat} °days	Phase 2 % GDD_{mat}	Phase 3 % GDD_{mat}	Harvest: days past planting	z_{top}^{\max} m	SLA m ² leaf g ⁻¹ C	χ_L index
15. C ₃ unmanaged crop	Stress Deciduous									0.03	-0.30
16. C ₃ irrigated crop	Stress Deciduous									0.03	-0.30
17. Corn (also referred to as Maize)	Crop/Managed	283.15	279.15	50	950-1850	3	55-65	≤165	2.50	0.05	-0.50
18. Temperate Cereals	Crop/Managed	280.15	272.15	50	≤1700	5	60	≤150	1.20	0.07	0.65
19. Winter cereals (place holder)	Crop/Managed		278.15	50	1900	5	40	≤265	1.20	0.07	0.65
20. Soybean	Crop/Managed	286.15	279.15	50	≤1700	3	70	≤150	0.75	0.07	-0.50

Notes: T_p and T_p^{\min} are coldest planting temperatures but for winter cereals T_p^{\min} is a warmest planting temperature. GDD_{\min} is the lowest (for planting) 20-year running mean growing degree days base 0°C (winter cereals) or 8 (other crops) tracked from April to September (NH). GDD_{mat} is a crop's 20-year running mean growing degree days needed for vegetative and physiological maturity. Harvest occurs at 100% GDD_{mat} or when the days past planting reach the number in the 10th column. Crop growth phases are described in the text. z_{top}^{\max} is the maximum top-of-canopy height of a crop, SLA is specific leaf area, and leaf orientation index, χ_L , equals -1 for vertical, 0 for random, and 1 for horizontal leaf orientation.

Table 2. Crop pfts in CLM4CNcrop and their parameters relating to allocation. Numbers in the first column correspond to the list of pfts in Table 2.1 of Oleson *et al.* (2010).

Number and pft corresponding or added to CLM's list of pfts	Phase 2		Phases 2 and 3		Phase 3				
	a_{leaf}^i fraction	L_{max} $m^2 m^{-2}$	a_{froot}^i Fraction	a_{froot}^f Fraction	a_{leaf}^f fraction	$a_{livestem}^f$ fraction	d_L dimensionless	d_{alloc}^{stem} dimensionless	d_{alloc}^{leaf} dimensionless
17. Corn (also referred to as Maize)	0.800	5	0.400	0.050	0.000	0.000	1.05	2	5
18. Temperate Cereals	0.750	7	0.300	0.000	0.000	0.050	1.05	1	3
19. Winter cereals (place holder)	0.425	7	0.300	0.000	0.000	0.050	1.05	1	3
20. Soybean	0.850	6	0.500	0.200	0.000	0.300	1.05	5	2

Notes: Crop growth phases and corresponding variables are described in the text

References

- Bonan GB, Lawrence PJ, Oleson KW, Levis S, Jung M, Reichstein M, *et al.*, 2011: Improving canopy processes in the Community Land Model (CLM4) using global flux fields empirically inferred from FLUXNET data. *J. Geophys. Res.*, 116, G02014, doi:10.1029/2010JG001593
- Castillo CKG and Levis S, in preparation: Evaluation of the new CNDV option of the Community Land Model: Effects of dynamic vegetation and interactive nitrogen on CLM4 means and variability. *J. Climate* (CESM1 special collection)
- Kattge J, Knorr W, Raddatz T, Wirth C, 2009: Quantifying photosynthetic capacity and its relationship to leaf nitrogen content for global-scale terrestrial biosphere models. *Global Change Biol.*, 15, 976–991
- Kucharik CJ, Foley JA, Delire C, Fisher VA, Coe MT, Lenters JD, Young-Molling C, and Ramankutty N, 2000: Testing the performance of a dynamic global ecosystem model: water balance, carbon balance, and vegetation structure. *Global Biogeochemical Cycles*, 14, 795–825
- Kucharik CJ and Brye KR, 2003: Integrated Biosphere Simulator (IBIS) yield and nitrate loss predictions for Wisconsin maize receiving varied amounts of nitrogen fertilizer. *Journal of Environmental Quality*, 32, 247–268
- Levis S, Thornton P, Bonan G, Kucharik C, 2009: Modeling land use and land management with the Community Land Model. *iLeaps newsletter*, No. 7
- Levis S, *et al.*, in preparation: Interactive crop management in the Community Earth System Model: Seasonal influences on land-atmosphere fluxes. *J. Climate* (CESM1 special collection)
- Lobell DB, Bala G, Duffy PB, 2006: Biogeophysical impacts of cropland management changes on climate. *Geophys Res Lett*, 33, L06708, doi:10.1029/2005GL025492
- Oleson KW, Dai Y, Coauthors, 2004: Technical description of the Community Land Model (CLM). NCAR Technical Note NCAR/TN-461+STR, 174 pp.
- Oleson KW, Lawrence DM, Bonan GB, Flanner MG, Kluzek E, Lawrence PJ, Levis S, *et al.*, 2010: Technical description of version 4.0 of the Community Land Model (CLM). NCAR Technical Note NCAR/TN-478+STR, 257 pp.
- Ramankutty N and Foley JA 1998. Characterizing patterns of global land use: an analysis of global croplands data. *Global Biogeochemical Cycles* 12, 667–685
- Thornton PE, in preparation: CLM4CN technical description

B. Technical description of the interactive irrigation model in the Community Land Model

William Sacks

The clm4 includes the option to irrigate cropland areas that are equipped for irrigation. The application of irrigation responds dynamically to climate. In the clm4, irrigation is implemented for the C3 generic crop only. Soon we hope to enable irrigation in conjunction with the specific crop types described in Part A. This irrigation algorithm is based loosely on the implementation of Ozdogan *et al.* (2010).

When irrigation is enabled, the cropland area of each grid cell is divided into an irrigated and unirrigated fraction according to a dataset of areas equipped for irrigation (Siebert *et al.*, 2007). The area of irrigated cropland in each grid cell is given by the smaller of (1) the grid cell's total cropland area, according to the default CLM dataset (Oleson *et al.* 2010), and (2) the grid cell's area equipped for irrigation. The remainder of the grid cell's cropland area (if any) is then assigned to unirrigated cropland. Irrigated and unirrigated crops are placed on separate soil columns, so that irrigation is only applied to the soil beneath irrigated crops.

In irrigated croplands, a check is made once per day to determine whether irrigation is required on that day. This check is made in the first time step after 6 AM local time. Irrigation is required if (1) crop leaf area > 0, and (2) $\beta_t < 1$, i.e., water is limiting for photosynthesis (see section 8.3 in Oleson *et al.*, 2010).

If irrigation is required, the model computes the deficit between the current soil moisture content and a target soil moisture content; this deficit is the amount of water that will be added through irrigation. The target soil moisture content in each soil layer i ($w_{target,i}$, kg m⁻²) is a weighted average of (1) the minimum soil moisture content that results in no water stress in that layer ($w_{o,i}$, kg m⁻²) and (2) the soil moisture content at saturation in that layer ($w_{sat,i}$, kg m⁻²):

$$w_{target,i} = (1 - 0.7) \cdot w_{o,i} + 0.7 \cdot w_{sat,i} \quad (\text{Eq. B1})$$

$w_{o,i}$ is determined by inverting equation 8.19 in Oleson *et al.* (2010) to solve for the value of s_i (soil wetness) that makes $\Psi_i = \Psi_o$ (where Ψ_i is the soil water matric potential and Ψ_o is the soil water potential when stomata are fully open), and then converting this value to units of kg m⁻². $w_{sat,i}$ is calculated simply by converting effective porosity (see section 7.2 in Oleson *et al.*, 2010) to units of kg m⁻². The value 0.7 was determined empirically, in order to give global, annual irrigation amounts that approximately match observed gross irrigation water use around the year 2000 (i.e., total water withdrawals

for irrigation: $\sim 2500 - 3000 \text{ km}^3 \text{ year}^{-1}$ (Shiklomanov, 2000)). The total water deficit ($w_{deficit}$, kg m^{-2}) of the column is then determined by:

$$w_{deficit} = \sum_i \max(w_{target,i} - w_{liq,i}, 0) \quad (\text{Eq. B2})$$

where $w_{liq,i}$ (kg m^{-2}) is the current soil water content of layer i (see section 7 in Oleson *et al.*, 2010). The max function means that a surplus in one layer cannot make up for a deficit in another layer. The sum is taken only over soil layers that contain roots. In addition, if the temperature of any soil layer is below freezing, then the sum only includes layers above the top-most frozen soil layer.

The amount of water added to this column through irrigation is then equal to $w_{deficit}$. This irrigation is applied at a constant rate over the following four hours. Irrigation water is applied directly to the ground surface, bypassing canopy interception (i.e., added to $q_{grnd,liq}$: see section 7.1 in Oleson *et al.*, 2010). Added irrigation is removed from total liquid runoff (R_{liq} : see section 11 in Oleson *et al.*, 2010), simulating removal from nearby rivers.

References

- Oleson KW, Lawrence DM, Bonan GB, Flanner MG, Kluzek E, Lawrence PJ, Levis S, *et al.*, 2010: Technical description of version 4.0 of the Community Land Model (CLM). NCAR Technical Note NCAR/TN-478+STR, 257 pp.
- Ozdogan, M., Rodell, M., Beaudoin, H.K., and Toll, D.L. 2010. Simulating the effects of irrigation over the United States in a land surface model based on satellite-derived agricultural data. *Journal of Hydrometeorology* 11:171-184.
- Shiklomanov, I.A. 2000. Appraisal and assessment of world water resources. *Water International* 25:11-32.
- Siebert, S., Döll, P., Feick, S., Hoogeveen, J., and Frenken, K. 2007. Global Map of Irrigation Areas version 4.0.1. Johann Wolfgang Goethe University, Frankfurt am Main, Germany / Food and Agriculture Organization of the United Nations, Rome, Italy. [Available online at <http://www.fao.org/nr/water/aquastat/irrigationmap/index.stm>]