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Laboratory:UPMC-SISYPHE
Supervisor: Agnes Ducharne

"What can we say about hydrological modelling uncertainties from the comparison of two models in the Durance watershed?"

Katerina STAMATI

Defense at UPMC on 15th July 2013
4 Place Jussieu, Paris

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1. Introduction

The proper estimation of the current water resources in the Durance watershed and their future evolution is of great significance as the river satisfies a variety of uses for many people living in the area. The natural complexity of the area and the big elevation differences create problems in terms of hydrological modeling, resulting in many uncertainties. It is very important to obtain a good representation of the hydrological processes in the Durance River watershed, especially in the context of climate change, as changes in the climate may lead to a severe decline in water resources, which in turn can lead to potential conflicts of water or land use. For these reasons, the implementation of Land Surface Models (LSMs) in the Durance watershed in order to estimate the different fluxes between the atmosphere and the surface is more than necessary.

LSMs are using as inputs near-surface meteorology forcings, in order to simulate the diurnal cycle of energy and water fluxes between the atmosphere and the land surface. In the last decades, the significance of a realistic representation of the land surface processes in General Circulation Models (GCMs) has been recognized by the scientific community. The correct representation of these processes is important for the simulated climate and the hydrological cycle. In the early 1980s, Mintz (1984) used sensitivity studies in GCMs, in order to show that the transfers between the atmosphere and the land surface are influenced by land surface processes. In the same period, models that calculate the different subfluxes of evaporation like interception loss and transpiration were developed (Deardorff, 1978, Sellers et al., 1986), in order to be used in GCMs. These models, commonly referred to as the Surface Vegetation Atmosphere Transfer (SVATs) schemes, give vegetation a more direct role in determining the water balance and surface energy. Later improvements include a focus on hydrological processes. For instance, methods based on Richards equation (Richards, 1931) were implemented to describe the vertical transfer of water within the soil (Abramopoulos et al., 1986, de Rosnay et al., 2002) and more complex parameterizations of soil moisture were introduced. A last step forward in the evolution of LSMs was the implementation of an improved treatment of the subgrid horizontal structure of hydrological processes, by taking into account the subgrid soil moisture variability and its effects on runoff and evaporation (Ducharne et al., 2000, Koster et al., 2000).

In this study, a Land Surface Model (LSM) called ORCHIDEE (Organizing Carbon and Hydrology in Dynamic EcosystEms) is applied in the Durance watershed, in order to estimate the energy and water fluxes between the land surface and the atmosphere. ORCHIDEE (Krinner et al., 2005) is a SVAT scheme, which is coupled to a biochemistry model and a dynamic vegetation model. ORCHIDEE can be coupled to an atmospheric general circulation model, but in this report the off-line mode has been used, where the model is forced by atmospheric forcing data. The simulations of a second LSM called Catchment Land Surface Model (CLSM) (Ducharne et al., 2000, Koster et al., 2000) in the same area are used in order to let us compare the results ORCHIDEE and CLSM give for the different fluxes, trying to estimate the similarities and differences and highlight the uncertainties between these two models in terms of hydrological modelling. All the CLSM simulations presented in this report were run by Claire Magand as a part for her Phd thesis (not submitted yet).

A first aim of this project is the correct implementation of ORCHIDEE in the Durance watershed, in order to obtain an estimation of the magnitude of the different fluxes between the atmosphere and the land surface. Special attention is given to water budget, snow processes and the partition of evaporation in subfluxes. After the implementation of the model, a very important thing that has to be done is its validation. This has been performed by comparing runoff simulations for both ORCHIDEE and CLSM against observed daily discharges that were provided by Electricite de France (EDF). As mentioned before, the main objective of this thesis is the comparison of the results of ORCHIDEE with the results of CLSM. In particular, the differences between the 2 models will be used to explore the uncertainties related to hydrological modelling. The comparison between the two models is performed not only for present time results but also for the results of climate change simulations. This helps us estimate the trend of the different fluxes, explain their main differences between the present and the future and observe the similarities and differences in their response in climate change.

This report is composed of 6 sections. In section 2, the ORCHIDEE LSM is described, with special focus on the hydrological processes and the snow dynamics. CLSM is described briefly in section 3, paying attention in the main differences between CLSM and ORCHIDEE. In chapter 4, some general information about the Durance watershed and the way in which it was spatially discretized for hydrological modelling are described. The different datasets that were used and the application to the Durance watershed are then presented in chapter 5. The results follow in section 6, including plots that present the comparison of ORCHIDEE and CLSM runoff results with the observed ones, comparison plots between ORCHIDEE and CLSM for present time and plots showing the evolution of fluxes in the future for both ORCHIDEE and CLSM. The main conclusions and some future perspectives are finally presented in chapter 7.

2. The land surface model ORCHIDEE

2.1. General concepts

ORCHIDEE is the land surface model of the IPSL (Institut Pierre-Simon Laplace) Atmosphere-Ocean General Circulation Model. It consists of three different models:

a) SECHIBA (Ducoudre et al., 1993, de Rosnay and Polcher, 1998) is a SVAT that has been developed for the LMD (Laboratoire de Meteorologique Dynamique, Paris) general circulation model. It describes the water and energy exchanges between the biosphere and the atmosphere within rectangular grid cells.
b) STOMATE (Saclay Toulouse Orsay Model for the Analysis of Terrestrial Ecosystems) is the module that describes photosynthesis, phenology and carbon dynamics.
c) LPJ (Sitch et al., 2003) is a dynamic global vegetation model (DVGM) that describes vegetation dynamics (fire, tree mortality, light competition).

Depending on the problem one wants to solve, ORCHIDEE can be run in different configurations. In our case, STOMATE and LPJ were deactivated and the distribution of vegetation was prescribed, as described in Verant et al. (2004).

In ORCHIDEE the distribution of vegetation is based on the approach of plant functional types (PFTs), which categorizes species with common or similar characteristics into the same functional type. 13 PFTs are used in the model, 11 of which are natural and 2 are agriculture (Table 1). In the end, the vegetation distribution in each grid cell is described using a mosaic approach, which means that different PFTs are allowed to coexist in each grid cell. As mentioned before, the module LPJ is deactivated in this study, so the fraction of PFTs in each grid element has to be prescribed by the user, before the beginning of each simulation.

PFT ID	Short name	Long name	natural/agricul
PFT1		bare ground	Natural
PFT2	TrBE	tropical broad-leaved evergreen	Natural
PFT3	TrBR	tropical broad-leaved raingreen	Natural
PFT4	TeNE	temperate needleleaf evergreen	Natural
PFT5	TeBE	temperate broad-leaved evergreen	Natural
PFT6	TeBS	temperate broad-leaved	Natural
PFT7	BoNE	boreal needleleaf evergreen	Natural
PFT8	BoBS	boreal broad-leaved	Natural
PFT9	BoNS	boreal needleleaf summergreen	Natural
PFT10	NC3	C3 grass	Natural
PFT11	NC4	C4 grass	Natural
PFT12	AC3	C3 agriculture	Agriculture
PFT13	AC4	C4 agriculture	Agriculture

Table 1. The 13 plant functional types (PFTs) used by ORCHIDEE

2.2. Hydrological processes

In ORCHIDEE, the user is able to choose between two different hydrology modules. The first one is a simple bucket-type model, which describes the soil using two soil layers (Ducoudre et al., 1993), following the Choisnel scheme. In this study, we used the second hydrology module (de Rosnay et al., 2002) which is derived from the hydrological model of the CWRR (Bruen 1997, Dooge et al., 1993). The Richards equation and a mass balance equation are used to describe the vertical soil water flow:

$$q = -D\frac{\partial\theta}{\partial z} + k \quad \textbf{(2.1)}$$

$$\frac{\partial\theta}{\partial t} = -\frac{\partial q}{\partial z} - S \quad \textbf{(2.2)}$$

where θ is the volumetric soil moisture content, q is the flux density, D is the soil water diffusivity, k is the hydraulic conductivity, S is a sink term representing the extraction of water by plant roots, z is the vertical coordinate and t is the time.

Equations (2.1) and (2.2) were solved using an implicit finite difference scheme. Finally, as detailed in de Rosnay et al. (2000) a vertical discretization of 11 layers was chosen in a 2m soil depth. After several tests, these writers chose this discretization as a good combination of precision and computational time. The layers are thinner near the surface, where big variations in soil moisture can be observed and become coarser as depth increases (Figure 1). In the bottom the boundary condition is chosen to be free drainage.

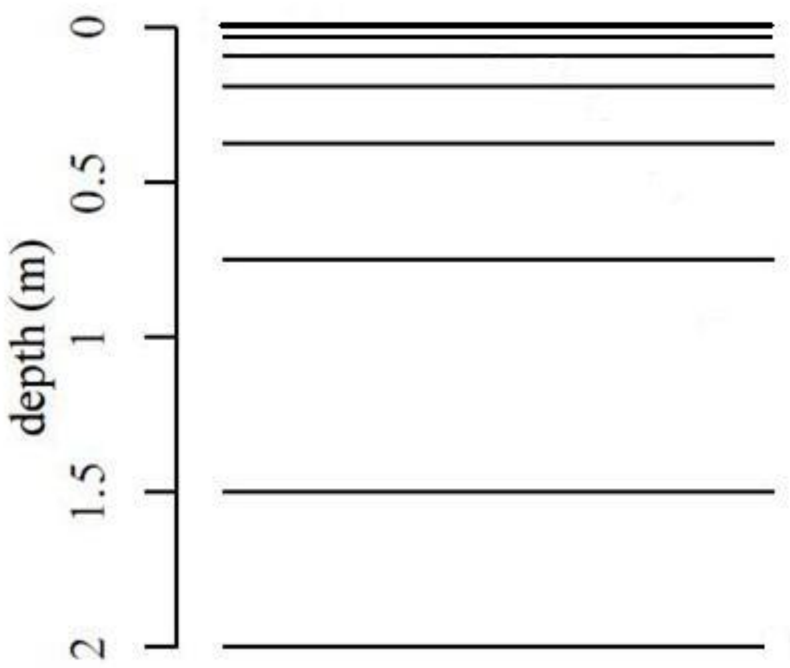

Figure 1. The 11-layer soil vertical discretization [de Rosnay et al., 2000]

As mentioned before, in ORCHIDEE a subgrid scale variability of vegetation is used. Fluxes are calculated independently for each subgrid and then averaged values are computed for each grid box. A similar approach is also used with soil texture. Zobler maps (Zobler 1986) are used in order to describe the soil texture at a scale of 1^{o} by 1^{o}. According to Zobler three main types of soils are taken into account: coarse, medium and fine textured. In the end, only the dominant texture for each grid cell is used by the model.

As far as evaporation is concerned, it is computed as a fraction of potential evaporation, limited by the resistances. The potential evaporation is given by:

$$E_{pot} = \frac{\rho}{r_a}(q_{sat}(T_s) - q_{air}) \quad \textbf{(2.3)}$$

where qsat(Ts) is the saturation humidity which corresponds to a particular surface temperature, qair is the specific humidity in the atmosphere just above the surface and r_a is the aerodynamic resistance.

For describing transpiration a root density profile (de Rosnay and Polcher, 1998) and a moisture profile in the soil are used together. For a given vegetation type, the total soil column transpiration is given by:

$$\mathrm{Transp} = (1 - \frac{I}{I_{max}})U_s\rho\frac{q_{sat}(T_s) - q_{air}}{r_a + r_0 + r_c} \quad \textbf{(2.4)}$$

where ρ is the air density, I is the amount of water intercepted by the foliage, $1 - \frac{I}{I_{max}}$ is the fraction of the foliage that is not covered by intercepted water, r_c is the canopy resistance, r_0 is the architectural resistance and Us is the water uptake function which represents the root-soil moisture interactions.

From the other three subfluxes of evaporation namely bare soil evaporation, interception loss and sublimation, only the bare soil evaporation is limited by the availability of soil moisture in the top layer.

In Orchidee three independent soil columns with separate water budgets are considered, as the 13 PFTs mentioned before are categorized into three groups (bare soil, grass, trees).

2.3. Snow processes

During winter, snow covers an important percentage of the land surface in the examined area, especially in the Upper Durance and in the northern catchments of the Mid Durance. Due to its physical properties such as high albedo and low thermal conductivity and its seasonal variability, snow gives a strong positive feedback on climate (Femandes et al., 2009, Flanner et al., 2010). It also plays an important role as a storage component in the hydrological cycle. For all these reasons, it is important to understand the ways in which snow processes are described in ORCHIDEE.

The snow model used in SECHIBA is quite simple (Figure 2). It includes a single snow layer, where internal processes such as liquid water refreezing are not taken into account. The snow density is constant and is equal to 330kg/m^3. The energy budget equation is used in order to calculate the snow surface temperature. The temperature in the first soil layer is considered equal to the snow temperature, as a mixed soil-snow structure is assumed. Melting occurs when the computed surface temperature is larger than the freezing point (273.15K). In particular, whenever the surface temperature is bigger than the freezing point it is reset automatically to 0^o and the excess of energy is the factor that creates snowmelt. This conversion of energy is given by the following equation:

$$snowmelt = \min\left[\frac{(T_{soilnew} - T_{freezing})soil\ cap}{Lat_{fus}}, snow\right] \quad \textbf{(2.5)}$$

where soilcap is the soil heat capacity, Lat_fus is the latent heat of fusion. $T_{soilnew}$ is the computed surface temperature.

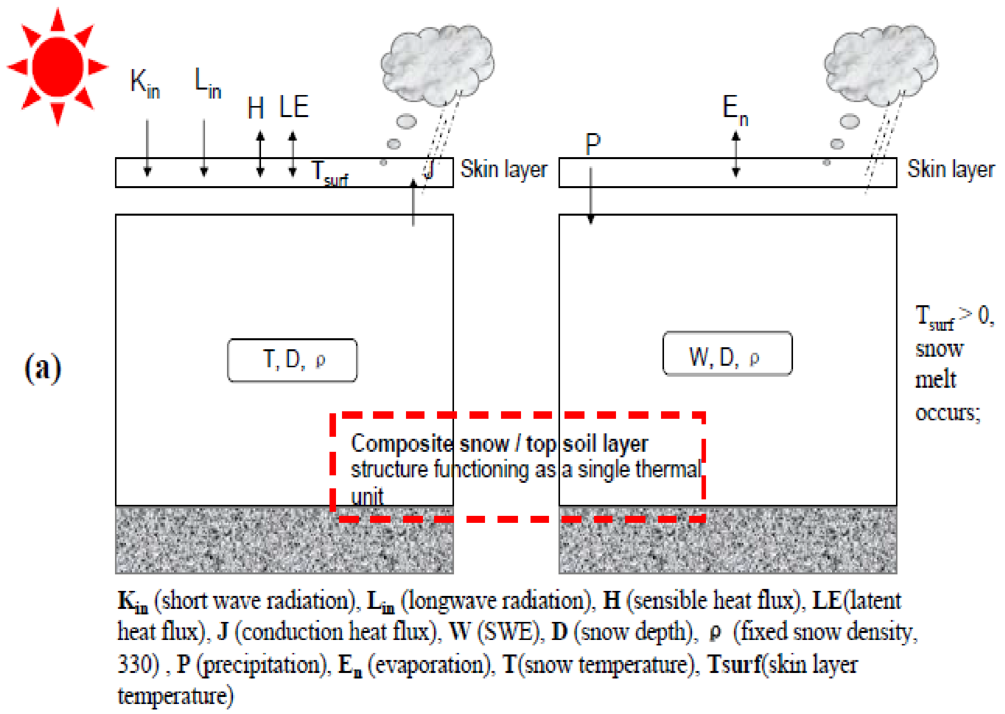

Figure 2. The one layer snow scheme used by SECHIBA. Left: energy budget, right: water budget [Wang, 2011)

As far as the snow albedo is concerned, a prognostic procedure is followed in order to calculate it. This means that the value of snow albedo at the timestep t+1 depends on the value of the snow albedo at the timestep t. In the initial state, the values of snow albedo over the bare soil fraction and each PFT are prescribed. Then, as described in Chalita and Le Treut (1994), the value of snow albedo changes, depending on the changes of snow age and snowfall. In ORCHIDEE, an important drop of snow albedo is simulated during the ablation period.

In addition, the snow water fraction on each grid box is calculated as a function of snow mass:

$$snowfrac = \frac{snow}{snow+10} \quad \textbf{(2.6)}$$

where snow is the snow mass.

Overall, the way in which the snow processes are described in ORCHIDEE is quite simple. As mentioned by Wang (2011) in his Phd thesis, SECHIBA calculates lower snow water equivalent (SWE) and smaller snow cover duration, compared to other snow models. Wang tried to solve this problem in his Phd thesis, by creating a new snow model for ORCHIDEE. This model has not been implemented yet in ORCHIDEE, so in this study we are using the old snow parameterization.

3. The main differences between CLSM and ORCHIDEE

CLSM is the second LSM which was used in this study, so that a comparison of the simulated results of CLSM and ORCHIDEE can be done. Like ORCHIDEE, CLSM can be coupled to a GCM, but in this study only off-line simulations are used. A basic characteristic of this model is the use of TOPMODEL concepts (Beven and Kirkby, 1979) to relate small-scale variability of soil moisture with topography. The parameterization of evaporation and vegetation comes from the Mosaic LSM (Koster and Suarez, 1996). Eight vegetation classes are defined in CLSM and a mosaic of vegetation types is allowed.

The main differences between CLSM and ORCHIDEE are:

1. CLSM is a catchment-based LSM. This means that the hydrological catchment is considered as the fundamental land surface in CLSM. By contrast, ORCHIDEE is run using a regular grid with rectangular grid cells.
2. As mentioned before, in ORCHIDEE a subdivision of each grid cell in three subgrids with different water budgets is performed. This categorization in three separate soil columns (soil, grass, trees) is based on vegetation. In CLSM a subdivision of each hydrological catchment in three areal fractions is also done, but based on topography. In each catchment the horizontal soil moisture variability is described by means of the topographic index distribution. The topographic index is a soil moisture indicator and it is given by the following equation:
   $x = \ln\left(\frac{a}{tan\beta}\right)$ **(2.7)**
   where a is the upstream area and tanβ is the slope.
   High values of topographic index denote high saturation potential and thus high soil moisture, whereas low values denote steep slopes with low saturation potential. The resulting soil moisture distribution is finally used for partitioning each catchment in three different moisture regimes (saturated, intermediate, and stressed).
3. The snow model included in CLSM (Lynch-Stieglitz, 1994) is more complex related to the one included in ORCHIDEE. The snowpack is vertically discretized into three layers. Each layer is described by its own snow water equivalent, heat content and snow depth. These variables are not constant. They vary in time being influenced by: a) the heat transfer between the atmosphere and the snowpack and between the layers, b) the mass transfer between the atmosphere and the snow and between the layers, c) the snow compaction in each layer. The albedo and the snow density depend on the age of the snow.

A new snow parameterization was implemented in CLSM by Claire Magand (Magand et al., 2013). In particular, it includes a new snow cover depletion curve with hysteresis. The snow hysteresis was implemented in CLSM to describe the difference between the kinetics of snow accumulation and snow ablation. Particularly, the occurrence of snowmelt at preferential locations leads to slower changes in snow cover extent during ablation than during accumulation (Figure 3).

After the initial CLSM simulation in the Durance watershed, a calibration of 3 soil hydrodynamic parameters was performed, so that the model presents the best possible performance compared with observations. Calibration is a significant step in modelling (Beven, 2001). In general, some parameters used by models are related with observations, but there are some others that are not measurable or don't have a physical interpretation. This leads to the need to adjust the values of these parameters, so that the model results can fit the observations. The three hydrodynamic parameters that were calibrated are: a) the soil depth (D), b) the saturated permeability (Ks) and c) another parameter describing the decay of Ks with depth.

All the CLSM simulations were run by Claire Magand and her results are used in this study.

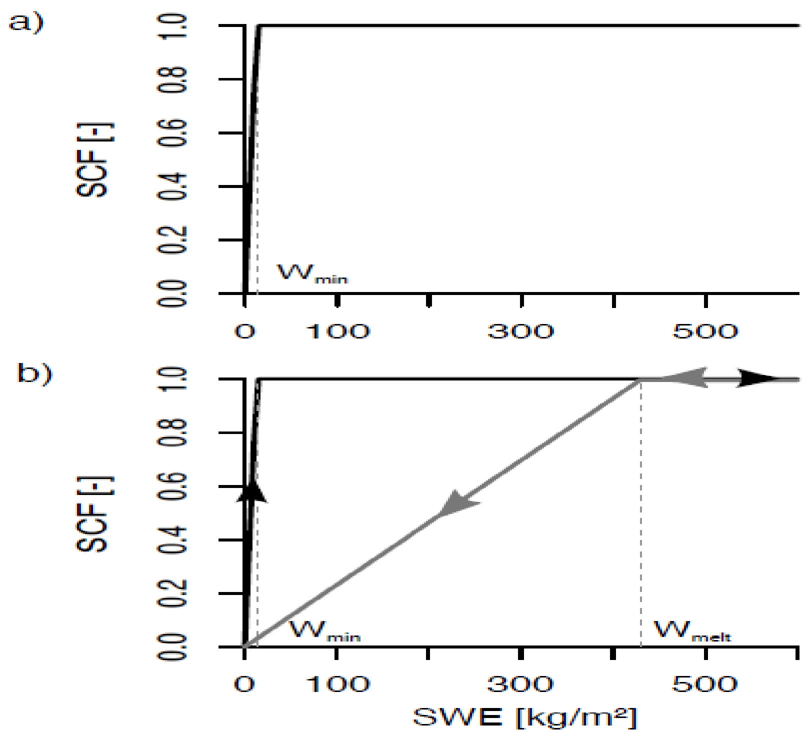

Figure 3. a)Initial snow cover depletion curve from CLSM, b)New snow cover depletion curve with hysteresis (black: accumulation path, grey: ablation path) [Magand et al.,2013]

4. The Durance watershed

4.1. General information

The Durance watershed is located in the southern French Alps and covers an area of approximately 14.000 km^2 (Figure 4). The Durance River is one of the main tributaries of the Rhone River, being around 320 km long. Its source is in the south-western Alps, in Montgenèvre and its confluence with Rhone is near Avignon. The natural complexity of the area and the big altitude range (4000 m) lead to important climatic contrasts, which in turn result in different hydrological regimes. Specifically, we observe a transition between a mountainous climate with nival hydrologic regime in the upper Durance, where snowfall has a dominant influence, to a Mediterranean climate in the downstream part of the river. Even in the downstream part of the river, the influence of snow in the hydrological regime is still noticeable, as the contribution of the upstream part of the basin to the downstream river discharge is important.

A proper estimation of the water resources in the present time and their evolution due to climate change is very important, as the Durance River supplies drinking water to more than 3 million people. Many of these people live outside of the watershed. For instance, it supplies drinking water to the residents of Marseille, which is the second biggest city in France. Furthermore, approximately 10% of French hydropower is produced there (Figure 4). The correct management of water resources in the Durance watershed satisfies also other uses for the people and the economy of the area such as irrigation and tourism.

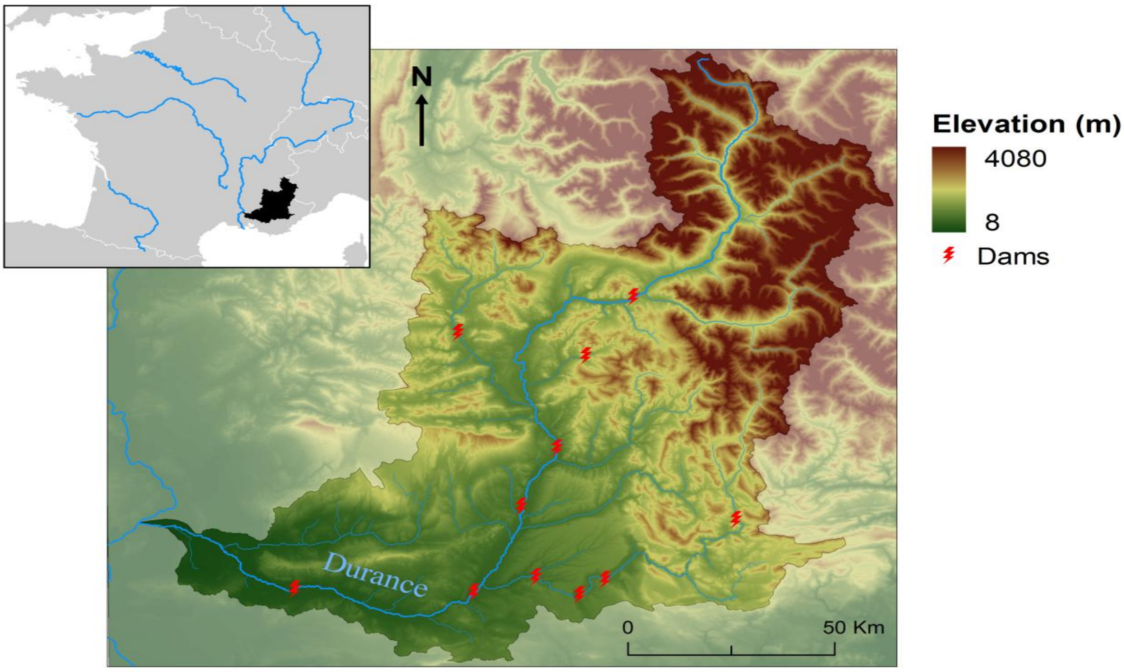

Figure 4. The Durance watershed and the location of the dams managed by EDF for hydropower

4.2. Subdivision into elementary catchments

In this study, we used the subdivision of the Durance watershed into 27 elementary catchments done by Claire Magand (Magand et al., 2013). Using CLSM, the watershed was subdivided into 27 catchments with an average area of 500km^2. An important factor that was taken into consideration in the division into elementary catchments is the location of the gauging stations. This factor plays a significant role in the validation of the simulation results with observations. Another thing that was checked for all the catchments is their homogeneity in terms of soil characteristics. Table 1 presents the main characteristics for each of the 27 catchments.

Catchment ID	long_min (West)	long_max (East)	latt_min (South)	latt_max (North)	Area (km²)	Mean altitude (m)	Upstream area at stations (km²)
1	6,342	6,903	44,785	45,093	661,987	2133,02	548
2	6,323	6,575	44,759	44,949	296,212	2267,01	
3	6,588	7,092	44,543	44,857	723	2175,66	723
4	6,328	6,815	44,498	44,801	501,146	1879,92	2170
5	6,744	6,971	44,495	44,655	146,712	2539,3	
6	6,624	6,958	44,333	44,552	397,411	2093,46	549
7	6,373	6,822	44,265	44,459	400,656	1902,68	946
8	6,231	6,655	44,419	44,652	460,582	1510,8	3582
9	5,827	6,482	44,206	44,614	1246,86	1024,94	6765
10	5,591	6,058	44,434	44,718	723,005	1238,84	723
11	5,461	5,961	44,163	44,493	754,372	903,63	6765
12	5,558	6,221	44,094	44,269	453,863	901,1	6765
13	5,858	6,064	43,910	44,109	197,077	553,73	11728
14	6,202	6,469	44,217	44,331	164,715	1456,13	164,715
15	6,011	6,549	43,996	44,298	738,956	1088,53	11728
16	6,226	6,526	43,332	44,110	381,628	1132,78	375
17	5,882	6,332	43,867	44,041	378,789	744,57	
18	5,614	6,040	43,696	44,137	840,029	622,25	11728
19	6,524	6,735	44,175	44,316	154,765	2042,56	158
20	6,401	6,726	43,869	44,230	500,312	1515,02	657
21	6,110	6,867	43,654	43,885	970,704	984,23	1625
22	5,872	6,252	43,752	43,764	290,64	626,95	
23	5,759	6,204	43,635	43,766	342,796	479,95	11728
24	5,485	5,929	43,540	43,770	534,569	390,97	12870
25	5,167	5,670	43,606	43,840	608,263	345,31	12870
26	5,208	5,722	43,606	44,150	1021,06	537,19	
27	4,727	5,266	43,680	43,921	470,657	128,24	

Table 2. Characteristics of each catchment in the Durance watershed

4.3. Subdivision into three zones

In order to help us distinguish the different hydrological regimes in the Durance river watershed and make the comparison of the results between ORCHIDEE and CLSM easier, we divided the watershed in three zones (Figure 5), with decreasing nival influence:

- The High Durance : from the sources until Serre-Ponçon (catchments 1-8)
- The Mid Durance : from Serre-Ponçon until Mirabeau (catchments 9-23)
- The Low Durance : from Mirabeau until the confluence with Rhône (catchments 24-27)

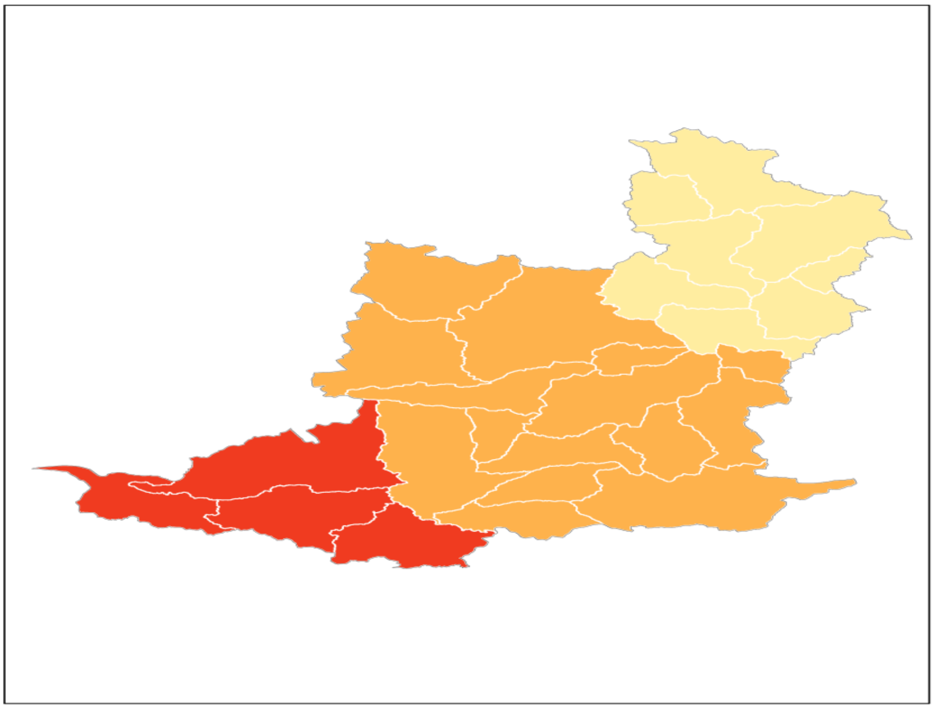

Figure 5. Division of the Durance watershed in three zones: a) High Durance(yellow), b)Mid Durance(orange), c)Low Durance(red)

5. The creation of the forcing files and the application to the Durance watershed

5.1 Meteorological data

a) Present time simulation

The meteorological data that are used as forcings to ORCHIDEE in this study are the same that are used by Claire Magand in her Phd thesis, because it is important to have exactly the same forcings for both models in order to make proper comparisons. In both models seven meteorological forcings are needed as inputs: air temperature and air humidity at 2m, wind speed at 10m, incoming shortwave and longwave radiation, snowfall and rainfall. ORCHIDEE also requires data for surface air pressure. These data weren't available, so a constant value of 1014hPa was taken regardless of the elevation of the area. The simulations were run within the time period 1977-2009.

The meteorological data were constructed based on two different meteorological reanalysis: a) SAFRAN (Quintana-Segui et al., 2008, Vidal et al., 2009) and b) SPAZM (Gottardi 2009). SAFRAN provides the seven meteorological forcings mentioned above at an hourly timestep and on a 8-km grid. Lafaysse (2012) showed that SAFRAN underestimates precipitation and especially snowfall compared to SPAZM, mainly due to the lack of meteorological stations at high altitudes. This is the reason why data from SPAZM were also used. In this data base, precipitation is 27% higher than in SAFRAN, because it uses a statistical approach that takes into account the orographic effect on precipitation. In addition, this dataset has a finer resolution than SAFRAN, providing information on a 1-km grid. However, it only gives information about mean precipitation and temperatures at a daily timestep. In the end, as described in Magand et al. (2013) a hybridization of SAFRAN and SPAZM was done in order to keep the advantages of both datasets. The resulting reanalysis is called DuO (Durance MeteO) and it includes hourly data on a 1-km grid. Finally, for each variable one mean value for each of the 27 CLSM's unit catchments was calculated at an hourly timestep.

ORCHIDEE reads the forcings at a half-hourly timestep, so a parameter which is called SPLIT_DT=2 was used in the model configuration in order to split the hourly forcings in half-hourly. Moreover, ORCHIDEE is coded to use gridded forcings, so a regular rectangular grid with 9 rows and 3 columns was constructed in order for the model to run correctly. Each grid cell represents one elementary catchment. The last thing that was done in order to prepare the meteorological input file was the transformation of files in NetCdf format, as this format is required by ORCHIDEE for all the inputs.

b) Climate change simulations

The meteorological forcings needed in the climate change simulations are the same that were used in the present time simulation. The climate change simulations were run within the period 1960-2064. The main tool that is used to obtain data in order to study the future climate is GCMs. In most of the cases, the impact of climate change on water resources is studied by following a top to bottom approach: an emission scenario is used to run a GCM simulation, which is then downscaled. In the end, a hydrological model is forced by these data. In this study 11 climate change scenarios coming from 5 different GCMs were used:

- 1 from CNCM33: Centre National de Recherches Météorologiques, France (Royer, 2008)
- 3 from DMIEH5C : Danish Meteorological Institute, Danenmark (May, 2008)
- 1 from EGMAM2: Freie Universitat Berlin (Huebener and Koerper, 2008)
- 3 from IPCM4: Institut Pierre Simon Laplace, France (Dufresne, 2007)
- 3 from MPEH5C : Max Planck Institute for Meteorology, Germany (Roeckner, 2008)

The need to downscale the outputs of GCMs comes from the fact that they can't be used directly in regional and local scales, because of their coarse resolution. According to Solomon et al. (2007) the current resolution of GCMs is 300km. In this scale they can't take into account spatial heterogeneities such as altitudinal gradients and, in addition, they are often biased. There are two different procedures of downscaling the outputs of GCMs over space and time: a) the dynamic downscaling method which is computationally expensive and usually keeps most of the biases and b) the statistical downscaling method which is less expensive (Mearns et al., 2009). To obtain the data that are used in this study, a statistical downscaling method described with details in Mezghani and Hingray (2009) was used.

5.2 Vegetation

For CLSM, the distribution of vegetation in each elementary catchment was extracted from ECOCLIMAP (Masson et. al., 2003), which is a global database containing data for several surface parameters at 1 km resolution. The eight classes of vegetation which are defined in CLSM are shown in Table 3:

Vegetation ID	Vegetation Type
1	broadleaf evergreen trees
2	broadleaf decidious trees
3	needleleaf trees
4	Grassland
5	broadleaf shrubs
6	dwarf trees
7	bare soil
8	desert soil

Table 3. The 8 vegetation classes used by CLSM

The conversion from the CLSM classes to ORCHIDEE's PFTs was done in the following way:

- Deciduous 2 ⟶ PFT 6 (TeBS)
- Needleleaf 3 ⟶ PFT 4 (TeNE)
- Grassland 4 ⟶ PFT 10 (NC3)
- Bare ground or desert 7,8 ⟶ PFT 1 (Bare soil)

Before running ORCHIDEE, the vegetation file was transformed in NetCdf format. The vegetation information is read by ORCHIDEE in the first year of simulation and remains unchanged during the simulation period.

5.3. Soil parameters

The two soil parameters that are needed by ORCHIDEE for simulations are: a) soil texture and b) soil color. The way in which the soil texture and the soil color files were created is described with details in the following paragraphs. Once again, before running the simulations all the input files were transformed in NetCdf format.

a) Soil texture

ECOCLIMAP provides the fractions of sand and clay at 1 km resolution. From these data, soil texture was defined for every 1 km pixel using the USDA triangle (Figure 6), before defining the dominant texture in each elementary catchment.

In ORCHIDEE the Zobler classification (Zobler, 1986) is used to parameterize the soil texture. This classification consists of seven classes. Class 0 represents the oceans and class 6 the glaciers. The remaining five textural classes are: fine, medium-fine, medium, medium-coarse, and coarse. The percentages of sand, clay and silt for each Zobler soil class are defaults numbers in ORCHIDEE. Using these percentages the five remaining Zobler classes were corresponded to a USDA category (Figure 6) and then for each catchment the known dominant USDA category was corresponded to the closest Zobler class.

In the end of this procedure almost all the catchments were found to belong in Zobler's class 3 (medium), except of catchment 3 which was found to belong in Zobler's class 2 (medium-fine). In ORCHIDEE the Zobler's remaining 5 classes are finally reduced to three (fine, medium, coarse), as the medium category comprises the medium-fine, medium and medium-coarse Zobler classes. Hence, in the end the class for all the 27 catchments is medium.

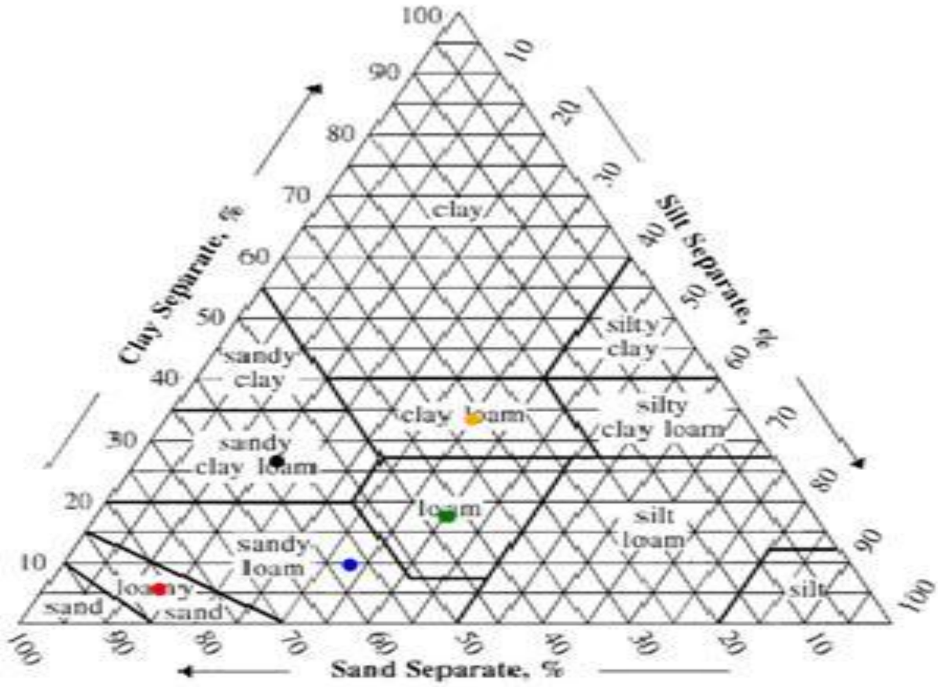

Figure 6. The five Zobler classes represented in USDA triangle (class 1: red, class 2: blue, class 3: green, class 4: black, class 5: orange)

b) Soil color

The soil color classification of Wilson and Henderson-Sellers (1985) is used by ORCHIDEE. These authors define 9 soil color types, ranging from 0 to 8. The color type 0 represents the water. ORCHIDEE reads the soil color type and transforms it into bare soil albedo.

Values for bare soil albedo were available from ECOCLIMAP for all the catchments. Using the correspondence table in ORCHIDEE's code, each bare soil albedo value was corresponded to a soil color. In this way, an input file of 27 values of soil color types was constructed.

One last information required by ORCHIDEE before launching the model is a topographic input file, including the mean slope for each elementary catchment.

5.4. Runoff validation dataset

ORCHIDEE and CLSM runoff simulations were validated against observations of daily discharge provided by EDF. In the Durance watershed 14 gauging stations can be found. The values in this dataset represent discharges that would have been observed without any human disturbance. This means that the data series was reconstructed, assuming zero dams influences in the values of river discharge. This 'naturalized' discharge was then converted into runoff in order to be compared with the spatially weighted-average simulated runoff.

6. Results

6.1. Validation of simulated runoff against observations

A very important step after the performing of simulations is the validation of their results against observations. In this section a validation of ORCHIDEE's and CLSM's simulated runoffs against observations of daily discharges provided by EDF is presented. Observations were available at 14 catchments at high and mid Durance, whereas at low Durance data of observations weren't available. The time period in which the simulations were run was 1977-2009. Before comparing the simulations with observations, an average of the runoff of the upstream catchments over 10 days was calculated, as in both ORCHIDEE and CLSM routing procedures weren't included.

The quality of the simulations is assessed using two objective functions. The relative bias of total runoff is given by:

$$\%\text{Bias} = \frac{\sum_t(\text{Qsim}-\text{Qobs})}{\sum_t(\text{Qobs})} \quad \textbf{(6.1)}$$

where Qsim and Qobs are the simulated and the observed flow respectively.

The Nash-Sutcliffe efficiency is used to evaluate the fit between simulation and observation curves:

$$NSQ = 1 - \frac{\sum_i(Qobs-Qsim)^2}{\sum_i(Qobs-\overline{Qsim})^2} \quad \textbf{(6.2)}$$

The Nash-Sutcliffe efficiency can range from -∞ to 1. An efficiency of 1 (NSQ=1) corresponds to a perfect fit of modeled runoff to the observed data. An efficiency of 0 (NSQ=0) means that the model simulation is as accurate as the mean of the observed data, whereas an efficiency smaller than zero (NSQ<0) indicates that the observed mean is a better predictor than the model.

In this study, the results of one ORCHIDEE simulation and three different CLSM simulations are presented. The simulations of the CLSM were all run by Claire Magand and her results are presented here. Details for the aforementioned simulations are given in the following paragraphs:

1. ORCHIDEE (red color in the plots). It is the simulation run by ORCHIDEE. The meteorological forcings and the vegetation and soil characteristics as described with details in section 5 were used to run the model.
2. CLSM raw (purple color in the plots). It is the initial configuration of CLSM model that uses the meteorological forcings mentioned in section 5 and the vegetation and soil characteristics extracted from ECOCLIMAP.

3. CLSM hydro (green color in the plots). It includes the calibration described with details in section 3 so that the model presents the best possible performance compared with observations.
4. CLSM (blue color in the plots). It is the previous configuration including the new snow parameterization described in section 3.

Figure 7 and Figure 8 present the comparison between the simulations and the observations for 4 elementary catchments in high and mid Durance respectively. The biases and NSQs for each catchment are also shown in these figures. In high Durance the discharge observations are typical of nival hydrological regimes, with high seasonal flows. There is one big peak in spring (from April to June) mainly due to snowmelt and one smaller in autumn (October, November) mainly due to high precipitation. Two low flow periods exist during the year, one in winter when snow accumulates and one in summer when the precipitation is low and the total evaporation is high. The more southern the catchment is, the smaller the spring peak becomes (Figure 8). This happens because the altitude in the southern catchments is much lower, resulting in less snowfall during the winter, and thus in limited effect of snowmelt on spring's total runoff. In general, discharges in the mountainous catchments are higher than in catchments located at lower altitudes. This results from higher precipitation amounts due to orographic effects, but also from lower evaporation due to low temperatures.

As far as the simulations are concerned, the simulated total runoffs from the initial configurations (ORCHIDEE and CLSM raw) have significant differences from the observed ones. Taking into account the whole watershed, both ORCHIDEE and CLSM raw overestimate the total runoff by approximately 30% and 8% respectively. By means of water conservation this means that evaporation is underestimated to an important extent by ORCHIDEE and to a lesser extent by CLSM. Further details concerning the simulated water budget for both models are given in the next chapter. In the northern catchments, the total runoff curve calculated by CLSM shows a sharper peak during spring than the observations curve. Moreover, this peak appears to happen a month too early. The same defect is also shown in the results of ORCHIDEE, but here the peak is smoother than the one in CLSM raw. In ORCHIDEE however, the peak appears to happen two months earlier compared to the observations and one month earlier compared to CLSM, since both models share the exact same meteorological input data. This time difference in the appearance of the peak between simulations and observations is probably caused by the way in which snowmelt is parameterized in both models and probably implies that it is simulated as a faster process than it is in reality.

As expected, CLSM hydro significantly improved CLSM's simulated runoff, leading to a much better fit between the simulation and the observation curve. This is the reason why calibration was performed in the first place. However, even after the calibration of the hydrodynamic parameters, the aforementioned problem with the earlier peak in spring's runoff still existed. The introduction of hysteresis in snow depletion curves created the needed time lag of one month in spring's total runoff peak and in the same time smoothed the peak.

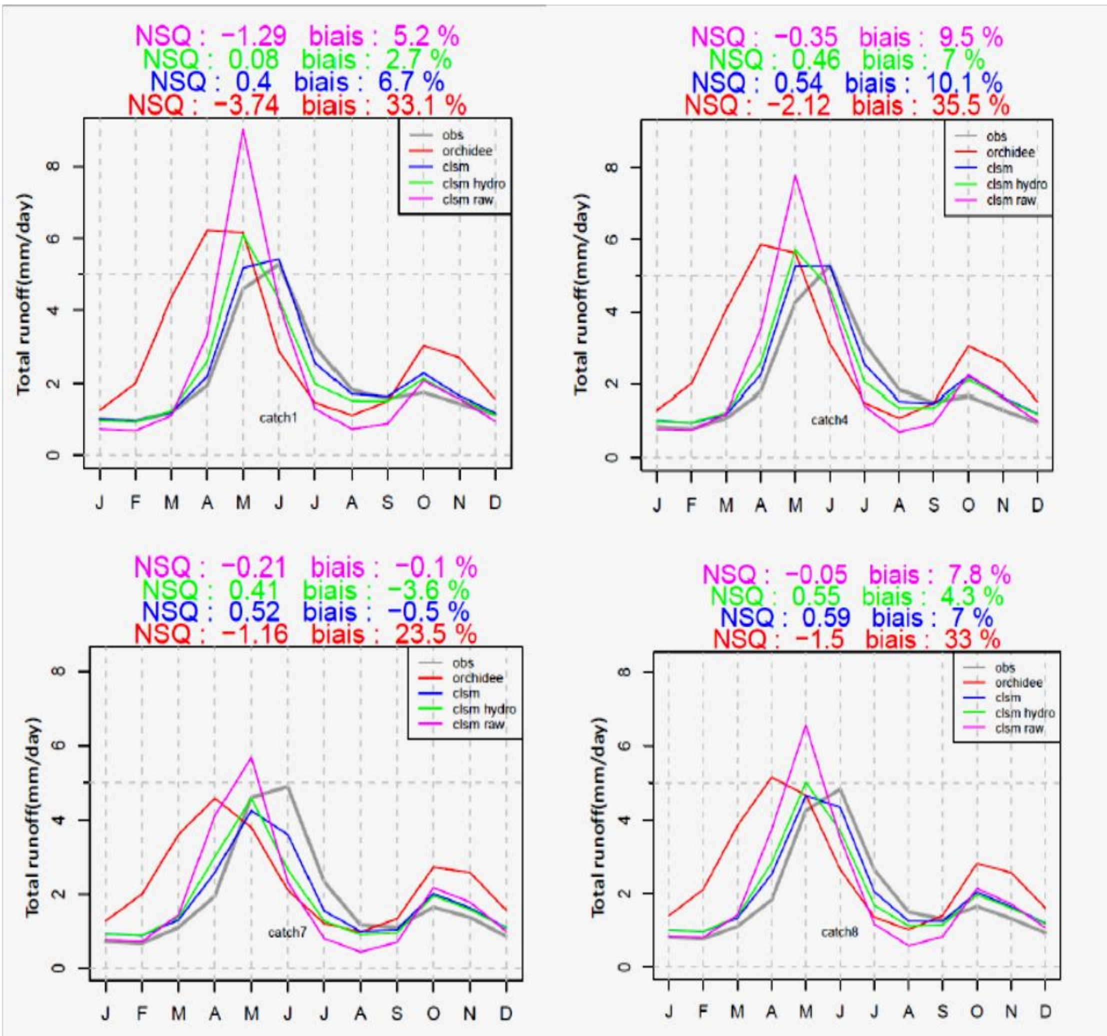

Figure 7. Simulated runoffs against observations in High Durance (topleft: catchment 1, topright: catchment 4, bottomleft: catchment 7, bottomright: catchment 8). The relative biases and the Nash-Sutcliffe efficiencies (NSQs) for each catchment are also shown for each of the 4 simulations.

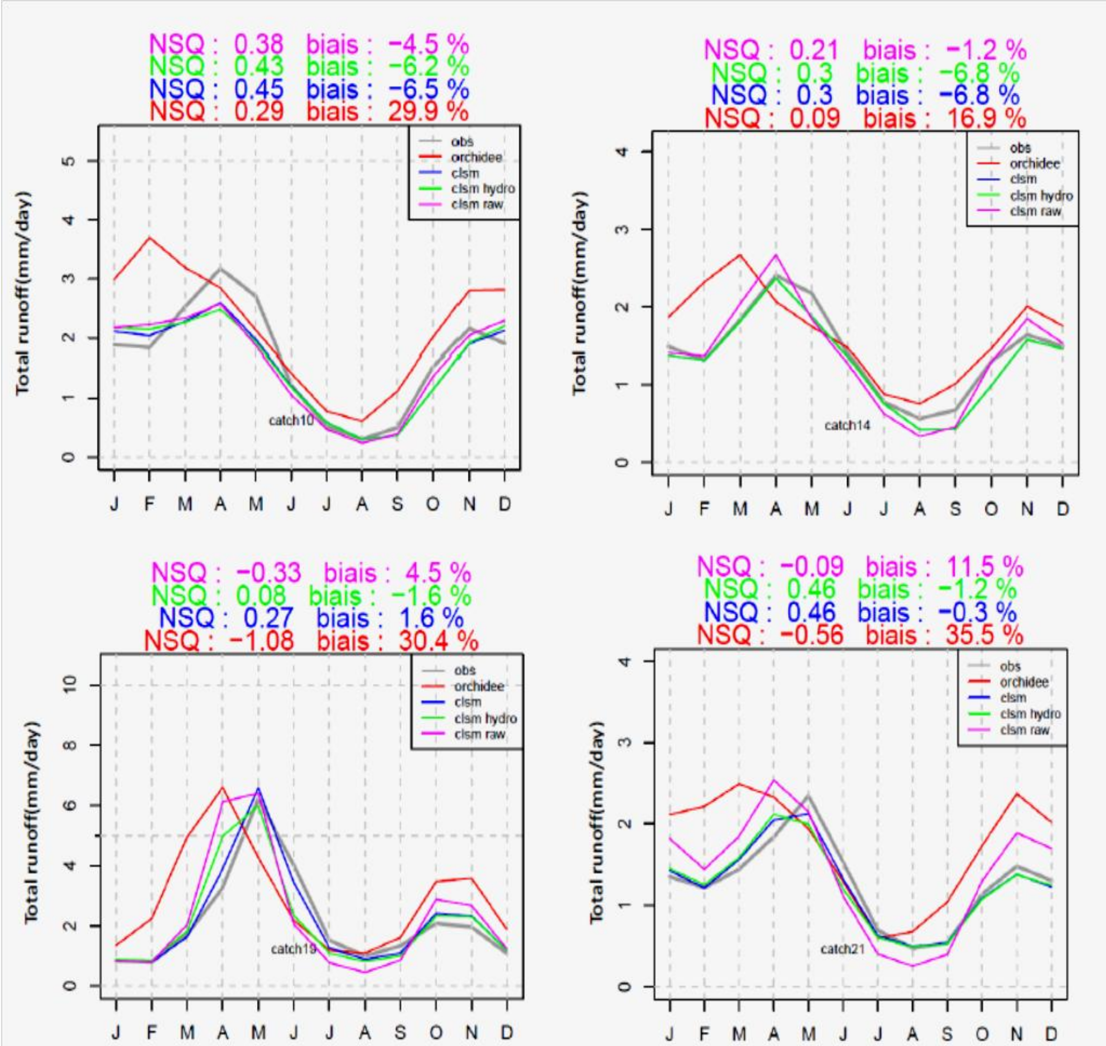

Figure 8. Simulated runoffs against observation in Mid Durance (topleft: catchment 10, topright: catchment 14, bottomleft: catchment 19, bottomright: catchment 21). The relative biases and the Nash-Sutcliffe efficiencies (NSQs) for each catchment are also shown for each of the 4 simulations.

6.2. Comparison between ORCHIDEE and CLSM in present time simulations

The above part showed that the differences between ORCHIDEE and CLSM were larger than the differences between the different versions of CLSM. In this part the comparison between ORCHIDEE and CLSM is focused on the simulated processes, particularly the ones governing the water budget, the partition of evaporation in subfluxes, and the snow processes. The results from the four simulations are presented, but we focus especially on the differences between ORCHIDEE (red) and the final version of CLSM (blue).

Figure 9 and Figure 10 present the partition of precipitation in evaporation and total runoff and the snow processes respectively in the whole Durance watershed. The calculated curves for the two models have many similarities, because both of them are strongly driven by the seasonality of the input meteorological data. An important peak in evaporation during June and July can be observed for all the simulations, related to high incoming radiation and temperature. The total runoff curves show two peaks during the year, as already mentioned: one in spring due to the effect of snowmelt and one in autumn due to high precipitation levels. As far as the snow mass and the snow melt are concerned, high values are observed - as expected - during the winter, and a rapid drop is shown during the spring leading to zero or almost zero values in summer.

However, some important differences can be found between ORCHIDEE and CLSM. Firstly, there is a different partition of precipitation in evaporation and total runoff. In general, ORCHIDEE calculates bigger mean annual total runoff and smaller mean annual evaporation than CLSM. In table 4 we can see that this difference in partition occurs mainly in the catchments with the higher altitudes, which means that it is probably related to differences in the parameterization of snow processes. This hypothesis is confirmed by the observed differences in the snow mass and the snow melt curves. The mean annual snow mass calculated by ORCHIDEE is much smaller than in CLSM simulations. This is consistent with the references in bibliography (Wang, 2011), which mention that SECHIBA calculates smaller values for snow mass than most of the other snow schemes. These smaller calculated values for snow mass lead in turn in smaller snow evaporation, which results in lower values in total evaporation flux. On the other hand, the mean annual snowmelt is bigger in ORCHIDEE than in CLSM. Figure 10 shows that snowmelt is much higher in ORCHIDEE during autumn and winter and it is lower in spring and summer, leading to the conclusion that snowmelt is a faster process in ORCHIDEE's snow scheme. This could be an explanation for the earlier peak in ORCHIDEE's total runoff curve and for its larger values in autumn compared to CLSM. Another explanation could be a faster water flux within the soil column in ORCHIDEE than in CLSM.

Zones	ORCHIDEE		CLSM raw		CLSM hydro		CLSM	
	evap/ precip	runoff/ precip	evap/ precip	runoff/ precip	evap/ precip	runoff/ precip	evap/ precip	runoff/ precip
High	29.2%	69.9%	43.7%	56.3%	45.8%	54%	44%	56%
Mid	52.7%	47.8%	58.9%	41%	63.4%	37%	63.3%	37%
Low	74.4%	25.3%	77.1%	23%	83%	17%	83%	17%
The whole watershed	47%	52.6%	56.2%	43.8%	60%	40%	59.6%	40%

Table 4. Partition of precipitation in evaporation and total runoff for each zone and for the whole Durance watershed

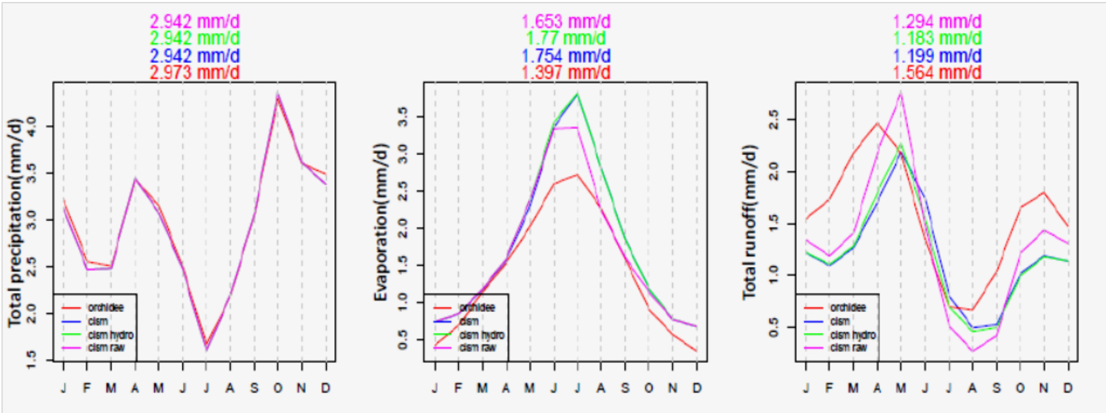

Figure 9. The partition of precipitation in evaporation and total runoff in the whole Durance watershed (Top of each figure: mean annual values for all the simulations).

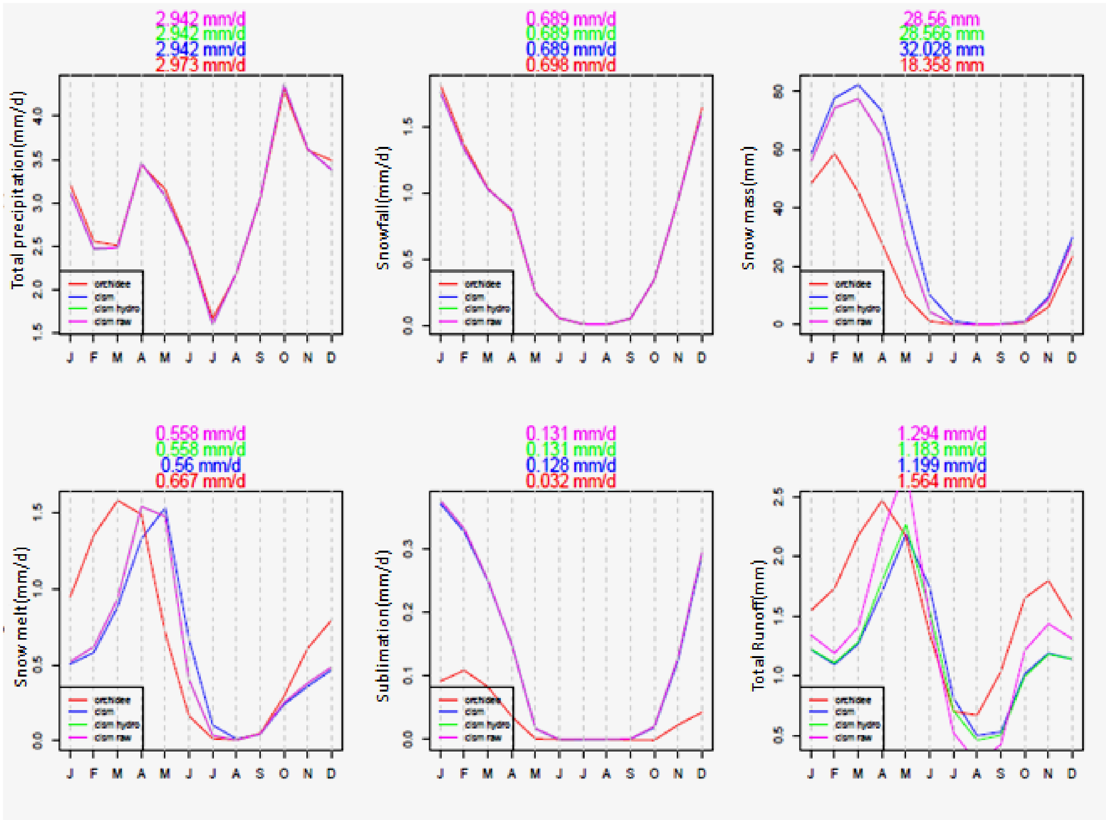

Figure 10. The snowpack budget in the whole Durance watershed (Top of each figure: mean annual values for all the simulations).

Figure 11 shows the partition of total runoff in drainage and surface runoff in the whole Durance watershed. In both ORCHIDEE and CLSM raw, the peak of drainage occurs the same month as the peak of surface runoff, whereas the retention in the soil was expected to delay the drainage peak. CLSM hydro and CLSM seem to have a better response, since a time delay of one month can be observed between the peak in surface runoff and the peak in drainage (May and June respectively). In the basin scale, ORCHIDEE calculates a bigger percentage of drainage over total runoff and a smaller percentage of surface runoff over total runoff compared to CLSM. However, the situation is not the same for the different zones (Table 5). In particular, in high Durance ORCHIDEE calculates a much bigger mean annual drainage and a smaller mean annual surface runoff than CLSM. Exactly the opposite situation is observed in Low Durance. Overall, from Upper to Low Durance, an abrupt drop in the percentage of drainage over total runoff was calculated by ORCHIDEE, whereas in CLSM a much smaller drop is observed. Something that can explain these differences is the way in which the models parameterize the infiltration. ORCHIDEE seems to simulate higher infiltration if the same amount of water is regularly distributed over time. This means that the infiltration in ORCHIDEE is sensitive to intensity, while this dependence is indirect in CLSM. The intensity of snowmelt rate is much smaller than the intensity of precipitation, which favors a higher infiltration in ORCHIDEE when snow melts than if the same amount of water had been received as precipitation. This explain the large percentage of drainage over runoff in High Durance, where the influence of snow processes is important and the smaller percentages as the nival influence is reduced.

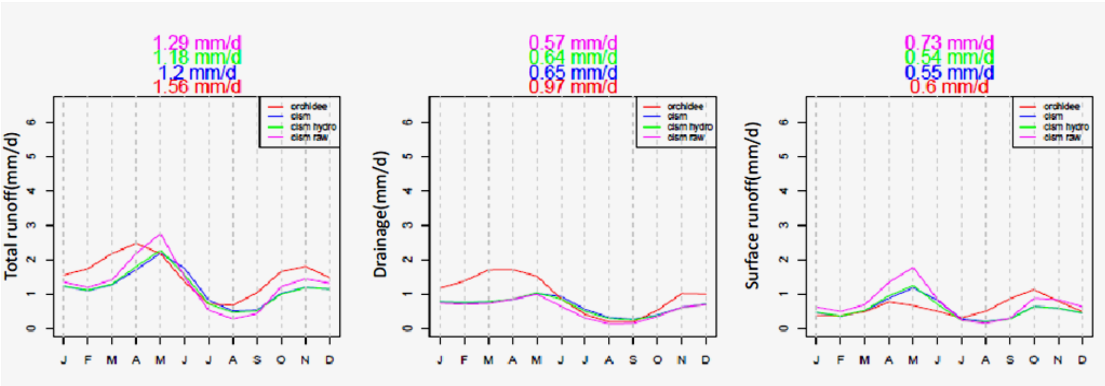

Figure 11. The partition of total runoff in drainage and surface runoff in the whole Durance watershed (Top of each figure: mean annual values for all the simulations).

Zone	CLSM drainage/total runoff	ORCHIDEE drainage/total runoff
High	**54.46%**	**72.55%**
Mid	**56.88%**	**57.64%**
Low	**37.14%**	**20.75%**
The whole watershed	**54.17%**	**62.18%**

Table 5. Percentage of drainage in total runoff for the each zone separately and for the whole watershed.

To further analyze the results and obtain a better understanding about the observed differences between the two models we plot in Figure 12 the different subfluxes of evaporation for the whole Durance watershed. The mean annual evaporation flux is bigger in CLSM compared to ORCHIDEE. This difference is larger in the High Durance than in the Mid and the Low (CLSM-ORCHIDEE= 0.532 > 0,341 > 0,155mm/d respectively). As mentioned above, this is partially related to snow sublimation, which explains the bigger differences in High Durance, where the effect of snowfall is important. In the Low Durance the snowfall rate is very small, resulting in a minor contribution of sublimation in the total evaporation flux. Hence, there should be another reason why this difference in total evaporation is still observed. Figure 12 helps us understand that the flux that creates the aforementioned problem is interception loss, which is much smaller in ORCHIDEE. A difference in interception loss may be explained by different parameterization of this process between the models. In CLSM each unit of Leaf Area Index (LAI) creates an interception capacity of O.2 mm compared to 0.1 mm in ORCHIDEE. This can partially explain the observed difference.

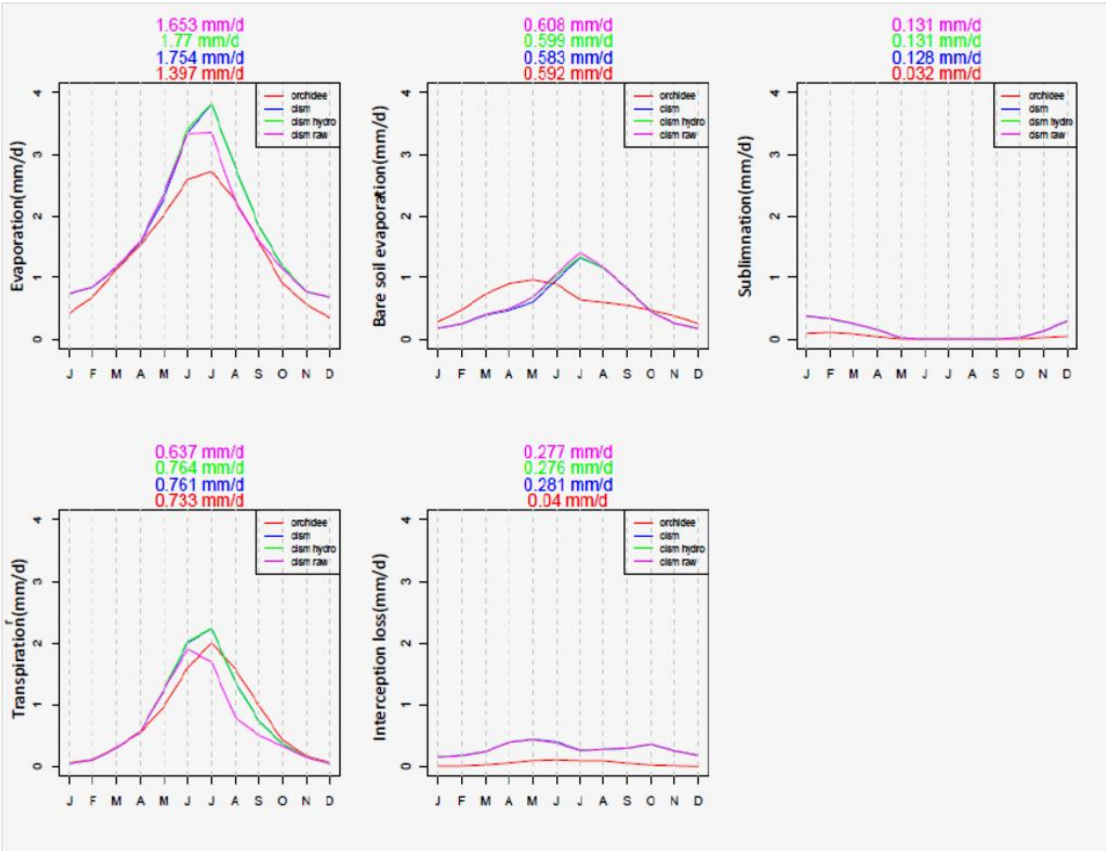

Figure 12. The different subfluxes of evaporation in the whole Durance watershed (Top of each figure: mean annual values for all the simulations).

To sum up, the main difference between ORCHIDEE and CLSM is that ORCHIDEE is a "wetter " model than CLSM. It calculates higher mean annual total runoff in all the zones and in the entire watershed. This leads to an underestimation of the total evaporation flux compared to CLSM. In High Durance, the strong influence of snow processes in the hydrological regime amplifies the discrepancies between the models, as the different snow processes are not parameterized in the same way. In particular, ORCHIDEE calculates higher snowmelt rates and smaller sublimation which favors total runoff against total evaporation. In the same time snowmelt begins earlier in ORCHIDEE, leading to the observed one month offset of the total runoff curve. The higher sensitivity of ORCHIDEE in intensities probably explains the difference in the partition of total runoff in drainage and surface runoff, as the much smaller intensity of snowmelt compared to precipitation results in higher infiltration in high altitudes, where the contribution of snowmelt in total runoff is significant. In Low Durance a better resemblance between the two models is observed. The minor influence of snow in this zone is evident, as the simulated snowmelt rate and sublimation are very small for both models. The flux that seems to create the bigger dissemblance between the models is interception loss, which is much smaller in ORCHIDEE compared to CLSM. This is the factor that favors total runoff against total evaporation in Low Durance. In Mid Durance an intermediate situation between the above two is observed. The catchments that are in high altitudes are still influenced by the different snow processes but to a lesser extent, whereas in the southern catchments the snow and water budget are similar with the ones in Low Durance.

6.3. Comparison between ORCHIDEE and CLSM in climate change simulations

The climate change simulations were run within the period 1960-2064. Two periods of 28 years were selected to compare present and future climate. For present climate the selected period is 1980-2008. The period selected for the future is 2036-2064. Vegetation distribution, soil color and soil texture were considered identical to current situation. In this part only two simulations are taken into consideration: a) the simulation run by ORCHIDEE and b) the simulation run by the "final" version of CLSM.

Figure 13 presents the evolution of meteorological forcings with time in the whole watershed. The difference shown in the header of the plots is the difference between the mean annual value in the future (2036-2064) and the mean annual value in the present (1960-2064). Another element presented in the plots is the significance of a trend for each variable, assessed by means of Mann Kendall test. According to this test, the null hypothesis H_0 assumes that the data are independent and randomly ordered (no trend). This is tested against another hypothesis H_1, which assumes a trend. This test is performed for each simulation, to give a measure of the consensus between the different downscaled climate change projections. In addition, Kendall's tau measures the strength of the relationship between two variables, here a meteorological variable and time. Its range is between -1 and 1. The positive correlation indicates that both variables increase together, which in our case means that the variable increases with time.

In Figure 13 an evident upward trend is shown for both air temperature and air humidity. The change in temperature ranges from 1.25 K in Low Durance to 1.5 K in Upper Durance. The higher temperature increase over mountainous areas is consistent with the results of Schadler and Weingartner (2010) for the Alpine regions of Switzerland. The upward trend in air humidity is a direct response to the temperature increase, as the saturated water vapor increases with temperature. Snowfall rates appear to decrease in the future (ranging from -15.65% in Upper Durance to -32.24% in Low Durance) mainly due to the increase in air temperature. On the other hand, the trends of total precipitation and rainfall aren't so evident. Total precipitation seems to decrease with time in all the three zones. This trend is more evident in the Mid and Low Durance, whereas it is statistically insignificant in the Upper Durance where 8 out of the 11 scenarios show no trend. Despite the fact that in basin scale the rainfall trend is downward, in the upper Durance the trend is upward but statistically insignificant. To get a better understanding of the trend of total precipitation we plot the mean monthly evolution of total precipitation, snowfall and rainfall in the Upper Durance (Figure 14). This figure shows that during winter and early spring, the decrease of snowfall rate due to higher air temperature is partially compensated with a simultaneous increase in rainfall. It was expected in absence of total precipitation change, as if total precipitation does not freeze to snow, it falls as rainfall.

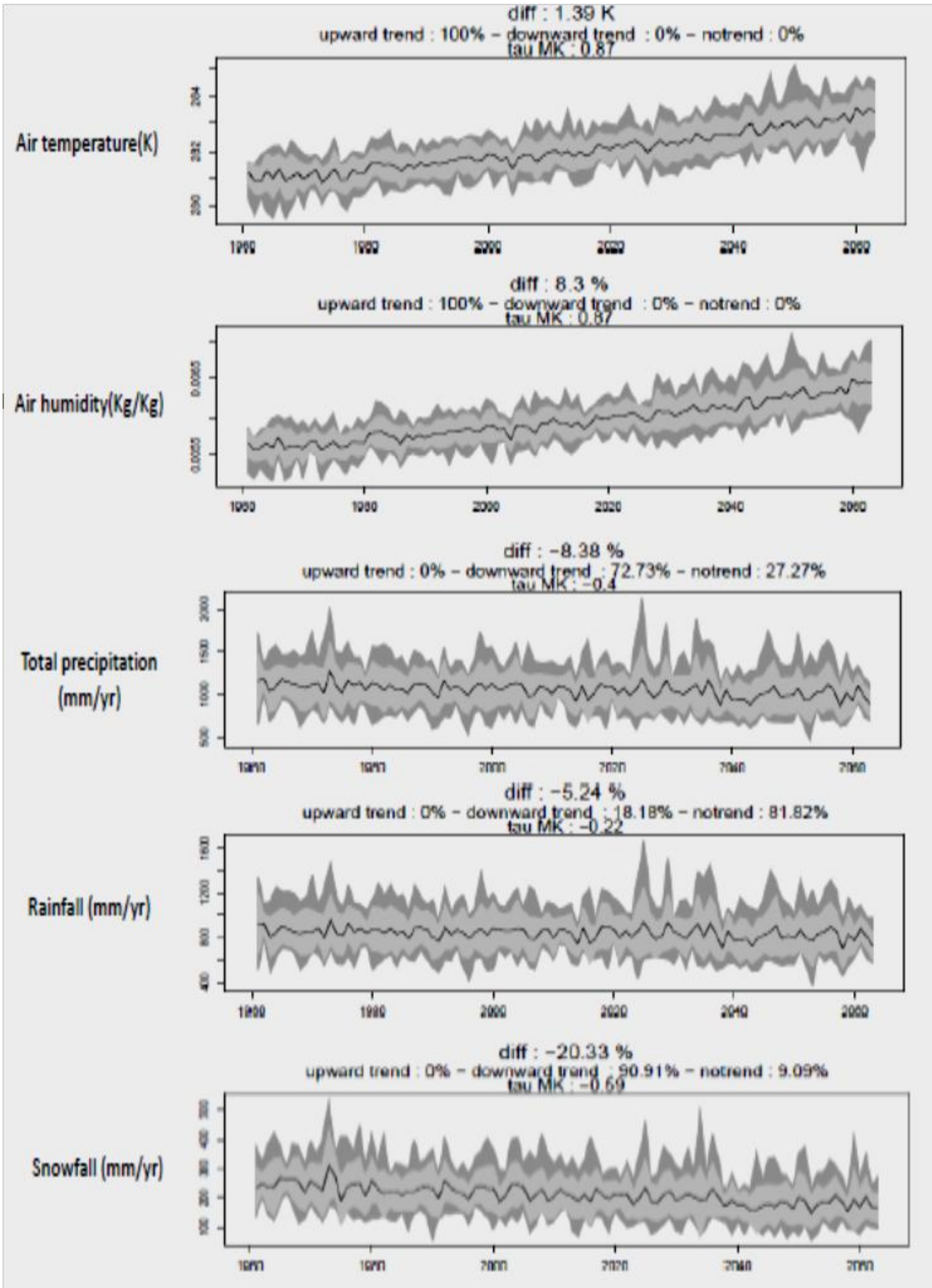

Figure 13. Future evolution of the meteorological forcings in the whole watershed. The first row in the header is the difference between the mean annual value in the future (2036-2064) and the mean annual value in the present (1960-2064). The second and the third row show the significance of the trend, by means of Mann Kendall test.

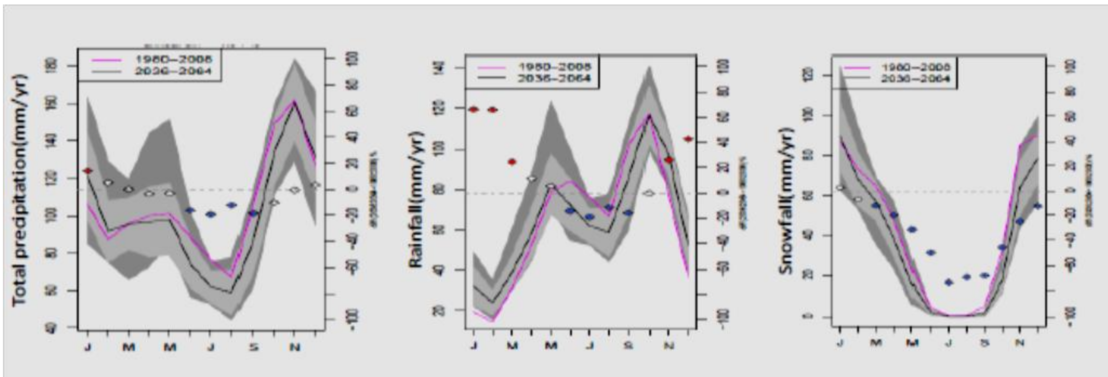

Figure 14. Mean monthly evolution of total precipitation, snowfall and rainfall in Upper Durance. The dark grey envelope shows the envelope of minimum to maximum future simulations; the light grey envelope shows the envelope of the mean of future simulations minus or plus the standard deviation; the diamonds are related to the right vertical axis and give the mean relative change between the two periods, with color inside when the monthly difference is statistically significant using a Student test.

These differences in meteorological forcings between future and present time result in changes in water budget and snow processes. Hence, it is interesting to examine whether the two land surface models used in this study estimate these changes in a similar way or not.

Table 6 presents the future evolution of total runoff in the Durance watershed. In particular it shows the difference in the mean annual total runoff between the future and the present and the percentages of scenarios showing upward downward or no trend for the three zones and the entire Durance watershed. The mean annual runoff decreases in both models in all the zones and in the entire watershed. The decrement percentages of ORCHIDEE and CLSM are quite close in all the cases, with the exception of Low Durance where CLSM decrease in total runoff (-27.25%) is much bigger than the one in ORCHIDEE (-16.63%). The big decrease in Low Durance found by CLSM is consistent with repeated observations in which CLSM results in more severe reductions of total runoff with climate change than other LSMs and hydrological models in situations of water stress (Ducharne et al., 2007, Ducharne et al., 2011). A decrease in total runoff is in accordance with what was found in bibliography for the Durance watershed (Etchevers et al., 2002), where a reduction of 23% in the river's discharge was calculated.

Zones	ORCHIDEE				CLSM			
	Diff	Upward trend	Downward trend	No trend	Diff	Upward trend	Downwar d trend	No trend
Upper	-11.21%	0%	63.64%	36.36%	-14.32%	0%	81.82%	18.18%
Mid	-18.91%	0%	90.91%	9.09%	-18.92%	0%	81.82%	18.18%
Low	-16.63%	0%	81.82%	18.18%	-27.26%	0%	81.82%	18.18%
The whole watershed	`-15.4%	0%	72.73%	27.27%	-17.47%	0%	81.82%	18.18%

Table 6. Future evolution of total runoff in the Durance watershed

In order to better observe the future differences between the nival and the Mediterranean hydrological regime, we plot the monthly evolution of total runoff for the Upper and the Low Durance (Figure 15). In the high altitude catchments the future total runoff in winter is bigger for both ORCHIDEE and CLSM. This is explained by: a) the aforementioned increase in liquid precipitation in the same period and b) an increase in snowmelt rate from December to February (Figure 16). For all the other months of the year, future runoffs are smaller than present time runoffs for both models. In downstream catchments, a general reduction of the runoff during the whole year is shown.

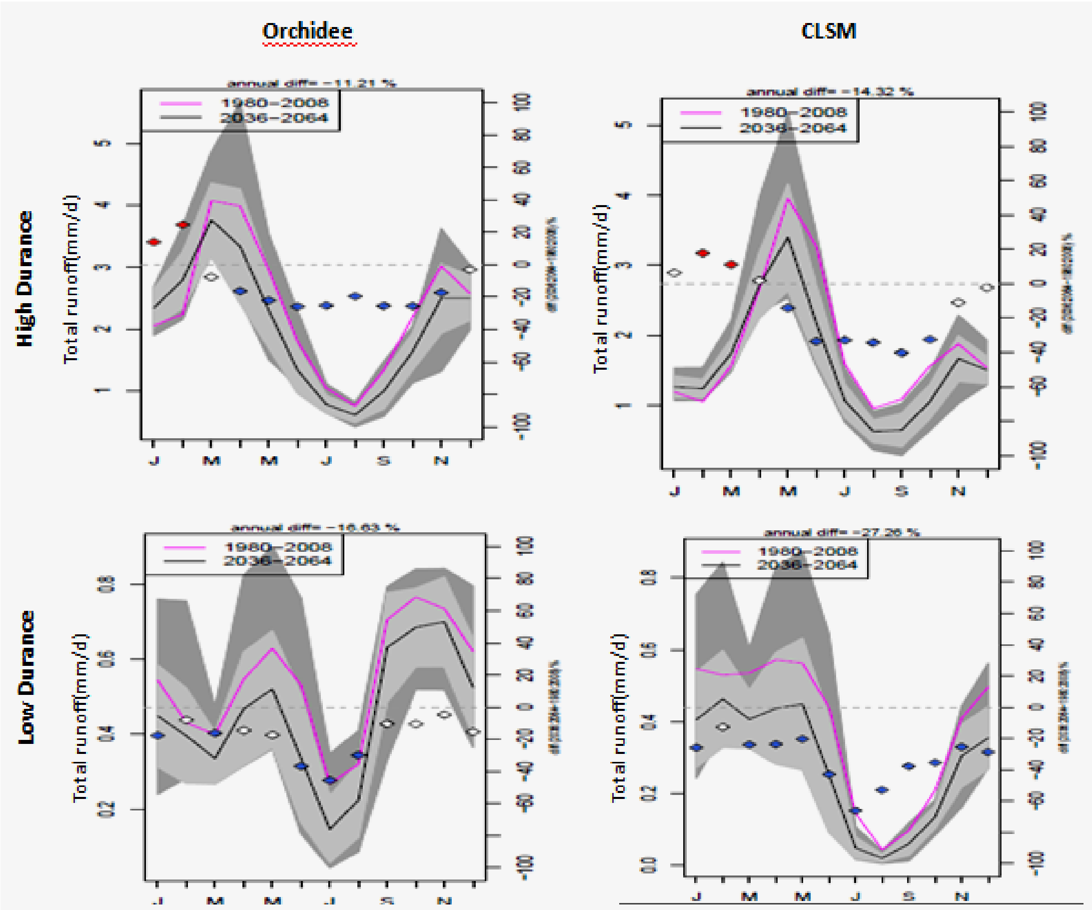

Figure 15. Monthly evolution of total runoff for Upper (first row) and Low (second row) Durance (on the left: ORCHIDEE, on the right: CLSM). The dark grey envelope shows the envelope of minimum to maximum future simulations; the light grey envelope shows the envelope of the mean of future simulations minus or plus the standard deviation; the diamonds are related to the right vertical axis and give the mean relative change between the two periods, with color inside when the monthly difference is statistically significant using a Student test.

Table 7 presents the future evolution of snowmelt rate for ORCHIDEE and CLSM. Both models show statistically significant downward trends in each zone separately and in the entire Durance watershed. The decrement percentages of ORCHIDEE and

CLSM are very close in all the cases. As mentioned before, Figure 16 shows that only during the winter in Upper Durance, the future snowmelt rate is higher than the current one, mainly due to the projected increase in temperature. In CLSM's future snowmelt curve for High Durance an earlier peak is observed (April instead of May), which is consistent with what is found in the bibliography (Etchevers et al., 2002). ORCHIDEE future simulations, however, doesn't seem to predict this offset in the snowmelt curve. As far as the snowpack is concerned, it appears to be very sensitive to climate changes. In the entire watershed and in each zone separately, snow water equivalent (SWE) is decreasing significantly for both models (Table 8). The decrement percentages at basin scale are -25.12% for ORCHIDEE and -23.53% for CLSM. The decrease is bigger for the southern catchments in both the models, which is in accordance with other bibliographic references (Etchevers et al., 2002). Finally, in both ORCHIDEE and CLSM the snowpack seems to appear a month later and disappears one month earlier compared to the present time. In other words, the snow cover duration is smaller in the future simulations by approximately 2 months.

Zones	ORCHIDEE				CLSM			
	Diff	Upward trend	Downward trend	No trend	Diff	Upward trend	Downward trend	No trend
Upper	-14.43%	0%	72.73%	27.27%	-13.58%	0%	63.64%	36.36%
Mid	-23.91%	0%	90.91%	9.09%	-22.61%	0%	90.91%	9.09%
Low	-29.79%	0%	72.73%	27.27%	-31.23%	0%	72.73%	27.27%
The whole watershed	-17.91%	0%	81.82%	18.18%	-17.07%	0%	72.73%	27.27%

Table 7. Future evolution of snowmelt in the Durance watershed

Zones	ORCHIDEE				CLSM			
	Diff	Upward trend	Downward trend	No trend	Diff	Upward trend	Downward trend	No trend
Upper	-23.84%	0%	72.73%	27.27%	-22.89%	0%	90.91%	9.09%
Mid	-30.26%	0%	63.64%	36.36%	-28.69%	0%	81.82%	18.18%
Low	-32.58%	0%	45.45%	54.55%	-27.37%	0%	45.45%	54.55%
The whole watershed	-25.12%	0%	72.73%	27.27%	-23.53%	0%	90.91%	9.09%

Table 8. Future evolution of snow mass in the Durance watershed

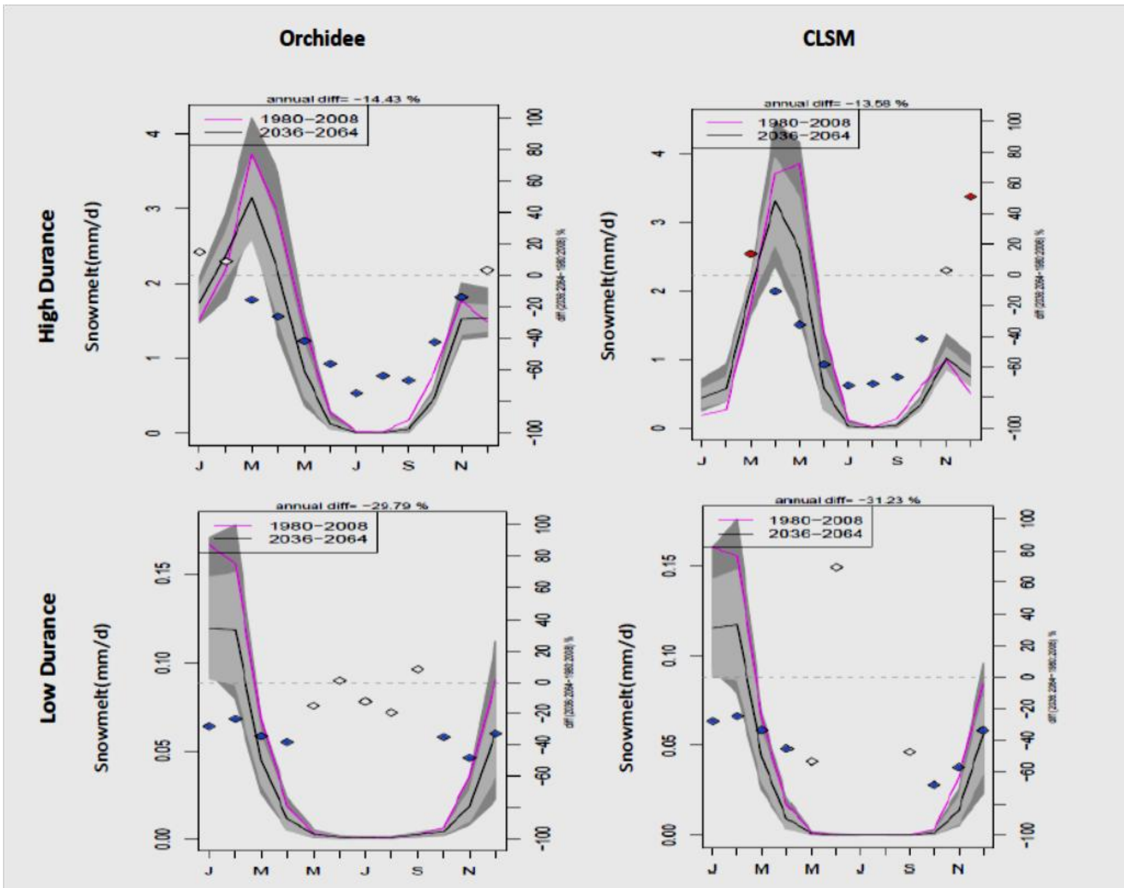

Figure 16. Monthly evolution of snowmelt rate for Upper (first row) and Low (second row) Durance (on the left: ORCHIDEE, on the right: CLSM). The dark grey envelope shows the envelope of minimum to maximum future simulations; the light grey envelope shows the envelope of the mean of future simulations minus or plus the standard deviation; the diamonds are related to the right vertical axis and give the mean relative change between the two periods, with color inside when the monthly difference is statistically significant using a Student test.

Table 9 shows the future evolution of the total evaporation flux. For both CLSM and ORCHIDEE a clear upward trend in Upper Durance and a downward trend in Low Durance can be observed. In Mid Durance ORCHIDEE shows a small upward trend, whereas CLSM shows a small downward trend, which is consistent with the "hydrid" functioning of the Mid-Durance between the Upper and Low Durance, together with the specificities of the two models in the latter sub-basins. In the whole Durance the trend appears to be statistically insignificant for both models, slightly upward for ORCHIDEE and slightly downward for CLSM. In high altitudes, the decrease in the amounts of solid precipitation, which in turn leads to limited snow cover duration, can explain the increase in evaporation, as bare soil evaporation and transpiration begin sooner in spring and continue later in autumn. The downward evaporation trend in Low Durance is probably due to the significant decrease in total precipitation (-11.24%) in the same area.

Zones	ORCHIDEE				CLSM			
	Diff	Upward trend	Downward trend	No trend	Diff	Upward trend	Downward trend	No trend
Upper	10.27%	100%	0%	0%	6.83%	100%	0%	0%
Mid	1.90%	72.73%	0%	27.27%	-1.39%	18.18%	0%	81.82%
Low	-8.93%	0%	81.82%	18.18%	-7.29%	0%	72.73%	27.27%
The whole watershed	1.41%	27.27%	0%	72,73%	-0.42%	18.18%	0%	81.82%

Table 9. Future evolution of total evaporation in the Durance watershed

To sum up, despite the discrepancies between the models in the present time simulation, the differences in the future simulations are very small. Both models project an important decrease in total runoff, which is bigger for the southern catchments compared to the northern ones. The difference between the models in the decrement percentages in Low Durance is quite important, but as mentioned above a high decrease in total runoff under water stress situations has been repeatedly observed in CLSM's climate change simulations. The trend for snowmelt and snow mass are downward for both the models (statistically significant). On the other hand, at a basin scale a clear trend regarding evaporation isn't shown for both ORCHIDEE and CLSM. However, both the models show a significant upward trend at high altitudes and a downward trend in low altitudes.

7. Conclusions

A good representation of the hydrological processes in the Durance River watershed which in turn will result in a proper estimation of the water resources -both in present time and in the future- is very important, as the river plays a significant role for the people and the economy of the area. In this work, a Land Surface Model (LSM) called ORCHIDEE was implemented in the Durance watershed in order to estimate the different fluxes between the atmosphere and the land surface in present time and in the future. The results of ORCHIDEE were compared with the results of another LSM called CLSM.

Before the comparison of the two models in present time, a validation of the simulated runoff against daily discharge observations provided by EDF had been performed. Both models overestimated total runoff, which by means of water conservation means that they both underestimated total evaporation. However, the runoff overestimation of CLSM was much smaller compared to ORCHIDEE, which resulted in a better fit between the simulation and observation curves for CLSM.

The comparison between the two models in present time showed that the main difference between them is that ORCHIDEE is a “wetter” model. This means that it calculates higher mean annual total runoff, and thus, lower evapotranspiration than CLSM. This difference was larger in high altitudes, showing that it is partially related to differences in snow parameterization between the models. In particular, ORCHIDEE simulated smaller snow mass and sublimation and larger snowmelt rate, which favors runoff against evaporation. A smaller dissemblance between the models in the Low Durance was also observed, mainly due to differences in the parameterization of interception loss.

A very interesting question in which this study tried to give an answer is whether the observed differences between the two models in the current hydrological behavior result in a different response of the models in climate change simulations. Our results show that despite the aforementioned discrepancies between the models in the present time simulations, the observed differences in the climate change simulations are very small. Particularly, both models project a statistically important downward trend for total runoff. Especially in the low Durance, a severe decline in future water resources was found by both models (larger in CLSM). The trends for snowmelt and snow mass are also downward for both the models and the decrement percentages are very close for ORCHIDEE and CLSM in all the cases. Only in the case of total evaporation the response of the two models wasn’t clear at a basin scale, as ORCHIDEE shows a slight increase in evaporation, whereas CLSM shows a slight decrease, with both of these trends being statistically insignificant. At a sub-basin scale an evident upward trend for total evaporation in high altitudes and a downward trend in low altitudes are projected by both models.

To sum up, the proper estimation of the future evolution of water resources in the Durance watershed is very important, as the river satisfies many uses. A severe decrease in water resources, like the one projected in this study by both ORCHIDEE and CLSM, can cause conflicts for water and land use. This is the reason why we believe that the work done in this study should be continued in the future, so that we will obtain an even better estimation concerning the future evolution of the water resources in the area. A first thing that can be done in a future study is the implementation of the new snow parameterization (Wang, 2011) in ORCHIDEE and the comparison of the new simulation with both the initial simulation of ORCHIDEE and the final “version” of CLSM. This will help us understand to which extent the overestimation of total runoff by ORCHIDEE in the present time simulation is caused by the snow parameterization. Another perspective for the future would be the calibration of ORCHIDEE, in order to obtain a better fit between the simulated and the observed curves. Finally, more validation datasets should be used in the future so that the simulated fluxes for both ORCHIDEE and CLSM could be validated against as many observations as possible.

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