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Giessen Global Generic Water Conductance Model

GIWACOM

Documentation: Model Versions 2.10 and 2.20

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Dedicated to

Helmut Lieth

on the occasion of his 75th birthday

Contents

Chapter 1

Introduction

The Giessen Global Generic Water Conductance Model (GIWACOM) is a model of the land surface conductance (i.e. the conductance of a square meter of land surface for the water flux from the soil to the atmosphere). It has been developed as an instrument to investigate the role of plants for the change of the conductance of land surface for water vapor under variable environmental conditions including weather, soil water, soil texture, atmospheric CO_2 concentration, and variable system states given by varying vegetation types and leaf biomass. It has to meet, therefore, several demands: (1) include all known relevant processes in a mechanistic manner; (2) use universal (generic) functions to describe the processes, in the sense that they cover all conditions which occur on the earth's land surface; (3) design the functions so that their parameters and coefficients may be determined by experimental approaches; (4) provide a global parameterization of the model functions which is open for further improvements as new experimental evidence will become available.

The GIWACOM has two major components: A procedure to calculate the stomatal conductance of transpiring plant material, and a scheme to aggregate the stomatal conductance for a square meter of ground surface considering the stand biomass and structure.

A first version of the model included the processes in the stomatal apparatus for certain plant species (Hoffstadt 2000).

A second version was expanded to include processes of the CO_2 budget in the leaves, processes in the soil, and processes of scaling up to the stand level. This version has been globally parameterized. From this second version, the two models described in this documentation were derived:

Version 2.10 of GIWACOM has been designed to model the stomatal conductance

Table 1.1: Some terms which are frequently used in this document together with the explanation of their meaning in this documentation. The variables which represent the terms in the model code may be (rarely) scalars or one– to multi–dimensional arrays.

term	synonym	meaning
pool	state variable	the compartments of the system containing matter (ions, water, CO_2, etc.) or energy
flux	process	transport of matter or energy from one pool to another. Fluxes are used to balance the pools
coefficient		variable in an equation which is updated once at the beginning or several times during a model time step. The current values of coefficients depend on the state of the system (pools) and/or on the current boundary conditions and driving forces.
parameter		variable in an equation which is set at the very beginning of the model run. Parameters depend on either initial conditions or boundary conditions which are assumed to be constant during the model run (i.e., vegetation type, soil type and texture, etc.).
driving force	control variable	(independent) variable in an equation which changes during time but is not changed by the model itself. Driving forces may either be read from files or provided by other coupled model(s). They are often pools (state variables) in other than the currently modelled systems.
initial condition		Value assigned to a pool before the time evolution of the model starts.

on a global grid of 0.5 degrees latitude and longitude at high time resolution ($\leq$24 minutes). A time step of 24 minutes was chosen so that the relevant output variables of the climate model ECHAM of the Max Planck Institute for Meteorology, Hamburg, could be used as driving forces for GIWACOM, since the ECHAM time step is also 24 minutes.

GIWACOM 2.10 is a generic version which is driven by external data sets and includes a fully transparent global parameterization. Any future developments including research to evolve the parameterization will use this version of the model.

Version 2.20 of GIWACOM has been designed to run on–line with the ECHAM cli-

mate model. It has, therefore, a variable grid structure determined by the ECHAM grid: When ECHAM calls GIWACOM, it will pass the resolution and the actual latitudinal band to work on.

GIWACOM 2.20 uses the same parameterization as 2.10. The main difference is that model parameters are weighted means of the parameters of the higher resolution version and are not explicitly calculated during each model run. Version 2.20 also includes a module for aggregating the stomatal conductance for a square meter of ground surface using biomass and stand data. These biomass and stand data are provided by the High Resolution Biosphere Model (HRBM, Esser et al. 1994) through either on–line or off–line coupling.

GIWACOM's structure is modular. Each module is independent of the other modules and consists of a number of "tasks" which again are independent. The tasks work on the entire model grid (or for version 2.20: latitudinal band), so that the state variables, coefficients, parameters, and driving forces are arrays of the respective grid. The documentation follows the **Module** and **Task** structure of the model code.

In this documentation, we use several terms which are explained in table 1.1. The following conventions are used unless differently indicated:

- Variables in mathematical terms are written in *italics*.
- Variables related to the program code are written in `typewriter`.
- m^2 means square meter of ground surface area.
- g means gram of plant dry matter

The program code of the GIWACOM versions has been written in standard FORTRAN 77. Only two exceptions were made: (1) we use the command `include` to include common block structures in the modules, and (2) we use the non standard character _ (underline) in names of variables. Either have become standard with FORTRAN 90.

Chapter 2

Description of GIWACOM version 2.10

This version of GIWACOM consists of the modules giwacom2.10, readgen, readforces, clcparams, cffclc, psir, dgl, output. In the following these modules are explained in detail.

GIWACOM 2.10 in its standard configuration is designed to run for one standard day in March or August, respectively.

2.1 Module giwacom2.10

The module "giwacom2.10" initializes the state variables (pools) at the model start. It includes the time loops and organizes the calling sequence and frequency of the model modules. In the innermost time loop (seconds) it contains the loop of steps (`nstep`) to integrate the model by one elementary time step (currently one second). A forth order Runge–Kutta method is used to integrate the differential equations which are included in the module "dgl".

The tasks include:

2.1.1 Initialize GIWACOM

At the very beginning of a GIWACOM run, the set of parameters of the model must be acquired. This is done by running the modules "readgen", "readforces", and "clcparams".

After that, initial values are assigned to the model pools. The pools of osmotic substances ("ions") are initialized from an assumed initial concentration *cinit* [mol·m^{-3}]

which is a global constant:

$$g = cinit \cdot vol_g \tag{2.1}$$

$$s = cinit \cdot vol_s \tag{2.2}$$

where g and s are the amount of ions [mol] in the guard cells and in the subsidiary cells, respectively. The cell volumes vol_g and vol_s are in [m^3].

The water pools of the guard cells and subsidiary cells vg and vs are set to the respective cell volumes, so that, after initialization, the turgor potential of these cells equals zero:

$$vg = vol_g \tag{2.3}$$

$$vs = vol_s \tag{2.4}$$

The amount of water rw [m^3] in the soil cylinder of radius rad_{rw} [m] around a root of 1 m length is set to the initial water content bw [%] of the soil:

$$volrw = rad_{rw}^2 \cdot \pi \cdot 1 \tag{2.5}$$

$$rw = \frac{bw}{100} \cdot volrw \tag{2.6}$$

The amount of CO_2 in the leaf intercellulars in [μmol·g^{-1}] is set to a low value:

$$in = 10^{-2} \tag{2.7}$$

2.1.2 Organize the time loops

GIWACOM2.10 is designed to run driven by the output of a climate model. Since we used ECHAM to create the input driving forces, the time structure of ECHAM is used: One day, which is assumed to be the time span to be modeled, is subdivided in 60 steps (`istep`) of 24 minutes each. Minutes are subdivided in seconds, so that the loops are:

`istep`= $1, \ldots, 60$

`minute`= $1, \ldots, 24$

`second`= $1, \ldots, 60$

The modules "psir" and "cffclc" (in this sequence) are run each minute. Most of the features in "cffclc" are calculated from driving forces which are only updated each `istep`. Running "cffclc" each `istep` would therefore be sufficient. To maintain maximum clarity (GIWACOM2.10 is a research version) we have not eliminated the equations from "cffclc" which use the root soil water potential Ψ_{rw}, calculated in "psir" from root soil water, which is updated in the inner integration loop (see 2.1.3). Therefore, a more

frequent call to "psir" and "cffclc" is needed in this version 2.10. In chapter 4.3 we give some suggestions to improve the performance of the code (since the model is essentially unchanged).

2.1.3 Integrate the model

In this version of GIWACOM each second is subdivided into `nstep` integration steps. For stability reasons (this version is not optimized for best performance) `nstep` has to be 100. Integration proceeds by $\frac{1}{100}$ sec each integration step.

A 4th order Runge–Kutta method is used for integration. The module "dgl" is called four times each `nstep` with the current values or the test values of the pools, respectively, and the slopes (derivatives) of the pool/time trajectories at these points are returned. With their weighted averages the entire `nstep` is then made.

2.2 Module readgen

This module reads parameters which are assumed to be typical for plant species, plant functional types, vegetation formations, or groups of vegetation formations. Since these parameters, in a sense, may be considered to be genetically fixed, the name of this module "read-gen" was created. "readgen" is run only once at the beginning of a GIWACOM run. It must be run in advance of all the other modules (except giwacom2.10).

Besides that, the global geographical distribution of vegetation formations is read into an array of the form `vegfor(igrid)`, with `igrid` being the array of grid elements ($igrid = 1, \ldots, 62\,483$). For GIWACOM (as well as for the global carbon cycle model HRBM, see Esser et al. 1994) we grouped related vegetation formations into groups. We have grouped the 176 vegetation formations into 31 groups. The groups are read into an array of the form `group(iveg)` and may be used in the model on grid element level as `group(vegfor(igrid))`. We use units 50 and 51 to read `vegfor(igrid)` and `group(iveg)`, respectively.
The tasks to be carried out in this module include:

2.2.1 Open parameter files

Units 40–49 are used for the parameter files. The files must be available in the relative directory `input/`. Due to the strategy described in 2.2.4 on page 9 two files exist for most of the parameter types.

A detailed description of the data sources and the structure of the data files is given in chapter 5 on page 39.

2.2.2 Open files with vegetation formations and groups

Units 50 and 51 are used for the groups of vegetation formations and for the grid related vegetation formations, respectively. The files are expected in the relative directory `input/`.

A detailed description of the data sources and the structure of the data files is given in chapter 5 on page 39.

2.2.3 Read vegetation formation numbers and related group numbers

For each grid element, $igrid = 1, \ldots, 62\,483$, one vegetation formation is assigned: `vegfor(igrid)` with $vegfor = 1, \ldots, 176$. The vegetation formation is part of a group `group(iveg)`, with $iveg = 1, \ldots, 176$ and $group(iveg) = 1, \ldots, 31$.

2.2.4 Read parameters related to vegetation

Vegetation related parameters are accessed by modules via the vegetation formation, not the group, like this: `parameter(vegfor(igrid))`. This has the advantage to combine estimates for groups with refined detailed data on single formations where available. The strategy to do so is as follows:

1. Group number `grp` and value of the parameter for the group `par(grp)` are read from a parameter file "by group".

2. The group parameters are assigned to the parameter arrays for the vegetation formations: `parameter(iveg) = par(group(iveg))`.

3. Special parameter files "by formation" are read, if available, and the more general group data are replaced.

The parameters, their units, and meaning are as follows:

Parameter	unit	meaning
vol_g	[m^3]	volume of two guard cells
vol_s	[m^3]	volume of their subsidiaries

vol_a	[m^3]	volume of the apoplast of g and s
R_{xs}	[MPa·sec·m^{-3}]	hydraulic resistance xylem to subsidiary cells
R_{se}	[MPa·sec·m^{-3}]	hydraulic resistance subsidiary cells to apoplast
R_{eg}	[MPa·sec·m^{-3}]	hydraulic resistance apoplast to guard cells
nst	[m^{-2}]	number of stomata per unit leaf area
sla	[m^2·(100gC)$^{-1}$]	leaf area per 100 g leaf carbon
T_{ref}	[°C]	reference temperature of physiological processes
Km_{par}	[μE·m^{-2}·sec^{-1}]	PAR of half saturation

The parameter T_{ref} exists for vegetation formations only, Km_{par} exists for groups only.

2.3 Module readforces

This module provides the driving forces of the model. These include at present:

1. Driving forces which change in any time step. These include: soil water content, photosynthetically active radiation, transpiration, leaf temperature.

2. Driving forces which may be assumed to be constant in short time periods (hour to days) but change seasonally: leaf and root phytomass.

3. Driving forces which are assumed to be constant during decades or even a century: long–term Priestley–Taylor moisture index and soil texture.

4. Driving force which is assumed to be independent of the grid position. It may be set once each model run or vary in time: atmospheric CO_2 concentration.

This model version 2.10 is designed to run for one standard day in March or August. The standard day is subdivided into 60 time steps "istep" of 24 minutes each: `istep`= $1, \ldots, 60$.

The driving forces listed under 1. are therefore two–dimensional arrays of the form: `variable(igrid,istep)`, with `igrid` being the array of grid elements (`igrid`= $1, \ldots, 62\,483$ for this model version with 0.5 degrees of spatial resolution). Two sets of values are available either for a standard day in March or in August. The set of values which is read depends on the specified month (value of `monws`: for March `monws`= 3, for August `monws`= 8).

The driving forces under 2. are one–dimensional arrays of the form `variable(igrid)`, but the set of values which is read depends on the specified month (value of `monws`).

The driving forces under 3. are not dependent on seasonal influences. Thus only one set for each grid element exists. Their form is `variable(igrid)`.
The tasks carried out in this module are:

2.3.1 Set month to be selected

This version 2.10 of GIWACOM is provided with data sets for modelling one standard day in March or August, alternatively. The switch "monws" is set to 3 or 8 to select the month. The correct data sets for the selected month will be chosen automatically.

The model may be used to model any other date or time span. Then the data sets of driving forces must be provided and this module must be modified to read the correct sets.

2.3.2 Set CO_2 concentration

The CO_2 concentration of the atmosphere is set as a global value for the day of the month under consideration, assuming a globally well–mixed atmosphere. The model parameterization is valid for at least a range of 100 to 1200 [μl·l^{-1}] (=[ppmv]).

2.3.3 Open files for the selected month

The units 70–74 are used to open the files. It is assumed that the relative path to the files is `echamdaten/` for the files containing soil water, photosynthetically active radiation, transpiration, and leaf (skin) temperature while it is `input/` for the file containing phytomass.

2.3.4 Open files for time–independent data

Units 75 and 76 are used to open the files containing the long–term moisture index and the soil texture in the relative directory `input/`.

2.3.5 Read data from the files

A detailed description of the data sources and the structure of the data files is given in chapter 5 on page 39.

The following data are read: soil water content (bw) in percent water volume per soil volume; photosynthetically active radiation (PAR) [μE·m^{-2}·sec^{-1}]; transpiration (e) in [kg·m^{-2}·sec^{-1}]; leaf (skin) temperature (T_{leaf}) [°C]; phytomass of leaves (pha) and of fine

roots (phb) as carbon in [g·m^{-2}]; moisture index (mi) dimensionless ranging from 0 to 1; soil texture ($textur$) in classes numbered from 1 to 9.

2.4 Module clcparams

The parameters of model functions are calculated in this module. These are either physical constants or depend on the plant (biome, functional) type, or are determined by long–term climatic or other environmental influences. The parameters are used in the module "cffclc" to calculate the coefficients or in the module "dgl" to calculate model fluxes.

Parameters not listed here may be found in the module "readgen" since they are directly read from files.

Due to the specification of its tasks "clcparams" runs only once at the beginning of a GIWACOM run.

2.4.1 Physical constants

Set value of universal gas constant:

$$R = 8.3144 \cdot 10^{-6} \qquad [\mathrm{J} \cdot \mathrm{K}^{-1} \cdot \mu\mathrm{mol}^{-1}] \tag{2.8}$$

Set molar volume of liquid water:

$$vm = 18 \cdot 10^{-6} \qquad [\mathrm{m}^3 \cdot \mathrm{mol}^{-1}] \tag{2.9}$$

2.4.2 Soil parameters

Effective radius of the soil cylinder around a root:

$$rad_{rw} = 5 \cdot 10^{-3} \qquad [\mathrm{m}] \tag{2.10}$$

2.4.3 Plant parameters

Elastic modulus for guard cells:

$$\varepsilon_g = 3 \qquad [\mathrm{MPa}] \tag{2.11}$$

Elastic modulus for subsidiary cells:

$$\varepsilon_s = 5 \qquad [\mathrm{MPa}] \tag{2.12}$$

Influence of leaf temperature on ion pumps in the plasmalemma of guard cells:

$$Q10 = 2 \tag{2.13}$$

The maximum pump rate $k_{sg}0$ at $T_{leaf} = T_{ref}$, which is achieved at maximum activation by light and no inhibition by the soil water status, is assumed to depend on the maximum concentration of osmotic substances $cmax_g$ [mol·m^{-3}] in the guard cells, the guard cell volume vol_g [m^3], and a typical time for closing of 20 minutes. The maximum ion concentration is assumed to depend on the Pristley–Taylor moisture index mi, which is defined as the quotient of actual evapotranspiration and potential evapotranspiration ($0 \leq mi \leq 1$), assessed over the full year (Hare 1980). mi can be considered as an integrated measure of the annual amount of growth–limiting drought stress on plants (Prentice et al. 1992). We followed the algorithm suggested by Prentice, Sykes and Cramer (1993) to calculate mi.

$$cmax_g = 11\,982 - 10\,579 \cdot mi \tag{2.14}$$

$$k_{sg}0 = cmax_g \cdot \frac{vol_g}{20 \cdot 60} \tag{2.15}$$

Ion concentration $cinit$ [mol·m^{-3}] in the cells of the stomatal apparatus if the ions were equally distributed between the guard and subsidiary cells (for initialization of the model):

$$cinit = 400 \tag{2.16}$$

Parameters describing the influence of soil water and light on the ion balance: Production rate of abscisic acid (ABA) in roots (k_Ψ [μmol·m^{-3}·MPa^{-1}]), effectivity of ABA in the leaves (k_{ABA} [m$^3 \cdot \mu$mol^{-1}]), ABA produced in leaves (ABA_l [μmol·m^{-3}]), parameter $f0$:

$$k_\Psi = 100 \tag{2.17}$$

$$k_{ABA} = 0.0063 \tag{2.18}$$

$$ABA_l = 0 \tag{2.19}$$

$$f0 = 0.04 \tag{2.20}$$

Calculate the parameters for the function $k_{gs} = f(c_i)$ (see equation(2.62) on page 20 in the module "dgl") from the Priestley–Taylor moisture index mi:

$$a_{kgs} = 721 \cdot 10^{-19} - 661 \cdot 10^{-19} \cdot mi \tag{2.21}$$

$$b_{kgs} = 1.52 + 1.78 \cdot mi \tag{2.22}$$

$$c_{kgs} = 0.00136 + 0.0113 \cdot mi \tag{2.23}$$

Calculate the maximum stomatal conductance $gsdm_{mx}$ from the moisture index mi:

$$gsdm_{mx} = 0.6653 \cdot \mathrm{e}^{7.21 \cdot (mi + 0.2582)} + 344.8 \tag{2.24}$$

2.4.4 Parameters for the CO_2 fluxes in the leaf

The extinction coefficient for light[1] in the leaf dry matter k_e [$\mathrm{m^2 \cdot g^{-1}}$]:

$$k_e = 0.2 \tag{2.25}$$

Respiration rate for dry matter at reference temperature[1] [$\mu\mathrm{mol \cdot g^{-1} \cdot\ sec^{-1}}$]:

$$rref = 0.0013 \tag{2.26}$$

CO_2 concentration in the leaf at the compensation point[1] [$\mu\mathrm{l \cdot l^{-1}}$]:

$$\Gamma = 50 \tag{2.27}$$

Temperature dependency of plant respiration in leaves[1]:

$$Q10_{res} = 2.3 \tag{2.28}$$

Activation energy for Rubisco carboxylation [$\mathrm{J \cdot mol^{-1}}$]:

$$ea = 59\,356 \tag{2.29}$$

Carboxylation coefficient[1] [$\mu\mathrm{mol \cdot g^{-1} \cdot sec^{-1} \cdot ppm^{-1}}$] for Rubisco in leaf dry matter at reference temperature calculated from the Priestley–Taylor moisture index mi:

$$k_{ar}0 = 0.28 \cdot 10^{-4} \cdot \mathrm{e}^{2.923 \cdot mi} \tag{2.30}$$

2.5 Module cffclc

The module "cffclc" includes the equations which are necessary to calculate the coefficients of the flux equations in "dgl" from the driving forces and/or the system state. Its call is required at the begin of each time step (i.e. data–supported time step). The tasks are:

[1] Calculated from our own unpublished data measured in many climate zones of the world

2.5.1 Coefficient of ion pumping from subsidiary to guard cells

It is assumed that ion pumps are activated by photosynthetically active radiation, PAR (Zeiger 1983; Willmer, Fricker 1996):

$$fpar = \frac{\frac{PAR}{PAR+Km_{PAR}} + f0}{1 + f0} \tag{2.31}$$

With $0 \leq fpar \leq 1$ being the relative activation of the pumps by light, $f0$ the minimum activity of the pumps[2], PAR the photosynthetically active irradiation ($\lambda = 400, \ldots, 700$ nm) [μE·m^{-2}·sec^{-1}], Km_{PAR} the irradiation (PAR) for half maximum activation.

It is assumed that ion pumps are inhibited by abscisic acid (ABA), which is produced in the roots according to the soil water potential Ψ_{rw} in the vicinity of the roots (Schulze 1986; Turner 1986; Tardieu et al. 1996; Croker et al. 1998), and possibly additionally in the leaf:

$$faba = \mathrm{e}^{-k_{aba}\cdot(-k_\Psi\cdot\Psi_{rw}+ABA_l)} \tag{2.32}$$

With $1 \geq faba \geq 0$ being the residual relative activity of the pumps, k_{aba} the inhibition coefficient of the pumps by ABA [m$^3 \cdot \mu$mol^{-1}], k_Ψ the production coefficient of ABA in roots [μmol·m^{-3}·MPa^{-1}], Ψ_{rw} the water potential in the root zone [MPa], ABA_l the concentration of ABA produced in the leaf [μmol·m^{-3}].

The coefficient of ion pumping is calculated under consideration of the leaf temperature influence:

$$k_{sg} = k_{sg}0 \cdot Q10^{\frac{T_{leaf}-T_{ref}}{10}} \cdot fpar \cdot faba \tag{2.33}$$

$k_{sg}0$ [mol·sec^{-1}] is the pump rate at T_{ref}, at maximum activation by light, and no inhibition by ABA, $Q10$ is the activation by temperature, T_{leaf} and T_{ref} are the leaf temperature and the reference (adaptation) temperature.

2.5.2 Conductivity coefficient of water in soil

The coefficient of conductivity of water in soil k_{rw} [m^3·m^{-2}·MPa^{-1}·sec^{-1}] depends on the soil texture and the soil water content. It may be calculated, therefore, from the bulk soil water potential (Becher 1970):

$$k_{rw} = 5 \cdot 10^2 \cdot \exp(-25.5 - 1.639 \cdot \ln(-\Psi_r)) \tag{2.34}$$

[2] approximately, since: $fpar(PAR = 0) = \frac{0+f0}{1+f0} = \frac{f0}{1+f0} \approx f0$ when $1 \gg f0$

2.5.3 Coefficients of the CO_2 fluxes in leaves

Calculate the specific molar transpiration per dry matter of leaves $emol$ [μmol·g^{-1}·sec^{-1}] from the transpiration flux with respect to ground surface area e [kg·m^{-2}·sec^{-1}]:

$$emol = \frac{e}{vm} \cdot \frac{0.45}{pha} \cdot 10^6 \tag{2.35}$$

With vm being the mole–volume of liquid water [m^3·mol^{-1}], pha the leaf–phytomass in carbon [g·m^{-2}], the factor 0.45 converts carbon in dry matter.

Calculate the carboxylation coefficient of Rubisco per gram leaf dry matter k_{ar} [μmol·g^{-1}·sec^{-1}] by an Arrhenius function:

$$k_{ar} = k_{ar}0 \cdot \exp\left(\frac{T_{leaf} - T_{ref}}{T_{ref}} \cdot \frac{ea}{R \cdot T_{leaf}}\right) \tag{2.36}$$

Where ea is the energy of activation for the carboxylation reaction by Rubisco [J·mol^{-1}], R the gas constant [J·K^{-1}·mol^{-1}], and $k_{ar}0$ the value of k_{ar} at reference temperature.

Calculate the PAR absorbed by one gram of leaf dry matter PAR_{abs} [μE·g^{-1}·sec^{-1}]:

$$PAR_{abs} = PAR \cdot \frac{1}{pha/0.45} \cdot \mathrm{e}^{-k_e \cdot pha/0.45} \tag{2.37}$$

Where PAR is the incident photon flux density [μE·m^{-2}·sec^{-1}], pha the leaf phytomass (carbon) [g·m^{-2}], k_e the extinction coefficient for leaf dry matter [m^2·g^{-1}].

Electron transport rate je [μmol·g^{-1}·sec^{-1}] in the leaf light harvesting complexes per gram leaf dry matter (one electron produced for two photons absorbed):

$$je = \frac{PAR_{abs}}{2} \cdot \frac{1}{1 + PAR_{abs}/Km_{PAR}} \tag{2.38}$$

Where Km_{PAR} is the irradiation (PAR) for half maximum saturation of the electron transport chains (see equation 2.31 on page 15).

Calculate the production rate jn [μmol·g^{-1}·sec^{-1}] of NADPH+H$^+$ (one NADPH+H$^+$ got for two electrons):

$$jn = 0.5 \cdot je \tag{2.39}$$

Calculate the CO_2 production rate $resp$ [μmol·g^{-1}·sec^{-1}] per gram leaf dry matter from oxidative decarboxylation:

$$resp = rref \cdot Q10_{res}^{\frac{T_{leaf} - T_{ref}}{10}} \tag{2.40}$$

$rref$ is the production rate [μmol·g^{-1}·sec^{-1}] at reference temperature. $resp$ is limited to 0 for deserts and inland ice fields:

$$resp = 0 \begin{cases} \text{for} & pha < 10^{-3} \quad [\mathrm{g \cdot m^{-2}}] \\ \text{for} & textur = 9 \end{cases} \tag{2.41}$$

2.6 Module psir

The module "psir" (Ψ_r) calculates soil water potentials from the soil water pools of GIWACOM. GIWACOM distinguishes two different pools of soil water: (1) the average water content bw of the bulk soil down to rooting depth [g H_2O / 100 g soil]. This value is either set or provided by a climate model like ECHAM. (2) the water content rw of a soil cylinder of the length 1 meter and the radius rad_{rw} around 1 meter of root length. This soil cylinder is assumed to be depleted in water compared with bw as a consequence of the water uptake by the root and the conductivity (permeability) of the soil for water. The value of rw is available from "dgl" after integration of the system.

It is assumed that the soil water content changes slowly compared to the stomatal apparatus. Therefore, and due to the complex procedures to be carried out for the determination of the soil water potentials, "psir" is applied only once at the beginning of each minute (and not included in "dgl").

2.6.1 Set parameters for the basic soil particle fractions

The soil water potential depends on the soil texture. Textures are assumed to be composed of 1–3 of the following basic particle fractions:

- coarse ("sand")
- medium ("silt")
- fine ("clay")

The composition of texture classes of the texture data set (Staub and Rosenzweig 1987) is assumed to be as showed in table 2.1.

For each of the three particle sizes a set of parameters exists to theoretically parameterize equations (2.55) and (2.56). The parameter fk is the maximum pore volume ("field capacity" in % = [g H_2O / 100g soil]. The parameter Ψ_{fk} is the water potential [MPa] at field capacity (Nobel 1991). k is an adjustable parameter for each particle size. The values are stored in parameter arrays with three entries, subscribed by $pc = 1$, $pm = 2$, $pf = 3$:

$$k(pc) = 1.974 \tag{2.42}$$

$$k(pm) = 2.303 \tag{2.43}$$

$$k(pf) = 4.605 \tag{2.44}$$

Table 2.1: The texture classes of the global gridded soil texture data file (Staub and Rosenzweig 1987) and their composition of basic particle fractions as assumed for this module. In grid elements having the texture class 0 (water) we assumed the means of the textures of the surrounding grid elements.

texture class	type	values of		
		coarse	*medium*	*fine*
0	water			
1	coarse	1	0	0
2	medium	0	1	0
3	fine	0	0	1
4	coarse–medium	1	1	0
5	coarse–fine	1	0	1
6	medium–fine	0	1	1
7	coarse–medium–fine	1	1	1
8	organic	0	0	1
9	land ice	1	0	0

$$fk(pc) = 10 \tag{2.45}$$

$$fk(pm) = 30 \tag{2.46}$$

$$fk(pf) = 40 \tag{2.47}$$

$$\left.\begin{array}{r}\Psi_{fk}(pc)\\ \Psi_{fk}(pm)\\ \Psi_{fk}(pf)\end{array}\right\} = -0.015 \tag{2.48}$$

2.6.2 Calculate weighted means of parameters for the soil texture classes

The values given in the equations (2.42–2.48) are not directly used to parameterize equations (2.55) and (2.56). Instead, weighted means of the three versions of each parameter are used, depending on the texture classes given in table 2.1 and on the water content of the soil. With respect to the water content of the soil the assumption is made that the fine pores are filled first (i.e. at low water content), then the coarser ones.

Therefore, the soil water potential is dominated by the fine pores if the water content is low. The coarse pores contribute mainly in very wet soils.

Factors for weighing the parameters according to the texture for coarse, medium, and fine are:

$$fc = coarse \cdot \max\left(0.01, 1 - \frac{fk(pc) - bw}{fk(pc)}\right) \tag{2.49}$$

$$fm = medium \cdot \sqrt{\max\left(0.01, \frac{bw \cdot fk(pm) - bw^2}{fk(pm)^2}\right)} \tag{2.50}$$

$$ff = fine \cdot \max\left(0.01, \frac{fk(pf) - bw}{fk(pf)}\right) \tag{2.51}$$

The weighted means of the parameters for equations (2.55) and (2.56), $mk, mfk, m\Psi_{fk}$, are then calculated according to:

$$mk = \frac{fc \cdot k(pc) + fm \cdot k(pm) + ff \cdot k(pf)}{fc + fm + ff} \tag{2.52}$$

$$mfk = \frac{fc \cdot fk(pc) + fm \cdot fk(pm) + ff \cdot k(pf)}{fc + fm + ff} \tag{2.53}$$

$$m\Psi_{fk} = \frac{fc \cdot \Psi_{fk}(pc) + fm \cdot \Psi_{fk}(pm) + ff \cdot \Psi_{fk}(pf)}{fc + fm + ff} \tag{2.54}$$

2.6.3 Calculate the soil water potentials

Now the soil water potentials Ψ_r and Ψ_{rw} may be calculated from the respective pools using the set of mean parameters mk, mfk, and $m\Psi_{fk}$:

$$\Psi_r = m\Psi_{fk} \cdot \exp\left(mk \cdot \frac{1 - \frac{bw}{mfk}}{\frac{bw}{mfk}}\right) \tag{2.55}$$

$$\Psi_{rw} = m\Psi_{fk} \cdot \exp\left(mk \cdot \frac{1 - \frac{rw}{mfk}}{\frac{rw}{mfk}}\right) \tag{2.56}$$

2.7 Module dgl

The module "dgl" includes the mass balance equations for osmotic substances (ions) and water in the stomatal apparatus, for the CO_2 in the intercellular spaces, and for the soil water in the root compartment. It also includes the equations for the fluxes between the pools and the coefficients if they directly depend on state variables.

2.7.1 Calculate c_i from the pool

The internal CO_2 concentration c_i [μl·l^{-1}] is calculated from the pool *in*:

$$c_i = in \cdot 24.04 \cdot 10^3 \tag{2.57}$$

2.7.2 Balance of osmotic substances in stomatal apparatus

Osmotically active substances (called "ions" in the following text) are moved between guard cells (g) and subsidiary cells (s) of the stomatal apparatus in order to modify the water potential in the guard cells and, as a consequence, the internal pressure (turgor) in the guard cells. Turgor changes of the guard cells open or close the stomatal pore and by that change the conductance.
Calculate ion concentrations [mol·m^{-3}] in the subsidiary cells c_s and in the guard cells c_g from ion pools s/g and water pools vs/vg:

$$c_s = \frac{s}{vs} \tag{2.58}$$

$$c_g = \frac{g}{vg} \tag{2.59}$$

Calculate the ion fluxes.

The fluxes are in [mol·sec^{-1}]:

- Active pumping from subsidiary into guard cells:

$$f_{sg} = k_{sg} \frac{1}{c_s + km0} \cdot c_s \tag{2.60}$$

  With $km0 = 1$.

- Regulated diffusion through variable ion channels from guard cells to subsidiary cells:

$$f_{gs} = k_{gs}(c_g - c_s) \tag{2.61}$$

  The coefficient k_{gs}, the conductivity of ion channels, has to be calculated here (not in cffclc.f) since it depends on the internal CO_2 concentration c_i:

$$k_{gs} = \frac{a_{kgs}}{1 + \exp(b_{kgs} - c_{kgs} \cdot c_i)} \tag{2.62}$$

  With $k_{gs} \geq 0$

Mass balance of ions in subsidiary and guard cells.

$$\frac{\mathrm{d}s}{\mathrm{d}t} = f_{gs} - f_{sg} \tag{2.63}$$

$$\frac{\mathrm{d}g}{\mathrm{d}t} = f_{sg} - f_{gs} \tag{2.64}$$

2.7.3 Water balance in the stomatal apparatus

The fluxes of water in the stomatal apparatus are driven by water potentials [MPa] of the subsidiary and guard cells and the apoplasmatic spaces. The water potentials include osmotic, turgor, matrix potentials.

Calculate the water potentials.

Xylem vessels. Water potential (hydrostatic potential) of xylem vessels is set to 0 since other values would only cause an offset of all the other potentials:

$$\Psi_x = 0 \tag{2.65}$$

Subsidiary cells. Osmotic potential:

$$\pi_s = -c_s \cdot R \cdot (T_{leaf} + 273.) \tag{2.66}$$

With r being the gas constant and T_{leaf} the leaf temperature [°C].
Turgor potential:

$$p_s = \varepsilon_s \cdot \frac{vs - vol_s}{1.2 \cdot vol_s - vs} \qquad \text{but always} \quad p_s \geq 0 \tag{2.67}$$

With ε_s being the elastic modulus of the subsidiary cell walls, vs the water volume in the subsidiary cells and vol_s the water volume at $p_s = 0$. p_s reaches infinity when v_s approaches $1.2\, vol_s$, limiting cell expansion.
Water potential of subsidiary cells:

$$\Psi_s = \pi_s + p_s \tag{2.68}$$

Guard cells. Their water potential is calculated in a similar way as with subsidiary cells:

$$\pi_g = -c_g \cdot R \cdot (T_{leaf} + 273) \tag{2.69}$$

$$p_g = \varepsilon_g \cdot \frac{vg - vol_g}{2.5 \cdot vol_g - vg} \qquad \text{but always} \quad p_g \geq 0 \tag{2.70}$$

$$\Psi_g = \pi_g + p_g \tag{2.71}$$

Apoplast. In the apoplast a matrix potential Ψ_e is induced which, for our purpose, depends on the transpiration flux J_e through one stomatal pore:

$$J_e = \frac{e}{1000} / p_{ha} \cdot \frac{sla}{100} / nst \tag{2.72}$$

With: J_e water flux through one stoma [$m^3 \cdot sec^{-1}$], e transpiration per m^2 ground surface [$kg \cdot m^{-2} \cdot sec^{-1}$], pha leaf phytomass per m^2 ground surface [$gC \cdot m^{-2}$], sla specific leaf area [$m^2 \cdot (100gC)^{-1}$], nst number of stomata per square meter of leaves [m^{-2}].

$$\Psi_e = \frac{R_{eg}\Psi_s + R_{se}\Psi_g - R_{eg}R_{se}J_e}{R_{eg} + R_{se}} \tag{2.73}$$

With R the respective resistances to water flux [$MPa \cdot sec \cdot m^{-3}$].

Calculate the net fluxes of water from the potentials and resistances

The net fluxes are [$m^3 \cdot sec^{-1}$]:

$$J_{xs} = \frac{\Psi_x - \Psi_s}{R_{xs}} \tag{2.74}$$

$$J_{se} = \frac{\Psi_s - \Psi_e}{R_{se}} \tag{2.75}$$

$$J_{eg} = \frac{\Psi_e - \Psi_g}{R_{eg}} \tag{2.76}$$

Water balance for guard cells and subsidiary cells

$$\frac{\mathrm{d}vg}{\mathrm{d}t} = J_{eg} \tag{2.77}$$

$$\frac{\mathrm{d}vs}{\mathrm{d}t} = J_{xs} - J_{se} \tag{2.78}$$

2.7.4 Calculate the stomatal conductance

Calculate the relative aperture of stomatal pore

The relative aperture ($0 \leq relapt \leq 1$) is calculated from the turgor (hydrostatic) pressure [MPa] in the guard cells and the subsidiary cells:

$$relapt = \frac{1}{1 + \mathrm{e}^{a - b \cdot p_g}} - c \cdot p_s \tag{2.79}$$

For $p_s \geq 0$. The parameters are $a = 2$, $b = 1$, $c = 0.55$.

Calculate the conductance for water vapor

The stomatal conductance per gram of leaf dry matter $gsdm$ [$\mu mol \cdot gDM^{-1} \cdot sec^{-1}$] is calculated from $relapt$ and the maximum value for a given vegetation formation:

$$gsdm = relapt \cdot gsdm_{mx} \tag{2.80}$$

$gsdm$ is limited to 0.5 for deserts and over inland ice fields:

$$gsdm = 0.5 \begin{cases} \text{for} & p_{ha} < 10^{-3} \\ \text{for} & textur = 9 \end{cases} \tag{2.81}$$

2.7.5 Water balance in a soil compartment in the vicinity of the roots

As a consequence of the limited water conductance of soils, during transpiration a soil compartment around a root is water depleted in comparison to the total soil pool. This reduced water content determines the soil water potential Ψ_{rw} "seen" by the plant.

Ψ_{rw} is calculated from the water pool in a soil compartment around a root of 1 m length. The radius of the soil cylinder around the root is rad_{rw}.

Transpiration flux through 1 m of root length

The transpiration flux J_{tr} [$m^3 \cdot sec^{-1}$] through 1 m of root length is calculated from e [kg $\cdot$ $m^{-2} \cdot$ sec^{-1}], the root phytomass phb [$gC \cdot m^{-2}$], the specific root length 10 [$m \cdot (gDM)^{-1}$]:

$$J_{tr} = \frac{e}{1000} \cdot \frac{1}{phb \cdot \frac{10}{0.45}} \tag{2.82}$$

Water balance in the root soil compartment

The change of the amount of water in the root soil compartment is the balance of the diffusion flux due to the soil water potential gradient from the bulk soil to the root soil and the uptake by 1 m of root.

First the surface area $area_{rw}$ of the soil cylinder around 1 m of root is calculated:

$$area_{rw} = 2 \cdot rad_{rw} \cdot \pi \cdot 1 \tag{2.83}$$

The water balance is:

$$\frac{\mathrm{d}rw}{\mathrm{d}t} = k_{rw} \cdot area_{rw} \cdot (\Psi_r - \Psi_{rw}) - J_{tr} \tag{2.84}$$

Where k_{rw} is the specific soil conductance for liquid water [$m^3 \cdot m^{-2} \cdot MPa^{-1} \cdot sec^{-1}$].

2.7.6 Mass balance of CO_2 in the intercellular spaces

This is the most dynamic process in the model with a typical time of less than one second to reach a steady state.

The photosynthesis aph is calculated from the part ar limited by c_i and from the part an limited by electron transport and thus NADPH+H^+ production:

$$ar = k_{ar} \cdot (c_i - \Gamma) \tag{2.85}$$

$$jn = f(PAR, phytomass) \tag{2.86}$$

$$an = \frac{jn}{2} \cdot \frac{c_i - \Gamma}{c_i + 2\Gamma} \tag{2.87}$$

$$aph = min(ar, an) \tag{2.88}$$

with Γ the value of c_i at the CO_2 compensation point. The NADPH+H^+ production jn is calculated in the module "cffclc". aph is set to 0 in deserts (i.e. leaf phytomass is less than 10^{-3} g) and over inland ice (i.e. soil texture is "9").

The respiration flux $resp$ is a function of leaf temperature and leaf type:

$$resp = rref \cdot Q10_{res}^{\frac{T_{leaf}-T_{ref}}{10}} \tag{2.89}$$

with:

$rref$ respiration of plant type at reference temperature T_{ref}

$Q10_{res}$ Q10 value for the leaf tissue of a plant type

The net Assimilation of CO_2 per g dry matter of the leaf $anet$ is calculated from photosynthesis aph and respiration $resp$:

$$anet = aph - resp \tag{2.90}$$

The mass balance equation of the amount of intercellular CO_2 is:

$$\begin{aligned} \frac{\mathrm{d}in}{\mathrm{d}t} &= \frac{gsdm}{1.56}(c_a - c_i) \cdot 10^{-6} && \text{diffusion through stomata} \\ &\quad -anet && \text{assimilation of } CO_2 \\ &\quad -\frac{c_a + c_i}{2} \cdot emol \cdot 10^{-6} && \text{correction for water vapor diffusion} \end{aligned} \tag{2.91}$$

Meaning of the variables:

in amount of CO_2 in the intercellular spaces [μmol·g^{-1}]

$gsdm$ conductivity for water vapor [μmol·g^{-1}·sec^{-1}]

c_a, c_i CO_2 concentrations in atmosphere and intercellular spaces [μmol·mol^{-1}]

$anet$ net assimilation of CO_2 [μmol·g^{-1}·sec^{-1}]

$emol$ molar transpiration of leaf [μmol·g^{-1}·sec^{-1}]

The conductivity $gsdm$ for water vapor is a function of *all* state variables of the model, the driving forces, and initial conditions (vegetation formation).

2.8 Module output

This module is used for organizing the model output. It may be run any time *after the module "dgl"*, i.e. at the end of any of the time loops in the module "giwacom2.10" according to the user's request. The module may be adapted by the user.

The state variables of the model and other data are made available to "output" by common blocks (see section 4.2 on page 34).

The module includes the opening procedures for the output files. A counter is used to open the files at the first run of "output" only.

Chapter 3

Description of GIWACOM version 2.20

GIWACOM version 2.20 is designed to run as a submodel of the climate model ECHAM of the Max Planck Institute for Meteorology, Hamburg. The resolution is T42. Since GIWACOM2.20 has an adaptable spatial resolution, other resolutions of ECHAM will not require changes of GIWACOM's program code, but only new parameter files.

ECHAM's regional structure is based on latitudinal bands, beginning at the first band just north of the equator, and working to the poles while alternating between the northern and southern hemispheres.

GIWACOM2.20 runs on one latitudinal band at a time, considering only grid elements on land. The latitudinal band is specified by ECHAM. The grid elements in a band are defined by ECHAM's land mask. Since GIWACOM is a global model the arrays have to be of the form `variable(igrid,j)`, with $igrid = 1, \ldots, maxgrd(j)$ the array of grid elements on land of the latitudinal band j, and $j = 1, \ldots, 64$.

ECHAM provides arrays of driving forces each time GIWACOM is activated to calculate the conductance array for a latitudinal band, which is then returned to ECHAM. The arrays of driving forces include soil water, photosynthetically active radiation, transpiration, and leaf (skin) temperature, all of them given for the land grid elements of the band. The atmospheric CO_2 concentration is an additional scalar driving force. After activation for a latitudinal band, GIWACOM evolves its own state variables for this band by another 24 minutes (ECHAM time step).

While GIWACOM2.10 was designed to run for one standard day of a selected month, GIWACOM2.20 must be able to run for many years. The data sets were adapted to this requirement.

Table 3.1: Comparison of the module sets of GIWACOM versions 2.10 and 2.20 and the grade of modification. "e" eliminated in version 2.20, "n" new in version 2.20.

GIWACOM2.10	GIWACOM2.20	modifications
`giwacom2.10`	`giwacom2.20`	major
`readgen`	—	e
`readforces`	`readforces`	major
—	`readphytomass`	n
`clcparams`	—	e
—	`setparams`	n
`cffclc`	`cffclc`	minor
`psir`	`psir`	minor
`dgl`	`dgl`	minor
`output`	`output`	minor
—	`scaleup`	n

GIWACOM2.10, as the research version of the model, has modules to create a full parameterization of the model "a priori" at each model start. This is based on vegetation maps, vegetation–related data sets, and long–term climate situations. For the coarse spatial resolution T42 used in GIWACOM2.20 this procedure would be inappropriate, because it would require averaging of vegetation types and vegetation data from the 0.5 degrees grid to the T42 grid (about 5.6 degrees latitude and longitude).

Instead, we generated a parameterization for GIWACOM2.20 by calculating the parameters for a 0.5 degree grid with GIWACOM2.10 first. In a second step these parameters are averaged for the T42 grid and stored in files. GIWACOM2.20 reads these files when it is first started during a coupled run. Thus the parameterization of both versions is similar.

Modules have been modified, eliminated, and added in version 2.20 to achieve the above requirements. In table 3.1 we list the module names of both versions and indicate the grade of modification. Only those modules are explained below, which have undergone at least major modifications.

3.1 Module giwacom2.20

As in version 2.10, this module organizes the initialization of the pools, and the sequence and frequency the other modules are run. It includes the integration loop in the inner time–loop.

Since this module is directly called from the respective modules of ECHAM, it carries out 24 minutes integration for one latitudinal band per call. It includes counters which keep track of the number of calls to this module and the number of calls for each latitudinal band.

At the first call of "giwacom2.20" the modules "readforces", "setparams", and "readphytomass" are run in order to make available the respective arrays.

At each call of "giwacom2.20" the arrays of driving forces provided by ECHAM are assigned to the respective internal arrays of forces of GIWACOM. The ECHAM arrays are distinguished by a subscript: $array_{ec}$.

At the first call of each latitudinal band the pool arrays are initialized. The assumptions to assign initial values are the same as explained in section 2.1.1 on page 6.

The time loops are simplified: There is an outer loop $minute = 1, \ldots, 24$ and an inner loop $second = 1, \ldots, 60$. The integration loop and the integration procedure are similar to those described in section 2.1.3 on page 8.

After the time loops are completed, i.e. after the pools of the current latitudinal band have been evolved through 24 minutes, the modules "scaleup" and "output" are run and the control is given back to ECHAM.

3.2 Module readforces

"readforces" could be strongly shortened in version 2.20 since most of the driving forces are provided by ECHAM.

The soil texture is read here only, from the file `inputham/texture` using unit 70, into a two–dimensional array of the form `textur(igrid,j)` with the grid elements in a band $igrid = 1, \ldots, maxgrd(j)$ and the band $j = 1, \ldots, 64$.

3.3 Module readphytomass

In GIWACOM2.10 the values for above–ground and below–ground herbaceous phytomass were read for one given month only. This could be done in the module "readforces".

Here a separate module is used to read these phytomasses since they are required for each month of the year. They are in carbon [g·m^{-2}].

The files are in the relative directory `inputham/`. The file names are of the form `phab`n`.ham` with n for the respective month (1–12).

The values are read into three–dimensional arrays of the type `value(i,j,month)` with `value` being either `pha` (phytomass herbaceous above ground) or `phb` (phytomass herbaceous below ground), `i` being the grid element of the band `j` and month one value from 1 to 12.

3.4 Module setparams

This module provides the parameters for the model equations. It replaces, therefore, two modules of version 2.10: "readgen" for the plant–dependent parameters and "clcparams" for the others.

In "setparams" the parameters are not calculated as in "clcparams" but read from files. The plant dependent parameters are also read from files as arrays of the grid, not as arrays of plant– or vegetation types as in "readgen".

The general structure of this module is similar to "clcparams" of version 2.10. All scalars are identical and are not discussed here again. The arrays are of T42 resolution and are means of the respective arrays of the 0.5 degrees resolution model, which were calculated by a model run of GIWACOM2.10.

The general form of the parameter arrays is:
`parameter(j, igrid), igrid=1, maxgrd(j)`
so that a set of parameters is available for the grid elements of a latitudinal band `j` at each call of GIWACOM by ECHAM. The parameter arrays read from files include: $k_{sg}0$, Km_{par}, R_{xs}, R_{se}, R_{eg}, vol_g, vol_s, vol_a, sla, nst, T_{ref}, a_{kgs}, b_{kgs}, c_{kgs}, $gsdm_{max}$, $k_{ar}0$.

3.5 Module scaleup

This module transforms the conductivity per leaf dry weight [μmol·g^{-1}·sec^{-1}] which was calculated in the module "dgl" into a conductivity per square meter ground area of the vegetation stand [μmol·m^{-2}·sec^{-1}]. The information about the leaf phytomass pha [g·m^{-2}] is taken from the High Resolution Biosphere Model (Esser et al. 1994).

The normal procedure for scaling up would be to integrate conductivity vertically. To do this correctly the vertical distribution functions for all plant dependent parameters

used in GIWACOM and for the leaf phytomass would be required globally. Since nothing like that is available we used a different integrated approach: the contribution function of each piece of leaf area to the stand conductivity is calculated.
To do this the following tasks are carried out:

3.5.1 Calculate leaf area index

The LAI is calculated from the actual leaf phytomass pha [g·m^{-2}] and the specific leaf area sla [m^2·(100 g)$^{-1}$]:

$$LAI = pha \cdot \frac{sla}{100} \tag{3.1}$$

3.5.2 Calculate the contribution function of LAI

When LAI is very low (very open vegetation), each leaf contributes similarly to the stand conductivity. If the LAI is high, additional leaves contribute little or nothing. This leads to a saturation function ("contribution function") of the LAI of a given stand (effective LAI):

$$LAI_{eff} = m_{LAI} \cdot \frac{LAI}{(LAI/a_{LAI}) + 1} \tag{3.2}$$

We set the initial slope $m_{LAI} = 1$ since $LAI_{eff} = LAI$ at low values of LAI. The parameter a_{LAI} is the value of LAI at which $LAI_{eff} = \frac{LAI}{2}$. This is an adjustable parameter for the vegetation formations. We set $a_{LAI} = 5$.

3.5.3 Calculate stand conductivity

The stand conductivity gw_b [μmol·m^{-2}·sec^{-1}] for water vapor is calculated according to:

$$gw_b = gsdm \cdot \frac{1}{sla} \cdot \frac{100}{0.45} \cdot LAI_{eff} \tag{3.3}$$

Chapter 4

The program code

For best portability and performance GIWACOM has been entirely programmed in FORTRAN 77 (ANSI–Document X3.9–1978). No calls to external libraries or other software products which are not standard FORTRAN have been included. The only exception is that we use the non–standard FORTRAN 77 command "include" and the special character _ (underline). These two modifications are supported by probably any modern compiler and have become standard in FORTRAN 90.

4.1 Program structure

The representation in the program code of the model structures explained in the model description is as follows:

model structure	program code representation
module GIWACOM2.10	main program
module GIWACOM2.20	subroutine
all other modules	subroutines
task	one or several grid element loops

The structure of the program code of GIWACOM2.10 is found in figure 4.1. The structure of GIWACOM2.20 is found in figure 4.2.

The model code of either version of GIWACOM is not optimized for performance. It was not intended to optimize the GIWACOM2.10 code since this version is a research model which requires transparent code. The CPU time requirements of GIWACOM2.20 as described in chapter 3 are vast and therefore the code is not directly suitable for practical applications. Again, the description is for maximum clarity and comparability with

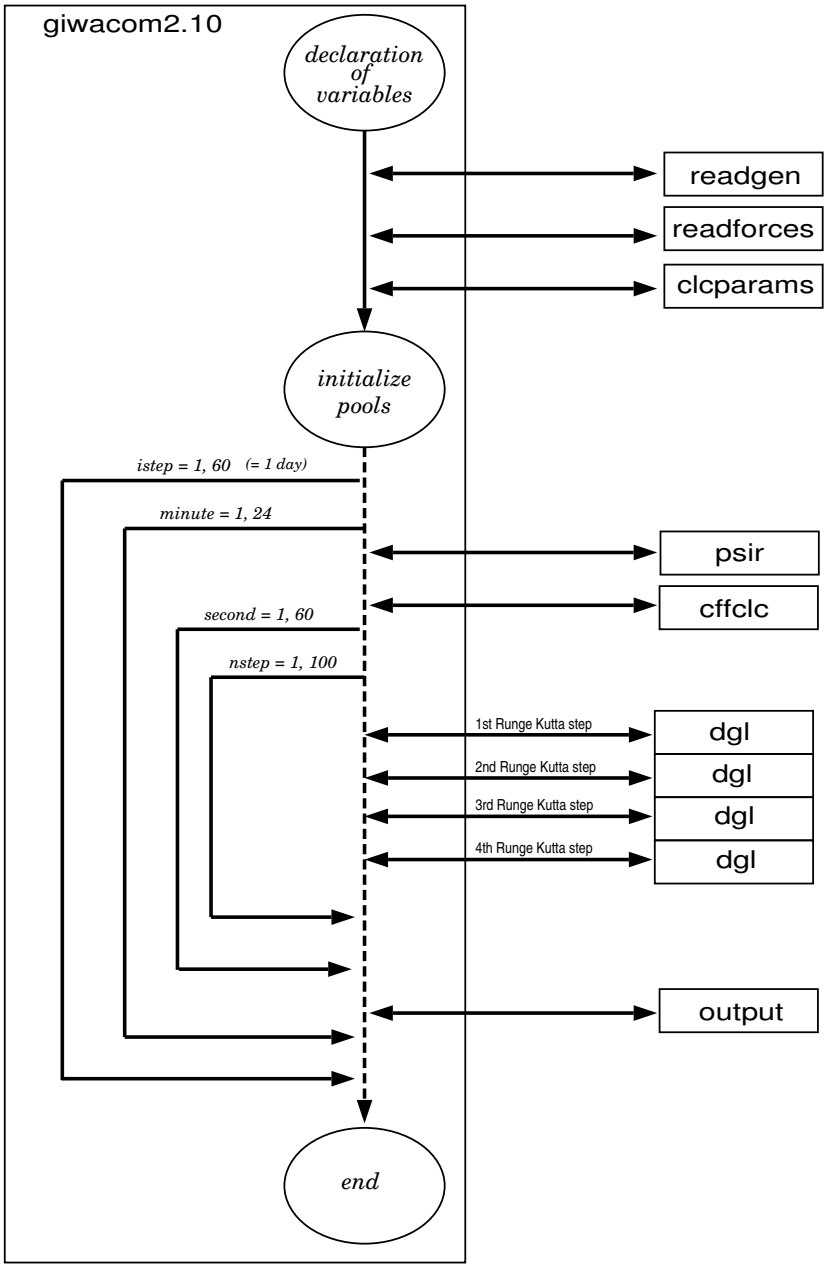

Figure 4.1: Structure of the stand–alone program of GIWACOM2.10. The outer loop $istep = 1, 60$ covers one day since 60×24 minutes $= 1$ day. The spatial resolution of the model is a global 0.5 degree grid of land areas (62 483 grid elements).

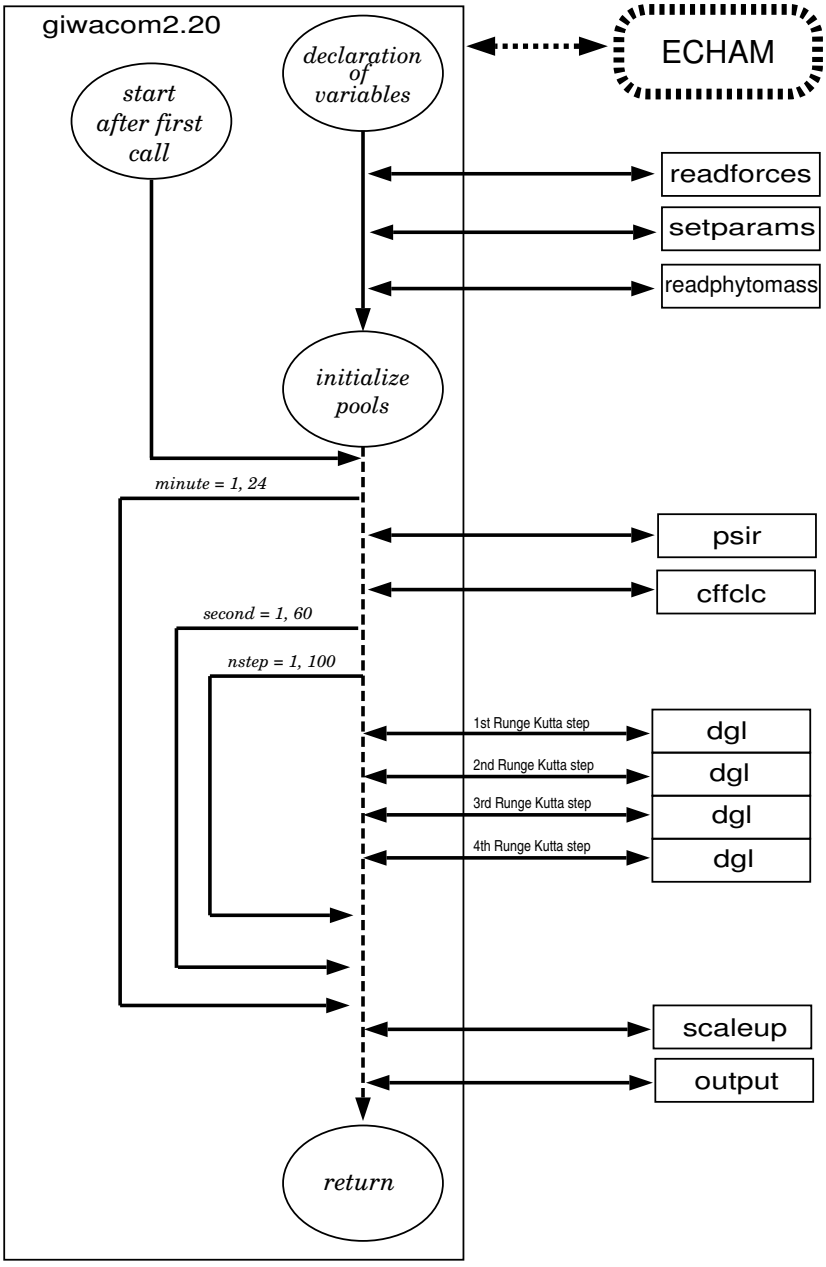

Figure 4.2: Structure of the program of GIWACOM2.20. The main module "giwacom2.20" runs as a subroutine of the climate model "ECHAM" (Max Planck Institute for Meteorology Hamburg). At every call by "ECHAM" the model runs on one latitudinal band, so that in T42 resolution 50 calls are required for the total coverage of the land areas (ECHAM has 64 bands including ocean–only bands and Antarctica). The time–evolution is 24 minutes per call.

GIWACOM2.10. In section 4.3 we make some remarks how to optimize GIWACOM's performance.

4.2 Data sharing and common blocks

In some cases clarity of programming requires passing arguments while calling a subroutine. The modules which use such a list and the variables included are listed in tables 4.1 and 4.2. The notation of the variables is as in the program code.

Table 4.1: The modules of GIWACOM2.10 which are called with arguments and the variables included in the list.

module	variables in the list
psir	*p, istep*
cffclc	*istep*
dgl (1st Runge–Kutta step)	*p, m, istep*
dgl (2nd–4th Runge–Kutta step)	*ptmp, m, istep*
output	*istep, minute*

Table 4.2: The modules of GIWACOM2.20 which are called with a variable–list and the variables included in the list.

module	variables in the list
giwacom2.20 (called by ECHAM)	*j, month, ca_ec, bw_ec, par_ec, e_ec, gw_b*
psir	*p, j*
cffclc	*j, month*
dgl (1st Runge–Kutta step)	*p, m, j, month*
dgl (2nd–4th Runge–Kutta step)	*ptmp, m, j, month*
scaleup	*gw_b, j, month*
output	*minute, j, gw_b*

In all other cases the modules share data by named common blocks. The files with the common block definitions are expected to be in the relative directory `common/`. The file names are identical with the common block names. Each common block file consists of three parts:

1. Declaration of the types of variables

2. Common declaration of the variables

3. Save declaration of the common block

Common blocks are included in the modules using the non–standard FORTRAN 77 command `include`. A common block may contain variables which are not necessarily used by all modules which include this common block; i.e. modules may use a part of the variables only.

The following list gives the names of the common blocks in alphabetical order. The common blocks may be slightly different for either model version and they may be used by different modules. Also listed are the variables contained in the common blocks, and the module(s) which use the common blocks. The notation of the variables is as in the program code, **not** as in the model description. For comparison of both notations see chapter 6.

ci

version: **2.10**
variables: `ke, gamma, ea, rref, Q10res, k_ar0, k_ar, jn, resp, cin, anet`
used by: cffclc, clcparams, dgl, output

ci

version: **2.20**
variables: `ke, gamma, ea, rref, Q10res, k_ar0, k_ar, jn, resp, cin, anet`
used by: cffclc, dgl, output, setparams

coeffs

version: **2.10, 2.20**
variables: `k_gs, k_sg, k_rw`
used by: cffclc, dgl, psir

conduct

version: **2.20**
variables: `gsdm`
used by: dgl, output, scaleup

control

version: **2.20**
variables: `maxgrd`
used by: cffclc, dgl, giwacom2.20, output, psir, readforces, scaleup, setparams

forces

version: **2.10**
variables: `ca, par, temp, e, emol, mi, tleaf, lai, bw, textur`
used by: cffclc, clcparams, dgl, giwacom2.10, psir, readforces

forces

version: **2.20**
variables: `ca, par, e, emol, tleaf, bw, textur`
used by: cffclc, dgl, giwacom2.20, psir, readforces, setparams

params

version: **2.10**
variables: `q10, abal, kaba, kpsi, f0, eps_g, eps_s, r, vm, cinit, nst, sla, cmaxg, gsdmmx, kmpar, volg, vols, vola, tref, r_xs, r_se, r_eg, akgs, bkgs, ckgs, k_sg0, radrw`
used by: cffclc, dgl, giwacom2.10, psir, readforces, readgen

params

version: **2.20**
variables: `q10, abal, kaba, kpsi, f0, eps_g, eps_s, r, vm, cinit, nst, sla, gsdmmx, kmpar, volg, vols, vola, tref, r_xs, r_se, r_eg, akgs, bkgs, ckgs, k_sg0, radrw`
used by: cffclc, dgl, giwacom2.20, psir, readforces, scaleup, setparams

phytomass

version: **2.10**
variables: `pha, phb`
used by: cffclc, clcparams, dgl, readforces

phytomass	version:	**2.20**
	variables:	`pha, phb`
	used by:	cffclc, dgl, readphytomass, scaleup
potentials	version:	**2.10, 2.20**
	variables:	`psi_r, psi_rw`
	used by:	cffclc, dgl, output, psir
run	version:	**2.10**
	variables:	`monws`
	used by:	readforces
variables	version:	**2.10**
	variables:	`c_g, c_s, psi_x, psi_s, psi_g, psi_e, pi_g, pi_s, p_g, p_s, gsdm, relapt`
	used by:	dgl, output
variables	version:	**2.20**
	variables:	`c_g, c_s, psi_x, psi_s, psi_g, psi_e, pi_g, pi_s, p_g, p_s, relapt`
	used by:	dgl, output

4.3 How to improve the model's performance

The program code of the two versions of GIWACOM is not at all optimized for performance. The models are research tools. They are designed for further development of the model structure and the parameterization.

Therefore, we provide dynamic mass balance equations which require, due to the "fast" processes which are included, very short integration steps. The result is extensive consumption of computing time. The models are *not suitable for practical applications* (production runs) in the state they are documented here.

Minor changes of the model code will improve the performance considerably and reduce the computing time by several orders of magnitude. For example, "stiff" differential equations may be eliminated from the module "dgl" and, instead, a steady–state

solution of these equations may be included.

Since the transformation of equations to steady state solutions always makes assumptions necessary, which depend on the context in which the model will be used, we do not provide solutions here. We will be pleased to help you with the necessary changes.

Chapter 5

Data files

5.1 Data files for model version 2.10

5.1.1 Files read in the module readforces

Files with driving forces provided by the climate model

The files provide driving forces for each time step during a standard day in March and August, respectively. For the entire day of 60×24 minutes 60 global arrays of 62 483 grid elements of the respective variable are provided in the file, beginning with midnight (UTC). Each array begins with a header which includes the variables `istep, idate, itime` (format `3i7`), where `istep` is the current number of the time step $(1, \ldots, 60)$, `idate` is the date of the day and `itime` the time of the beginning of the time step (minutes).

The data were calculated by the climate model ECHAM in T42 resolution and regridded to GIWACOM2.10's 0.5 degree grid. The files are expected in the subdirectory `echamdaten/` relative to the current directory.

File name	variables	data format	dimension
soilwater.march.05.60 soilwater.august.05.60	`bw(igrid,istep)`	`(f5.1)`	%
par.march.05.60 par.august.05.60	`par(igrid,istep)`	`(f5.0)`	$[\mu\mathrm{E}\cdot\mathrm{m}^{-2}\cdot\mathrm{sec}^{-1}]$
transpiration.march.05.60 transpiration.august.05.60	`e(igrid,istep)`	`(e10.5)`	$[\mathrm{kg}\cdot\mathrm{m}^{-2}\cdot\mathrm{sec}^{-1}]$
skintemp.march.05.60 skintemp.august.05.60	`tleaf(igrid,istep)`	`(f5.1)`	$[^{\circ}\mathrm{C}]$

Files with driving forces provided by the carbon cycle model

The files are expected in the subdirectory `input/` relative to the current directory.

File name	variables	data format	dimension
phytomass.march phytomass.august	`pha(igrid), phb(igrid)`	`(2f15.5)`	$[\mathrm{g{\cdot}m^{-2}}]$

"Phytomass herbaceous above ground" and "phytomass herbaceous below ground" are provided as their carbon equivalents. The values were calculated by the High Resolution Biosphere Model (Esser et al. 1994) for a standard day in March and August, respectively. `igrid` $(1, \ldots, 62\,483)$ is the number of the grid element according to a standard layout of a global grid of the land masses except Antarctica.

Files with long–term climate and soil characteristics

The files are expected in the subdirectory `input/` relative to the current directory.

File name	variables	data format	dimension
priestley–taylor.05	`mi(igrid)`	`(f5.2)`	dimensionless
texture.05	`textur(igrid)`	`(i1)`	dimensionless

Global arrays (`igrid` $= 1, \ldots, 62483$) are provided. We followed the algorithm suggested by Prentice, Sykes and Cramer (1993) to calculate mi. The soil texture data are from Staub and Rosenzweig (1987).

5.1.2 Files read in the module readgen

The files are expected in the subdirectory `input/` relative to the current directory.

The files containing the group data (see section 2.2.4 on page 9) have the extension `.grp`, those with the formation related data `.form`. The data sets were created by our own microscopic investigation of plant material from many climate zones of the world.

File name	variables	data format	dimension
volumes.grp volumes.form	`iv, volg(iv),vols(iv),vola(iv)`	`(i2,3d10.1)`	[m^3]
resistances.grp resistances.form	`iv, r_xs(iv),r_se(iv),r_eg(iv)`	`(i2,3d10.1)`	[MPa·sec·m^{-3}]
nstomata.grp nstomata.form	`iv, nst(iv)`	`(i2,d10.1)`	[m^{-2}]
sla.grp sla.form	`iv, sla(iv)`	`(i2,d7.2)`	[$m^2 \cdot 100g^{-1}$]
kmpar.grp	`grp, kmpar(grp)`	`(i2,d6.0)`	[μE·m^{-2}·sec^{-1}]
reftemp.form	`iv, tref(iv)`	`(i3,f5.1)`	[°C]

Two more files are provided: One contains the number codes of the 176 vegetation formations and the groups they belong to, the other a global grid of the vegetation formations. The vegetation files were digitized by the author's group on the basis of the "Atlas zur Biogeographie" (Schmithüsen 1976).

File name	variables	data format
vegets	`iveg, group(iveg)`	`(i3,2x,i2)`
schmithuesen.05	`vegfor(igrid)`	`(i3)`

5.2 Data files for model version 2.20

All the files read in the modules `readforces, readphytomass` and `setparams` have a similar structure according to the special purpose of GIWACOM2.20 to run with the ECHAM climate model: The data are arranged in latitudinal bands. One band is one record. Only bands exist which include at least one grid element on land. Antarctica is excluded.

The records in the files begin with the number of the latitudinal band (north to south), the number of grid elements included in the band (only those on land), the data for the grid elements.

5.2.1 Files read in the module readforces

File name	variables	data format
texture.ham	`j, maxgrd(j), textur(j,igrid)`	`(2i4,128i2)`

5.2.2 Files read in the module readphytomass

Twelve files with the phytomass arrays for January through December:

File name	variables	data format
phab1.ham	`j, n, (pha(j,i,1), phb(j,i,1)`	`(2i4,256e12.6)`
phab2.ham	`j, n, (pha(j,i,2), phb(j,i,2)`	
phab3.ham	`j, n, (pha(j,i,3), phb(j,i,3)`	
⋮	⋮	
phab12.ham	`j, n, (pha(j,i,12), phb(j,i,12)`	

5.2.3 Files read in the module setparams

File name	variables	data format	dimension
k_sg0.ham	`j, maxgrd(j), k_sg0(j,igrid)`	`(2i4,128e12.6)`	[mol·sec^{-1}]
kmpar.ham	`j, maxgrd(j), kmpar(j,igrid)`	`(2i4,128e12.6)`	[μE·m^{-2}·sec^{-1}]
r_xs.ham	`j, maxgrd(j), r_xs(j,igrid)`	`(2i4,128e12.6)`	[MPa·sec·m^{-3}]
r_se.ham	`j, maxgrd(j), r_se(j,igrid)`	`(2i4,128e12.6)`	[MPa·sec·m^{-3}]
r_eg.ham	`j, maxgrd(j), r_eg(j,igrid)`	`(2i4,128e12.6)`	[MPa·sec·m^{-3}]
akgs.ham	`j, maxgrd(j), akgs(j,igrid)`	`(2i4,128e12.6)`	–
bkgs.ham	`j, maxgrd(j), bkgs(j,igrid)`	`(2i4,128e12.6)`	–
ckgs.ham	`j, maxgrd(j), ckgs(j,igrid)`	`(2i4,128e12.6)`	–
gsdmmx.ham	`j, maxgrd(j), gsdmmx(j,igrid)`	`(2i4,128e12.6)`	[μmol·g^{-1}·sec^{-1}]
k_ar0.ham	`j, maxgrd(j), k_ar0(j,igrid)`	`(2i4,128e12.6)`	[μmol·g^{-1}·sec^{-1}·ppm^{-1}]
volg.ham	`j, maxgrd(j), volg(j,igrid)`	`(2i4,128e12.6)`	[m^3]
vols.ham	`j, maxgrd(j), vols(j,igrid)`	`(2i4,128e12.6)`	[m^3]
vola.ham	`j, maxgrd(j), vola(j,igrid)`	`(2i4,128e12.6)`	[m^3]
sla.ham	`j, maxgrd(j), sla(j,igrid)`	`(2i4,128e12.6)`	[m^2·100g^{-1}]
nst.ham	`j, maxgrd(j), nst(j,igrid)`	`(2i4,128e12.6)`	[m^{-2}]
tref.ham	`j, maxgrd(j), tref(j,igrid)`	`(2i4,128e12.6)`	[°C]

Chapter 6

List of variables

The list of variables includes the variables used in this documentation in alphabetical order. The notation given in column one is according to this reference documentation. Column two gives the respective notation as used in the program code.

The variables are scalars, one– or multi–dimensional arrays, of `real` or `integer` type, and their precision may be single or double (`real*8`) or higher, as requested. For details see the program code.

Some variables are used in version 2.10 or version 2.20 only. This is indicated in columns 3 and 4 in the table.

name of variable		in version		meaning	dimension
docu	code	2.10	2.20		
ABA_l	`abal`	*	*	ABA produced in leaves	[μmol·m^{-3}]
a_{kgs}	`akgs`	*	*	parameter in equation (2.62) on page 20	[m^3·sec^{-1}]
α_{LAI}	`alai`		*	parameter (LAI) of the contribution function where $LAI_{eff} = LAI/2$	–
$anet$	`anet`	*	*	net assimilation of carbon in leaves	[μmol·g^{-1}·sec^{-1}]
aph	`aph`	*	*	carbon assimilation flux by photosynthesis	[μmol·g^{-1}·sec^{-1}]
$area_{rw}$	`arearw`	*	*	surface area of the soil cylinder around 1 m of root	[m^2]
b_{kgs}	`bkgs`	*	*	parameter in equation (2.62) on page 20	–
bw	`bw`	*	*	water content of the bulk soil	[%]
bw_{ec}	`bw_ec`		*	water content of the bulk soil from ECHAM	[%]
c_a	`ca`	*	*	CO_2 concentration in ambient air	[μl·l^{-1}]
ca_{ec}	`ca_ec`		*	CO_2 concentration in ambient air from ECHAM	[μl·l^{-1}]
c_g	`c_g`	*	*	ion concentration in guard cells	[mol·m^{-3}]
c_i	`cin`	*	*	CO_2 concentration in the leaf intercellulars	[μl·l^{-1}]
$cinit$	`cinit`	*	*	initial concentration of osmotic substances in guard cells and subsidiary cells	[mol·m^{-3}]
c_{kgs}	`ckgs`	*	*	parameter in equation (2.62) on page 20	[μl·l^{-1}]
$cmax_g$	`cmaxg`	*	*	maximum ion concentration in guard cells	[mol·m^{-3}]
$coarse$	`coarse`	*	*	basic soil particle fraction “coarse”	–
c_s	`c_s`	*	*	ion concentration in subsidiary cells	[mol·m^{-3}]
e	`e`	*	*	transpiration flux	[kg·m^{-2}·sec^{-1}]
ea	`ea`	*	*	activation energy for Rubisco carboxylation	[J·mol^{-1}]

name of variable		in version		meaning	dimension
docu	code	2.10	2.20		
e_{ec}	e_ec		*	transpiration flux from ECHAM	[kg·m^{-2}·sec^{-1}]
ε_g	eps_g	*	*	elasticity module for subsidiary cells	[MPa]
$emol$	emol	*	*	molar transpiration per dry matter of leaves	[μmol·g^{-1}·sec^{-1}]
ε_s	eps_s	*	*	elasticity module for guard cells	[MPa]
$f0$	f0	*	*	numerical stability parameter	–
$faba$	faba	*	*	relative inhibition of ion pumps in guard cells by ABA	–
fc	fc	*	*	weighting factor for soil particle fraction "coarse"	–
ff	ff	*	*	weighting factor for soil particle fraction "fine"	–
f_{gs}	f_gs	*	*	flux diffusion out of guard cells through ion channels	[mol·sec^{-1}]
$fine$	fine	*	*	basic soil particle fraction "fine"	–
fk	fk	*	*	maximum pore volume ("field capacity")	[%]
fm	fm	*	*	weighting factor for soil particle fraction "medium"	–
$fpar$	fpar	*	*	relative activation of ion pumps in the guard cells	–
f_{sg}	f_sg	*	*	ion flux by active pumping from subsidiary into guard cells	[mol·sec^{-1}]
g	p(g)	*	*	pool of osmotic substances in guard cells	[mol]
Γ	gamma	*	*	CO_2 concentration in the leaf intercellulars at the CO_2 compensation point	[μl·l^{-1}]
$group$	group	*		number of the group of vegetation formations $vegfor$ belongs to	–
$gsdm$	gsdm	*	*	stomatal conductance	[μmol·g^{-1}·sec^{-1}]
$gsdm_{mx}$	gsdmmx	*	*	maximum stomatal conductance	[μmol·g^{-1}·sec^{-1}]
gw_b	gw_b		*	stand conductivity	[μmol·m^{-2}·sec^{-1}]

name of variable		in version		meaning	dimension
docu	code	2.10	2.20		
igrid	`igrid`	*	*	number of the current grid element	–
in	`p(in)`	*	*	amount of CO_2 in the intercellular spaces	[mol·g^{-1}]
istep	`istep`	*		a time–step of 24 minutes	–
j	`j`		*	number of the current latitudinal band	–
je	`je`	*	*	electron transport rate in leaf light systems	[μmol·g^{-1}·sec^{-1}]
J_e	`j_e`	*	*	transpiration flux through one stomatal pore	[m^3·sec^{-1}]
J_{eg}	`j_eg`	*	*	net water flux apoplast to guard cells	[m^3·sec^{-1}]
jn	`jn`	*	*	production rate of NADPH+H$^+$ in leaf dry substance	[μmol·g^{-1}·sec^{-1}]
J_{se}	`j_se`	*	*	net water flux subsidiary cells to apoplast	[m^3·sec^{-1}]
J_{tr}	`j_tr`	*	*	transpiration flux through 1 m of root length	[m^3·sec^{-1}·m^{-1}]
J_{xs}	`j_xs`	*	*	net water flux xylem to subsidiary cells	[m^3·sec^{-1}]
k	`k`	*	*	coefficient to calculate water potential in soil, see equations (2.55) and (2.56)	
k_{ABA}	`kaba`	*	*	effectivity of ABA in leaves	[m^3 · μmol]
k_{ar}	`kar`	*	*	carboxylation coefficient for Rubisco in leaf dry matter	[μmol·g^{-1}·sec^{-1}·ppm^{-1}]
$k_{ar}0$	`kar0`	*	*	carboxylation coefficient for Rubisco in leaf dry matter at T_{ref}	[μmol·g^{-1}·sec^{-1}·ppm^{-1}]
k_e	`ke`	*	*	extinction coefficient for light in leaf	[m^2·g^{-1}]
k_{gs}	`k_gs`	*	*	conductivity of ion channels	[m^3·sec^{-1}]
$km0$	`km0`	*	*	ion concentration of half–saturation of ion pump activity	[mol·m^{-3}]
Km_{par}	`kmpar`	*	*	PAR of half saturation of light–dependent processes	[μE·m^{-2}·sec^{-1}]

name of variable		in version		meaning	dimension
docu	code	2.10	2.20		
k_Ψ	kpsi	*	*	production rate of abscisic acid (ABA) in roots	[μmol·m^{-3}·MPa^{-1}]
k_{rw}	k_rw	*	*	conductivity coefficient of water in soil	[m^3·m^{-2}·MPa^{-1}·sec^{-1}]
k_{sg}	k_sg	*	*	coefficient of ion pumping in guard cells	[mol·sec−1]
$k_{sg}0$	k_sg0	*	*	maximum pump rate at $T_{leaf} = T_{ref}$, maximum activation by $fpar$ und no inhibition by $faba$	[mol·sec^{-1}]
LAI	lai		*	leaf area index	–
LAI_{eff}	laieff		*	contribution function of LAI to stand conductivity ("effective" LAI)	–
$medium$	medium	*	*	basic soil particle fraction "medium"	–
mfk	mfk	*	*	weighted mean of fk	[%]
mi	mi	*		Priestley–Taylor moisture index	–
$minute$	minute	*	*	time step minute	[min]
mk	mk	*		weighted mean of k	–
m_{LAI}	mlai		*	initial slope of the LAI contribution function	–
$month$	month		*	current month	
$monws$	monws	*		switch to select the current month: March (3) or August (8)	–
$m\Psi_{fk}$	mpsifk	*	*	weighted mean of Ψ_{fk}	[MPa]
nst	nst	*	*	number of stomata per unit leaf area	[m^{-2}]
$nstep$	nstep	*	*	number of integration steps during the time of a second	–
PAR	par	*	*	incident photosynthetically active radiation ($\lambda = 400, \ldots, 700$nm)	[μE·m^{-2}·sec^{-1}]
PAR_{abs}	parabs	*	*	photosynthetically active radiation ($\lambda = 400, \ldots, 700$nm) absorbed in leaf	[μE·g^{-1}·sec^{-1}]
PAR_{ec}	par_ec		*	incident photosynthetically active radiation density ($\lambda = 400, \ldots, 700$nm) from ECHAM	[μE·m^{-2}·sec^{-1}]

name of variable		in version		meaning	dimension
docu	code	2.10	2.20		
p_g	p_g	*	*	turgor potential of guard cells	[MPa]
pha	pha	*	*	above–ground herbaceous phytomass	[g·m^{-2}]
phb	phb	*	*	below–ground herbaceous phytomass	[g·m^{-2}]
π_g	pi_g	*	*	osmotic potential of guard cells	[MPa]
p_s	p_s	*	*	turgor potential of subsidiary cells	[MPa]
π_s	pi_s	*	*	osmotic potential of subsidiary cells	[MPa]
Ψ_e	psi_e	*	*	matrix potential in the apoplast	[MPa]
Ψ_{fk}	psifk	*	*	soil water potential at field capacity	[MPa]
Ψ_g	psi_g	*	*	water potential of guard cells	[MPa]
Ψ_r	psi_r	*	*	water potential in the bulk soil	[MPa]
Ψ_{rw}	psi_rw	*	*	water potential in the soil cylinder with diameter rad_{rw} surrounding a root	[MPa]
Ψ_s	psi_s	*	*	water potential of subsidiary cells	[MPa]
Ψ_x	psi_x	*	*	water potential in xylem vessels	[MPa]
$Q10$	q10	*	*	influence of leaf temperature on ion pumps in the plasmalemma of guard cells	–
$Q10_{res}$	q10res	*	*	temperature dependency of plant respiration in leaves	–
R	r	*	*	universal gas constant	[MJ·K^{-1}·mol^{-1}]
rad_{rw}	radrw	*	*	radius of a soil cylinder around a root	[m]
R_{eg}	r_se	*	*	water resistance apoplast to guard cells	[MPa·sec·m^{-3}]
relapt	relapt	*	*	relative aperture of the stomatal pore	–
resp	resp	*	*	CO_2 production rate per leaf dry matter from oxidative decarboxylation	[μmol·g^{-1}·sec^{-1}]

name of variable		in version		meaning	dimension
docu	code	2.10	2.20		
rref	`rref`	*	*	respiration rate of plant matter at T_{ref}	[μmol·g^{-1}·sec^{-1}]
R_{se}	`r_se`	*	*	water resistance subsidiary cells to apoplast	[MPa·sec·m^{-3}]
rw	`p(rw)`	*	*	amount of water in a soil cylinder of radius rad_{rw} and length 1 m around a root	[m^3]
R_{xs}	`r_xs`	*	*	water resistance xylem to subsidiary cells	[MPa·sec·m^{-3}]
s	`p(s)`	*	*	pool of osmotic substances in subsidiary cells	[mol]
second	`second`	*	*	time step second	[sec]
sla	`sla`	*	*	leaf area per 100 g leaf carbon	[m^2 · (100gC)$^{-1}$]
textur	`textur`	*	*	soil texture (classes)	–
T_{leaf}	`tleaf`	*	*	leaf temperature	[°C]
T_{ref}	`tref`	*	*	reference temperature of physiological processes in *vegfor*	[°C]
vegfor	`vegfor`	*		vegetation formation in a grid element	–
vg	`p(vg)`	*	*	actual volume of guard cells	[m^3]
vm	`vm`	*	*	molar volume of liquid water	[m^3·mol^{-1}]
vol_g	`volg`	*	*	standard volume of guard cells	[m^3]
vol_s	`vols`	*	*	standard volume of subsidiary cells	[m^3]
volrw	`volrw`	*	*	volume of a soil cylinder with the radius rad_{rw} around a root of length 1 m	[m^3]
vs	`p(vs)`	*	*	actual volume of subsidiary cells	[m^3]

Chapter 7

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