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# Verification of the new ECMWF ERA-Interim reanalysis over France

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**Verification of the new ECMWF ERA-Interim reanalysis**

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**Abstract**

An evaluation of the global ECMWF atmospheric reanalysis ERA-Interim (with a 0.5° grid) is performed over France, based on the high resolution (8 km) SAFRAN atmospheric reanalysis. The ERA-Interim precipitation, Incoming Solar Radiation (ISR), air temperature, air humidity, and wind speed, are compared with their SAFRAN counterparts. Also, interpolated in situ ISR observations are used in order to consolidate the evaluation of this variable. The daily precipitation estimates produced by ERA-Interim over France correlate very well with SAFRAN. However, the values are underestimated by 26%. A GPCP-corrected version of ERA-Interim is less biased (10–15%). The ERA-Interim estimates of ISR correlate very well with SAFRAN and with in situ observations on a daily basis. Whereas SAFRAN underestimates the ISR by 6–8 $W m^{-2}$, ERA-Interim overestimates the ISR by 9–10 $W m^{-2}$. In order to assess the impact of the ERA-Interim errors, simulations of the ISBA-A-gs land surface model are performed over the SMOSREX grassland site in southwestern France using ERA-Interim (with and without GPCP rescaling) and SAFRAN. Latent and sensible heat fluxes are simulated, together with carbon dioxide fluxes. The rescaled ERA-Interim performs better than the original ERA-Interim and permits to achieve flux scores similar to those obtained with SAFRAN.

## 1 Introduction

Soil moisture controls the exchange of water and heat energy between the land surface and the atmosphere through evaporation and plant transpiration. As a result, it is a key variable in short- and medium-range meteorological modelling, climate and hydrological studies. A significant amount of studies have been conducted to obtain soil moisture products. For that purpose, land surface modelling (Dirmeyer et al., 1999; Georgakakos and Carpenter, 2006 among others) and remote sensing (Wagner et al., 1999a, b; Njoku et al., 2003; Kerr et al., 2007) techniques are used. Another variable,





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the Leaf Area Index (LAI), is defined as the total one sided area of photosynthetic tissues per unit ground surface area. Monitoring the distribution and changes of LAI is important to monitor vegetation. It is a fundamental parameter in land-surface models. This variable controls the link between the biosphere and the atmosphere through various processes such as photosynthesis, respiration, transpiration, and rain interception. Long time series of accurate LAI products are essential for climate change studies, and to validate biochemical models (Brut et al., 2009).

In the framework of the HYMEX (HYdrological cycle in the Mediterranean EXperiment) project (HYMEX White Book, 2008) and particularly with the aim of developing a soil moisture and vegetation biomass climatology over Europe and North Africa, this study investigates the quality of the European Center for Medium range Weather Forecasting (ECMWF) ERA-Interim (ERA-I) gridded atmospheric reanalysis over France, where a high resolution atmospheric analysis (Système d'Analyse Fournissant des Renseignements A la Neige – SAFRAN; Durand et al., 1993) is available. In the HYMEX project, this climatology will be used to drive land surface and runoff models, like the Total Runoff Integrating Pathways (TRIP; Oki et al., 1997) coupled to the Interactions between Soil Biosphere and Atmosphere (ISBA) model (Noilhan and Planton, 1989; Noilhan and Mahfouf, 1996) to build a soil moisture, LAI and river flow climatology over the Mediterranean basin. The TRIP model is able to isolate the river basins, inter-basin translation of water through river channels, as well as collect and route runoff to the river mouth(s) for all the major rivers (Oki et al., 1998). The river flow simulated by TRIP can be used for the verification of the variables simulated by the land surface model because the river flow is driven by the runoff simulated by ISBA.

Because the Mediterranean basin will probably be affected by climate change to a large extent (Gibelin and Déqué, 2003), it is important to build a monitoring system of the land surface variables and of the hydrological variables (river flow,...) over this region. The ISBA model is driven by atmospheric variables such as precipitation, downwelling radiation (shortwave and longwave), wind speed, air temperature and air humidity. Over France (Fig. 1), the SAFRAN analysis provides high resolution (8 km)





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gridded atmospheric variables. Over the whole Mediterranean domain, gridded high resolution atmospheric reanalyses are not available so far. The ERA-I data produced by the ECMWF could be used to drive the ISBA model at a spatial resolution of 0.5°, and to produce surface flux and runoff estimates. In order to verify the quality of the low resolution ERA-I data, the SAFRAN reanalysis can be used as a reference, over France. In this study, the ERA-I estimates of atmospheric variables (precipitation, Incoming Solar Radiation (ISR), air temperature, air humidity and wind speed) are compared with the SAFRAN product for two years: 2001 and 2003. In 2003, France was affected by a large scale heat wave, which caused a severe drought in many areas. On the other hand, 2001 was a rather normal year, representative of the climatology. In the case of ISR, another high resolution product (Brion et al., 2005), based on in situ observations, is used as well. Finally, the impact of using ERA-I instead of SAFRAN in ISBA is assessed over a grassland site in southwestern France, for which surface flux and soil moisture profile observations are available.

## 2 Data and methods

This section presents ERA-I and the different datasets used for the verification of the ERA-I atmospheric variables at the surface. The precipitation and the ISR products are presented first. Then, the other variables (air temperature, air humidity, and wind speed) are described. In order to assess the impact of using ERA-I instead of SAFRAN, the ISBA model was run using the two atmospheric reanalyses over the SMOSREX grassland site (De Rosnay et al., 2006) in southwestern France for a long period of seven years (2001–2007), as in Albergel et al. (2010a). The simulated soil moisture and surface energy, water, and $CO_2$ fluxes derived from ERA-I were compared with the reference SAFRAN-derived values at the SMOSREX site.





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## 2.1 Precipitation data

Precipitation is the most important parameter for a great number of applications, but, at the same time, this variable is not easily mapped because of its discontinuity in space and time. Along with SAFRAN and the ERA-I original data, a number of precipitation products are considered: the rescaled ERA-I precipitation, GPCP (product of the Global Precipitation Climatology Project; Adler et al., 2003), GPCC (product of the Global Precipitation Climatology Centre; Rudolf et al., 2005), and Persiann (Precipitation Estimation from Remotely Sensed Information using Artificial Neural Networks; Sorooshian et al., 2000).

### 2.1.1 The SAFRAN analysis

SAFRAN is a mesoscale atmospheric analysis system for surface variables. It produces an analysis at the hourly time step using atmospheric simulations and ground data observations. SAFRAN is based on climatically homogeneous zones and is able to take topography effects into account. Originally intended for mountainous areas, it was later extended to cover France. The detailed validation of the SAFRAN analysis over France (Quintana et al., 2008) and feedbacks from the operational implementation showed that SAFRAN was robust (wind, temperature, relative humidity, precipitation...) and provided accurate meteorological values to force ISBA. As far as precipitation is concerned, SAFRAN uses a large number of rain gauges and can be considered as a reference. The surface atmospheric variables are given at 2 m a.g.l., except for wind speed (10 m a.g.l.).

### 2.1.2 The ERA-I reanalysis

The ERA-I reanalysis starts in January 1989 and provides meteorological data until present (the data are available in near real-time, with a delay of approximately one month). These atmospheric forcing data were projected on a grid of $0.5^{\circ} \times 0.5^{\circ}$ from





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the original Gaussian reduced grid (T255 reduced Gaussian grid of about 0.7° × 0.7°), at 3-h intervals (00:00, 03:00, 06:00, 09:00, 12:00, 15:00, 18:00 and 21:00 UTC). ERA-I relies on a 4D-VAR system which uses observations within the windows of 15:00 UTC to 03:00 UTC and 03:00 UTC to 15:00 UTC (in the next day) to initialize forecast simulations starting at 00:00 UTC and 12:00 UTC, respectively. In order to allow sufficient spin-up, the first nine hours of the forecast simulations are not used. All the surface atmospheric variables are given at 10 m a.g.l. More information of the full ERA-I reanalysis products can be found in Simmons et al. (2007).

### 2.1.3 ERA-I rescaled

A scale-selective rescaling procedure that corrects ERA-I 3-hourly precipitation was implemented by ECMWF in order to represent better the monthly accumulated precipitation provided by the Global Precipitation Climatology Project (GPCP v2.1) product. This method extracts the information from GPCP v2.1 at the scale for which this dataset is provided (2.5° × 2.5°) and rescales the ERA-I precipitation at full resolution. For this reason, this method preserves the fairly high resolution of ERA-I while correcting for large-scale errors detected from GPCP. It must be noted that the rescaling method was calibrated using available high resolution precipitation estimates over the USA. Furthers details of the specific method used to rescale ERA-I can be found in Balsamo et al. (2010).

### 2.1.4 Other monthly precipitation datasets

In order to assess the performance of ERA-I and ERA-I rescaled precipitation products, three other products were evaluated over France: GPCC, GPCP, and Persiann.

The Global Precipitation Climatology Centre (GPCC) provides global monthly precipitation analyses for monitoring and research of the earth's climate at 1° × 1° resolution. The centre is a German contribution to the World Climate Research Programme (WCRP), to the Global Climate Observing System (GCOS), and to the Global Earth





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Observation System of Systems (GEOSS). The objective of GPCC is to assess water resources, climate variability and trends and to improve the monitoring of floods and droughts. GPCC published in 2008 a new global monthly precipitation climatology for the 1901–2007 period. The GPCC data base comprises monthly precipitation totals from more than 70 000 rain gauge stations in the world. It can be noted that there is an intensive quality control of observation data and station metadata. A quality control procedure permits to produce a high quality analysis (Fuchs et al., 2009).

The GPCP v2.1 data is a monthly climatology provided globally at 2.5° × 2.5° resolution and covering the period from 1979 to present. The general objective of GPCP is to combine the precipitation information available from several sources into a final merged product. For this reason, the GPCP dataset combines different sources of data, such as satellite data, together with rain gauge data which are assembled and analyzed by the GPCC of the Deutscher Wetterdienst and by the Climate Prediction Center of the National Oceanic and Atmospheric Administration (NOAA). GPCP v2.0 is described in Adler et al. (2003). The processing strategy for GPCP v2.1 is substantially the same as described for v2.0 but version 2.1 takes advantage of the improved GPCC gauge analysis and the usage of additional satellite-derived products such as the Outgoing Longwave Radiation Precipitation Index (OPI) data from the NOAA series satellites. Further information of these improvements are given in Huffman et al. (2009).

Persiann is an automated system for Precipitation Estimation from Remotely Sensed Information using Artificial Neural Networks and has been developed for the estimation of rainfall from geosynchronous satellite infrared imagery. Persiann provides data at the resolution of 0.25° × 0.25° and with a 6-h time step (Sorooshian et al., 2000). Over tropical regions, the accuracy of the rainfall product is improved by adaptively adjusting the network parameters using the instantaneous rain-rate estimates from the Tropical Rainfall Measurement Mission (TRMM) Microwave Imager (TMI).



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### 2.1.5 Intercomparison approach

In this study, a comparison of different precipitation data sets is performed for 2001 and 2003. In order to verify the quality of ERA-I and to assess to what extent the rescaling of ERA-I improves the precipitation estimates, the comparison is performed at different temporal and spatial scales. First, the average precipitation over the France domain derived from ERA-I and ERA-I rescaled are compared with SAFRAN with monthly and daily time steps. Second, the comparison is performed at the scale of the ERA-I grid (0.5°). For the sake of comparison, the resolution of the SAFRAN analysis was reduced from 8 km to 0.5° by aggregation, resulting in a grid of 308 points. In order to compare the three datasets, three scores are studied: the square correlation coefficient (temporal correlation), the mean bias, and the root mean square error (RMSE). Also, the spatial correlations between SAFRAN and either ERA-I or ERA-I rescaled is presented to show the correlation from a grid cell to another. Finally, a comparison between all datasets (presented before) for a monthly time step over the whole France is examined.

## 2.2 Incoming Solar Radiation (ISR) data

The same comparison with SAFRAN was performed for the Incoming Solar Radiation (ISR). It is important to note that in SAFRAN, the ISR is not derived from ground observations, but calculated by a radiation scheme. From 1994 onward, another product based on ground observations is available (Brion et al., 2005). Brion et al. (2005) have shown that the interpolated ground observations are often closer to independent observations than SAFRAN. For this variable, ERA-I was compared with both SAFRAN and Brion data sets. As ground observations are scarce in mountainous areas, the quality of the Brion product is poor in these regions. Therefore, above 1500 m a.s.l., the SAFRAN product is used in the Brion data set. Under 500 m a.s.l., the Brion data are considered alone, and from 500 m a.s.l. to 1500 m a.s.l. a linear mixing equation is used to combine the Brion and SAFRAN estimates. Like the precipitation, the





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comparison for the ISR is performed for both Brion and Safran at different temporal and spatial scales (over whole France or at the scale of ERA-I grid and at a monthly time step or a daily time step).

### 2.3 Temperature, humidity and wind speed data

Air temperature, air humidity and wind speed provided by ERA-I are compared with SAFRAN. The comparison is performed at two times: morning (06:00 UTC) and noon (12:00 UTC). For both morning and noon variables, statistical scores (square correlation coefficient, bias and RMSE) were computed for the years 2001 and 2003 based on one value per day. It is important to note that the data are estimated at different heights. In SAFRAN, air temperature and air humidity are analyzed at 2 m and wind speed at 10 m above the surface. In ERA-I, the three variables are analysed at 10 m. Although wind speed is calculated at the same height for SAFRAN and ERA-I, it is important to remember that the definition of air temperature and air humidity differ from SAFRAN to ERA-I.

### 2.4 Impact study on the SMOSREX site

The impact of using ERA-I is assessed on the SMOSREX grassland site in southwestern France.

#### 2.4.1 The SMOSREX experimental site

The SMOSREX (Surface Monitoring Of the Soil Reservoir EXperiment) experimental site is located in Mauzac, near Toulouse, in the south of France (De Rosnay et al., 2006). It is a field campaign, which has been in operation since January 2001. Part of the SMOSREX experimental site is covered by a grassland of about $3.2\times10^4$ m$^2$ (180 m × 180 m), mown once a year at wintertime. At SMOSREX, all the atmospheric forcing variables required to run ISBA-A-gs are measured: there are continuous ground measurements of atmospheric pressure, air humidity, air temperature, long-wave and





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short-wave incident radiation, rain rate, wind speed. Soil moisture is observed at ten depths (0–6, 10, 20, 30, 40, 50, 60, 70, 80, 90 cm) with an half hourly time step. It can be noted that from those measurements it is possible to estimate the root-zone soil moisture content $w_2$ ($m^3\,m^{-3}$), integrated over the root-zone profile (0–95 cm).

### 2.4.2 The land surface model ISBA-A-gs

On the basis of ISBA (Noilhan and Planton, 1989; Noilhan and Mahfouf, 1996), Calvet et al. (1998) developed ISBA-A-gs. It is a $CO_2$ responsive version of ISBA which accounts for the effect of the atmospheric $CO_2$ concentration and for the interactions between all environmental factors on the stomatal aperture. The most important modification in the A-gs version compared to the classic ISBA is that photosynthesis and its coupling with stomatal conductance at a leaf level is accounted for. The vegetation net assimilation is computed and used as an input to a simple growth sub-model able to predict LAI. ISBA-A-gs is able to simulate GPP (Gross Primary Production), NEE (Net Ecosystem Exchange), LAI, the energy and mass fluxes such as sensible and latent heat fluxes, and soil moisture. ISBA-A-gs was implemented in the SURFEX (SURFace Externalisée) modelling platform (Le Moigne et al., 2009). In this study, SURFEX is used "offline", i.e. without coupling the land surface with an atmospheric model. The comparison of the different atmospheric parameters between SAFRAN and ERA-I was performed on the grid cell corresponding to the SMOSREX site for a 16-year (1990–2007) period, corresponding to the available ERA-I data set. After comparing the different SAFRAN and ERA-I atmospheric variables throughout the 16-year period, ISBA-A-gs is used to simulate the SMOSREX grassland for the period 2001–2007, with these two atmospheric forcing data sets. The same comparison was made with the precipitation of ERA-I rescaled.





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## 3 Results

This section presents the results obtained for each atmospheric parameter for the year 2001 and the year 2003.

### 3.1 Precipitation data

The purpose of this section is to evaluate the ERA-I precipitation data against precipitation derived from the SAFRAN analysis. In order to make a first assessment of ERA-I, Fig. 2 presents the mean daily precipitation over France for 2001, through time series derived from SAFRAN and ERA-I. At the scale of the whole country, the ERA-I mean daily precipitation is very close to SAFRAN. Figure 2 shows that a significant correlation exists between the two data sets ($R^2 = 0.89$): the two curves are very similar throughout 2001 and the precipitation events occur at the same time. It can be noticed that small differences may arise between the two data sets, particularly in January, February, April, August and September for this particular year. This bias is always in the same direction: on a daily scale, ERA-I tends to underestimate the precipitation.

In order to assess the bias correction of ERA-I rescaled, Fig. 2 presents this data set too. Figure 2 shows that the ERA-I rescaled dataset is closer to SAFRAN than the original ERA-I. The rescaling improves the quality of the precipitation estimates. Although smaller differences are observed between ERA-I rescaled and SAFRAN, it can be noted that when the precipitation are more abundant (in March, April, October 2001), ERA-I rescaled tends to overestimate the precipitation. Figure 3 (left) shows the same characteristics but for a monthly time step. Also, Fig. 3 (right) presents the same comparison 2003. The precipitation estimates for 2003 confirm the conclusions obtained for 2001. Table 1 summarizes the scores corresponding to these comparisons. The square correlation coefficient between the daily precipitation estimates was computed for each ERA-I grid-cell (308 values) for the whole year 2001 (365 values) and these coefficients were plotted in Fig. 4 (left). Figure 4 (right) presents the annual mean bias between ERA-I and SAFRAN, as well. The correlations obtained at the different





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grid points are good over a large part of France ($R^2 > 0.8$). Topography seems to be an issue as (Fig. 1) ERA-I does not perform very well, e.g., in Corsica, close to the Mediterranean Sea and in the eastern Pyrenees, which present complex terrains. Regarding the bias, for most grid cells, ERA-I slightly underestimates precipitation. This underestimation is more important in mountainous areas (Massif Central, Vosges, Pyrenees, Alps, Jura). The same comparison is shown in Fig. 4 for ERA-I rescaled. Regarding the $R^2$ score, ERA-I rescaled performs better than the original ERA-I for a large part of France (in Corsica, and close to the Mediterranean Sea). However, the rescaling does not improve (and even degrade) the correlation in the eastern Pyrenees. Figure 4 (right) illustrates the bias reduction induced by the rescaling: the number of grid cells with a low bias (less than 5 mm $y^{-1}$) increases and a number of points now present an overestimation of the precipitation, especially in southern France.

Figure 5 illustrates the spatial correlation of ERA-I and ERA-I rescaled with SAFRAN, for four months (January, April, July, October) of 2001, i.e. ERA-I vs. SAFRAN monthly accumulated precipitation calculated for each ERA-I grid cell. Table 2 details the performance of ERA-I and ERA-I rescaled on a monthly basis, for 2001 and 2003. Figure 5 shows, again, that ERA-I tends to underestimate the precipitation. In July and in October 2001, it can be noted that a few outlier grid cells present a particularly large underestimation. These grid cells gather in the same region, depending on the weather situation, and represent intensive precipitation events related to fine scale processes occurring in mountainous areas. Those processes are not represented well by ERA-I.

Table 2 shows that the square correlation coefficients vary from 0.32 (January 2003) to 0.69 (December 2001). With ERA-I rescaled, $R^2$ varies from 0.09 (June 2003) to 0.75 (September 2001). Also, the bias and RMSE vary from one month to another. The temporal variation of the scores does not seem to depend on the precipitation amount: there is no correlation between the monthly $R^2$ values and the mean monthly precipitation data ($R^2 = 0.006$) and a rather poor correlation between the mean monthly SAFRAN precipitation and the monthly bias ($R^2 = 0.22$). On average, ERA-I underestimates the reference SAFRAN data by 26.5% and ERA-I rescaled by 12%.



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In order to assess the quality of ERA-I and ERA-I rescaled, relative to other global precipitation estimates, the comparison was performed with the GPCC, GPCP and Persiann data sets. Figure 3 shows the mean monthly precipitation for 2001 and 2003, for all these data sets (SAFRAN, ERA-I, ERA-I rescaled, GPCP and GPCC) except for Persiann which presents a very large bias over France. Both GPCC and GPCP monthly estimates are closer to SAFRAN than ERA-I (either rescaled or not). Table 3 presents the scores obtained for this comparison and shows that the correlation between GPCC, GPCP and SAFRAN (on a monthly basis) is very good and that the bias is small. ERA-I is rescaled with GPCP data but it can be noticed that the mean annual bias (for 2001 and 2003) between GPCP and SAFRAN is less important than the mean bias between ERA-I rescaled and SAFRAN. The correlation computed between Persiann and SAFRAN is poor and the bias is very high. This is why this data set is not represented with the others in Fig. 3. Note that while the GPCP/GPCC data sets offer invaluable verification material for precipitation, only high temporal and spatial resolution data sets (such as SAFRAN/ERA-I) can be used for land surface modeling applications.

### 3.2 ISR data

A comparison of three ISR products (ERA-I, SAFRAN and Brion) was performed. SAFRAN cannot be considered as a reference data set for ISR, and the unbiased ISR Brion reference is used in this section. The three estimates of the daily ISR over France for 2001 are presented in Fig. 6. At the scale of the country, the three data sets are very similar. ERA-I correlates very well with SAFRAN and Brion ($R^2 = 0.96$ for SAFRAN and $R^2 = 0.98$ for Brion). At wintertime, when the ISR is low, the 3 estimates are almost the same, and the bias is close to zero. At summertime, when the ISR is high, more differences are observed between the three data sets. Figure 7 presents the same comparison but for a monthly time step, and illustrates the rather large difference between ERA-I and Brion at summertime. The corresponding scores





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are listed in Table 4. It can be noted that the difference between ERA-I and SAFRAN is higher than between ERA-I and Brion. ERA-I tends to overestimate the ISR, which is consistent with the underestimation of the precipitation found in Sect. 3.1. The mean overestimation of the monthly ISR by ERA-I represents up to 6% of the reference Brion estimates. Although SAFRAN tends to underestimate the ISR, it correlates well with the other estimates.

In a second stage, the comparison was performed at the scale of the ERA-I grid cell. For the sake of comparison, the high resolution (8 km) SAFRAN and Brion grid cells were aggregated at the 0.5° resolution of ERA-I. The square correlation coefficient between ERA-I and SAFRAN time series (daily time step) with Brion, and the mean bias, were calculated for each ERA-I grid cell for 2001 and were plotted in Fig. 8. ERA-I correlates better with the reference Brion product than SAFRAN. In coastal regions of the Atlantic ocean and the Mediterranean Sea where ERA-I correlates less with SAFRAN ($R^2 < 0.98$ in Fig. 7) higher correlations of ERA-I with Brion are observed. The same trend is observed in the centre of France. In general, ERA-I correlates very well with Brion ($R^2 > 0.99$ for a large part of France), with the exception of Corsica and northern Alps. This is not observed with SAFRAN as for these areas, the Brion product is based on SAFRAN ($R^2 = 1$ and no bias). Concerning the bias, similar conclusions can be derived from Fig. 8. More often than not, the ERA-I estimates are greater than the Brion estimates. The difference between the two data sets is relatively weak excepted for Corsica, Brittany and the Pyrenees, where ISR is slightly more overestimated and in the Alps where ERA-I underestimates the values. Consistent with Fig. 7, SAFRAN and ERA-I tend to underestimate and overestimate the ISR, respectively. However, fewer ERA-I estimates are affected by a large bias: for areas where Brion is based on in situ observations (i.e. excluding mountainous areas and Corsica), 8% and 1.4% of the grid cells present a mean bias lower than $-20\,\mathrm{W\,m^{-2}}$ or greater than $20\,\mathrm{W\,m^{-2}}$, for SAFRAN and ERA-I, respectively.

The scores obtained between ERA-I and Brion or Safran were examined for the 12 months of 2001 (not shown). The square correlation coefficient vary from 0 (May)





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to 0.82 (December) for SAFRAN and from 0.03 (May) to 0.91 (February) for Brion. No significant correlation could be found between the monthly scores and the mean monthly ISR.

### 3.3 Air temperature, air humidity and wind speed

In SAFRAN, the analyses of air temperature, air humidity and wind speed are performed every six hours using all available observations. The vertical profiles of these quantities are analyzed with a vertical resolution of 300 m. The analysed values are linearly interpolated to an hourly time step. More information about these analyses can be found in Quintana-Segui et al. (2008).

They found that the SAFRAN surface air temperature and relative humidity were well reproduced, presenting no bias. Wind speed was also well reproduced, however it was underestimated by SAFRAN with a mean bias of $-0.3\,\mathrm{m\,s^{-1}}$.

Table 5 presents the comparison (annual bias, RMSE and square correlation coefficient) between ERA-I and SAFRAN for three atmospheric variables (air temperature, air humidity and wind speed) over France for 2001 and for 2003. Data are considered at 06:00 and at 12:00 UTC each day. The ERA-I air temperature and air humidity correlate very well with SAFRAN, with $R^2 > 0.97$, and the mean difference between the two datasets over France is relatively small. At 06:00 UTC, ERA-I tends to overestimate both air temperature and air humidity. At 12:00 UTC, ERA-I tends to underestimate these quantities. At the grid cell level, more specific information can be extracted. Regarding air temperature at 06:00 UTC, ERA-I overestimates the values from 0.5 K to 4 K for a large part of France and particularly in Brittany, close to the Atlantic coast, in the mountains (Alps and Pyrenees), in southeastern France and in Corsica. This overestimation is greater in mountainous areas for both 2001 and 2003. SAFRAN (8 km) and ERA-I ( ~70 km) do not work at the same spatial scale and for this reason, the topography is represented better by SAFRAN than by ERA-I. The smoother ERA-I topography could explain the overestimation of air temperature in these areas. At 12:00 TU, ERA-I tends to underestimate air temperature for a large part of France (except for central regions) and particularly in coastal regions (Atlantic and Mediterranean coasts and Corsica). In mountainous areas, ERA-I may overestimate air temperature by more than 4 K. Regarding air humidity, although the mean bias over France at 06:00 UTC for 2001 is greater than 0 (on average, ERA-I overestimates air humidity), ERA-I slightly underestimates (mean bias of $-2.7 \times 10^{-4}$ kg kg$^{-1}$) air humidity for 66% of the considered area. For the rest of France (33%), ERA-I overestimates the values (mean bias of $5.6 \times 10^{-4}$ kg kg$^{-1}$) and it can be noted that in Corsica, in southeastern France and in mountainous areas, ERA-I markedly overestimates air humidity. The same conclusions can be drawn for 12:00 UTC except for Brittany and in southern France (Mediterranean coast and Corsica) where the bias is very small. At least part of the difference between ERA-I and SAFRAN may be explained by the height at which these quantities are considered (at 2 m for SAFRAN and 10 m for ERA-I). Regarding wind speed, the correlation between ERA-I and SAFRAN is good ($R^2 > 0.9$). However, a rather large bias is observed between the two estimates, of about 0.9 m s$^{-1}$ at 06:00 UTC. ERA-I provides higher wind speed values in a large part of France, except for mountainous areas and for southwestern France where it slightly underestimates the values. However, it must be noted that SAFRAN tends to underestimate wind speed by 0.3 m s$^{-1}$, on average (Quintana-Segui et al., 2008).

### 3.4 Studies on the SMOSREX site

In order to investigate possible trends in the time series and to compare SAFRAN and ERA-I over a long period of time, the two data sets were studied at the grid-cell corresponding to the SMOSREX site in southern France, for the 1990–2005 period. No trend could be detected for any variable (precipitation, air temperature, air humidity, Incoming Solar Radiation, incoming longwave radiation and wind speed).

Table 6 presents the comparison scores obtained for each variable. Table 6 shows very good correlations between ERA-I and SAFRAN for air humidity, incoming longwave radiation and ISR ($R^2 > 0.7$). Correlations are not as good for air temperature, wind speed ($R^2 \sim 0.6$) and precipitation ($R^2 \sim 0.5$). The precipitation rescaling of ERA-I





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data slightly improves the correlation. Regarding the bias, it is relatively high for ISR and precipitation (difference greater than 15%). The rescaling reduces the magnitude of the bias for the precipitation (for this site, ERA-I rescaled overestimates the SAFRAN precipitation by 7%). The mean biases for wind speed and air humidity are close to −10% and are less important for the incoming longwave radiation (about −4%).

## 4 Discussion

Although ERA-I data sets correlate well with the French SAFRAN reference, differences are observed between the two data sets. While the precipitation rescaling performed by ECMWF reduced the mean bias of about 50%, no correction was proposed so far for the Incoming Solar Radiation. This might be critical, as the difference between ERA-I and the reference Brion estimates is more important than for SAFRAN, especially at summertime. The bias affecting the ERA-I and SAFRAN ISR, may have an impact on soil moisture, LAI and other biophysical variables produced by land surface models forced by these ISR estimates. The precipitation bias of ERA-I and ERA-I rescaled may also significantly impact the simulations. An attempt was made to quantify the impact of errors in the atmospheric forcing on the simulations of the ISBA-A-gs model for the SMOSREX grassland. Over this experimental site, a number of studies have shown that the ISBA-A-gs model is able to simulate well the water, energy $CO_2$ fluxes, LAI and root-zone soil moisture (e.g. Albergel et al., 2010a, b), using the locally observed atmospheric forcing or SAFRAN. ISBA-A-gs was run with ERA-I, ERA-I rescaled and SAFRAN and the different biophysical parameters and fluxes obtained with the different atmospheric forcings were inter-compared.

The SMOSREX comparison was performed for the 2001–2007 period and Fig. 9 shows the results obtained for LAI and root-zone soil moisture. Regarding the root zone soil moisture, the ISBA-A-gs simulations forced by ERA-I rescaled are much closer to the simulations forced by SAFRAN than to the simulations forced by the original ERA-I. Figure 9 shows a large difference between the ERA-I and ERA-I rescaled





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derived simulations of the root soil moisture. Consistent with the underestimation of precipitation by ERA-I (Table 6), the root-zone soil moisture driven by ERA-I is underestimated in comparison to the root-zone soil moisture driven by SAFRAN and ERA-I rescaled, at summertime and also, more often than not, at wintertime. Concerning LAI, similar conclusions can be drawn from Fig. 9. LAI is underestimated when ISBA-A-gs is forced with ERA-I. Moreover, the leaf onset is systematically delayed. This is due to the increased drought limitation to plant growth caused by the underestimated precipitation.

Table 7 presents the various ISBA-A-gs scores obtained for soil moisture and LAI (for which observations are available over the 2001–2007 period) and for surface fluxes (2005–2007 period, only), with the different atmospheric forcings (ERA-I and ERA-I rescaled) compared to the values obtained with the SAFRAN atmospheric data set. The $R^2$ values between ERA-I- and SAFRAN-derived simulations of root zone soil moisture, surface soil moisture, LAI and $CO_2$ flux are improved by the use of the ERA-I rescaled precipitation. Biases are decreased by the use of ERA-I rescaled, particularly for the two soil moisture variables (root-zone and surface soil moisture). This sensitivity study shows that the bias on the ERA-I precipitation may have a large impact on the simulation of the different biophysical variables and fluxes, except for the sensible and latent heat fluxes. It appears that the precipitation rescaling improves the different $R^2$ skill scores for the different parameters but the rescaling mainly impacts LAI and the $CO_2$ flux.

Another comparison between ERA-I rescaled and SAFRAN was performed in order to assess the relative impact of precipitation and ISR, which are the most biased ERA-I variables on the ISBA-A-gs simulations. ISBA-A-gs was run in three configurations: (1) SAFRAN, (2) SAFRAN except for SAFRAN precipitation replaced by the ERA-I rescaled precipitation, and (3) SAFRAN except for SAFRAN ISR replaced by the ERA-I ISR. The comparison was performed on the 2001–2007 period and Fig. 10 shows the results obtained for LAI and root zone soil moisture. Regarding the root zone soil moisture simulations, the three curves are very similar. However, the root-zone soil





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moisture obtained from SAFRAN with ERA-I ISR tends to be lower than the reference SAFRAN simulation. This difference is more pronounced from August to November. Indeed, the period from April to August is characterized by the overestimation of ISR by ERA-I. This tends to enhance evapotranpiration, resulting in a significantly dryer soil from August to November. At wintertime and springtime, when the ERA-I ISR is very close to SAFRAN, the two simulations are similar. The use of the ERA-I rescaled precipitation data set, has an opposite effect on the root-zone soil moisture: the root-zone soil moisture is overestimated, consistent with the 7% overestimation of the precipitation by ERA-I rescaled for this site (Table 6). For the LAI, the use of the ERA-I ISR has little impact on the simulations. The difference obtained with SAFRAN with the ERA-I rescaled precipitation is more significant, with higher LAI values at summertime and during the autumn. This is caused by the reduced drought impact on LAI caused by the overestimated precipitation. The scores obtained for the two configuration simulations (SAFRAN + ERA-I ISR and SAFRAN + ERA-I rescaled precipitation) compared with the reference SAFRAN-derived ISBA-A-gs simulation are presented in Table 7. For root-zone soil moisture simulations, the ERA-I ISR does not have a large impact on correlation ($R^2 = 0.97$) but causes lower simulated values. ERA-I rescaled precipitation impact $R^2$ more significantly but have a lower impact than ISR on the bias. Overall, at the SMOSREX site, it seems that the quality of the ERA-I precipitation data is more critical than the quality of the ERA-I ISR to simulate soil moisture. For LAI, the use in SAFRAN of the ERA-I rescaled precipitation tends to degrade the scores more than using all the variables of the ERA-I rescaled data set. The impact of using the ERA-I ISR in SAFRAN is much lower. Regarding the $CO_2$ flux, similarly to LAI and soil moisture, it seems that the quality of precipitation is more essential than the quality of ISR. Regarding the sensible heat and water fluxes (*H* and *LE*), a different response is observed, with a larger impact of the ERA-I ISR. Overall, Fig. 10 and Table 7 show that the ERA-I ISR and precipitation impact the ISBA-A-gs simulations. Changes in precipitation affect all the simulations generated by ISBA-A-gs, while ISR more particularly affects *H* and *LE*.





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In order to complete this analysis, it would be interesting to consider other sites or perform 2-D simulations over France, permitting to compare the three data sets and to assess the consequences of the biases of the ERA-I ISR and ERA-I rescaled precipitation. These results did not show a dramatic impact of ISR on the biophysical variables simulated for the SMOSREX site but more studies are needed to investigate the ISR bias effect.

## 5 Conclusions

ERA-I surface meteorological variables and ERA-I rescaled precipitation were compared with the SAFRAN high resolution atmospheric analysis over France and with the Brion reference Incoming Solar Radiation (ISR) product.

- The daily precipitation estimates produced by ERA-I over France correlate well ($R^2 > 0.6$ for 75% of France, and $R^2 > 0.8$ for 25% of France) with SAFRAN and are underestimated by 26%. A GPCP-corrected version of ERA-I is less biased (11–13%), in comparison with SAFRAN.
- The Incoming Solar Radiation from ERA-I is close to the Brion reference data set. The correlation is very good ($R^2 > 0.98$ for 75% of France). Whereas SAFRAN underestimates the ISR by 5%, ERA-I overestimates the ISR by 6%.
- The precipitation product is less satisfactory in mountainous areas, in Corsica and in the Mediterranean coast, where the correlations are less significant and the biases are more pronounced.
- Correlations are very high for air temperature, air humidity and wind speed.
- The impact of using ERA-I and ERA-I rescaled variables was assessed on the biophysical variables simulated by the ISBA-A-gs model over a grassland site in southwestern France (SMOSREX). It seems that changes in precipitation impact more the simulations than changes in ISR. However, more work is needed in order to analyze the impact of using ERA-I.





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**Table 1.** Precipitation over France in 2001 and 2003: temporal and spatial squared correlation coefficient and RMSE of ERA-I and ERA-I rescaled with respect to the SAFRAN analysis.

| Comparison type | Score | ERA-I 2001 | ERA rescaled 2001 | ERA-I 2003 | ERA rescaled 2003 |
|---|---|---|---|---|---|
| Temporal | $R^2$ | 0.89 | 0.89 | 0.90 | 0.90 |
| (365 days) | RMSE (mm/day) | 1.26 | 1.09 | 1.12 | 0.94 |
| Spatial | $R^2$ | 0.59 | 0.58 | 0.48 | 0.54 |
| (308 grid cells) | RMSE (mm/year) | 326 | 235 | 274 | 179 |



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**Table 2.** Monthly precipitation over France in 2001 as estimated by ERA-I, ERA-I and ERA-I rescaled vs. SAFRAN for the spatial repartition of precipitation ($R^2$, Bias and RMSE, for 308 grid-cells).

| Month | | | Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep | Oct | Nov | Dec |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | SAFRAN Mean Precipitation (mm month$^{-1}$) | | 127 | 54 | 170 | 109 | 69 | 49 | 102 | 63 | 85 | 87 | 68 | 49 |
| 2001 | Era-I | $R^2$ | 0.36 | 0.40 | 0.64 | 0.63 | 0.63 | 0.66 | 0.42 | 0.45 | 0.65 | 0.40 | 0.51 | 0.69 |
| | | Bias (mm month$^{-1}$) | −32 | −13 | −33 | −33 | −8 | −10 | −23 | −23 | −27 | −33 | −22 | −11 |
| | | RMSE (mm month$^{-1}$) | 48 | 21 | 52 | 43 | 25 | 26 | 40 | 32 | 39 | 42 | 32 | 19 |
| | Era-I rescaled | $R^2$ | 0.52 | 0.52 | 0.69 | 0.65 | 0.73 | 0.58 | 0.37 | 0.49 | 0.75 | 0.52 | 0.58 | 0.70 |
| | | Bias (mm month$^{-1}$) | −16 | −8 | −12 | −13 | −12 | −3 | −9 | −11 | −12 | −10 | −16 | −12 |
| | | RMSE (mm month$^{-1}$) | 35 | 18 | 42 | 31 | 23 | 27 | 34 | 24 | 26 | 26 | 27 | 19 |
| | SAFRAN Mean Precipitation (mm month$^{-1}$) | | 96 | 51 | 35 | 55 | 67 | 46 | 53 | 41 | 54 | 124 | 93 | 97 |
| 2003 | Era-I | $R^2$ | 0.32 | 0.60 | 0.54 | 0.49 | 0.60 | 0.38 | 0.57 | 0.42 | 0.59 | 0.5 | 0.50 | 0.59 |
| | | Bias (mm month$^{-1}$) | −26 | −17 | −10 | −13 | −21 | −11 | −15 | −15 | −10 | −34 | −24 | −21 |
| | | RMSE (mm month$^{-1}$) | 38 | 28 | 16 | 22 | 27 | 21 | 23 | 25 | 28 | 48 | 41 | 39 |
| | Era-I rescaled | $R^2$ | 0.4 | 0.65 | 0.61 | 0.62 | 0.55 | 0.09 | 0.52 | 0.33 | 0.68 | 0.70 | 0.69 | 0.72 |
| | | Bias (mm month$^{-1}$) | −15 | −9 | −6 | −6 | −11 | −2 | −8 | −2 | −2 | −14 | −9 | −9 |
| | | RMSE (mm month$^{-1}$) | 30 | 22 | 13 | 16 | 21 | 30 | 19 | 25 | 23 | 31 | 26 | 27 |





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**Table 3.** Representation of the seasonal variability of the precipitation over France in 2001 and 2003: Mean monthly bias, RMSE and squared correlation coefficient for ERA-I, ERA-I rescaled, GPCC, GPCP and Persiann with respect to SAFRAN data precipitation (from 12 monthly averages).

| Year | Score | ERA-I | ERA rescaled | GPCC | GPCP | Persiann |
|---|---|---|---|---|---|---|
| 2001 | $R^2$ | 0.955 | 0.991 | 0.995 | 0.972 | 0.443 |
| | Bias (mm/month) | −22.5 | −11.2 | −5.7 | −1.7 | 86 |
| | RMSE (mm/month) | 24.3 | 11.7 | 6.6 | 6.2 | 111.3 |
| | Mean Precipitation (Safran) | 1032 mm in 2001 | | | | |
| 2003 | $R^2$ | 0.984 | 0.989 | 0.993 | 0.980 | |
| | Bias (mm/month) | −18.1 | −7.7 | −2.7 | 3.1 | |
| | RMSE (mm/month) | 19.4 | 8.7 | 3.7 | 5.3 | |
| | Mean Precipitation (Safran) | 810 mm in 2003 | | | | |





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**Table 4.** Incoming Solar Radiation (ISR) over France in 2001 and 2003: Annual Bias, RMSE and squared correlation coefficient for ERA-I with respect to SAFRAN and Brion data (for 365 days) and RMSE and squared correlation coefficient for the spatial repartition of the average annual ISR (for 308 grid cells).

| Year | Score | Brion | SAFRAN | Comparison type |
|---|---|---|---|---|
| 2001 | $R^2$ | 0.97 | 0.96 | Temporal (365 days) |
| | Bias ($W\,m^{-2}$) | 9 | 15.8 | |
| | RMSE ($W\,m^{-2}$) | 17.7 | 25 | |
| | Mean ISR Brion | 141 $W\,m^{-2}$ | | |
| 2003 | $R^2$ | 0.98 | 0.95 | |
| | Bias ($W\,m^{-2}$) | 9.2 | 16.7 | |
| | RMSE ($W\,m^{-2}$) | 18.1 | 27 | |
| | Mean ISR Brion | 156 $W\,m^{-2}$ | | |
| 2001 | $R^2$ | 0.85 | 0.66 | Spatial (308 grid cells) |
| | RMSE ($W\,m^{-2}$) | 11.6 | 19.2 | |
| 2003 | $R^2$ | 0.72 | 0.52 | |
| | RMSE ($W\,m^{-2}$) | 11.4 | 19.7 | |





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**Table 5.** Morning and noon atmospheric variables: ERA-I vs. SAFRAN (annual Bias, RMSE and squared correlation coefficient) for air temperature, air humidity, wind speed and ISR over France (for 365 days) at 06:00 and 12:00 TU.

| Year | Score | Air Temperature (06:00 UTC) | Air Temperature (12:00 TU) | Air Humidity (06:00 TU) | Air Humidity (12:00 TU) | Wind Speed (06:00 TU) | Wind Speed (12:00 TU) | ISR (12:00TU) |
|---|---|---|---|---|---|---|---|---|
| 2001 | $R^2$ | 0.97 | 0.99 | 0.99 | 0.99 | 0.94 | 0.92 | 0.92 |
| | Bias | 0.59 K | −0.48 K | $6.9\times10^{-6}$ kg kg$^{-1}$ | $-5\times10^{-4}$ kg kg$^{-1}$ | 0.97 m s$^{-1}$ | 0.65 m s$^{-1}$ | 24.1 W m$^{-2}$ |
| | RMSE | 1.26 K | 1.03 K | $2.6\times10^{-4}$ kg kg$^{-1}$ | $6\times10^{-4}$ kg kg$^{-1}$ | 1.0 m s$^{-1}$ | 0.84 m s$^{-1}$ | 67.4 W m$^{-2}$ |
| | Mean Annual Parameter (SAFRAN) | 281 K | 287 K | $6.7\times10^{-3}$ kg kg$^{-1}$ | $7.3\times10^{-3}$ kg kg$^{-1}$ | 2.5 m s$^{-1}$ | 3.7 m s$^{-1}$ | 428 W m$^{-2}$ |
| 2003 | $R^2$ | 0.98 | 0.99 | 0.99 | 0.98 | 0.94 | 0.91 | 0.91 |
| | Bias | 0.71 K | −0.54 K | $2.1\times10^{-5}$ kg kg$^{-1}$ | $-3\times10^{-4}$ kg kg$^{-1}$ | 0.87 m s$^{-1}$ | 0.38 m s$^{-1}$ | 27.3 W m$^{-2}$ |
| | RMSE | 1.27 K | 1.14 K | $2.4\times10^{-5}$ kg kg$^{-1}$ | $5\times10^{-4}$ kg kg$^{-1}$ | 0.94 m s$^{-1}$ | 0.65 m s$^{-1}$ | 73.0 W m$^{-2}$ |
| | Mean Annual Parameter (SAFRAN) | 282 K | 288 K | $6.7\times10^{-3}$ kg kg$^{-1}$ | $7.1\times10^{-2}$ kg kg$^{-1}$ | 2.4 m s$^{-1}$ | 3.6 m s$^{-1}$ | 459 W m$^{-2}$ |





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**Table 6.** Performance of ERA-I for the SMOSREX site: mean bias, RMSE and square correlation coefficient for the different atmospheric parameters over the period 1990–2007 (with a daily time step), as compared with SAFRAN.

| Score | Air Temperature | Wind Speed | Air Humidity | Incoming Solar Radiation | Incoming Longwave Radiation | Precipitation (ERA-I) | Precipitation (ERA-I rescaled) |
|---|---|---|---|---|---|---|---|
| $R^2$ | 0.62 | 0.6 | 0.94 | 0.82 | 0.72 | 0.47 | 0.51 |
| Bias | −1.3 K | −0.3 m s$^{-1}$ | $-9.4\times10^{-4}$ kg kg$^{-1}$ | 22.3 W m$^{-2}$ | −12.8 W m$^{-2}$ | −0.016 mm h$^{-1}$ | 0.006 mm h$^{-1}$ |
| RMSE | 5.4 K | 1.2 m s$^{-1}$ | $1.2\times10^{-3}$ kg kg$^{-1}$ | 46.1 W m$^{-2}$ | 23.1 W m$^{-2}$ | 0.15 mm h$^{-1}$ | 0.162 mm h$^{-1}$ |
| Mean Annual Value | 286.3 K | 3.1 m s$^{-1}$ | $8.0.\times10^{-3}$ kg kg$^{-1}$ | 147.4 W m$^{-2}$ | 325.7 W m$^{-2}$ | 0.086 mm h$^{-1}$ | 0.086 mm h$^{-1}$ |
| Relative Bias (%)* | | −9.7% | −11.8% | 15.1% | −3.9% | −18.6% | 7% |

* Mean annual bias compared to the mean annual value.

**Table 7.** Performance of the ISBA-A-gs model for the SMOSREX site with different atmospheric forcing data sets (ERA-I, ERA-I rescaled): mean bias, RMSE, $R^2$ and NASH for various biophysical variables and fluxes obtained from the reference SAFRAN atmospheric forcing data on the SMOSREX site.

| | Score | Biophysical variables (2001–2007) | | | Surface fluxes (2005–2007) | | |
|---|---|---|---|---|---|---|---|
| Atmospheric data set | | $w_2$ (Root zone soil moisture) | LAI (Leaf Area Index) | $w_g$ (Surface soil moisture) | $H$ (Sensible heat flux) | $LE$ (Latent heat flux) | F[$CO_2$] (Carbon dioxyde flux) |
| ERA-I | $R^2$ | 0.82 | 0.61 | 0.64 | 0.64 | 0.71 | 0.22 |
| | Bias | 0.030 $m^3 m^{-3}$ | 0.30 $m^2 m^{-2}$ | 0.029 $m^3 m^{-3}$ | −7.6 $W m^{-2}$ | −3.4 $W m^{-2}$ | −0.001 $\mu mol m^{-2} s^{-1}$ |
| | RMSE | 0.039 $m^3 m^{-3}$ | 0.67 $m^2 m^{-2}$ | 0.054 $m^3 m^{-3}$ | 22.2 $W m^{-2}$ | 21.5 $W m^{-2}$ | 0.010 $\mu mol m^{-2} s^{-1}$ |
| | NASH | 0.27 | 0.50 | 0.47 | | | |
| ERA-I rescaled | $R^2$ | 0.93 | 0.89 | 0.66 | 0.64 | 0.69 | 0.60 |
| | Bias | 0.001 $m^3 m^{-3}$ | −0.20 $m^2 m^{-2}$ | 0.004 $m^3 m^{-3}$ | −44.3 $m^{-2}$ | −8.4 $W m^{-2}$ | 0.002 $\mu mol m^{-2} s^{-1}$ |
| | RMSE | 0.012 $m^3 m^{-3}$ | 0.38 $m^2 m^{-2}$ | 0.046 $m^3 m^{-3}$ | 22.1 $W m^{-2}$ | 24.3 $W m^{-2}$ | 0.007 $\mu mol m^{-2} s^{-1}$ |
| | NASH | 0.93 | 0.84 | 0.61 | | | |
| SAFRAN + ERA-I rescaled precipitation | $R^2$ | 0.95 | 0.86 | 0.73 | 0.76 | 0.78 | 0.64 |
| | Bias | −0.003 $m^3 m^{-3}$ | −0.43 $m^2 m^{-2}$ | −40 008 $m^3 m^{-3}$ | 6.9 $W m^{-2}$ | −7.2 $W m^{-2}$ | 0.003 $\mu mol m^{-2} s^{-1}$ |
| | RMSE | 0.011 $m^3 m^{-3}$ | 0.58 $m^2 m^{-2}$ | 0.040 $m^3 m^{-3}$ | 17.5 $W m^{-2}$ | 20.0 $W m^{-2}$ | 0.008 $\mu mol m^{-2} s^{-1}$ |
| | NASH | 0.94 | 0.62 | 0.72 | | | |
| SAFRAN + ERA-I ISR | $R^2$ | 0.97 | 0.94 | 0.91 | 0.69 | 0.76 | 0.88 |
| | Bias | 0.008 $m^3 m^{-3}$ | −0.12 $m^2 m^{-2}$ | 0.006 $m^3 m^{-3}$ | −7.2 $W m^{-2}$ | −3.4 $W m^{-2}$ | 0.001 $\mu mol m^{-2} s^{-1}$ |
| | RMSE | 0.012 $m^3 m^{-3}$ | 0.26 $m^2 m^{-2}$ | 0.024 $m^3 m^{-3}$ | 22.2 $W m^{-2}$ | 19.0 $W m^{-2}$ | 0.004 $\mu mol m^{-2} s^{-1}$ |
| | NASH | 0.93 | 0.93 | 0.90 | | | |





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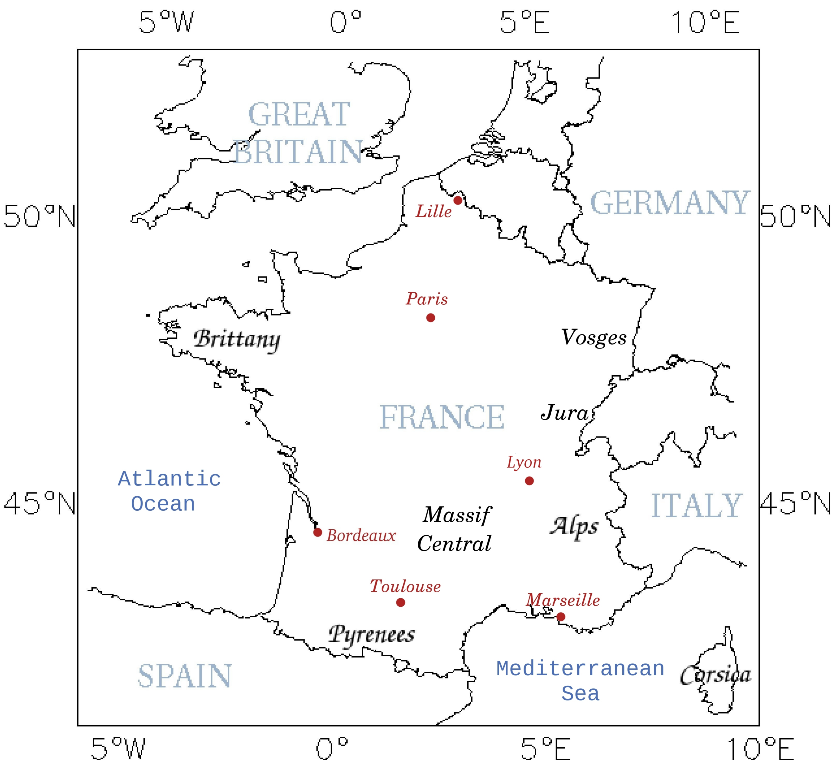


**Fig. 1.** Map of France, main areas discussed in this study.





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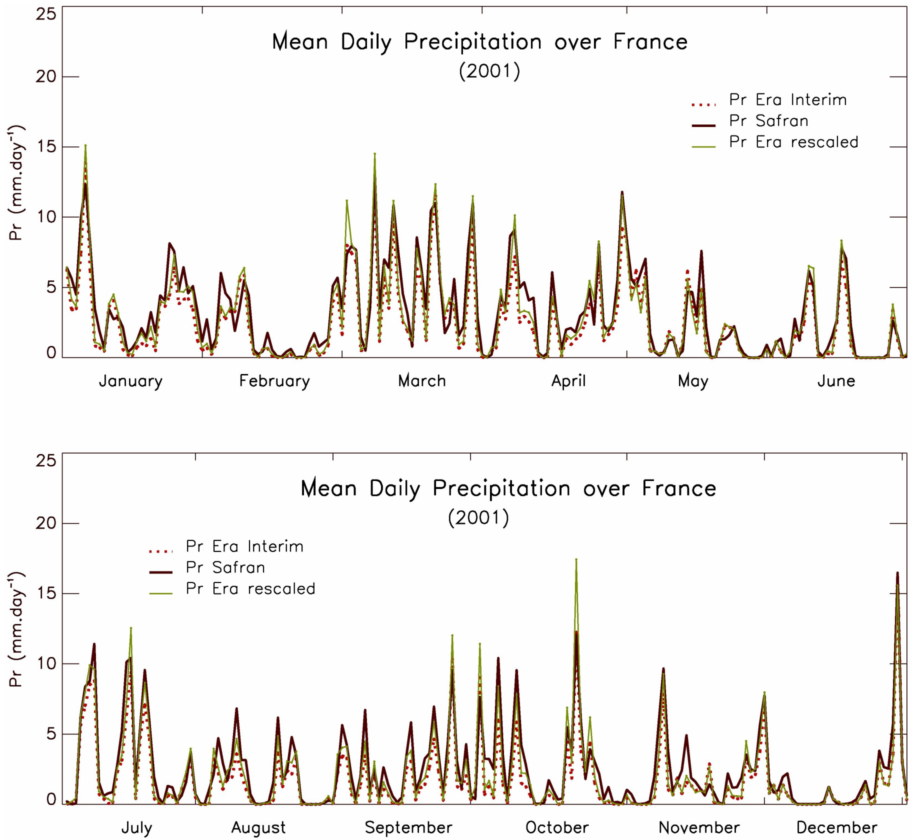


**Fig. 2.** Mean Daily Precipitation over France for SAFRAN, ERA-I and ERA-I rescaled: from (top) January to June 2001, and from (bottom) July to December 2001.





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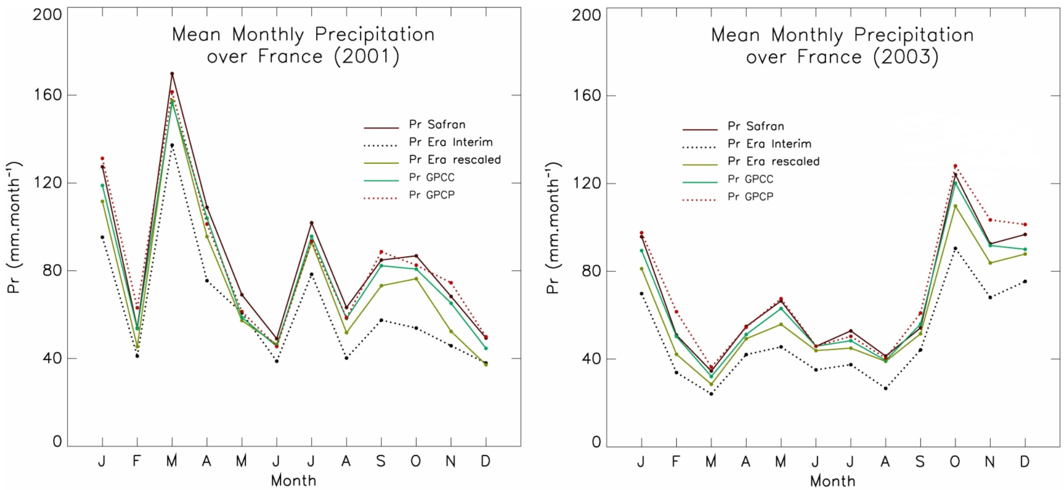


**Fig. 3.** Mean monthly precipitation over France for SAFRAN, ERA-I, ERA-I rescaled, GPCC and GPCP: (left) 2001, and (right) 2003.

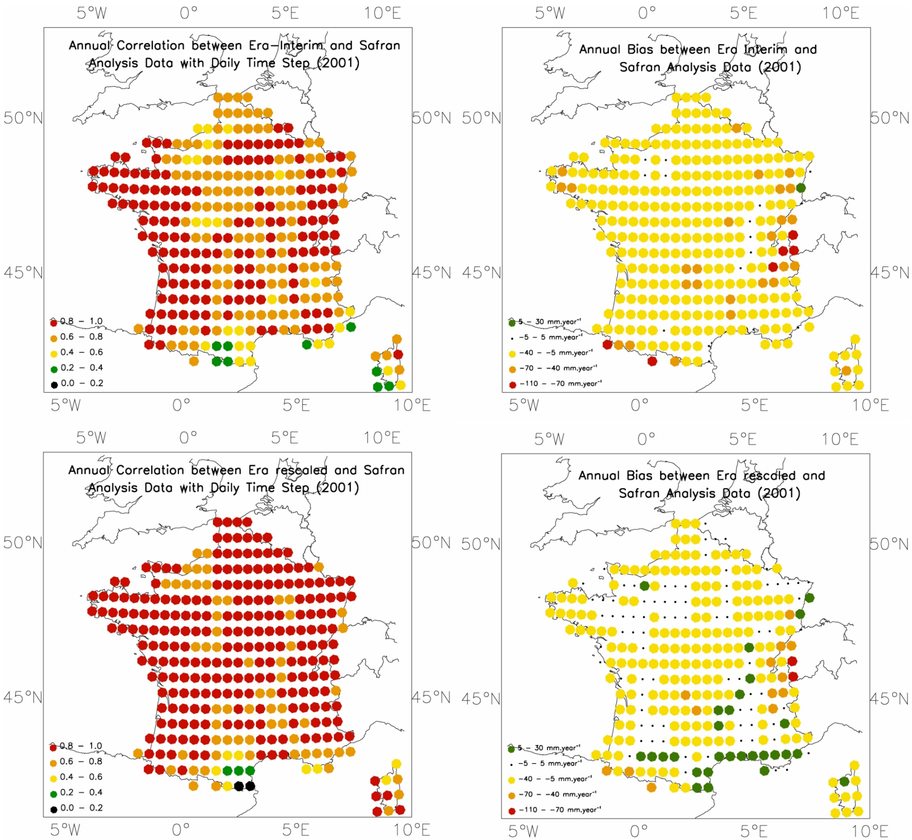


**Fig. 4.** Daily precipitation estimates in 2001: (top) ERA-I and (bottom) ERA-I rescaled, vs. SAFRAN in terms of (left) temporal correlation ($R^2$) and (right) mean bias.





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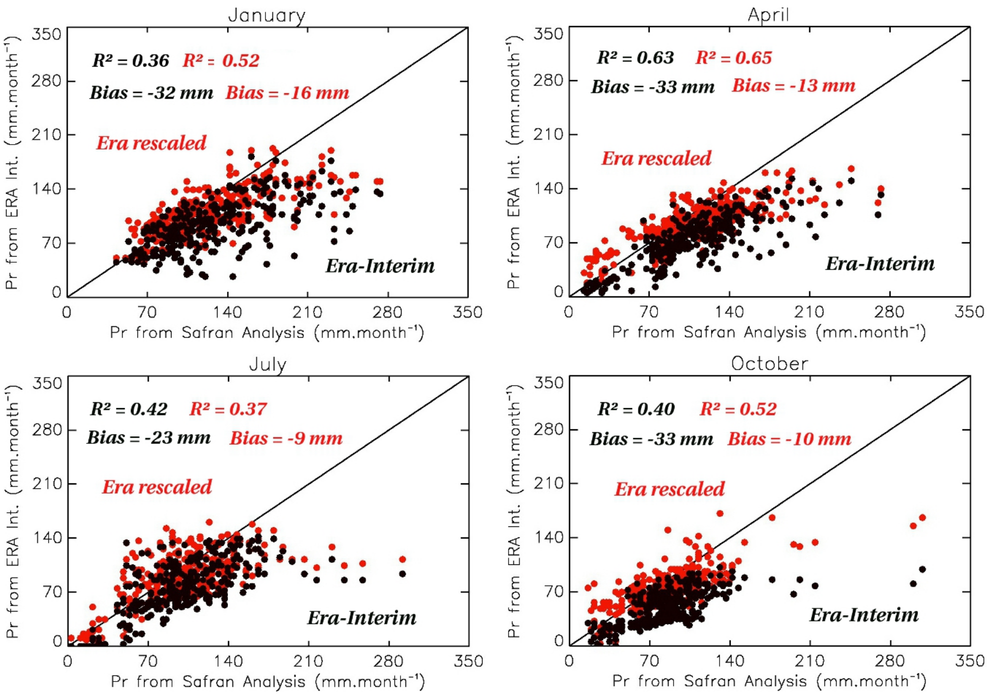


**Fig. 5.** Spatial Correlation of the monthly precipitation data from ERA-I and ERA-I rescaled (308 grid-cells) with SAFRAN, in January, April, July, and October 2001.





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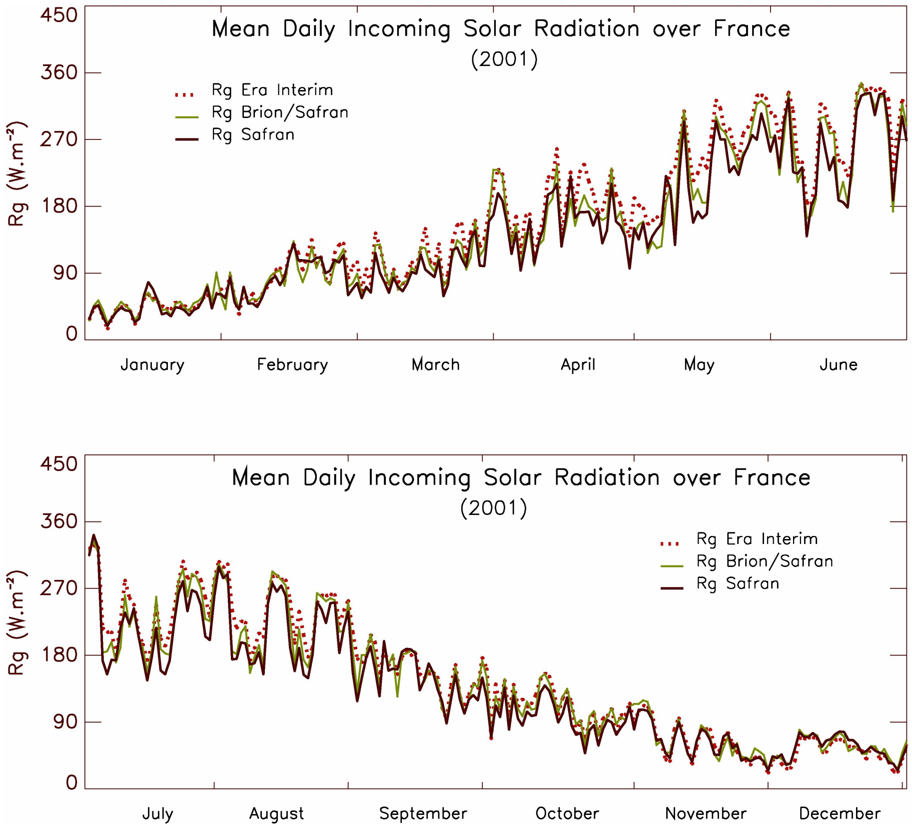


**Fig. 6.** Mean Daily ISR over France for SAFRAN, ERA-I and Brion: from (top) January to June 2001, and from (bottom) July to December 2001.

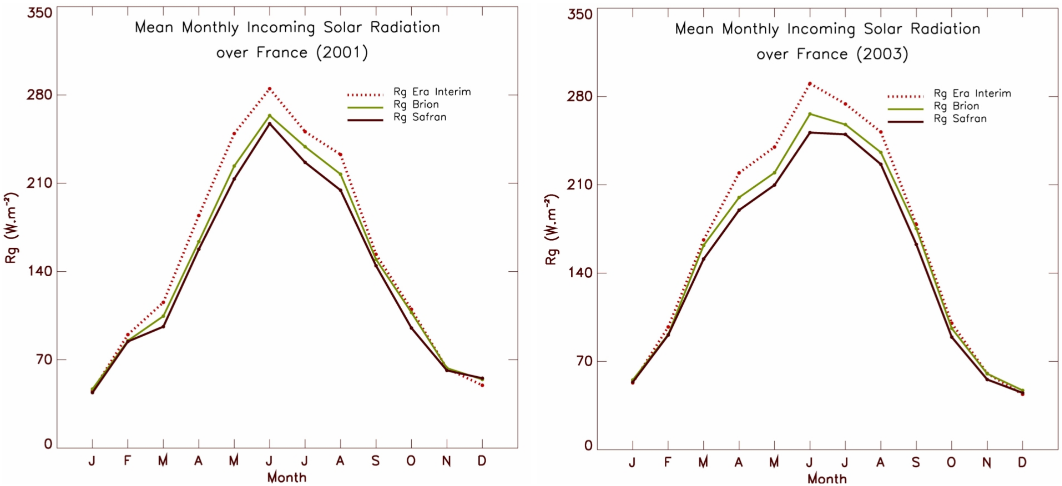


**Fig. 7.** Mean Monthly ISR over France for SAFRAN, ERA-I and Brion: (left) 2001, and (right) 2003.





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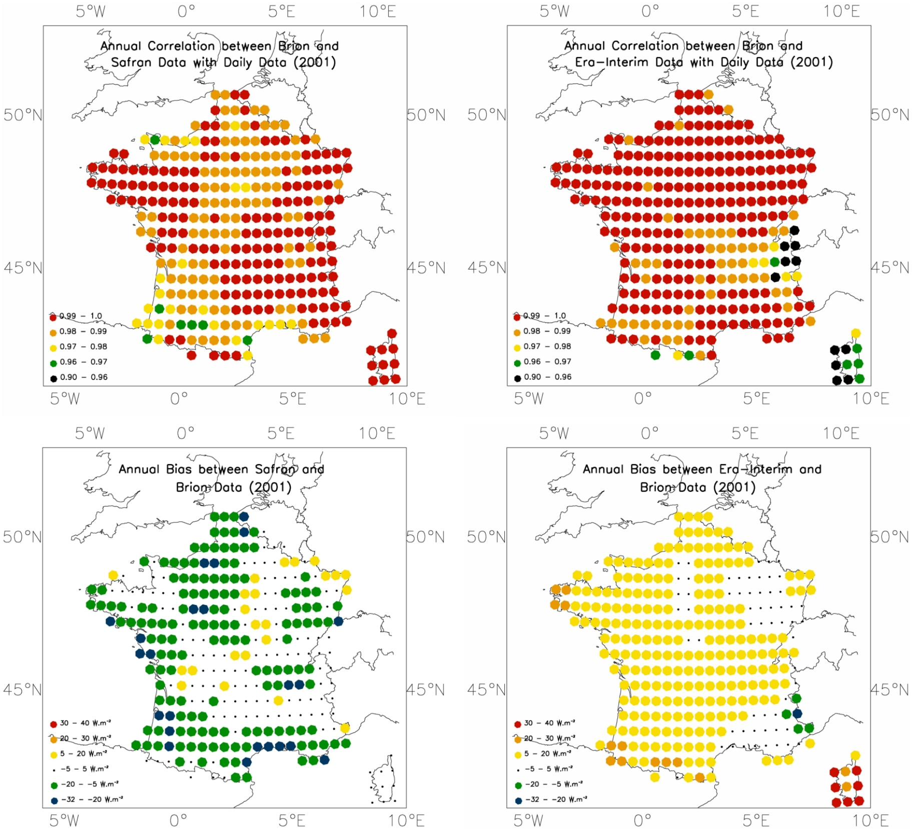


**Fig. 8.** Daily incoming solar radiation estimates in 2001: (left) SAFRAN and (right) ERA-I, vs.Brion in terms of (top) temporal correlation ($R^2$) and (bottom) mean bias.

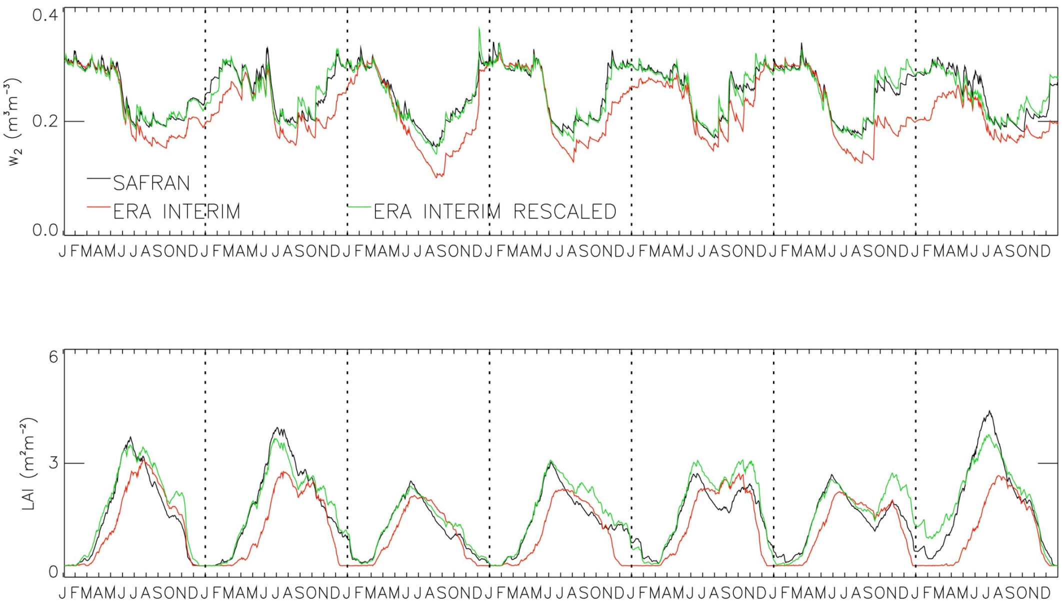


**Fig. 9.** Impact of the use of different atmospheric forcings (SAFRAN, ERA-I, ERA-I rescaled) on the ISBA-A-gs simulations of (top) root zone soil moisture and (bottom) leaf area index of the SMOSREX grassland in southwestern France (2001–2007).

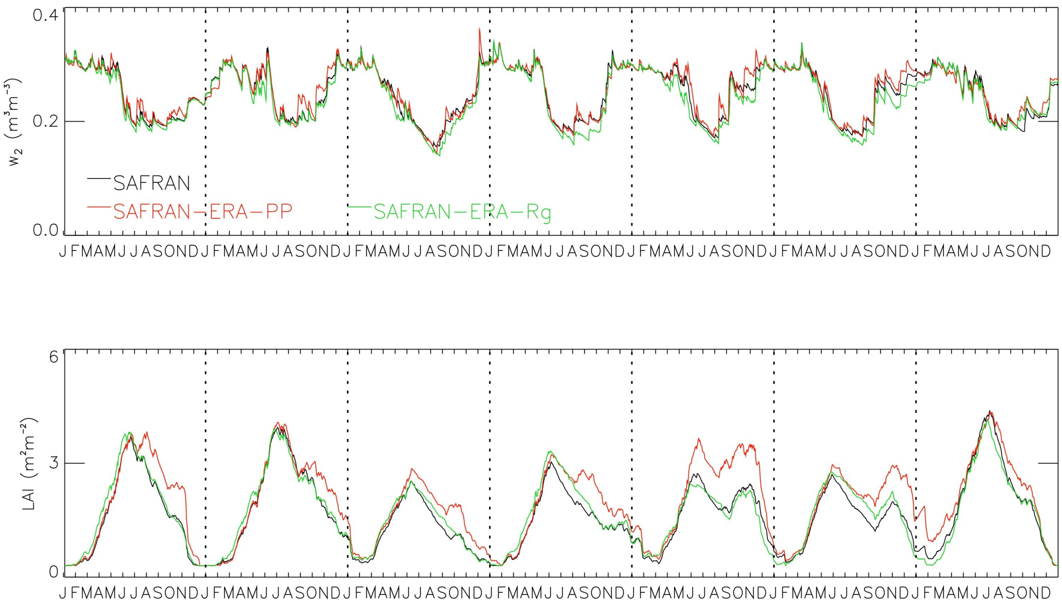


**Fig. 10.** As in Fig. 9, except for SAFRAN with ERA-I rescaled precipitation and SAFRAN with ERA-I ISR (2001–2007).





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