MINISTERIO DE CIENCIA E INNOVACIÓN · Financiado por la Unión Europea NextGenerationEU · Plan de Recuperación, Transformación y Resiliencia · AGENCIA ESTATAL DE INVESTIGACIÓN

MEMORIA CIENTÍFICO-TÉCNICA DE PROYECTOS INDIVIDUALES
Convocatoria 2021 - «Proyectos de Transición Ecológica y Transición Digital»

AVISO IMPORTANTE - La memoria no podrá exceder de 20 páginas. Para rellenar correctamente esta memoria, lea detenidamente las instrucciones disponibles en la web de la convocatoria. Es recomendable rellenarla en inglés si se solicita 100.000 € o más (en costes directos).

IMPORTANT – The research proposal cannot exceed 20 pages. Instructions to fill this document are available in the website. If the project cost is equal or greater than 100.000 €, this document should be filled in English.

1. PORTADA

IP 1 (Nombre y apellidos)**: Juan Ignacio López Moreno**

IP 2 (Nombre y apellidos)**: Jorge Pey Betrán**

TÍTULO DEL PROYECTO (ACRÓNIMO): Impacto del polvo Sahariano en la fusión de nieve del Pirineo: Mejorando la adaptación de la gestión de la nieve y el agua en un contexto de cambio climático (SNOWDUST)

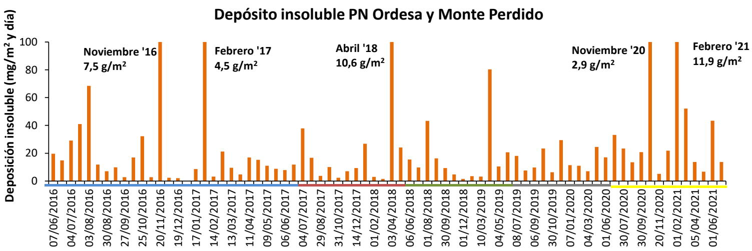
TITLE OF THE PROJECT (ACRONYM): Impact of Saharan Dust on snowmelting in the Pyrenees: Improving the snow and water management in a context of climate change (SNOWDUST)

2. JUSTIFICACIÓN DE LA PROPUESTA - *JUSTIFICATION OF THE PROPOSAL*

Spain hosts extense mountain areas where snow cover is persistent, lasting from the end autumn to the end of spring. In these areas, almost every environmental and socioeconomic process is ruled out by the presence of snow and its thickness (Barnet et al., 2005). Thus, land management needs to properly understand the cycles of snow accumulation and melting and how they will change as climate will progressively warm as a consequence of antropogenic greenhouse gases emissions (López-Moreno et al., 2020). Such changes will impact on the availability of water resources and its direct impacts on agriculture, hydropower generation and tourism (García-Ruiz et al., 2011; Morán-Tejeda 2014; López-Moreno et al., 2014), the phenology of fauna and vegetation (including forestry production and health, Sanmiguel-Vallelado et al. 2020 y 2021), road and train transportation that may affect even key cross-border passages, and the economy of many mountain areas that is increasingly linked to the winter tourism based on snow activities (Gilaberte et al., 2017). In last years ski resorts sum more than 5M skiers per year and represents more than 5% of the growth domestic product of some regions in Spain, as Aragón (Gilaberte et al., 2017). In addition, snow also represents a risk that could be exhacerbated by climate change since heavy snowfalls may increase at high elevation despite to warmer temperatures (López-Moreno et al., 2011; Le Roux et al., 2021) leading to snow avalanches that every year causes fatalities, road disruptions, and damages in infraestuctures. Fast melting and rain on snow events also trigger some of the largest floods of Spanish rivers (Morán-Tejeda et al., 2020; López-Moreno et al., 2021), like the recent floods of the Ebro river in February 2016 or December 2021 that were responsible of huge economic losses along its flood plain. Then, it is not exagerated when Sturm et al. (2017) claim that snow is "*a trillion dollar science question*".

For all above exposed reasons, there has been an increasing interest to improve the understanding about snow dynamics and to develop the most accurate scenarios for the evolution of snow in the coming decades. It is becoming necessary to produce robust indicators and scenarios of snow change, and how they will affect to different economic sectors, serving as scientific basis to provide clear guidelines to improve adaptation to changing snow conditions. In this way, the applicant research team has obtained different national and international I+D+i projects to develop novel technologies to observe snowpack (López-Moreno et al., 2017b and 2020; Gascoin et al., 2020; Revuelto et al., 2014 y 2021), and to simulate its changes under different climatic and environmental conditions projected to come in the future (López-Moreno et al., 2013 y 2021; Alonso-González et al., 2021). However, we have also identified key gaps in our understanding of snow dynamics and in our capabilities to properly simulate it under present and future conditions (López-Moreno et al., 2017). **From all of them, the effect of the presence of light absorbing impurities (LAI) on the snow reflectivity** of incoming solar energy, (and in turn on snow melting) **is the most relevant uncertainty, and it needs urgent understanding to improve our models and to better anticipate the consequences of climate change on the concerned environmental and socioeconomic sectors.**

The presence of LAI strongly affects the radiative properties of snowpack causing a sharp reduction of the albedo in the visible wavelength (Warren 1982). When snow absorbes more radiation, more energy enters into the system leading to i) an accelerated melting; and ii) the formation of weak layers prone to trigger snow avalanches (Anderson et al., 2006). The mineral dust (MD) and the presence of Black Carbon (BC) are the dominant LAI on snow (Dumont et al., 2014; Di Mauro et al., 2015). BC deposition tends to be very constant in time and space since the emission of these aerosols to the atmosphere is rather constant, but MD deposition is episodic and its frecuency and magnitude display an important intra- and interanual variability (Figure 1 left, Pey et al., 2013 and 2020a), as well as significant and unexpected spatial differences (Pey et al., 2020a). The presence of MD is particularly relevant in mountains exposed to wind tracks coming from source areas. This is the case of the Iberian Peninsula, which is frequently touched by dust aerosols from North African deserts. These source areas of MD release around 60% of the overall mineral dust emitted to the atmosphere at the global scale (Figure 1 right, Shao et al, 2011). **The occurrence of severe dust deposition events is evident in our environment; however still a comprehensive analisis of their current impacts on snow processes and how this phenomenon can evolve in the next future, has to be done. This is the main objective of the current proposal.**



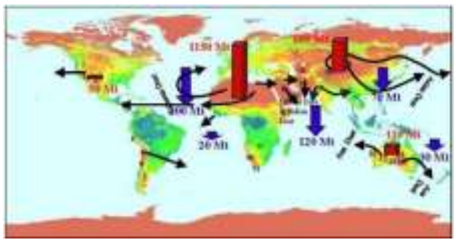


Figure 1: Left; insoluble aerosol deposition at Ordesa and Monte Perdido National Park 2016-2021 (DONAIRE and POSAHPI project results). **Right;** global dust emissions (brown bars), dust transport routes (black arrows) and estimates of ocean dust deposition (blue arrows), Shao et al. (2011).

Thus, it exists a real need to understand how the arrival of Saharan dust affects the spatio-temporal variability of snowpack in order to improve the parametrization of the models used for seasonal prediction of the snowpack or the short-term hydrological and avalanche forecasts and early warning systems (as provided by the main river basin authorities); to foreseen snow evolution in ski resorts and help in decision making for snow farming procedures (Spandre et al., 2019); and to create robust projections of snow availability for the future. The later will depend i) on the amount of dust arriving from the Sahara under changing atmospheric circulation patterns (Pey et al 2013); ii) on the changes in incoming radiation from the atmosphere (Alonso-González et al., 2020); and ii) on the complex interactions that may exists between a warmer climate and LAIs (Flanner et al., 2009). In this line, there exists a body of literature that confirms the strong influence of MD in the energy balance of the snowpack impacting on snow duration, albedo, runoff and the mass balance of the glaciers (Skiles et al. 2012; Painter et al., 2018). However, there are not studies yet that systematically research the full chain of dust transport, deposition processes and evolution of mineral particles until snowmelting along the snow profile; neither it has been studied their influence on melting rates at different spatial scales, and contrasted elevation and topographic context. The main difficulties to address these type studies lie in the complexity to get high quality observations of snowpack simultaneously to and LAI concentrations and their optical properties (Pey et al., 2020b). It is also difficult to corroborate that punctual observations are representative of their surrounding areas (Painter et al., 2011, Di Mauro et al., 2015). Finally, the presence of impurities on the snow surface triggers and amplifies a positive feedback based on the increase of grain size of the snow that boosts the decline in albedo.

The main outcomes of this proposal are: 1) to develop new protocols to monitor aerosols concentrations on snowpack at different spatial scales; 2) to relate such concentrations and their reflective properties with the atmospheric circulations and; 3) to implement such findings to simulate snowpack under current and projected future climate. We expect to provide clear information and useful tools to improve observation and simulation of snow dynamics to public and private entities involved in snow and water management. These are ambitious goals for a short duration project, but combining the strong expertise of the research team in snow and aerosol observations, the modelling of the snow energy of the snowpack, climatic studies and climate change assessment and their feedbacks gives very high chances of suceeding in the project´s objectives. PI1 and PI2 have led 3 and 2 I+D+i projects on snow and aerosols dynamics in the Pyrenees and Spanish mountains, respectively. This project is a golden opportunitiy to merge both fields and to develop the proposed frontier research. In order to optimize the timing of the execution all the research will be devoloped at different spatial scales in a single sector of the Central Pyrenees. This can be considered as a pilot case study to be subsequently expanded to the rest of the Spanish mountains, making use of the infraestructure and human networks created in previous projects.

We consider that **expected advances in this field are imperative to obtain refined tools that will improve our adaptation capacity to climate change**, to improve a sustainable use of water resources and to support the management of the territory including environmental politics and giving support to key productive sectors such as hydropower generation, agriculture and tourism. In addition, we aim that **the planned activities and the improvement in our monitoring sites and equipment will permit to convert our research group in one of the reference research groups on this topic, increasing our competitiveness and leadership as researchers in the international arena**. For all these reasons we strongly think that our proposal falls within the objectives of the present project´s call.

This project is completely novel in terms of objectives regarding the previous I+D+i projects led by the PIs (and rest of research team) of the proposal. However the success in the planned objectives is impossible to be understood without the infraestructure, methodological approaches and knowledge generated in previous projects. Indeed, this proposal is the main gap we are currently lacking in our research. PI1 has lead the projects (HIDRONIEVE-CGL2011-27536/HID; IBERNIEVE-CGL2014-52599-P; HIDROIBERNIEVE CGL2017-82216-R) in which the Izas experimental station was modernized, terretrial laser scanner and drones were implemented to measure snow depth and snow water equivalent, and numerical simulations of the snow energy balance and hydrological models were used to better understand mountain hydrology under current and future climate in the Iberian Peninsula. Recently PI1 has also applied to a I+D+i project in the call 2021 (MARGISNOW-PID2021-1242200B-100) to advance in the research on shallow (marginal) snowpacks, from which a tentative study on the relation between LAI and snowmelt is foreseen. The PI1 has also leaded several european projects projects and workpackages focussed on adaptation to climate change, mostly oriented to improve the management of snow in ski resorts and to optimaze water management in dams to face climate change (some examples: “Cross-sectoral impact assessment of droughts in complex European basins-CROSSDRO” ERANET-AXIS; Integrated approach for the development across Europe of user oriented climate indicators for GFCS high-priority sectors: agriculture, disaster risk reduction, energy, health, water and tourism-ERA4C-JPI H2020; Capitalización, observación, transferencia y apropiación de estrategias de adaptación al cambio climático en los Pirineos en un contexto de cooperación transfronteriza. ADAPYR- INTERREG-POCTEFA; “Assessment of climate change impacts on the quantity and quality of water in mountains” EU-FP7 ACQWA; and “Creación de un modelo de alta resolución espacial para cuantificar la esquiabilidad y la afluencia turística en el Pirineo bajo distintos escenarios de cambio climático CTP1/12-EU INTERREG). PI2 has deployed a network of aerosol deposition observatories (DONAIRE-CGL 2015-68993-R) covering northern, eastern and southern areas in the Iberian Peninsula as well as the Balearic Islands, from which dust inputs and aerosols from other sources are discriminated. Thanks to the DONAIRE network, the next comprehensive project is focused on the study of dust aerosols from a historic perspective, that is, covering the whole Holocene (POSAHPI, PID2019-108101RB-I00). In between these projects, PI1 and PI2 had the opportunity to shortly collaborate in a project funded by the Fundación Biodiversidad to explore the relation between MD and BC deposition on snow transformation and properties (AERONIVAL, PRCV00464), but the information retrieved was very limited due to hard meteorological conditions occurred in 2018 and the short duration of the project (only one year).

** References at the end of the proposal*

3. OBJETIVOS, METODOLOGÍA Y PLAN DE TRABAJO - *OBJECTIVES, METHODOLOGY AND WORK PLAN*

The main objective of this project is to understand the modifier effect induced by MD deposition from Saharan deserts on the physical properties of the mountain snowpacks, on their melting rates and duration; and to which extent these impacts could be boosted under the the available climate projections for the next decades. Such general objective can be divided in the following specific subobjectives (SO) that are closely interlinked, summarized in Figure 2:

SO1- To identify the meteorological scenarios favouring the transport of Saharan dust to the Iberian Peninsula, with special focus to the Central Pyrenees, from 1948 to 2020.

Interest: we can isolate the main meteorological scenarios responsible for the dust transport and its deposition on the snowpack of the Pyrenees and the rest of the Spanish mountains, and we will be able to identify possible trends in this phenomenon during the last 70 years.

SO2- To quantify and to characterize the deposition of impurities on the snowpack, disentangling what proportion comes from Saharan dust (versus local sources), and how the concentration changes over different spatial scales (plots of 3x3 m, areas of 200x200 m, and the slope or valley scale).

Interest: on one hand to quantify the overall Saharan dust deposition along the snow season; on the other to know which chemicals are forming the whole set of impurities to separate those from the Sahara and those from other sources, and to pinpoint the exact source areas in Northern Africa that may refine our findings in SO1.

SO3- To determine the impact of LAI concentration and composition on the albedo of the snow surface and to implement such relation into the snow energy balance simulations.

Interest: to establish sound relations between LAI concentrations and the spectral signal of the snow surface. This SO will permit to know how different characteristics of deposited aerosols (aerosol load, composition, origin) and with climate and snow conditions affect the albedo of the snowpack. This is a key step to improve our capabilities to conduct numerical modelling of the snowpack including key parameters related to LAI.

SO4- To quantify the impact of LAI on snow characteristics, melting rates and snow duration (based on measurements and findings from SO3), and to dermine how such influences may vary under different climatic and topographic conditions.

Interest: by combining observations and simulations we will determine the effect that Saharan dust and other LAI had in the past evolution of snowpack under different elevation and topographic contexts. It will also allow the discrimination between meteorology and LAI in the observed melt rates. SO4 will permit to improve the short-term and seasonal forecast of the snowmelting.

SO5- To estimate the impact of projected climate change on the arrival and deposition of Saharan dust on snow, and determine its role on snow stability and melting for the next decades.

Interest: all the knowledge gathered from previous SOs will be used to answer the main question of the proposal: which is the most plausible scenario for next decades? which role will play Saharan dust in the future on the snowpack and associated environmental and socioeconomic sectors?. The answer to this question will permit providing to snow and water managers clear information and management tools to anticipate the consequences of climate change.

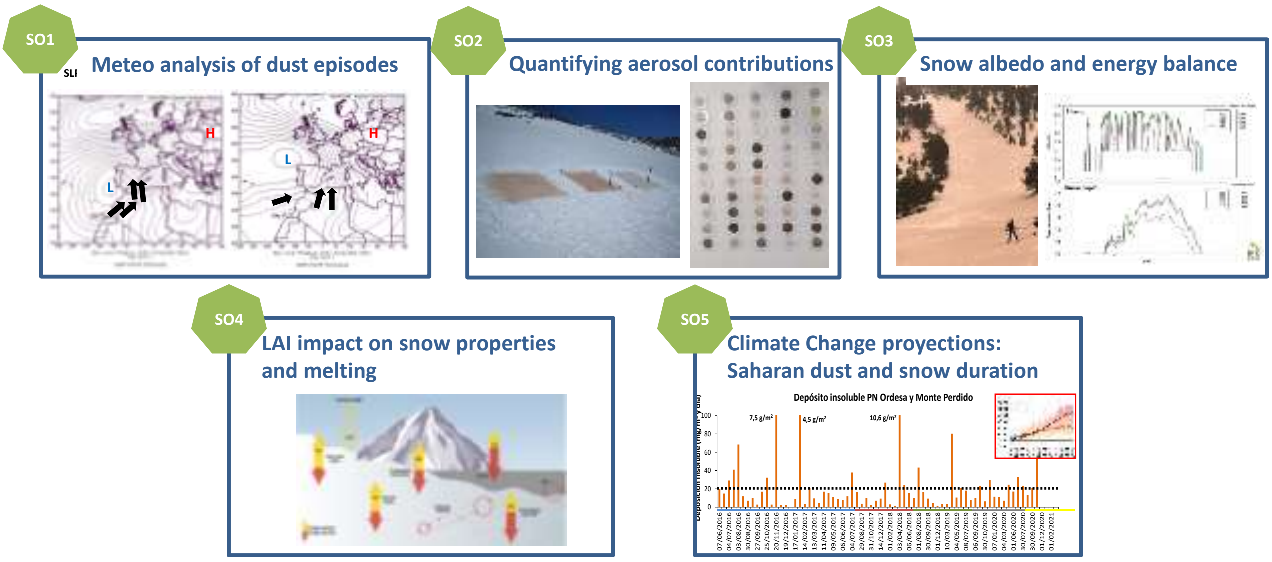


Figure 2. Summary of the specific objectives (SO) of SNOWDUST project.

The planned methodology is estructured in five tasks related to each of the previously discerned specific objectives.

Task 1- To analyze the meteorological scenarios favouring the transport of Saharan dust to the Spanish mountains, with special focus in Central Pyrenees. *Jorge Pey, P. Salvador, E. Morán y E. Alonso.*

Differences in source regions of dust may confer specific geochemical, mineralogical or optical signatures to the emitted dust. Usually, dust observations are made far away from dust sources and, therefore, the identification of dust origin is not straightforward. One of the methods used for this purpose is the calculation of air mass back-trajectories, usually for 1-7 day periods. The integration of dust observations into a temporal database of air mass back-trajectories by means of specific multivariate analysis techniques known as “trajectory statistical methods-TSM” may provide an indication about dust origin. In this sense, the Residence Time Analysis-RTA (Salvador et al., 2004;

2008), the Cluster Analysis-CA (Salvador et al., 2010) and the Concentration Fields Methodology-CFM (López et al., 2019) are the most-widely used methods (Belis et al., 2019 and references therein). TSM techniques will be applied to dust deposition observations from former DONAIRE and POSAHPI projects (data from 2016 to 2021). SNOWDUST will be able to infer whether or not different source regions of dust impact on their chemical characteristics. The HYSPLIT model v4.0 and global meteorological databases (GDAS), both managed by the Atmospheric Research Laboratory - National Oceanic and Atmospheric Administration – ARL/NOAA, which are freely available: https://ready.arl.noaa.gov, will be used for this purpose.

Another issue on this task is the identification of the meteorological dust-transport scenarios in past decades (1948-2020). With this aim, a long-term re-analysis database containing different fields of meteorological variables that describe atmospheric circulation at the synoptic scale will be processed. There are a number of available re-analysis databases, but in SNOWDUST we will use we will use the NCEP/NCAR (National Centers for Environmental Prediction/National Centre for Atmospheric Research) dataset provided by NOAA/OAR/ESRL PSD, USA: http://www.esrl.noaa.gov/psd/data/". To retrieve the main synoptic circulation patterns that produced the long-range transport of Saharan dust towards the regions of study from this database, a circulation classification methodology (Salvador et al., 2021) will be applied. After this, a new database having number of episodes each year according to the different circulation types will be obtained. Multi-year to decadal variations in the frequency of meteorological dust transport scenarios in general, or in the frequency of certain circulation types will inform us about current trends in dust transport towards the Iberian Peninsula.

Timing: February-December 2022
Expected output: Understand atmospheric circulation paterns and climatic conditions favorable to dust arrival and deposition on snowpacks
Deliverable: Scientific paper by the end of 2022 (D1.1). Presentation in international conference by the end of 2022-early 2023 (D1.2).

Task 2- To quantify aerosol deposition on the snowpack and to characterize their chemical cmposition, disentangling what proportion comes from Saharan dust (versus local sources), and how the concentration varies over different spatial scales. *J.I. López-Moreno, A. Sanmiguel, J., Revuelto, A, Sensoy, I. Vidaller, S. Gascoin, A. Serreta.*

During the winters of 2022 and 2023 we will monitor the concentrations of Saharan dust and other LAIs in atmospheric samples and in snow samples at three different spatial scales: valley, parcel and plot. The main test zone will be around the Izas experimental catchment (Tena Valley) managed by IPE-CSIC (next to AEMET station and telenivometer of the Ebro Basisn authorities since more than 3 decades ago. The test zone covers 200 hectars where 8 plots (3x3 meters) at different elevation and slope aspect will be intensively sampled.

The applied methods for each analysed spatial scale will be as follows:

(i) At detailed scale (3x3 meters) we will measure the reflectivity of the snow surface with a hyperspectral radiometer (ASD® HandHeld 2) ranging from the infrared to the visible spectrum (Painter et al 2007; Pey et al., 2020b). These observations will be complemented by the collection of aerosol samples (one every 4 days during one year (90 samples foreseen), by using a sequential low-volume sampler fitted with a PM10 inlet) together with the collection of snow samples (sections of 10x10x3 cm) to estimate the LAI concentration and the chemical to mineral composition of the LAI (anions and cations by ionic chromatography; organic and elemental carbonby using a thermo-optical analyzer; and the inorganic fraction by means of sample digestion and subsequent ICP-AES and ICP-MS analyses; see details in Pey et al., 2020b). The complete dataset of aerosol and snow samples will be prepared for a source apportionment analysis by means of Positive Matrix Factorization (Amato et al., 2009). With this procedure we will be able to extract the main sources of atmospheric aerosols and snow-deposited aerosols, together with their contributions, which will be useful to discriminate thereafter their individual relation with snow albedo changes and snow melting processes. In addition, we will characterize the size and type of snow grains (with a x16 len) that also affect and interact with LAI over the spectral signature of reflected radiation by snow. Snow profiles will be dug at each plot to analyze the vertical profile of snow density and temperature as well as LAI content.

ii) At medium scale, we will use a drone DJI-Matrix300 with thermal and multiespectral camera (Micasense Altum) to estimate the distribution of LAI in the surface and the albedo based in the RGB and near infrarred response (Di Mauro et al., 2015). In addition, photogrammetric techniques will provide information of snowdepth at very high spatial resolution (3x3 meters) that combined with information from snow profiles will be converted into snow water equivalent (Revuelto et al., 2021). Information on LAI concentrations and albedo will be validated with information collected at the detailed scale.

iii) For large spatial scales (Tena Valley, 400 km^2) we will use the satellite Sentinel-2 to get information of snow albedo at a resolution of 20x20 meters (Gascoin et al., 2020). Results will be validated and related with the observationes obtained at finer spatial resolutions.

Timing: February 2022-May 2023 (field campaigns between February and May), Satellite all year long.
Expected output: Data set of presence of snow on the snowpack and its vertical distribution in the snow profile at different spatial scales
Deliverable: Data uploaded in a public open repository (by end of the project, D2.1) and publication of a data paper (D2.2)

Task 3- To quantify the impact of LAI on snow characteristics, melting rates and snow duration, and how such influences vary under different climatic and topographic conditions.

J.I. López-Moreno, J. Revuelto, J. Pey, J. Pomeroy, E. Morán, I. Vidaller

Information collected in Task 2 will be used to link the characteristics of the snow surface with the evolution of albedo. Together with the field campaigns, Izas Experimental Catchment and Formigal-AEMET continuously measures broad band albedo and snowdepth at 10 minutes resolution. In 2022 we also expect to continuously measure the multiespectral reflectance (see solicited equipment). In addition, LAI concentration and snow reflectivity measured in-situ will serve to validate estimations of LAI concentration from drone and Sentinel-2. These estimations will enable to perform a robust link between LAI and Albedo, being these relationships translated to new snow model parametrizations under different topographic and climatic situations. Aditional analisis of LAI concentrations along the vertical snow profiles will provide novel information on the dynamics of dust since it is deposited on the snow surface, how is buried by new snowfalls or percolate to deeper layers (creating crusts and weak layers), and how and when reappears in the surface along the melting period. Understanding properly such dynamics is key to succeed in the following methodological steps.

We will simulate the snow and mass energy balance using the multi-layer model Crocus (Vionnet et al., 2012) driven by the model HARMONIE-AROME (Bengstsson et al., 2017; used for operational forecasts by AEMET) and also as validation with the weather stations existing in Izas and Formigal. Simulations will be performed: i) not including the effect of LAI (as they are generally performed); and ii) including the impact of LAI concentrations that we have measured at detailed and medium spatial scales; and iii) using the estimations of MD deposition retrieved from the BSC-Dust model (operational model in Mediterranean region; Basart et al., 2012 http://www.bsc.es/ess/bsc-dust-daily-forecast) for the large spatial scale. This dataset will be previously validated with our own observations taken in Tasks 1 and 2. The main adventage of using CROCUS is that it has recently included the module TARTES (Tuzet et al., 2019) which to our knowledge is the only existing one that explicitly implements the impact of LAI in the physical snow simulations.

Timing: July 2022-July 2023
Expected output: Have model simulations tuned with parametrizations based on data from Task 2.
Deliverable: Presentation in international conference by the end of 2023 (D3.1).

Task 4- To quantify the impact of LAI on snow characteristics, melting rates and snow duration (based on measurements and findings in Task 3), and how such influences vary under different climatic cand topographic conditions. *J.I. López-Moreno, E, Morán, J. Revuelto, S. Gascoin, J. Martín, M. Pons, J. Pey.*

The comparison of the two ways of simulating snow (Task 3) will provide a realistic quantitative approach of the impact of LAI on snow physics and the duration of the snow cover in contrasted climatic and topocraphic context. In a further step, we will adjust the model (following Spandre et al., 2019) to include the snow farming technique applied in ski resorts (namely snow making and grooming). The model willl be run and validated in Formigal ski resort (see letter of support). In this way we can compare the impact of LAI on snow duration in natural and managed snowpacks, and propose optimal treatments of the snow to face deposition of dust. We will also perform an uncertainty analisis at each methodological step (modeling transport and deposition of dust, driving data of snow models, the snow model itself, etc) thanks to the comparison of the used data with the high quality observations that we already have (for aerosols) and we will acquire along the project in the Tasks 1 and 2. One the uncertainty is determined we will conduct a simulation for whole Tena Valley for the period 1979-2021 using Crocus driven with the reanalysis data from BSC-Dust for the period 1979- 2021 (https://sds-was.aemet.es/projects-research/dustclim). Simulations will enable quantifying the impact of Saharian dust and other LAI on snowpack in the last decades having a long enough period to detect interanual and decadal variability in dust arrival, incoming solar radiation and a strong signal of temperature warming over the study area. We will also have enough data to analyze extreme events (in terms of heavy melting, extreme deposition of dust or conditions of extreme risk of avalanche), and also performing analog studies for the future (by analysing in detail the processes occurred during the warmest years of the period compared to years closet o the average). We will pay particular atention to assess how results vary according to elevation and different topographic settings.

Timing: May 2022-August 2023
Expected output: To have accurate cuantification of the impact of LAI on melt rates and snow duration at different spatial scales and contrasted elevation and topographic contexts
Deliverable: Scientific paper by the end of 2023(D4.1), presentation in international conference onwards (D4.2).

Task 5- To estimate the impact of projected climate change on the arrival and deposition of Saharan dust on the snow, and determine their role in snow accumulation and melting for the next decades. *J. Pey, J.I. López-Moreno, P. Salvador, E. Alonso, J. Revuelto, M. Pons, S. Fassnacht.*

All knowledge and tools generated in previous tasks will serve to develop future projections about changes in dust arrival, its deposition and its impact on melt rates and snow duration. We will have the valuable information retrieved in Task 1 for the last 70 years (current and recent trend) and we will use the climatic projections developed by EUROCORDEX (Jacob et al., 2014; https://www.euro-cordex.net/). This database is the most updated repository of high resolution climate models based on the IPCC scenarios (IPCC-CMIP5 and 6). We will use available simulations for RCPs 4.5 y 8.5 (considering intense and very intense emissions respectively for the rest of 21st century). With this data we will assess potential changes in atmospheric patterns and favorable conditions for dust deposition (mostly rain on snow events), and their variability with elevation. We will consider the time horizons 2041-2071 and 2071-2100. The same simulations will be also used to run Crocus model for the Tena Valley to know i) if changes in the snow energy balance of the snow and the timing during snow develops will intensify or reduce the importance of LAI in melting rates (based on results of Tasks 3 and 4); and generate realistic information on how Saharan dust will impact on snowpack and generate new snow projections for the Tena valley adding all generated knowledge. Methodology will be ready to be applied to wider portions of the Pyrenees and other mountain areas of the Iberian Peninsula (and elsewhere), final objective of the project.

Timing: March 2023-November 2023
Expected output: To have new scenarios on snowpack unde different climate projections and assessment of impacts in water management and snow management.
Deliverable: Draft paper at the end of the project, probably published in the first trimester of 2024 (D5.1). Elaboration of recommended guidelines document for water and snow managers at the end of 2023 (D5.2).

CRONOGRAM

01/01/2022

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
T1											D1.1			D1.2										
T2																	D2.2							D2.1
T3																			D3.1					

T4																						D4.1	D4.2	
T5																							D5.1	D5.2

Potential Risks and Contingency Plan. The largest risk involved in this proposal is the short duration of the call and the possibility of having years with low LAI deposition that difficult some of the proposed analyses. We are aware that we will need to be extremely rigid in the timing of the cronogram and start to collect information and start tuning modelling approaches in winter 2022 before the resolution of the project call. The laboratories of IPE-CSIC can perform most of the analyses and we will reserve in advance the need of the analyses of the samples to get results few days after each field campaign. The large experience of both PIs and rest of involved researchers in their respective fields together with the use of the requested observational and modelling tools, the management of fully operative alpine research sites and focussing in a single 200 ha parcel for medium scales and a Pyrenean Valley will facilitate this task. We will obtain interesting tools and results but it is clear that we are offering a pilot study that will need to be applied to larger areas in the future, and it will be suceptible of improvements as the period of collected data will be longer. The potential lack of Saharan dust deposition during two consequtive years is highly improbable. However, in case that any winter month (December-March) records aerosol deposition bellow 0,5 g/m^2 we will perform at each plot dopes of dust at different concentrations ($1g/m^2$; 3 g/m^2; 10 g/m^2) as we have made in exploratory previous experiments and we will focus more in the detalled scales for calibrating and validating the models, before run the valley-scale simulations. We estimate that even with no dust deposition in the two years, around 80% of the expected outcomes might be reached.

Interdisciplinar approach of the proposal

SNOWDUST will need to merge a deep knowledge on mountain hydrology, snow physics, atmospheric sciences and geology; as well as a large variety of observational techniques (snow profiles, drone and satellite-based information, radiometric measurements of the surface, use and maintenance of meteorological instrumental in the field), modellling approaches (snow energy balance of the snow, climate models), statististical analyses and laboratory work. The project benefits from a long trajectory of snow and aerosols research in the Iberian Peninsula and strong links of the research team with other scientists and initiatives working on this field worlwide. The chosen topic of this proposal arises as a scientific need identified during the work done in five previously accomplished I+D+i National Plan projects and other regional and European projects.

The research and work teams are integrated by geologists, geographers, engineers and environmentalists with experience on the individual aspects of the methodology to be presented in the proposal. They have strong background in monitoring the snow properties using manual and remote sensing tecniques, including unmanned aerial vehicles (UAV), and optical and thermal products from satellites. They have also wide experience in aerosols, meteorological and hydrological instrumentation. Measurements and observations derived from the above indicated techniques have been used as forcing, calibration, assimilation and validation data of physically-based energy and mass balance snow models (FSM, SNOWPACK and CROCUS). All of them have also exhibited large involvement in educational programs and science dissemination and outreach activities. The work team includes PhD students and Postdoc fellows closely related with the investigation group who cannot apply as investigation team, and also a considerable number of foreign researchers (USA, Canada, France and Turkey) who are among the most reputed snow scientists. The previous collaboration with all the team members is solid and demonstrated by common publications and participation in national and international research projects and networks.

Available equipment and infraestructures

The research team accounts with a privileged starting point to face the proposed tasks. First, we directly manage the Experimental Catchment of Izas (2056 m a.s.l.) the highest research site for snow and hydrology monitoring, which has been continuously operative since the early 90´s. This site is complemented by the Experimental Formigal-Sarrios AEMET site that is the only site in Spain with reference data for snow and solid precipitation for the World Meteorological Organization, where we have been installing our own devices and using their data for filling gaps in our records or validating variables that we do not measure in Izas due to lack of electric supply line. From previous projects we have adquired broad band albedometers, an aethelometer, two drones with big autonomy and capacity to carry multiespectral and thermal cameras, a terrestrial laser scanner and all equipment to develop the field work. We only ask in this call for a continuous multiespectral radiation sensor that will highly improve our monitoring capabilities on albedo.

For this project we will use the information retrieved by the DONAIRE and POSAHPI projects (historic data from 2016 onwards). The observational network covers from pristine to urban sites in Iberia and the Balearic Islands (see Pey et al. 2020a). The results from the Ordesa and Monte Perdido site will be preferentially used. Bulk aerosol deposition is obtained monthly. Once collected, samples are derived to IPE-CSIC laboratories in which they are registered, filtered and analysed internally or externally. The IPE-CSIC infrastructures and laboratories allow the complete analysis of water and solid samples, including anions and cations; isotopic water analyser (Picarro L2130-i); elemental analysis of carbon, sulfur and nitrogen (LECO CNS928); simultaneous dual ICP-AES (Thermo ICAP DUO 6300) for major element concentrations. For other determinations including trace elements (by means of ICP-MS) or organic and elemental carbon (by a Thermo Optical Analyser SUNSET), as well as for the identification of individual particles (Scanning Electron Microscope) or the study mineral dust mineralogy (by X-Ray Diffraction) we prepare the sub-samples to be analysed in other laboratories (CSIC-IGME and IDAEA-CSIC). For this project, the information provided by a Magee Scientific Aethalometer AE33, in operation at the Experimental Formigal-Sarrios AEMET since January 2019, will be used. This instrument provides in real time the concentrations of aerosol absorption at 7 optical wavelengths spanning the spectrum from 370 nm to 950 nm. Increases in optical absorption at shorter wavelengths may be interpreted in terms of the presence of so-called “Brown” carbonaceous material, usually an indicator of emissions from biomass combustion, whereas increased in larger wavelengths is more related to MD. Thus, the real time data provided by this instrument will inform us about the presence and magnitude of BC and MD aerosols in the vicinity of the experimental set-up.

4. IMPACTO CIENTÍFICO-TÉCNICO - *SCIENTIFIC-TECHNICAL IMPACT*

To our knowledge this is the first attempt to design a research on impacts of LAI on snow that cover in detail the full interconnected chain of processes from aerosols´transport, deposition and evolution of impurities in the snow profile to the impacts on melting rates, stability of the snow and the quality of snow for winter sports. The objectives of this project meet with one of the hottest research problems in snow studies that have resulted in publication in top journals (i.e. Skiles et al., 2018; Rowe et al., 2019; Bair et al., 2021), and this proposal could be the seed of a new research line that currently is prioritary for NASA, CEN (Centre dÉtudes de la Neige Francia), Swiss Snow and Avalanche Institute (SLF) and Finish Meteorological Institute (FMI). Our proposal is obviously more humble but it could serve to increase the current interaction that we already have with the mentioned institutions, increasing our competitiveness, leadership and access to international funding.

The almost lack of studies on this topic in Mediterranean mountains, and the scientific and applied interest of the proposal warrants the obtention of high impact publications from the proposed tasks. This is also supported by the solid experience of the applicants in this regard (only the two PIs sum more than 350 JCR publications that have received more than 25000 citations). Publications will be made in open access format (facilitated by agreements of CSIC with main editorials) to increase the accessibility and visibility of our results. In addition, we will not only present the results in the most important international conferences, but also we will propose to chair specific sessions on this topic in the the European and American Geophysical Union meetings as we have been doing in previous editions. This plan will increase the international projection of our research institutions and the visibility of the funding agency.

Given the duration of the project we aim to work in a "pilot" case study that is the Tena Valley in Central Pyrenees. This case study will serve to ellaborate a methodological framework covering all the mentioned steps that will be developed in open source software (R and or Phyton) that will be carefully reported and will be made public in repositories such as PyPi (https://pypi.org/) or GitHub (https://github.com/). The aim is to expand this research to rest of Pyrenees and Spanish mountains after the end of the project. We plan to collect a novel record on atmospheric patterns, aerosols arrival and deposition on snow, albedo and melt rates that is rather unique filling important knowledge gaps in this field. This dataset may be also of great interest for other researchers interested to validate their own models or perform global approaches. For this reason, by the end of the project we will make publicly available in Zenodo (https://zenodo.org/) all generated datasets (in .txt or .csv for tables and .netcdf for 4D information), including all required metadata to facilitate its use by the widest research and management community as possible. In addition, the new research tools and original analysis are expected to be integrated in the main national and international networks to study mountains, criosphere and climate change. This is particularly useful for being involved in the highest level international projects funded by The European Comission (H2020, JPI, ERANET, LIFE, FEDER-POCTEFA) and international consortiums (i.e. GEWEX, European Spatial Agency, etc).

5. IMPACTO SOCIAL Y ECONÓMICO - *SOCIAL AND ECONOMIC IMPACT*

The present project aims to study the deposition of Saharan dust and other LAI on snow and its influence on melt rates and snow duration in the Pyrenees with a double purpose: 1) to improve the projections of snow availability in the next decades; and 2) improve the capability of early warning systems and seasonal forecasts on snow melting, avalanche hazards and snow quality in ski resorts. Both questions have direct implications on 1) the protection of the environments and natural resources -water availability, vegetation and fauna fenology, forest productivity, etc-; 2) the economy of mountain areas and surrounding lowlands linked to dam management for agricultural, hydropower and urban supply; and 3) the safety of local population by developing better information to be directly implemented in avalanche forecast and road maintenance. Only focussing on Aragon, where de pilot study will be performed, it accounts of 400,000 hectars of irrigated crops from Pyrenean reservoirs, the 40% of the municipalities and the 43.7% of the territory are in mountains, and a 5% of the PIB (GI) depends on tourism related with snow thanks to 1.5M of skiers per year.

All the above mentioned markedly justifies the connection of this project proposal with the ecological transition objectives in which this proposal relies.
In addition to the generated scientific knowledge, we plan to generate fully replicable and publicly available methodological tools that can be implemented in the Automatic Information System (SAIH) of the Ebro basin authority (CHE), improving their capabilities to estimate the water stored as snow in the different catchments, to improve the seasonal and short-term predictions of runoff that are key to optimize the management of dams for different water supplies and flood risk mitigation purposes. Our products can be also of interest for AEMET who are the responsable of elaborating the avalanche risk bulletins that may be improved if implementing the effect of LAI concentrations on snow stability. Finally, the results are needed to planify and improve the management of snow (snow farming) in ski resorts. In this case we will work hand in hand with Formigal-Aramón ski resort that is next to our study site and they are facilitating our research since years ago. The three (CHE, AEMET and Formigal-ARAMON) institutions are aware of this proposal and they have provided respective letters of interest. We will keep at least two in-person meetings with them along the project (one to discuss the methodology and revise specific products of their interest, and a second to present the results). In addition, we will provide to each of them a summary report adapted individually to their needs, including good practise guidelines to improve their adaptation to climate change. The reports will be made publicly available in the IPE-CSIC site and sent to different regional and national organisms in charge of natural resources, environment and/or land management.

The project will be also accompanied by an ambitious dissemination and outreach plan, composed by the following actions: I) preparation of a profesionally edited documentary (8-12 minutes) explaining different aspects of the research objectives, methods and results of the projects to be uploaded in the Youtube channel of the Pyrenean Institute of Ecology (IPE); ii) presentation of the project in conferences or seminars for students from 10 to 17 years in schools and institutes; and also divulgative talks in villages or towns near the study site; iii) organization of courses about the interaction between aerosols and snow in summer courses of the University of Zaragoza and the International University Menéndez Pelayo (UIMP) as we have been doing regularly in the last years; iv) women participants in the research team, will participate in the activities organized by CSIC in the field of promoting the gender equity in science and highlighting the research activity made by women, and also to promote science specially for young girls, activities particularly relevant in the field of earth sciences research, even more in snow science, where despite of big advances in the last decade, there is still a clear unbalance; v) using our existing contacts with journalists and the comunication services of CSIC and IPE we will give visibility of our research in media, maintining the high presence on newspapers, radio and TV that our team already have. To highlight that in the three last years our research has been twice in the front page of El País, we were filmed for a full chapter of the RTVE program “Informe Semanal” and for TV3 “30 minutes”; vi) IPE-CSIC has a community manager that ensures fluid presentation of our main results and project´s advances in the most common social media channels.


EXPONE

HACE CONSTAR

SAMUEL TOMAS BUISAN SANZ

6. CONDICIONES ESPECÍFICAS PARA LA EJECUCIÓN DE DETERMINADOS PROYECTOS (ANEXO III de la convocatoria)– *SPECIFIC CONDITIONS FOR THE EXECUTION OF CERTAIN PROJECTS*

NO PROCEDE

REFERENCIAS (* indica referencias con participación del equipo solicitante)

*Alonso-González, E. et al. (2020). ‘Snowpack sensitivity to temperature, precipitation, and solar radiation variability over an elevational gradient in the Iberian mountains.’ Atmospheric Research 243, 104973.

*Amato, F. et al. (2009). ‘Quantifying road dust resuspension in urban environment by Multilinear Engine: a comparison with PMF2’. Atmospheric Environment 43, 2770-2780.

*Anderson, A., et al. (2006). ‘The Effects of Dust on Avalanche Formation’. Proceedings of the 2006 International Snow Science Workshop, Telluride, Colorado.

*Barry, R. and Gan, T.Y. (2011). ‘The Global Cryosphere: Past, Present and Future’. Cambridge University Press, ISBN 9780521156851, 498 pp.

*Barnet, T.P. et al. (2005). ‘Potential Impacts of a Warming Climate on Water Availability in Snow-Dominated Regions’. Nature, 438, 303-309.

*Basart, S. et al. (2012), ‘Development and Evaluation of BSC-DREAM8b Dust Regional Model over North Africa, Mediterranean and Middle East’. Tellus B: Chem. & Phys.Met. 64(1), 18539.

* Belis, C.A. et al. (2019). 'European guide on air pollution source apportionment with receptor models - Revised version 2019', EUR 29816 EN, Publications Office of the European Union, Luxembourg, 2019, ISBN 978-92-76-09001-4, doi:10.2760/439106, JRC117306.

*Bengtsson, L. et al., 'The HARMONIE–AROME Model Configuration in the ALADIN–HIRLAM NWP System', Monthly Weather Review 145(5), 1919–1935.

*Di Mauro, B. et al. (2015). 'Mineral dust impact on snow radiative properties in the European Alps combining ground, UAV, and satellite observations'. Journal of Geophysical Research (Atmosheres), 120, 6080– 6097.

*Dumont, M. et al., (2014). 'Contribution of Light-Absorbing Impurities in Snow to Greenland's Darkening since 2009'. Nature Geoscience 7, 509–512.

*Jacob, D. et al. (2014). 'EURO-CORDEX: New High-Resolution Climate Change Projections for European Impact Research'. Regional Environmental Change 14 (2).

*Flanner, M.G. et al. (2007), 'Present-day Climate Forcing and Response from Black Carbon in Snow'. Journal of Geophysical Research, 11, D11202.

*Flanner, M.G. et al. (2009), 'Springtime Warming and Reduced Snow Cover from Carbonaceous Particles', Atmos. Chem. Phys. 9, 2481–2497.

*García-Ruiz et al. (2011) 'Mediterranean Water Resources in a Global Change Scenario', Earth-Science Reviews 105, 3–4.

*Gascoin, S. et al. (2020). 'Estimating fractional snow cover in open terrain from Sentinel-2 using the normalized difference snow index'. Remote Sensing, 12(18), 2904.

*Gilaberte-Búrdalo, M. et al. (2017). 'Assessment of ski condition reliability in the Spanish and Andorran Pyrenees for the second half of the 20th century'. Applied Geography, 70, 127-142.

*Lee, Y.H. et al. (2013) 'Evaluation of Preindustrial to Present-Day Black Carbon and Its Albedo Forcing from Atmospheric Chemistry and Climate Model Intercomparison Project (ACCMIP)'. Atmospheric ChemIstry and PhysIcs, 13, 2607–2634.

*López-Moreno, J.I., García-Ruiz, J.M. (2004). 'Influence of snow accumulation and snowmelt on streamflow in the Central Spanish Pyrenees'. International Journal of Hydrological Sciences 49(5), 787-802.

*López-Moreno, J.I et al. (2011). 'Effects of climate change on the intensity and frequency of heavy snowfall events in the Pyrenees'. Climatic Change 105, 489–508.

*López-Moreno, J.I. et al. (2013). Response of snow processes to climate change: spatial variability in a small basin in the Spanish Pyrenees. Hydrological Processes 27 (18).

*López-Moreno, J.I. et al. (2017). 'Different sensitivities of snowpack to warming in Mediterranean climate mountain areas'. Environmental Research Letters, 12: 074006.

*López-Moreno, J.I. et al (2020). 'Decoupling of warming mountain snowpacks from hydrological regimes'. Environmental Research Letters 15:11.

*López-Moreno, J.I. et al (2021). 'Rain on snow events in a warmer climate'. Environmental Research Letters 16:4.

* López, V. et al. (2019). 'Influence of the origin of the air mass on the background levels of atmospheric particulate matter and secondary inorganic compounds in the Madrid air basin'. Environmental Science and Pollution Research, 26, 30426–30443.

*Le-Roux, G. et al. (2021). 'Elevation-dependent trends in extreme snowfall in the French Alps from 1959 to 2019'. The Cryosphere, 15, 4335–4356.

*Morán-Tejeda, E. et al. (2014). 'Streamflow timing of mountain rivers in Spain: Recent changes and future projections'. Journal of Hydrology, 517,1114-1127.

*Pey, J. et al. (2013). 'African dust outbreaks over the Mediterranean Basin during 2001–2011: PM10 concentrations, phenomenology and trends, and its relation with synoptic and mesoscale meteorology'. Atmospheric Chemistry and Physics, 13, 1395-1410.

*Pey, J. et al. (2020a). 'Phenomenology and geographical gradients of atmospheric deposition in southwestern Europe: results from a multi-site monitoring network'. Science of the Total Environment, 140745.

*Pey, J. et al. (2020b). 'Snow impurities in the Central Pyrenees: from their geochemical and mineralogical composition towards their impacts on snow albedo'. Atmosphere 11(9), 937.

*Revuelto, J. et al. (2014). 'Mapping the annual evolution of snow depth in a small catchment in the Pyrenees using the long-range terrestrial laser scanning'. Journal of Maps 10(3): 379-393.

*Revuelto, J. et al. (2021). 'Light and Shadow in Mapping Alpine Snowpack with Unmanned Aerial Vehicles in the Absence of Ground Control Points'. Water Resources Research, 57(6).

*Querol, X. et al. (2009). 'African dust contributions to mean ambient PM10 levels across the Mediterranean Basin'. Atmospheric Environment, 43, 4266-4277.

*Painter, T.H. et al. (2018). 'Variation in Rising Limb of Colorado River Snowmelt Runoff Hydrograph Controlled by Dust Radiative Forcing in Snow'. Geophysical Research Letters, 45(2), 797–808.

* Painter, T.H. et al. (2013). 'End of the Little Ice Age in the Alps Forced by Industrial Black Carbon', PNAS, 110(38), 15216-15221.

*Painter, T.H. et al. (2011) 'Response of Colorado river runoff to dust radiative forcing in snow', PNAS 107, 40.

*Painter, T.H. et al., (2007). 'Contact Spectroscopy for Determination of Stratigraphy of Snow Optical Grain Size'. Journal of Glaciology 53(180), 121–127

*Salvador, P. et al. (2021). 'Synoptic classification of meteorological patterns and their impact on air pollution episodes and new particle formation processes in a south European air basin'. Atmospheric Environment, 245, 118016.

*Salvador, P. et al., 2004. 'Identification and characterisation of sources of PM10 in Madrid (Spain) by statistical methods'. Atmospheric Environment, 38, 435-447.

*Salvador, P. et al., 2008. 'A combined analysis of backward trajectories and aerosol chemistry to characterise long-range transport episodes of particulate matter: The Madrid air basin, a case study'. Science of the Total Environment, 390, 495-506.

*Salvador, P. et al., 2010. 'Evaluation of aerosol sources at European high altitude background sites with trajectory statistical methods'. Atmospheric Environment, 44, 2316-2329.

*Sanmiguel-Vallelado, A. et al. (2020). 'Variable effects of forest canopies on snow processes in a valley of the central Spanish Pyrenees'. Hydrological Processes 34: 2247– 2262.

*Sanmiguel-Vallelado, A. et al. (2021). 'Snow dynamics influence tree growth by controlling soil temperature in mountain pine forests'. Agricultural and Forest Meteorology, 296, 108205.

*Shao, Y. et al. (2011). 'Parameterization of size-resolved dust emission and validation with measurements'. Journal of Geophysical Research, 116, D08203.

*Skiles et al. (2012) 'Dust radiative forcing in snow of the upper Colorado river basin: 2. Interannual variability in radiative forcing and snowmelt rates', Water Resour. Res 48, W07522.

*Spandre et al. (2019). 'Winter tourism under climate change in the Pyrenees and the French Alps: relevance of snowmaking as a technical adaptation'. The Cryosphere, 13, 1325–1347.

*Sturm (2017). 'Water and life from snow: `A trillion dollar science question´. Water Resources Research, 53, 3534– 3544.

*Vionnet et al. (2012). 'The Detailed Snowpack Scheme Crocus and Its Implementation in SURFEX v7.2', Geoscientific Model Development 5, 3.

*Warren, S.G. (1982). 'Optical Properties of Snow', Reviews of Geophysics 20, no. 1.