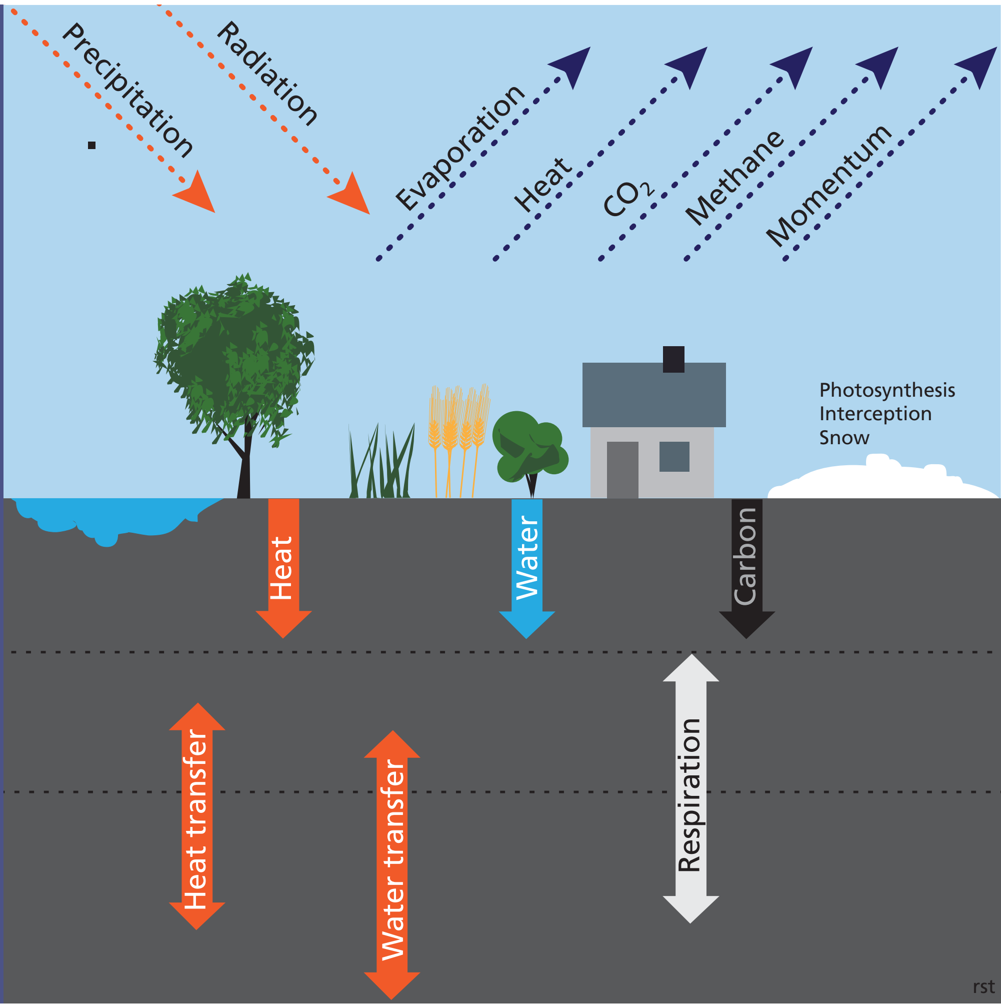
Representation of catchment hydrology, water balance, runoff and discharge in the JULES and SURFEX land surface models

Tuomo Saloranta

1
2011

R E P O R T



Representation of catchment hydrology, water balance, runoff and discharge in the JULES and SURFEX land surface models

Norwegian Water Resources and Energy Directorate
2011

Report no. 1 – 2011

Representation of catchment hydrology, water balance, runoff and discharge in the JULES and SURFEX land surface models

Published by: Norwegian Water Resources and Energy Directorate

Editor:

Authors: Tuomo Saloranta

Print: Norwegian Water Resources and Energy Directorate

Number printed: 31

Cover photo: NVE

ISSN: 1502-3540

ISBN: 978-82-410-0740-8

Abstract: In this literature study the representation of hydrological processes in the land surface models JULES and SURFEX are reviewed. The main focus in JULES and SURFEX is on simulating vertical exchanges of water, heat and carbon at the land surface, and coupling these fluxes with operational weather prediction and climate models. Both models can be used also in offline applications in e.g. hydrology and vegetation monitoring. This report is structured around the terms in the generic catchment water balance equation (i.e. precipitation, evapotranspiration, stream outflow, ground-water flow and water storage) emphasizing the models' capability to handle runoff production in a defined catchment and routing of that water to the catchment outlet. This is an important feature since usually hydrological models are calibrated and evaluated against discharge data measured at the (sub-)catchment outlet.

JULES and SURFEX do not to differ fundamentally in the way and level of detail the hydrological processes are formulated in these models, although SURFEX seems to provide some more options for the user to select between different schemes of soil processes and discretizations. Both JULES and SURFEX models simulate snow and soil ice processes which are needed to properly simulate Nordic hydrological conditions. The water balance can be closed in both models, except for evaporation from lake surfaces which does not draw on any conserved water stores. In principle, it is possible to extract variables describing the hydrological cycle from e.g. the UM or HARMONIE weather prediction model runs, of which JULES and SURFEX are, respectively, parts of.

Key words: hydrology, land surface models

Norwegian Water Resources and Energy Directorate
Middelthunsgate 29
P.O. Box 5091 Majorstua
N 0301 OSLO
NORWAY

Telephone: +47 22 95 95 95
Fax: +47 22 95 90 00
E-mail: nve@nve.no
Internet: www.nve.no

March 2011

Contents

Preface

This report, describing the representation of hydrological processes in the land surface models JULES and SURFEX, is a product from a collaborative modelling project between the Norwegian Meteorological Institute (met.no) and the Norwegian Water Resources and Energy Directorate (NVE). The author thanks warmly Thomas Skaugen and Ingjerd Haddeland at NVE, as well as Dag Bjørge at met.no for advice and constructive comments.

Oslo, March 2011

Morten Johnsrud

Director

Rune Engeset

Head of Section

Summary

In this literature study the representation of hydrological processes in the land surface models JULES and SURFEX are reviewed. The main focus in JULES and SURFEX is on simulating vertical exchanges of water, heat and carbon at the land surface, and coupling these fluxes with operational weather prediction and climate models. Both models can be used also in offline applications in e.g. hydrology and vegetation monitoring. This report is structured around the terms in the generic catchment water balance equation (i.e. precipitation, evapotranspiration, stream outflow, ground-water flow and water storage) emphasizing the models' capability to handle runoff production in a defined catchment and routing of that water to the catchment outlet. This is an important feature since usually hydrological models are calibrated and evaluated against discharge data measured at the (sub-)catchment outlet.

JULES and SURFEX do not to differ fundamentally in the way and level of detail the hydrological processes are formulated in these models, although SURFEX seems to provide some more options for the user to select between different schemes of soil processes and discretizations. Both JULES and SURFEX models simulate snow and soil ice processes which are needed to properly simulate Nordic hydrological conditions. The water balance can be closed in both models, except for evaporation from lake surfaces which does not draw on any conserved water stores. In principle, it is possible to extract variables describing the hydrological cycle from e.g. the UM or HARMONIE weather prediction model runs, of which JULES and SURFEX are, respectively, parts of.

1 Introduction

Land surface models (LSMs) were originally developed for providing better surface energy fluxes to atmospheric models. However, they can also be used for other purposes, such as providing estimation of the hydrological cycle. The purpose of this literature study is to find out how the hydrological processes in a catchment are represented in the land surface models JULES and SURFEX, and how well-suited these models are to simulate catchment response to rain- and snowfall, as well as the water balance in a defined catchment (primarily in Norway). Methods for translation of individual gridbox runoff production to integrated discharge at the catchment outlet (e.g. to the sea) are discussed in section 2.1.3.

This study is structured around the terms in the generic catchment water balance equation, which is for any period of time (Dingman, 2002):

$$P + G_{in} - (Q + ET + G_{out}) = \Delta S \tag{1}$$

where P is precipitation (both liquid and solid forms), G_{in} and G_{out} are the ground-water inflow and outflow, respectively, Q is stream outflow, ET evapotranspiration and ΔS water storage change (both liquid and solid forms). Units for all the terms are [kg s^{-1}], or [kg m^{-2} s^{-1}] if the terms are divided by the total catchment area. However, often volumetric units [m^3 s^{-1}] or [m s^{-1}] are used (dividing Eq. 1 by constant water density).

1.1 Introduction to JULES

JULES (Joint UK Land Environment Simulator) is a land surface model based on MOSES (Met Office Surface Exchange System), the land surface model used in the Unified Model (UM) of the UK Met Office. The main focus in JULES is on simulating vertical exchanges of water, heat and carbon at the land surface, and coupling these fluxes with an atmospheric model (see Figure 1). Although originally designed to represent the land surface in meteorological and climate models, JULES can also be run separately from these models in an "offline" mode and is increasingly used for also other purposes, e.g. predicting river flows, identifying global wetlands and quantifying water resources. The development of the JULES code is ongoing in many different scientific communities. The JULES website (www.jchmr.org/jules/) is used to update the scientific community on what changes and improvements are being included in the official JULES model releases. These updates are coded and tested in the Met Office UM, and some changes may only be used in the offline version of JULES. The JULES code development is moving towards the goal of having Unified Model jobs built from a separate JULES code repository, removing the need to have a mirrored code.

The Norwegian Meteorological Institute (met.no) uses the UM in operational weather prediction (their latest UM release is 7.7). The met.no have applied and tested JULES offline versions (currently applying the latest JULES releases 2.1 and 2.2), but so far JULES has not been implemented online in UM runs, although this might be possible with some restrictions, at least in the earlier UM version 7.5 via the graphical user interface UMUI. In UM runs, the default MOSES land surface scheme (of which JULES is based on) is applied (Dag Bjørge, pers. comm., December 2010).

The scientific basis of the JULES model code is described in a technical documentation, which comprises basically the older, but somewhat updated, technical documentations for the component models MOSES 2.2, (Essery et al., 2001) and TRIFFID (the dynamic vegetation model, described in Hadley Center Technical Note 24). However, some parts of the technical documentation for the current JULES version releases (vs. 2.1 and 2.2) are not yet complete, most notably for the new multi-layer snow scheme. There are two description papers currently being written that will bring this more up to date when they are published (Matt Pryor, pers. comm., December 2010).

JULES functions on subdaily (hourly) time step, and for solving both the energy and water balances at the surface it requires the following atmospheric forcing data: precipitation (separated as rain and snow), air temperature, wind speed, specific humidity, surface pressure, and incoming short- and long-wave radiation. For the current JULES releases (vs. 2.1 and 2.2) the model can be run in distributed mode and the land surface of a catchment can be represented on a grid with flexible resolution. The NetCDF format is supported for both input and output data (recommended for distributed runs). Within one gridbox in JULES, nine surface types ("tiles") are recognized: broadleaf trees, needleleaf trees, temperate grass, tropical grass, shrubs, urban, inland water, bare soil and ice. Except for those classified as land-ice, a land gridbox can be made up from any mixture of the first 8 surface types. Separate surface temperatures, heat fluxes, canopy moisture contents, snow masses and snow melt rates are computed for each surface type in a gridbox. Fractions of surface types within each land-surface gridbox are read from an ancillary file or modelled by TRIFFID.

The presence of a canopy on a tile functions as an intermediate layer intervening on heat and water exchange between the atmosphere and the ground. The canopy includes a separate water store, which is, among others, used up for evaporating water before vegetation transpiration and evaporation from soil.

The representation of the different terms of the water balance equation (Eq. 1) in JULES is described in more details in section 2.1.

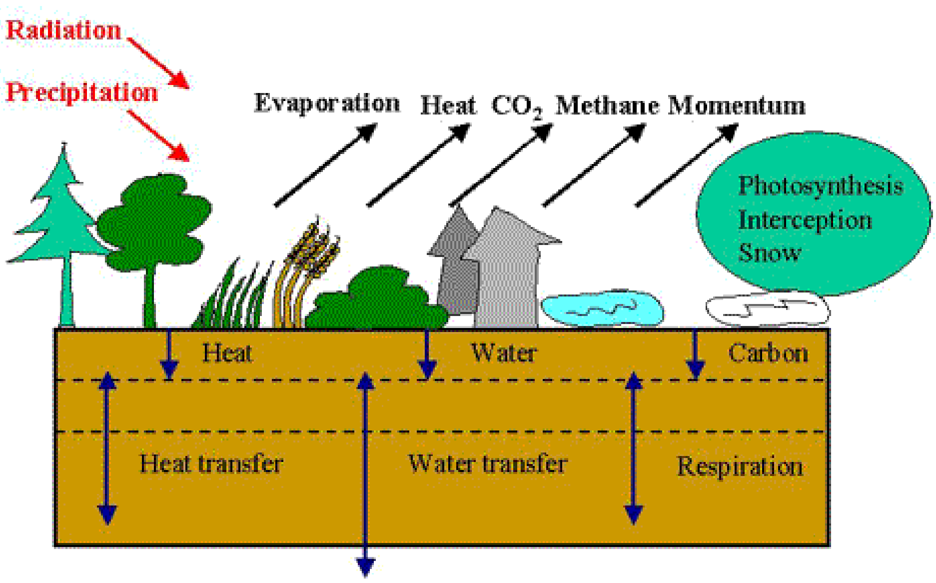


Figure 1. *Schematical representation of the simulated processes in JULES land surface model (Figure from JULES website).*

1.2 Introduction to SURFEX

SURFEX (SURFace EXternalisée) is a land surface model developed at Météo-France. Conceptually SURFEX is overall very similar to JULES (as illustrated in Figures 1 and 2), although the detailed formulation of the process equations differ between the two models. SURFEX is also somewhat more modular in its structure than JULES and provides more options for the user to select between the different schemes used to simulate the land surface processes. Just like JULES, SURFEX simulates the vertical exchanges of heat, water and carbon, and it can be both coupled with operational weather prediction and climate models (ALADIN, ARPEGE, meso-NH) and used in offline applications in e.g. hydrology and vegetation monitoring. The coupled system, of which SURFEX is a part, is called AROME (a high resolution modelling system called HARMONIE, using AROME as basis, is under development). SURFEX includes also simulation of dust and chemical fluxes and features a data assimilation module, which are not included in JULES.

The SURFEX website (http://www.cnrm.meteo.fr/surfex/) contains scientific and user manuals for the model (release v5) as well as a list of relevant publications and training course presentations.

The Norwegian Meteorological Institute (met.no) has applied and tested the different process schemes (especially on snow and surface drag coefficients) in SURFEX offline versions (v. 4.8 og 5.1). SURFEX is also part of the HARMONIE weather prediction model system which met.no is currently testing (Trygve Aspelien, pers. comm., January 2011).

The atmospheric data SURFEX requires for forcing includes: air temperature, specific humidity, horizontal wind components, pressure, total precipitation, long-wave radiation, shortwave direct and diffuse radiations (and optionally concentrations of chemical species and dust). SURFEX can be run in distributed mode on a grid with flexible resolution and projection, and several formats can be applied for input and output data (including ASCII, binary and NetCDF).

Within one gridbox in SURFEX, four surface types are recognized: 1) sea/oceans, 2) lakes, 3) nature, and 4) urban areas. Separate surface temperatures, heat fluxes, canopy moisture contents, snow masses and snow melt rates are computed for each surface type in a gridbox (although a mean, surface type fraction weighted value for a gridbox is used when interacting with the atmospheric model). The soil and vegetation are included in the "nature" tile, and up to 12 different patches of natural functional types (snow/ice, rock, wetland, different vegetation types) can be defined within the "nature" tile. Each patch is having its own set of prognostic variables and surface energy and water balances. However, as for JULES, all patches lie over and interact with the same gridbox soil column. A global database of land surface parameters at 1 km resolution, ECOCLIMAP, can be used to describe model surface parameters. Only four primary parameters are required in SURFEX to describe the nature of the land surface and its vegetation coverage, namely the percentages of (i) sand and (ii) clay in the soil, (iii) the dominant vegetation type, and (iv) the land-sea mask.

In addition to the very simple ideal flux surface scheme options, the user can select more detailed surface schemes for the four surface types. A one-dimensional ocean model and the FLake lake model can be applied for simulating processes and evolving water surface temperature within the "sea/oceans" and "lake" tiles, respectively. A TEB (Town Energy Balance) scheme can be applied for the "urban area" tile. This scheme is based on a “canyon approach” where a town is represented with a roof, a road and two facing walls with characteristics playing a key role in the town energy budget.

For the “nature” tile (the main focus of this report) SURFEX applies the ISBA (Interaction between Soil Biosphere and Atmosphere) land surface scheme, originally developed in late 1980s (Noilhan and Planton, 1989; Noilhan and Mahfouf, 1996). ISBA provides several different options for simulating soil moisture, soil temperature and snow cover. For soil moisture and temperature, the user can select either a scheme based on diffusive multilayer approach, or a 2/3-layer scheme based on the force-restore method (see e.g. Boone et al. 1999) where the surface temperature or water content T_s evolves due to both the diurnal forcing and a restoring term towards its daily mean value T_m. In contrast, the mean value T_m only varies according to a slower relaxation towards T_s. ISBA can also be coupled to the A-gs vegetation model, which simulates the diurnal cycle of leaf area index (LAI) and biomass and accounts for different feedbacks in response to changes in CO_2.

The different approaches, schemes and algorithms in SURFEX are well documented and cited in the SURFEX scientific documentation (Le Moigne, 2009). The user guide (Le Moigne, 2009b) provides information on model set-up and execution, and on the different optional schemes that can be applied. Both documents are available at the SURFEX website.

The representation of the different terms of the water balance equation (Eq. 1) in SURFEX is described in more details in section 2.2.

2 Hydrology in JULES and SURFEX

2.1 Hydrology in JULES

In the following subsections the representation of the terms in the water balance equation (Eq. 1) in JULES are discussed in more details. In addition, the inclusion of anthropogenic drivers (dams, irrigation) is mentioned in section 2.2.6. Figure 2 shows the conceptual hydrological model in JULES.

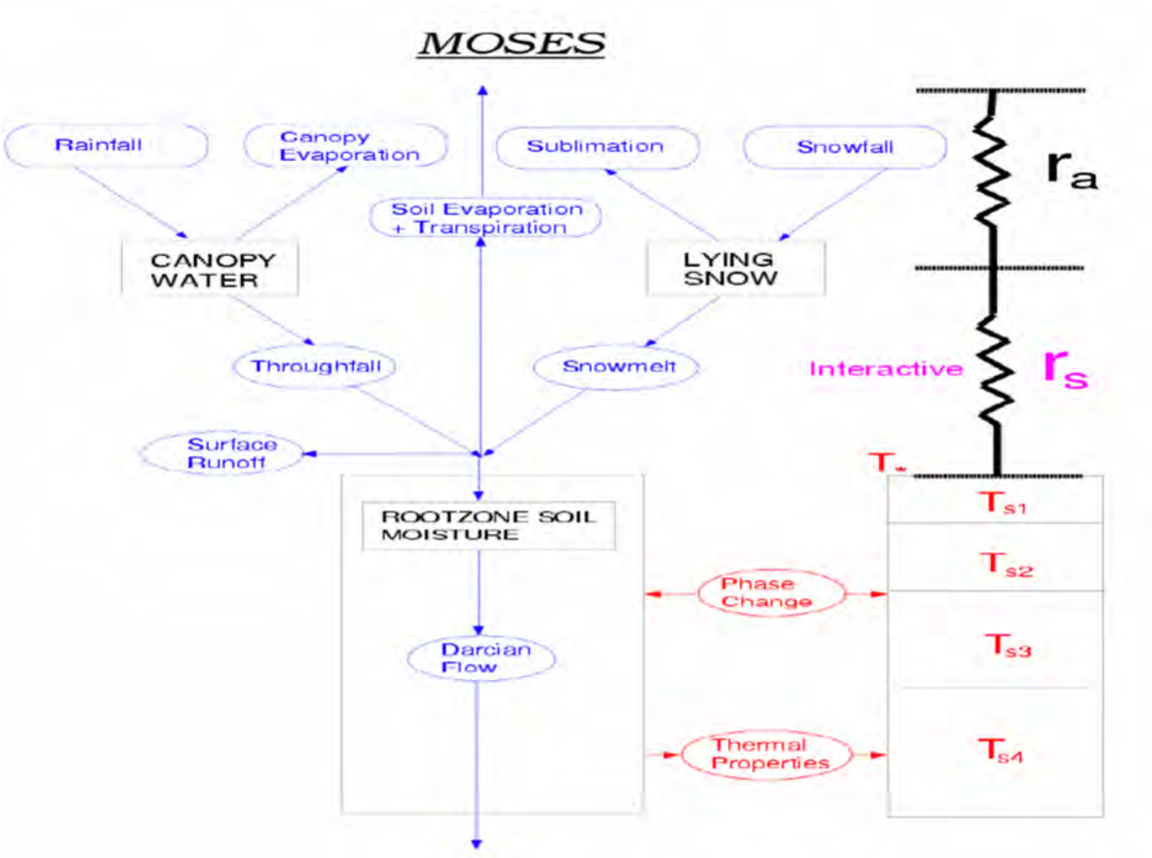


Figure 2. *The conceptual hydrological model in MOSES (i.e. JULES) (Figure from JULES website; from presentation of Nic Gedney at JULES science meeting, January 2008).*

2.1.1 Liquid and solid precipitation *(P)*

According to the brief model code description at JULES website, the rainfall rate is assumed to be distributed exponentially across the gridbox area. In addition, if the rainfall is convective, then it is assumed to cover only 0.3 of the area. This part of the JULES model aims to overcome the problem of GCM-drizzle, whereby every time it rains, a small amount of water covers the entire area, is held on the leaves of the vegetation and re-evaporates, without entering the soil matrix. In practice the rainfall can be intense over small areas and this means the rainfall falls through the vegetation canopy and into the ground. It is possible to turn this feature off if observed rainfall is being used to drive the model (where the rainfall is less frequent but more intense). The partitioning of precipitation into interception, throughfall, surface runoff and infiltration is described in the JULES technical documentation and in Gregory and Smith (1990) and is applied separately on each tile. Separate liquid and solid precipitation forcing time series are given for JULES as input.

2.1.2 Evapotranspiration (*ET*)

According to the brief model code description at the JULES website, surface evaporation is drawn from soil, canopy and snow moisture stores. Evaporation from saturated parts of the surface (lakes, wet vegetation canopies and snow) is calculated at the potential rate (i.e. subject to an aerodynamic resistance only). Evaporation from transpiring vegetation is controlled by the canopy conductance. The ability of vegetation to access moisture at each level in the soil is determined by root density, which is assumed to follow an exponential distribution with depth. The evaporative flux extracted from each soil layer is dependent on the soil moisture availability factor. Bare-soil evaporation is extracted from the surface soil layer for bare-soil tiles and for a fraction of vegetated tiles. A fraction of the tile is assumed to be saturated and hence has aerodynamic resistance only. This factor is 1 for lake, ice or snow-covered tiles, and varies for a vegetated tile with canopy moisture content and canopy capacity.

It is worth noting that evaporation from lake surfaces in JULES does not draw on the conserved moisture stores (term ΔS in Eq. 1) and therefore violates the conservation of water and the closure of the water balance. A revised lake tile algorithm, based on the FLake model, is planned to be included in future JULES versions (Rooney and Jones, 2010), improving especially the lake tile heat balance and lake ice condition simulations.

2.1.3 Stream outflow (discharge) (*Q*)

2.1.3.1 Background

The processes governing the production of runoff at a hillslope scale are complex and show strong spatiotemporal variation. Runoff is often classified as surface runoff, in which the water flows over the land surface, or subsurface runoff. As Clark and Gedney (2008) point out, surface runoff can be divided into that generated by infiltration excess and saturation excess mechanisms. Infiltration excess runoff occurs when the rainfall rate is greater than that at which the water can infiltrate into the soil. Rainfall in excess of infiltration will then flow downslope as overland flow towards stream channels. Saturation excess overland flow occurs when rain falls onto saturated soil, often in valley bottoms and riparian areas. This flow can be supplemented with soil water that "leaks" to surface from saturated soil. Furthermore, water that infiltrates the soil will eventually reach a layer of low permeability, at which point it becomes a downslope subsurface flow. In many catchments ground-water aquifers also contribute to the subsurface flow.

For simulating how the runoff produced at various gridboxes within a catchment is transferred to the river network, and along the stream channels to the catchment stream outflow (discharge), e.g. to the sea, a runoff routing model is often applied (although a simple summation may do the job as well, as discussed in section 2.1.3.4). A runoff routing model integrates spatiotemporally the catchment response to water input, and ideally should consider lateral water movements both in the soil (hillslope processes) and in the stream network, including lakes. The signal of the water input can be significantly delayed and modified (damped, smoothed) when it arrives at the catchment outlet, and often the outflowing water may consist of “old water” which is displaced by the “new water” of the rainfall/snowmelt input.

The actual physical mechanisms by which the rainfall/snowmelt input at the surface can be transferred to stream channel include (i) precipitation directly to channel, (ii) overland flow (surface runoff) and (iii) subsurface flow (both in the water-saturated and -unsaturated zones) (Dingman, 2002). When the water has arrived in the stream, its movement through the open-channel network can be characterized as a flood wave propagating downstream towards the catchment outlet. The dynamics of the flood wave are governed by channel hydraulics and river bank storage effects. Generally, in small catchments (< ~50 km^2) the water signal travel time to catchment outlet is governed mostly by the hillslope processes and travel time, while in larger catchments the travel time in the stream network becomes increasingly important (Dingman, 2002). The catchment response which can be associated with a given rainfall/snowmelt input event (“event-flow”) can often be a small fraction of the total water input, as much of the water flow can occur so long after the event in form of a “baseflow” (or ground-water outflow) that it cannot be associated with a particular event peak (Dingman, 2002). Much of the input event water can also leave the catchment by evapotranspiration.

2.1.3.2 Runoff production in JULES

There are two runoff components in the default runoff scheme in JULES (see Essery et al., 2001), i) surface runoff (runoff due to surface infiltration excess and supersaturation in soil layers) and ii) subsurface runoff, represented by the free drainage from the deepest soil layer. According to Essery et al. (2001), supersaturation of soil layers can occur in MOSES (i.e. in JULES) when drainage from the base of a soil layer is impeded, either by frozen soil water or by an assumed reduction of soil saturated hydrological conductivity (K_s) with depth. Dingman (2002) points out that infiltration excess surface flow is an important response mechanism only in semiarid regions where low surface conductivity is combined with intense rainfalls, or in areas where soil frost or human (or animal) activity has made the ground near-impermeable. Clark and Gedney (2008) also point out that infiltration excess surface runoff is a relatively rare phenomenon on the gridscale of a climate model, and thus most of the runoff produced by MOSES (i.e. by JULES) is via subsurface runoff (drainage from the deepest soil layer).

Clark and Gedney (2008) implemented different large-scale hydrology (LSH) representations of soil moisture and runoff production processes in the MOSES land surface model. The default algorithm (see Essery et al., 2001) was compared with two other runoff generation parameterizations based on either the Probability Distributed Model (PDM) or modified forms of TOPMODEL, all of which used probability functions to describe the subgrid distribution of soil moisture. In the PDM method, the fraction of the gridbox that is saturated is estimated and surface runoff can be generated from this fraction (even though the gridbox is not saturated as a whole). In the TOPMODEL method, the tendency of soil saturation in the points within the gridbox is based on a “topographic index” which is calculated from detailed terrain elevation models (maps) on the basis of the particular point’s drainage area and hillslope inclination. TOPMODEL method produces both surface runoff (equal to rainfall on the saturated subgrid surface fraction) and subsurface flow (“baseflow”).

Clark and Gedney (2008) compared the model results with observed streamflow in three catchments in southern France. After calibration, the PDM- and TOPMODEL-based parameterizations performed substantially better than the default model where the modelled flow was dominated by drainage (over 99% of the total), with negligible surface runoff. Therefore, the default model simulated generally too low and late flow peaks, consistent with the fact that runoff was largely generated by drainage through the bottom of the soil column, while there was too much flow during recessions (i.e. during periods of gradually declining flow after the peak flow). The TOPMODEL approach gave the best results through allowing a more responsive subsurface flow that contributed to peak flows and also better captured the slower changes during recessions. This approach was sensitive to uncertainty in the value of the topographic index. The PDM-based model only changed the calculation of surface runoff and retained the standard description of subsurface runoff, and this limited the possible improvement in model performance.

These two additional runoff production schemes, PDM and TOPMODEL(gc), are now included as options in JULES (since version 2.1.2.; see also Gedney and Cox (2003) for more detailed description of the type of TOPMODEL implemented in MODES/JULES). In MOSES/JULES the TOPMODEL subsurface flow description is implemented in an additional deep layer below the standard soil layer description. The JULES version 2.2. user manual (Clark et al., 2010) lists the following runoff related output variables:

Single values at each land gridbox :

drain:	gridbox drainage at bottom of soil column [kg m^{-2} s^{-1}]
qbase:	gridbox baseflow (lateral subsurface runoff) [kg m^{-2} s^{-1}]
qbase_zw:	gridbox baseflow (lateral subsurf. runoff) from deep layer [kg m^{-2} s^{-1}]
runoff:	gridbox runoff rate [kg m^{-2} s^{-1}]
sat_excess_roff:	gridbox saturation excess runoff [kg m^{-2} s^{-1}]
subSurfRoff:	gridbox sub-surface runoff [kg m^{-2} s^{-1}]
surfRoff:	gridbox surface runoff [kg m^{-2} s^{-1}]

In addition, the following variable is hidden, but can be accessed with extra code:
surfRoffInf: gridbox infiltration excess surface runoff [kg m^{-2} s^{-1}]

No separate runoff values are produced for the individual soil layers in JULES. The *qbase* and *qbase_zw* seem to be specific for the TOPMODEL option.

2.1.3.3 Runoff routing options used with JULES

The focus in JULES is on vertical exchange processes, since practically all of the heat and carbon exchange occurs in the vertical dimension. However, for water exchange, lateral processes of water flow are non-negligible. In addition, as Habets et al. (2008) point out, coupling a land surface model to a streamflow routing model permits the assessment of the water budget over large areas through comparison with observed river flows, and thus allows the identification of the model's main qualities and defects.

The brief model code description at the JULES website states that the model code is being developed so that is will include a rainfall-runoff module and a runoff routing scheme, but that at present these options are not available. However, e.g. Dadson and Bell (2010) have applied and tested two different runoff routing modules for JULES, namely Grid-to-Grid (G2G) and Total Runoff Integrating Pathways (TRIP) for use in global and regional climate models (application on continental scale catchments, like Amazon, Kongo, Ob, etc.). They used surface and sub-surface runoff data from JULES forced with GSWP-2 data.

According to Dadson and Bell (2010), the aim of TRIP is to provide a method for routing runoff from the land surface to river basin outlets in order to enable the validation of the runoff part of land-surface parametrizations in global climate models (GCMs), and to estimate the effect of climate change on runoff. The TRIP scheme consists of two main components: (i) a gridded dataset of river flow pathways; and (ii) a relation expressing the time-varying integral of runoff over all gridboxes that comprise a river basin (i.e. a hydrograph). Flow pathways for use with TRIP are available on the TRIP grid at 1° or 0.5° horizontal resolution, depending on the version used. The river flow routing scheme used in TRIP assumes a single linear river routing store, i.e.

$$w_{IN} - Q = T^{*} \frac{dQ}{dt} \tag{2}$$

where w_{IN} is the water input, Q is (event) discharge at the outlet, and T^{*} is a time-constant that characterizes the catchment response (Dingman, 2002).

According to Dadson and Bell (2010), the G2G model was developed for regional applications and is based on a one-dimensional kinematic wave routing model. Overall, aside from possible water losses in TRIP, the main difference between the two schemes is likely to be due to the fact that G2G uses two parallel routing pathways (surface and sub-surface routing wave speeds being faster and slower, respectively), while TRIP has only a single routing component. As Figure 5 indicates, the TRIP module is included in the latest JULES releases (since version 2.1.).

2.1.3.4 Some methods used for runoff routing in Norwegian catchments

The Norwegian Water and Energy Resources Directorate (NVE) uses the HBV model (see e.g. Sælthun, 1996) in operational flood forecasting. The HBV model is a semi-distributed model set up for each catchment, where the catchment is divided into altitude zones in order to the represent, among others, the dependence of temperature and precipitation on altitude. However, the soil in the catchment is represented only by two layers, namely the upper zone and the lower ground-water zone. The runoff generated in the upper and lower zones can in the HBV model be routed in three different ways (in addition to the no-routing option): (i) lake routing, where discharge is modelled as a function of lake water level (rating curve method), or (ii) moving average smoothing of the runoff production with six weights or (iii) with discharge dependent weights (assuming triangular form for the time response of the discharge, i.e. for the unit hydrograph).

Beldring et al. (2003) applied a gridded version of the HBV model and simulated water balance and runoff production in 1x1 km gridboxes in the whole Norway. They calibrated the model against monthly observed discharge in 141 catchments, and evaluated the model against both daily and monthly discharge observations, including data from 43 additional catchments not used in model calibration.

The simplest approach that Beldring et al. (2003) applied to calculate discharge at the catchment outlets was "no routing" (only simple summation) where the catchment divide was defined and all runoff production from the gridboxes within the catchment was transmitted to the catchment outlet without delay or loss underway.

In addition to the "no routing" option, a more detailed routing model described in Motovilov et al. (1999) was applied in three catchments (119 – 2469 km^2) in the upper River Glomma where the hierarchy of river network was described. Each gridbox was assumed to drain into the nearest river segment or lake element in the river network (no subsurface or overland flow dynamics were simulated). River flow dynamics were calculated by a kinematic wave approximation to the open-channel flow equations.

Outflows from lakes were modelled by the linear reservoir method (Eq. 2). River segments were placed at the gridbox boundaries, while lake elements always filled the whole gridbox.

Figure 3 shows the discrepancies generated by applying the "no routing" option in the model for the Masi catchment (5693 km^2). Beldring et al. (2003) denote that flood peaks for daily data occur too early and discharge is not damped to the same extent as in the observations. However, monthly mean discharge simulations agreed well with the observations in this catchment. Beldring et al. (2003) also concluded that the effects of including the routing procedure by Motovilov et al. (1999) were insignificant for the daily discharge in the three somewhat smaller upper Glomma catchments, and that simulations in other large catchments performed well with the simple "no routing" approach. Thus, generally, the river networks in the Norwegian catchments, included in the study by Beldring et al. (2003), do not seem to influence the dynamics of daily discharge to the extent which necessitates inclusion of a routing procedure in the gridded HBV model application.

Whether one needs to explicitly simulate the routing in the river network depends clearly on the size and characteristics (e.g. lake fraction) of the catchment and the desired time resolution of discharge simulations at the catchment outlet. For example, for more accurate simulations of the *daily* discharges to the sea at the mouth of large catchments in Norway (Glomma, Drammenselva, Tanaelva, Skienselva, etc.), the delay and dampening of the input in the river network probably should be taken into account by applying a routing model (see Figure 3 for the error produced by applying the "no-routing" option in Masi catchment). On a *monthly* resolution, however, the simple "no routing" option might be again well justified.

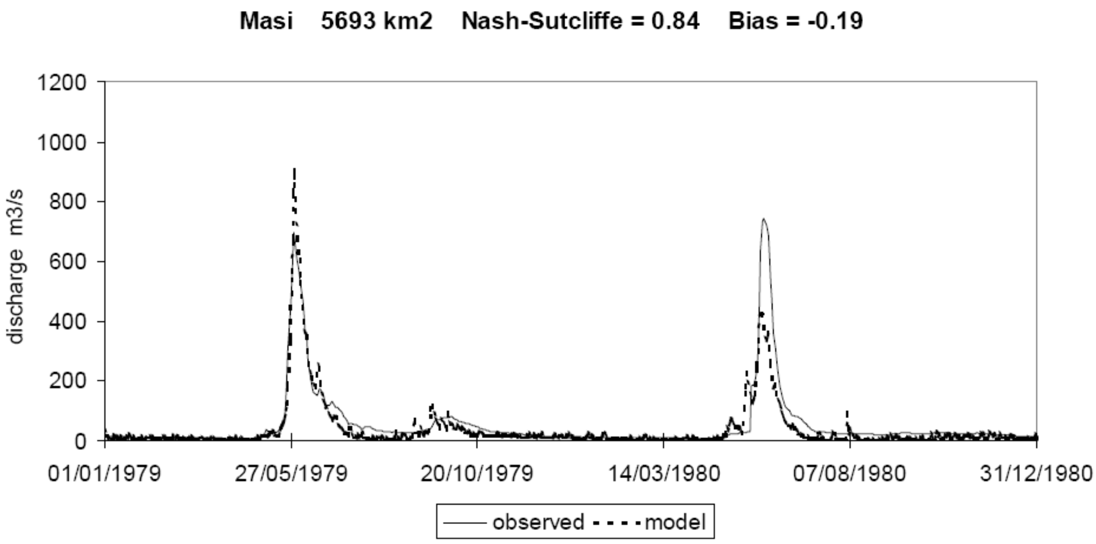


Figure 3. *Observed and simulated daily discharge in the Masi catchment with the "no routing" model applied (Figure from Beldring et al. 2003).*

2.1.4 Ground-water in- and outflow (Q_{in} and Q_{out})

The representation of the ground-water in- and outflow to/from the catchment in the water balance equation (Eq. 1) belongs clearly in the domain of the routing models, as these flow components are defined as lateral subsurface flows over the catchment boundaries, and cannot be directly related to the runoff at the individual gridboxes of

JULES. Generally, ground-water flows are often considered to be negligible in water balance calculations. According to Dingman (2002), ground-water inflows G_{in} can usually be neglected in water balance calculations, since catchments are defined topographically, and since ground-water flow is driven by gravity. However, Dingman (2002) points out that the higher the relief of the catchment and the more hydraulically conductive its geologic composition, the more likely it is to lose water also by subsurface outflow G_{out}. On the other hand, the importance of ground-water outflow generally decreases as the size of the catchment increase, since much of the subcatchment ground-water outflow eventually ends up in the stream flow. The routing modules in the HBV model, for example, direct all the runoff from the lower zone (representing ground-water) to the same streamflow discharge, and thus do not separate between stream and ground-water outflows.

2.1.5 Water storage change (ΔS; both liquid and solid forms)

2.1.5.1 Snow store modelling

The old single-layer composite snow model has been replaced by a new flexible multi-layer snow model structure in JULES vs. 2.1. in order to distinguish the thermal regime of the snow from that of the soil. Separate temperatures, densities and liquid water contents are calculated for each snow layer at each timestep. Melting of snow is diagnosed from the surface energy balance, and sublimation of snow is simulated too. A prescribed fraction of the mass in each snow layer can be stored as liquid water, delaying runoff from the base of the snowpack. Snow/ice storing in glaciers is not included yet in official JULES releases (at least schematic plans of glacier submodel have been made, though; see JULES website for a presentation by Richard Essery at the JULES science meeting, June 2009). A paper describing the new multi-layer snow scheme in more details is in preparation.

2.1.5.2 Soil moisture and ground-water store modelling

According to the brief model code description at the JULES website, the default soil hydrology component of JULES is based on a finite difference approximation to the Richards' equation (Richards, 1931), with the same vertical discretization as the soil thermodynamics module (4 soil layers as default). The total soil moisture content within a soil layer is incremented by the diffusive water flux flowing in from the layer above, the diffusive flux flowing out to the layer below, and the evaporation extracted directly from the layer by plant roots and soil evaporation. These are calculated from the total evaporation, based on the profiles of soil moisture and root density. The water fluxes are given by the Darcy equation which depends on the hydraulic conductivity and the soil water suction. To close the model it is necessary to assume forms for the hydraulic conductivity and the soil water suction as a function of the soil moisture concentration. Either of the dependencies suggested by Clapp and Hornberger (1978) and van Genuchten et al. (1991) can be used in JULES.

As pointed out in section 2.1.3.2, the default soil moisture scheme can be replaced in JULES by the alternative (and, according to Clark and Gedney (2008), substantially better performing) PDM or TOPMODEL approaches, which use probability functions to describe the subgrid distribution of soil moisture.

No explicit river channel, lake, or ground-water stores are simulated in JULES, but their storage effect can be indirectly included by applying the routing procedures described in sections 2.1.3.3-2.1.3.4.

2.1.6 Anthropogenic drivers (dams, irrigation)

According to a work report (2009) from Joint Centre for Hydro-Meteorological Research (JCHRM; www.jchmr.org) irrigation can be modelled in JULES in two possible modes. The first method, only available in offline runs, involves running the model twice, once for the irrigated area of each gridbox and once for the non-irrigated area. The second method, which incorporates the moisture transfer in the soil and its extraction due to evapotranspiration for both the non-irrigated and irrigated areas of each gridbox, was in its final development stage in 2009. The representation of dams is not included in the current standard JULES release, but is currently underway (Douglas Clark, pers. comm., 2011).

2.2 Hydrology in SURFEX

In the following subsections the representation of the terms in the water balance equation (Eq. 1) in SURFEX are discussed in more details. In addition, the inclusion of anthropogenic drivers (dams, irrigation) is mentioned in section 2.2.6. The following sections are much based on information described in the SURFEX scientific documentation (Le Moigne, 2009).

2.2.1 Liquid and solid precipitation *(P)*

Similar to JULES, SURFEX provides options to simulate uniform or exponential distribution of the rainfall rate across the gridbox area (option “CRAIN”, see section 8.4 in Le Moigne (2009b)). The exponential option affects also calculation of Horton overland runoff (see section 2.2.3.1) and runoff (throughfall) from the canopy interception reservoir. This reservoir is filled by rainfall and dew intercepted by the foliage, and its maximum capacity depends on the density of the canopy, i.e., is roughly proportional to leaf area index (LAI).

2.2.2 Evapotranspiration (*ET*)

The evapotranspiration flux in SURFEX accounts for the evaporation of liquid water from the soil surface and from the vegetation, as well as the sublimation from the snow and soil ice. At the canopy, water evaporates at a potential rate from calculated fraction of the foliage covered with a film of water, while the remaining fraction transpires. When coupling the A-gs photosynthesis model to ISBA, the transpiration from vegetation is controlled by the aperture of the stomates, the component of the leaves that regulates the balance between the transpiration and the assimilation of CO2. The representation of root zone, from which moisture is drawn by the plants for transpiration, depends on the soil scheme selected (see section 2.2.5.2). Generally, bare soil evaporation is extracted from the uppermost soil layer only, while transpiration can be extracted from layer 2 if using the force-restore soil representation option, or from multiple layers if using the diffusive soil representation option.

It seems that, similar to JULES, the evaporation from lake surfaces does not draw on the conserved moisture stores (term ΔS in Eq. 1) and therefore violates the conservation of water and the closure of the water balance.

2.2.3 Stream outflow (discharge) (*Q*)

Within the "nature" surface type (ISBA-scheme) there are two runoff components simulated, as in JULES, i) surface runoff and ii) subsurface runoff. The particular processes and soil layers that contribute to these runoff pathways vary depending on the selected options for soil representation and processes (options selected via variables "CISBA", "CRUNOFF", "CHORT" and "CKSAT"; see sections 6.7 and 8.4 in Le Moigne (2009b)). Basically, only the percentages of sand and clay are used to define the physical soil parameters for ISBA.

2.2.3.1 Surface runoff production in SURFEX

The default option in "CRUNOFF" simulates saturation excess runoff, as in JULES, where surface runoff is generated if the whole surface of the gridbox is saturated (second layer in 2/3-layer force-restore soil scheme). However, since this rarely occurs over the whole gridbox spatial scale (while in reality, a fraction of the gridbox is saturated and does produce surface runoff), two subgrid soil moisture and runoff production scheme options are selectable via "CRUNOFF".

The first of these subgrid scheme options is the "Variable Infiltration Capacity" (VIC) scheme, which resembles the PDM scheme optional in JULES (see section 2.1.3.2). In the VIC scheme the fraction of the gridbox that is saturated is a function of some soil parameters (the soil water content at saturation, the wilting point and the root depth), the soil water content of the root zone (second layer in 2/3-layer force-restore soil scheme) and a parameter *b* which represents the shape of the heterogeneity distribution of effective soil moisture capacity (values for *b* are given via variables "XUNIF_RUNOFFB" or "YRUNOFFB"; see section 6.7 in Le Moigne, 2009b)). Basically the saturated fraction of the gridbox then produces surface runoff.

The second optional subgrid soil moisture and runoff production scheme is based on the TOPMODEL approach, also available for JULES (see section 2.1.3.2). The saturated fraction of the gridbox is calculated and produces surface runoff in case of precipitation. The active layer for the TOPMODEL scheme in SURFEX is the root zone and no subsurface "baseflow" is produced by the TOPMODEL scheme in SURFEX, contrary to JULES where a new deep layer is added under the standard soil column to simulate baseflow.

In addition, the somewhat rare phenomenon of surface infiltration excess runoff (also called Hortonian runoff; see section 2.1.3.2) can be simulated on the non-saturated fraction of the gridbox by selecting it via the variable "CHORT" (see section 8.4 in Le Moigne, 2009b).

Within the "town" surface type (TEB scheme), rain- and snowfall are intercepted by both roofs and roads (assumed impermeable). There is runoff from roofs and roads to the sewer system, when the maximum allowed liquid water amount on these surfaces (set equal to 1 mm) is exceeded. A fraction of these surfaces covered by the water is simulated (fractional water pools), while the other parts are assumed to be dry. Furthermore, urban dew is taken into account (in case of negative latent heat flux), and can fill the roof and road interception reservoirs.

2.2.3.2 Subsurface runoff production in SURFEX

When soil water content exceeds the field capacity, gravitational drainage occurs in SURFEX. The drainage from the deepest layer is contributing to the subsurface runoff (together with saturation excess of the third layer, if a 3-layer force-restore soil scheme is selected). In addition, a “background” subsurface runoff due to e.g. unresolved ground-water reservoirs can be represented in SURFEX. The parameter w_{drain} required in this option is preferably calibrated in dry conditions (values for w_{drain} are given via “XUNIF_WDRAIN” or “YWDRAIN”; see section 6.7 in Le Moigne (2009b)).

2.2.3.3 Runoff routing options used with SURFEX

The options in SURFEX (see section 8.4 in Le Moigne (2009b)) seem to include a runoff routing by the TRIP method (see section 2.1.3.3). In addition, a “flooding scheme” is available, but its purpose or functioning is seemingly not described in the SURFEX scientific documentation (Le Moigne, 2009). Of course, the simple summation (“no-routing”) or other external routing methods, discussed in section 2.1.3.4, can be applied to SURFEX too.

Habets et al. (2008) applied a SIM (SAFRAN-ISBA-MODCOU) model where the SURFEX’s land surface scheme ISBA was coupled to an atmospheric analysis system SAFRAN and to a ground-water reservoir and river routing model MODCOU. The SIM model has been used operationally at Météo-France since 2003 in order to monitor the water budget and resources and to estimate the soil wetness at the national scale in near real time. In addition, 10-day ensemble precipitation forecasts are taken from the European Centre for Medium-Range Weather Forecasts (ECMWF), disaggregated in space, and then employed as an input for the ISBA-MODCOU hydrometeorological system to make 10-day forecasts of the river flows.

In order to assess the quality of the SIM system over France, Habets et al. (2008) applied the SIM model in a retrospective run for the period 1995-2005, assessing model performance against observed river flows, groundwater levels, and snow depths. The drainage simulated by ISBA was transferred to MODCOU as the input flow for the simulation of the evolution of the ground-water reservoirs, while the surface runoff computed by ISBA was routed within the hydrographical network by MODCOU to compute the river flow. The MODCOU model also computes the exchanges between the ground-water and rivers.

In the application of Habets et al. (2008) the SIM model was found to give good estimation of the water fluxes as it produced reasonable results for more than 66% of the 610 river gauges simulated. Worse results were obtained during the dry years, though, likely due to the fact that only few ground-water reservoirs were simulated explicitly.

2.2.4 Ground-water in- and outflow (*Q_{in}* and *Q_{out}*)

As with JULES, the representation of the ground-water in- and outflow to/from the catchment in the water balance equation (Eq. 1) belongs clearly in the domain of the routing models, as these flow components are defined as lateral subsurface flows over the catchment boundaries, and cannot be directly related to the runoff at the individual gridbox level (see section 2.1.4). As pointed out in previous subsection, Habets et al. (2008) simulated ground-water reservoirs in France by coupling the MODCOU model with ISBA and by using the subsurface drainage from ISBA as input to the ground-water part of MODCOU.

2.2.5 Water storage change (ΔS; both liquid and solid forms)

2.2.5.1 Snow store modelling

The variable “CSNOW” (see section 7.6 in Le Moigne (2009b)) allows the user to select between three different snow scheme options. Two of these are single layer composite schemes, where single soil-vegetation-snow energy budget is calculated (the Douville “D95” scheme, and the Bazile “EBA” scheme which is the operational snow scheme in the ARPEGE atmospheric model). The third scheme is a 3-layer snow scheme (“3-L”), which resolves the large thermal and density gradients which can exist in the snow cover, distinguishes the surface energy budgets of the snow and non-snow covered portions of the surface, includes the effects of liquid water storage in the snow cover, models the absorption of incident radiation within the snowpack, and calculates explicit heat conduction between the snow and the soil. Coupling of the multilayer CROCUS snow model (of which the 3-layer scheme is based on) to SURFEX is ongoing and expected to be included as a option in the upcoming SURFEX version 6 (Trygve Aspelien, pers. comm., January 2011).

2.2.5.2 Soil moisture and ground-water store modelling

Three different soil discretization and physics schemes in ISBA can be selected via the variable “CISBA” (see section 6.7 in Le Moigne (2009b)), namely the “force-restore method” with 2 or 3 layers for hydrology, and the “diffusive” method with any user-defined number of layers.

In the force-restore scheme with two layers it is not possible to distinguish the root zone and the total soil water reservoirs. In the three-layer version, bulk soil layer (layer 2 in the two layer scheme) is divided into a root-zone layer (layer 2) and base-flow layer (layer 3). The latter layer may provide water to the root zone through capillary rise. The first layer in both schemes is very thin (set to 1 cm).

The parameters in the force-restore scheme are made dependent on the soil textures and moistures, and if the exponential profile of the soil hydraulic conductivity option is selected via the variable “CKSAT” (see section 8.4 in Le Moigne (2009b)) then the parameters are modified accordingly. Furthermore, soil freezing is taken into account via addition of phase change terms to the thermal and hydrologic transfer equations. The vapor phase transfer is considered for very dry soils (i.e. water content below the wilting point).

In the diffusive approach (similar to the default soil moisture scheme used in JULES, based on Richards' equation (Richards, 1931)) Darcy’s law for liquid water transfer is applied together with the water flux due to vapor transfer. In addition, a background subgrid subsurface runoff term (w_{drain}; see section 6.7 in Le Moigne (2009b)) is applied to maintain a minimum streamflow under dry conditions. As the soil freezes, ice is assumed to become part of the soil matrix thereby reducing the liquid water holding capacity of the soil. The hydraulic conductivity and soil water potential are related to the liquid volumetric soil water content through the same relations as in JULES described by Clapp and Hornberger (1978). The lower boundary condition is modelled as gravitational drainage (vertical diffusion is neglected). The upper boundary condition represents infiltration where a maximum water flux into the surface soil layer is set equal to the saturated hydraulic conductivity (the infiltration excess is assumedly directed to surface runoff, possibly depending on the option selected via the “CHORT”). Alternatively, the VIC sub-grid surface runoff scheme (see section 2.2.3.1) can be used in ISBA diffusive soil representation option. Whether the optional TOPMODEL scheme can also be applied with the diffusive soil approach is not clearly described in the scientific documentation (Le Moigne, 2009).

Similar to JULES, no explicit river channel, lake, or ground-water stores are simulated in SURFEX but their storage effect can be indirectly included by applying the routing procedures described in section 2.1.3.3.

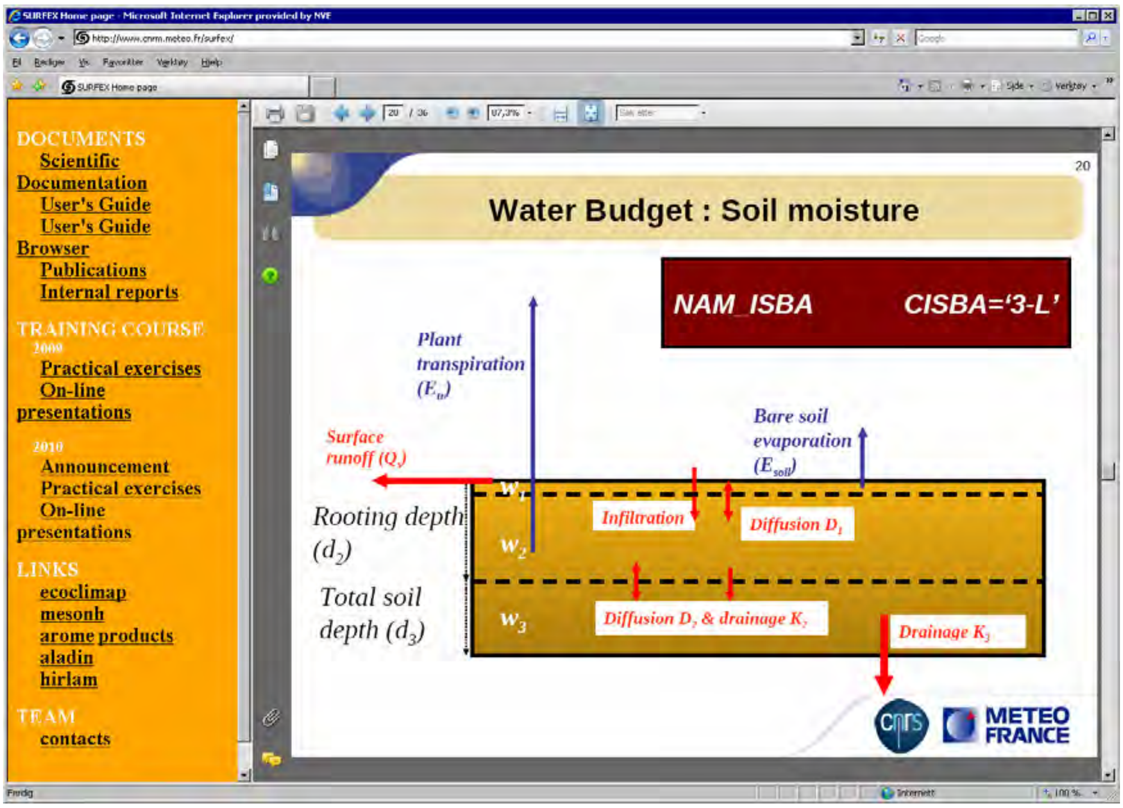


Figure 4. *Schematic representation of the water budget in the 3-layer force-restore soil scheme (Figure from SURFEX website; from 2009 training course presentation of B. Decharme ("force-restore ISBA scheme").*

2.2.6 Anthropogenic drivers (dams, irrigation)

It seems that inclusion of dams and/or irrigation to the water balance simulated in SURFEX is not possible in the current release. The vegetation module A-gs can take into account irrigation for plant water supply, though, but this water source is probably not connected to ISBA.

3 Concluding remarks

In this literature study the representation of hydrological processes in the land surface models JULES and SURFEX has been reviewed, emphasizing the models' capability to handle runoff production in a defined catchment and routing of that water to the catchment outlet. This is an important feature since usually hydrological models are calibrated and evaluated against discharge data measured at the (sub-)catchment outlet.

JULES and SURFEX do not to differ fundamentally in the way and level of detail the hydrological processes are formulated in these models, although SURFEX seems to provide some more options for the user to select between different schemes of soil processes and discretizations. As pointed out by Richard Betts (see JULES website for his presentation at the JULES science meeting, June 2010), different JULES model configurations and submodels are tested and used in different applications of JULES, e.g. when combined with QUEST or HadGEM2-ES earth system models, or when applied offline in e.g. the WATCH-project (see www.eu-watch.org). Figure 5 shows some different configuration possibilities and the configuration used in one of the latest JULES offline releases (version 2.1), together with an overview of the different optional schemes in the ISBA land surface scheme of SURFEX (v5).

Both JULES and SURFEX models simulate snow and soil ice processes which are needed to properly simulate Nordic hydrological conditions. The water balance can be closed in both models, except for evaporation from lake surfaces which does not draw on any conserved water stores. In principle, it is possible to extract variables describing the hydrological cycle from e.g. the UM or HARMONIE weather prediction model runs.

A literature search in the ISI Web of Science with keywords "JULES model" or "MOSES model" gave 32 relevant articles, of which 11 were about hydrology. A similar search for "SURFEX model" or "ISBA model" gave 84 relevant articles, and 52 of them were about hydrology.

It is, of course, difficult to rank one model better than another on the basis of a literature study only. Generally, the goodness of a particular model code is dependent on the purpose and site of the particular model application. Therefore, a practical testing and evaluation of the JULES or SURFEX model applications against observed data is needed to reveal how well these model codes really can simulate the complexity and spatial and temporal variability of hydrological processes. Evaluation and intercomparison of a variety of different land surface models (including JULES/MOSES and ISBA) has been made in several previous and ongoing model intercomparison projects (see e.g. Bowling et al. 2003; Boone et al. 2004; Haddeland et al. 2011).

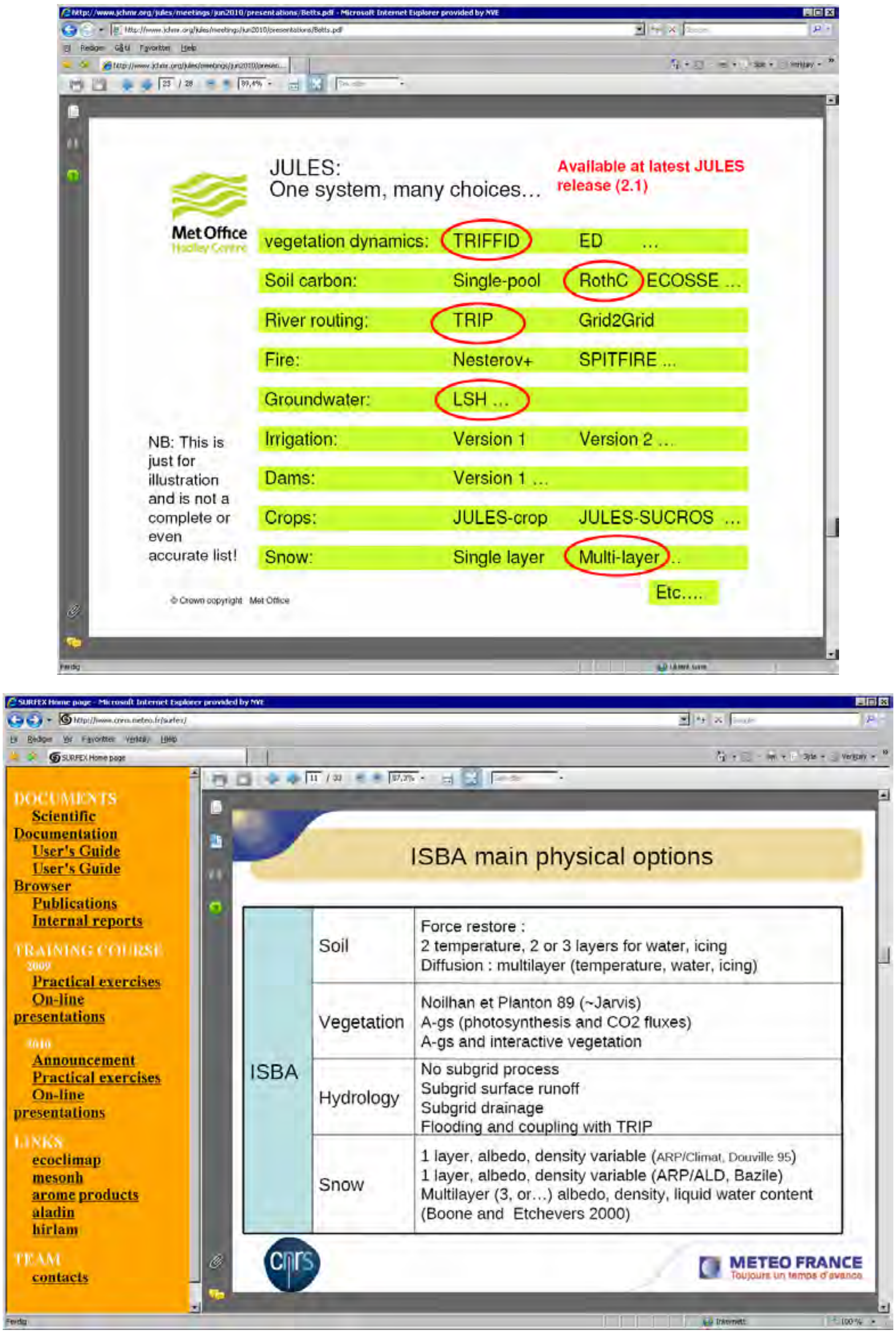


Figure 5. *Illustration of the different land surface process descriptions used in different JULES applications (upper panel), and those selectable in ISBA scheme in SURFEX (lower panel). The schemes included in the JULES vs. 2.1 release are marked with red ovals (Figures from JULES website, from presentation by Richard Betts at JULES science meeting, June 2010 and from SURFEX website, from 2009 training course presentation "Introduction to SURFEX" by E. Martin).*

4 References

Beldring et al. 2003: Estimation of parameters in a distributed precipitation-runoff model for Norway. *Hydrology and Earth System Sciences 7*, 304-316.

Boone et al. 2004: The Rhône-Aggregation Land Surface Scheme Intercomparison Project: An Overview. *J. Climate 17*, 187-208.

Boone, A., J. C. Calvet, and J. Noilhan 1999: Inclusion of a third soil layer in a land surface scheme using the force-restore method, *J. Appl. Meteorol. 38*, 1611– 1630.

Bowling et al. 2003: Simulation of high-latitude hydrological processes in the Torne–Kalix basin: PILPS Phase 2(e) 1: Experiment description and summary intercomparisons. *Global and Planetary Change 38*, 1 –30.

Clapp, R., and G. Hornberger, 1978: Empirical equations for some soil hydraulic properties. *Water Resources Research, 14*, 601-604.

Clark, D. and Gedney, N. 2008: Representing the effects of subgrid variability of soil moisture on runoff generation in a land surface model. *Journal of Geophysical Research, 113* (D10111). doi:10.1029/2007/JD008940

Clark et al. 2010: Joint UK Land Environment Simulator (JULES): Version 2.2., User Manual.

Dadson S. J. and Bell V. A. 2010: Comparison of Grid-2-Grid and TRIP runoff routing schemes. CEH report, August 2010.

Dingman, 2002: *Physical hydrology* (2nd ed.) Prentice Hall.

Essery, R, Best, M. and Cox, P. 2001: MOSES 2.2 technical documentation. Hadley Centre Technical Note 30.

Gedney, N., and Cox, P. M. 2003: The sensitivity of global climate model simulations to the representation of soil moisture heterogeneity, *Journal of Hydrometeorology*, *4*, 1265-1275.

Gregory, D., and R. N. B. Smith, 1990: Canopy, surface and soil hydrology. Unified Model documentation paper 25, Meteorological Offce, London Rd, Bracknell, Berkshire, RG12 2SY.

Habets, F., Boone, A., Champeaux, J. L., Etchevers, P., Franchist´eguy, L., Leblois, E., Ledoux, E., Moigne, P. L., Martin, E., Morel, S., Noilhan, J., Quintana Segu´ı, P., Rousset-Regimbeau, F., Viennot, P., Mar. 2008: The SAFRAN-ISBA-MODCOU hydrometeorological model applied over France. *Journal of Geophysical Research 113*, D06113.

Haddeland et al. 2011: Multi-Model Estimate of the Terrestrial Global Water Balance: Setup and First Results (revised manuscript submitted to *J. Hydrometeorology*).

LeMoigne, P. (Ed.) 2009: SURFEX Scientific documentation (SURFEX v5 - Issue nr.1 – May 11, 2009). Available at http://www.cnrm.meteo.fr/surfex/

LeMoigne, P. 2009b: SURFEX off-line user's guide (SURFEX version v5, September 21, 2009). Available at http://www.cnrm.meteo.fr/surfex/

Motovilov et al. 1999: Validation of a distributed hydrological modelagainst spatial observations. *Agr. Forest Meteorol. 98/99*, 257-277.

Noilhan, J., and J.-F. Mahfouf 1996: The ISBA land surface parameterization scheme, *Global Planet. Change 13*, 145–159.

Noilhan, J., and S. Planton 1989: A simple parameterization of land surface processes for meteorological models, *Mon. Weather Rev. 117*, 536– 549.

Richards, L., 1931: Capilliary conduction of liquids through porous mediums. *Physics*, 1, 318-333.

Rooney G. G. and Jones, I. D. 2010: Coupling the 1-D lake model FLake to the community land-surface model JULES, *Boreal Environment Res. 15*, 501-512.

Sælthun, N. R. 1996: The “Nordic” HBV model. Norwegian Water Resources and Energy Administration (NVE) Publication 7, 26 pp.

van Genuchten, M., F. Leij, and S. Yates, 1991: The RETC code for quantifying the hydraulic functions of unsaturated soils. Technical Report EPA/600/2-91/065, U.S. Environmental Protection Agency.

This series is published by Norwegian Water Resources and Energy Directorate (NVE)

Published in the Report series 2010

Nr. 1 Representation of catchment hydrology, water balance, runoff and discharge in the JULES and SURFEX land surface models. Tuomo Saloranta (26 s.)

Norwegian
Water Resources and
Energy Directorate

Norwegian Water Resources
and Energy Directorate

Middelthunsgate 29
PB. 5091 Majorstuen,
N-0301 Oslo Norway

Telephone: +47 22 95 95 95
Internet: www.nve.no