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The SURFEXv7.2 land and ocean surface platform for coupled or offline simulation of earth surface variables and fluxes

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Abstract. SURFEX is a new externalized land and ocean surface platform that describes the surface fluxes and the evolution of four types of surfaces: nature, town, inland water and ocean. It is mostly based on pre-existing, well-validated scientific models that are continuously improved. The motivation for the building of SURFEX is to use strictly identical scientific models in a high range of applications in order to mutualise the research and development efforts. SURFEX can be run in offline mode (0-D or 2-D runs) or in coupled mode (from mesoscale models to numerical weather prediction and climate models). An assimilation mode is included for numerical weather prediction and monitoring. In addition to momentum, heat and water fluxes, SURFEX is able to simulate fluxes of carbon dioxide, chemical species, continental aerosols, sea salt and snow particles. The main principles of the organisation of the surface are described first. Then, a survey is made of the scientific module (including the coupling strategy). Finally, the main applications of the code are summarised. The validation work undertaken shows that replacing the pre-existing surface models by SURFEX in these applications is usually associated with improved skill, as the numerous scientific developments contained in this community code are used to good advantage.

1 Introduction

Accurate simulations of fluxes at the earth's surface are needed for a large number of applications ranging from surface monitoring and hydrology to numerical weather prediction and global climate simulations. Among others, these fluxes include sensible and latent heat fluxes, and fluxes of momentum, carbon dioxide, chemical species, continental aerosols, sea salt and snow particles. For example, in hydrological applications, accurate estimates of surface and bottom runoff are important, as are the possible feedbacks from the hydrological components of the systems to the surface, the atmosphere and the ocean (through interactions between the water table and the root zone, flooded areas or routing of water to the ocean).

For these reasons, surface models continue to increase in complexity and accuracy as a result of improvements to existing process parameterization or the addition of new processes. Examples of such models include CLASS (Verseghy et al., 1991), CLM (Lawrence et al., 2011), JULES (Best et al., 2011; Clark et al., 2011), LIS (Kumar et al., 2006), Noah (Ek et al., 2003), ORCHIDEE (Krinner et al., 2005), and TESSEL (Balsamo et al., 2009). Much effort has been put into the development of land data assimilation systems at various scales: from continental scale (e.g. Mitchell et al., 2004) to global scale (e.g. Rodell et al., 2004), based on various land-surface models. The recent improvements in these models draw more and more benefits from multidisciplinary research and need highly flexible community codes so that the same code can be used for various applications. This is the only option if code duplications and errors in recoding between applications are to be avoided.

Taking advantage of the continuous development of the surface models ISBA (Noilhan and Planton, 1989) and TEB (Masson, 2000), and their coupling to both the atmospheric models Meso-NH (Lafore et al., 1998), ARPEGE (Courtier et al., 1991), ALADIN (Fischer et al., 2005), AROME (Seity et al., 2011; Brousseau et al., 2011), ALARO (Gerard et al., 2009; Hamdi et al., 2012), and the hydrological models TRIP (Decharme et al., 2008) and MODCOU (Habets et al., 2008), the construction of a fully externalized surface scheme (i.e. a unique code that can be run in coupled and offline configurations) was undertaken. This surface scheme, SURFEX (from the French "Surface externalisée"; Fig. 1; www.cnrm.meteo.fr/surfex/), was built with the following specifications:

1. Include parameterizations for all components of the surface (ocean and land surface, including urban areas and inland water) and simplified parameterizations for theoretical studies.

2. Provide an interface with physiographic databases allowing the creation of various domain types (from point scale to various domain configurations).

3. Include a data assimilation component for numerical weather prediction applications and land-surface monitoring.

4. Preserve a single scientific code for all the surface applications (offline or fully coupled with several atmospheric models).

An additional constraint in the building of SURFEX is that it is designed for a wide range of applications: point scale research simulation, 2-D offline applications at regional, continental and global scale including the coupling with hydrological models, mesocale to global applications within various atmospheric models including operational weather prediction and long climate runs. Assimilation is used in both the numerical weather prediction chain and in the framework

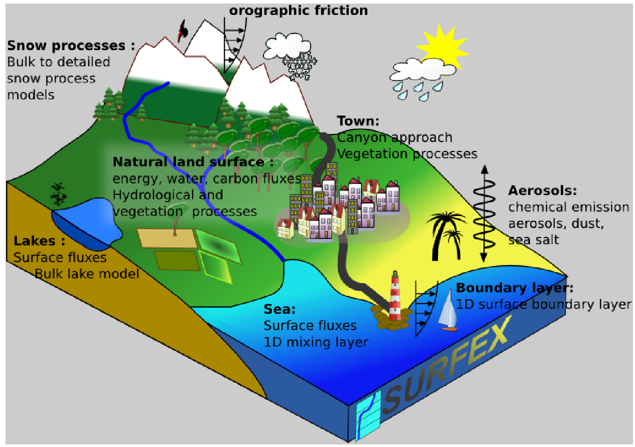

Fig. 1. Schematic representations of the main processes and functionalities of SURFEX.

of a land data assimilation system. The system needs to be modular, highly flexible with clearly specified interfaces.

The objective of this paper is to describe the present status of SURFEX (version 7.2). This is the first article of this type on SURFEX and it summarises the main features of the present state of the code, whose development began nearly 10 yr ago. The main principles of the model and the link with physiographic databases are described in Sects. 2 and 3, respectively. Then the physical schemes and their options are described in Sect. 4. Section 5 is devoted to chemistry, aerosols and sea salt. The strategy for coupling with atmospheric and hydrological models is described in Sect. 6. The assimilation is described in Sect. 7. Finally, Sect. 8 reviews the evaluation of the model and gives some examples of applications.

2 Main principles of the model

Due to its multiple uses, SURFEX is built in a modular way to allow an easy implementation of new technical and scientific features. The entry points of SURFEX are PGD (to prepare the physiographic data), PREP (to initialise prognostic variables), RUN (for offline and inline simulations) and ASSIM (for assimilation Fig. 2.). The code is written in FORTRAN90, which is a higher level of the code using strict coding norms identical for all tiles/patches and is devoted to the coupling with the atmosphere, aggregation/disaggregation of fluxes and the calling of the scientific models. Diagnostics are coded in a similar way for all tiles. Various input/ouput formats depending on the host model are available.

SURFEX can be run on linux personal computers up to supercomputers in case of large runs, especially when used in an atmospheric model or on a global scale. SURFEX can be used in parallelized models, in this case the parallelisation is governed by the host model. Parallelization is also possible in offline mode for the mode RUN. However, some components

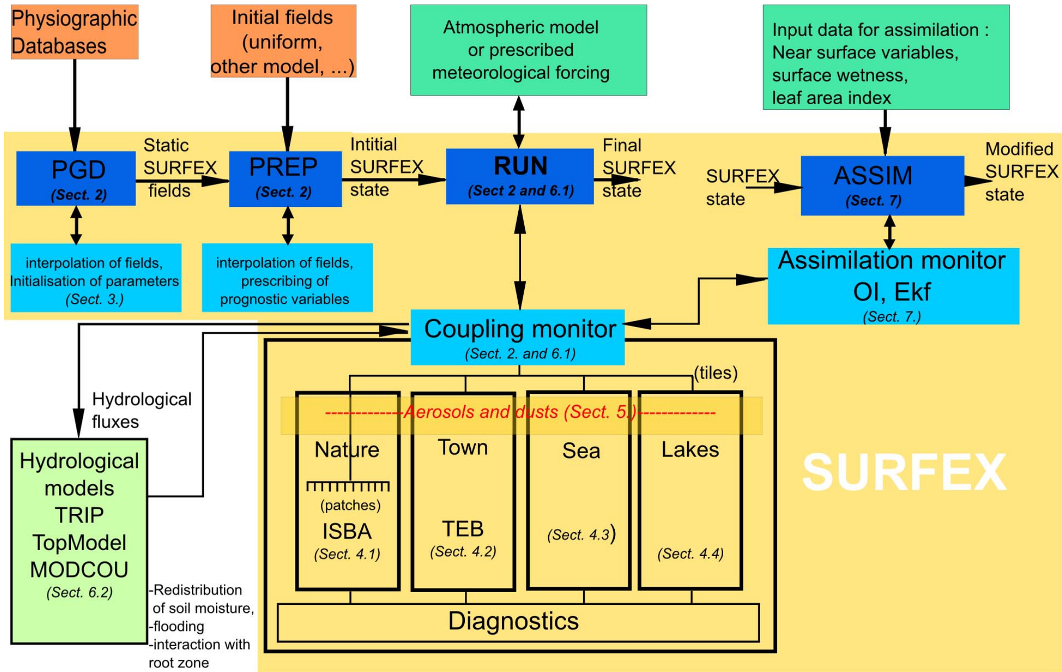

Fig. 2. Schematic representation of the main scientific and technical components of SURFEX (on a yellow background) and their interaction with other models and data.

are not yet parallelized, which is a limitation when SURFEX is used on large grids.

2.1 The tiling aproach

An accurate estimation of surface fluxes over a wide range of spatial resolutions needs to account for subgrid heterogeneities (Essery et al., 2003). SURFEX offers the possibility to use tiles or to aggregate the surface parameters for lumped runs. Four main tiles are defined:

1. continental natural surfaces (“nature” tiles) including bare soils, rocks, permanent snow, glaciers, natural vegetation and agricultural landscapes;
2. town (including buildings, roads and transportation infrastructures, gardens);
3. inland water (including lakes and rivers);
4. sea and ocean.

In order to account for heterogeneity within the continental natural surfaces, this tile can be divided into “subtiles” (referred to as patches in what follows, Fig. 3.). A maximum of twelve patches which correspond to the plan functional types described in ECOCLIMAP (Table 1) can be described by SURFEX to account for the variety of soil and vegetation behaviour within a grid point. This allows non-vegetated surfaces (bare soil, rocks, permanent snow) to be treated separately and accounts for the main plant functional types (tropical vs. temperate vegetation, low vs. tall vegetation, deciduous vs. evergreen trees, various types of crops, etc.). In the tiling approach, each tile has the same meteorological forcing, while the model prognostic variables (liquid water content, surface temperature, snow cover) and model parameters (soil depth, roughness length, LAI, etc.) and the corresponding fluxes are different.

Table 1. Patches used for the description of the nature continental tile.

Bare soil	C3 crops
Rocks	C4 crops
Permanent snow	Irrigated crops
Needle leaf trees	Herbaceous
Evergreen broadleaf trees	Tropical herbaceous
Deciduous broadleaf trees	Wetlands

The tiling is defined by the user and is quite flexible (the number of patches can vary from 1 to 12), lakes can be accounted for or not, the town can be represented using the TEB model or as rocks. Aggregation laws were defined by Noilhan et al. (1997) and Noilhan and Lacarrère (1995) for surface and soil parameters,. However, schemes accounting for the carbon cycle must be run with twelve patches, as the definition of aggregated effective parameters for such models is not straightforward.

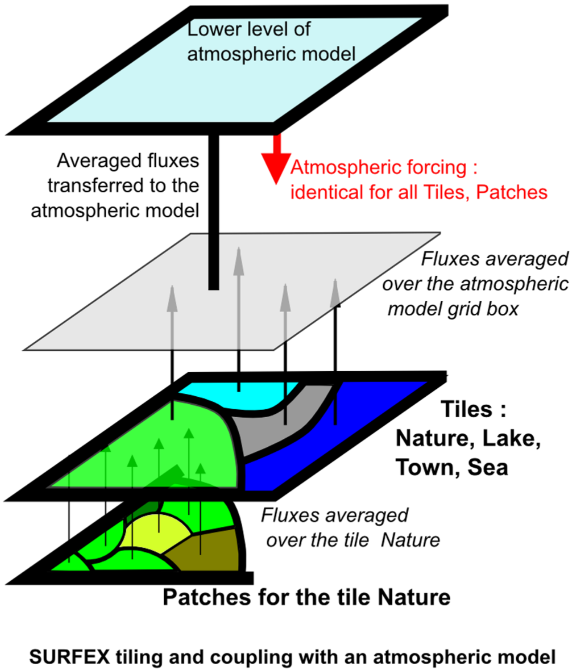

Fig. 3. Schematic representation of the organisation of the surface using four main tiles and patches for nature (soil and vegetation tile).

3 Physiographic data

SURFEX is fully coupled with the global, 1 km resolution, land cover database ECOCLIMAP. The original version (ECOCLIMAP1) is described by Masson et al. (2003). Versions with improvements over western Africa (Kaptué Tchuenté et al., 2010) and Europe (Faroux et al., 2013) were developed later. The ECOCLIMAP database is composed of more than 550 cover types all over the world. Each cover is an ensemble of pixels with similar surface characteristics (e.g. sea, lakes, vegetated areas, suburban areas, etc.). They also account for the vegetation variability that depends on location, climate and phenology. This classification was established using land cover maps and satellite data.

The classification is complemented by look-up tables that allow the parameters for all physical schemes of SURFEX to be retrieved from the ECOCLIMAP covers:

1. Fraction of the surface occupied by each tile (sea, inland water, nature or town).

2. Urban parameters: characteristics concerning buildings and roads. vegetation properties of gardens.

3. Primary parameters for natural continental surfaces that depend on the cover and are defined for each of the 12 patches described in Table 1. These are the leaf area index (LAI), the height of trees and the soil depth (surface, root and deep zones).

4. Secondary parameters that mainly depend on the patches (i.e. identical values for a given patch all over the world): vegetation fraction, emissivity, etc.

The covers are interpolated over the chosen grid. Then all urban, primary and secondary parameters are computed and aggregated if the number of patches is lower than 12. The town garden areas can be included in the nature tile or in the town tile (allowing for interaction with buildings). Some types of cover can be changed: lakes can be removed and replaced by nature and towns can be replaced by rocks.

Other physiographic datasets are needed by SURFEX:

1. Topography (e.g. Gtopo30 at 1 km, Gesch et al., 1999, or SRTM, Farr et al., 2007, for higher resolution, from which the mean grid-cell altitude and sub-grid topography parameters are derived).

2. Soil properties (clay and sand proportions, organic matter) derived from, e.g. FAO (FAO, 2006) or HWSD (Nachtergaele et al., 2012) databases.

3. Lake depth (Kourzeneva et al., 2012).

4. Ocean Bathymetry (e.g. Etopo2 by Smith and Sandwell, 1997).

The databases cited above are fully interfaced with SURFEX, but all parameters can be prescribed separately by the user. SURFEX is not limited to a particular database, hence databases other than those cited here can be used provided that they are put on a format that can be read by SURFEX.

4 Description of the physical models for land and ocean surface processes

4.1 The Interaction Soil–Biosphere–Atmosphere (ISBA) land surface model

The evolution of the soil and vegetation biophysical variables within the nature tiles, and their interactions with the atmosphere, are computed by the ISBA land surface model (LSM). ISBA has evolved considerably since its original formulation by Noilhan and Planton (1989). The original force-restore method was developed in order to capture first-order processes critical to numerical weather prediction while optimizing the input parameters and minimizing the land surface computations. However, over the last two decades, the demands of the user and research communities, and also computational resources, have grown considerably. ISBA has been progressively enriched with more detailed representations of processes in all compartments of the model. This section describes the model physical parameterizations and options (summarised in Table 2) currently available in ISBA.

Table 2. Summary of the main parameterizations available in ISBA.

Model component	Parameterisation	References
Soil	Force restore: two layers (2L)	Noilhan and Planton (1989), Mahfouf and Noilhan (1996)
	Force restore: three layers (3L)	Boone et al. (1999)
	Explicit multilayer scheme (DIF)	Boone (2000), Decharme et al. (2011)
	Soil water phase changes	Boone et al. (2000)
	Hydraulic conductivity profile	Decharme et al. (2006)
Vegetation and carbon variables	Standard evapotranspiration (forced LAI)	Noilhan and Planton (1989)
	Photosynthesis and CO_2 fluxes (forced LAI)	Calvet et al. (1998)
	Biomass evolution	Calvet et al. (1998), Gibelin et al. (2006)
	Biomass evolution and terrestrial carbon cycle	Gibelin at al. (2008)
Sub-grid hydrology	Runoff over saturated areas (Dunne): VIC	Habets et al. (1999a)
	Runoff over saturated areas (Dunne): TOPMODEL	Decharme and Douville (2006a)
	Infiltration excess runoff (Horton)	Decharme and Douville (2006a)
	Residual drainage	Habets et al. (1999b)
	Spatial heterogeneities in rainfall intensities	Decharme and Douville (2006a)
Snow processes	Single layer bulk snow model	Douville et al. (1995), Bazile et al. (2001)
	Intermediate complexity: ISBA-ES	Boone and Etchevers (2001)
	Detailed model: CROCUS	Vionnet et al. (2012), Brun et al. (1989, 1992)

4.1.1 Surface energy budget

The ISBA surface energy budget is computed using a soil-vegetation composite approach. A single surface temperature is used in the computation of the surface energy balance of the land/cover system (Noilhan and Planton, 1989). The surface heat flux, G ($\mathrm{W\,m^2}$), into this soil-vegetation-snow composite is equal to the sum of all the surface–atmosphere energy fluxes: the net radiation (R_n), the sensible heat flux (H) and the latent heat flux (LE). R_n is the sum of the net short-wave radiation and the net long-wave radiation computed using surface composite soil-vegetation-snow albedo and emissivity. H is calculated by means of the Louis (1979) aerodynamics formulae depending upon the thermal stability of the atmosphere, modified by Mascart et al. (1995) in order to consider different roughness length for heat and momentum. Finally, LE is related to the sum of evaporation from the bare soil surface, sublimation from the snow pack and from soil ice, and evapotranspiration from the vegetation. More details can be found in Noilhan and Planton (1989), Douville et al. (1995) and Boone et al. (2000).

The surface soil-vegetation temperature (T_s) is approximated as the temperature of a thin superficial layer having a depth fixed at 0.01 m. It varies according to the surface heat flux (G) and a soil heat flux. The latter depends on the soil scheme (see Sect. 4.1.2 for more details on the soil schemes). In the case of the force-restore approach (Noilhan and Planton, 1989), T_s is restored towards its mean value over one day as proposed by Bhumralkar (1975) and Blackadar (1976). It also depends on the surface composite thermal inertia coefficient, which is parameterized as the harmonic mean of soil (with or without soil ice), snow and vegetation thermal inertia coefficients (weighted by surface vegetation and snow fractions; Noilhan and Planton, 1989; Douville et al., 1995; Boone et al., 2000). If an explicit multi-layer soil scheme (Boone, 2000; Decharme et al., 2011) is used, the surface soil-vegetation temperature (T_s) varies according to the surface heat flux (G) and the soil heat flux calculated by combining the thermal gradient between the thin superficial layer and the second soil layer with the soil properties.

Surface energy budget in the presence of snow

In the case of one-layer bulk snow models, the force-restore composite surface temperature also accounts for snow. But when explicit multi-layer snow schemes are used (ISBA-ES or Crocus see Sect. 4.1.4), the surface energy budget is computed as the sum of the soil-vegetation composite energy budget and the snow energy budget weighted by the snow fraction (Boone and Etchevers, 2001). In this case, the “radiative” surface temperature is computed using the composite soil-vegetation and the snow surface temperatures. This option is always used with the ISBA multi-layer soil diffusion scheme (Boone et al., 2000; Decharme et al., 2011). Note that bulk snow schemes cannot be used with explicit multi-layer soil schemes.

4.1.2 Soil

Force restore approach

In this approach, the surface temperature is restored towards a restore temperature, accounting for the soil heat flux. The so-called restore temperature is representative of the layer affected by a daily damping depth. For longer term simulations, there are two options to prevent model drift. The first method is to prescribe an external deep layer temperature. The restore temperature is itself restored to this temperature, which can be based on observational data and can be constant or time varying. The second method is a multilayer force-restore approach, each layer accounting for a given timescale (from 1 day to 1 yr). The latter method is applied for long climate runs. Note that, in the configurations mentioned above, the thermal properties between the surface and the base of the restore layer(s) are assumed to be vertically homogeneous.

The vertical soil water transfer is represented by either two (2L) or three (3L) layers based on the force-restore method proposed by Deardorff (1977). The volumetric water content of the surface superficial layer (first layer) is restored towards the volumetric water content of the combined bulk surface and rooting layer (second layer). A set of force-restore coefficients were computed by Noilhan and Planton (1989) using hydraulic parameter values from Clapp and Hornberger (1978) based on either a simple analytical solution relying on Darcy's law or a calibration using a high resolution one-dimensional model representation of Richard's equation.

In addition to the classic force-restore approach described above, several improvements have been made. A gravitational drainage coefficient has been added, which relaxes the water content to the field capacity value when this value is exceeded (Mahfouf and Noilhan, 1996), where the field capacity is the volumetric water content corresponding to a gravitational drainage of $0.1\,\mathrm{mm\,day^{-1}}$ (Wetzel and Chang, 1987). The 3L version accounts for a third sub-root-zone layer to better represent the vertical soil moisture gradient in the vadose zone, so an additional calibrated coefficient has been added to represent the diffusion between the root zone and the sub-root zones (Boone et al., 1999). If the water content of the bulk root or deep layers exceeds the soil porosity, a saturation excess runoff is generated. Note that this form of runoff is less likely when a sub-grid hydrological option is used (see Sect. 4.1.5). Finally, soil water can be extracted from the root zone for transpiration until the soil water decreases to the wilting point volumetric water content (corresponding to a matrix potential of $-15\,\mathrm{bar}$). Bare soil evaporation can continue at water contents below wilting point, depending on both moisture and temperature, by water vapour transfer (Braud et al., 1993; Giard and Bazile, 1996). Finally, all force-restore coefficients and soil hydrological parameters are related to soil textural properties and moisture using the continuous relationships from Noilhan and Lacarrère (1995), which were derived from the Brooks and Corey (1966) model and the Clapp and Hornberger (1978) parameters (Noilhan and Planton, 1989; Noilhan and Mahfouf, 1996; Boone et al., 1999).

Explicit multilayer soil scheme

In contrast to the force-restore method, the surface and subsurface layers are coupled via an explicit heat flux computation based on the classical one-dimensional Fourrier law. The total soil heat capacity is computed as the sum of both water and soil matrix heat capacity. Following Johansen (1975), Farouki (1986) and Peters-Lidard et al. (1998), and the soil thermal conductivity is expressed as a function of volumetric water and ice contents, soil porosity and dry soil conductivity. The surface and soil temperatures are computed using a method that permits fully implicit coupling with the atmosphere (see Sect. 6.1.1).

The explicit soil hydrology uses the so-called "mixed" form of the Richards equation to simulate the vertical water mass transfer within the soil via Darcy's law. The water evolution is solved in terms of volumetric water, the hydraulic gradient being solved in terms of water pressure head. This mixed form is generally considered superior to the pressure-based or moisture-based forms because it maintains a high accuracy mass balance. In addition, the mixed form is applicable to homogeneous or heterogeneous soils and to saturated or unsaturated soils (Milly, 1985; Decharme et al., 2011). The relationship between soil moisture, soil matrix potential, and hydraulic conductivity is determined using the Brooks and Corey (1966) relationships. For dry soils, water vapour transfer can be significant and maintain evaporation from the soil. Therefore, vapour and liquid water conductivity are summed, resulting in an effective conductivity. This depends on the soil texture, water content, and temperature (Braud et al., 1993). The water transfer between two layers depends on the inter-layer effective hydraulic conductivity (geometric mean between the conductivity of the two layers). This method reduces the weighting error, improves the hydraulic transfer between layers, and is generally applicable in all situations of moisture gradient (Decharme et al., 2011). Water sinks include water extraction owing to evapotranspiration and gravitational drainage. Soil evaporation is drawn from the superficial layer, while transpiration is removed throughout the root zone using an exponential distribution of roots (Jackson et al., 1996). Water sources include condensation on the surface layer, a possible mass influx at the lower boundary (when coupled to an aquifer model), and infiltration, which is parameterized via a Green and Ampt (1911) approach.

Richard's equation is solved numerically using the Crank–Nicolson implicit time scheme where the implicit vertical flux terms are linearized using a first-order Taylor series expansion. The resulting linear set of diffusion equations can be cast in a tri-diagonal form and solved quickly. This type of algorithm is considerably less expensive than an iterative method and is more suitable for regional to global large-scale applications. For large time steps, such as in a global climate model, a linear time splitting option is also activated, which further improves numerical stability.

Most LSMs use a zero heat flux lower boundary condition, the soil must be sufficiently deep with respect to the duration of the simulation in order to prevent model drift. For this reason, the soil thermal computations use additional layers compared to the soil hydrological computational grid. To compute the heat capacity and thermal conductivity of these additional layers, the soil moisture is extrapolated downward assuming hydrostatic equilibrium in order to save computer time and while maintaining good hydrological simulations (e.g. river flow).

The default diffusion configuration of the model uses 14 layers to represent 12 m depth. Eight of these layers are in the top metre of the soil since Decharme et al. (2011) has shown that this was the minimum number of layers required to maintain a robust numerical solution of the Richards equation.

Hydraulic conductivity profile

ISBA can account for the effect of soil heterogeneities on the vertical soil water transfer by using an exponential profile of the saturated hydraulic conductivity, k_{sat}, with soil depth for both the force-restore and diffusion schemes. The main hypothesis is that roots and organic matter favour the development of macropores and enhance the water movement near the soil surface, and that soil compaction is an obstacle for vertical water transfer in the deeper soil. This parameterization (described in detail by Decharme et al., 2006) depends on only two parameters, which represent the rate of decline of the k_{sat} profile and the depth where k_{sat} reaches its so-called "compacted value". The first parameter can be related to soil properties but cannot exceed $2\,m^{-1}$, and the second is assumed to be equal to the rooting depth. These two parameters can also be tuned to improve streamflow forecasts (Quintana Seguí et al., 2009).

Soil water phase changes

Soil ice increases when water and energy are available for ice production. In contrast, the soil ice decreases due to melting and/or sublimation. During phase changes, the total soil water content for each soil layer is conserved, so as a soil freezes (resp. thaws), the liquid water content will decrease (resp. increase), corresponding to an increase (resp. decrease) in soil ice content. Since the surface is a composite layer, a surface insulation coefficient is introduced in order to partition the available energy into a portion which causes soil water phase changes and a part which heats or cools the vegetation (Giard and Bazile, 2000). A characteristic timescale for phase changes is also introduced in order to prevent a time step dependence of the phase change. In order to avoid a computationally intensive iterative solution procedure, the soil temperature profile is first calculated, then the phase change term is evaluated and temperatures are adjusted accordingly.

There are two methods available for soil water phase change. The first option corresponds to a simple energy-limited method (Giard and Bazile, 2000; Boone et al., 2000) which consists of freezing water whenever the soil temperature falls below the freezing point, and melting soil ice when this temperature is exceeded. This simple method was developed in order to reproduce the first-order effects of phase change on surface fluxes and lower atmospheric variables within the context of a force-restore approach. The second method determines a maximum liquid water content as a function of temperature using the Gibbs free energy concept (similar to that proposed by Cherkauer and Lettenmaier, 1999). Using this method, the soil phase changes follow the so-called soil specific freezing characteristic curve, so that liquid water can exist at sub-freezing temperatures. The relation between the soil water potential and temperature for sub-freezing conditions is from Fuchs et al. (1978), and the Brooks and Corey (1966) model is used to transform the soil matrix potential in the presence of ice into the maximum unfrozen (liquid) water content. This method is more physically based than the simple energy-limited method, and is more consistent with the multilayer soil option. It is better suited for longer timescale applications.

In terms of hydrology, soil ice has the effect of decreasing the hydraulic conductivity relative to a thawed soil with the same total soil moisture, since freezing–thawing can be modelled as drying–moistening to a good approximation (Kane and Stein, 1983; Spans and Baker, 1996). Therefore, as a soil freezes, ice is assumed to become part of the soil matrix, thereby reducing the soil porosity (Boone et al., 2000). Note that very large liquid water gradients can develop when significant soil water freezing occurs, so an ice impedance coefficient is calculated following Johnsson and Lundin (1991) and used to prevent an overestimation of the upward liquid water flux at the freezing front.

4.1.3 Vegetation and carbon variables

Photosynthesis and CO_2 fluxes

The standard version of ISBA uses the simple Jarvis (1976) approach to estimate the evapotranspiration. This approach is based on four factors accounting for the photosynthetically active radiation, the water stress, the water vapour deficit and an air-temperature dependence on the surface resistance. In contrast, photosynthesis and surface CO_2 fluxes are comprehensively modelled by ISBA-A-gs. ISBA-A-gs is a CO_2-responsive LSM able to simulate the diurnal cycle of carbon and water vapour fluxes (Calvet et al., 1998; Gibelin et al., 2006). It is based on a photosynthesis-driven representation of the leaf stomatal conductance based on the model of Goudriaan et al. (1985) modified by Jacobs (1994) and Jacobs et al. (1996). This parameterization is derived from the set of equations commonly used in other land surface models (Farquhar et al., 1980, for C3 plants and Collatz et al., 1992, for C4 plants) and it has the same formulation for C4 plants as for C3 plants, differing only by the input parameters. Moreover, the slope of the response curve of the light-saturated net rate of CO_2 assimilation to the internal CO_2 concentration is represented by the mesophyll conductance (g_m). Therefore, the value of the g_m parameter is related to the activity of the Rubisco enzyme (Jacobs et al., 1996) while, in the model by Farquhar et al. (1980), this quantity is represented by a maximum carboxylation rate parameter $V_{C,max}$. The model also includes a detailed representation of the soil moisture stress. Two different types of drought responses are distinguished for herbaceous vegetation (Calvet, 2000) and forests (Calvet et al., 2004), depending on the evolution of the water use efficiency (WUE) under moderate stress: WUE increases in the early soil water stress stages in the case of the drought-avoiding response, whereas it decreases or remains stable in the case of the drought-tolerant response. In all cases, the soil moisture deficit impacts g_m, which permits the limitation of photosynthesis during water stress to be described (Galle et al., 2009) in conjunction with other environmental factors such as leaf temperature or the leaf-to-air saturation deficit. It should be noted that, unlike the Jarvis-type parameterization used in the initial version of ISBA (Noilhan and Planton, 1989), the model parameters of heterogeneous grid-cells cannot be aggregated. Instead, simulations must be performed over all patches.

Biomass evolution, carbon allocation and leaf phenology

ISBA-A-gs simulates the leaf biomass and the LAI (defined as the leaf area per unit ground area), using a simple growth model (Calvet et al., 1998). On a daily timestep, the leaf biomass is supplied with the carbon assimilated by photosynthesis during the course of the day, and decreased by turnover and respiration terms. LAI is inferred from the leaf biomass multiplied by the specific leaf area (SLA), which depends on the leaf nitrogen concentration (Calvet and Soussana, 2001; Gibelin et al., 2006).

Unlike most other land surface and vegetation models, there is no phenology module based on the accumulation of favourable days (like growing degree days for temperate deciduous phenology for instance). The phenology is directly the result of the photosynthetic activity and leaf mortality.

Ecosystem respiration

The net ecosystem exchange (NEE) of CO_2 results from the balance between photosynthesis (or gross primary production, GPP) and the ecosystem respiration (R_{eco}). In ISBA-A-gs, the latter is calculated using a simple Q_{10} response to soil temperature, weighted by surface soil moisture (Albergel et al., 2010a). For natural vegetation, the basal R_{eco} rate can be calibrated to obtain an equilibrium between the accumulated R_{eco} and GPP, on an annual or multi-annual basis. As opposed to the ISBA-CC model (see below), the various autotrophic and heterotrophic respiration terms are not calculated.

Terrestrial carbon storage

Gibelin et al. (2008) developed the ISBA-Carbon Cycle (ISBA-CC) LSM in order to simulate the main components of the terrestrial carbon cycle. ISBA-CC is based on ISBA-A-gs and provides a number of additional variables representing the vegetation biomass (wood and root compartments), the above- and below-ground litter pools and the soil carbon pools. ISBA-CC uses the carbon fluxes, and the leaf growth and senescence calculated by ISBA-A-gs to simulate the biomass in the wood and roots compartments. Biomass resulting from photosynthesis (minus leaf respiration) is first entirely allocated to leaves and twigs by the ISBA-A-gs module. It is then translocated to the other biomass pools at rates depending on the growth or senescence states of the plant, and the respiration of the pool. The litter and soil biogeochemistry module included in ISBA-CC is based on the well-known CENTURY model (Parton et al., 1987) that partitions the soil carbon among pools with different residence times. Since the autotrophic and heterotrophic respiration terms are calculated, the net primary production (NPP) can be simulated. In the case of forests, the wood biomass growth is simulated and equilibrium climax biomass values can be determined. There is no representation of disturbance, whether natural or of human origin; for example, a forest management module would need to be implemented in order to represent the carbon sink due to forest re-growth (Bellassen et al., 2010).

4.1.4 Snow

The snow component of LSMs in use by the atmospheric research community is generally classified into three levels of general model complexity (Boone and Etchevers, 2001; Armstrong and Brun, 1998). Simple composite force-restore (e.g. Douville et al., 1995; Yang et al., 1997) or single-layer bulk snow (e.g. Verseghy, 1991; Slater et al., 1998) schemes attempt to model the main effects of snow cover on the atmosphere using very simple first-order snow physics. At the other end of the spectrum are explicit internal-snow-process models which use multiple layers with a relatively fine vertical resolution and detailed physical parameterization schemes (e.g. Anderson, 1976; Jordan, 1991; Brun et al., 1992; Bartelt and Lehning, 2002). Applications of such models have so far mostly included avalanche forecasting and detailed local-scale studies. Finally, explicit snow schemes of intermediate complexity are based on the complex models but with fewer layers and similar but generally simplified processes (e.g. Loth et al., 1993; Lynch-Stieglitz, 1994; Boone and Etchevers, 2001). Such models were designed to bridge the gap between the detailed schemes and the simple models for meso- to large-scale meteorological and hydrological applications, limiting the computation costs and simplifying the initialization issues (see Essery et al., 2013 for a comprehensive overview of the current state of the art of snow modelling). SURFEX currently contains three snow model options, which cover the entire spectrum of the model complexity mentioned above, and the users make their choice according to the scientific goals, computing resources and evaluation data available for a particular study.

Single layer bulk snow models

Two options using the so-called first-order schemes are available (Douville et al., 1995; Bazile et al., 2001) and have been used extensively for global climate and numerical weather prediction applications. Both schemes use the composite-surface method based on the force-restore approach, and they contain three prognostic variables for a single-layer snow pack: the snow water equivalent (SWE), the average snow cover bulk density and an age-dependent snow albedo. Some noteworthy distinctions can be made between the two models. In Douville et al. (1995), the surface thermal inertia includes a contribution from the snow thermal properties, the minimum snow albedo is 0.50, the surface temperature used to compute snowmelt is linearly related to the restore temperature by the vegetation fraction, and the vegetation snow cover fraction depends on the vegetation aerodynamic roughness length. In Bazile et al. (2001), the surface thermal inertia is unchanged by the presence of a snow cover, the minimum snow albedo is 0.65, the snow-melt energy is directly computed using the surface temperature and the vegetation snow cover fraction depends on LAI and snow age. In both cases, in the presence of permanent snow or glacier, the minimum snow albedo is higher than in the case of seasonal snow.

Intermediate complexity model: ISBA-Explicit snow

ISBA-Explicit Snow (ISBA-ES: Boone and Etchevers, 2001) was designed for implicit coupling with atmospheric models and spatially distributed hydrological modelling applications. There are three variables saved at each time step that are used to describe the state of the snow for multiple layers: the heat content (or specific enthalpy), the snow density, and the layer thickness. The snow albedo constitutes a fourth prognostic variable (which is the same as in Douville et al., 1995). In terms of the number of snow layers, the default value is three (the minimum number to capture vertical gradients of density and temperature for most climate conditions) but some applications use up to 10 layers. Key processes represented include transmission of radiation within the snowpack, freeze-thaw, compaction and settling, and liquid water storage and through-flow. The snowpack is coupled to the underlying ground through a heat flux term in which the interfacial thermal conductivity represents both snow and soil-vegetation thermal properties.

Explicit internal-snow-processes model: Crocus

Crocus was primarily developed for the detailed study of the snowpack evolution at a particular location, and for operational avalanche prediction (Brun et al., 1989, 1992). It models the snow stratigraphy using a one-dimensional finite-element grid. The number of layers depends on a set of specific rules intended to properly capture the snowpack layering dynamics by representing the vertical gradients of the snowpack with high resolution. Each snow layer is described by its thickness, temperature, density, liquid water content, grain types (dendricity, sphericity, size, and age), and a historical variable that indicates whether there has been liquid water or faceted crystals in the layer. In addition, Crocus takes the slope angle of the surface into account when computing the compaction. The impact of drifting snow on compaction, metamorphism and sublimation can also be taken into consideration. Crocus has recently been rewritten to match the ISBA-ES structure and interfaces within SURFEX. The model is driven by meteorological variables observed, analysed, or modelled at the snow surface, or it can be implicitly coupled with an atmospheric model. The coupling with the underlying ground is identical to that used by ISBA-ES. See Vionnet et al. (2012) for an up to date, comprehensive overview of Crocus in SURFEX.

4.1.5 Subgrid hydrology

At regional or global scale, the land surface water budget is calculated on grid cells with sides that typically measure from several km to 300 km. At such a resolution, the sub-grid distribution of the atmospheric fluxes and land surface characteristics has a significant impact on the mean water budget simulated within each grid box. In other words, regional and global hydrological simulations are generally sensitive to the horizontal resolution of the computation grid (Boone et al., 2004; Decharme et al., 2006). Nevertheless, this sensitivity can be reduced in ISBA by using sub-grid parameterizations of the main hydrological processes (Decharme and Douville, 2006a, 2007). In ISBA, five optional parameterizations account for the sub-grid variability of soil moisture, soil maximum infiltration capacity, soil hydraulic properties, precipitation, and/or vegetation properties. Note that all these options are described and validated in detail in Decharme and Douville (2006a):

1. First, the surface runoff over saturated areas, named *Dunne runoff*, can be computed using one of the two options that attempt to represent soil moisture spatial heterogeneities:

   a. The Variable Infiltration Capacity (VIC) scheme (Zhao, 1992; Dümenil and Todini, 1992; Wood et al., 1992; Habets et al., 1999a) in which the saturated fraction of the grid cell depends on soil moisture, precipitation intensity and a shape parameter,

B. B, that can be fixed manually (generally around 0.5) or computed using the standard deviation of orography in each grid cell at the model resolution considered (Decharme and Douville, 2007).

b. A simple TOPMODEL (TOPography based MODEL) approach. TOPMODEL attempts to combine the important distributed effects of channel network topology and dynamic contributing areas for runoff generation (Beven and Kirkby, 1979; Silvapalan et al., 1987). This formalism takes topographic heterogeneities into account explicitly by using the spatial distribution of the topographic indices. The coupling between TOPMODEL and ISBA was proposed by Habets and Saulnier (2001) and generalized by Decharme et al. (2006). Its formulation does not require calibration (Decharme and Douville, 2006a).

2. The second mechanism that produces surface runoff is called *Horton runoff* and occurs for a rainfall intensity that exceeds the effective maximum infiltration capacity of the soil. This process is parameterized using a sub-grid exponential distribution of the soil maximum infiltration capacity. Two maximum infiltration capacity functions proportional to the liquid water and ice content of the soil are used. They enable the Horton runoff to be represented explicitly over unfrozen and frozen soil (Decharme and Douville, 2006a).

3. The third parameterization allows linear residual drainage when the soil moisture of each layer is below the field capacity. The idea is to take the spatial heterogeneity of soil moisture and soil hydraulic properties into account within a grid box (Habets et al., 1999b; Etchevers et al., 2001). This linear residual drainage depends on a coefficient which can be calibrated basin by basin or assumed constant and uniform.

4. The fourth parameterization accounts for spatial heterogeneities in rainfall intensity. As a first-order approximation, this sub-grid variability is given by an exponential probability density distribution. The main assumption is that, generally, the rainfall intensity is not distributed homogeneously over the entire grid cell. A fraction of the grid cell affected by rainfall can then be determined (Fan et al., 1996; Peters-Lidard et al., 1997). This parameterization affects the dripping from the canopy reservoir (Mahfouf et al., 1995) and the two maximum infiltration capacity functions used in the Horton runoff computation (Decharme and Douville, 2006a).

5. Last, the tiling approach in the nature tiles (patches, see Sect. 2) is also a means to account for land cover and soil depth heterogeneities: each sub-grid patch extends vertically throughout the soil-vegetation-snow column. So, one rooting depth and one soil depth are assigned to each patch. Hence the hydrology response of a grid point is modified.

4.2 The town energy balance (TEB) model

Most urban parameterizations follow simplified approaches (Masson, 2006). The most common way to do this is to use a vegetation–atmosphere transfer model whose parameters have been modified. Cities are then modelled as bare soil or a concrete plate. The roughness length is often large (one to a few metres; Wieringa, 1993; Petersen, 1997).

The Town Energy Balance (Masson, 2000; Lemonsu et al., 2004) scheme is the first numerical scheme built following the canyon approach. The physics treated by the scheme is relatively complete. Because of the complex shape of the city surface, the urban energy budget is split into different parts, in such a way that three surfaces are considered: roofs, roads, and walls. This type of approximation has been used in some models (e.g. Martilli, 2002; Kondo et al., 2005), while others choose to keep only two energy balances: roofs and effective canyons (encompassing both walls and roads) (e.g. Best et al., 2006; Dupont and Mestayer, 2006; Porson et al., 2009). All these models simulate more accurate fluxes to the atmosphere than modified-vegetation models. A review and intercomparison of all these models is available in Grimmond et al. (2010, 2011). However, when the focus shifts to impacts on the people in the cities (in buildings or on the road) or economics (e.g. energy consumption in buildings), it becomes necessary to clearly separate buildings, canyon air, roads, and, if present, gardens.

The physical processes taken into account in TEB are (Fig. 4):

1. Short-wave and long-wave trapping effect of canyon geometry: up to two reflections between canyon surfaces (walls and road) for long-wave fluxes and an infinite number of reflections for solar radiation are simulated. Shadows of buildings on roads are taken into account.

2. Anthropogenic sensible heat flux: this flux comes either from heated surfaces, or prescribed fluxes from traffic and industry (interacting with the canyon air).

3. Water and snow interception by roofs and roads: the snow cover is simulated using a one-layer scheme derived from the bulk snow model of ISBA, and snow albedo rapidly decreases over time to take account of the fact that snow quickly becomes dirty in urban or road environments.

4. Heat conduction and heat storage in buildings and roads. These are computed using the equation of heat conduction. It allows several distinct layers to be described in the materials. For example, an insulation layer can be included properly in walls, either in the interior of the wall or on the outside.

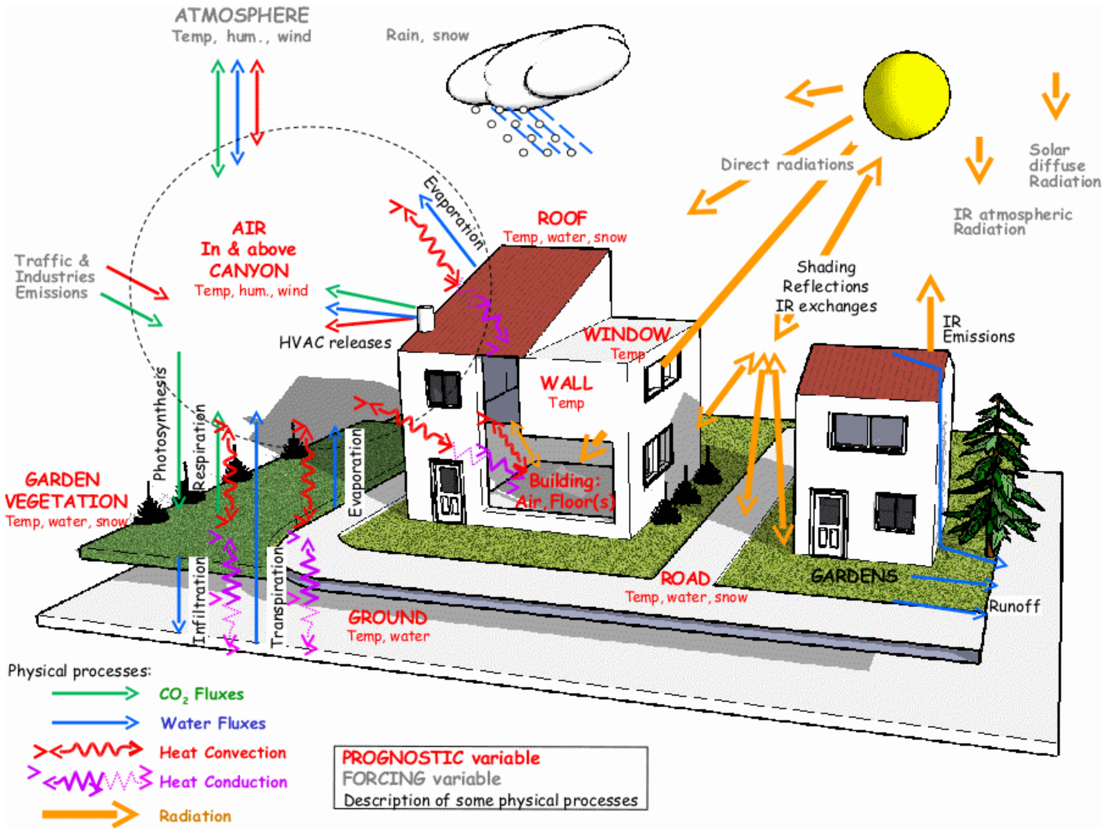

Fig. 4. Schematic representation of the main prognostic variables and processes in the TEB model (HVAC in the figure stands for heat-ventilation-air conditioning system).

5. Interaction between canyon air and the built surfaces: the canyon micro-climate (temperature, humidity, wind, possibly turbulence) is computed by TEB using either a quasi-equilibrium equation for fluxes (classical approach) or the surface boundary layer scheme (see Sect. 6.1) down to the street. In the latter, buildings produce a drag force on wind, produce additional turbulence, and heat and water fluxes from roofs and walls are directly included at the correct height in and above the canyon. The turbulence mixing length and drag coefficient come from state-of-the art parameterizations developed using computational fluid dynamics (Santiago and Martilli, 2010).

A new feature recently introduced into the model is the ability to include gardens inside the street canyon (whereas they were previously treated separately by ISBA). The physiological behaviour of the plants and the treatment of the soil are still computed by ISBA (to take advantage of all the possibilities of this scheme, including the calculation of CO_2 fluxes). In the garden areas, shadows from the buildings now interfere with the vegetation, and the vegetation is in contact with the canyon air. The geometry of the canyon is now better represented (buildings are too close together if gardens are discarded). The gardens improve the simulation of the canyon micro-climate (opening the path to comfort studies), the snowmelt and, more generally, the incoming radiation on building walls (Lemonsu et al., 2012). Further developments will include vegetated roofs and improved internal building energetics (note that the latter is pertinent because the wall energy balance is treated separately from the road). This allows the efficiency to be quantified (in terms of energy consumption or comfort) for scenarios of climate change adaptation in cities.

4.3 Sea and ocean surfaces

Surfaces fluxes can be calculated using several models and parameterizations for the estimation of the sea surface temperature (SST) and the turbulent fluxes. Concerning the SST, several options of increasing complexity are available:

1. For short simulations (covering a few days), only a fixed SST may be needed. In this case, sea ice is assumed to be present as soon as the initial SST is below –2 °C. The sea-ice extent does not change during the run.

2. For longer atmospheric simulations, a 1-D ocean model may be used, provided that horizontal advection can be

neglected. This model may be used for short periods of time, when strong coupling occurs between the marine atmospheric boundary layer and the ocean mixed layer (e.g. in thunderstorm or hurricane conditions). In the model, the turbulent vertical mixing is based on a parameterization of the second-order turbulent moments expressed as a function of the turbulent kinetic energy (Gaspar et al., 1990). In this formulation, the vertical mixing coefficients are provided by the calculation of two turbulent length scales representing upward and downward conversions of turbulent kinetic energy (TKE) into potential energy. By allowing a response to high frequencies in the surface forcing, the scheme improves the representation of the vertical mixed layer structure, sea surface temperature and upper-layer current (Blanke and Delécluse, 1993). However, this parameterization fails to properly simulate the mixing in strongly stable layers in the upper thermocline (Large et al., 1994; Kantha and Clayson, 1994). Consequently, a parameterization of the diapycnal mixing (Large et al., 1994) was introduced into Gaspar's turbulence parameterization model in order to take the effects of the vertical mixing occurring in the thermocline into account (Josse et al., 1999). This non-local source of mixing, mainly due to internal wave breaking and current shear between the mixed layer and upper thermocline, impacts the temperature, salinity, momentum and turbulent kinetic energy inside the mixed layer, particularly during restratification periods. This parameterization was widely used, for instance, to successfully study the diurnal cycle in the Equatorial Atlantic (Wade et al., 2011), the Equatorial Atlantic cold tongue (Giordani and Caniaux, 2011), and the production of modal waters in the northeast Atlantic (Giordani et al., 2005) or to derive surface heat flux corrections (Caniaux et al., 2005). This model does not include a sea-ice model yet.

3. If climate simulations are to be made over several years or decades, a full 3-D ocean model that solves the oceanic circulation and associated heat transfer is needed. SURFEX does not include such a model. Coupling with an oceanic model in the CNRM-CM5.1 global climate model used for phase 5 of the Coupled Model Intercomparison Project (CMIP) runs (Voldoire et al., 2012) was achieved through the OASIS coupling software (Redler et al., 2010). The sea-ice component was embedded into the ocean model in this case.

Whatever the configuration chosen, turbulent air–sea exchanges of heat, moisture and momentum can be computed inside SURFEX using various bulk formulas. A first parameterization uses Charnock's (1955) formula for the roughness length and Louis's (1979) formulations for a direct computation of the exchange coefficients. Iterative computations of the air–sea surface turbulent fluxes can also be activated. In these formulations, the exchange coefficients are obtained iteratively as a function of the wind speed vertical gradient between the sea surface and 10 m height, both parameters being reduced to neutral stratification conditions. First, the COARE 3.0 iterative algorithm of Fairall et al. (2003) can be used. SURFEX also includes the ECUME (Exchange Coefficients from Unified Multi-campaigns Estimates, Belamari, 2005; Belamari and Pirani, 2007) iterative parameterization, derived from multi-campaign measurements in situ (Weill et al., 2003) and covering the widest possible range of atmospheric and oceanic conditions from very light winds up to cyclones. The two latter parameterizations can include optional corrections (due to gustiness, precipitation, density effects) to the sea surface heat and momentum fluxes.

Lastly, SURFEX includes the computation of the shortwave upward component of the radiative fluxes, using either a fixed albedo value or an evolving one depending on the zenith angle (Taylor et al., 1996).

4.4 Inland water surfaces

There are two ways to calculate the fluxes at the air-water interface over a lake in SURFEX. The first, which is relatively simple, is based on the calculation of the roughness length from the Charnock (1955) formula. The surface turbulent fluxes are then calculated with the parameterization of Louis (1979), using a constant surface temperature of the water throughout the run. This method, although easy to implement, has the drawback of not taking the diurnal cycle of the water surface temperature into account. This approach can be justified for deep lakes (or seas and oceans) for which the thermal amplitude remains low over several hours during the daytime. However, it seems more questionable for small to medium-sized shallow lakes, where the daily temperature range can reach several degrees. A correct simulation of this type of lakes is important for high resolution NWP models.

The alternative to using this simple parameterization is to use lake models that are able to predict the evolution of the temperature structure of lakes of various depths, at different timescales. The freshwater lake model (FLake; Mironov et al., 2010) has been coupled to SURFEX. FLake is an integral (bulk) model. It is based on a two-layer parametric representation of the evolving temperature profile within the water column and on the integral energy budget for these layers. The structure of the stratified layer between the upper mixed layer and the basin bottom, the lake thermocline, is described using the concept of self-similarity (assumed shape) of the temperature-depth curve. The same concept can be used optionally to describe the temperature structure of the thermally active upper layer of bottom sediments and of the ice and snow cover. Finally, FLake also deals with snow and ice above the lake.

The model requires external parameters, the most relevant of which is the lake depth. A global database of lake depths has been developed for that purpose (Kourzeneva et al., 2012). The extinction coefficient is also important, but no databases are available at this stage. This parameter can be prescribed uniformly, but the possibility to use maps is already implemented. It should be noted that FLake is a shallow water model that has no representation of the hypolimnion, a third layer usually present between the thermocline and the bottom of deep lakes. Thus, a limiting value of 60 m should be taken for lake depth, based on the results of Perroud et al. (2009). Knowledge of sediment properties and of the optical characteristics of the water are also important, but this information is largely unavailable and prescribed values are usually adopted.

The surface fluxes can be calculated with the formulation of Louis (1979), using the surface temperature calculated by FLake, or by the original flux parameterization of FLake.

The FLake model was also incorporated as a lake parameterization module in SURFEX because it was successfully coupled with NWP models like the limited-area NWP model HIRLAM, the UK Met Office Unified Model, the COSMO-EU (Europe) configuration of the COSMO model and also with regional climate models like CLM (http://www.clm-community.eu/), RCA SMHI – from the Swedish Meteorological and Hydrological Institute, and the ECMWF Integrated Forecasting System. In addition, FLake's modular structure substantially facilitated its implementation within the SURFEX environment (Salgado and Le Moigne, 2010). Finally, the parametric approach of this two-layer model leads to a low computational cost, which is a necessary condition for its use in an operational environment. The LakeMIP intercomparison exercise (Stepanenko et al., 2010) showed that, despite its simplicity, FLake satisfactorily reproduced the water temperature profiles under various forcing conditions when compared to other one-dimensional lake models such as Simstrat (Peeters et al., 2002), LAKE (Stepanenko and Lykosov, 2005), Hostetler's model (Hostetler and Bartlein, 1990) or CLM-VRLS (Subin et al., 2012).

5 Chemistry, dusts, sea salts

5.1 Gas and anthropogenic aerosol emissions

Gas and primary aerosol emissions are extremely heterogeneous (e.g. traffic emissions depend on traffic congestion, emissions from industries are highly variable, etc.) and can hardly be modelled. These emission are prescribed in SURFEX using emission inventories: maps of potential emissions for each chemical species for several sectors (traffic, industry, refining, agriculture, etc.) and are modulated by typical (or observed if available) time information (usually depending on time of day and week/weekend or holiday days). On the other hand, the biogenic volatile organic compound (BVOC) emissions by vegetation depend on meteorological conditions and can be directly parameterized (Solmon et al., 2004; Guenther et al., 1995). These biogenic emissions can either be prescribed or simulated dynamically in SURFEX.

For anthropogenic aerosols, the mass flux is converted into two log-normal modes for the representation of Aitken mode and accumulation mode (Tulet et al., 2005).

5.2 Dust emission over deserts

Dust is an important aerosol with annual global emissions ranging from 1000 to 3000 $\mathrm{Tg\,yr^{-1}}$ and average global load around 10–30 Tg (Zender et al., 2004). Dust is mobilized from dry desert surfaces when the wind friction velocity reaches a threshold value of approximately 0.2 $\mathrm{m\,s^{-1}}$.

Dust is mobilized by two related processes called saltation and sandblasting. Saltation is the horizontal movement of soil grains in a turbulent near-surface layer. Sandblasting is the release of fine dust when the saltating grains hit the surface. Several papers document these two processes. Marticorena and Bergametti (1995) and references therein describe the physics of saltation, and Shao et al. (1993) describe the physics of sandblasting. The dust fluxes are calculated using the Dust Entrainment and Deposition (DEAD) model (Zender et al., 2004) introduced into SURFEX by Grini et al. (2006) and recently improved by Mokhtari et al. (2012) to better account for the soil aggregate distribution.

The dust particles follow a tri-modal distribution that is compatible with the log-normal distribution of aerosols (Crumeyrolle et al., 2011).

5.3 Sea salt

Sea salt aerosols are produced as films and jet droplets through disruption of the sea surface by bubbles entrained in the water by breaking waves (Blanchard, 1983) and, at wind speeds exceeding about 9 $\mathrm{m\,s^{-1}}$, through direct disruption of the wave tops (spume droplets) (Monahan et al., 1986). Sea salt emission is parameterized using the formulation of Vignati et al. (2001) (effective source function) or a lookup table defined by Schulz et al. (2004). Vignati et al. (2001) provide a formulation of the particle emission flux that depends on the wind speed at 10 m above the sea surface. Sea salt particles follow a tri-modal distribution, in a manner similar to dust.

5.4 Dry deposition of chemical species and aerosols

Dry deposition refers to the removal of gases from the atmosphere by turbulent transfer and uptake at the surface. This process enables some chemically reactive gases to be efficiently removed from the atmosphere. Dry deposition is usually parameterized through a deposition velocity v_d, defined by $v_\mathrm{d} = V - V F_\mathrm{c}/c(z)$, where F_c is the flux of the compound in question (F_c is assumed constant over the range of heights considered) and $c(z)$ is the concentration at height z ($\mathrm{molecules\,cm^{-3}}$). v_d depends on many variables such as wind speed, temperature, radiation, chemical properties of species (Henry constant, biological reactivity and molecular mass) and surface conditions. It is commonly described through a resistance analogy (e.g. Wesely and Hicks, 1977).

Note that, in cities, the total surface available for exchanges (i.e. including walls) is taken into account. Above vegetation, chemical species interact in more complex ways. Dry deposition velocities are computed from theoretical considerations based, for instance, on solubility and equilibrium: calculations in combination with simulation of vegetation specific processes, such as accumulation, transfer process through stomata, mesophyll, cuticles, etc. (Baldocchi et al., 1987; Wesely, 1989). In SURFEX, the deposition of each chemical species is computed following Weseley (1989) and Seinfeld and Pandis (1997) and the code is split for all tiles and patches (Tulet et al., 2003).

For dry deposition of aerosols (dust, sea salt and anthropogenic aerosols) a sedimentation term is added (Seinfeld and Pandis, 1997). The formulation of the sedimentation velocity has been re-written by Tulet et al. (2005) for use by a multi-moment log-normal aerosol model.

6 Coupling strategies

6.1 Exchanges with the atmosphere

In SURFEX, the exchanges between the surface and the atmosphere are modelled using a standardized interface (Best et al., 2004) that proposes a generalized coupling method between the atmosphere and the surface (Fig. 3). During a model time step, each surface tile and patch receives the upper air temperature, specific humidity, horizontal wind components, pressure, total precipitation, long-wave radiation, short-wave direct and diffuse radiation fluxes (the atmospheric spectral bands are aggregated into three bands: ultraviolet, visible and near infrared) and possibly concentrations of chemical species and dust. In return, SURFEX computes averaged fluxes for momentum, sensible and latent heat, and possibly chemical species and dust fluxes, and then sends these quantities back to the atmosphere with the addition of radiative terms like surface temperature, surface direct and diffuse albedo (for each wavelength) and also surface emissivity. This information is then used as the lower boundary condition for atmospheric radiation and turbulence schemes.

6.1.1 Implicit/explicit coupling

SURFEX can be coupled to numerical atmospheric models in order to provide them with the surface boundary condition. Climate models use long time steps (up to 30 mn) that need to implement fully implicit coupling between the atmosphere and the surface in order to avoid numerical oscillations. Best et al. (2004) proposed a simple interface to allow implicit coupling between the atmosphere and a tiled surface, which has been implemented in SURFEX. The surface scheme computations for the fluxes are just slightly modified to take account of an additional coefficient describing the relationship between the surface flux (e.g. heat flux) and the variable it will modify (e.g. temperature).

The coupling between the atmosphere and ISBA is implicit for all variables. The coupling for other schemes is only implicit for the wind (but there is no evidence so far of any oscillation with these schemes for other variables, due to an internal implicit evolution for the variables in the schemes).

6.1.2 Atmospheric surface-boundary-layer (SBL)

To improve the description of the physical coupling between the air and the surface, a one-dimensional surface boundary layer has been implemented in SURFEX in order to account for the vertical gradients of the variables of the lowest part of the atmosphere (Masson and Seity, 2009; Fig. 5). The main objectives of the use of an SBL in SURFEX are to

1. Better simulate the profile of wind, temperature, humidity and turbulence between the surface and the forcing level (usually, this is done diagnostically using Monin-Obuhkov similarity laws). This improves the forecast of near-surface air temperature at night when stability is strong (Masson and Seity, 2009).

2. Take account of the effect of vegetation or urban canopies on the in-canopy air. For example, it allows the micro-climate between buildings to be simulated in TEB, or the wind profile to be modified by the trees. For wind, it uses a drag force of the form $\mathrm{d}u/\mathrm{d}t = -C_\mathrm{d}(z)u$, where u is the wind speed and where the drag coefficient depends on building density or the leaf area index of trees. Heat and water fluxes directly influence the atmospheric surface layer at the height where they are released.

3. Better force the surface model, using air characteristics at the corresponding level (e.g. in TEB, near-road air temperature is used for roads, while mid-height canyon air temperature is used for walls).

One SBL profile is implemented for each of the four main tiles. First layers are usually at 50 cm, 2 m, 4 m, 7 m, and 10 m above the surface, but can be modified. Two metre temperature and humidity, and 10 m wind, are prognostically computed by the SBL scheme for each tile. Note that the SBL scheme is implicitly coupled with the surface schemes, but not with the atmosphere, which may cause instabilities for long time steps. Hence, the SBL is not used for climate runs.

6.1.3 Orographic friction

Subgrid-scale orography is well known for its friction effect on the atmosphere. Observations (Grant and Mason, 1990; Kustas and Brutsaert, 1986) have shown that small hills tend to produce a logarithmic wind profile above themselves, typical of a large roughness length. Therefore, roughness length

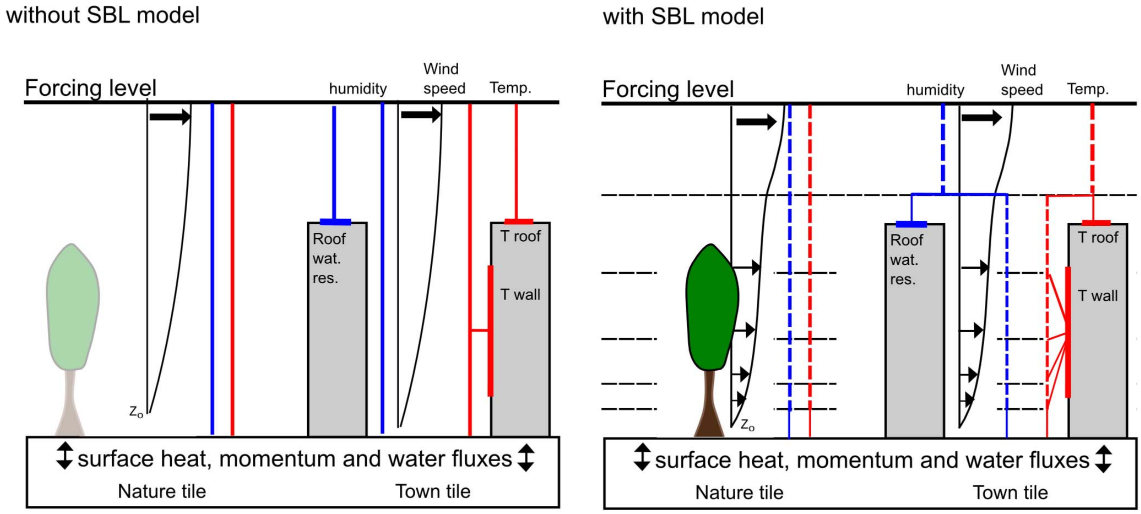

Fig. 5. Schematic view of the coupling between the surface (ISBA and TEB) and the atmosphere without the SBL model **(a)** and with the SBL model **(b)**. In the latter case, a drag force is applied in the Nature and Town tiles for the wind. The temperature profile in the SBL model is influenced by the road, wall and roof temperatures. The humidity profile is influenced by the road and roof humidities.

approaches have been widely used, even for large mountains (e.g. Wood and Mason, 1993; Georgelin et al., 1994). Recent works (Beljaars et al., 2004) have preferred to parameterize orographic drag not only at the surface but throughout a certain height above it (adding a drag force directly in the wind equations of the lowest layers of atmospheric models). Thanks to the SBL scheme included in SURFEX, the latter option can now be used in the surface scheme itself.

The friction can be computed by a roughness length or directional roughness length (mostly depending on the main subgrid-valley directions, Georgelin et al., 1994), or by using Beljaars et al.'s (2004) approach, in which case an additional SBL scheme with only wind and turbulence needs to be added. Orographic friction is caused by obstacles of a much larger horizontal scale than trees or even buildings. Therefore, these frictions are computed separately (assuming that the processes are independent of each other): the friction of natural land surface, towns, water and sea surface are averaged, and then only orographic friction is added, in the following way: $(u_*(\text{total})^2 = u_*(\text{surface})^2 + u_*(\text{orography})^2)$. This also has the advantage that low-level air temperature and humidity are consistent with the characteristics of the land cover below (including its own roughness).

6.2 Coupling with hydrology

The main function of river routing models (RRMs) is to convert runoff simulated by LSMs into river discharge. The routing of runoff estimates from LSMs is important to model river flow from large river basins and to estimate freshwater inflow into the oceans. The coupling of SURFEX with RRMs appears to be a powerful tool for understanding the regional and global water cycles (Habets et al., 1999b; Decharme and Douville, 2007; Alkama et al., 2010), predicting streamflow (Habets et al., 2004; Quintana Seguí et al., 2009; Thirel et al., 2010), and improving model parameterizations (Boone et al., 2004; Decharme et al., 2006, 2010, 2011; Decharme and Douville, 2006a).

At catchment scale, ISBA can be coupled with the hydrodynamical TOPODYN model (Pellarin et al., 2002). Up to now, this coupling has been used to simulate flash-flood events, such as those that occur over Mediterranean basins of France (Vincendon et al., 2010; Bouilloud et al., 2010). The northwestern Mediterranean area is prone to severe rainy events, especially in autumn. High cumulative amounts of precipitation fall on small to medium catchments, which are characterised by steep slopes and short hydrological response times. Mediterranean flash-floods are thus essentially driven by Dunne runoff over saturated areas. According to the TOPMODEL approach (Beven and Kirkby, 1979), the TOPODYN model is based on the lateral soil water transfer following the topographical information but also takes the spatial variability of rainfall over a given catchment into account.

The interest of the ISBA-TOPODYN coupling (Vincendon et al., 2010; Bouilloud et al., 2010) is to take advantage of the topography driven processes managed by TOPODIN at small scale to provide a subscale spatial distribution of soil moisture according to the topography (wetter soil in the flat bottoms of valleys than on the steep slopes). This leads to significant differences in the spatial distribution of the soil moisture at surface scheme scale, which then impact the estimation of the soil water fluxes. Vincendon et al. (2010) showed that ISBA-TOPODYN was efficient to simulate French Mediterranean flash-floods using hourly observed rainfall data such as radar precipitation estimates. For this application, spatial resolutions of 1 km for ISBA and 50 m for TOPODYN were used.

At the regional scale, SURFEX will soon have replaced an older version of ISBA within the Météo-France hydrometeorological system SAFRAN-ISBA-MODCOU (SIM, Habets et al., 2008) over France. In this suite, SURFEX is fed by a mesoscale meteorological analysis (SAFRAN, Quintana Seguí et al., 2008) and feeds a distributed hydrological model over France (MODCOU). Decharme and Douville (2006a) have also shown that this system is an interesting tool to evaluate new model versions such as the set of sub-grid parameterizations described in Sect. 4.1.

Finally, SURFEX is coupled with the global TRIP RRMs in order to study the continental part of the global hydrological cycle (Decharme and Douville, 2007; Alkama et al., 2010) and/or to close the hydrological budget in the CNRM-GAME climate model (Voldoire et al., 2012). The original TRIP RRM was developed by Oki and Sud (1998) at the University of Tokyo. It is used at Météo-France to convert the simulated runoff into river discharge using a global river channel network at 1° or 0.5° resolution. TRIP considers a surface river reservoir, a simple one-dimensional groundwater reservoir and a variable stream flow velocity (Decharme et al., 2010). Decharme et al. (2008, 2012) developed interactive coupling between SURFEX and TRIP to simulate seasonal flood events and to represent their impact on the continental evapotranspiration and energy budget for large-scale applications and climate modelling. The flood dynamics is described by including a prognostic flood reservoir in the daily coupling between ISBA and TRIP. This reservoir is full when the water level exceeds the bank-full limit and vice-versa. Its dimension evolves dynamically according to the flood water mass and the sub-grid topography in a given grid-cell. The reservoir interacts with surrounding soil through infiltration and with the overlying atmosphere through precipitation interception and free water surface evaporation.

7 Data assimilation

The initialization of the prognostic variables of the surface schemes is an important issue for short- and medium-range weather forecasts, particularly for quantities that evolve more slowly than atmospheric timescales (e.g. deep soil moisture and temperature, snow reservoir). Without a dedicated initialization, spurious feedbacks can take place between the atmosphere and the surface, driving the soil variables into unrealistic states (Viterbo and Courtier, 1995). The best initialization is obtained from data assimilation systems that merge observations and model short-range forecasts optimally. Monitoring of land surface fluxes can also be significantly improved when observations are assimilated in surface schemes (e.g. Reichle et al., 2007).

7.1 Optimal interpolation

A first data assimilation system based on local optimum interpolation (OI), originally proposed by Mahfouf (1991) and adapted to operational numerical weather prediction systems at Météo-France (Giard and Bazile, 2000), ECMWF (Douville et al., 2000) and CMC (Bélair et al., 2003), is available in SURFEX for the assimilation of screen-level observations from the surface network (e.g. SYNOP and METAR reports). The OI scheme allows soil moisture contents and soil temperatures to be corrected through the knowledge of short-range forecasts errors in temperature and relative humidity at 2 m. Analytical OI coefficients have been derived from Monte-Carlo single column experiments in clear-sky situations and need to be reduced when near-surface atmospheric errors are not informative about errors in the soil variables.

7.2 Extended Kalman filter (EKF)

Although still used by a number of numerical weather services, the OI scheme has a number of known weaknesses, such as its lack of flexibility regarding the observation types to be assimilated (only screen-level temperature and relative humidity) and the model variables to be initialized (only the two soil reservoirs of the ISBA version based on the force-restore method). For these reasons, a new surface assimilation scheme based on the EKF has been developed within SURFEX. This scheme compares favourably with the OI scheme for the assimilation of screen-level observations (Mahfouf et al., 2009). The “offline” version of SURFEX forced by atmospheric parameters above screen level (around 20 m in the surface boundary layer) can efficiently compute (reduced numerical cost) the Jacobian matrix of the observation operator. Also, the capability of the EKF to assimilate satellite-derived superficial soil moisture products from the radiometer AMSR-E/Aqua has been demonstrated (Draper et al., 2009). The combined assimilation of satellite-derived soil moisture and screen-level observations with the EKF was examined by Draper et al. (2011b). A simplified version of the SURFEX EKF using analytical Jacobians of the ISBA scheme has also been developed in order to examine the impact of satellite-derived soil moisture from the scatterometer ASCAT on numerical weather predictions (Mahfouf, 2010). Recently, Mahfouf and Bliznak (2011) proposed a method to efficiently combine information coming from precipitation analyses (radars or raingauges) and from screen-level measurements within the EKF.

Regarding land surface monitoring, the EKF has been used to assimilate the LAI and superficial soil moisture measurements jointly in the ISBA-Ags version, where biomass reservoirs are prognostic variables (Barbu et al., 2011), both at local scale using in situ measurements from the SMOSREX field experiment and over France as a whole using satellite-derived products (ASCAT derived soil moisture, CYCLOPES and SPOT/VGT LAI product). The use of the ISBA-Ags model has allowed the Jacobians of a new variable, the vegetation biomass, to be examined (Rüdiger et al., 2010), and also the formulation of the EKF to be extended to the availability of 12 patches in a grid box (i.e. different surface and soil prognostic variables for each patch) and one single "grid-averaged" observation. Draper et al. (2011a) showed that the assimilation of the satellite-derived ASCAT soil moisture improve runoff and river discharge simulations when assimilated in the hydrometeorological model SIM (Habets et al., 2008) using the SURFEX EKF data assimilation system. It must be noted that some products such as LAI and soil moisture are biased and require a pre-processing, as SURFEX assumes that observations are unbiased. For the present applications, the biases are corrected using a "CDF (cumulative distribution function) matching technique" (Reichle and Koster, 2004).

Finally, studies are currently under way to improve the specification of the covariance matrix of background errors in the EKF through a better description of model errors. Using a model error term derived from an ensemble of short-range forecasts of precipitation, which is cycled through the filter, generates realistic spatial variability patterns in the background errors.

8 Model applications and evaluations

Most pre-existing scientific models (e.g. ISBA and TEB) were used and validated in various configurations before the building of SURFEX, both in offline mode and coupled with the atmosphere. As an example, ISBA (Noilhan and Planton, 1989) has been regularly improved over more than 20 yr. The scientific work of improvement and validation of the physics continued during the transition from the pre-existing codes to SURFEX while, from a technical point of view, the progressive replacement of the surface components implied significant technical work. In most cases, the introduction of SURFEX into the applications (in particular atmospheric models) allowed an improvement of the surface parameterization and scores, drawing benefit from the use of an up to date externalized surface scheme.

It is beyond the scope of this paper to provide a comprehensive review of all the validations of the sub-models included in SURFEX. In the first sub-section, the applications and validations in offline mode (either local or distributed) will be reviewed rapidly. Then, the impact of the introduction of SURFEX in atmospheric models will be shown.

8.1 Applications in offline mode

8.1.1 ISBA

The original version of ISBA (Noilhan and Planton, 1989) and further improved versions have been extensively validated against measurements at the local scale and participated in many intercomparison projects that have stimulated improvements in the model:

- PILPS (Henderson-Sellers et al., 1993): ISBA application to the Cabaw (Chen et al., 1997), and Arkansas River (Wood et al., 1998; Liang et al., 1998; Lohmann et al., 1998) datasets, leading to improved subgrid hydrology. The simulation of a Scandinavian basin (Habets et al., 2003) was the first application of the multilayer soil option of ISBA for hydrology and validated the cold processes in the soil. Valdaï (Slater et al., 2001 and Luo et al., 2003) was the occasion to further validate the snow and cold processes in the soil.

- GSWP (Dirmeyer et al., 1999, 2006): validation and intercomparison of hydrological parameterization at the global scale, including uncertainties associated with the forcing data (Decharme and Douville, 2006b).

- Rhone-Aggreg (Boone et al., 2004): testbed for scale changes, subgrid hydrology and the use of the multilayer snow model (ISBA-ES).

- SnowMIP (Etchevers et al., 2003; Rutter et al., 2009): importance of the representation of albedo in snowpack models, simulation of the liquid water content in the snow for an accurate prediction of snowmelt, importance of the interaction between snow and vegetation for an accurate simulation of the snow cover in forests.

More recently, SURFEX has been applied in Africa within ALMIP (AMMA Land Surface Models Intercomparison Project; Boone et al., 2009), a validation of the surface energy budget over France using different sources for the incoming solar radiation, including METEOSAT satellite estimates, has been undertaken by Carrer et al. (2012) and the multilayer soil scheme (Boone et al., 2000) has been extensively validated by Decharme et al. (2011) at the SMOSREX (Surface Monitoring Of Soil Reservoir Experiment) site in the south west of France.

The representation of cryospheric processes in the soil has been validated by Boone (2000) on a well-instrumented site in Ilinois (USA), by Bazile (1999) in the context of numerical weather prediction, and by Habets et al. (2003) over a Scandinavian basin. Concerning snow processes, the focus in recent months has been on the validation of Crocus, with a new SURFEX version completely rewritten and coupled with ISBA (Vionnet et al., 2012). Crocus has been evaluated at the point scale at the Col de Porte site (1325 m a.s.l., French Alps) using in situ driving and evaluation data spanning a time period of 18 yr (Vionnet et al., 2012), at distributed scale using ERA-Interim (Dee et al., 2011) meteorological forcing and ground-surface snow depth, snow water equivalent and ground temperature evaluation data (Brun et al., 2013), and under Antarctic conditions at Dome C in both offline and online mode (Brun et al., 2011).

Considerable efforts have gone into the validation of the advanced parameterization of vegetation processes, including carbon variables. Gibelin et al. (2006) have shown that ISBA-A-gs simulates realistic LAI values at the global scale under various environmental conditions. Noilhan et al. (2011) have shown the added value of both the tiling and A-gs approaches on the quality of regional atmospheric simulations. Brut et al. (2009) and Lafont et al. (2012) have shown that, over France, ISBA-A-gs efficiently captures the LAI interannual variability as observed from space by satellite sensors. Also, this capability applies to the above-ground biomass of cereals and grasslands and can be verified using agricultural statistics (Calvet et al., 2012). On the other hand, the seasonal variability of the simulated LAI may present shortcomings (Brut et al., 2009; Lafont et al., 2012). In particular, a delay in the leaf onset is observed. No specific phenology model is used by ISBA-A-gs as vegetation growth and senescence are entirely driven by photosynthesis. In consequence, the simulated LAI is sensitive to imperfections in the model parameterization and in the atmospheric forcing used to drive the simulation. The simulated LAI is flexible and prescribing cuts at given dates (Calvet and Soussana, 2001) or when LAI has reached a predefined threshold (Calvet et al., 2012) is not difficult. This property can be used to assimilate LAI observations into the model (Sabater et al., 2008; Albergel et al., 2010b; Rüdiger et al., 2010; Barbu et al., 2011). Also, provided that the impact of the nitrogen limitation on SLA is accounted for (Calvet et al., 2008), the interactive vegetation simulations of ISBA-A-gs can be used to represent the uncertainties on the plant response to decadal-to-centennial changes in the atmospheric CO_2 concentration (Queguiner et al., 2011).

The coupled ISBA–TRIP model including a flood scheme has been validated at the global (Decharme et al., 2008; Decharme et al., 2012) and regional scales (Pedinotti et al., 2012). This system simulated a reasonable distribution of the global floodplains compared to satellite-derived estimates. In addition, the river discharges have generally been well reproduced using this flood scheme over many basins of the world (Fig. 6). The efficiency scores of the version with a flood scheme are increased (increase higher than 0.05) over 50 % of the 122 gauging stations and only reduced (decrease lower −0.05) for 5 stations. Considering only stations with a positive efficiencies (68 for the new scheme against 61 for the control run), the mean score is 0.57 for the new scheme against 0.54 for the control run. The mean RMSE over all station is also reduced from 0.64 to 0.56 mm day^{-1}. Two mechanisms mainly explain this positive impact: an increase in evapotranspiration, which limits the annual discharge overestimation found when flooding is not taken into account, and a smoothed river peak flow when the floodplain storage is significant.

8.1.2 TEB

TEB has been intensively validated against in situ measurements, for various types of cities and urbanization, under various climates: from wintertime Montreal (Lemonsu et al., 2010; Leroyer et al., 2010) to Ouagadougou in the African Sahel (Offerle et al., 2005a). The other sites where TEB has been validated are old city centres, Marseilles, Toulouse, Basel, Lodz, Mexico City (Masson et al., 2002, 2008; Lemonsu et al., 2004; Offerle et al., 2005b; Pigeon et al., 2008; Hamdi and Masson, 2008), light-industry sites (Masson et al., 2002), and suburban areas of Oklahoma city (Lemonsu et al., 2009), Melbourne and Nantes (Grimmond et al., 2010, 2011; Lemonsu et al., 2007).

8.2 Applications in coupled mode with an atmospheric model

In recent years, SURFEX has been progressively implemented and validated in various atmospheric models used either for process studies or for operational numerical weather prediction and climate runs. The new convective-scale model AROME (Seity et al., 2011; Brousseau et al., 2011), with a 2.5 km grid, has used SURFEX since the beginning, in 2008. SURFEX was introduced into the ALADIN model (7.5 km grid) in September 2010 (French Antilles/Guyana, French Polynesia and New Caledonia). Réunion Island has been using SURFEX since 2011. At this date, an optimal interpolation (OI) assimilation for soil moisture was implemented in all the numerical suites. SURFEX has also been introduced into version 5 of the general circulation model CNRM-CM5 (Voldoire et al., 2012). An interactive model of desert dust emission within ALADIN has been tested (Mokhtari et al., 2012). This sub-section presents a selection of applications and validations of SURFEX in coupled mode.

8.2.1 Evaluation of SURFEX within the ALADIN/France meteorological model

In ALADIN, a maximum of three tiles (sea, nature and lakes) are activated. The town tile is currently not activated in this configuration owing to some numerical instabilities which occured when TEB used without wind implicitation was coupled to the atmosphere using long time steps. For now, town surfaces are simply replaced by the rock class within the nature tile. A three-layer force-restore version of ISBA is used (instead of the former two-layer version) with a one-layer snow scheme. The ECUME parameterization of sea surface fluxes is used over seas. Over continents, the prognostic SBL is used. Physiographic data have also been improved (GTOPO30, ECOCLIMAP1, and FAO maps for soil texture).

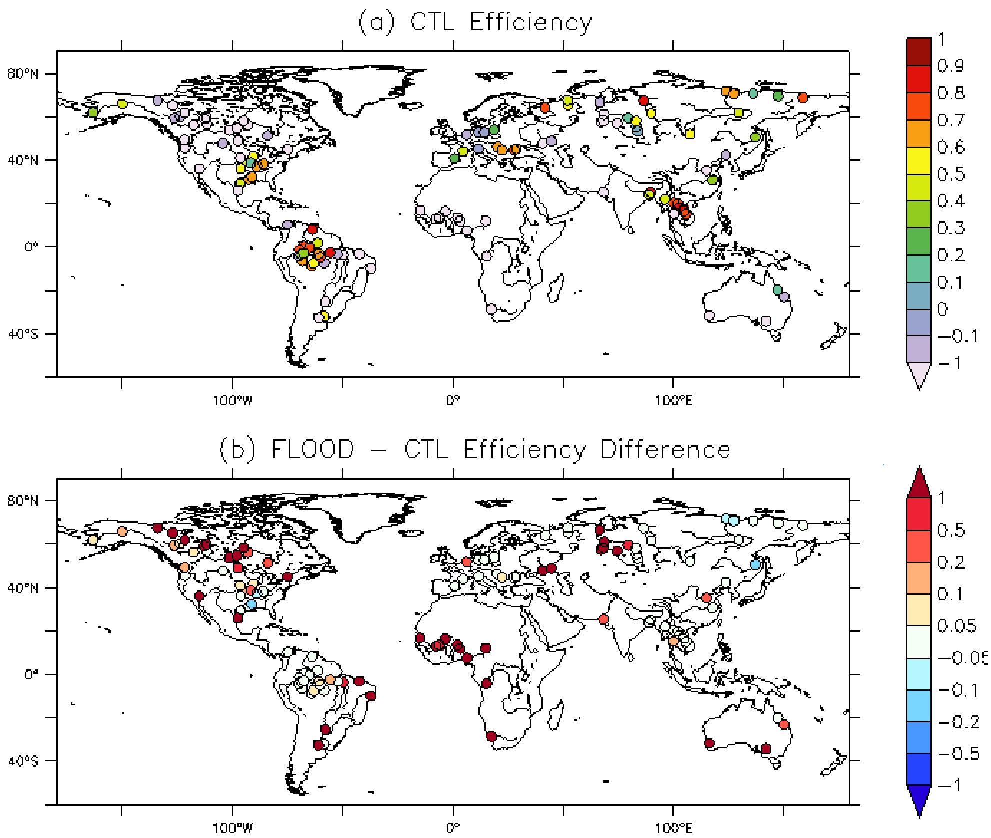

Fig. 6. Validation of the ISBA/TRIP simulation with in situ discharge measurements using the 1986–2006 period. **(a)** Efficiency of the original simulation (without flood parameterization). **(b)** Variation of the efficiency when the flood coupling between ISBA and TRIP is activated.

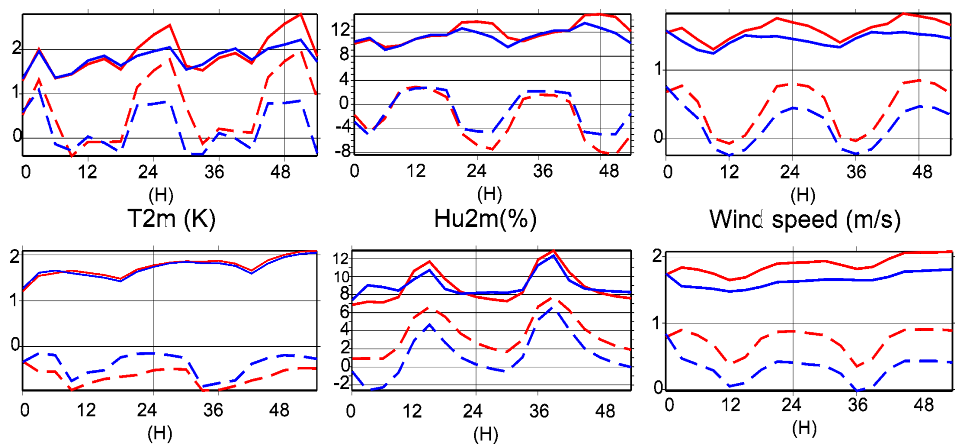

Fig. 7. Evaluation of SURFEX within the ALADIN/France configuration for a summer period (June–September 2010) (top) and a winter period (December 2010–March 2011) (bottom). Biases (dashed lines) and rms (continuous lines) as a function of the forecast lead time are presented for the ALADIN without SURFEX (in red) and with SURFEX (in blue). Left: 2 m temperature (K), centre: 2 m humidity (%), right: 10 m wind speed (m s^{-1}).

Extensive tests contributing to the definition of the operational version described above were conducted to assess ALADIN's performance with and without SURFEX. The forecasts were compared to screen-level observations. The introduction of SURFEX was neutral on surface pressure, precipitation, total cloudiness and 10 m wind direction (not shown) but improved the scores for 2 m temperature, humidity and wind speed (Fig. 7).

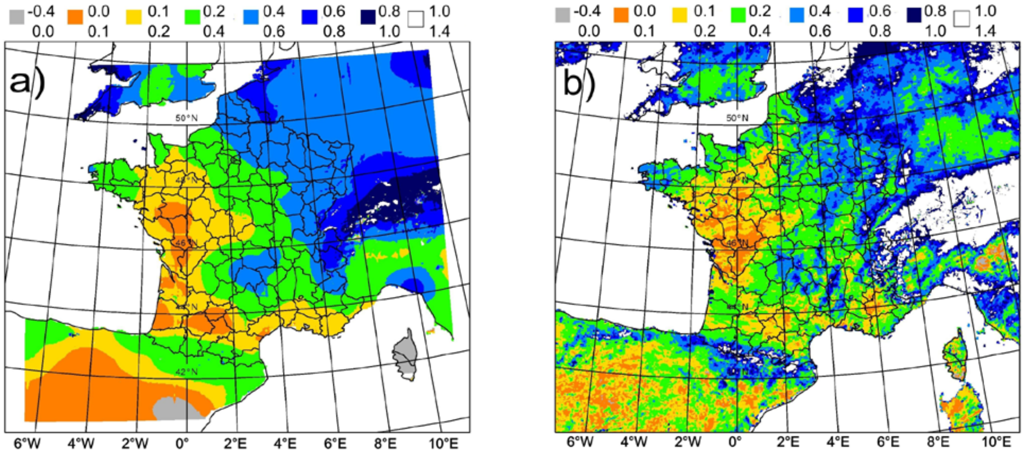

Fig. 8. Soil wetness index (negative values are associated with very dry soils; values larger than one indicate moist soils evaporating at maximum rate) on 1 October 2010. **(a)** Operational AROME suite (soil moisture field interpolated from the one produced for the global-scale model ARPEGE). **(b)** Experimental AROME suite (having its own surface analysis system).

8.2.2 Impact of the introduction of a fine scale soil moisture assimilation into AROME

The assimilation of screen-level temperature and humidity described in Sect. 7.1 was implemented in the AROME model in November 2010. This model has a dedicated atmospheric data assimilation system providing optimal corrections every 3 h to short-range forecasts using specific mesoscale observations such as radar data. These corrections lead to an improved state of the atmosphere (analysis) from which new forecasts can be established. The quality of fine scale forecasts also depends upon the land surface state (soil temperatures and moisture contents) since this strongly influences water and energy exchanges with the atmosphere. Figure 8 shows the soil wetness index produced on 1 October 2010 by the operational AROME suite (interpolation from the ARPEGE model) and by the experimental AROME suite (having its own surface analysis). Most dry and wet regions in the domain are similar between the two maps. However, the interest of correcting AROME forecasts is clear in the better resolution of small scale features, particularly over mountainous regions: the dryer soil of the Alsace plain (in the northeast of France) is clearly differentiated from the wetter mountain ranges in the vicinity (Vosges and Black Forest). The introduction of a SURFEX analysis coherent with the SURFEX configuration of the land surface scheme of the model systematically improved the surface variables, in particular precipitation. Figure 9 shows that the assimilation reduced the frequency bias of the model and improved the Heidke Skill score for almost all precipitation classes over a three-week test period.

8.2.3 Validation of SURFEX within the global climate model CNRM-CM

SURFEX was introduced in the general circulation model CNRM-CM5.1, developed jointly by CNRM-GAME and CERFACS (Centre Européen de Recherche et de Formation avancée en Calcul Scientifique) for the phase 5 of CMIP. The main improvements since the previous version (CNRM-CM3) are the following: increase in resolution, revised dynamical core, new radiation scheme with improved treatment of aerosols, new ocean model, and introduction of SURFEX. These developments generally led to a more realistic representation of the mean recent climate and to a reduction of climate drifts. The changes in the model and basic evaluations are described in detail by Voldoire et al. (2012). Between the two model versions, the surface physics has only evolved slightly but the introduction of SURFEX will allow state-of-the-art surface parameterizations to be activated in future versions. In CNRM-CM5.1, the main improvements resulting from the SURFEX implementation were the use of the ECUME parameterization for air–sea fluxes, the soil freezing parameterization (Boone et al., 2000) and tuning of the snow scheme. Figure 10 shows the performance of CNRM-CM3 and CNRM-CM5 in simulating the sea surface temperature (resp. near-surface temperature) over oceans (resp. continents), compared to the HadiSST database (resp. CRU2.1 database). The mean bias and the rms error are significantly reduced in CNRM-CM5.1 when compared to CNRM-CM3. The main improvement over continents is the reduction of strong warm biases over high latitudes in winter, attributed to the freezing parameterization. The ECUME parameterization is also shown to greatly improve wind intensities in the mid-latitude storm tracks of the southern hemisphere and therefore the sea surface pressure around the Antarctic. On

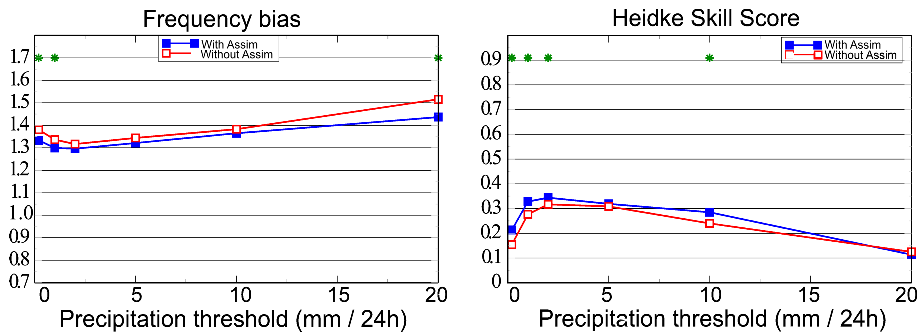

Fig. 9. Twenty-four hour accumulated precipitation forecast scores (Bias and Heidke Skill score) obtained with (blue curves) and without (red curves) soil analysis by the AROME model over a three week period (21 April 2010–15 May 2011). A green star indicates that the score difference is significant with a 90 % confidence level.

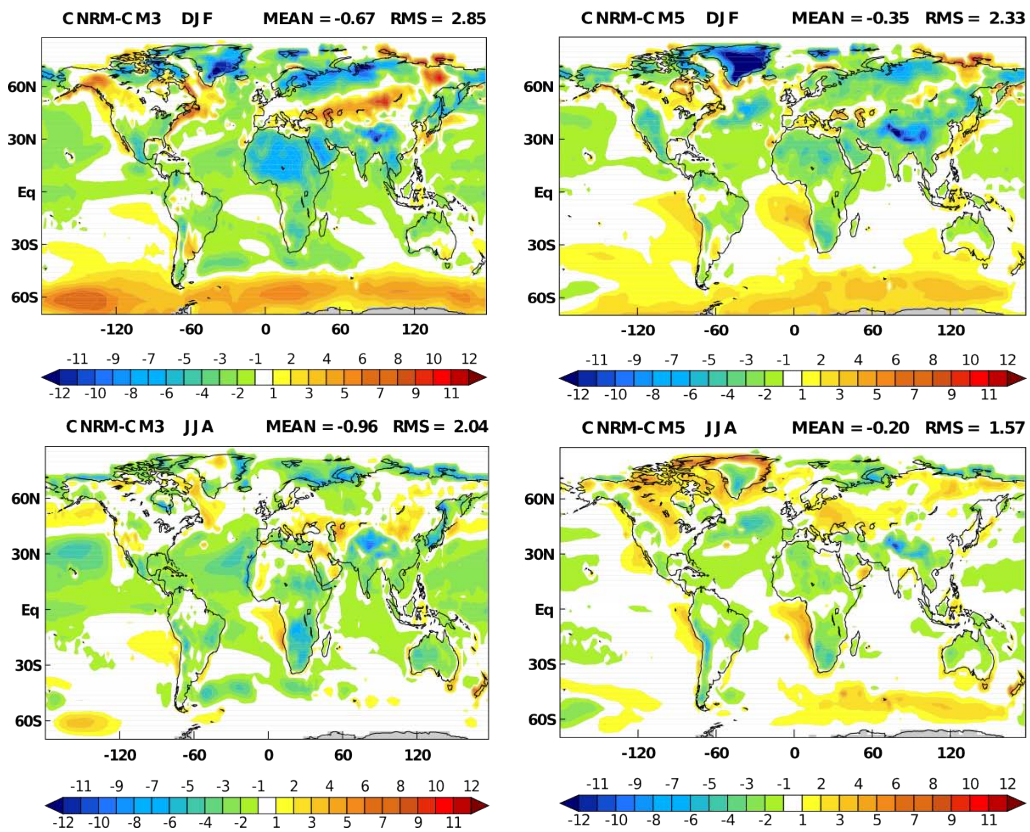

Fig. 10. Near-surface temperature over continents and sea surface temperature over oceans (K) averaged over 1970–1999: (left) CNRM-CM3 simulations minus 1970–1999 CRU2.1 over continents and CNRM-CM3 simulations minus 1970–1999 HadiSST over oceans, (top) winter, (bottom) summer, and (right) same for the CNRM-CM5.1 runs. The CNRM-CM5 runs are averaged over an ensemble of 10 members.

the other hand, a positive bias appears in summer over Eastern Europe and most of North America. This warm bias results from positive feedback triggered by a deficit in cloud cover that favours spring evaporation and thus leads to excessive summer drying that further reduces the cloud cover.

8.2.4 Interactive modelling of desert dust emission

The last example of the use of SURFEX illustrates the interest of the online coupling between surface models and regional models for the simulation of desert dust emissions. Figure 11 shows the mean annual emissions of desert dust calculated by the ALADIN model coupled to SURFEX to simulate desert dust emissions and deposition (Mokhtari et

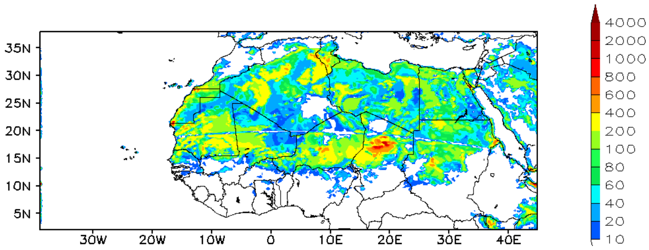

Fig. 11. Annual mean of the aerosol dust emission (in $\mathrm{g\,m^{-2}}$) over West Africa, simulated by ALADIN-SURFEX between 2006 and 2011.

al., 2012). In this case, the contribution of this type of modelling is that all processes of desert dust emission are taken into account (convective turbulence, storms). This is a breakthrough compared to previous studies carried out with climate models that did not have the capacity to represent all the atmospheric processes, particularly those at small-scale or those provided by satellite observations, which were limited by their return time and by the horizontal or intrinsic resolution of their sensors.

9 Conclusions

The primary purpose of this paper was to provide a detailed description of the scientific and technical aspects of the externalized surface platform SURFEX. The building of SURFEX, its validation and the coupling to the atmospheric model and existing databases was a broad community effort and constitutes a significant advance relative to the pre-existing individual models such as ISBA or TEB and the surface components of the atmospheric models.

One originality of SURFEX is that it covers all surface types (natural surfaces, town, inland water and oceans) and can be directly coupled to an atmospheric model. The number of tiles (and patches for nature) is flexible. Currently, the number of patches for a nature tile can vary from 1 to 12, and some tiles can be transformed (e.g. inland water to nature, or town to rocks) allowing a high degree of flexibility for specific applications. SURFEX includes some specific features for the coupling with atmospheric models: a parameterization of the subgrid-scale orographic friction, a simple one-dimensional surface boundary layer model and the availability of implicit coupling with the atmosphere, which is necessary for long time steps (for numerical weather prediction or climate applications). SURFEX is able to adapt to a large range of grid sizes, from hundreds of kilometres, when coupled to a global climate model, to several metres in the case of large eddy simulations. SURFEX is also used for hydrological applications at scales from global to several tens of km.

Another originality of the SURFEX individual models is probably the large number of options in ISBA that allow various degrees of sophistication in almost all compartments: soil, vegetation and carbon variables, hydrology and snow. ISBA is able to describe vertical heterogeneities in the soil and to account for different soil depths according to the vegetation type. The latter point is important for hydrological simulations and agricultural applications (e.g. Calvet et al., 2012). Since the recent introduction of Crocus (Vionnet et al., 2012), SURFEX covers the whole range of the snow model complexity, from the single layer bulk model to a multilayer model describing snow metamorphism. The TEB model was the first model to use the canyon approach to simulate fluxes with the atmosphere. It also simulates wet processes (surface water, snow cover, water exchanges in gardens). Besides classical applications in NWP, it can be used to estimate the energy consumption in relation with meteorological conditions. Its capacity to simulate the micro climate in the street, human comfort, hydrology, and vegetation processes in the street allows it to be used for urban planning. In addition, SURFEX coupling with ocean models, associated with an improvement of the air–sea surface flux representation (Lebeaupin Brossier et al., 2008, 2009), is also a significant benefit for medium- to long-term simulations.

Finally, SURFEX has an assimilation system fully compatible with the physics of the model. The assimilation system is presently used for operational numerical weather forecasting and for land-surface monitoring (Barbu et al., 2011).

10 Perspectives

The development and validation work will be actively pursued in the coming years in order to increase the domain of use for SURFEX and its realism. At present, there are some technical limitations for large grids (e.g. global grids for NWP) that must be solved. This implies an optimization and parallelization of the code, in particular the preparation of physiographic and initial fields. Other improvements are needed from a scientific point of view. For instance, the present version of ISBA, does not account for interactions between low vegetation or snowpack and the surrounding high vegetation, which impairs the quality of the model for the simulation of near-surface variables and the interpretation of satellite data. The lumped energy budget of ISBA lead to discrepancies in the SnowMIP2 runs in forest (Rutter et al., 2009). The surface energy budget will be improved to consider separate energy budgets for soil, snow and vegetation (above or partially covered by snow). The use of a separate budget for soil and vegetation will introduce a vegetation temperature that will allow a more accurate estimation of photosynthesis, vegetation growth and a better interpretation of satellite data in the infrared band. Through the interaction of the multiple energy budget with all the other parameterizations of ISBA, the strategy will be to build and validate a configuration that includes the most advanced parameterizations (multiple energy budget, explicit simulation of photosynthesis, multilayer soil and multilayer snow model, permafrost) that will be used as a reference to design simplified configurations for the various uses of SURFEX. In the future, ISBA will be completed by coupling with a Dynamic Global Vegetation Model. The dynamic vegetation applications will focus on simulating shifts in potential vegetation and its associated biogeochemical and hydrological cycles in response to shifts in climate while the hydrological applications will focus on the interaction between the surface and the groundwater. An interactive coupling between SURFEX and a regional (Habets et al., 2008) or global (Vergnes and Decharme, 2012; Vergnes et al., 2012) aquifer model will be developed.

TEB will be completed for energy consumption (Bueno et al., 2012), renewable energy production and vegetation (vegetated roofs) processes, allowing more detailed studies of the urban environment, including adaptation studies (Masson et al., 2013). The reference configuration of SURFEX for oceans will consist of parameterizations that account for the ocean surface state (waves and sprays) in the calculation of surface turbulent fluxes. This configuration will be extensively tested so as to define simplified versions suited to the various domains of application.

The development of the assimilation will focus on albedo, FaPAR (Fraction of Absorbed Photosynthetically Active Radiation) and land surface temperature, in order to progressively build a land data assimilation system.

SURFEX has been designed with a modular structure, which means that new elements of the sciences concerned can be easily introduced as new models or options. A steering committee has recently been set up to coordinate the scientific and technical evolution of the code to ensure that SURFEX will remain a state-of-the-art model in both aspects. For further details, including how to obtain a copy of the code, see http://www.cnrm.meteo.fr/surfex/.

Supplementary material related to this article is available online at: http://www.geosci-model-dev.net/6/929/2013/gmd-6-929-2013-supplement.pdf.

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